Agilent Technologies

Advanced Design System 2002

Circuit Components
Nonlinear Devices

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Chapter 1: Devices and Models, Diode

Bin Model

The BinModel in the Diodes library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

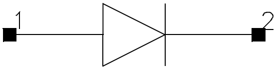
For information on the use of the binning feature, refer to the section *"Bin Model (Bin Model for Automatic Model Selection."* This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components.*

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

Diode (PN-Junction Diode)

Symbol



Parameters

Model = name of a Diode_Model

Area = scaling factor that scales certain parameter values of the Diode_Model (default 1)

Periph = scaling factor that affects the sidewall parameters of the Diode_Model (default=0)

Width = Geometric width of diode junction (meters, default = 0)

Length = Geometric length of diode junction (meters, default = 1)

Region = state of the diode: off, on (default: on) that the DC simulator will use as its initial guess. Its sole purpose is to give the DC simulator a good initial guess to enhance its convergence properties.

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)

Noise = noise generation (yes = 1; default) (no =0)

_M = number of devices in parallel (default: 1)

Range of Usage

Area > 0

Periph ≥ 0

Width = 0

Length = 0

Notes/Equations/References

The size of the diode may be specified geometrically using the Width and Length parameters if the Area and Periph parameters are not explicitly specified. Default values for the width and length are taken from the width and length specified in the model if they are not specified in the instance. The model parameters Shrink and Dwl are also used. The area and periphery are calculated using the following:

$W' = \text{Width} \times \text{Shrink} + \text{Dwl}$

$L' = \text{Length} \times \text{Shrink} + \text{Dwl}$

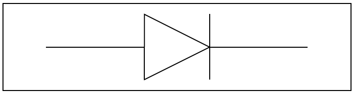
$\text{Area} = W' \times L'$

$\text{Periph} = 2 \times W' + 2 \times L'$

1. If the width and length are not specified, then the area and periphery are taken as specified. If the area is not specified on the instance, then the default area is taken from the model if a non-zero value is specified there; otherwise the area defaults to 1. If the periphery is not specified on the instance, then the default periphery is taken from the model if a non-zero value is specified there; otherwise the periphery defaults to 0.
2. In either case, the area must be greater than zero. The periphery may be zero, in which case the sidewall components are not simulate.
3. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated Diode_Model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to Diode_Model to see which parameter values are scaled.
4. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
5. This device has no default artwork associated with it.
6. *SPICE2: A Computer Program to Simulate Semiconductor Circuits*, University of California, Berkeley.
7. P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE*, Second Edition, McGraw-Hill, Inc., 1993.

Diode_Model (PN-Junction Diode Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 1-1. Diode_Model Parameters

Parameter	Description	Unit	Default
Level	Model level selector (1=standard, 3=geometry)		1
Is[†, ††]	saturation current (with N, determines diode dc characteristics)	A	10^{-14}
Rs[†]	ohmic resistance	ohm	0.0
N	emission coefficient (with Is, determines diode dc characteristics)		1.0
Tt	transit time	sec	0.0
Cjo[†, ††]	zero-bias junction capacitance	F	0.0
Vj[††]	junction potential	V	1.0
M	grading coefficient		0.5
Fc	forward-bias depletion capacitance coefficient		0.5
Imax	explosion current beyond which diode junction current is linearized	A	1.0
Isr[†, ††]	recombination current parameter	A	0.0
Nr	emission coefficient for Isr		2.0

[†] Parameter value is scaled with Area specified with the Diode device.

[††] Value varies with temperature based on model Tnom and device Temp.

[†††] Sbd = Schottky Barrier Diode.

[‡] jn=PN junction diode.

[‡‡] Value 0.0 is interpreted as infinity.

* Parameter value is scaled with the Periph specified with the Diode device/

Table 1-1. Diode_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Ikf[†]	high-injection knee current	A	infinity[‡‡]
Ikr[†]	Reverse high injection knee current	A	0
IkModel	Model to use for Ikf/Ikr: 1=ADS/Libra/Pspice, 2=Hspice		1
Xti	saturation-current temperature exponent (with Eg, helps define the dependence of Is on temperature)		3.0 jn [‡] 2.0 Sbd
Bv	reverse breakdown voltage	V	infinity[‡‡]
Ibv[†]	current at reverse breakdown voltage	A	0.001
Nbv	reverse breakdown ideality factor		1.0
Ibvl[†]	low-level reverse breakdown knee current	A	0.0
Nbvl	low-level reverse breakdown ideality factor		1.0
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0
Ffe	flicker noise frequency exponent		1.0
Jsw*[††]	sidewall saturation current	A	0.0
Cjsw*[††]	sidewall zero-bias capacitance	F	0.9
Msw	sidewall grating coefficient		0.33
Vjsw[††]	sidewall junction potential	V	Vj
Fcsw	sidewall forward-bias depletion capacitance coefficient		0.0
Area	Default area for diode		0

[†] Parameter value is scaled with Area specified with the Diode device.

[††] Value varies with temperature based on model Tnom and device Temp.

[†††] Sbd = Schottky Barrier Diode.

[‡] jn=PN junction diode.

[‡‡] Value 0.0 is interpreted as infinity.

* Parameter value is scaled with the Periph specified with the Diode device/

Table 1-1. Diode_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Periph	Default periphery for diode		0
Width	Default width for diode	m	0
Length	Default length for diode	m	0
Dwl	Geometry width and length addition	m	0
Shrink	Geometry shrink factor		1.0
Tnom			
Tlev	Temperature equation selector (0/1/2)		0
Tlevc	Temperature equation selector for capacitance (0/1/2/3)		0
Xti	saturation-current temperature exponent (with Eg, helps define the dependence of Is on temperature)		3.0 jn ‡ 2.0 Sbd
Eg	energy gap (with Xti, helps define the dependence of Is on temperature)	eV	1.11 0.69 Sbd††† 0.67 Ge 1.43 GaAs
EgAlpha	Energy gap temperature coefficient alpha	eV/^{o}C	7.02e-4
EgBeta	Energy gap temperature coefficient beta	K	1108
Tcjo	Cjo linear temperature coefficient	1/^{o}C	0
Tcjsw	Cjsw linear temperature coefficient	1^{o}C	0
Ttt1	Tt linear temperature coefficient	1/^{o}C	0
Ttt2	Tt quadratic temperature coefficient	1/(^{o}C)^2	0

† Parameter value is scaled with Area specified with the Diode device.

†† Value varies with temperature based on model Tnom and device Temp.

††† Sbd = Schottky Barrier Diode.

‡ jn=PN junction diode.

‡‡ Value 0.0 is interpreted as infinity.

* Parameter value is scaled with the Periph specified with the Diode device/

Table 1-1. Diode_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Tm1	Mj linear temperature coefficient	1/°C	0
Tm2	Mj quadratic temperature coefficient	$1/(^{o}C)^{2}$	0
Tvj	Vj linear temperature coefficient	1/°C	0
Tvjsw	Vjsw linear temperature coefficient	1/°C	0
Trs	Rs linear temperature coefficient	1/°C	0
Tbv	Bv linear temperature coefficient	1/°C	0
wBv	reverse breakdown voltage (warning)	W	0.0
wPmax	maximum power dissipation (warning)	W	0.0
AllParams	name of DataAccessComponent for file-based parameter values		

† Parameter value is scaled with Area specified with the Diode device.

†† Value varies with temperature based on model Tnom and device Temp.

††† Sbd = Schottky Barrier Diode.

‡ jn=PN junction diode.

‡‡ Value 0.0 is interpreted as infinity.

* Parameter value is scaled with the Periph specified with the Diode device/

Notes/Equations/References

1. This model supplies values for a Diode device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.
3. Area and Periph

   When level is set to standard:

   Device's Area will be used if it is specified and > 0, Otherwise the model's area will be used.

   Device's Periph will be used if it is specified, otherwise the model's Periph will be used.

   When level is set to geometry:

   Device Width and Length will be used if they are specified, otherwise the model's Width and Length will be used.

   If both Width > 0 and Length > 0

   $\text{Area} = w \times l$

   $\text{Periph} = 2 \times (w + l)$

   $\text{where } w = \text{Width} \times \text{Shrink} + \text{Dwl}$

   $l = \text{Length} \times \text{Shrink} + \text{Dwl}$

   otherwise the Area and Periph specified in the device or model (follow the same logic described in the Level = standard case) will be used to compute the new area and periph.

   $\text{Area} = \text{area (from device/model)} \times \text{Shrink}^2$

   $\text{Periph} = \text{periph (from device/model)} \times \text{Shrink}$

   and the effective area

   $$\text{aeff} = \text{Area} \times \text{Periph} \times \frac{Isw}{Is}$$

4. Currents and Conductances

   Is and Isr in the following equations have been multiplied by the effective area factor aeff.

   If vd > vmax

   $\text{idexp} = [\text{Imax} + (\text{vd} - \text{vmax}) \times \text{gmax}]$

gdexp = gmax

where

vmax = N × vt × ln $\left(\frac{Imax}{Is} + 1\right)$

gmax = $\frac{Imax + Is}{N + vt}$

vt is thermal voltage

If vmax ≥ vd ≥ - 10 × N × vt

idexp = $Is\left(e^{\frac{vd}{N \times vt}} - 1\right)$

gdexp = $\frac{Is}{N \times vt} \times e^{\frac{vd}{N \times vt}}$

If vd < -10 × N × vt

idexp = $\left[Is(e^{-10} - 1) + \frac{Is \times e^{-10}}{N \times vt}(vd + 10 \times N \times vt)\right]$

gdexp = $\frac{Is}{N \times vt} \times e^{-10}$

Breakdown current contribution is considered if Bv is specified and Ibv is not equal to zero.

If -(vd + Bv) > vbmax

ib= -{Imax + [-(vd + Bv) - vbmax] × gbmax - ibo}

gb = gbmax

where vbmax = Nbv × vt × ln $\left(\frac{Imax}{Ibv}\right)$

gbmax = $\left(\frac{Imax}{Nbv \times vt}\right)$

If vbmax ≥ -(vd + Bv) > -MAXEXP × Nbv × vt

$$\text{ib} = \left(-Ibv \times e^{\frac{-(vd+Bv)}{Nbv \times vt}} - ibo\right) \times aeff$$

$$\text{gb} = \frac{-ib}{Nbv \times vt}$$

Otherwise

ib = 0

gb = 0

For ibo

If Bv < MAXEXP × Nbv × vt

$$\text{ibo} = Ibv \times e^{\frac{-Bv}{Nbv \times vt}}$$

Otherwise

ibo = 0

MAXEXP is the maximum exponent supported by the machine. The value ranges from 88 to 709.

Low level reverse breakdown current is considered if Ibvl is specified and not equal to zero.

If -(vd + Bv) > vlbmax

ilb = -{Imax + [-(vd + Bv) - vlbmax] × glbmax - ilbo}

glb = glbmax

$$\text{where vlbmax} = \text{Nbvl} \times \text{vt} \times \ln \frac{Imax}{Ibvl}$$

$$\text{glbmax} = \frac{Imax}{Nbvl \times vt}$$

If vlbmax ≥ -(vd + Bv) > - MAXEXP × Nbvl × vt

$$\text{ilb} = -\left(Ibvl \times e^{\frac{-(vd+Bv)}{Nbvl \times vt}} - ilbo\right) \times aeff$$

$$\text{glb} = \frac{-ilb}{Nbvl \times vt}$$

Otherwise

ilb = 0

glb = 0

For ilbo

If Bv < MAXEXP × Nbvl × vt

ilbo = Ibvl × $e^{\frac{-Bv}{Nbvl \times vt}}$

Otherwise

ilbo = 0

Recombination current is considered if Isr is specified and not equal to zero.

If vd > vrmax

ir = Imax + (vd - vrmax) × grmax

gr = grmax

where vrmax = Nr × vt × ln $\left(\frac{Imax}{Isr} + 1\right)$

grmax = $\frac{Imax + Isr}{Nr \times vt}$

If vrmax ≥ vd ≥ - 10 × Nr × vt

ir = Isr × $\left(e^{\frac{Vd}{Nr \times vt}} - 1\right)$

gr = $\frac{Isr}{Nr \times vt} \times e^{\frac{vd}{Nr \times vt}}$

If vd < - 10 × Nr × vt

ir = $\left[Isr \times (e^{-10} - 1) + Isr \times \frac{e^{-10}}{Nr + vt}(vd + 10 \times Nr \times vt)\right]$

gr = $\frac{Isr}{Nr \times vt} \times e^{-10}$

iexp = idexp + ib + ilb

gexp = gdexp + gb + glb

There are two ways to model high injection effect.

When IkModel is set to ADS/Libra/Pspice and when Ikf is not equal to zero and iexp > 0.

Ikfa = Ikf × aeff

$$\text{id} = \text{iexp} \times \sqrt{\frac{Ikfa}{Ikfa + iexp}}$$

$$\text{gd} = \text{gexp} \times \frac{1}{2}\left(1 + \frac{Ikfa}{Ikfa + iexp}\right)\sqrt{\frac{Ikfa}{Ikfa + iexp}}$$

When IkModel is set to Hspice:

If Ikf is not equal to zero and iexp > 0

Ikfa = Ikf × Area

$$\text{id} = \text{iexp} \times \frac{1}{1 + \sqrt{\frac{iexp}{Ikfa}}}$$

$$\text{gd} = \text{gexp} \times \left(\frac{1}{1 + \sqrt{\frac{iexp}{Ikfa}}}\right) \times \left(1 - \frac{\sqrt{\frac{iexp}{Ikfa}}}{2\left(1 + \sqrt{\frac{iexp}{Ikfa}}\right)}\right)$$

Otherwise if Ikr is not equal to zero and iexp < 0

Ikra = Ikr × Area

$$\text{id} = \text{iexp} \times \frac{1}{1 + \sqrt{\frac{-iexp}{Ikra}}}$$

$$\text{gd} = \text{gexp} \times \left(\frac{1}{1 + \sqrt{\frac{-iexp}{Ikra}}}\right) \times \left(1 - \frac{\sqrt{\frac{-iexp}{Ikra}}}{2\left(1 + \sqrt{\frac{-iexp}{Ikra}}\right)}\right)$$

The total diode dc current and conductance

Id = id + ir + Gmin × vd

Gd = gd + gr + Gmin

where Gmin is minimum junction conductance.

5. **Diode Capacitances**:

Diffusion capacitance

$$\mathrm{Cdiff} = \mathrm{Tt} \times \mathrm{gdexp}$$

Junction capacitance

If vd ≤ Fc × Vj

$$\mathrm{Cj} = \mathrm{Area} \times \mathrm{Cjo} \times \left(1 - \frac{vd}{Vj}\right)^{-M}$$

If Vd > Fc × Vj

$$\mathrm{Cj} = \mathrm{Area} \times \frac{Cjo}{(1 - Fc)^{M}}\left[1 + \left(\frac{M}{Vj \times (1 - Fc)}\right) \times (vd - Fc \times Vj)\right]$$

For side wall capacitance

If vd ≤ Fcsw × Vjsw

$$\mathrm{Cjsw} = \mathrm{Periph} \times \mathrm{Cjsw} \times 1 - \left(\frac{vd}{Vjsw}\right)^{-Msw}$$

If vd > Fcsw × Vjsw

$$\mathrm{Cjsw} = \mathrm{Periph} \times \frac{Cjsw}{(1 - Fcsw)^{Msw}}\left[1 + \left(\frac{Msw}{Vjsw \times (1 - Fcsw)}\right) \times (vd - Fcsw \times Vjsw)\right]$$

Total capacitance

$$\mathrm{Cd} = \mathrm{Cdiff} + \mathrm{Cj} + \mathrm{Cjsw}$$

6. **Temperature Effects**

Parameters Eg, Is, Isr, Cjo, and Vj are temperature dependent.

Note Expressions for temperature dependence of energy gap and intrinsic carrier concentration are for silicon only. Depletion capacitances for non-silicon diodes may not scale properly with temperature even if values of Eg and Xti are altered as noted in the parameters Table 1-1.

For more information on Diode_Model, its parameters and equations, see [1].

Parameters Eg, Is, Isr, Cjo, Vj, Jsw, Cjsw and Vjsw are temperature-dependent.

7. Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation currents Is, Isr, and Jsw scale as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{qEg}{kNTemp} + \frac{Xti}{N}ln\left(\frac{Temp}{Tnom}\right)\right]$$

$$Isr^{NEW} = Isr \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{qEg}{kNrTemp} + \frac{Xti}{Nr}ln\left(\frac{Temp}{Tnom}\right)\right]$$

$$Jsw^{NEW} = Jsw \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{qEg}{kNTemp} + \frac{Xti}{N}ln\left(\frac{Temp}{Tnom}\right)\right]$$

The energy bandgap E_G and intrinsic concentration n_i for silicon vary as:

$$E_G(T) = 1.16 - \frac{7.02 \times 10^{-4} T^2}{T + 1108}$$

$$n_i(T) = 1.45 \times 10^{10}\left(\frac{T}{300.15}\right)^{3/2} \exp\left(\frac{E_G(300.15)}{2k300.15/q} - \frac{E_G(T)}{2kT/q}\right)$$

The junction potential VJ and Vjsw vary as:

$$Vj^{NEW} = Vj\frac{Temp}{Tnom} + \frac{2kTemp}{q}ln\left(\frac{n_i(Tnom)}{n_i(Temp)}\right)$$

$$Vjsw^{NEW} = Vjsw\frac{Temp}{Tnom} + \frac{2kTemp}{q}ln\left(\frac{n_i(Tnom)}{n_i(Temp)}\right)$$

The junction depletion capacitances Cjo and Cjsw vary as:

$$Cjo^{NEW} = Cjo\left(1 + M\left[1 + 4 \times 10^{-4}(Temp - Tnom) - \frac{Vj^{NEW}}{Vj(Tnom)}\right]\right)$$

$$Cjsw^{NEW} = Cjsw\left(1 + Msw\left[1 + 4 \times 10^{-4}(Temp - Tnom) - \frac{Vjsw^{NEW}}{Vjsw(Tnom)}\right]\right)$$

Noise Model

Thermal noise generated by resistor Rs is characterized by the following spectral density:

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Shot noise and flicker noise (Kf, Af, Ffe) generated by the dc current flow through the diode is characterized by the following spectral density:

$$\frac{< i_d^2 >}{\Delta f} = 2qI_D + \mathrm{k}_f \frac{I_D^{a_f}}{f^{f_{fe}}}$$

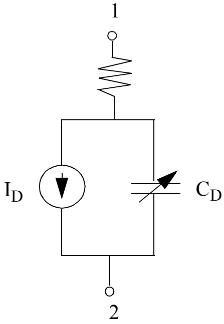
In the preceding expressions, *k* is Boltzmann’s constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, *kf*, *af*, and *ffe* are model parameters, *f* is the simulation frequency, and Δ*f* is the noise bandwidth.

8. The sidewall model parameters model a second ideal diode that scales with the instance parameter Periph, in parallel with the main diode that scales with the instance parameter Area. The series resistance Rs scales only with Area, not with Periph.
9. To model a Zener diode, the model parameters Bv and Ibv can be used. Bv should be set to the Zener reverse breakdown voltage as a positive number. Ibv is set to the breakdown current that flows at that voltage as a positive number; typically this is in the range of 1 to 10 mA. The series resistance Rs should also be set; a typical value is 1 Ohm.

References:

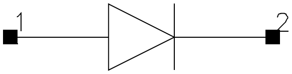
[1] Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

Equivalent Circuit



HPDiode (HP_Root Diode)

Symbol



Parameters

Model = name of model instance

Area = junction (default: 1.0)

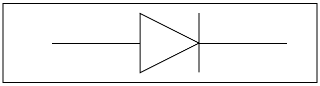
_M = number of devices in parallel (default: 1)

Range of Usage

Area > 0

HP_Diode_Model (HP_Root Diode Model)

Symbol



Parameters

File = name of rawfile

Rs = series resistance (default: 0)

Ls = parasitic inductance (default: 0)

Tt = transit time, in seconds (default: 0.0)

All Params = DataAccessComponent-based parameters

Range of Usage

N/A

Notes/Equations/References

1. This model supplies values for an HPDiode device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.
3. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.
4. For more information refer to:

   D. Root, “Technology independent large signal non quasi static FET model by direct construction from automatically characterized device data,” in *21st EuMC*, 1991, p. 927.

   D. E. Root, S. Fan, and J. Meyer, “Technology-independent large-signal FET models: A measurement-based approach to active device modeling,” in *Proc. 15th ARMMS Conf., Bath, U.K.*, Sept. 1991, pp. 1-21.

   D. E. Root, M. Pirola, S. Fan, W. J. Anklam, and A. Cognata, “Measurement-based large-signal diode modeling system for circuit and device design,” *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2211-2217, Dec. 1993.

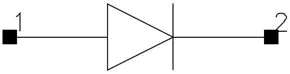
D. E. Root and B. Hughes, “Principles of nonlinear active device modeling for circuit simulation,” in *32nd ARFTG Conf. Dig*., Tempe, AZ, 1988, pp. 3-26.

D. E. Root, S. Fan, and J. Meyer, “Technology-independent large-signal non quasi static FET models by direct extraction from automatically characterized device data,” in *21st European Microwave Conf. Proc.*, Stuttgart, Germany, 1991, pp. 927-932.

D. E. Root and S. Fan, “Experimental evaluation of large-signal modeling assumptions based on vector analysis of bias-dependent S-parameters data from MESFET's and HEMT's,” in *IEEE MTT-S Int. Microwave Symp. Tech. Dig.*, 1992, pp. 927-932.

JUNCAP (Philips JUNCAP Device)

Symbol



Parameters

Model = name of a JUNCAP device

Ab = Diffusion area, m^2 (default: 1.0e-12)

Ls =Length of sidewall of the diffusion area that is not under the gate, m.(default = 1.0e -6)

Lg = Length of sidewall of the diffusion area that is under the gate, m.(default = 1.0e -6)

Region = DC operating region; 0 =on, 2=rev, 3 = sat (default = on)

Temp = Device operating temperature (default = 25)

Mode = simulation mode: linear, nonlinear, standard (default = nonlinear

Noise = noise generation; yes, no, standard. (default = yes)

_M = number of devices in parallel (default = 1)

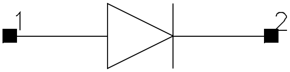
Notes/Equations/References

1. Additional information is available from the following website:

   http://www.semiconductors.com/Philips_Models/documentation/add_models/

Juncap_MODEL (Philips JUNCAP Model)

Symbol



Parameters

Tr= Temperature at which the parameters for the reference transistor have been determined, in Celsius (default: 25)

Vr = Voltage at which parameters have been determined (default: 0.0)

Jsgbr = Bottom saturation-current density due to electron-hole generation at V = Vr.
A/m^2 (default: 1.0e-3)

Jsdbr = Bottom saturation-current density due to diffusion from back contact.
A/m^2 (default: 1.0e-3)

Jsgsr = Sidewall saturation-current density due to electron-hole generation at V =Vr.
A/m (default: 1.0e-3)

Jsdsr = Sidewall saturation-current density due to diffusion from back contact.
A/m (default: 1.0e-3)

Jsggr = Gate-edge saturation-current density due to due to electron-hole generation at V =Vr.
A/m^2 (default: 1.0e-3)

Jsdgr = Gate-edge saturation-current density due to diffusion from back contact.
A/m (default: 1.0e-3)

Cjbr = Bottom-junction capacitance at V = Vr. F/m^2 (default = 1.0e-12)

Cjsr = Sidewall-junction capacitance at V = Vr. F/m (default = 1.0e-12)

Cjgr = Gate-edge junction capacitance at V = Vr. F/m (default = 1.0e-12)

Vdbr = Diffusion voltage of the bottom junction at T = Tr (default = 1.0)

Vdsr = Diffusion voltage of the sidewall junction at T = Tr (default = 1.0)

Vdgr = Diffusion voltage of the gate-edge junction at T = Tr (default = 1.0)

Pb = Bottom-junction grading coefficient (default: 0.4)

Ps = Sidewall-junction grading coefficient (default: 0.4)

Pg = Gate-edge-junction grading coefficient (default: 0.4)

Nb = Emission coefficient of the bottom forward current (default:1.0)

Ns = Emission coefficient of the sidewall forward current (default:1.0)

Ng = Emission coefficient of the gate-edge forward current (default:1.0)

Gmin = minimum conductance added in parallel to the P-N junction, in Siemens (default: 1.0e-15)

All Params = DataAccessComponent-based parameters

Notes/Equations/References

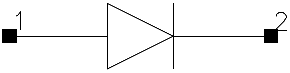
1. Additional information is available from the following website:

   http://www.semiconductors.com/Philips_Models/documentation/add_models/

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.

PinDiode (PIN Diode)

Symbol



Parameters

Model = name of a PinDiode Model

Area = junction area (default: 1)

Region = state of the diode: off, on (default: on) that the DC simulator will use as its initial guess. Its sole purpose is to give the DC simulator a good initial guess to enhance its convergence properties.

Temp = default operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)

_M = number of devices in parallel (default: 1)

Range of Usage

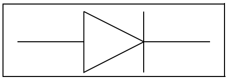
Area > 0

Notes/Equations/References

1. The Temp parameter is only used to calculate the noise performance of this device. Temperature scaling of model parameters is not performed for this device.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. This device has no default artwork associated with it.

PinDiodeModel (PIN Diode Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 1-2. PinDiodeModel Parameters

Parameter	Description	Unit	Default
Is†	saturation current	A	10^{-14}
Vi	I-region forward bias voltage drop	V	0
Un	electron mobility	$cm^2/(V\times S)$	900
Wi	I-region width	m	10^{-6}
Rr†	I-region reverse bias resistance	ohm	0
Cmin†	P-I-N punchthrough capacitance	F	0
Tau	ambipolar lifetime within I region	sec	10^{-7}
Rs†	ohmic resistance	ohm	0
Cjo†	zero-bias junction capacitance	F	0
Vj	junction potential	V	1.0
M	grading coefficient		0.5
Fc	coefficient for forward-bias depletion capacitance		0.5
Imax	explosion current	A/m^2	1
Kf	flicker-noise coefficient		0
Af	flicker-noise exponent		1.0
Ffe	flicker noise frequency exponent		1.0
wBv	diode reverse breakdown voltage (warning)	V	0.0
wPmax	maximum power dissipation warning	W	0.0
AllParams	DataAccessComponent-based parameters		

† Parameter value is scaled by Area specified with the PinDiode device.

Notes/Equations/References

1. This model supplies values for a PinDiode device.
2. PinDiodeModel is based on its high-frequency characteristics. The following assumptions have been made in this model derivation and, therefore, its usefulness.
    - You must first bias the PIN diode in either forward or reverse condition and determine its characteristic.
    - Periods of all time-variant signals applied to the circuit in transient analysis are much shorter than the ambipolar lifetime in the I-region.
    - In reverse bias, the I-region is punchthrough.
3. Limitations of PinDiodeModel:
    - After dc condition of the diode model has been determined, the PIN diode characteristics are fixed. The model will not respond correctly with subsequent changing in dc condition of the diode during transient analysis.
    - Periods of all time variant signals applied to the circuit in transient analysis must be shorter compared to the ambipolar lifetime in the I-region; otherwise, a regular diode should be used.
    - The model does not vary with temperature.
4. The equation for Vi, the I-region forward bias voltage drop is:
    - R=Ri, C=depletion capacitance if forward bias
    - R=Rr, C=Cmin if reverse bias

    where

    Ri=Vi/Idc
5. Idc is the DC current through the pin diode in DC analysis. It replaces R with a DC voltage source with Vi volt.
6. If Vi is not specified or equal to zero,

$$Vi = \frac{3}{4} \cdot \frac{Wi^2}{Un \bullet 10^{-4} \bullet Tau} \tag{1-1}$$

7. Depletion capacitance:

If

$$Vc < Fc \bullet Vj \tag{1-2}$$

$$C = Cjo \bullet \left(1 - \frac{Vc}{Vj}\right)^{-M} \tag{1-3}$$

If

$$Vc \geq Fc \bullet Vj \tag{1-4}$$

$$C = Cjo \bullet \left(\frac{1 - Fc(1+M) + M\left(\frac{Vc}{Vj}\right)}{(1 - Fc)^{(1+M)}} \right) \tag{1-5}$$

8. Noise Model. Thermal noise generated by resistor Rs is characterized by the spectral density:

   $$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

   Shot noise and flicker noise (Kf, Af, Ffe) generated by dc current flow through the diode is characterized by the spectral density:

   $$\frac{\langle i_{ds}^2 \rangle}{\Delta f} = 2qI_D + \mathrm{k}_f \frac{I_D^{a_f}}{f^{f_{fe}}}$$

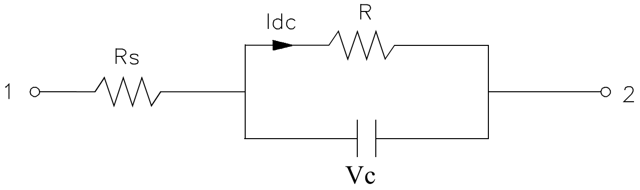
   In the preceding expressions, k is Boltzmann's constant, T is the operating temperature in Kelvin, q is the electron charge, k_{f}, $a_{\mathrm{f},}$ and f_{fe} are model parameters, f is the simulation frequency, and Δf is the noise bandwidth.

9. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.

10. Joseph F. White, Ph.D., Microwave Semiconductor Engineering, Van Nostrand Reinhold Publishing Company, 1982.

11. S.M. Sze, Physics of Semiconductor Devices, second edition, John Wiley & Sons, 1981.

Equivalent Circuit



Chapter 2: Devices and Models, BJT

Bin Model

The BinModel in the BJT library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

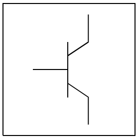
For information on the use of the binning feature, refer to the section *"Bin Model (Bin Model for Automatic Model Selection."* This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components.*

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

BJT_Model (Bipolar Transistor Model)

Symbol



Parameters

Model parameters must be specified in SI units/

Table 2-1. BJT_Model Parameters

Parameter	**Description**	**Unit**	**Default**
NPN	NPN bipolar transistor		yes
PNP	PNP bipolar transistor		no
Is	saturation current	A	
Bf	forward beta		100
Nf	forward emission coefficient		1.0
Vaf	forward early voltage	V	
Ikf	High current corner for forward beta	A	infinity[†††]
Ise	base-emitter leakage saturation current	A	1.5
Ne	base-emitter leakage emission coefficient		1.5
Br[†]	reverse beta		1.0[††]
Nr	reverse emission coefficient		infinity[†††]
Var	reverse early voltage	V	infinity[†††]
Ikr	high current corner for reverse beta	A	infinity[†††]
Isc[†, ††]	base-collector leakage saturation current	A	0.0
Nc	base-collector leakage emission coefficient		2.0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Rb[‡]	zero-bias base resistance (Rb may be high-current dependent)	ohms	0.0
Irb	Current for base resistance midpoint	A	
Rbm	Minimum base resistance for high currents	Ohms	
Re	Emitter resistance	Ohms	
Rc	Collector resistance	Ohms	
Imax	Explosion current	A	
Cje[†, ††]	base-emitter zero-bias depletion capacitance (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)	F	0.0
Vje[†]	base-emitter junction built-in potential (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)	V	0.75
Mje	base-emitter junction exponential factor (Cje, Vje and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)		0.33
Cjc[†, ††]	base-collector zero-bias depletion capacitance (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)	F	0.0
Vjc[†]	base-collector junction built-in potential (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)	V	0.75
Mjc	base-collector junction exponential factor (Cjc, Vjc and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)		0.33
Xcjc	fraction of Cjc that goes to internal base pin		1.0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Cjs[†, ††]	zero-bias collector substrate (ground) capacitance (Cjs, Mjs and Vjs determine nonlinear depletion-layer capacitance for C-S junction)	F	0.0
Vjs[†]	substrate junction built-in potential (Cjs, Vjs, Mjs determine nonlinear depletion-layer capacitance for C-S junction)	V	0.75
Mjs	substrate junction exponential factor (Cjs, Vjs, Mjs determine nonlinear depletion-layer capacitance for C-S junction)		0.0
Fc	forward-bias depletion capacitance coefficient		0.5
Tf	ideal forward transit time (Tr and Tf, along with the depletion-layer capacitances model base charge storage effects; Tf may be bias-dependent)	sec	0.0
Xtf	coefficient of bias-dependence for Tf		0.0
Vtf	voltage dependence of Tf on base-collector voltage	V	infinity[†††]
Itf[††]	high-current effect on Tf	A	0.0
Ptf	excess phase at frequency = 1 / (Tf × 2π)	degrees	0.0
Tr	ideal reverse transit time (Tr, Tf, and depletion-layer capacitances model base charge storage effects)	sec	0.0
Kf	flicker-noise coefficient		0.0
Af	flicker-noise exponent		1.0
Kb	burst noise coefficient		0.0
Ab	burst noise exponent		1.0
Fb	burst noise corner frequency	hertz	1.0
Iss[†, ††]	collector-substrate P-N junction saturation current	A	0.0
Ns	collector-substrate P-N junction emission coefficient		1.0
Nk	high-current roll-off coefficient		0.5

[†] This parameter value varies with temperature based on model Tnom and device Temp.
[††] This parameter value scales with Area specified with the BJT or BJT4 model.
[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	Description	Unit	Default
Ffe	flicker noise frequency exponent		1.0
Lateral	lateral substrate geometry type		no
RbModel	base resistance model: Spice=1, MDS=0		MDS
Approxqb	use approximation for Qb vs early voltage		yes
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Tlev	temperature equation selector (0/1/2/3)		0
Tlevc	temperature equation selector for capacitance (0/1/2/3)		0
Eg	energy gap for temperature effect on Is	eV	1.11
EgAlpha	energy gap temperature coefficient alpha	V/°C	7.02e-4
EgBeta	energy gap temperature coefficient beta	K	1108
Tbf1	Bf linear temperature coefficient	1/°C	0
Tbf2	Bf quadratic temperature coefficient	$1/(°C)^2$	0
Tbr1	Br linear temperature coefficient	1/°C	0
Tbr2	Br quadratic temperature coefficient	$1/(°C)^2$	0
Tcbc	Cbc linear temperature coefficient	1/°C	0
Tcbe	Cbe linear temperature coefficient	1/°C	0
Tccs	Ccs linear temperature coefficient	1/°C	0
Tikf1	Ikf linear temperature coefficient	1/°C	0
Tikf2	Ikf quadratic temperature coefficient	$1/(°C)^2$	0
Tikr1	Ikr linear temperature coefficient	1/°C	0
Tikr2	Ikr quadratic temperature coefficient	$1/(°C)^2$	0
Tirb1	Irb linear temperature coefficient	1/°C	0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Tirb2	Irb quadratic temperature coefficient	1/(°C)^2	0
Tis1	Is/Ibe/Ibc linear temperature coefficient	1/°C	0
Tis2	Is/Ibe/Ibc quadratic temperature coefficient	1/(°C)^2	0
Tisc1	Isc linear temperature coefficient	1/°C	0
Tisc2	Isc quadratic temperature coefficient	1/(°C)^2	0
Tise1	Ise linear temperature coefficient	1/°C	0
Tise2	Ise quadratic temperature coefficient	1/(°C)^2	0
Tiss1	Iss linear temperature coefficient	1/°C	0
Tiss2	Iss quadratic temperature coefficient	1/(°C)^2	0
Titf1	Itf linear temperature coefficient	1/°C	0
Titf2	Itf quadratic temperature coefficient	1/(°C)^2	0
Tmjc1	Mjc linear temperature coefficient	1/°C	0
Tmjc2	Mjc quadratic temperature coefficient	1/(°C)^2	0
Tmje1	Mje linear temperature coefficient	1/°C	0
Tmje2	Mje quadratic temperature coefficient	1/(°C)^2	0
Tmjs1	Mjs linear temperature coefficient	1/°C	0
Tmjs2	Mjs quadratic temperature coefficient	1/(°C)^2	0
Tnc1	Nc linear temperature coefficient	1/°C	0
Tnc2	Nc quadratic temperature coefficient	1/(°C)^2	0
Tne1	Ne linear temperature coefficient	1/°C	0
Tne2	Ne quadratic temperature coefficient	1/(°C)^2	0
Tnf1	Nf linear temperature coefficient	1/°C	0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Tnf2	Nf quadratic temperature coefficient	1/(°C)^{2}	0
Tnr1	Nr linear temperature coefficient	1/°C	0
Tnr2	Nr quadratic temperature coefficient	1/(°C)^{2}	0
Tns1	Ns linear temperature coefficient	1/°C	0
Tns2	Ns quadratic temperature coefficient	1/(°C)^{2}	0
Trb1	Rb linear temperature coefficient	1/°C	0
Trb2	Rb quadratic temperature coefficient	1/(°C)^{2}	0
Trc1	Rc linear temperature coefficient	1/°C	0
Trc2	Rc quadratic temperature coefficient	1/(°C)^{2}	0
Tre1	Re linear temperature coefficient	1/°C	0
Tre2	Re quadratic temperature coefficient	1/(°C)^{2}	0
Trm1	Rbm linear temperature coefficient	1/°C	0
Trm2	Rbm quadratic temperature coefficient	1/(°C)^{2}	0
Ttf1	Tf linear temperature coefficient	1/°C	0
Ttf2	Tf quadratic temperature coefficient	1/(°C)^{2}	0
Ttr1	Tr linear temperature coefficient	1/°C	0
Ttr2	Tr quadratic temperature coefficient	1/(°C)^{2}	0
Tvaf1	Vaf linear temperature coefficient	1/°C	0
Tvaf2	Vaf quadratic temperature coefficient	1/(°C)^{2}	0
Tvar1	Var linear temperature coefficient	1/°C	0
Tvar2	Var quadratic temperature coefficient	1/(°C)^{2}	0
Tvjc	Vjc linear temperature coefficient	1/°C	0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-1. BJT_Model Parameters (continued)

Parameter	Description	Unit	Default
Tvje	Vje linear temperature coefficient	1/°C	0
Tvjs	Vjs linear temperature coefficient	1/°C	0
Xtb	temperature exponent for forward- and reverse-beta. Xtb partly defines dependence of base current on temp.		0.0
Xti	temperature exponent for saturation current		3.0
wVsubfwd	substrate junction forward bias (warning)	V	
wBvsub	substrate junction reverse breakdown voltage (warning)	V	
wBvbe	base-emitter reverse breakdown voltage (warning)	V	
wBvbc	base-collector reverse breakdown voltage (warning)	V	
wVbcfwd	base-collector forward bias (warning)	V	
wIbmax	maximum base current (warning)	A	
wIcmax	maximum collector current (warning)	A	
wPmax	maximum power dissipation (warning)	W	

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Notes/Equations/References

BJT_Model supplies values for BJT devices (BJT4 devices include a substrate terminal). Adapted from the integral charge control model of Gummel and Poon, it includes several effects at high bias levels. It reduces to the simpler Ebers-Moll model when certain parameters required for Gummel-Poon are not specified.

Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

The dc characteristics of a modified Gummel-Poon BJT are defined by:

- Is, Bf, Ikf, Nf, Ise, and Ne, which determine forward-current gain characteristics.
- Is, Br, Ikr, Nr, Isc, and Nc, which determine reverse-current gain characteristics
- Vaf and Var, which determine output conductances for forward and reverse regions.

- Is (saturation current). Eg and Xti partly determine temperature dependence of Is.
- Xtb determines base current temperature dependence.
- Rb, Rc, and Re are ohmic resistances. Rb is current dependent.

The nonlinear depletion layer capacitances are determined by:

- Cje, Vje and Mje for the base-emitter junction.
- Cjc, Vjc and Mjc for the base-collector junction.
- Cjs, Vjs and Mjs for the collector-substrate junction (if vertical BJT), or for the base-substrate junction (if lateral BJT)

The collector or base to substrate junction is modeled as a PN junction.

Substrate Terminal

There are five model parameters that control the modeling of the substrate junction. Cjs, Vjs and Mjs model the nonlinear substrate junction capacitance. Iss and Ns model the nonlinear substrate P-N junction current.

When the BJT4_NPN or BJT4_PNP devices are used, explicitly connect the substrate terminal as required. But when the three terminal BJT_NPN or BJT_PNP devices are used, the substrate terminal is implicitly grounded. This should not affect the simulation if the substrate model parameters Cjs and Iss are not specified, as they default to zero.

The model parameter Lateral changes the connection of the substrate junction. At its default setting of no, the substrate junction models a vertical bipolar transistor with the substrate junction connected to the collector. When Lateral=yes, a lateral bipolar transistor is modeled with the substrate junction connected to the base.

DC Equations

There are two components of base current associated with the bias on each junction. For the emitter junction, an ideal exponential voltage term, *Ibei* arises, due to recombination in the inactive base region and carrier injected into the emitter. A non-ideal exponential voltage term, Iben, predominates at low bias due to recombination in the emitter junction spaced charge region.

$$Ibei = Is\left(\exp\left(\frac{Vbe}{Nf \times V_T}\right) - 1\right) \tag{2-1}$$

$$Iben = Ic\left(\exp\left(\frac{Vbe}{Ne \times V_T}\right) - 1\right) \tag{2-2}$$

Similarly, emission and recombination near the collector junction result in similar terms.

$$Ibci = Is\left(\exp\left(\frac{Vbc}{Nr \times V_T}\right) - 1\right) \tag{2-3}$$

$$Ibcn = Isc\left(\exp\left(\frac{Vbc}{Nc \times V_T}\right) - 1\right) \tag{2-4}$$

Base Terminal Current (without substrate current)

$$Ib = \frac{Ibei}{Bf} + Iben + \frac{Ibci}{Br} + Ibcn \tag{2-5}$$

Collector Terminal Current (without substrate current)

$$Ic = \frac{Ibei - Ibci}{Qb} - \frac{Ibci}{Br} - Ibcn \tag{2-6}$$

Collector-emitter current

$$Ice = \frac{Ibei - Ibci}{Qb} \tag{2-7}$$

where the normalized base charge is Qb.

If Approxqb = yes

$$Qb = \frac{1}{2\left(1 - \frac{Vbc}{Vaf} - \frac{Vbe}{Var}\right)} \times \left(1 + \left(1 + 4\left(\frac{Ibei}{Ikf} + \frac{Ibci}{Ikr}\right)\right)^{Nk}\right) \tag{2-8}$$

If Approxqb = no

$$Qb = \frac{1 + \frac{Vbc}{Vaf} + \frac{Vbc}{Var}}{2} \times \left(1 + \left(1 + 4\left(\frac{Ibei}{Ikf} + \frac{Ibci}{Ikr}\right)\right)^{Nk}\right) \tag{2-9}$$

Substrate Current

Lateral = no (Vertical BJT)

$$Isc = Iss\left(\exp\left(\frac{Vsc}{Ns \times V_T}\right) - 1\right) \tag{2-10}$$

Lateral = yes (Lateral BJT)

$$Ibs = Iss\left(\exp\left(\frac{Vbs}{Ns \times V_T}\right) - 1\right) \tag{2-11}$$

Base Resistance

The base resistance *RBb* consists of two separate resistances. The contact and sheet resistance *Rbm* and the resistance of the internal (active) base register, *vbi,* which is a function of the base current.

If Rbm is zero or IB < 0, RBb = Rb

If *Ivb* is not specified

$$RBb = Rbm + \frac{Rb - Rbm}{Qb} \tag{2-12}$$

If *Ivb* is specified

$$RBb = \mathrm{Rbm} + vbi \tag{2-13}$$

There are two equations for vbi. *RbModel* determines which equations to use.

If RbModel = Spice

$$vbi = 3(Rb - Rbm)\left(\frac{\tan(z) - z}{z\tan^2(z)}\right) \tag{2-14}$$

where

$$z = \frac{\sqrt{1 + \frac{144}{\pi^2} \times \frac{Ib}{Irb}} - 1}{\frac{24}{\pi^2}\sqrt{\frac{Ib}{Irb}}} \tag{2-15}$$

If RbModel = MDS

$$vbi = \frac{Rb - Rbm}{\sqrt{1 + 3\left(\frac{Ib}{Irb}\right)^{0.852}}} \tag{2-16}$$

Capacitance Equations

The capacitances in the small-signal model contain the junction depletion layer capacitance and the diffusion capacitance due to the minority charge storage in the base region.

Base-Emitter Depletion Capacitances

$$Vbe < \text{Fc x Vje} \tag{2-17}$$

$$Cbedep = Cje\left(1 - \frac{Vbe}{vje}\right)^{-Mje} \tag{2-18}$$

$$Vbe \geq \text{Fc x Vje} \tag{2-19}$$

$$Cbedep = Cje\left(\frac{1 - Fc(1 + Mje) + Mje\left(\frac{Vbe}{Vje}\right)}{(1 - fc)^{(1 + Mje)}}\right) \tag{2-20}$$

Base-Emitter Diffusion Capacitance

$$Cbediff = \frac{2Qbediff}{2Vbe} \tag{2-21}$$

where the transit charge

$$Qbdiff = Tf\left(1 + xtf \times \exp\left(\frac{Vbc}{1.442695Vtf}\right)\left(\frac{Ibei}{Ibei + Itf}\right)^2 \times \frac{Ibei}{Qb}\right) \tag{2-22}$$

$$Cbe = \text{Cbedep + Cbediff} \tag{2-23}$$

Base-Collector Depletion Capacitances

When Xcjc is not equal to one, the base-collector depletion capacitance is modeled as a distributed capacitance.

The internal base-internal collector depletion capacitance

$$Vbc < \text{Fc x Vjc} \tag{2-24}$$

$$Cbcdep = Xcjc \times Cjc\left(1 - \frac{Vbc}{Vjc}\right)^{-Mjc} \tag{2-25}$$

$$Vbc \geq \text{Fc x Vjc} \tag{2-26}$$

$$Cbcdep = Xcjc \times Cje\left(\frac{1 - Fc(1 + Mjc) + Mjc\left(\frac{Vbc}{Vjc}\right)}{(1 - fc)^{(1 + Mjc)}}\right) \tag{2-27}$$

The external base-internal collector depletion capacitance

$$VBc < \text{fc x Vjc} \tag{2-28}$$

$$Cbcdep = (1 - Xcjc)Cjc\left(1 - \frac{Vbc}{Vjc}\right)^{-Mjc} \tag{2-29}$$

$$VBc \geq \text{Fc x Vjc} \tag{2-30}$$

$$Cbcdep = (1 - Xcjc)Cjc\left(\frac{1 - Fc(1 + Mjc) + Mjc\left(\frac{Vbc}{Vjc}\right)}{(1 - fc)^{(1 + Mjc)}}\right) \tag{2-31}$$

$$CBc = \text{CBcdep} \tag{2-32}$$

Base-Collector Diffusion Capacitances

$$Cbcdiff = \frac{2Qbcdiff}{2Vbc} \tag{2-33}$$

where the transit charge

$$Qbcdiff = \text{Tr x Ibci} \tag{2-34}$$

$$Cbc = \text{Cbcdep + Cbcdiff} \tag{2-35}$$

Base-Collector Substrate Capacitance

Lateral = no (vertical BJT)

$$Vsc < 0 \tag{2-36}$$

$$Csc = Cjs\left(1 - \frac{Vsc}{Vjs}\right)^{-Mjs} \tag{2-37}$$

$$Vsc \geq 0 \tag{2-38}$$

$$Csc = Cjs\left(1 + Mjs \times \frac{Vsc}{Vjs}\right) \tag{2-39}$$

Lateral = yes (Lateral BJT)

$$Vbs < 0 \tag{2-40}$$

$$Cbs = Cjs\left(1 - \frac{Vbs}{Vjs}\right)^{-Mjs} \tag{2-41}$$

$$Vbs \geq 0 \tag{2-42}$$

$$Cbs = Cjs\left(1 + Mjs \times \frac{Vbs}{Vjs}\right) \tag{2-43}$$

Excess Phase

An additional phase shift at high frequencies is added to the frequent transconductance model to account for the distributed phenomena in the transistor. The effective phase shift added to the *Ibei* item in the *Ic* equation is calculated as follows for *Ibei* (with excess phase):

$$Ibei = \frac{3Wo^2}{S^2 + 3Wos + 3Wo^2} \times Ibei \tag{2-44}$$

where

$$Wo = \frac{1}{Ptf \times Tf \times \frac{Tc}{180}} \tag{2-45}$$

The current implementation in ADS is applying the shifting factor to the collector current IC.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device Temp parameter. (Temperatures in the following equations are in Kelvin.)

Saturation currents Is, Ise, Isc and Iss scale as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right] \tag{2-46}$$

$$Ise^{NEW} = Ise \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times Ne \times Temp} + \frac{Xti}{Ne} \times ln\left(\frac{Temp}{Tnom}\right)\right] \tag{2-47}$$

$$Isc^{NEW} = Isc \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times Nc \times Temp} + \frac{Xti}{Nc} \times ln\left(\frac{Temp}{Tnom}\right)\right] \tag{2-48}$$

$$Iss^{NEW} = Iss \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times Ns \times Temp} + \frac{Xti}{Ns} \times ln\left(\frac{Temp}{Tnom}\right)\right] \tag{2-49}$$

Depletion capacitances Cje, Cjc and Cjs vary as:

$$Cje^{NEW} = Cje\left[\frac{1 + Mje[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mje[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right] \tag{2-50}$$

$$Cjc^{NEW} = Cjc\left[\frac{1 + Mjc[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mjc[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}\right] \tag{2-51}$$

$$Cjs^{NEW} = Cjs\left[\frac{1 + Mjs[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mjs[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}\right] \tag{2-52}$$

where γ is a function of the junction potential and the energy gap variation with temperature.

Junction potentials Vje, Vjc and Vjs vary as:

$$Vje^{NEW}{}_{je} = \frac{Temp}{Tnom} \times Vje + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right) \tag{2-53}$$

$$Vjc^{NEW} = \frac{Temp}{Tnom} \times Vjc + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right) \tag{2-54}$$

$$Vjs^{NEW} = \frac{Temp}{Tnom} \times Vjs + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right) \tag{2-55}$$

where n_i is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

Both forward beta Bf and reverse beta Br vary with temperature:

$$Bf^{NEW} = Bf\left(\frac{Temp}{Tnom}\right)^{Xtb} \tag{2-56}$$

$$Br^{NEW} = Br\left(\frac{Temp}{Tnom}\right)^{Xtb} \tag{2-57}$$

Noise Model

Thermal noise generated by resistors Rb, Rc, and Re is characterized by the spectral density:

$$\frac{<i^2>}{\Delta f} = \frac{4kT}{R} \tag{2-58}$$

Shot noise, flicker noise (Kf, Af, Ffe), and burst noise (Kb, Ab, Fb) generated by the dc base current is characterized by the spectral density:

$$\frac{<i_{be}^2>}{\Delta f} = 2qI_{BE} + \mathrm{k}_f \frac{I_{BE}^{a_f}}{f^{f_{fe}}} + \mathrm{k}_b \frac{I_{BE}^{a_b}}{1 + (f/f_b)^2} \tag{2-59}$$

Shot noise generated by the dc collector-to-emitter current is characterized by the spectral density:

$$\frac{<i_{ce}^2>}{\Delta f} = 2qI_{CE} \tag{2-60}$$

Shot noise generated by the dc collector-to-substrate current (BJT4 only) is characterized by the spectral density:

$$\frac{<i_{cs}^2>}{\Delta f} = 2qI_{CS} \tag{2-61}$$

In the preceding expressions, *k* is Boltzmann's constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, $\mathrm{k_f}$, $\mathrm{a_f}$, $\mathrm{f_{fe}}$, $\mathrm{k_b}$, $\mathrm{a_b}$, and $\mathrm{f_b}$ are model parameters, *f* is the simulation frequency, and Δf is the noise bandwidth.

Area Dependence of the BJT Model Parameters

The AREA factor used for the BJT model determines the number of equivalent parallel devices of a specified model. The BJT model parameters affected by the AREA factor are:

ls = ls * AREA

lse = lse * AREA

lsc = lsc * AREA

lkf = lkf * AREA

lkr = lkr * AREA

lrb = lbr * AREA

ltf = ltf * AREA

Cjc(0) = Cjc(0) * AREA

Cje(0) = Cje(0) * AREA

Cjs(0) = Cjs(0) * AREA

rB = rB/AREA

rBM = rBM/AREA

rE = rE/AREA

rC = rC/AREA

The default value for the AREA parameter is 1.

DC Operating Point Device Information

Definitions

- Ic (collector current)
- Ib (base current)
- Ie (emitter current)
- Is (substrate current)
- Ice (collection-emitter current)

- power (dissipated power)

BetaDc Ic/Ib

where

Ib = sign(ib) x Max (Abs(Ib), ie-20) (2-62)

$$Gm = \frac{dIce}{dVbe} + \frac{dIce}{dVbc} \quad (2\text{-}63)$$

$$Rpi = \frac{1}{\left(\frac{dIb}{dVbc}\right)} \quad (2\text{-}64)$$

$$Rmu = \frac{1}{\left(\frac{dIb}{dVbc}\right)} \quad (2\text{-}65)$$

Rx = RBb (2-66)

$$Ro = \frac{-1}{\left(\frac{dIce}{dVbc}\right)} \quad (2\text{-}67)$$

Cpi = Cbe (2-68)

Cmu = Cbc (2-69)

Cbx = CBx (2-70)

Ccs = Ccs if vertical BJT (2-71)

= Cbs if lateral BJT (2-72)

$BetAc$ = Gm x Rpi (2-73)

$$Ft = \frac{1}{(2\pi(tau + (Rc + Re)(Cmu + Cbx)))} \quad (2\text{-}74)$$

where

$$tau = \frac{Max(Cpi + Cnm + Cbx, ie - 20)}{Max(Gm, ie - 20)} \quad (2\text{-}75)$$

$$Vbe = \nu(B) - \nu(E) \quad (2\text{-}76)$$

$$Vbc = \nu(B) - \nu(C) \tag{2-77}$$

$$Vce = \nu(BC) - \nu(E) \tag{2-78}$$

References:

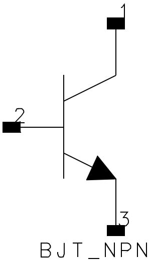
[1] P. Antognetti and G. Massobrio, *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

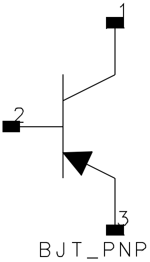
BJT (Bipolar Junction Transistors)

BJT_NPN (Bipolar Junction Transistor, NPN)

BJT_PNP (Bipolar Junction Transistor, PNP)

Symbol





Parameters

Model = name of BJT_Model, EE_BJT2_Model, or MEXTRAM_Model

Area = factor that scales certain parameter values of the model (default: 1)

Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear)

_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/Reference

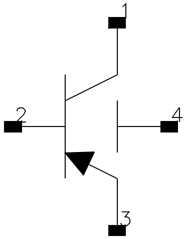
1. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=*linear* are linearized about their dc operating point.
2. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the associated model to see which parameter values are scaled.
3. This device has no default artwork associated with it.

4. The substrate terminal is connected to ground. The substrate current is affected by the ISS and CJS model parameters. There should be no problems with this except perhaps in a PNP transistor where the ISS model parameter is specified. This could cause excess current flow as the substrate PN junction might end up being forward biased. If the connection of the substrate terminal to ground is not acceptable, use the BJT4 component and connect its substrate terminal to the appropriate place.
5. For information on area dependence, refer to the section “Area Dependence of the BJT Model Parameters” for the BJT_Model component.
6. I. E. Getreu, *CAD of Electronic Circuits, 1; Modeling the Bipolar Transistor*, Elsevier Scientific Publishing Company, 1978.
7. P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE*, Second Edition, McGraw-Hill, Inc., 1993.

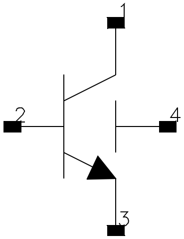
BJT4 (Bipolar Junction Transistors w/Substrate Terminals)

BJT4_NPN (Bipolar Junction Transistor w/Substrate Terminal, NPN)
BJT4_PNP (Bipolar Junction Transistor w/Substrate Terminal, PNP)

Symbol



BJT4_PNP



BJT4_NPN

Parameters

Model = name of BJT_Model or MEXTRAM_Model

Area = factor that scales certain parameter values of the model (default: 1)

Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear) (refer to Note 2)

_M = number of devices in parallel (default: 1)

Range of Usage

N/A

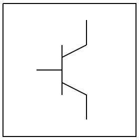
Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the model to see which parameter values are scaled.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. The fourth terminal (substrate) is available for connection to an external circuit.

4. This device has no default artwork associated with it.
5. I. E. Getreu, *CAD of Electronic Circuits, 1; Modeling the Bipolar Transistor,* Elsevier Scientific Publishing Company, 1978.
6. P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE,* Second Edition, McGraw-Hill, Inc., 1993.

EE_BJT2_Model (EEsof Bipolar Transistor Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 2-2. EE_BJT2_Model Parameters

Name	Description	Unit	Default
Type	NPN or PNP		NPN
Nf	forward-current emission coefficient		1.0
Ne	base-emitter leakage emission coefficient		1.5
Nbf	forward base emission coefficient		1.06
Vaf	forward Early voltage	V	infinity†
Ise	base-emitter leakage saturation current	A	0.0
Tf	ideal forward transit time (Tr and Tf, along with the depletion-layer capacitances, model base charge storage effects; Tf may be bias-dependent)	sec	0.0
Ikf	corner for forward-beta high current roll-off	A	infinity†
Xtf	coefficient of bias-dependence for Tf		0.0
Vtf	voltage dependence of Tf on base-collector voltage	V	infinity†
Itf	parameter for high-current effect on Tf	A	0.0
Nbr	reverse base emission coefficient		1.04
Nr	reverse-current emission coefficient		1.0
Nc	base-collector leakage emission coefficient		2.0
Isc	base-collector leakage saturation current	A	0.0
Ikr	corner for reverse-beta high-current roll-off	A	infinity†

† A value of 0.0 is interpreted as infinity

Table 2-2. EE_BJT2_Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
Var	reverse Early voltage	V	infinity[†]
Tr	ideal reverse transit time (Tr and Tf, along with the depletion-layer capacitances, model base charge storage effects)	sec	0.0
Isf	forward saturation current	A	9.53×10^{-15}
Ibif	forward base saturation current	A	1.48×10^{-16}
Isr	reverse saturation current	A	1.01×10^{-14}
Ibir	reverse base saturation current	A	6.71×10^{-16}
Tamb	ambient temperature of measurement and model parameter extraction	°C	25
Cje	base-emitter zero-bias depletion capacitance (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)	F	0.0
Vje	base-emitter junction built-in potential (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)	V	0.75
Mje	base-emitter junction exponential factor (Cje, Vje, and Mje determine nonlinear depletion-layer capacitance for base-emitter junction)		0.33
Cjc	base-collector zero-bias depletion capacitance (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)	F	0.0
Vjc	base-collector junction built-in potential (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)	V	0.75
Mjc	base-collector junction exponential factor (Cjc, Vjc, and Mjc determine nonlinear depletion-layer capacitance for base-collector junction)		0.33
Rb	base resistance	ohms	10^{-4}

[†] A value of 0.0 is interpreted as infinity

Table 2-2. EE_BJT2_Model Parameters (continued)

Name	Description	Unit	Default
Re	emitter resistance	ohms	10^{-4}
Rc	collector resistance	ohms	10^{-4}
Fc	forward-bias depletion capacitance coefficient		0.5
wVsubfwd	substrate junction forward bias (warning)	V	
wBvsub	substrate junction reverse breakdown voltage (warning)	V	
wBvbe	base-emitter reverse breakdown voltage (warning)	V	
wBvbc	base-collector reverse breakdown voltage (warning)	V	
wVbcfwd	base-collector forward bias (warning)	V	
wIbmax	maximum base current (warning)	A	
wIcmax	maximum collector current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	name of DataAccessComponent for file-based model parameter values		

† A value of 0.0 is interpreted as infinity

Notes/Equations/References

1. This model specifies values for BJT_NPN or BJT_PNP devices.
2. EEBJT2 is the second generation BJT model designed by HP EEsof. The model has been created specifically for automatic parameter extraction from measured data including dc and S-parameter measurements. The goal of this model is to overcome some of the problems associated with EEBJT1 or Gummel-Poon models limited accuracy and parameter extraction difficulty with regard to silicon rf/microwave transistors. EEBJT2 is not generally equivalent or compatible with the Gummel-Poon or EEBJT1 models. EEBJT2 can provide a reasonably accurate reproduction of transistor behavior, including dc bias solution, bias-dependent S-parameters including the effects of package parasitics, and true nonlinear harmonic output power. The model is quasi-static, analytical, and isothermal. The model does not scale with area since parameters are intended to be extracted directly from measured data and not from layout considerations. Default values of some parameters are chosen from an average of the first EEBJT2 library model parameters.
3. To prevent numerical problems, the setting of some model parameters is trapped by the simulator. The parameter values are changed internally:

- Mjc and Mje must be ≤ 0.99
- Fc must be ≤ 0.9999
- Rb, Rc, and Re must be ≥ 10^{-4}

4. The Temp parameter is only used to calculate the noise performance of this device. Temperature scaling of model parameters is not performed for this device.
5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.
6. This device has no default artwork associated with it.

Equations

Base-Emitter and Base-Collector Current

The base-emitter current in the BJT has been changed significantly from the Gummel-Poon and other earlier models. These models assume that the non-leakage base-emitter current is related to the collector-emitter current by a simple constant, known as beta. Observation of base-emitter current in both silicon and AlGaAs devices has shown that this assumption is incorrect. Difficulties with this method of modeling base current have been observed for many years. A large, very bias-dependent base resistance in the modified Gummel-Poon model in Berkeley SPICE has been used to attempt to correct the problem with the base-emitter current expressions. This base resistance value and its variation is often extracted from dc data only, with the result that the behavior of the device over frequency is often poorly modeled. This problem is then *solved* by assigning some fraction of the base-collector capacitance to either side of the base in a distributed manner.

HP EEsof's experience with EEBJT2 has shown that properly modeled base-emitter current and conductance renders both the large bias-dependent base resistance and distributed base-collector capacitance unnecessary and greatly improves both the dc and ac accuracy of the resulting model.

EE_BJT2 models the base-emitter current with two non-ideal exponential expressions, one for the bulk recombination current (usually dominant in silicon devices), and one for other recombination currents (usually attributed to surface leakage).

$$Ibe = \left(Ibif\left(exp(\frac{Vbe}{(NbfV_T)}) - 1.0\right)\right) + \left(Ise\left(exp(\frac{Vbe}{(Ne \times V_T)}) - 1.0\right)\right)$$

where

$$V_T = \frac{k \times Tamb}{q}$$

where

k is Boltzmann’s constant, and q is deviceary charge.

Note that Nbf is not necessarily 1.0, which is effectively the case in the Gummel-Poon model.

The base-collector current is similarly modeled:

$$Ibc = \left(Ibir\left(exp(\frac{Vbc}{(Nbr V_T)}) - 1.0\right)\right) + \left(Isc\left(exp(\frac{Vbc}{(Nc \times V_T)}) - 1.0\right)\right)$$

Virtually all silicon rf/microwave transistors are vertical planar devices, so the second current term containing Isc and Nc is usually negligible.

The total base current Ib is the sum of Ibe and Ibc. Note that this method of modeling base current obsoletes the concept of a constant beta.

Collector-Emitter Current

The forward and reverse components of the collector-emitter current are modeled in a manner similar to the Gummel-Poon model, but with more flexibility. Observation of collector-emitter current behavior has shown that the forward and reverse components do not necessarily share identical saturation currents, as in the Gummel-Poon model. The basic expressions in EE_BJT2, not including high-level injection effects and Early effects, are:

$$Icf = Isf \times \left(exp(\frac{Vbe}{(Nf \times V_T)}) - 1.0\right)$$

$$Icr = Isr \times \left(exp(\frac{Vbc}{(Nr \times V_T)}) - 1.0\right)$$

where Isf and Isr are not exactly equal but are usually very close. Nf and Nr are not necessarily equal or 1.0, but are usually very close. Careful control of ambient temperature during device measurement is required for precise extraction of all of the saturation currents and emission coefficients in the model.

The effects of high-level injection and bias-dependent base charge storage are modeled via a normalized base charge, similar to the Gummel-Poon model:

$$Ice = \frac{(Icf - Icr)}{Qb}$$

where

$$Qb = \left(\frac{Q1}{2.0}\right) \times (1.0 + \sqrt{1.0 + (4.0 \times Q2)})$$

and

$$Q1 = \frac{1.0}{\left(1.0 - \left(\frac{Vbc}{Vaf}\right) - \left(\frac{Vbe}{Var}\right)\right)}$$

$$Q2 = \left(\left(\frac{Isf}{Ikf}\right) \times \left(exp(\frac{Vbe}{(Nf \times V_T)}) - 1.0\right)\right) + \left(\left(\frac{Isf}{Ikf}\right) \times \left(exp(\frac{Vbc}{(Nr \times V_T)}) - 1.0\right)\right)$$

Note All computations of the exponential expressions used in the model are linearized to prevent numerical overflow or underflow at large forward or reverse bias conditions, respectively.

Base-Emitter and Base-Collector Capacitances

Diffusion and depletion capacitances are modeled for both junctions of the transistor model in a manner very similar to the Gummel-Poon model.

for $Vbc \le Fc \times Vjc$

$$Cbc = Cbc_{diffusion} + Cbc_{depletion}$$

where

$$Cbc_{diffusion} = \frac{Tr \times Icr}{Nr \times V_T}$$

and

$$Cbc_{depletion} = \frac{Cjc}{\left(1.0 - \left(\frac{Vbc}{Vjc}\right)\right)^{Mjc}}$$

for $Vbc > Fc \times Vjc$

$$Cbc_{depletion} = \left(\frac{Cjc}{(1.0 - Fc)^{Mjc}}\right) \times \left(1.0 + \left(\frac{Mjc(Vbc - Fc \times Vjc)}{VJjc(1.0 - Fc)}\right)\right)$$

for $Vbe \le Fc \times Vje$

$$Cbe = Cbe_{diffusion} + Cbe_{depletion}$$

where

$$Cbe_{depletion} = \frac{Cje}{\left(1.0 - \left(\frac{Vbe}{Vje}\right)\right)^{Mje}}$$

for Vbe > Fc × Vje

$$Cbe_{depletion} = \left(\frac{Cje}{(1.0 - Fc)^{Mje}}\right) \times \left(1.0 + \left(\frac{Mje(Vbe - (Fc \times Vje))}{Vje(1.0 - Fc)}\right)\right)$$

The diffusion capacitance for Cbe is somewhat differently formulated vs. that of Cbc. The transit time is not a constant for the diffusion capacitance for Cbe, but is a function of both junction voltages, formulated in a manner similar to the modified Gummel-Poon model. The total base-emitter charge is equal to the sum of the base-emitter depletion charge (which is a function of Vbe only) and the so-called transit charge (which is a function of both Vbe and Vbc).

$$Q_{transit} = Tff \times \left(\frac{Icf}{Qb}\right)$$

where

$$Tff = Tf \times \left(1.0 + Xtf\left(\frac{Icf}{Icf + Itf}\right)^{2.0} \times exp\left(\frac{Vbc}{1.44 \times Vtf}\right)\right)$$

and

$$Cbe_{diffusion}(Vbe) = \frac{\partial Q_{transit}}{\partial Vbe}$$

and

$$Cbe_{diffusion}(Vbc) = \frac{\partial Q_{transit}}{\partial Vbc}$$

Noise Model

Thermal noise generated by resistors Rb, Rc, and Re is characterized by the following spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

Shot noise generated by each of the dc currents flowing from base to emitter, base to collector, and collector to emitter is characterized by the following spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = 2qI_{DC}$$

In the previous expressions, k is Boltzmann's constant, T is the operating temperature in Kelvin, q is the electron charge, and Δf is the noise bandwidth.

Flicker and burst noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources I_NoiseBD and V_NoiseBD can be connected external to the device to model flicker or burst noise.

References:

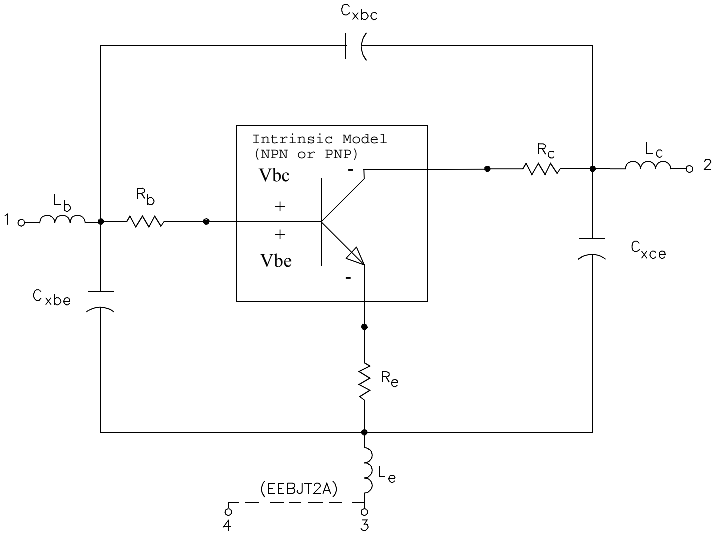
[1] J. J. Ebers and J. L. Moll. “Large Signal Behaviour of Junction Transistors,” Proc. I.R.E. 42, 1761 (1954).

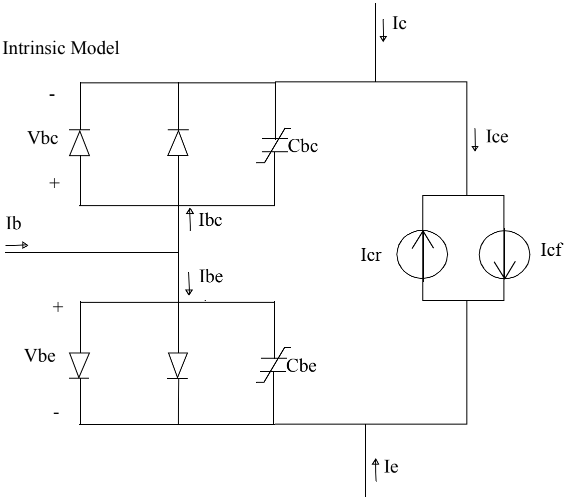
[2] H. K. Gummel and H. C. Poon. “An Integral Charge-Control Relation for Bipolar Transistors,” Bell Syst. Techn. J. 49, 115 (1970).

[3] SPICE2: A Computer Program to Simulate Semiconductor Circuits, University of California, Berkeley.

[4] P. C. Grossman and A. Oki. “A Large Signal DC Model for GaAs/GaxAl1-xAs Heterojunction Bipolar Transistors,” Proceedings of the 1989 IEEE Bipolar Circuits and Technology Meeting, pp. 258-262, September 1989.

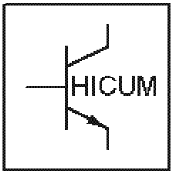
Equivalent Circuit




Intrinsic Model
Ic
-
Vbc
+
Cbc
Ice
Ibc
Ib
Icr
Icf
Ibe
+
Vbe
Cbe
-
Ie

HICUM_Model

Symbol



Parameters

Parameter	Description	Units	Default
c10	ICCR constant (=I_SQ_{p0})	A^2s	1E-28
Qp0	zero-bias hole charge	As	25
Ich	high-current correction for 2D/3D-ICCR	A	∞
hfC	GICCR weighing factor for Q_{fC} (mainly for HBTs)		1.0
hfE	GICCR weighing factor for Q_{Ef} in HBTs		1.0
hjci	GICCR weighing factor for Q_{jCi} in HBTs		1.0
hjei	GICCR weighing factor for Q_{jEi} in HBTs		1.0
aliT	factor for additional delay time of i_T		0.45
CjEi0	zero-bias value	F	10E-15
VDEi	built-in voltage	V	0.9
zEI	exponent coefficient		0.5
aljEi	ratio of maximum to zero-bias value		2.5
CjCi0	zero-bias value	F	2E-15
VDCi	built-in voltage	V	0.7
zCi	exponent coefficient		0.4
VPTCi	punch-through voltage (=$qN_{Ci}{}^{w2}{}_{Ci}/(2\varepsilon)$)	V	∞
T0	low-current transit time at $V_{B'C'}$=0	s	5E-12

Parameter	**Description**	**Units**	**Default**
dTOh	time constant for base and BC SCR width modulation	s	2E-12
Tbv1	voltage for modeling carrier jam at low $V_{C'E'}$	s	4E-12
TEf0	storage time in neutral emitter	s	1E-12
gTfE	exponent factor for current dep. emitter transit time		1
ThcS	saturation time constant at high current densities	s	30E-12
ALhc	smoothing factor for current dep. C and B transit time		0.1
fTHc	partitioning factor for base and collector portion		0.6
alQf	factor for additional delay time of Q_f		0.22
rCi0	low-field resistance of internal coll. region	Ω	150
Vlim	voltage separating ohmic and SCR regime	V	0.4
VPT	epi punch-through voltage of BC SCR	V	3
VCEs	internal CE saturation voltage	V	0.1
Tr	time constant for inverse operation	s	0
IBEiS	BE saturation current	A	1E-19
mBEi	BE non-ideality factor		1.002
IREis	BE recombination saturation current	A	1E-30
mREi	BE recombination non-ideality factor		2.0
IBCiS	BE saturation current	A	IE-30
mBCi	BE non-ideality factor		1.5
fAVL	prefactor for CB avalanche effect	1/V	0
qAVL	exponent factor for CB avalanche effect	As	0
rBi0	value at zero-bias	Ω	0
fDQr0	correction factor for modulation by BE and BC SCR		0.2
fgeo	geometry factor (value corresp. to long emitter stripe)		0.6557
fQi	ratio of internal to total minority change		0.75
fCrBi	ration of h.f. shunt to total internal capacitance		0.0
LATb	scaling factor for Q_{fC} in b_E direction		0

Parameter	**Description**	**Units**	**Default**
LATl	scaling factor for Q_{fC} in l_E direction		0
CjEp0	zero-bias value	F	0
VDEp	built-in voltage	V	0.9
zEp	depletion coefficient		0.5
aljEp	ratio of maximum to zero-bias value		2.5
IBEps	saturation current	A	1E-19
MBEp	non-ideality factor		1.002
IREpS	recombination saturation current	A	1E-30
mREp	recombination non-ideality factor		2.0
IBEtS	saturation current	A	0
ABEt	exponent coefficient		40
CjCx0	zero-bias depletion value	F	0
VDCx	built-in voltage	V	0.7
zCx	exponent coefficient		0.4
VPTCx	punch-through voltage	V	∞
CCox	collector-oxide capacitance	F	0
fBC	partitioning factor for $C_{BCx}=C'_{BCx}+C'_{BCx}$		0.7
IBCxS	saturation current	A	1E-30
mBCx	non-ideality factor		1.5
CEox	emitter-base isolation (overlap) capacitance	F	0
rBx	exteranl base series resistance	Ω	0
rE	emitter series resistance	Ω	0
rCx	external collector series resistance	Ω	0
Itss	transfer saturation current	A	1E-16
msf	non-ideality factor (forward transfer current)		1.05
tSf	minority charge storage (transit) time		1.05

Parameter	**Description**	**Units**	**Default**
Iscs	saturation current of CS diode	A	1E-17
msc	non-ideality factor of CS diode		1.0
CjS0	zero-bias value of CS depletion capacitance	F	0
VDS	built-in voltage	V	0.6
zS	exponent coefficient		0.5
VPTS	punch-through voltage	V	∞
rSu	substrate series resistance	Ω	0
CSu	substrate capacitance from permittivity of bulk material	F	0
kF	flicker noise factor (no unit only for a_F=2!)		0
aF	flicker noise exponent factor		2.0
krBi	factor for internal base resistance		1.0
VGb	bandgap-voltage	V	1.17
alB	rel. temperature coefficient of forward current gain	1/K	5E-3
alt0	first-order relative temperature coefficient of τ_{f0}	1/K	0
kt0	second-order relative temperature coefficient of τ_{f0}	1/K	0
zetaci	temperature exponent factor r_{Ci0}		1.6
alvs	rel. temperature coefficient of satur. drift velocity	1/K	1E-3
alces	relative temperature coefficient of $V_{C'E's}$	1/K	0.4E-2
zetarBi	temperature exponent factor of r_{Bi0}		1.0
zetarBx	temperature exponent factor of r_{Bx}		0.3
zetarCx	temperature exponent factor of r_{Cx}		0.3
zetarE	temperature exponent factor of r_E		0
ALfav	rel. temperature coefficient for avalanche breakdown	1/K	8.3E-4
ALqav	rel. temperature coefficient for avalanche breakdown	1/K	2E-3
Rth	thermal resistance	K/W	0
Cth	thermal capacitance	Ws/K	0

Parameter	**Description**	**Units**	**Default**
TNOM	temperature for which parameters are valid	C	27
DT	temperature change for particular transistor	C	0

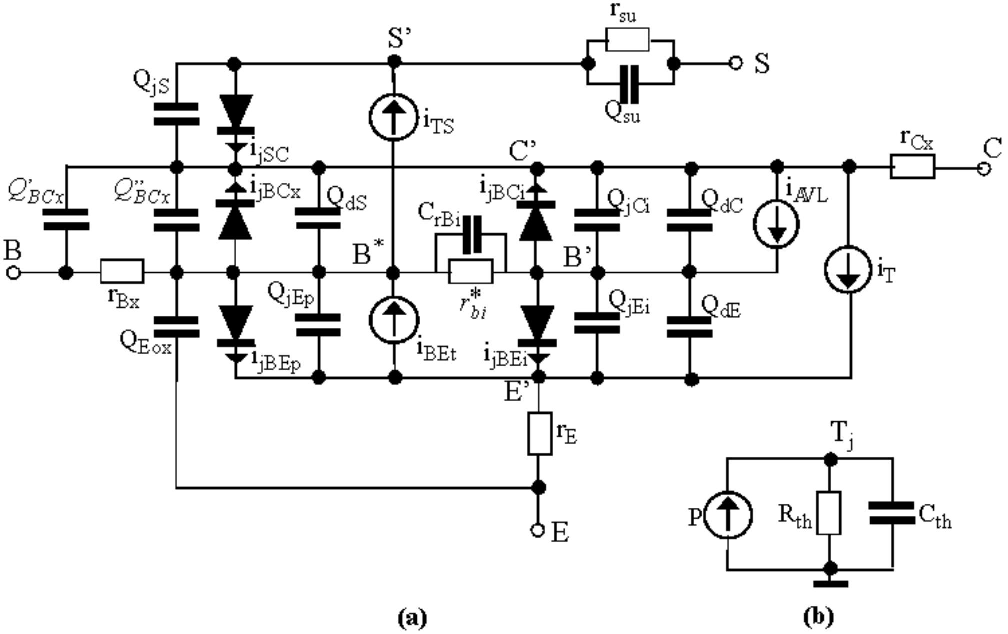
Range of Usage

N/A

Notes/Equations/References

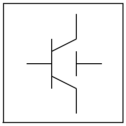
1. The important physical and electrical effects taken into account by HICUM are briefly summarized below:
   - high-current effects (incl. quasi-saturation)
   - distributed high-frequency model for the external base-collector region
   - emitter periphery injection and associated charge storage
   - emitter current crowding (through a bias dependent internal base resistance
   - two- and three-dimensional collector current spreading
   - parasitic (bias independent) capacitances between base-emitter and base-collector terminal
   - vertical non-quasi-static (NQS) effects for transfer current and minority charge
   - temperature dependence and self-heating
   - weak avalanche breakdown at the base-collector junction
   - tunneling in the base-emitter junction
   - parasitic substrate transistor
   - bandgap differences (occurring in HBTs)
   - lateral scalability
2. The non quasi-static effects have not been implemented in the transient and harmonic balance analyses for this release.

Equivalent Circuit



MEXTRAM_Model (MEXTRAM Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 2-3. MEXTRAM_Model Parameters

Parameter	**Description**	**Unit**	**Default**
NPN	NPN model type		yes
PNP	PNP model type		no
Release	model level		503
Exmod	flag for extended modelling of reverse current gain		yes
Exphi	flag for distributed high-frequency effects in transient		yes
Exavl	flag for extended modelling of avalanche currents		yes
Is	collector-emitter saturation current	A/m^2	9.6369×10^{-18}
Bf	ideal forward current gain		138.9
Xibi	fraction of ideal base current that belongs to sidewall		0.0
Ibf	saturation current of non-ideal forward base current	A/m^2	2.7223×10^{-15}
Vlf	crossover voltage of non-ideal forward base current	V	0.6181
Ik	high-injection knee current	A/m^2	$1.5\times10^{-}$
Bri	ideal reverse current gain		6.243
Ibr	saturation current of non-ideal reverse base current	A	4.6066×10^{-14}
Vlr	crossover voltage of non-ideal reverse base current	V	0.5473
Xext	part of I_{EX}, Q_{EX}, Q_{TEX} and I_{SUB} that depends on base-collector voltage V_{BC1}		0.5358
Qb0	base charge at zero bias		9.3424×10^{-14}
Eta	factor of built-in field of base (= η).		4.8

Table 2-3. MEXTRAM_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Avl	weak avalanche parameter		76.43
Efi	electric field intercept (with Exavl=1)		0.7306
Ihc	critical current for hot carriers	A/m^2	5.8359×10^{-4}
Rcc	constant part of collector resistance	Ω/m^2	11.09
Rcv	resistance of unmodulated epilayer	Ω/m^2	981.9
Scrcv	space charge resistance of epilayer	Ω/m^2	1769
Sfh	current spreading factor epilayer		0.3556
Rbc	constant part of base resistance	Ω/m^2	134.4
Rbv	variable part of base resistance at zero bias	Ω/m^2	307.7
Re	emitter series resistance	Ω/m^2	1.696
Taune	minimum delay time of neutral and emitter charge	sec	6.6626×10^{-12}
Mtau	non-ideality factor of the neutral and emitter charge	S	1
Cje	zero bias base-emitter depletion capacitance	F/m^2	4.9094×10^{-14}
Vde	base-emitter diffusion voltage	V	0.8764
Pe	base-emitter grading coefficient		0.3242
Xcje	fraction of base-emitter depletion capacitance that belongs to sidewall		0.26
Cjc	zero bias base-collector depletion capacitance	F/m^2	8.7983×10^{-14}
Vdc	base-collector diffusion voltage	V	0.6390
Pc	base-collector grading coefficient variable part		0.6135
Xp	constant part of Cjc		0.5
Mc	collector current modulation coefficient		0.5
Xcjc	fraction of base-collector depletion capacitance under emitter area		2.7018×10^{-2}
Tref	reference temperature	°C	22
Dta	difference of device temperature to ambient temperature ($T_{Device}=T_{Ambient}+Dta$)	°C	0

Table 2-3. MEXTRAM_Model Parameters (continued)

Parameter	Description	Unit	Default
Vge	emitter bandgap voltage	V	1.129
Vgb	base bandgap voltage	V	1.206
Vgc	collector bandgap voltage	V	1.120
Vgj	emitter-base junction band-gap voltage	V	1.129
Vi	ionization voltage base dope	V	2.1×10^{-2}
Na	maximum base dope concentration	cm^{-3}	4.4×10^{17}
Er	temperature coefficient of Vlf and Vlr		2×10^{-3}
Ab	temperature coefficient resistivity base		1.0
Aepi	temperature coefficient resistivity of the epilayer		1.9
Aex	temperature coefficient resistivity of the extrinsic base		0.31
Ac	temperature coefficient resistivity of the buried layer		0.26
Kf	flicker noise coefficient ideal base current		0
Kfn	flicker noise coefficient non-ideal base current		0
Af	flicker noise exponent		1.0
Iss	base-substrate saturation current	A/m^2	5.8602×10^{17}
Iks	knee current of the substrate	A/m^2	6.7099×10^{-6}
Cjs	zero bias collector-substrate depletion capacitance	F/m^2	2.2196×10^{-13}
Vds	collector-substrate diffusion voltage	V	0.5156
Ps	collector-substrate grading coefficient		0.3299
Vgs	substrate bandgap voltage	V	1.12
As	for closed buried or an open buried layer		1.9
wVsubfwd	substrate junction forward bias (warning)	V	
wBvsub	substrate junction reverse breakdown voltage (warning)	V	
wBvbe	base-emitter reverse breakdown voltage (warning)	V	
wBvbc	base-collector reverse breakdown voltage (warning)	V	
wVbcfwd	base-collector forward bias (warning)	V	

Table 2-3. MEXTRAM_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
wIbmax	maximum base current (warning)	A	
wIcmax	maximum collector current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	name of DataAccessComponent for file-based model parameter values		

Notes/Equations/References

1. This model (version 503) supplies values for BJT_NPN, BJT_PNP, BJT4_NPN, and BJT4_PNP devices.
2. For the MEXTRAM bipolar transistor model, model equations are explicit functions of internal branch voltages; therefore, no internal quantities are solved iteratively. Transistor parameters are discussed where relevant; most parameters can be extracted from capacitance, dc, and f_T measurements, and are process and transistor layout (geometry) dependent. Initial/predictive parameter sets can be computed from process and layout data. This model does not contain extensive geometrical or process scaling rules (only multiplication factors to put transistors in parallel). The extended modeling of reverse behavior, the increase of the avalanche current when the current density in the epilayer exceeds the doping level, and the distributed high-frequency effect are optional and can be switched on by setting flags. Besides the NPN transistor a PNP model description is available, both with and without substrate (discrete transistors) modeling.
3. The Philips model uses the MULT parameter as a scaling factor. In ADS, MULT is implemented as AREA, which has the same mathematical effect. Because the Philips model uses MULT as the multiplier/scaling, the values are in measurements such as Amps. However, in ADS, units of area are m^2, so they are listed accordingly. This accounts for differences in reporting of some units in the Phillips documentation.
4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

Survey of Modeled Effects

- Temperature effects
- Charge storage effects

- Substrate effects and parasitic PNP
- High-injection effects
- Built-in electric field in base region
- Bias-dependent Early effect
- Low-level non-ideal base currents
- Hard and quasi-saturation
- Weak avalanche
- Hot carrier effects in the collector epilayer
- Explicit modeling of inactive regions
- Split base-collector depletion capacitance
  - Current crowding and conductivity modulation for base resistance
  - First-order approximation of distributed high-frequency effects in the intrinsic base (high-frequency current crowding and excess phase-shift).

Active Transistor

Main Current

In the MEXTRAM model the Moll-Ross relation is used to take into account the depletion and diffusion charges:

$$I_n = \frac{(I_f - I_r)}{1 + (Qt_e + Qt_c + Qb_e + Qb_c)/Qb0}$$

$$Qb_e = f_1(n_o)$$

$$Qb_c = f_2(n_b)$$

The depletion charges are represented by Qt_e and Qt_c. The computation of the diffusion charges Qb_e and Qb_c is based directly on the solution of the differential equation for the majority carriers in the neutral base region and relates the charges to the injected minority carrier concentrations at the emitter (no) and collector edges (nb). These concentrations, in turn, depend on the internal junction voltages Vb_2e_1 and Vb_2c by considering the p-n product at both junctions. In this way high injection, bias-dependent current gain, a current- dependent transit time, and the effect of the built-in electric field are included. The ideal forward and reverse current are given by:

$$I_f - I_r = Is \times (\exp(Vb_2e_1/V_t) - \exp(Vb_2c_2/V_t))$$

where V_t is the thermal voltage.

The parameters are:

Is = extracted from Gummel plot at low V_{be}

Qb0 = integral of base charge extracted from reverse Early effect

Xcjc = fraction of Cj_c underneath emitter; obtained from forward Early effect

Ik = from gain fall-off: only one knee current

Eta = built-in field in the base due to the doping profile. This parameter is normally between 3 and 6. It is difficult to obtain from direct measurements, and has a weak influence on computed currents and charges.

Ideal Forward Base Current

The ideal forward base current is defined in the usual way. The total base current has a bottom and a sidewall contribution. The separation is given by the factor XIb_1. This factor can be determined by analyzing the maximum current gain of transistors with different geometries.

$$Ib_1 = (1 - Xibi) \times \frac{Is}{Bf}(\exp(Vb_2e_1/V_t) - 1)$$

The parameters are:

Bf = ideal forward current gain

Xibi = fraction of ideal base current that belongs to the sidewall

Non-Ideal Forward Base Current

The non-ideal base current originates from the recombination in the depleted base-emitter region:

$$Ib_2 = Ibf \times \frac{\exp(Vb_2e_1/V_t) - 1}{\exp(Vb_2e_1/(2 \times V_t)) + \exp(Vlf/(2 \times V_t))}$$

Formulation of the non-ideal base current differs from the Gummel-Poon model. The MEXTRAM formulation is less flexible than the Gummel-Poon model. The formulation is the same when in the MEXTRAM model Vl_f is small (<0.4V), and when in the Gummel-Poon model parameter n_e=2. The parameters are:

Vlf = crossover voltage of the non-ideal forward base current

Ibf = saturation current of the non-ideal forward base current

Base-Emitter Depletion Charge

The base-emitter depletion charge is modeled in the classical way using a grading coefficient. The depletion charge is partitioned in a bottom and a sidewall component by the parameter Xcje.

$$Ct_e = (1 - Xcje) \times \frac{Cje}{1 - (Vb_2 e_1 / Vde)^{Pe}}$$

The capacitance becomes infinity at Vb_2e_1 = Vde. Therefore in the model the integral of equation is slightly modified and consequently Ct_e. The capacitance now has a maximum at the base-emitter diffusion voltage Vde and is symmetrical around the diffusion voltage. The maximum capacitance is determined by the value of K and the grading coefficient Pe. The value of K is a model constant and is taken equal to 0.01. When Pe=0.4, the maximum is approximately three times the capacitance at zero bias. The parameters are:

Cjc = zone bias base-emitter depletion capacitance

Vde = base-emitter diffusion voltage

Pe = base-emitter grading coefficient

Base-Collector Depletion Charge

The base-collector depletion capacitance underneath the emitter Qtc, takes into account the finite thickness of the epilayer and current modulation:

$$Ct_c = Xcjc \times Cjc \times \left(\frac{(1 - Xp) \times f(Vc_1 c_2)}{1 - ((Vb_2 \times c_2)/(Vdc))^{Pc}} + Xp \right)$$

$$f(Vc_1 \times c_2) = \left(1 - \frac{Vc_1 c_2}{Vc_1 c_2 + Ihc \times Rcv} \right)^{Mc}$$

The function $f(Vc_1c_2)$ equals one when $Ic_1c_2 = Vc_1c_2 = 0$, and becomes zero when the current density in the epilayer exceeds the doping level ($Vc_1c_2 >$ Ihc· Rcv). The parameters are:

Cjc = zero bias base-collector depletion capacitance

Xcjc = part of Cjc underneath emitter

Vdc = base-collector diffusion voltage

Pc = base-collector grading coefficient

Xp = depletion layer thickness at zero bias divided by epilayer thickness

Mc = collector current modulation coefficient ($0.3 < m_c < 0.5$)

Cjc**,** Pc and Xp is obtained from CV measurements; Vdc must be extracted from the quasi-saturation regime; Xcjc is obtained from the forward Early-effect.

Neutral Base and Emitter Diffusion Charge

The neutral base-emitter diffusion charge (Q_n) is given by:

$$Q_n = Qn_0 \times \left(\exp\left(\frac{Vb_2e_1}{Mtau \times V_t} \right) - 1 \right)$$

The charge Qn0 is calculated from the transit time Taune and Mtau. The parameters (extracted from the maximum value of the cut-off frequency, f_T) are:

Taune = minimum delay time of neutral and emitter charge

Mtau = non-ideality factor of the neutral and emitter charge; in most cases Mtau=1

Base-Charge Partitioning

Distributed high-frequency effects are modeled, in first order approximation, both in lateral direction (current crowding) and in vertical direction (excess phase-shift). The distributed effects are an optional feature of the MEXTRAM model, and can be switched on and off by flag Exphi (on: Exphi - 1; off: Exphi = 0). In vertical direction (excess phase-shift), base charge partitioning is used; for simplicity, it is implemented for forward base charge (Qb_e) and low-level injection only. No additional parameters.

$$Q'b_e = (1 - q_c(Eta)) \times Qb_e$$

$$Q'b_c = Qb_c + q_c(Eta) \times Qb_e$$

Modeling of Epilayer Current Charges

The epilayer resistance depends on the supplied collector voltage and current, imposed primarily by base-emitter voltage. The effective resistance of the epilayer is strongly voltage- and current-dependent because:

- In the forward mode of operation, the internal base charge junction voltage (Vb_2c_2) may become forward-biased at high collector currents (quasi-saturation). When this happens, the region in the collector near the base is injected by carriers from the base, causing the region to become low resistive.

- In the reverse mode of operation, both the external and internal base charge junction voltages are forward biased, flooding the whole epitaxial layer with carriers, which causes it to become low resistive.
- The current flow in the highly-resistive region is ohmic if the carrier density (n) is low ($n \ll N_{epi}$), and space-charge-limited if the carrier density exceeds the doping level (N_{epi}).
- Current spreading in the epilayer reduces the resistance and is of special importance if the carrier density exceeds N_{epi}. In the latter case, the carriers move with the saturated drift velocity, V_{sat} (hot-carrier current-flow).

A compact modal formulation of quasi-saturation is given by Kull et al [1]. The Kull model is valid only if the collector current density is below the critical current density (J_{hc}) for hot carriers:

$$J_{hc} = q \times N_{epi} \times v_{sat}$$

The Kull formulation has served as a basis for the epilayer model in MEXTRAM.

Collector Resistance Model

The Kull model is based on charge neutrality ($p + N_{epi} \approx n$) and gives the current through the epilayer (Ic_1c_2) as a function of the internal and external b.c. junction voltage. These voltages are given by the solution vector of the circuit simulator. The final equations of the Kull formulation [1] are:

$$Ic_1c_2 = \frac{E_c + Vb_2c_2 - Vb_2c_1}{Rcv}$$

$$E_c = V_t \times \left[K_0 - K_w - \ln\left(\frac{K_0 + 1}{K_w + 1}\right)\right]$$

$$K_0 = \sqrt{1 + 4 \times \exp[(Vb_2c_2 - Vd_c)/V_t]}$$

$$K_w = \sqrt{1 + 4 \times \exp[(Vb_2c_1 - Vd_c)/V_t]}$$

$$V_t = k \times \frac{T}{q}$$

Voltage source (E_c) takes into account the decrease in resistance due to carriers injected from the base into the collector epilayer. If both junctions are reverse biased ($Vb_2c_1 - Vd_c$ and $Vb_2c_2 - Vd_c$ are negative), E_c is zero and we have a simple constant resistance (Rcv). Because of this, this model does not take into account the hot-carrier behavior (carriers moving with the saturated drift-velocity) in the lightly-doped collector epilayer. The model is valid if the transistor operates in the reverse mode (reverse-biased b.e. junction, forward-biased b.c. junction). Then the entire epilayer is filled with carriers and a space-charge region does not exist. The derivation of the MEXTRAM epilayer resistance model is published in de Graaff and Kloosterman [2]. In the end, the following equations are found:

$$\frac{X_i}{W_{epi}} = \frac{E_c}{Ic_1c_2 \times Rcv}$$

$$I_{low} = \frac{Ihc \times Vc_1c_2}{Vc_1c_2 + Ihc \times Rcv \times (1 - X_i / W_{epi})}$$

$$Ic_1c_2 = (I_{low} + S_f) \times \frac{Vc_1c_2 - I_{low} \times Rcv \times (1 - X_i / W_{epi})}{Scrcv \times (1 - X_i / W_{epi})^2}$$

Where X_i/W_{epi} is the thickness of the injected region of the epilayer.

Substitution of equations and into equation gives a cubic equation. The epilayer current (Ic_1c_2) is computed by solving the cubic equation. The complex computation can be done with real variables. Summarizing, the epilayer resistance model takes into account:

- Ohmic current flow at low current densities
- Decrease in resistance due to carriers injected from the base if only the internal base-collector junction is forward biased (quasi-saturation), and if both the internal and external base-collector junctions are forward biased (reverse mode of operation)
- Space charge limited current flow at high current densities
- Current spreading in the epilayer

The model parameters are:

$$Ihc = q \times N_{epi} \times A_{em} \times v_{sat} \times \frac{1 + Sf_l}{\alpha_{cf}}$$

$$Rcv = \frac{W_{epi}}{q \times N_{epi} \times \mu \times A_{em}} \times \frac{\alpha_{cf}}{1 + Sf_l}$$

$$Scrcv = \frac{W^2{}_{epi}}{2 \times \varepsilon \times v_{sat} \times A_{em}} \times \frac{\alpha_{cf}}{1 + Sf_h}$$

$$Vdc = V_t \times \ln\left\{(N_{epi}/n_i)^2\right\}$$

$$Sfh = \frac{2}{3} \times \tan(\alpha_h) \times W_{epi} \times \left(\frac{1}{H_e} + \frac{1}{L_e}\right)$$

where

$$A_{em} = H_e \times L_e \ ,$$

$$Sf_l = \tan(\alpha_h) \times W_{epi} \times \left(\frac{1}{H_e} + \frac{1}{L_e}\right) \quad ,$$

α_l = the spreading angle at low current levels (Ic_1c_2 < Ihc)
α_h = the spreading angle at high current levels Ic_1c_2 > Ihc)
α_{cf} = the fraction of Ic_1c_2 flowing through the emitter floor area
L_e = the length of the emitter stripe.

The turnover from equations and in the forward mode to equation in the reverse mode does not give discontinuities in the first and second derivative. The third derivative is discontinuous. Parameter Sfh depends on transistor geometry and the decrease in gain and cutoff frequency will be affected by this parameter. SF_1 is included in Rcv and Ihc, and not needed as a separate parameter. In most cases, Vdc is computed directly from the doping level. Rcv, Ihc, and Scrcv are extracted from the quasi-saturation regime at low values of Vce.

Diffusion Charge of the Epilayer

The diffusion charge of the epilayer can be easily derived by applying the Moll-Ross relation to the base + collector region (from node e_1 to node c_1):

$$I_n = Ic_1c_2 = \frac{Is \times \{\exp(Vb_2e_1/V_t) - \exp(Vb_2c_1/V_t)\}}{1 + \dfrac{Q_{te} + Q_{tc} + Q_{be} + Q_{bc} + Q_{epi}}{Qb0}}$$

Subtracting equation , the expression for Q_{epi} becomes:

$$Q_{epi} = Is \times Qb0 \times \frac{\exp(Vb_2c_1/V_t) - \exp(Vb_2c_1/V_t)}{Ic_1c_2}$$

In the transition from forward to reverse mode, Ic_1c_2 passes zero and numerical problems can be expected. Substitution of equation into equation leads in the case where $Vb_2c_2 \approx Vb_2c_1$ to the following expression for Q_{epi}:

$$p_0 = \frac{2 \times \exp\{(Vb_2c_2 - Vdc)/V_t\}}{1 + K_0}$$

$$p_w = \frac{2 \times \exp\{(Vb_2c_1 - Vdc)/V_t\}}{1 + K_w}$$

$$Q_{epi} = Is \times Qb0 \times Rcv \times \exp(Vdc/V_t) \times \frac{p_0 + p_w}{2 \times V_t}$$

Avalanche Multiplication Model

Due to the high-electric field in the space-charge region, avalanche currents are generated; this generation strongly depends on the maximum electric field. The maximum electric field may reside at the base charge junction or at the buried layer. The generation of avalanche current in Kloosterman and de Graaff [3] is only a function of the electric field at the internal base charge junction. Therefore, the validity of this model is restricted to low current levels (Ic_1c_2<Ihc).

Current spreading in the collector region changes the electric-field distribution and decreases the maximum electric field. Because the generation of avalanche current is sensitive with respect to the maximum electric-field, it is difficult to set up an accurate and still simple model for high collector current densities. Because this operating area (high voltages, high current levels) is not of practical interest (due to power dissipation) and, more importantly, the convergency behavior of the model degrades, we must carefully consider the extension of the avalanche model to the high current regime.

At low current densities (Ic_1c_2<Ihc), the model is essentially the same as in Kloosterman and de Graaff [3]. As an optional feature, the model is extended to current levels exceeding Ihc (negative output resistance: snap-back behavior). Due to negative output resistance, serious convergency problems are imaginable. Without this feature, output resistance can be very small, but is always positive.

The generation of avalanche current is based on Chynoweth's empirical law for the ionization coefficient [4]:

$$P_n = \alpha_n \times \exp\left(\frac{-b_n}{|E|}\right)$$

Because only weak avalanche multiplication is considered, the generated avalanche current is proportional with the main current (I_n):

$$I_g = I_n \times \int_{x=0}^{x=X_d} \alpha_n \times \exp\left(\frac{-b_n}{|E(x)|}\right) \times dx$$

X_d = the boundary of the space-charge region.

To calculate the avalanche current, we must evaluate the integral of equation in the space-charge region. This integral is determined by the maximum electric field. We make a suitable approximation around the maximum electric field:

$$E(x) = E_m \times \left(1 - \frac{x}{\lambda}\right) \cong \frac{E_m}{1 + x/\lambda}$$

λ = the point where the extrapolated electric-field is zero.

Then the generated avalanche current becomes:

$$\frac{I_g}{I_n} = \frac{\alpha_n}{b_n} \times E_m \times \lambda \times \left\{\exp\left(\frac{-b_n}{E_m}\right) - \exp\left(\frac{-b_n}{E_m} \times \left(1 + \frac{X_d}{\lambda}\right)\right)\right\}$$

The maximum electric field (E_m), the depletion layer thickness (X_d), and the intersection point (λ) are calculated using the charge model of Q_{tc} and the collector resistance model. The model parameters are:

$$Avl = b_n \times \sqrt{\frac{2 \times \varepsilon \times Vdc}{q \times N_{epi}}}$$

$$F_i = 2 \times \frac{1 + 2 \times Sf_l}{1 + 2 \times Sfh} \times \frac{2 + Sf_l + 2 \times Sfh}{2 + 3 \times Sf_l}(-1)$$

Avl = obtained from the decrease of I_b at high V_{cb} and low I_c values

Sfh = equation

Sf_l = equation
Efi = used in extended avalanche model only

Sfh and Efi are extracted from the output characteristics at high V_{ce} and high I_c. Because most devices are heated due to power dissipation in this operation regime, parameter extraction is cumbersome. Calculating Efi and Sfh is often a good alternative.

Extrinsic Regions

Reverse Base Current

The reverse base current is affected by high injection and partitioned over the two external base-collector branches:

$$ah_b = 2 \times \left(\frac{1 - \exp(-Eta)}{Eta}\right)$$

$$al_b = \exp(-Eta)$$

$$g_1 = \frac{4 \times Is \times {ah_b}^2 \times \exp\left(\frac{Vb_1c_1}{V_t}\right)}{I_k \times {al_b}^2}$$

$$n_{b_{ex}} = al_b \times \frac{g_1}{2 \times (1 + \sqrt{1 + g_1})}$$

$$I_{ex} = \frac{(1 - Xext)}{Bri} \times \left(\frac{al_b + n_{b_{ex}}}{ah_b + n_{b_{ex}}} \times \frac{Ik}{ah_b} \times n_{b_{ex}} - Is\right)$$

The current XI_{ex} is computed in a similar way using the voltage Vbc1. Because the computing time to evaluate the extrinsic regions is doubled due to this partitioning, it is an optional feature. The parameters are:

Bri = ideal reverse current gain

Xext = partitioning factor

Non-Ideal Reverse Base Current

The non-ideal reverse base current (Ib3) is modeled in the same way as the forward non-ideal base current. The parameters are:

Ibr = saturation current of the non-ideal reverse base current

Vlr = crossover voltage of the non-ideal reverse base current

Extrinsic Base-Collector Depletion Capacitance

The base-collector depletion capacitance of the extrinsic region is divided over the external-base node b_1 (part: Q_{tex}). The model formulation is obtained by omitting the current modulation term in the formulation of Q_{tc} (equation).

$$Ctc_{ex} = (1 - Xext) \times (1 - Xcjc) \times Cjc \times \left(\frac{1 - Xp}{1 - (Vb_1c_1/\mathrm{Vdc})^{Pc}} + Xp \right)$$

$$Xctc_{ex} = Xext \times (1 - Xcjc) \times Cjc \times \left(\frac{1 - Xp}{1 - (Vb_1c_1/(Vdc))^{Pc}} + Xp \right)$$

Parameter Xext is partitioning factor for the extrinsic region.

This partitioning factor is important for the output conductance (Y12) at high frequencies.

Diffusion Charge of the Extrinsic Region

These charges are formulated in the same way as Qb_c and Q_{epi}, now using voltages Vc_1b_1 and Vbc_1, and the appropriate area (1 - Xcjc)/Xcjc.

No additional parameters.

Parasitic PNP

The substrate current of the PNP takes into account high injection. The parameters are:

Iss = substrate saturation current

Iks = knee in the substrate current; when the value of *Iks* is low, the reverse current gain increases at medium reverse current levels

When the collector-substrate junction becomes forward biased, only a signal current (Is_f) is present in the model.

$$Is_f = Iss \times (\exp((Vsc_1)/(Vt)) - 1)$$

No additional parameters.

Collector-Substrate Depletion Capacitance

The collector-substrate charge (Qt_s) is modeled in the usual way:

$$Ct_s = \frac{Cjs}{1 - (Vsc_1/(Vds))^{Ps}}$$

Parameters Cjs, Vds, and P*s* are obtained from collector-substrate CV measurement.

Base-Emitter Sidewall

Base-emitter sidewall base current Sib_1:

$$Sib_1 = Xibi \times \frac{Is}{Bf} \times (\exp(Vb_1e_1/V_t) - 1)$$

Parameter *Xibi* obtained from geometrical scaling of the current gain.

Base-emitter sidewall depletion capacitance SQt_e:

$$SCt_e = \frac{Xcje \times Cje}{1 - (Vb_1e_1/\mathrm{Vde})^{Pe}}$$

Parameter Xcje obtained from geometrical scaling of the capacitances.

Variable Base Resistance

The base resistance is divided in a variable part (R_{bv}) and a constant part (R_{bc}). The variable part is modulated by the base width variation (depletion charges at the junctions Q_{te} and Q_{tc}) and at high current densities it decreases because of the diffusion charges Q_{be} and Q_{bc}. The parameter Rbv is the resistance at zero base-emitter and base-collector voltage. The resistance model also considers DC current crowding. The resistance decreases at high base currents when V_{b1b2} is positive, and it increases when V_{b1b2} is negative (reversal of the base e current).

Charge modulation:

$$R_b = \frac{Rbv}{1 + (Qt_e + Qt_c + Qb_e + Qb_c)/(Qb0)}$$

DC current crowding:

$$Ib_1b_2 = \frac{2 \times V_t}{3 \times R_b} \times (\exp(Vb_1b_2 / V_t) - 1) + \frac{Vb_1b_2}{3 \times R_b}$$

Ac current crowding is an optional feature of the model (Exphi=1):

$$Qb_1b_2 = Vb_1b_2 \times (Ct_e + Cb_e + C_n) / 5$$

Constant Series Resistances

The model contains three constant series resistors at the base, emitter, and collector terminals (Rbc, Re, Rcc). (Substrate resistance is not incorporated in the model.)

Temperature Scaling Rules

Temperature scaling rules are applied to these parameters.

Resistances: Rbc, Rbv, Re, and Rcc

Capacitances: Cje, Vde, Cjc, Vdc, Xp, Cjs, Vds, Qbo, Qn_0, and Mtau

Saturation Currents: Is and Iss

Gain Modeling: Bf, Ibf, Vif, Bri, Ibr, Vlr, Ik, and Iks

Avalanche: Avl

These parameters are used in the temperature scaling rules:

Bandgap Voltages: Vge, Vgb, Vgc, Vgs, and Vgj

Mobility Exponents: Ab, Aepi, Aex, Ac, and As

Qb0: Vi and Na

Vlf and Vlr: Er

Noise Model

Thermal Noise: Resistances Rbc, Rbv, Re, and Rcc

Shot Noise: $I_{n,}$ Ib1, Sib1, Ib_2, Ib_3, I_{ex}, and XI_{ex}

1/F noise: Ib_1, SIb_1, Ib_2, and Ib_3

1/F noise parameters: Kf, Kfn, and Af

Equivalent Circuit

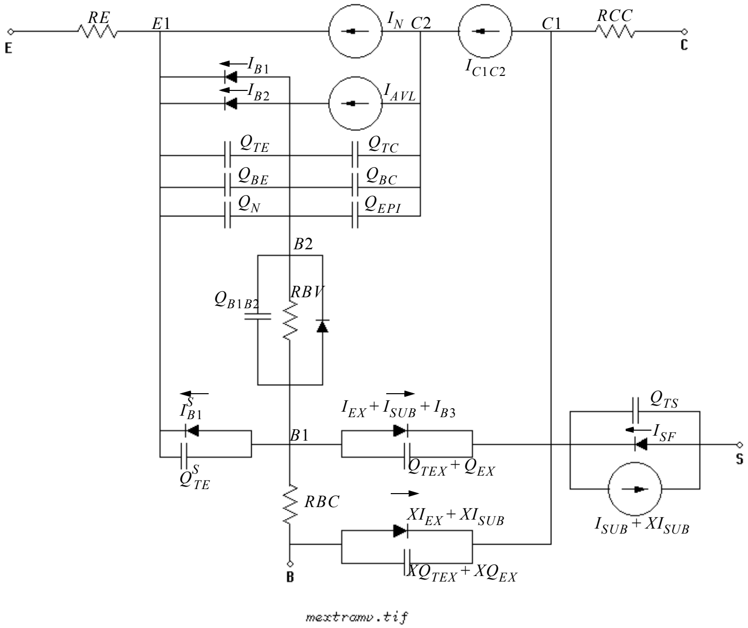


Figure 2-1. Equivaent Circuit for Vertical NPN Transistor

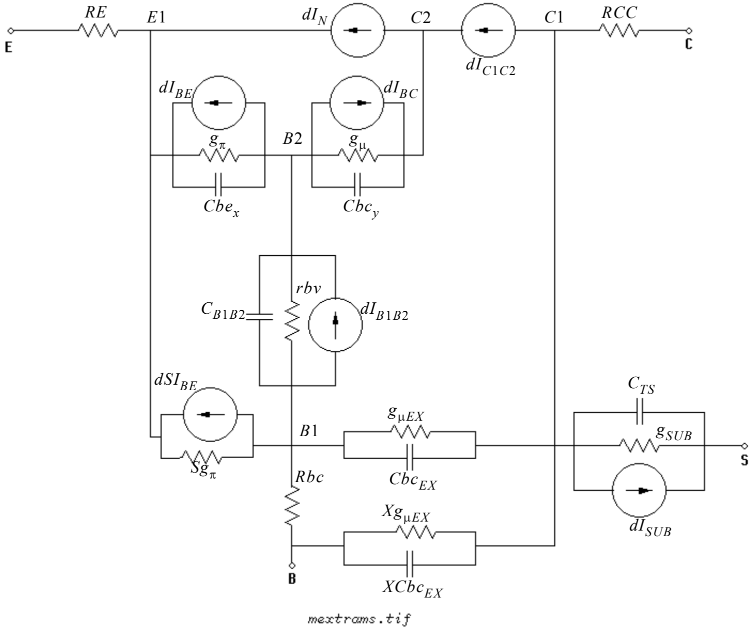


Figure 2-2. Small Signal Equivalent Circuit for Vertical NPN Transistor

References

[1] G. M. Kull, L. W. Nagel, S. Lee, P. L. Loyd, E. J. Prendergast, H. Dirks: “A Unified Circuit Model for Bipolar Transistors Including Quasi-Saturation Effects.” IEEE Transaction on Electron devices, Vol. ED-32, No. 6, June 1985.

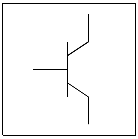
[2] H.C. de Graaff and W.J. Kloosterman: “Modeling of the collector Epilayer of a Bipolar Transistor in the Mextram Model.” IEEE Transaction on Electron devices, Vol. ED-42, p. 274, February 1995.

[3] W.J. Kloosterman, H.C. de Graaff: “Avalanche Multiplication in a Compact Bipolar Transistor Model for Circuit Simulation.” IEEE Transactions on Electron Devices, Vol. 36, No. 7, 1989.

[4] A.G. Chynoweth: “Ionization rates for electron and holes in silicon.” Phys. Rev., Vol. 109, p. 1537, 1958.

STBJT_Model (ST Bipolar Transistor Model)

Symbol



Parameters

Model parameters must be specified in SI units/

Table 2-4. STBJT_Model Parameters

Parameter	Description	Unit	Default
Type	1 is NPN; 2 is PNP		1
Timeas	measurement temperature	Celsius	27.0
Is	forward transport saturation current	A	1.0e-16
Isn	reverse transport saturation current	A	Is
Bf	ideal forward current gain		100.0
Nf	forward current emission coefficient	...	1.0
Br	ideal reverse current gain	...	1.0
Nr	reverse emission coefficient	...	1.0
Isf	ideal B-E junction saturation current	A	Is/Bf
Nbf	ideal B-E junction emission coefficient	...	Nf
Isr	ideal B-C junction saturation current	A	Isn/Br
Nbr	ideal B-C junction emission coefficient	...	Nr
Ise	B-E recombination saturation current	A	0.0
Ne	B-E recombination emission coefficient	...	2.0
Isc†, ††	B-C recombination saturation current	A	0.0
Nc	B-C recombination emission coefficient		1.5

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area specified with the BJT or BJT4 model.

††† A value of 0.0 is interpreted as infinity.

Table 2-4. STBJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Vaf	forward early voltage	V	0.0[†††]
Var	reverse early voltage	V	0.0[†††]
Enp	base push out exponent	...	2.0
Rp	BPO fitting parameter	...	1.0e-3
Rw	ratio of collector width to the base	...	0
Vij	modified B-C potential	V	0.8
Vrp	voltage drop across vertical Rc	V	1.0e-9
Bvc	junction breakdown of C-B junction	V	0.0[†††]
Mf	exponent of B-C multiplication factor		0.0
Fa	Bvcbo/Bvc		0.95
Avc	fitting parameter		1.0
Bve	junction breakdown of the E-B junction	V	fixed to infinity
Mr	exponent of the E-B multiplication factor		0.0
Fb	Bvebo/Bve	...	0.95
Ave	fitting parameter	...	1.0
Rb	zero-bias base resistance	Ohm	0.0
Irb	current when base resistance falls halfway to its minimum value	A	0.0[†††]
Rbm	minimum base resistance at high current (0 means Rb)	Ohm	0.0
Re	emitter resistance	Ohm	0.0
Rc	collector resistance under the emitter	Ohm	0.0
Rcs	collector resistance in saturation	Ohm	0.0
Cje	B-E zero-bias depletion capacitance	F	0.0

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area specified with the BJT or BJT4 model.

[†††] A value of 0.0 is interpreted as infinity.

Table 2-4. STBJT_Model Parameters (continued)

Parameter	Description	Unit	Default
Vje	B-E junction built-in potential	V	0.75
Mje	B-E grading coefficient		0.33
Fc	forward-bias depletion gap		1.0
Cjc	B-C zero-bias depletion gap	F	0.0
Vjc	B-C junction built-in potential	V	0.75
Mjc	junction grading coefficient	...	0.33
Xjbc	fraction of Cjc connected to B int node		1.0
Cjs	zero-bias collector substrate (ground) cap	F	0.0
Vjs	C-s (B-S) built-in potential	V	0.75
Mjs	C-s (B-S) grading coefficient		0.33
Xjbs	fraction of B-S cap connected to B int node		1.0
Vert	1 = vertical structures; 0 = else		0
Subsn	N substrate if 1	...	0
Tf	ideal forward transit time	S	0.0
Xtf	coefficient of bias dependence for TF		0.0
Vtf	voltage dependence of Tf on B-C voltage (0 means infinity)	V	fixed to infinity
Itf	parameter for Tf high currents roll off	A	set to infinity
Ptf	excess phase	degrees	0.0
Tfcc	Tf BPO model (1 if Spice)	...	0.0
Tr	ideal reverse transit time	S	0.0
Kf	flicker noise coefficient	...	0.0
Af	flicker noise exponent		0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area specified with the BJT or BJT4 model.

††† A value of 0.0 is interpreted as infinity.

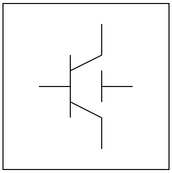
Table 2-4. STBJT_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Eg	bandgap voltage at OK	V	1.11
Xti	temperature exponent		3.0
Xtb	temperature exponent for gain currents	...	0.0
Trb1	linear temperature coefficient for Rb	Kelvin	0.0
Trb2	quadratic temperature coefficient for Rb	...	0.00
Trbm1	linear temperature coefficient for Rbm	...	0.0
Trbm2	Quadratic temperature coefficient for Rbm	...	0.0
Tre1	linear temperature coefficient for Re	Kelvin	0.0
Tre2	quadratic temperature coefficient for Re	...	0.0
Trc1	linear temperature coefficient for Rc	...	0.0
Trc2	quadratic temperature coefficient for Rc	...	0.0
Trcs1	linear temperature coefficient for Rcs	Kelvin	0.0
Trcs2	quadratic temperature coefficient for Rcs	...	0.0
Ikf	forward Ik (0 means infinity)	A	set to infinity
Ikr	reverse IK (0 means infinity)	A	set to infinity
Gmin	minimum conductance	...	1e-12
All Params	name of DataAccessComponent for file-based model parameter values	...	...

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area specified with the BJT or BJT4 model.
††† A value of 0.0 is interpreted as infinity.

VBIC_Model (VBIC Model)

Symbol



Parameters

Table 2-5. VBIC_Model Parameters

Parameter	Definition	Unit	Default
NPN	N-channel model type		yes
PNP	P-channel model type		no
Tnom	nominal ambient temperature	°C	25
Rcx†	extrinsic collector resistance	Ω	0.0
Rci†	intrinsic collector resistance	Ω	0.0
Vo†	epi drift saturation voltage	V	0.0
Gamm†	epi doping parameter		0.0
Hrcf	high-current RC factor		1.0
Rbx†	extrinsic base resistance	Ω	0.0
Rbi†	intrinsic base resistance	Ω	0.0
Re†	emitter resistance	Ω	0.0
Rs†	substrate resistance	Ω	0.0
Rbp†	parasitic base resistance	Ω	0.0
Is†	transport saturation current	A	10^{-16}
Nf†	forward emission coefficient		1.0
Nr†	reverse emission coefficient		1.0
Fc	forward bias junction capacitance threshold		0.9
Cbeo	base-emitter small signal capacitance	F	0.0
Cje†	base-emitter zero-bias junction capacitance	F	0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

Table 2-5. VBIC_Model Parameters (continued)

Parameter	Definition	Unit	Default
Pe†	base-emitter grading coefficient		0.75
Me	base-emitter junction exponent		0.33
Aje	base-emitter capacitance smoothing factor		–0.5
Cbco	extrinsic base-collector overlap capacitance	F	0.0
Cjc†	base-collector zero-bias capacitance	F	0.0
Qco	collector charge at zero bias	C	0.0
Cjep†	base-emitter extrinsic zero-bias capacitance	F	0.0
Pc†	base-collector grading coefficient		0.75
Mc	base-collector junction exponent		0.33
Ajc	base-collector capacitance smoothing factor		–0.5
Cjcp†	base-collector zero-bias extrinsic capacitance	F	0.0
Ps†	collector-substrate grading coefficient		0.75
Ms	collector-substrate junction exponent		0.33
Ajs	collector-substrate capacitance smoothing factor		–0.5
Ibei†	ideal base-emitter saturation current		10^{-18}
Wbe	portion of Ibei from Vbei, 1−Wbe from Vbex		1.0
Nei	ideal base-emitter emission coefficient		1.0
Iben†	non-ideal base-emitter saturation current		0.0
Nen	non-ideal base-emitter emission coefficient		2.0
Ibci†	ideal base-collector saturation current		10^{-16}
Nci	ideal base-collector emission coefficient		1.0
Ibcn†	non-ideal base-collector saturation current		0.0
Ncn	non-ideal base-collector emission coefficient		2.0
Isp†	parasitic transport saturation current		0.0
Wsp	portion of Iccp from Vbep, 1−Wsp from Vbci		1.0
Nfp	parasitic forward emission coefficient		1.0

† This parameter value varies with temperature based on model Tnom and device Temp.

Table 2-5. VBIC_Model Parameters (continued)

Parameter	**Definition**	**Unit**	**Default**
Ibeip†	ideal parasitic base-emitter saturation current		0.0
Ibenp†	non-ideal parasitic base-emitter saturation current		0.0
Ibcip†	ideal parasitic base-collector saturation current		0.0
Ncip	ideal parasitic base-collector emission coefficient		1.0
Ibcnp†	non-ideal parasitic base-collector saturation current		0.0
Avc1	base-collector weak avalanche parameter 1		0.0
Avc2†	base-collector weak avalanche parameter 2		0.0
Ncnp	non-ideal parasitic base-collector emission coefficient		2.0
Vef	forward Early voltage (0=infinity)		0.0
Ver	reverse Early voltage (0=infinity)		0.0
Ikf	forward knee current. (0=infinity)	A	0.0
Ikr	reverse knee current (0=infinity)	A	0.0
Ikp	parasitic knee current (0=infinity)	A	0.0
Tf	forward transit time	sec	0.0
Qtf	variation of Tf with base-width modulation		0.0
Xtf	coefficient of Tf bias dependence		0.0
Vtf	coefficient of Tf dependence on Vbc		0.0
Itf	coefficient of Tf dependence on Icc?		0.0
Tr	ideal reverse transit time	sec	0.0
Td	forward excess-phase delay time	sec	0.0
Kfn	flicker noise coefficient		0.0
Afn	flicker noise exponent		1.0
Bfn	flicker noise frequency exponent		1.0
Xre	temperature exponent of emitter resistance		0.0
Xrb	temperature exponent of base resistance		0.0
Xrc	temperature exponent of collector resistance		0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

Table 2-5. VBIC_Model Parameters (continued)

Parameter	**Definition**	**Unit**	**Default**
Xrs	temperature exponent of substrate resistance		0.0
Xvo	temperature exponent of Vo		0.0
Ea	activation energy for Is	eV	1.12
Eaie	activation energy for Ibei	eV	1.12
Eaic	activation energy for Ibci/Ibeip	eV	1.12
Eais	activation energy for Ibcip	eV	1.12
Eane	activation energy for Iben	eV	1.12
Eanc	activation energy for Ibcn/Ibenp	eV	1.12
Eans	activation energy for Ibcnp	eV	1.12
Xis	temperature exponent of Is		3.0
Xii	temperature exponent of Ibei/Ibci/Ibeip/Ibcip		3.0
Xin	temperature exponent of Iben/Ibcn/Ibenp/Ibcnp		3.0
Tnf	temperature coefficient of Nf		0.0
Tavc	temperature coefficient of Avc		0.0
Rth	thermal resistance	Ω	0.0
Cth	thermal capacitance	F	0.0
Imax	explosion current	A	1.0
wVsubfwd	substrate junction forward bias (warning)	V	
wBvsub	substrate junction reverse breakdown voltage (warning)	V	
wBvbe	base-emitter reverse breakdown voltage (warning)	V	
wBvbc	base-collector reverse breakdown voltage (warning)	V	
wVbcfwd	base-collector forward bias (warning)	V	
wIbmax	maximum base current (warning)	A	
wIcmax	maximum collector current (warning)	A	

† This parameter value varies with temperature based on model Tnom and device Temp.

Table 2-5. VBIC_Model Parameters (continued)

Parameter	Definition	Unit	Default
wPmax	maximum power dissipation (warning)	W	
AllParams	name of DataAccessComponent for file-based model parameter values		
† This parameter value varies with temperature based on model Tnom and device Temp.			

Notes/Equations/References

1. This model (version 1.1.4) supplies values for a VBIC device.
2. The VBIC vertical BJT model was developed specifically as a replacement for the SPICE Gummel-Poon model by representatives of the IC and CAD industries.

   VBIC includes improved modeling of the Early effect (output conductance), substrate current, quasi-saturation, and behavior over temperature—information necessary for accurate modeling of current state-of-the-art devices. However, it has additionally been defined so that, with default parameters, the model will simplify to be as similar as possible to the Gummel-Poon model.

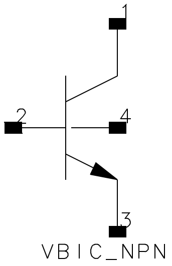
   - Advantages of VBIC over the Gummel-Poon model include:
   - An Early effect model based on the junction depletion charges
   - A modified Kull model for quasi-saturation valid into the Kirk regime (the high-injection effect at the collector)
   - Inclusion of the parasitic substrate transistor
   - An improved single-piece junction capacitance model for all 3 junction capacitances
   - Improved static temperature scaling
   - First-order modeling of distributed base and emitter ac and dc crowding
   - Overall improved high-level diffusion capacitance modeling (including quasi-saturation charge)
   - Inclusion of parasitic overlap capacitances; inclusion of the onset of weak avalanche current for the base-collector junction.
   - High-order continuity (infinite) in equations. A noise model similar to that of the Gummel-Poon model, with shot, thermal, and 1/f components

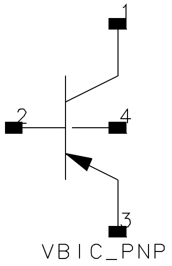
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those via AllParams.
4. Colin McAndrew, AT&T/Motorola; Jerry Seitchik, Texas Instruments; Derek Bowers, Analog Devices; Mark Dunn, Hewlett Packard; Mark Foisy, Motorola; IanGetreu, Analogy; Marc McSwain, MetaSoftware; Shahriar Moinian, AT&T Bell Laboratories; James Parker, National Semiconductor; Paul van Wijnen, Intel/Philips; Larry Wagner, IBM, *VBIC95: An Improved Vertical, IC Bipolar Transistor Model*.
5. W. J. Kloosterman and H. C. de Graaff. “Avalanche Multiplication in a Compact Bipolar Transistor Model for Circuit Simulation,” *IEEE 1988 BCTM.*
6. McAndrew and Nagel. “Spice Early Model,” *IEEE 1994 BCTM*.
7. Jorg Berkner, SMI System Microelectronic Innovation GmbH, Frankfurt/Oder, Germany. *A Survey of DC Methods for Determining the Series Resistance of Bipolar Transistors Including the New Delta ISub Method*.

VBIC (Nonlinear Bipolar Transistors)

VBIC_NPN, (VBIC Nonlinear Bipolar Transistor, NPN)
VBIC_PNP, (VBIC Nonlinear Bipolar Transistor, PNP)

Symbol





Parameters

Model = name of a VBIC_Model

Scale = scaling factor (default: 1)

Region = dc operating region: 0 = off, 1 = on, 2 = rev, 3 = sat (default: on)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: nonlinear, linear (default: nonlinear)

_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated VBIC_Model) certain model parameters are scaled such that the device is simulated at its operating temperature.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. This device has no default artwork associated with it.

Chapter 3: Devices and Models, GaAs

Bin Model

The BinModel in the GaAs library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

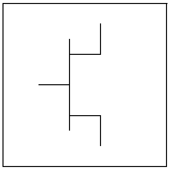
For information on the use of the binning feature, refer to the section *"Bin Model (Bin Model for Automatic Model Selection."* This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components.*

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

Curtice2_Model (Curtice-Quadratic GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-1. Curtice2_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		1
Vto†,	threshold voltage	V	−2
Beta†, ††	transconductance	A/V^2	10^{-4}
Lambda	channel length modulation	1/V	0.0
Alpha	hyperbolic tangent function	1/V	2.0
Tau	transit time under gate	sec	0.0
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Idstc	Ids temperature coefficient	A/Temp°C	0
Vtotc	Vto temperature coefficient	V/°C	0.0
Betatce	drain current exponential temperature coefficient	%/°C	0.0
Rin †††	channel resistance	ohms	0.0
Rf†††	gate-source effective forward- bias resistance	ohms	infinity‡

†This parameter value varies with temperature based on model Tnom and device Temp.

††This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-1. Curtice2_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgs[† ††]	zero bias gate-source junction capacitance	F	0.0
Cgd [†, ††]	zero bias gate-drain junction capacitance	F	0.0
Rgd[†††]	gate drain resistance	ohms	0.0
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Rd[†††]	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs[†††]	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds[††]	drain-source capacitance	F	0.0
Rc[†††]	used with Crf to model frequency dependent output conductance	ohms	infinity[‡]
Crf[††]	used with Rc to model frequency dependent output conductance	F	0.0
Gsfwd	0=none, 1=linear, 2=diode		linear
Gsrev	0=none, 1=linear, 2=diode		none
Gdfwd	0=none, 1=linear, 2=diode		none
Gdrev	0=none, 1=linear, 2=diode		linear

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area.

[†††] This parameter value scales inversely with Area.

[‡] A value of 0.0 is interpreted as infinity.

Table 3-1. Curtice2_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
R1†††	approximate breakdown resistance	ohms	infinity‡
R2†††	resistance relating breakdown voltage to channel current	ohms	0.0
Vbi†	built-in gate potential	V	0.85
Vbr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} < 0$)	V	10^{100}
Is†, †	gate junction saturation current (diode model)	A	10^{-14}
Ir	gate reverse saturation current	A	10^{-14}
Imax	explosion current	A	1.6
Xti	temperature exponent for saturation current		3.0
Eg	energy gap for temperature effect on Is	eV	1.11
N	gate junction emission coefficient (diode model)		1.0
Fnc	flicker noise corner frequency	Hz	0
R	gate noise coefficient		0.5
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9
Taumdl	second order Bessel polynomial to model tau effect in transient simulation		no
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	

†This parameter value varies with temperature based on model Tnom and device Temp.

††This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-1. Curtice2_Model Parameters (continued)

Parameter	Description	Unit	Default
wPmax	maximum power dissipation warning	W	
AllParams	DataAccessComponent for file-based model parameter values		
†This parameter value varies with temperature based on model Tnom and device Temp. ††This parameter value scales with Area. ††† This parameter value scales inversely with Area. ‡ A value of 0.0 is interpreted as infinity.			

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.
3. Drain-source current

   The drain current in the Curtice quadratic model is based on the work of W. R. Curtice [1].

   The quadratic dependence of the drain current with respect to the gate voltage is computed with the following expression in the region $V_{ds} \geq 0.0V$.

   $$I_{ds} = Beta \times (V_{gs} - Vto)^2 \times (1 + Lambda \times V_{ds}) \times \tanh(Alpha \times V_{ds}).$$

   Assuming symmetry, in the reverse region, the drain and source swap roles and the expression becomes:

   $$I_{ds} = Beta \times (V_{gd} - Vto)^2 \times (1 - Lambda \times V_{ds}) \times \tanh(Alpha \times V_{ds}).$$

   The drain current is set to zero in either case if the junction voltage (V_{gs} or V_{gd}) drops below the threshold voltage Vto.
4. Junction charge (capacitance)

   You are provided with two options in modeling the junction capacitance of a device. The first is to model the junction as a linear component (a constant capacitance). The second is to model the junction using a diode depletion capacitance model. If a non-zero value of Cgs is specified and Gscap is set to 1 (linear), the gate-source junction will be modeled as a linear component. Similarly, specifying a non-zero value for Cgd and Gdcap = 1 result in a linear gate-drain model. A non-zero value for either Cgs or Cgd together with Gscap =2 (junction) or Gdcap = 2 will force the use of the diode depletion capacitance model for that particular junction. Note, that each junction is modeled independent of the other and hence, it is possible to model one junction as a linear component while the other is treated nonlinearly. The junction depletion charge and capacitance equations are summarized below.

Gate-source junction

For $V_{gc} < Fc \times Vbi$

$$Q_{gs} = 2 \times V_{bi} \times Cgs\left[1 - \sqrt{1 - \frac{V_{gc}}{Vbi}}\right]$$

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{\sqrt{1 - \frac{V_{gc}}{Vbi}}}$$

For $V_{gc} \geq Fc \times Vbi$

$$Q_{gs} = 2 \times Vbi \times Cgs[1 - \sqrt{1 - Fc}] + \frac{Cgs}{(1 - Fc)^{3/2}}$$

$$\times \left[\left(1 - \frac{3 \times Fc}{2}\right) \times (V_{gc} - Fc \times Vbi) + \frac{V_{gc}^2 - (Fc \times Vbi)^2}{4 \times Vbi}\right]$$

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{(1 - Fc)^{3/2}} \times \left[1 - \frac{3 \times Fc}{2} + \frac{V_{gc}}{2 \times Vbi}\right]$$

Gate-drain junction

For $V_{gd} < Fc \times Vbi$

$$Q_{gd} = 2 \times Vbi \times Cgd \times \left[1 - \sqrt{1 - \frac{V_{gd}}{Vbi}}\right]$$

$$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{Cgd}{\sqrt{1 - \frac{V_{gd}}{Vbi}}}$$

For $V_{gd} \geq Fc \times Vbi$

$$Q_{gd} = 2 \times Vbi \times Cgd[1 - \sqrt{1 - Fc}] + \frac{Cgd}{(1 - Fc)^{3/2}}$$

$$\times \left[\left(1 - \frac{3 \times Fc}{2}\right) \times (V_{gd} - Fc \times Vbi) + \frac{V_{gd}^2 - (Fc \times Vbi)^2}{4 \times Vbi}\right]$$

$$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{Cgd}{(1 - Fc)^{3/2}} \times \left[1 - \frac{3 \times Fc}{2} + \frac{V_{gd}}{2 \times Vbi}\right]$$

5. Gate forward conduction and breakdown

Agilent’s implementation of the Curtice quadratic model provides a few options for modeling gate conduction current between the gate-source and gate-drain junctions. The simplest model is that proposed by Curtice for his cubic polynomial model (see Curtice3). This model assumes an *effective value* of forward bias resistance Rf and an approximate breakdown resistance R1. With model parameters Gsfwd = 1 (linear) and Rf reset to non-zero, gate-source forward conduction current is given by:

$I_{gs} = (V_{gs} - Vbi)/Rf$ when $V_{gs} > Vbi$

$= 0$ when $V_{gs} \leq Vbi$.

If Gsfwd = 2 (diode), the preceding expression for I_{gs} is replaced with the following diode expression:

$$I_{gs} = Is \times \left[exp\left(\frac{V_{gs}}{N \times v_t}\right) - 1\right]$$

Similarly, with parameter Gdfwd = 1 (linear) and Rf set to non-zero, gate-drain forward conduction current is given by:

$I_{gd} = (V_{gd} - Vbi)/Rf$ when $V_{gd} > Vbi$

$= 0$ when $V_{gd} \leq Vbi$.

If Gdfwd is set to 2 (diode), the preceding expression for Igd is replaced with a diode expression:

$$I_{gd} = Is \times \left[exp\left(\frac{V_{gd}}{N \times v_t} \right) - 1 \right]$$

The reverse breakdown current (I_{dg}) is given by the following expression if R1 is set non-zero and Gdrev = 1 (linear):

$I_{gd} = V_{dg} - V_b)/R1$ when $V_{dg} \geq V_b$ and $V_b > 0$
$= 0$ when $V_{dg} < V_b$ or $V_b \leq 0$
$V_b = Vbr + R2 \times I_{ds}$

If Gdrev is set to 2, the preceding Igd expression is replaced with a diode expression:

$$I_{gd} = -Ir \times \left[exp\left(\frac{Vdg - Vb}{Vjr} \right) - 1 \right]$$

With Gsrev -= 1 (linear) and R1 set to non-zero, the gate-source reverse breakdown current Igs is given by the following expression:

$I_{gs} = (V_{sg} - Vb)/R1$ when $V_{sg} \geq Vbi$ and $Vb > 0$

$= 0$ when $V_{sg} \leq Vbi$ or $Vb \leq 0$

If Gsrev is set to 2, the preceding Igs expression is replaced with a diode expression.

$$I_{gs} = -Ir \times \left[exp\left(\frac{Vsg - Vb}{Vjr} \right) - 1 \right]$$

When the diode equations are both enabled, the dc model is symmetric with respect to the drain and source terminals. The ac model will also be symmetric if, in addition to the latter, Cgs=Cgd.

6. Time delay

This implementation models the delay as an ideal time delay. In the time domain, the drain source current for the ideal delay is given by:

$I_{ds}(t) = I_{ds}(V_j(t - Tau), V_{ds}(t))$

where $V_j = V_{gs}$ or $V_j = V_{gd}$ (depending on whether V_{ds} is positive or negative). In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained

$$y_m = g_m \times \exp(-j \times \omega \times \mathrm{Tau})$$

7. High-frequency output conductance

   The series-RC network in Figure 3-1 is comprised of the parameters Crf and Rc and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that CRF is an effective short, the output conductance of the device can be increased by the factor 1/Rc. (For more on this, see [2].

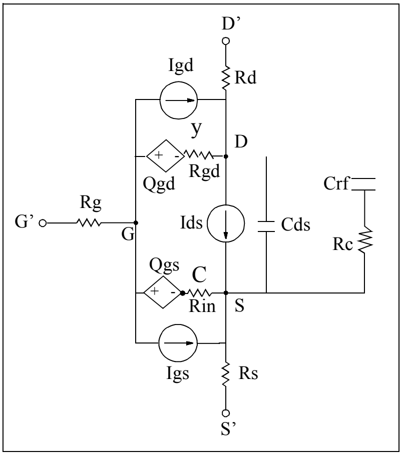


Figure 3-1. Curtice2_Model Schematic

8. Temperature Scaling

   The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

   The saturation current Is scales as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

   The gate depletion capacitances Cgs and Cgd vary as:

$$Cgs^{NEW} = Cgs\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

$$Cgd^{NEW} = Cgd\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

where γ is a function of the junction potential and the energy gap variation with temperature.

The gate junction potential Vbi varies as:

$$Vbi^{NEW} = \frac{Temp}{Tnom} \times Vbi + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

where n_i is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage Vto varies as:

$$Vto^{NEW} = Vto + Vtotc(Temp - Tnom)$$

The transconductance Beta varies as:

$$Beta^{NEW} = Beta \times 1.01^{Betatce(Temp - Tnom)}$$

If Betatc = 0 and Idstc ≠ 0

$Ids^{NEW} = Ids \times (1 + Idstc \times (Temp - Tnom)$

9. Noise Model

Thermal noise generated by resistors Rg, Rs, and Rd is characterized by the following spectral density:

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\ P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\, C_{gs}^2\, \omega^2\, R / g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\, C_{gs}\, \omega \sqrt{PR}\, C$$

References

[1] W. R. Curtice, “A MESFET model for use in the design of GaAs integrated circuits,” *IEEE Trans Microwave Theory Tech*, vol. MTT-28, pp. 448-456, May 1980.

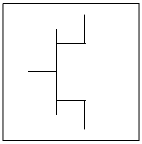
[2] C. Camacho-Penalosa and C.S. Aitchison, “Modelling frequency dependence of output impedance of a microwave MESFET at low frequencies,” *Electron. Lett.,* Vol. 21, pp. 528-529, June 6, 1985.

[3] P. Antognetti and G. Massobrio, *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

[4] A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Advanced_Curtice2_Model (Advanced Curtice-Quadratic GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-2. Advanced_Curtice2_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		1
Vto†	threshold voltage	V	–2
Beta†, ††	transconductance	A/V^2	10^{-4}
Lambda	channel length modulation	1/V	0.0
Alpha	hyperbolic tangent function	1/V	2.0
Tau	transit time under gate	sec	0.0
Taumdl	second order Bessel polynomial to model Tau effect in transient simulation		no
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Idstc	Ids temperature coefficient	A/Temp°C	0
Ucrit	critical field for mobility degradation		0
Vgexp	Vgs – Vto exponent		2
Gamds	effective pinch-off combined with Vds		–0.01

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.

Table 3-2. Advanced_Curtice2_Model Parameters (continued)

Parameter	Description	Unit	Default
Vtotc	Vto temperature coefficient	V/°C	0.0
Betatce	drain current exponential temperature coefficient	%/°C	0.0
Rgs†††	gate-source resistance	ohms	0
Rf†††	gate-source effective forward- bias resistance	ohms	infinity‡
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgs†, ††	zero bias gate-source junction capacitance	F	0.0
Cgd †, ††	zero bias gate-drain junction capacitance	F	0.0
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Rgd†††	gate drain resistance	ohms	0
Rd†††	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs†††	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds††	drain-source capacitance	F	0.0
Rc†††	used with Crf to model frequency dependent output conductance	ohms	infinity‡
Crf††	used with Rc to model frequency dependent output conductance	F	0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-2. Advanced_Curtice2_Model Parameters (continued)

Parameter	Description	Unit	Default
Gsfwd	0=none, 1=linear, 2=diode		linear
Gsrev	0=none, 1=linear, 2=diode		none
Gdfwd	0=none, 1=linear, 2=diode		none
Gdrev	0=none, 1=linear, 2=diode		linear
R1†††	approximate breakdown resistance	ohms	infinity‡
R2†††	resistance relating breakdown voltage to channel current	ohms	0.0
Vbi†	built-in gate potential	V	0.85
Vbr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with V_{ds}<0)	V	10^{100}
Vjr	breakdown junction potential	V	1
Is†, ††	gate junction rev. saturation current (diode model)	A	10^{-14}
Ir	gate reverse saturation current	A	10^{-14}
Imax	explosion current	A	1.6
Xti	temperature exponent for saturation current		3.0
Eg	energy gap for temperature effect on Is	eV	1.11
N	gate junction emission coefficient (diode model)		1.0
Fnc	flicker noise corner frequency	Hz	0
R	gate noise coefficient		0.5
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9
wVgfwd	gate junction forward bias (warning)	V	
wBvgs	gate-source reverse breakdown voltage (warning)	V	

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-2. Advanced_Curtice2_Model Parameters (continued)

Parameter	Description	Unit	Default
wBvgd	gate-drain reverse breakdown voltage (warning)	V	
wBvds	drain-source breakdown voltage (warning)	V	
wIdsmax	maximum drain-source current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	DataAccessComponent for file-based model parameter values		

† This parameter value varies with temperature based on model Tnom and device Temp.
†† This parameter value scales with Area.
††† This parameter value scales inversely with Area.
‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\ P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\ C_{gs}^2\ \omega^2\ R/g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\ C_{gs}\ \omega \sqrt{PR}\ C$$

   Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

3. Drain-source current

   The drain current in the Advanced Curtice quadratic model is based on the work of W. R. Curtice [1].

   The quadratic dependence of the drain current with respect to the gate voltage is computed with the following expression in the region $V_{ds} \geq 0.0$V.

$I_{ds} = Beta_{NEW} \times (V_{gs} - Vto_{NEW})^{Vgexp} \times (1 + Lambda \times V_{ds}) \times tanh(Alpha \times V_{ds})$

where

$Vto_{NEW} = Vto + Gainds \times Vds$

$Beta_{NEW} = Beta/(1 + (Vgs - Vto_{NEW} \times Ucrit)$

Assuming symmetry, in the reverse region, the drain and source swap roles and the expression becomes:

$I_{ds} = Beta_{NEW} \times (V_{gd} - Vto_{NEW})^{Vgexp} \times (1 - Lambda \times V_{ds}) \times tanh(Alpha \times V_{ds})$

where

$I_{ds} = Beta_{NEW} \times (V_{gd} - Vto_{NEW})^{Vgexp} \times (1 + Lambda \times V_{ds}) \times tanh(Alpha \times V_{ds})$.

where

$Vto_{NEW} = Vto + Gainds \times Vds$

$Beta_{NEW} = Beta/(1 + (Vgd - Vto_{NEW} \times Ucrit)$

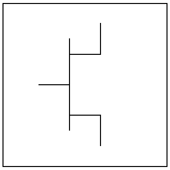
The drain current is set to zero in either case if the junction voltage (V_{gs} or V_{gd}) drops below the threshold voltage Vto.

If Ucrit is not equal to 0, the temperature coefficients Vtotc and Betatc are disabled.

4. A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Curtice3_Model (Curtice-Cubic GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-3. Curtice3_Model Parameters

Parameter	**Description**	**Unit**	**Default**
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		2
Beta2	coefficient for pinch-off change with respect to V_{ds}	1/V	10^{-4}
Rds0†††	dc conductance at Vgs=0	ohms	0
Vout0	output voltage (Vds) at which A0, A1, A2, A3 were evaluated	V	0.0
Vdsdc	Vds at Rds0 measured bias	V	0
Tau	transit time under gate	sec	0.0
Gamma	current saturation	1/V	2.0
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Idstc	Ids temperature coefficient	A/Temp°C	0
A0†, ††	cubic polynomial I_{ds} equation coefficient 1	A	0.0
A1†, ††	cubic polynomial I_{ds} equation coefficient 2	A/V	0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-3. Curtice3_Model Parameters (continued)

Parameter	Description	Unit	Default
A2†, ††	cubic polynomial I_{ds}equation coefficient 3	A/V^2	0.0
A3†, ††	cubic polynomial I_{ds} equation coefficient 4	A/V^3	0.0
Vtotc	A0, A1, A2, A3 temperature coefficient	V/°C	0.0
Betatce	drain current exponential temperature coefficient	%/°C	0.0
Rin†††	channel resistance	ohms	0.0
Rf†††	gate-source effective forward-bias resistance	ohms	infinity‡
Fc	forward-bias depletion capacitance coefficient (diode model)		0.5
Gscap	0=none,1=linear,2=junction,3=Statz charge,5=Statz cap		linear
Cgs††	zero-bias gate-source capacitance	F	0.0
Cgd††	zero-bias gate-drain capacitance	F	0.0
Rgd†††	gate drain resistance	ohms	0.0
Gdcap	0=none,1=linear,2=junction,3=Statz charge,5=Statz cap		linear
Rd††	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs†††	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds††	drain-source capacitance	F	0.0
Crf††	with Rds, models frequency dependent output conductance	F	0.0

† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-3. Curtice3_Model Parameters (continued)

Parameter	Description	Unit	Default
Rds[†††]	additional output resistance for RF operation	ohms	infinity[‡]
Gsfwd	0=none, 1=linear, 2=diode		linear
Gsrev	0=none, 1=linear, 2=diode		none
Gdfwd	0=none, 1=linear, 2=diode		none
Gdrev	0=none, 1=linear, 2=diode		linear
R1[†††]	approximate breakdown resistance	ohms	infinity[‡]
R2[†††]	resistance relating breakdown voltage to channel current	ohms	0.0
Vbi[†]	built-in gate potential	V	0.85
Vbr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} < 0$)	V	10^{100}
Vjr	breakdown junction potential		0.025
Is[†] [††]	gate junction saturation current (diode model)	A	10^{-14}
Ir	gate reverse saturation current	A	10^{-14}
Xti	temperature exponent for saturation current		3.0
Eg	energy gap for temperature effect on Is	eV	1.11
N	gate junction emission coefficient (diode model)		1.0
A5	time delay proportionality constant for Vds		0.0
Imax	explosion current	A	1
Taumdl	second order Bessel polynomial to model tau effect in transient simulation		no
Fnc	flicker noise corner frequency	Hz	0
R	gate noise coefficient		0.5

[†] This parameter value varies with temperature based on model Tnom and device Temp.

[††] This parameter value scales with Area.

[†††] This parameter value scales inversely with Area.

[‡] A value of 0.0 is interpreted as infinity.

Table 3-3. Curtice3_Model Parameters (continued)

Parameter	Description	Unit	Default
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9
wVgfwd	gate junction forward bias (warning)	V	
wBvgs	gate-source reverse breakdown voltage (warning)	V	
wBvgd	gate-drain reverse breakdown voltage (warning)	V	
wBvds	drain-source breakdown voltage (warning)	V	
wIdsmax	maximum drain-source current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	DataAccessComponent for file-based model parameter values		

□□□

□□□□□□□† This parameter value varies with temperature based on model Tnom and device Temp.

†† This parameter value scales with Area.

††† This parameter value scales inversely with Area.

□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. The Curtice cubic model is based on the work of Curtice and Ettenberg. Curtice3_Model contains most of the features described in Curtice's original paper plus some additional features that may be turned off. The following subsections review the highlights of the model. Refer to Curtice's paper [1] for more information.
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

Equations/Discussion:

Drain-Source Current

The drain current in Curtice3_Model is computed with the following expression:

$$I_{ds} = I_{dso} \times \tanh(\text{Gamma} \times V_{ds}),\ \text{Tau}_{NEW} = \text{Tau} + \text{A5} \times \text{Vds}$$

where

$$I_{dso} = [\text{A0} + \text{A1} \times V_1 + \text{A2} \times V_1{}^2 + \text{A3} \times V_1{}^3] + (\text{Vds} - \text{Vdsc})/\text{Rds0}$$
$$V_1 = V_{gs}(t - \text{Tau}_{NEW}) \times (1 + \text{Beta2} \geq (\text{Vout0} - V_{ds})),\ \text{when } V_{ds} \geq 0.0\ \text{V}$$
$$V_1 = V_{gd}(t - \text{Tau}_{NEW}) \times (1 + \text{Beta2} \geq (\text{Vout0} + V_{ds})),\ \text{when } V_{ds} < 0.0\ \text{V}$$

The latter results in a symmetrical drain-source current that is continuous at V_{ds}=0.0 V. For values of V_1 below the internal computed maximum pinchoff voltage Vpmax, which is the voltage at the local minimum of the function

$$\text{A0} + \text{A1} \times \nu + \text{A2} \times \nu^2 + \text{A3} \times \nu^3$$

I_{dso} is replaced with the following expression:

$$I_{dso} = [\text{A0} + \text{A1} \times \text{max} + \text{A2} \times \text{Vpmax}^2 + \text{A3} \times \text{Vpmax}^3] + + (\text{Vds} - \text{Vdsc})/\text{Rds0}$$

If the I_{dso} value is negative (for V_{ds} > 0.0V), current is set to 0.

This implementation models the delay as an ideal time delay.

Junction Charge (Capacitance)

You are provided with two options in modeling the junction capacitance of a device. The first is to model the junction as a linear component (a constant capacitance). The second is to model the junction using a diode depletion capacitance model. If a non-zero value of Cgs is specified and Gscap is set to 1 (linear), the gate-source junction will be modeled as a linear component. Similarly, specifying a non-zero value for Cgd and Gdcap = 1 result in a linear gate-drain model. A non-zero value for either Cgs or Cgd together with Gscap =2 (junction) or Gdcap = 2 will force the use of the diode depletion capacitance model for that particular junction. Note, that each junction is modeled independent of the other and hence, it is possible to model one junction as a linear component while the other is treated nonlinearly. The junction depletion charge and capacitance equations are summarized below.

Gate-Source Junction

For $V_{gc} < \text{Fc} \times \text{Vbi}$

$$Q_{gs} = 2 \times V_{bi} \times Cgs \times \left[1 - \sqrt{1 - \frac{V_{gc}}{Vbi}}\right]$$

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{\sqrt{1 - \frac{V_{gc}}{Vbi}}}$$

For $V_{gc} \geq Fc \quad \times Vbi$

$$Q_{gs} = 2 \times V_{bi} \times Cgs \times [1 - \sqrt{1 - Fc}] + \frac{Cgs}{(1 - Fc)^{3/2}}$$

$$\times \left[\left(1 - \frac{3 \times Fc}{2}\right) \times (V_{gc} - Fc \times Vbi)\left(\frac{V_{gc}^2 - (Fc \times Vbi)^2}{4 \times Vbi}\right)\right]$$

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} = \frac{Cgs}{(1 - Fc)^{3/2}} \times \left[1 - \frac{3 \times Fc}{2} + \frac{V_{gc}}{2 \times Vbi}\right]$$

Gate-Drain Junction

For $V_{gd} < Fc \times Vbi$

$$Q_{gd} = 2 \times V_{bi} \times Cgd \times \left[1 - \sqrt{1 - \frac{V_{gd}}{Vbi}}\right]$$

$$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{Cgd}{\sqrt{1 - \frac{V_{gd}}{Vbi}}}$$

For $V_{gd} \geq Fc \times Vbi$

$$Q_{gd} = 2 \times V_{bi} \times Cgd \times \left([1 - \sqrt{1 - Fc}] + \frac{Cgd}{(1 - Fc)^{3/2}}\right)$$

$$\times \left[\left(1 - \frac{3 \times Fc}{2}\right) \times \left(V_{gd} - F(c \times Vbi) + \frac{V_{gd}^2 - (Fbi)^2}{4 \times Vbi}\right)\right]$$

$$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} = \frac{Cgd}{(1-Fc)^{3/2}} \times \left[1 - \frac{3 \times Fc}{2} + \frac{V_{gd}}{2 \times Vbi}\right]$$

Gate Forward Conduction and Breakdown

Agilent's implementation of the Curtice quadratic model provides a few options for modeling gate conduction current between the gate-source and gate-drain junctions. The simplest model is that proposed by Curtice for his cubic polynomial model (see Curtice3). This model assumes an *effective value* of forward bias resistance Rf and an approximate breakdown resistance R1. With model parameters Gsfwd = 1 (linear) and Rf reset to non-zero, gate-source forward conduction current is given by:

$I_{gs} = (V_{gs} - Vbi)/Rf$ when $V_{gs} > Vbi$

$= 0$ when $V_{gs} \leq Vbi$.

If Gsfwd = 2 (diode), the preceding expression for I_{gs} is replaced with the following diode expression:

$$I_{gs} = Is \times \left[exp\left(\frac{V_{gs}}{N \times v_t}\right) - 1\right]$$

Similarly, with parameter Gdfwd = 1 (linear) and Rf set to non-zero, gate-drain forward conduction current is given by:

$I_{gd} = (V_{gd} - Vbi)/Rf$ when $V_{gd} > Vbi$

$= 0$ when $V_{gd} \leq Vbi$.

If Gdfwd is set to 2 (diode), the preceding expression for Igd is replaced with a diode expression:

$$I_{gd} = Is \times \left[exp\left(\frac{V_{gd}}{N \times v_t}\right) - 1\right]$$

The reverse breakdown current (I_{dg}) is given by the following expression if R1 is set non-zero and Gdrev = 1 (linear):

$I_{gd} = V_{dg} - V_b)/R1$ when $V_{dg} \geq V_b$ and $V_b > 0$
$= 0$ when $V_{dg} < V_b$ or $V_b \leq 0$
$V_b = Vbr + R2 \times I_{ds}$

If Gdrev is set to 2, the preceding Igd expression is replaced with a diode expression:

$$I_{gd} = -Ir \times \left[exp\left(\frac{Vdg - Vb}{Vjr} \right) - 1 \right]$$

With Gsrev -= 1 (linear) and R1 set to non-zero, the gate-source reverse breakdown current Igs is given by the following expression:

$$I_{gs} = (V_{sg} - Vb)/R1 \quad \text{when } V_{sg} \geq Vbi \text{ and } Vb > 0$$

$$= 0 \quad \text{when } V_{sg} \leq Vbi \text{ or } Vb \leq 0$$

If Gsrev is set to 2, the preceding Igs expression is replaced with a diode expression.

$$I_{gs} = -Ir \times \left[exp\left(\frac{Vsg - Vb}{Vjr} \right) - 1 \right]$$

When the diode equations are both enabled, the dc model is symmetric with respect to the drain and source terminals. The ac model will also be symmetric if, in addition to the latter, Cgs=Cgd.

High-Frequency Output Conductance

Curtice3_Model provides the user with two methods of modeling the high frequency output conductance. The series-RC network dispersion model (Figure 3-2) is comprised of the parameters Crf and Rds and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that Crf is an effective short, the output conductance of the device can be increased by the factor 1/Rds. (Also see [2]).

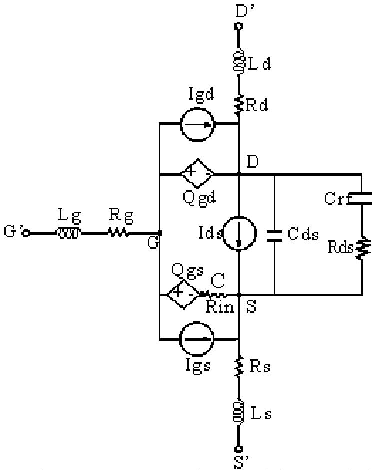


Figure 3-2. Curtice Cubic Model

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current Is scales as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

The gate depletion capacitances Cgso and Cgdo vary as:

$$Cgs^{NEW} = Cgs\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

$$Cgd^{NEW} = Cgd\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

where y is a function of junction potential and energy gap variation with temperature.

The gate junction potential Vbi varies as:

$$Vbi^{NEW} = \frac{Temp}{Tnom} \times Vbi + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

where n_i is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The cubic polynomial coefficients A0, A1, A2, and A3 vary as:

$$\Delta = Vtotc(Temp - Tnom)$$

$$A0^{NEW} = (A0 - \Delta \times A1 + \Delta^2 \times A2 - \Delta^3 \times A3) \times 1.01^{Betatce(Temp - Tnom)}$$

$$A1^{NEW} = (A1 - 2\Delta \times A2 + 3\Delta^2 \times A3 - \Delta^3 \times A3) \times 1.01^{Betatce(Temp - Tnom)}$$

$$A2^{NEW} = (A2 - 3\Delta \times A3) \times 1.01^{Betatce(Temp - Tnom)}$$

$$A3^{NEW} = (A3) \times 1.01^{Betatce(Temp - Tnom)}$$

Noise Model

Thermal noise generated by resistors Rg, Rs and Rd is characterized by the spectral density:

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m \; P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT \; C_{gs}^2 \; \omega^2 \; R/g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj \; C_{gs} \; \omega \sqrt{PR} \; C$$

Computation of Vto Parameter

The Vto parameter is not used in this model. Instead, it is computed internally to avoid the discontinuous or non-physical characteristic in ids versus vgs if A0, A1, A2, A3 are not properly extracted.

For a given set of A's, ADS will try to find the maximum cut off voltage (Vpmax), which satisfies the following conditions:

$Vpmax < 0$

$f(Vpmax) = A0 + A1 \times Vpmax + A2 \times Vpmax\times\times 2 + A3 \times Vpmax\times\times 3 \leq 0$

first derivative of $f(Vpmax) = 0$ (inflection point)

second derivative of $f(Vpmax) > 0$ (this is a minimum)

If Vpmax can't be found, a warning message appears, stating that the cubic model does not pinch off.

During analysis, the following are computed:

$vc = vgs \times (1 + Beta \times (Vout0 - vds))$

$ids = ((A0 + A1 \times vc + A2 \times vc\times\times 2 + A3 \times vc\times\times 3) + (vds - Vdsdc) / Rds0)$

$\times \tanh(Gamma \times vds)$

If $ids < 0$ then set $ids = 0$.

If $ids > 0$ and $Vc \leq Vpmax$ then compute ivc as follows:

$ivc = (f(Vpmax) + (vds - Vdsdc) / Rds0) \times \tanh(Gamma \times vds)$

If $ivc > 0$ then set $ids = ivc$ and give a warning message stating that cubic mode; does not pinch off

else set $ids = 0$

To ensure the model is physical and continuous, it is important to obtain a meaningful set of A's that Vpmax can be found.

References

[1] W. R. Curtice and M. Ettenberg, “A nonlinear GaAsFET model for use in the design of output circuits for power amplifiers,” *IEEE Trans of Microwave Theory Tech*, vol. MTT-33, pp. 1383-1394, Dec. 1985.

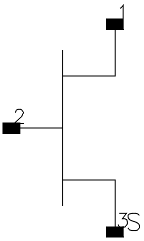
[2] C. Camacho-Penalosa and C.S. Aitchison, “Modelling frequency dependence of output impedance of a microwave MESFET at low frequencies,” *Electron. Lett.,* Vol. 21, pp. 528-529, June 6, 1985.

[3] P. Antognetti and G. Massobrio, *Semiconductor device modeling with SPICE,* New York: McGraw-Hill, Second Edition 1993.

[4] A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

EE_FET3 (EEsof Scalable Nonlinear GaAsFet, Second Generation)

Symbol



Parameters

Model = name of an EE_FET3_Model

Ugw = unit gate width, in length units (default: 0)

N = number of gate fingers (default: 1)

Temp = device operating temperature (default: 25)

_M = number of devices in parallel (default: 1)

Range of Usage

Ugw > 0

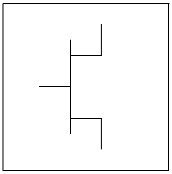
N > 0

Notes/Equations/References

1. Ugw and N are used for scaling device instance; refer to the model for these descriptions.

EE_FET3_Model (EEsof Scalable Nonlinear GaAsFet Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-4. EE_FET_3 Model Parameters

Name	Description	Unit	Default
Vto	zero bias threshold	V	-1.5
Gamma	Vds dependent threshold	1/V	0.05
Vgo	gate-source voltage where transconductance is a maximum	V	–0.5
Vdelt	controls linearization point for transconductance characteristic	V	0.0
Vch	gate-source voltage where Gamma no longer affects I-V curves	V	1.0
Gmmax	peak transconductance	S	70×10^{-3}
Vdso	output voltage where Vds dependence disappears from equations	V	2.0
Vsat	drain-source current saturation	V	1.0
Kapa	output conductance	1/V	0.0
Peff	channel to backside self-heating	W	2.0
Vtso	subthreshold onset voltage	V	–10.0
Is	gate junction reverse saturation current	A	10^{-20}
N	gate junction ideality factor		1.0
Ris	source end channel resistance	ohms	2.0
Rid	drain end channel resistance	ohms	0.0

Table 3-4. EE_FET_3 Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
Tau	gate transit time delay	sec	10^{-12}
Cdso	drain-source inter-electrode capacitance	F	80×10^{-15}
Rdb	dispersion source output impedance	ohms	10^{9}
Cbs	trapping-state capacitance	F	1.6×10^{-13}
Vtoac	zero bias threshold (ac)	V	–1.5
Vtoactc	linear temperature coefficient for Vtoac		0.0
Gammaac	Vds dependent threshold (ac)	1/V	0.05
Vdeltac	controls linearization point for transconductance characteristic (ac)	V/deg. C	0.0
Gmmaxac	peak transconductance (ac)	S	600×10^{-3}
Gmmaxtc	linear temperature coefficient for Gmmax		0.0
Gammatc	linear temperature coefficient for Gamma		0.0
Gmmaxactc	linear temperature coefficient for Gmmaxac		0.0
Gammaactc	linear temperature coefficient for Gammaac		0.0
Kapaac	output conductance (ac)	1/V	0.0
Peffac	channel to backside self-heating (ac)	W	10.0
Vtsoac	subthreshold onset voltage (ac)	V	–10.0
Gdbm	additional d-b branch conductance at Vds = Vdsm	S	0.0
Kdb	controls Vds dependence of additional d-b branch conductance.		0.0
Vdsm	voltage where additional d-b branch conductance becomes constant	V	1.0
C11o	maximum input capacitance for Vds=Vdso and Vdso>Deltds	F	0.3×10^{-12}
C11th	minimum (threshold) input capacitance for Vds=Vdso	F	0.03×10^{-12}
Vinfl	inflection point in C11-Vgs characteristic	V	–1.0
Vinfltc	linear temperature coefficient for Vinfl		0.0
Deltgs	C11th to C11o transition voltage	V	0.5

Table 3-4. EE_FET_3 Model Parameters (continued)

Name	Description	Unit	Default
Deltds	linear region to saturation region transition	V	1.0
Lambda	C11-Vds characteristic slope	1/V	1.5
C12sat	input transcapacitance for Vgs=Vinfl and Vds>Deltds	F	0.03×10^{-12}
Cgdsat	gate drain capacitance for Vds>Deltds	F	0.05×10^{-12}
Kbk	breakdown current coefficient at threshold		0.0
Vbr	drain-gate voltage where breakdown source begins conducting	V	15.0
Nbr	breakdown current exponent		2.0
Idsoc	open channel (maximum) value of Ids	A	100×10^{-3}
Rd	drain contact resistance	ohms	1.0
Rs	source contact resistance	ohms	1.0
Rg	gate metallization resistance	ohms	1.0
Ugw	unit gate width of device		0.0
Ngf	number of device gate fingers		1.0
Tnom	parameter measurement temperature		25.0
Rgtc	linear temperature coefficient for RG 1/degC		0.0
Rdtc	linear temperature coefficient for RD 1/degC		0.0
Rstc	linear temperature coefficient for RS 1/degC		0.0
Vtotc	linear temperature coefficient for pinchoff voltage		0.0
Gmmaxtc	linear temperature coefficient for Gmmax		0.0
Xti	saturation current temperature exponent		3.0
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	

Table 3-4. EE_FET_3 Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
wPmax	maximum power dissipation warning	W	
AllParams	DataAccessComponent for file-based model parameter values		

Notes/Equations/References

1. This model supplies values for an EE_FET3 device.
2. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed:

   $Rd = 10^{-4}$
   $Rs = 10^{-4}$
   $Rg = 10^{-4}$
   $Ris = 10^{-4}$
   $Rid = 10^{-4}$
   $Vsat = 0.1$
   $Peff = 10^{-6}$
   $Peffac = 10^{-6}$
   $Deltds = 0.1$
   $Deltgs = 0.1$
   $Idsoc = 0.1$
   $Is = 10^{-50}$

3. Model parameters such as Ls, Ld, and Lg (as well as other package related parameters that are included as part of the output from the EEFET3 IC-CAP model file) are not used by the EE_FET3 device in the simulator. Only those parameters listed in Tables 3-4 are part of the EE_FET3 device. Any extrinsic devices must be added externally by the user.

Equations/Discussion

EE_FET3 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of GaAs FETs. The model represents a complete redesign of the previous generation model EEFET1-2 and includes the following features:

- Accurate isothermal drain-source current model fits virtually all processes.
- Self-heating correction for drain-source current.
- Improved charge model more accurately tracks measured capacitance values.
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics.
- Improved breakdown model describes gate-drain current as a function of both V_{gs} and V_{ds}.
- Well-behaved (non-polynomial) expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as g_m-V_{gs} plots. The increased number of model parameters is commensurate with the improvement in accuracy as compared with other popular empirical models. Since the model equations are all well-behaved analytic expressions, EE_FET3 possesses no inherent limitations with respect to its usable power range. HP EEsof's IC-CAP program provides the user with the capability of extracting EEFET3 models from measured data.

Drain-Source Current

The drain-source current model in EE_FET3 is comprised of various analytic expressions that were developed through examination of g_m vs. bias plots on a wide class of devices from various manufacturers. The expressions below are given for $V_{ds} > 0.0$ V although the model is equally valid for $V_{ds} < 0.0$ V. The model assumes the device is symmetrical, and one need only replace V_{gs} with V_{gd} and V_{ds} with $-V_{ds}$ in order to obtain the reverse region ($V_{ds} < 0.0$ V) equations. The g_m, g_{ds} and I_{ds} equations take on four different forms depending on the value of V_{gs} relative to some of the model parameters. The I_{ds} expression is continuous through at least the second derivative everywhere.

if $V_{gs} \geq V_g$ and $V_{delt} \leq 0.0$

$$g_{mo} = Gmmax\{1 + Gamma(Vdso - V_{ds})\}$$

$$I_{dso} = Gmmax\left\{V_x(V_{gs}) - \frac{(Vgo + Vto)}{2} + Vch\right\}$$

$$g_{dso} = -Gmmax(Gamma(V_{gs} - Vch))$$

else if $V_{Delt} > 0.0$ and $V_{gs} > V_{gb}$

$$g_{mo} = g_{mm}(V_{gb}) + m_{g_{mm}} \times (V_{gs} - V_{gb})$$

$$I_{dso} = g_{mm}(V_{gb}) \times (V_{gs} - V_{gb}) + \frac{m_{g_{mm}}}{2}(V_{gs} - V_{gb})^2 + I_{dsm}(V_{gb})$$

$$g_{dso} = \frac{\partial(g_{mm}(V_{gb}))}{\partial V_{ds}}(V_{gs} - V_{gb}) + \frac{1}{2}(V_{gs} - V_{gb})^2 \times \frac{\partial m_{g_{mm}}}{\partial V_{ds}} - \frac{\partial V_{gb}}{\partial V_{ds}} g_{mo}$$

else if $V_{gs} \le V_t$

$$g_{mo} = 0.0$$

$$I_{dso} = 0.0$$

$$g_{dso} = 0.0$$

else

$$g_{mo} = g_{mm}(V_{gs})$$

$$I_{dso} = I_{dsm}(V_{gs})$$

$$g_{dso} = -\frac{Gmmax}{2} Gamma(V_{gs} - Vch)$$

$$\times \left\{\cos\left[\pi \times \frac{V_x(V_{gs}) - (Vgo - Vch)}{Vto - Vgo}\right] + 1\right\}$$

where

$$\begin{aligned} g_{mm}(V) &= \frac{Gmmax}{2}[1 + Gamma(Vdso - V_{ds})] \\ &\quad \times \left\{ \cos\left[\pi \times \frac{V_x(V) - (Vgo - Vch)}{Vto - Vgo}\right] + 1 \right\} \end{aligned}$$

$$\begin{aligned} I_{dsm}(V) &= \frac{Gmmax}{2}\Bigg(((Vto - Vgo)/\pi)\sin\left[\pi \times \frac{V_x(V) - (Vgo - Vch)}{Vto - Vgo}\right] \\ &\quad + V_x(V) - (Vto - Vch) \Bigg) \end{aligned}$$

$$V_x(V) = (V - Vch)[1 + Gamma(Vdso - V_{ds})]$$

$$V_g = \frac{Vgo - Vch}{1 + Gamma(Vdso - V_{ds})} + Vch$$

$$V_t = \frac{Vto - Vch}{1 + Gamma(Vdso - V_{ds})} + Vch$$

$$V_{gb} = \frac{(Vgo - Vdelt) - Vch}{1 + Gamma(Vdso - V_{ds})} + Vch$$

$$\begin{aligned} m_{g_{mm}} &= \left.\frac{\partial g_{mm}}{\partial V}\right|_{V = V_{gb}} \\ &= -\frac{Gmmax\pi}{2(Vto - Vgo)}[1 + Gamma(Vdso - V_{ds})]^2 \\ &\quad \times \sin\left[-\pi \times \frac{Vdelt}{Vto - Vgo}\right] \end{aligned}$$

$$\begin{aligned} g_{mm}(V_{gb}) &= \frac{Gmmax}{2}[1 + Gamma(Vdso - V_{ds})] \\ &\quad \times \left\{ \cos\left[-\pi \times \frac{Vdelt}{Vto - Vgo}\right] + 1 \right\} \end{aligned}$$

$$\begin{aligned} I_{dsm}(V_{gb}) &= \frac{Gmmax}{2}\Bigg(((Vto - Vgo)/\pi)\sin\left[-\pi \times \frac{Vdelt}{Vto - Vgo}\right] \\ &\quad + (Vgo - Vdelt - Vto) \Bigg) \end{aligned}$$

$$\frac{\partial(g_{mm}(V_{gb}))}{\partial V_{ds}} = -\frac{Gmmax}{2}Gamma\left\{\cos\left[-\pi \times \frac{Vdelt}{Vto - Vgo}\right] + 1\right\}$$

$$\begin{aligned}\frac{\partial m_{g_{mm}}}{\partial V_{ds}} &= \frac{Gmmax\pi}{(Vto - Vgo)}(Gamma)[1 + Ganna(Vdso - V_{ds})]\\ &\quad \times \sin\left[-\pi \times \frac{Vdelt}{Vto - Vgo}\right]\end{aligned}$$

$$\frac{\partial V_{gb}}{\partial V_{ds}} = \frac{(Vgo - Vdelt) - Vch}{[1 + Gamma(Vdso - V_{ds})]^2} \times Gamma$$

The preceding relations for I_{dso}, g_{mo} and g_{dso} can now be substituted in the following equations that model the current saturation and output conductance. This portion of the model can be recognized from the work of Curtice [1].

$$g'_m = g_{mo}(1 + Kapa \times V_{ds})\tanh\left(\frac{3V_{ds}}{Vsat}\right)$$

$$I'_{ds} = I_{dso}(1 + Kapa \times V_{ds})\tanh\left(\frac{3V_{ds}}{V(sat)}\right)$$

$$\begin{aligned}g'_{ds} &= \{g_{dso}(1 + Kapa \times V_{ds}) + I_{dso}Kapa\}\tanh\left(\frac{3V_{ds}}{Vsat}\right)\\ &\quad + I_{dso} \times \frac{3(1 + Kapa \times V_{ds})}{Vsat}\operatorname{sech}^2\left(\frac{3V_{ds}}{Vsat}\right)\end{aligned}$$

These expressions do an excellent job of fitting GaAs FET I-V characteristics in regions of low power dissipation; they will also fit pulsed (isothermal) I-V characteristics. In order to model negative conductance effects due to self-heating, the thermal model of Canfield was incorporated [2]. With this final enhancement, the dc expressions for I_{ds} and associated conductances become:

$$I_{ds} = \frac{I'_{ds}}{1 + \frac{P_{diss}}{Peff}}$$

$$g_m = \frac{g'_m}{\left[1 + \frac{P_{diss}}{Peff}\right]^2}$$

$$g_{ds} = \frac{g'_{ds} - \frac{I'^2_{ds}}{Peff}}{\left[1 + \frac{P_{diss}}{Peff}\right]^2}$$

where

$$P_{diss} = I'_{ds} V_{ds}$$

Qualitatively, operation of the drain-source model can be described as follows.

The V_{ds} dependence of the equations is dominated by the parameters Vsat, Gamma, Kapa, and Peff. Isothermal output conductance is controlled by Gamma and Kapa. The impact of Gamma on output conductance is more significant near threshold. At V_{gs}=Vch, the output conductance is controlled only by Kapa. The parameter Peff provides a correction to the isothermal model for modeling the self-heating effects manifested as a negative resistance on the I-V curves. The parameter Vsat represents the drain-source voltage at which the current saturates and output conductance becomes a constant (approximately).

The overall impact of Vch on the I-V characteristics is second order at best, and many different values of Vch will provide good fits to I-V plots. For most applications encountered, it is our experience that the default value of 1.0V is an adequate value for Vch. Similar to Vch, Vdso is a parameter that should be set rather than optimized. At V_{ds}=Vdso, the drain-source model collapses to a single

voltage dependency in V_{gs}. It is recommended that the user set Vdso to a typical V_{ds} operating point in saturation. At this point, many of the parameters can be extracted right off a I_{ds}-V_{gs} plot for V_{ds}=Vdso or preferably, a g_m(dc)-V_{gs} plot at V_{ds}=Vdso.

When V_{ds}=Vdso and Peff is set large (to disable the self-heating model), the significance of the parameters Vto, Vgo, Vdelt, Gmmax are easily understood from a plot of g_m(dc)–V_{gs}. Gmmax is the peak constant transconductance of the model that occurs at V_{gs}=Vgo. The parameter Vto represents the gate-source voltage where g_m goes to zero. If Vdelt is set to a positive value, then it causes the transconductance to become linear at V_{gs}= Vgo−Vdelt with a slope equal to that of the underlying cosine function at this voltage. The parameter definitions are illustrated in Figure 3-3.

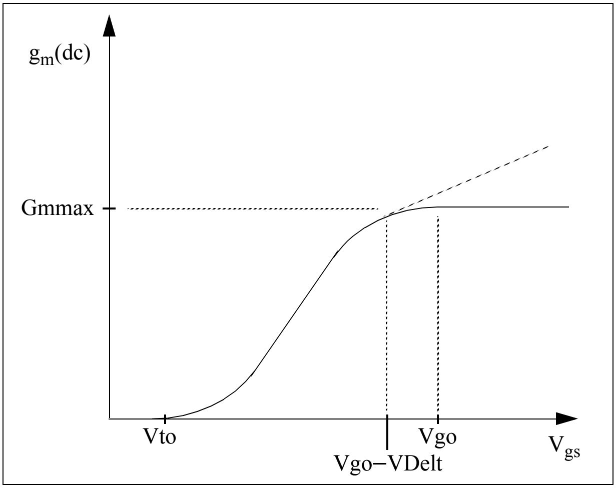


Figure 3-3. EEFET3 g_m-V_{gs} Parameters

Dispersion Current (Idb)

Dispersion in a GaAs MESFET drain-source current is evidenced by the observation that the output conductance and transconductance beyond some transition frequency is higher than that inferred by the dc measurements. A physical explanation often attributed to this phenomenon is that the channel carriers are subject to being trapped in the channel-substrate and channel-surface interfaces. Under slowly varying signal conditions, the rate at which electrons are trapped in these sites is equal to the rate at which they are emitted back into the channel. Under rapidly varying signals, the traps cannot follow the applied signal and the *high-frequency* output conductance results.

The circuit used to model conductance dispersion consists of the devices Rdb, Cbs (these linear devices are also parameters) and the nonlinear source $I_{db}(V_{gs}, V_{ds})$. The model is a large-signal generalization of the dispersion model proposed by Golio et al. [3]. At dc, the drain-source current is just the current I_{ds}. At high frequency (well above transition frequency), drain source current will be equal to I_{ds}(high frequency) = I_{ds}(dc) + I_{db}. Linearization of the drain-source model yields the following expressions for y_{21} and y_{22} of the intrinsic EE_FET3 model.

$$y_{21} = g_{dsgs} + g_{dbgs} - \frac{g_{dbgs}}{1 + j\omega \times Cbs(Rdb)}$$

$$y_{22} = g_{dsds} + g_{dbds} + \frac{1}{Rdb} - \frac{\left(g_{dbds} + \frac{1}{Rdb}\right)}{1 + j\omega \times Cbs(Rdb)}$$

where

$$g_{dsgs} = \frac{\partial I_{ds}}{\partial V_{gs}}$$

$$g_{dsds} = \frac{\partial I_{ds}}{\partial V_{ds}}$$

$$g_{dbgs} = \frac{\partial I_{db}}{\partial V_{gs}}$$

$$g_{dbds} = \frac{\partial I_{db}}{\partial V_{ds}}$$

Evaluating these expressions at the frequencies ω=0 and ω=infinity produces the following results for transconductance and output conductance:

for ω=0,

$$Re[y_{21}] = g_m = g_{dsgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds}$$

for ω=infinity,

$$Re[y_{21}] = g_m = g_{dsgs} + g_{dbgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds} + g_{dbds} + \frac{1}{Rdb}$$

Between these two extremes, the conductances make a smooth transition, the abruptness of which is governed by the time constant τ_{disp} = Rdb × □□Cbs. The frequency f_0 at which the conductances are midway between these two extremes is defined as

$$f_0 = \frac{1}{2\pi\tau_{disp}}$$

The parameter Rdb should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near f_0, the default values of Rdb and Cbs specified in Table 3-4 will be adequate for most microwave applications.

The EE_FET3 I_{ds} model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc I-V and ac conductances, EE_FET3 uses a simple scheme for modeling the I_{db} current source whereby different values of the same parameters can be used in the I_{ds} equations. The dc and ac drain-source currents can be expressed as follows:

$$
\begin{aligned}
I_{ds}^{dc}(Voltages, Parameters) = I_{ds}(&Voltages, Gmmax, Vdelt, Vto, \text{Gamma},\\
&Kapa, Peff, Vtso, Vgo, Vch, Vdso, Vsat)
\end{aligned}
$$

$$
\begin{aligned}
I_{ds}^{ac}(Voltages, Parameters) = I_{ds}(&Voltages, Gmmaxac, Vdeltac, Vtoac,\\
&Gammaac, Kappaac, Peffac, Vtsoac,\\
&Vgo, Vch, Vdso, Vsat)
\end{aligned}
$$

Parameters such as Vgo that do not have an ac counterpart (there is no Vgoac parameter) have been found not to vary significantly between extractions using dc measurements versus those using ac measurements. The difference between the ac and dc values of I_{ds}, plus an additional term that is a function of V_{ds} only, gives the value of I_{db} for the dispersion model

$$I_{db}(V_{gs}, V_{ds}) = I_{ds}^{ac}(V_{gs}, V_{ds}) - I_{ds}^{dc}(V_{gs}, V_{ds}) + I_{dbp}(V_{ds})$$

where I_{dbp} and its associated conductance are given by:

for V_{ds} > Vdsm and $Kdb \neq 0$:

$$
\begin{aligned}
I_{dbp} &= \sqrt{\frac{Gdbm}{Kdb}}\tan^{-1}((V_{ds} - Vdsm)\sqrt{Kdb(Gdbm)})\\
&\quad + Gdbm(Vdsm)\\
g_{dbp} &= \frac{Gdbm}{(Kdb(Gdbm(V_{ds} - Vdsm)^2 + 1))}
\end{aligned}
$$

for V_{ds} < -Vdsm and $Kdb \neq 0$:

$$I_{dbp} = \sqrt{\frac{Gdbm}{Kdb}}\tan^{-1}((V_{ds} + Vdsm)\sqrt{Kdb(Gdbm)})$$
$$-Gdbm \times Vdsm$$
$$g_{dbp} = \frac{Gdbm}{(Kdb(Gdbm(V_{ds} + Vdsm)^2 + 1))}$$

for $-Vdsm \le V_{ds} \le Vdsm$ or $Kdb = 0$:

$$I_{dbp} = Gdbm \times V_{ds}$$
$$g_{dbp} = Gdbm$$

By setting the 7 high-frequency parameters equal to their dc counterparts, the dispersion model reduces to I_{db}=I_{dbp}. Examination of the I_{dbp} expression reveals that the additional setting of Gdbm to 0 disables the dispersion model entirely. The I_{dbp} current is a function of V_{ds} only, and will impact output conductance only. However, the current function I_{ds}^{ac} will impact g_m and g_{ds}. Therefore, the model is primarily intended to use g_m data as a means for tuning I_{ds}^{ac}. Once this *fitting* is accomplished, Gdbm, Kdb and Vdsm can be tuned to optimize the g_{ds} fit.

Gate Charge Model

The EE_FET3 gate charge model was developed through careful examination of extracted device capacitances over bias. The model consists of simple closed form charge expressions whose derivatives fit observed bias dependencies in capacitance data. This capacitances data can be obtained directly from measured Y-parameter data.

$$C_{11} = \frac{im[y_{11}]}{\omega} = \frac{\partial q_g}{\partial V_{gs}}$$
$$C_{12} = \frac{im[y_{12}]}{\omega} = \frac{\partial q_g}{\partial V_{ds}}$$

The capacitance data is remarkably self-consistent. In other words, a single q_g function's derivatives will fit both C_{11} data and C_{12} data. The EE_FET3 gate charge expression is:

$$q_g(V_j, V_o) = \left[\frac{(C11o - C11th)}{2}g(V_j) + C11th(V_j - Vinfl)\right]$$
$$\times [1 + Lambda(V_o - Vdso)] - C11sat \times V_o$$

where

$$g(V_j) = V_j - Vinfl + \frac{Deltgs}{3}\log\left(\cosh\left(\frac{3}{Deltgs}(V_j - Vinfl)\right)\right)$$

This expression is valid for both positive and negative V_{ds}. Symmetry is forced through the following smoothing functions proposed by Statz [4]:

$$V_j = \frac{1}{2}\left(2V_{gs} - V_{ds} + \sqrt{V_{ds}^2 + Deltds^2}\right)$$

$$V_o = \sqrt{V_{ds}^2 + Deltds^2}$$

Differentiating the gate charge expression wrt V_{gs} yields the following expression for the gate capacitance C_{11}:

$$\begin{aligned} C_{11}(V_j, V_o) &= \left[\frac{(C11o - C11th)}{2} \times g'(V_j) + C11th\right] \\ &\quad \times [1 + Lambda(V_o - Vdso)] \end{aligned}$$

where

$$g'(V_j) = \frac{dg(V_j)}{dV_j} = 1 + \tanh\left[\frac{3}{Deltds}(V_j - Vinfl)\right]$$

The gate transcapacitance C_{12} is defined as:

$$\begin{aligned} C_{12}(V_j, V_o) &= \frac{\partial q_g}{\partial V_{ds}} = \frac{\partial q_g}{\partial V_j}\frac{\partial V_j}{\partial V_{ds}} + \frac{\partial q_g}{\partial V_o}\frac{\partial V_o}{\partial V_{ds}} \\ &= C_{11}(V_j, V_o) \times \frac{1}{2}\left[\frac{V_{ds}}{\sqrt{V_{ds}^2 + Deltds^2}} - 1\right] \\ &\quad + [[g'(V_j) + C11th(V_j - Vinfl)] \times Lambda(-C12sat)] \\ &\quad \times \frac{V_{ds}}{\sqrt{V_{ds}^2 + Deltds^2}} \end{aligned}$$

The EE_FET3 topology requires that the gate charge be subdivided between the respective charge sources q_{gc} and q_{gy}. Although simulation could be performed directly from the nodal gate charge q_g, division of the charge into branches permits the inclusion of the resistances Ris and Rid that model charging delay between the depletion region and the channel. EE_FET3 assumes the following form for the gate-drain charge in saturation:

$$q_{gy}(V_{gy}) = Cgdsat(V_{gy} + q_{gyo})$$

which gives rise to a constant gate-drain capacitance in saturation. The gate-source charge q_{gc} can now be obtained by subtracting the latter from the gate charge equation. Smoothing functions can then be applied to these expressions in saturation in order to extend the model's applicable bias range to all V_{ds} values.

These smoothing functions force symmetry on the q_{gy} and q_{gc} charges such that

$$q_{gy} = q_{gc} = \frac{q_g}{2}$$

at $V_{gc} = V_{gy}$. Under large negative V_{ds} (saturation at the source end of the device), q_{gy} and q_{gc} swap roles:

$$q_{gc}(V_{gc}) = Cgdsat(V_{gc} + q_{gco})$$

The following continuous charge equations satisfy these constraints and are specified in terms of the gate charge:

$$\begin{aligned} q_{gy}(V_{gc}, V_{gy}) = {} & \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times f_2 \\ & + Cgdsa \times V_{gy} \times f_1 \end{aligned}$$

$$\begin{aligned} q_{gc}(V_{gc}, V_{gy}) = {} & \{q_g(V_{gc}, V_{gc} - V_{gy}) - C(gdsat \times V_{gy})\} \times f_1 \\ & + Cgdsat \times V_{gc} \times f_2 \end{aligned}$$

where f_1 and f_2 are smoothing functions defined by

$$f_1 = \frac{1}{2}\left[1 + \tanh\left(\frac{3}{Deltds}(V_{gc} - V_{gy})\right)\right]$$

and

$$f_2 = \frac{1}{2}\left[1 - \tanh\left(\frac{3}{Deltds}(V_{gc} - V_{gy})\right)\right]$$

The capacitances associated with these *branch* charge sources can be obtained through differentiation of the q_{gc} and q_{gy} equations and by application of the chain rule to capacitances C_{11} and C_{12}. The gate charge derivatives re-formulated in terms of V_{gc} and V_{gy} are:

$$C_{ggy} = \frac{\partial q_g}{\partial V_{gy}} = -C_{12}(V_{gc}, V_{gc} - V_{gy})$$

$$C_{ggc} = \frac{\partial q_g}{\partial V_{gc}} = C_{11}(V_{gc}, V_{gc} - V_{gy}) + C_{12}(V_{gc}, V_{gc} - V_{gy})$$

The branch charge derivatives are:

$$C_{gygy} = \frac{\partial q_{gy}}{\partial V_{gy}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gy}}$$
$$+ f_2 \times C_{ggy} + Cgdsat \times \left[V_{gy} \times \frac{\partial f_1}{\partial V_{gy}} + f_1 \right]$$

$$C_{gygc} = \frac{\partial q_{gy}}{\partial V_{gc}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gc}}$$
$$+ f_2 \times [C_{ggc} - Cgdsat] + Cgdsat \times V_{gy} \times \frac{\partial f_1}{\partial V_{gc}}$$

$$C_{gcgc} = \frac{\partial q_{gc}}{\partial V_{gc}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gy}\} \times \frac{\partial f_1}{\partial V_{gc}}$$
$$+ f_1 \times C_{ggc} + Cgdsat \times \left[V_{gc} \times \frac{\partial f_2}{\partial V_{gc}} + f_2 \right]$$

$$C_{gcgy} = \frac{\partial q_{gc}}{\partial V_{gy}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - C(gdsat \times V_{gy})\} \times \frac{\partial f_1}{\partial V_{gy}}$$
$$+ f_1 \times [C_{ggy} - Cgdsat] + Cgdsat \times V_{gc} \times \frac{\partial f_2}{\partial V_{gy}}$$

where

$$\frac{\partial f_1}{\partial V_{gc}} = \frac{3}{2 \times Deltds} \operatorname{sech}^2\left(\frac{3(V_{gc} - V_{gy})}{Deltds}\right)$$

$$\frac{\partial f_1}{\partial V_{gy}} = -\frac{\partial f_1}{\partial V_{gc}}$$

$$\frac{\partial f_2}{\partial V_{gc}} = -\frac{\partial f_1}{\partial V_{gc}}$$

$$\frac{\partial f_2}{\partial V_{gy}} = \frac{\partial f_1}{\partial V_{gc}}$$

When V_{ds}=Vdso and Vdso>>Deltds, the gate capacitance C_{11} reduces to a single voltage dependency in V_{gs}. Similar to the I_{ds} model then, the majority of the important gate charge parameters can be estimated from a single trace of a plot. In this case, the plot of interest is $C_{11}–V_{gs}$ at V_{ds} = Vdso.

The parameter definitions are illustrated in Figure 3-4. The parameter Deltds models the gate capacitance transition from the linear region of the device into saturation. Lambda models the slope of the $C_{11}–V_{ds}$ characteristic in saturation. C12sat is used to fit the gate transcapacitance (C_{12}) in saturation.

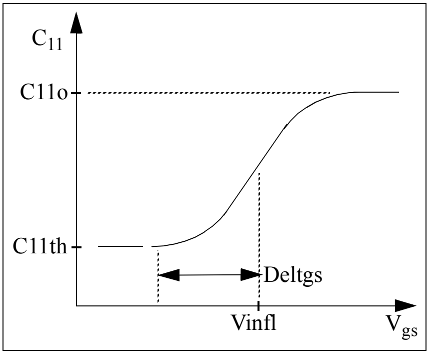


Figure 3-4. EE_FET3 C_{11}-V_{gs} Parameters

Output Charge and Delay

EE_FET3 uses a constant output capacitance specified with the parameter Cdso. This gives rise to a drain-source charge term of the form

$$q_{ds}(V_{ds}) = Cdso \times V_{ds}$$

The drain-source current previously described in this section is delayed with the parameter Tau according to the following equation:

$$I_{ds}(t) = I_{ds}(V_{gs}(t - Tau), V_{ds}(t))$$

In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained:

$$y_m = g_m \times \exp(-j \times \omega \times \mathrm{Tau})$$

Gate Forward Conduction and Breakdown

Forward conduction in the gate junction is modeled using a standard 2-parameter diode expression. The current for this gate-source current is:

$$I_{gs}(V_{gs}) = Is \times \left[e^{\frac{qV_{gs}}{nkT}} - 1 \right]$$

where q is the charge on an electron, k is Boltzmann's constant and T is the junction temperature.

The EE_FET3 breakdown model was developed from measured dc breakdown data and includes the voltage dependency of both gate-drain and gate-source junctions. EE_FET3 models breakdown for V_{ds}>0V only, breakdown in the V_{ds}<0V region is not handled. The model consists of 4 parameters that are easily optimized to measured data. The breakdown current is given by:

for $-V_{gd} > Vbr$

$$I_{gd}(V_{gd}, V_{gs}) = -Kbk\left(\left[1 - \frac{Ids(V_{gs}, V_{ds})}{I(dsoc)}\right] \times (-V_{gd} - Vbr)^{Nbr}\right)$$

for $-V_{gd} \le Vbr$

$$I_{gd}(V_{gd}, V_{gs}) = 0$$

Idsoc should be set to the maximum value attainable by I_{ds} to preclude the possibility of the gate-drain current flowing in the wrong direction.

Scaling Relations

Scaling of EE_FET3 model parameters is accomplished through the use of the model parameters Ugw and Ngf (see Table 3-4) and the device parameters Ugw (same name as the model parameter) and N. From these four parameters, the following scaling relations can be defined:

$$sf = \frac{Ugw^{new} \times N}{Ugw(Ngf)}$$

$$sfg = \frac{Ugw \times N}{Ugw^{new} \times Ngf}$$

where Ugw^{new} represents the device parameter Ugw, the *new* unit gate width.

Scaling will be disabled if any of the 4 scaling parameters are set to 0. The new EE_FET3 parameters are computed internally by the simulator according to the following equations:

$$Ris^{new} = \frac{Ris}{sf}$$

$$Rid^{new} = \frac{Rid}{sf}$$

$$Gmmax^{new} = Gmmax(sf)$$

$$Gmmaxac^{new} = Gmmaxac(sf)$$

$$Peff^{new} = Peff \times sf$$

$$Peffac^{new} = Peffac(sf)$$

$$Rdb^{new} = \frac{Rdb}{sf}$$

$$Gdbm^{new} = Gdbm(sf)$$

$$Kdb^{new} = \frac{Kdb}{sf}$$

$$Is^{new} = Is \times sf$$

$$Kbk^{new} = Kbk(sf)$$

$$Idsoc^{new} = Idsoc(sf)$$

$$Rg^{new} = \frac{Rg}{sfg}$$

$$Rd^{new} = \frac{Rd}{sf}$$

$$Rs^{new} = \frac{Rs}{sf}$$

$$Cbs^{new} = Cbs \times sf$$

$$C11o^{new} = C11o \times sf$$

$$C11th^{new} = C11th \times sf$$

$$C12sat^{new} = C12sat \times sf$$

$$Cgdsat^{new} = Cgdsat \times sf$$

$$Cdso^{new} = Cdso \times sf$$

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current Is scales as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

The threshold voltage Vto varies as:

$$Vto^{NEW} = Vto + Vtotc(Temp - Tnom)$$

Following are additional equations for the temperature scaling parameters:

$$RG^{NEW} = Rg((1 + Rgtc)(Temp - Tnom))$$

$$RD^{NEW} = Rd((1 + Rdtc)(Temp - Tnom))$$

$$RS^{NEW} = Rs((1 + Rstc)(Temp - Tnom))$$

$$VTOAC^{NEW} = Vtoac + Vtoactc(Temp - Tnom)$$

$$VTSO^{NEW} = Vtso + Vtotc(Temp - Tnom)$$

$$VTSOAC^{NEW} = Vtsoac + Vtoactc(Temp - Tnom)$$

$$GAMMA^{NEW} = GAMMA\left(\left[\frac{Temp}{Tnom}\right]^{GAMMATC}\right)$$

$$GAMMAAC^{NEW} = GAMMAAC\left(\left[\frac{Temp}{Tnom}\right]^{GAMMAACTC}\right)$$

$$GMMAX^{NEW} = GMMAX + GMMAXTC(Temp - Tnom)$$

$$GMMAXAC^{NEW} = GMMAXAC + GMMAXACTC(Temp - Tnom)$$

$$VINFL^{NEW} = Vinfl + Vinfltc(Temp - Tnom)$$

Noise Model

Thermal noise generated by resistors Rg, Rs, Rd, Ris, Rid, and Rdb is characterized by the following spectral density.

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

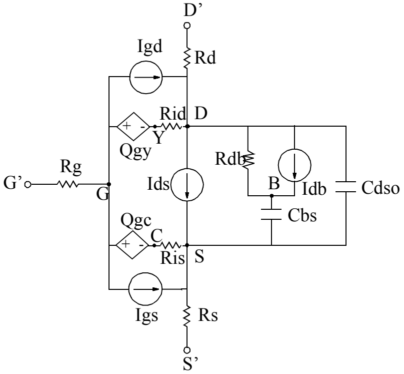
Channel noise generated by the dc transconductance g_m is characterized by the following spectral density:

$$\frac{\langle i_{ds}^2 \rangle}{\Delta f} = \frac{8kTg_m}{3}$$

In these expressions, k is Boltzmann's constant, T is the operating temperature in Kelvin, q is the electron charge, and Δf is the noise bandwidth.

Flicker noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources I_NoiseBD and V_NoiseBD can be connected external to the device to model flicker noise.

Equivalent Circuit



Device Operating Point Data

This model generates device operating point data during a DC simulation. The procedure for viewing device operating point data for a component is in the *Circuit Simulation* manual. The data that is displayed for the EE_FET3_Model (and EE_HEMT1_model) is:

EE_FET3	X1.A1
Id	0.167708
Ig	-9.99941e-015
Is	-0.167708
Power	0.838539
Gm	0.119883
Gds	0.0109841
GmAc	0.0487499
GdsAc	0.00342116
Ggs	2.31388e-017
Ggd	0
dIgd_dVgs	0
Cgc	1.40818e-012
dQgc_dVgy	-2.28547e-013
Cgy	5e-014
dQgy_dVgc	-4.57459e-025
Vgs	-0.25
Vds	5

I. Conductance Model:

The detailed operating point analysis returns information on the internal computations of EEfet3. Since the model accounts for dynamic affects found in conductance and transconductance of GaAs devices both “dc” and “ac” operation are reported for Gm and Gds.

Gm, Gds	DC transconductance, output conductance
GmAc, GdsAC	High frequency transconductance and output conductance
dIgd_dVgs	The transconductance effects of the gate-drain voltage.

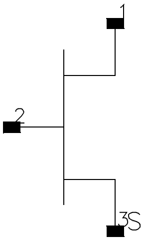
References

1. W. R Curtice. “A MESFET model for use in the design of GaAs integrated circuits,” *IEEE Transactions of Microwave Theory and Techniques*, Vol. MTT-28, pp. 448-456, May 1980.
2. P. C. Canfield, “Modeling of frequency and temperature effects in GaAs MESFETs” *IEEE Journal of Solid-State Circuits,* Vol. 25, pp. 299-306,Feb. 1990.

3. J.M. Golio, M. Miller, G. Maracus, D. Johnson, “Frequency dependent electrical characteristics of GaAs MESFETs,” *IEEE Trans. Elec. Devices*, vol. ED-37, pp. 1217-1227, May 1990.
4. H. Statz, P. Newman, I. Smith, R. Pucel, H. Haus, “GaAs FET device and circuit simulation in SPICE,” *IEEE Trans. Elec. Devices,* vol. ED-34, pp. 160-169, Feb. 1987.

EE_HEMT1 (EEsof Scalable Nonlinear HEMT)

Symbol



Parameters

Model = name of an EE_HEMT1_Model

Ugw = new unit gate width, in length units

N= new number of gate fingers

_M = number of devices in parallel (default: 1)

Range of Usage

Ugw > 0

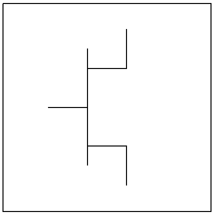
N > 0

Notes/Equations/References

1. Ugw and N are used for scaling device instance; refer to the model for these descriptions.

EE_HEMT1_Model (EEsof Scalable Nonlinear HEMT Model)

Symbol



Parameters

Model Data parameters must be specified in SI units.

Table 3-5. EE_HEMT1_Model Parameters

Name	Description	Unit	Default
Vto	zero bias threshold	V	–1.5
Gamma	Vds dependent threshold	1/V	0.05
Vgo	gate-source voltage where transconductance is a maximum	V	–0.5
Vdelt	not used	V	0.0
Vch	gate-source voltage where Gamma no longer affects I-V curves	V	1.0
Gmmax	peak transconductance	S	70×10^{-3}
Vdso	output voltage where Vo dependence disappears from equations	V	2.0
Vsat	drain-source current saturation	V	1.0
Kapa	output conductance	1/V	0.0
Peff	channel to backside self-heating	W	2.0
Vtso	subthreshold onset voltage	V	–10.0
Is	gate junction reverse saturation current	A	10^{-20}
N	gate junction ideality factor		1.0
Ris	source end channel resistance	ohms	2.0
Rid	drain end channel resistance	ohms	0.0

Table 3-5. EE_HEMT1_Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
Tau	gate transit time delay	sec	10^{-12}
Cdso	drain-source inter-electrode capacitance	F	80×10^{-15}
Rdb	dispersion source output impedance	ohms	10^{9}
Cbs	trapping-state capacitance	F	1.6×10^{-13}
Vtoac	zero bias threshold (ac)	V	−1.5
Gammaac	Vo dependent threshold (ac)	s	0.05
Vdeltac	not used	V	0.0
Gmmaxac	peak transconductance (ac)	S	600×10^{-3}
Kapaac	output conductance (ac)	1/V	0.0
Peffac	channel to backside self-heating (ac)	W	10.0
Vtsoac	subthreshold onset voltage (ac)	V	−10.0
Gdbm	additional d-b branch conductance at Vo = VDSM	S	0.0
Kdb	controls Vds dependence of additional d-b branch conductance.		0.0
Vdsm	voltage where additional d-b branch conductance becomes constant	V	1.0
C11o	maximum input capacitance for Vds=Vdso and Vdso>Deltds	F	0.3×10^{-12}
C11th	minimum (threshold) input capacitance for Vds=Vdso	F	0.03×10^{-12}
Vinfl	inflection point in C11-Vgs characteristic	V	−1.0
Deltgs	C11th to C11o transition voltage	V	0.5
Deltds	linear region to saturation region transition	V	1.0
Lambda	C11-Vds characteristic slope	1/V	1.0
C12sat	input transcapacitance for Vgs=Vinfl and Vds>Deltds	F	0.03×10^{-12}
Cgdsat	gate drain capacitance for Vds>Deltds	F	0.05×10^{-12}
Kbk	breakdown current coefficient at threshold		0.0

Table 3-5. EE_HEMT1_Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
Vbr	drain-gate voltage where breakdown source begins conducting	V	15.0
Nbr	breakdown current exponent	-	2.0
Idsoc	open channel (maximum) value of Ids	A	10010^{-3}
Rd	drain contact resistance	ohms	1.0
Rs	source contact resistance	ohms	1.0
Rg	gate metallization resistance	ohms	1.0
Ugw	unit gate width of device	M	0.0
Ngf	number of device gate fingers		1.0
Vco	voltage where transconductance compression begins for Vds=Vdso	V	10.0
Vba	transconductance compression tail-off	V	1.0
Vbc	transconductance roll-off to tail-off transition voltage	V	1.0
Mu	adds Vds dependence to transconductance compression onset		1
Deltgm	slope of transconductance compression characteristic	S/V	0.0
Deltgmac	slope of transconductance compression characteristic (ac)	S/V	0.0
Alpha	transconductance saturation to compression transition	V	10^{-3}
Kmod	library model number		1
Kver	version number		1
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	
wPmax	maximum power dissipation warning	W	
Rgtc	linear temperature coefficient for RG 1/degC		0.0

Table 3-5. EE_HEMT1_Model Parameters (continued)

Name	Description	Unit	Default
Rdtc	linear temperature coefficient for RD 1/degC		0.0
Rstc	linear temperature coefficient for RS 1/degC		0.0
Vtotc	linear temperature coefficient for pinchoff voltage	V/deg. C	0.0
Gmmaxtc	linear temperature coefficient for Gmmax		0.0
Xti	saturation current temperature exponent		3.0
Vinfltc	linear temperature coefficient for Vinfl		0.0
Gammatc	linear temperature coefficient for Gamma		0.0
Vtoactc	linear temperature coefficient for Vtoac		0.0
Gmmaxactc	linear temperature coefficient for Gmmaxac		0.0
Gammaactc	linear temperature co-officiate for Gammaac		0.0
Tnom	parameter measurement temperature		25.0
AllParams	DataAccessComponent for file-based model parameter values		

Notes/Equations/References

1. This model supplies values for an EE_HEMT1 device.
2. Model parameters such as Ls, Ld, and Lg (as well as other package related parameters that are included as part of the output from the EE_HEMT1 IC-CAP model file) are not used by the EE_HEMT1 component in the simulator. Only those parameters listed in Table 3-5 are part of the EE_HEMT1 component. Any extrinsic components must be added externally by the user.
3. In order to prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally as follows:

   Rd = 10^{-4}
   Rs = 10^{-4}
   Rg = 10^{-4}
   Ris = 10^{-4}
   Rid = 10^{-4}
   Vsat = 0.1
   Peff = 10^{-6}
   Peffac = 10^{-6}
   Deltds = 0.1
   Deltgs = 0.1
   Idsoc = 0.1
   Is = 10^{-50}

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

Equations/Discussion

EE_HEMT1 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of HEMTs. The model includes the following features:

- Accurate isothermal drain-source current model fits virtually all processes
- Flexible transconductance formulation permits accurate fitting of g_m compression found in HEMTs
- Self-heating correction for drain-source current
- Charge model that accurately tracks measured capacitance values
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics
- Accurate breakdown model describes gate-drain current as a function of both V_{gs} and V_{ds}.
- Well-behaved (non-polynomial) expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as g_m-V_{gs} plots. The increased number of model parameters is commensurate with the improvement in accuracy as compared with other popular empirical models. Since the model equations are all well behaved analytic expressions, EE_HEMT1 possesses no inherent limitations with respect to its usable power range. With the parameters Vdelt and Vdeltac set to zero, EE_FET3 becomes a subset of EE_HEMT1. The linear transconductance region modeled with the parameter Vdelt in EE_FET3 is omitted from EE_HEMT1 and replaced with a series of parameters designed to model transconductance compression. HP EEsof's IC-CAP program provides the user with the capability of extracting EE_HEMT1 models from measured data.

Drain-Source Current

The drain-source current model in EE_HEMT1 is comprised of various analytic expressions that were developed through examination of g_m versus bias plots on a wide class of devices from various manufacturers. The expressions below are given for $V_{ds} > 0.0V$ although the model is equally valid for $V_{ds} < 0.0V$. The model assumes the device is symmetrical, and one need only replace V_{gs} with V_{gd} and V_{ds} with $-V_{ds}$ in order to obtain the reverse region ($V_{ds} <$

0.0V) equations. The g_m, g_{ds} and I_{ds} equations take on four different forms depending on the value of V_{gs} relative to some of the model parameters. The I_{ds} expression is continuous through at least the second derivative everywhere.

if $V_{gs} \geq V_g$

$$g_{mo} = Gmmax\{1 + Gamma(Vdso - V_{ds})\}$$

$$I_{dso} = Gmmax\left\{V_x(V_{gs}) - \frac{(V(go) + Vto)}{2} + Vch\right\}$$

$$g_{dso} = -Gmmax \times Gamma(V_{gs} - Vch)$$

else if $V_{gs} \leq V_t$

$$g_{mo} = 0.0$$

$$I_{dso} = 0.0$$

$$g_{dso} = 0.0$$

else

$$g_{mo} = g_{mm}(V_{gs})$$

$$I_{dso} = I_{dsm}(V_{gs})$$

$$g_{dso} = -\frac{Gmmax}{2} Gamma(V_{gs} - Vch)$$

$$\times \left\{\cos\left[\pi \times \frac{V_x(V_{gs}) - (Vgo - Vch)}{Vto - Vgo}\right] + 1\right\}$$

where

$$g_{mm}(V) = \frac{Gmmax}{2}[1 + Gamma(Vdso - V_{ds})]$$

$$\times \left\{\cos\left[\pi \times \frac{V_x(V) - (Vgo - Vch)}{Vto - Vgo}\right] + 1\right\}$$

$$I_{dsm}(V) = \frac{Gmmax}{2}\left(((Vto - Vgo)/\pi) \sin\left[\pi \times \frac{V_x(V) - (Vgo - Vch)}{Vto - Vgo}\right] \right.$$

$$\left. + V_x(V) - (Vto - Vch) \right)$$

$$V_x(V) = (V - Vch)[1 + Gamma(Vdso - V_{ds})]$$

$$V_g = \frac{Vgo - Vch}{1 + Gamma(Vdso - V_{ds})} + Vch$$

$$V_t = \frac{Vto - Vch}{1 + Gamma(Vdso - V_{ds})} + Vch \quad .$$

The following voltages define regions of operation that are used in the g_m compression terms:

$$V_c = Vco + Mu \times (Vdso - V_{ds})$$

$$V_b = Vbc + V_c$$

$$V_a = V_b - Vba$$

For $V_{gs} > V_c$, the basic I_{dso}, g_{mo} and g_{dso} relations are modified as follows:

for $V_{gs} < V_b$,

$$g_{mo}^{comp} = g_{mo} - g_{mv}(V_{gs}, V_{ds})$$

$$I_{dso}^{comp} = I_{dso} - I_{dsv}(V_{gs}, V_{ds})$$

$$g_{dso}^{comp} = g_{dso} - g_{dsv}(V_{gs}, V_{ds})$$

for $V_{gs} \geq V_b$ and $b \neq -1$,

$$g_{mo}^{comp} = g_{mo} - [a(V_{gs} - V_a)^b + g_{moff}]$$

$$I_{dso}^{comp} = I_{dso} - \frac{a}{b+1}[(V_{gs} - V_a)^{b+1} - Vba^{b+1}] - g_{moff} \times (V_{gs} - V_b)$$

$$-I_{dsv}(V_b, V_{ds})$$

$$g_{dso}^{comp} = g_{dso} - Mu[a(V_{gs} - V_a)^b + g_{moff}] - g_{dsv}(V_b, V_{ds})$$

for $V_{gs} \ge V_b$ and $b = -1$,

$$g_{mo}^{comp} = g_{mo} - [a(V_{gs} - V_a)^b + g_{moff}]$$

$$I_{dso}^{comp} = I_{dso} - a[\log(V_{gs} - V_a) - \log(Vba)] - g_{moff} \times (V_{gs} - V_b)$$

$$-I_{dsv}(V_b, V_{ds})$$

$$g_{dso}^{comp} = g_{dso} - \frac{Mu \times a}{(V_{gs} - V_a)} - Mu \times g_{moff} - g_{dsv}(V_b, V_{ds})$$

where

$$a = \frac{g_{mv}(V_b, V_{ds}) - g_{moff}}{Vba^b}$$

$$b = \frac{s_{vb} \times Vba}{g_{mv}(V_b, V_{ds}) - g_{moff}}$$

$$s_{vb} = Deltgm \times \frac{Vbc}{\sqrt{Alpha^2 + Vbc^2}}$$

$$g_{mv}(V, V_{ds}) = Deltgm \times \left[\sqrt{Alpha^2 + (V - V_c)^2} - Alpha\right]$$

$$I_{dsv}(V, V_{ds}) = Deltgm \times \left(\frac{1}{2}\left((V - V_c)\sqrt{Alpha^2 + (V - V_c)^2}\right)\right)$$

$$-Alpha^2 \times \log\left[\frac{(V - V_c) + \sqrt{Alpha^2 + (V - V_c)^2}}{Alpha}\right]$$

$$-Alpha \times (V - V_c)^2$$

$$g_{dsv}(V, V_{ds}) = Deltgm \times Mu\left(\frac{1}{2}\left(\frac{2(V - V_c)^2 + Alpha^2}{\sqrt{Alpha^2 + (V - V_c)^2}}\right)\right)$$

$$+ \frac{Alpha^2}{(V - V_c) + \sqrt{Alpha^2 + (V - V_c)^2}}$$

$$\times \left[1 + \frac{(V - V_c)}{\sqrt{Alpha^2 + (V - V_c)^2}}\right] - Alpha$$

$$g_{moff} = g_{mo}(Vco, Vdso)$$

To prevent g_m from becoming negative at high gate-source biases, the following restriction is placed on the parameter Deltgm:

$$Deltgm < \frac{g_{moff}}{\sqrt{Alpha^2 + Vbc^2} - Alpha}$$

The preceding relations for I_{dso}^{comp} , g_{mo}^{comp} and g_{dso}^{comp} can now be substituted in the following equations that model current saturation and output conductance. This portion of the model can be recognized from the work of Curtice [1].

$$g'_m = g_{mo}^{comp}(1 + Kapa \times V_{ds})\tanh\left(\frac{3V_{ds}}{Vsat}\right)$$

$$I'_{ds} = I_{dso}^{comp}(1 + Kapa \times V_{ds})\tanh\left(\frac{3V_{ds}}{Vsat}\right)$$

$$g'_{ds} = \left\{g_{dso}^{comp}(1 + Kapa \times V_{ds}) + I_{dso}^{comp}Kapa\right\}\tanh\left(\frac{3V_{ds}}{Vsat}\right)$$

$$+ I_{dso}^{comp} \times \frac{3(1 + Kapa \times V_{ds})}{Vsat}\operatorname{sech}^2\left(\frac{3V_{ds}}{Vsat}\right)$$

These expressions do an excellent job of fitting HEMT I-V characteristics in regions of low power dissipation. They will also fit pulsed (isothermal) I-V characteristics. To model negative conductance effects due to self-heating, the thermal model of Canfield was incorporated [2]. With this final enhancement, the dc expressions for I_{ds} and its associated conductances become:

$$I_{ds} = \frac{I'_{ds}}{1 + \frac{P_{diss}}{Peff}}$$

$$g_m = \frac{g'_m}{\left[1 + \frac{P_{diss}}{Peff}\right]^2}$$

$$g_{ds} = \frac{g'_{ds} - \frac{I'^2_{ds}}{Peff}}{\left[1 + \frac{P_{diss}}{Peff}\right]^2}$$

where

$$P_{diss} = I'_{ds} V_{ds}$$

Qualitatively, the operation of the drain-source model can be described as follows.

The V_{ds} dependence of the equations is dominated by the parameters Vsat, Gamma, Kapa, and Peff. Isothermal output conductance is controlled by Gamma and Kapa. The impact of Gamma on output conductance is more significant near threshold. At V_{gs}=Vch, the output conductance is controlled only by Kapa. Peff provides a correction to the isothermal model for modeling the self-heating effects manifested as a negative resistance on the I-V curves. Vsat represents the drain-source voltage at which the current saturates and output conductance becomes a constant (approximately). Mu also impacts the I-V curves in the g_m compression region, but its effect is second order. In most cases, the g_m fit is more sensitive to the parameter Mu.

The overall impact of Vch on the I-V characteristics is second order at best, and many different values of Vch will provide good fits to I-V plots. For most applications encountered, the default value of 1.0V is an adequate value for Vch. Similar to Vch, Vdso is a parameter that should be set rather than optimized. At V_{ds}=Vdso, the drain-source model collapses to a single voltage dependency in V_{gs}. It is recommended that the user set Vdso to a typical V_{ds} operating point in saturation. At this point, many of the parameters can be extracted from a I_{ds}-V_{gs} plot for V_{ds}=Vdso or, preferably, a g_m(dc)-V_{gs} plot at V_{ds}=Vdso.

When V_{ds}=Vdso and Peff is set large (to disable the self-heating model), the significance of Vto, Vgo, Gmmax, Vco, Vba, Vbc, Deltgm and Alpha are easily understood from a plot of g_m(dc)-V_{gs}. Gmmax is the peak transconductance of the model that occurs at V_{gs}=Vgo. Vto represents the gate-source voltage where g_m goes to zero. Transconductance compression begins at V_{gs}=Vco. Alpha controls the abruptness of this transition while Deltgm controls the slope of the g_m characteristic in compression. At V_{gs}=Vco+Vbc, the linear g_m slope begins to tail-off and asymtotically approach zero. The shape of this *tail-off* region is controlled by Vba. The parameter definitions are illustrated in Figure 3-5.

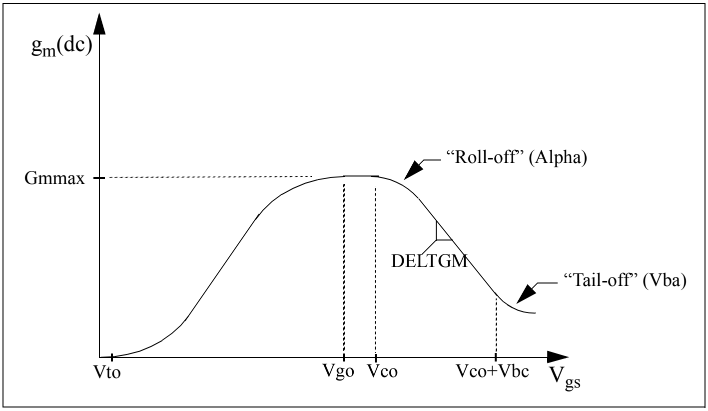


Figure 3-5. EE_HEMT1 g_m–V_{gs} Parameters

Dispersion Current (Idb)

Dispersion in a GaAs MESFET or HEMT drain-source current is evidenced by the observation that the output conductance and transconductance beyond some transition frequency is higher than that inferred by the dc measurements. A physical explanation often attributed to this phenomenon is that the channel carriers are subject to being trapped in the channel-substrate and channel-surface interfaces. Under slowly varying signal conditions, the rate at which electrons are trapped in these sites is equal to the rate at which they are emitted back into the channel. Under rapidly varying signals, the traps cannot follow the applied signal and the *high-frequency* output conductance results.

The circuit used to model conductance dispersion consists of the Rdb, Cbs (these linear components are also parameters) and the nonlinear source $I_{db}(V_{gs}, V_{ds})$. The model is a large-signal generalization of the dispersion model proposed by Golio et al. [3]. At dc, the drain-source current is just the current I_{ds}. At high frequency (well above the transition frequency), the drain source current will be equal to I_{ds}(high frequency) = I_{ds}(dc) + I_{db}. Linearization of the drain-source model yields the following expressions for y_{21} and y_{22} of the intrinsic EE_HEMT1 model:

$$y_{21} = g_{dsgs} + g_{dbgs} - \frac{g_{dbgs}}{1 + j\omega \times Cbs(Rdb)}$$

$$y_{22} = g_{dsds} + g_{dbds} + \frac{1}{Rdb} - \frac{\left(g_{dbds} + \frac{1}{Rdb}\right)}{1 + j\omega \times Cbs(Rdb)}$$

where

$$g_{dsgs} = \frac{\partial I_{ds}}{\partial V_{gs}}$$

$$g_{dsds} = \frac{\partial I_{ds}}{\partial V_{ds}}$$

$$g_{dbgs} = \frac{\partial I_{db}}{\partial V_{gs}}$$

$$g_{dbds} = \frac{\partial I_{db}}{\partial V_{ds}}$$

Evaluating these expressions at the frequencies ω=0 and ω=infinity, produces the following results for transconductance and output conductance:

for ω = 0,

$$Re[y_{21}] = g_m = g_{dsgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds}$$

for ω = infinity,

$$Re[y_{21}] = g_m = g_{dsgs} + g_{dbgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds} + g_{dbds} + \frac{1}{Rdb}$$

Between these two extremes, the conductances make a smooth transition, the abruptness of which is governed by the time constant τ_{disp} = Rdb × □Cbs. The frequency f_0 at which the conductances are midway between these two extremes is defined as

$$f_0 = \frac{1}{2\pi\tau_{disp}}$$

The parameter Rdb should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near f_0, the default values of Rdb and Cbs will be adequate for most microwave applications.

The EE_HEMT1 I_{ds} model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc I-V characteristics and ac conductances, EE_HEMT1 uses a simple scheme for modeling the I_{db} current source whereby different values of the same parameters can be used in the I_{ds} equations. The dc and ac drain-source currents can be expressed as follows:

I_{ds}^{dc} (Voltages, Parameters) = I_{ds} (Voltages, Gmmax, Vdelt, Vto, Gamma,
Kapa, Peff, Vtso, Deltgm, Vgo, Vch, Vdso, Vsat

I_{ds}^{ac} (Voltages, Parameters) = I_{ds} (Voltages, Gmmaxac, Vdeltac, Vto,
Gammaac, Kapaac, Peffac, Vtsoac, Deltgmac,
Vgo, Vch, Vdso, Vsat

Parameters such as Vgo that do not have an ac counterpart (there is no Vgoac parameter) have been found not to vary significantly between extractions utilizing dc measurements versus those using ac measurements. The difference between the ac and dc values of Ids, plus an additional term that is a function of Vds only, gives the value of Idb for the dispersion model

$$I_{db}(V_{gs}, V_{ds}) = I_{ds}^{ac}(V_{gs}, V_{ds}) - I_{ds}^{dc}(V_{gs}, V_{ds}) + I_{dbp}(V_{ds})$$

where I_{dbp} and its associated conductance are given by:

for V_{ds} > Vdsm and $Kdb \neq 0$:

$$I_{dbp} = \sqrt{\frac{Gdbm}{Kdb}} \tan^{-1}((V_{ds} - Vdsm)\sqrt{Kdb(Gdbm)} + Gdbm \times Vdsm)$$

$$g_{dbp} = \frac{Gdbm}{(Kdb(Gdbm(V_{ds} - Vdsm)^2 + 1))}$$

for V_{ds} ≤Vdsm and $Kdb \neq 0$:

$$I_{dbp} = \sqrt{\frac{Gdbm}{Kdb}} \tan^{-1}((V_{ds} + Vdsm)\sqrt{Kdb(Gdbm)}) - Gdsm \times Vdsn$$

$$g_{dbp} = \frac{(Gdbm)}{(Kdb(Gdbm(V_{ds} + Vdsm)^2 + 1))}$$

for $-Vdsm \leq V_{ds} \leq Vdsm$ or $Kdb = 0$:

$$I_{dsm} = Gdbm \times V_{ds}$$

$$g_{dbm} = Gdbm$$

By setting the eight high-frequency parameters equal to their dc counterparts, the dispersion model reduces to I_{db}=I_{dbp}. Examination of the I_{dbp} expression reveals that the additional setting of Gdbm to zero disables the dispersion model entirely. Since the I_{dbp} current is a function of V_{ds} only, it will impact output conductance only. However, the current function

$$I_{ds}^{AC}$$

will impact both g_m and g_{ds}. For this reason, the model is primarily intended to utilize g_m data as a means for tuning

$$I_{ds}^{AC}$$

Once this *fitting* is accomplished, the parameters Gdbm, Kdb and Vdsm can be tuned to optimize the g_{ds} fit.

Gate Charge Model

The EE_HEMT1 gate charge model was developed through careful examination of extracted device capacitances over bias. The model consists of simple closed form charge expressions whose derivatives fit observed bias dependencies in capacitance data. This capacitance data can be obtained directly from measured Y-parameter data:

$$C_{11} = \frac{im[y_{11}]}{\omega} = \frac{\partial q_g}{\partial V_{gs}}$$

$$C_{12} = \frac{im[y_{12}]}{\omega} = \frac{\partial q_g}{\partial V_{ds}}$$

The capacitance data is remarkably self-consistent. In other words, a single q_g function’s derivatives will fit both C_{11} data and C_{12} data. The EE_HEMT1 gate charge expression is:

$$q_g(V_j, V_o) = \left[\frac{C11o - C11th}{2} g(V_j) + C11th(V_j - Vinfl)\right]$$

$$\times [1 + Lambda(V_o - Vdso)] - C12sat \times V_o$$

where

$$g(V_j) = V_j - Vinfl + \frac{Deltgs}{3}\ln\left(\cosh\left(\frac{3}{Deltgs}(V_j - Vinfl)\right)\right)$$

This expression is valid for both positive and negative V_{ds}. Symmetry is forced through the following smoothing functions proposed by Statz [4]:

$$V_j = \frac{1}{2}\left(2V_{gs} - V_{ds} + \sqrt{V_{ds}^2 + Deltds^2}\right)$$

$$V_o = \sqrt{V_{ds}^2 + Deltds^2}$$

Differentiating the gate charge expression wrt V_{gs} yields the following expression for the gate capacitance C_{11}:

$$C_{11}(V_j, V_o) = \left[\frac{C11o - C11th}{2} g'(V_j) + C11th\right] \times [1 + Lambda(V_o - Vdso)]$$

where

$$g'(V_j) = \frac{dg(V_j)}{dV_j} = 1 + \tanh\left[\frac{3}{Deltgs}(V_j - Vinfl)\right]$$

The gate transcapacitance C_{12} is defined as:

$$C_{12}(V_j, V_o) = \frac{\partial q_g}{\partial V_{ds}} = \frac{\partial q_g}{\partial V_j}\frac{\partial V_j}{\partial V_{ds}} + \frac{\partial q_g}{\partial V_o}\frac{\partial V_o}{\partial V_{ds}}$$

$$= C_{11}(V_j, V_o) \times \frac{1}{2}\left[\frac{V_{ds}}{\sqrt{V_{ds}^2 + Deltds^2}} - 1\right]$$

$$+ \left[\frac{C11o - C11th}{2} g(V_j - Vinfl)\right]$$

$$\times Lambda - C12sat \times \frac{V_{ds}}{\sqrt{V_{ds}^2 + Deltds^2}}$$

The EE_HEMT1 topology requires that the gate charge be subdivided between the respective charge sources q_{gc} and q_{gy}. Although simulation could be performed directly from the nodal gate charge q_g, division of the charge into branches permits the inclusion of the resistances Ris and Rid that model charging delay between the depletion region and the channel. EE_HEMT1 assumes the following form for the gate-drain charge in saturation:

$$q_{gy}(V_{gy}) = Cgdsat \times (V_{gy} + q_{gyo})$$

which gives rise to a constant gate-drain capacitance in saturation.

The gate-source charge q_{gc} can now be obtained by subtracting the latter from the gate charge equation. Smoothing functions can then be applied to these expressions in saturation in order to extend the model's applicable bias range to all V_{ds} values. These smoothing functions force symmetry on the q_{gy} and q_{gc} charges such that

$$q_{gy} = q_{gc} = \frac{q_g}{2}$$

at $V_{gc} = V_{gy}$. Under large negative V_{ds} (saturation at the source end of the device), q_{gy} and q_{gc} swap roles, i.e:

$$q_{gc}(V_{gc}) = Cgdsat \times (V_{gc} + q_{gco})$$

The following continuous charge equations satisfy these constraints and are specified in terms of the gate charge:

$$q_{gy}(V_{gc}, V_{gy}) = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times f_2$$
$$+ Cgdsat \times V_{gy} \times tf_1$$

$$q_{gc}(V_{gc}, V_{gy}) = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gy}\} \times f_1$$
$$+ C(Ggdsat) \times V_{gc} \times f_2$$

where f_1 and f_2 are smoothing functions defined by

$$f_1 = \frac{1}{2}\left[1 + \tanh\left(\frac{3}{Deltds}(V_{gc} - V_{gy})\right)\right]$$

and

$$f_2 = \frac{1}{2}\left[1 - \tanh\left(\frac{3}{Deltds}(V_{gc} - V_{gy})\right)\right]$$

The capacitances associated with these *branch* charge sources can be obtained through differentiation of the q_{gc} and q_{gy} equations and by application of the chain rule to the capacitances C_{11} and C_{12}. The gate charge derivatives re-formulated in terms of V_{gc} and V_{gy} are:

$$C_{ggy} = \frac{\partial q_g}{\partial V_{gy}} = -C_{12}(V_{gc}, V_{gc} - V_{gy})$$

$$C_{ggc} = \frac{\partial q_g}{\partial V_{gc}} = C_{11}(V_{gc}, V_{gc} - V_{gy}) + C_{12}(V_{gc}, V_{gc} - V_{gy})$$

The branch charge derivatives are:

$$C_{gygy} = \frac{\partial q_{gy}}{\partial V_{gy}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gy}}$$

$$+ f_2 \times C_{ggy} + Cgdsat \times \left[V_{gy} \times \frac{\partial f_1}{\partial V_{gy}} + f_1\right]$$

$$C_{gygc} = \frac{\partial q_{gy}}{\partial V_{gc}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gc}\} \times \frac{\partial f_2}{\partial V_{gc}}$$

$$+ f_2 \times [C_{ggc} - Cgdsat] + Cgdsat \times V_{gy} \times \frac{\partial f_1}{\partial V_{gc}}$$

$$C_{gcgc} = \frac{\partial q_{gc}}{\partial V_{gc}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gy}\} \times \frac{\partial f_1}{\partial V_{gc}}$$

$$+ f_1 \times C_{ggc} + Cdsat \times \left[V_{gc} \times \frac{\partial f_2}{\partial V_{gc}} + f_2\right]$$

$$C_{gcgy} = \frac{\partial q_{gc}}{\partial V_{gy}} = \{q_g(V_{gc}, V_{gc} - V_{gy}) - Cgdsat \times V_{gy}\} \times \frac{\partial f_1}{\partial V_{gy}}$$

$$+ f_1 \times [C_{ggy} - Cgdsat] + Cgdsat \times V_{gc} \times \frac{\partial f_2}{\partial V_{gy}}$$

where

$$\frac{\partial f_1}{\partial V_{gc}} = \frac{3}{2 \times Deltds} \operatorname{sech}^2\left(\frac{3(V_{gc} - V_{gy})}{Deltds}\right)$$

$$\frac{\partial f_1}{\partial V_{gy}} = -\frac{\partial f_1}{\partial V_{gc}}$$

$$\frac{\partial f_2}{\partial V_{gc}} = -\frac{\partial f_1}{\partial V_{gc}}$$

$$\frac{\partial f_2}{\partial V_{gy}} = \frac{\partial f_1}{\partial V_{gc}}$$

When V_{ds}=Vdso and Vdso>>Deltds, the gate capacitance C_{11} reduces to a single voltage dependency in V_{gs}. Similar to the I_{ds} model, the majority of the important gate charge parameters can then be estimated from a single trace of a plot. In this case, the plot of interest is C_{11}-V_{gs} at V_{ds} = Vdso. The parameter definitions are illustrated in Figure 3-6.

The parameter Deltds models the gate capacitance transition from the linear region of the device into saturation. Lambda models the slope of the C_{11}-V_{ds} characteristic in saturation. C12sat is used to fit the gate transcapacitance (C_{12}) in saturation.

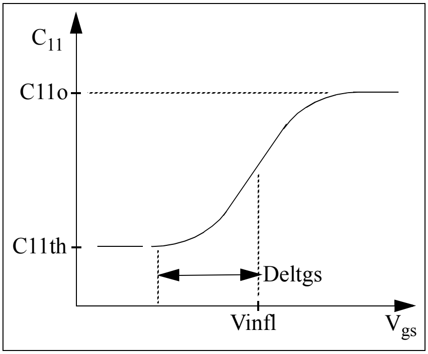


Figure 3-6. EE_HEMT1 C_{11}-V_{gs} Parameters

Output Charge and Delay

EE_HEMT1 uses a constant output capacitance specified with the parameter Cdso. This gives rise to a drain-source charge term of the form

$$q_{ds}(V_{ds}) = Cdso \times V_{ds}$$

The drain-source current described previously, is delayed with the parameter TAU according to the following equation:

$$I_{ds}(t) = I_{ds}(V_{gs}(t - Tau), V_{ds}(t))$$

In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained

$$y_m = g_m \times \exp(-j \times \omega \times \mathrm{Tau})$$

Gate Forward Conduction and Breakdown

Forward conduction in the gate junction is modeled using a standard 2-parameter diode expression. The current for this gate-source current is:

$$I_{gs}(V_{gs}) = IS \times \left[e^{\frac{qV_{gs}}{nkT}} - 1 \right]$$

where q is the charge on an electron, k is Boltzmann's constant, and T is the junction temperature.

The EE_HEMT1 breakdown model was developed from measured dc breakdown data and includes the voltage dependency of both gate-drain and gate-source junctions. EE_HEMT1 models breakdown for Vds > 0V only, breakdown in the Vds < 0V region is not handled. The model consists of four parameters that are easily optimized to measured data. The breakdown current is given by:

for $-V_{gd} > Vbr$

$$I_{gd}(V_{gd}, V_{gs}) = -Kbk\left[1 - \frac{Ids(V_{gs}, V_{ds})}{Idsoc}\right] \times (-V_{gd} - Vbr)^{Nbr}$$

for $-V_{gd} \le Vbr$

$$I_{gd}(V_{gd}, V_{gs}) = 0$$

Some care must be exercised in setting Idsoc. This parameter should be set to the maximum value attainable by I_{ds}. This precludes the possibility of the gate-drain current flowing in the wrong direction.

Scaling Relations

Scaling of EE_HEMT1 model parameters is accomplished through model parameters Ugw and Ngf and device parameters Ugw (same name as the model parameter) and N. From these four parameters, the following scaling relations can be defined:

$$sf = \frac{Ugw^{new} \times N}{Ugw \times Ngf}$$

$$sfg = \frac{Ugw \times N}{Ugw^{new} \times Ngf}$$

where Ugw^{new} represents the device parameter Ugw, the *new* unit gate width.

Scaling will be disabled if any of the four scaling parameters are set to 0. The new EE_HEMT1 parameters are computed internally by the simulator according to the following equations:

$$Ris^{new} = \frac{Ris}{sf}$$

$$Rid^{new} = \frac{Rid}{sf}$$

$$Gmmax^{new} = Gmmax \times sf$$

$$Gmmaxac^{new} = Gmmaxac \times sf$$

$$Deltgm^{new} = Deltgm \times sf$$

$$Deltgmac^{new} = Deltgmac \times sf$$

$$Peff^{new} = Peff \times sf$$

$$Peffac^{new} = Peffac \times sf$$

$$Rdb^{new} = \frac{Rdb}{sf}$$

$$Gdbm^{new} = Gdbm \times sf$$

$$Kdb^{new} = \frac{Kdb}{sf}$$

$$Is^{new} = Is \times sf$$

$$Kbk^{new} = Kbk \times sf$$

$$Idsoc^{new} = Idsocs \times sf$$

$$Rg^{new} = \frac{Rg}{sfg}$$

$$Rd^{new} = \frac{Rd}{sf}$$

$$Rs^{new} = \frac{Rs}{sf}$$

$$Cbs^{new} = Cbs \times sf$$

$$C11o^{new} = C11o \times sf$$

$$C11th^{new} = C11th \times sf$$

$$C12sat^{new} = C12sat \times sf$$

$$Cgdsat^{new} = Cgdsat \times sf$$

$$Cdso^{new} = Cdso \times sf$$

Noise Model

Thermal noise generated by resistors Rg, Rs, Rd, Ris, Rid, and Rdb is characterized by the following spectral density.

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Channel noise generated by the dc transconductance g_m is characterized by the following spectral density:

$$\frac{< i_{ds}^2 >}{\Delta f} = \frac{8kTg_m}{3}$$

In the preceding expressions, k is Boltzmann’s constant, T is the operating temperature in Kelvin, q is the electron charge, and Δf is the noise bandwidth.

Flicker noise for this device is not modeled in this version of the simulator. However, the bias-dependent noise sources I_NoiseBD and V_NoiseBD can be connected external to the device to model flicker noise.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current Is scales as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

The threshold voltage Vto varies as:

$$Vto^{NEW} = Vto + Vtotc(Temp - Tnom)$$

Following are additional equations for the temperature scaling parameters:

$$RG^{NEW} = Rg((1 + Rgtc)(Temp - Tnom))$$

$$RD^{NEW} = Rd((1 + Rdtc)(Temp - Tnom))$$

$$RS^{NEW} = Rs((1 + Rstc)(Temp - Tnom))$$

$$VTOAC^{NEW} = Vtoac + Vtoactc(Temp - Tnom)$$

$$VTSO^{NEW} = Vtso + Vtotc(Temp - Tnom)$$

$$VTSOAC^{NEW} = Vtsoac + Vtoactc(Temp - Tnom)$$

$$GAMMA^{NEW} = GAMMA\left(\left\lceil\frac{Temp}{Tnom}\right\rceil^{GAMMATC}\right)$$

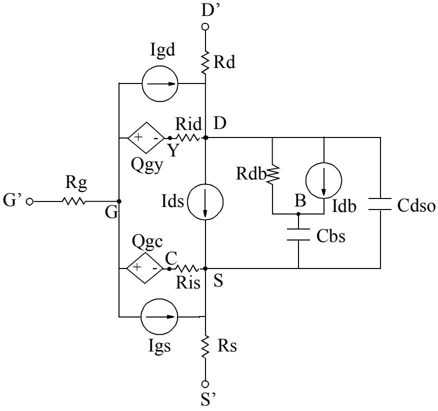
$$GAMMAAC^{NEW} = GAMMAAC\left(\left\lceil\frac{Temp}{Tnom}\right\rceil^{GAMMAACTC}\right)$$

$$GMMAX^{NEW} = GMMAX + GMMAXTC(Temp - Tnom)$$

$$GMMAXAC^{NEW} = GMMAXAC + GMMAXACTC(Temp - Tnom)$$

$$VINFL^{NEW} = Vinfl + Vinfltc(Temp - Tnom)$$

Equivalent Circuit



References

[1] W. R. Curtice, “A MESFET model for use in the design of GaAs integrated circuits,” *IEEE Transactions of Microwave Theory and Techniques,* Vol. MTT-28, pp. 448-456, May 1980.

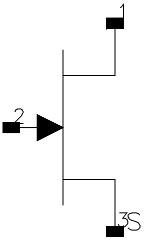
[2] P. C. Canfield, “Modeling of frequency and temperature effects in GaAs MESFETs” *IEEE Journal of Solid-State Circuits,* Vol. 25, pp. 299-306, Feb. 1990.

[3] J. M. Golio, M. Miller, G. Maracus, D. Johnson, “Frequency dependent electrical characteristics of GaAs MESFETs,” *IEEE Trans. Elec. Devices*, vol. ED-37, pp. 1217-1227, May 1990.

[4] H. Statz, P. Newman, I. Smith, R. Pucel, H. Haus. “GaAs FET device and circuit simulation in SPICE,” *IEEE Trans. Elec. Devices,* vol. ED-34, pp. 160-169, Feb. 1987.

GaAsFET (Nonlinear Gallium Arsenide FET)

Symbol



Parameters

Model = name of a GaAsFET model

Area = scaling factor that scales certain parameter values of the associated model item (default: 1.0)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: linear; nonlinear (default: nonlinear) (refer to Note 3)

_M = number of devices in parallel (default: 1)

Range of Usage

Area > 0

Notes/Equations/References

1. Advanced_Curtice2_Model, Curtice2_Model, Curtice3_Model, Materka_Model, Modified_Materka_Model, Statz_Model, and Tajima_Model are the nonlinear model items that define the GaAsFET.
2. The Area parameter permits changes to a specific semiconductor because semiconductors may share the same model.
    - Parameters scaled proportionally to Area: A0, A1, A2, A3, Beta, Cgs, Cgd, Cgs, Cds, Is.
    - Resistive parameters scaled inversely proportional to Area: Rd, Rg, Rs. For example, Model = Curtice2 and Area=3 use the following computations:

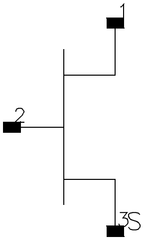
Rd/3:	Cgs × 3	Beta × 3
Rg/3:	Cgdo × 3	
Rs/3:	Cds × 3	

These computations have the same effect as placing three devices in parallel to simulate a larger device and are much more efficient.

3. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
4. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model item) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the appropriate model to see which parameter values are scaled.
5. This device has no default artwork associated with it.

HP_FET (HP_Root FET)

Symbol



Parameters

Model = name of an HP_FET model

Wtol = total device gate width, in length units (default: 10^{-4})

N = number of device gate fingers (default: 1)

_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/References

1. If Wtot or N is specified as *Rawfile value* or zero, the default gate width as specified in the model file is used. For other values, these values can be used to scale the extracted model for different geometries. The scaling remains valid for ratios up to 5:1.
2. Wtot is the total gate width—not the width per finger; the parameter N is the number of fingers; therefore, the width per finger is Wtot/N.
3. Currents and capacitances scale linearly with gate width

   $I = I_0 \times Wtot / W_0$
   $C = C_0 \times Wtot / W_0$

   The parasitic resistances scale as:

   $$Rg = R_{G0} \quad \frac{Wtot}{W_0}\left(\frac{N_0}{N}\right)^2$$

   $Rd = R_{D0} \times W_0 / Wtot$

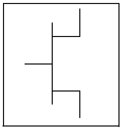
$Rs = R_{S0} \times W_0 / Wtot$

where Wtot and N are the user-specified values and W_0 and N_0 are the extracted values given in HP_FET_Model. The parasitic inductances do not scale.

4. Care should be taken when using the transistor outside of the region at which the model measurements were taken. Extrapolation of the measured data may occur without warning during dc, harmonic balance, and time-domain analyses. This extrapolated data may produce unreliable results.
5. HP_FET currents can be measured with the standard current measurements, except that pins must be specified by number instead of name; for example, 1=G, 2=D, 3=S.
6. The HP_FET cannot be temperature scaled and is noiseless.

HP_FET_Model (HP Root Model GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-6. HP_FET_Model Parameters

Parameter	Description	Unit	Default
File	name of file containing measured data		
Rs	source resistance (overrides extracted value)	ohms	rawfile value
Rg	gate resistance (overrides extracted value)	ohms	rawfile value
Rd	drain resistance (overrides extracted value)	ohms	rawfile value
Ls	source inductance (overrides extracted value)	H	rawfile value
Lg	gate inductance (overrides extracted value)	H	rawfile value
Ld	drain inductance (overrides extracted value)	H	rawfile value
AllParams	DataAccessComponent for file-based model parameter values		

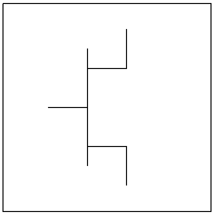
Notes/Equations/References

1. This model supplies values for an HP_FET device.
2. The default extension for the model file is *.raw*. This file should be in the same format as HP Root model data.
3. If Rs, Rg, Rd, Ls, Lg, or Ld is specified as *rawfile value* or zero, the default parasitic value is taken from the extracted values stored in the data file named by File parameter. Generally, *rawfile value* should be used.
4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

5. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.
6. For a list of HP Root Model references, refer to "HP_Diode_Model (HP_Root Diode Model)" on page 1-18.

Materka_Model (Materka GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-7. Materka_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		4
Idss	saturation drain current	A	0
Vto†	threshold voltage	V	−2
Alpha	hyperbolic tangent function	V	2
Beta2	coefficient for pinch-off change with respect to Vds	1/V	0
Tau	transit time under gate	sec	0
Lambda	channel length modulation	1/V	0
Rin	channel resistance	ohms	0
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgs	zero bias gate-source junction capacitance	F	0

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-7. Materka_Model Parameters (continued)

Parameter	Description	Unit	Default
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgd	zero bias gate-drain junction capacitance	F	0.0
Rd	drain ohmic resistance	ohms	0.0
Rg	gate resistance		0.0
Rs	source resistance		0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Gsfwd	0-none, 1=linear, 2=diode		linear
Gsrev	0-none, 1=linear, 2=diode		none
Gdfwd	0-none, 1=linear, 2=diode		none
Gdrev	0-none, 1=linear, 2=diode		linear
Vbi†	built-in gate potential	V	0.85
Vjr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} < 0$)	V	0.025
Is	gate junction reverse saturation current (diode model)	A	10^{-14}
Ir	gate reverse saturation current	A	10^{-14}
Imax	explosion current	A	1.6
N	gate junction ideality factor (diode model)		
Vbr	gate junction reverse bias breakdown voltage	V	
Fnc	flicker noise corner frequency	Hz	10^{100}
R	gate noise coefficient		0.5

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-7. Materka_Model Parameters (continued)

Parameter	Description	Unit	Default
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9
Taumdl	second order Bessel polynomial to model tau effect in transient simulation		no
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
wVgfwd	gate junction forward bias (warning)	V	
wBvgs	gate-source reverse breakdown voltage (warning)	V	
wBvgd	gate-drain reverse breakdown voltage (warning)	V	
wBvds	drain-source breakdown voltage (warning)	V	
wIdsmax	maximum drain-source current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	DataAccessComponent for file-based model parameter values		

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\, P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\, C_{gs}^2\, \omega^2\, R/g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\, C_{gs}\, \omega \sqrt{PR}\, C$$

3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.
4. The drain current in Materka_Model is computed with the following expression:

   Vp = Vto + Beta2 × Vds

   if (Vfc - Vp ≤ 0 or Vp ≥ 0)

   else

   TI = ABS (Alpha × Vds)

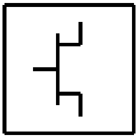
   TanhF = tanh (TI/(Vgc – Vp))

$$Ids - Idss \times \left(\frac{Vgc}{Vp} - 1\right)^2 \times TanhF \times (1 + Lambda \times Vds)$$

5. A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Mesfet_Form (Symbolic MESFET Model)

Symbol



Parameters

Table 3-8. Mesfet_Form Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		6
Ids	user-defined equation for drain-source current		See Notes
Qgs	user-defined equation for gate-source charge	V	See Notes
Qgd	user-defined equation for gate-drain charge	1/V	See Notes
Igd	user-defined equation for gate-drain current	1/V	See Notes
Igs	user-defined equation for gate-source current	1/V	See Notes
Beta	transconductance	A/V^2	1.0e-4
Lambda	channel length modulation parameter	1/V	0.0
Alpha	current saturation	1/V	2.0
B	doping tail extending		0.3
Tnom	nominal ambient temperature	ohms	25
Idstc	IDS temperature coefficient	ohms	0
Vbi	built-in gate potential	V	0.85
Tau	transit time under gate	S	0.0

Table 3-8. Mesfet_Form Parameters (continued)

Parameter	Description	Unit	Default
Rds0	DC conductance at Vgs = 0		0
Betatce	BETA exponential temperature coefficient	%/deg. C	0.0
Delta1	capacitance transition voltage	V	0.3
Delta2	capacitance threshold transition voltage	V	0.2
Gscap	0=none, 1=linear, 2 = junction, 3 = Statz Charge, 4 = Symbolic, 5 = Statz Cap		linear
Gdcap	0=none, 1=linear, 2 = junction, 3 = Statz Charge, 4 = Symbolic, 5 = Statz Cap		linear
Cgs	zero-bias G-S junction cap	F	0.0
Cgd	zero-bias G-D junction cap	F	0.0
Rgs	G-S resistance	Ohm	0.0
Rgd	gate drain resistance	Ohm	0.0
Rf	G-S effective forward-bias resistance (0 = infinity)	Ohm	0.0
Tqm	temperature coefficient for triquint junction capacitance		0.2
Vmax	maximum junction voltage before capacitance limiting		0.5
Fc	coefficient for forward-bias depletion cap		0.5
Rd	drain ohmic resistance	Ohm	fixed at 0
Rg	gate resistance	Ohm	fixed at 0
Rs	Source ohmic resistance	Ohm	fixed at 0
Ld	drain inductance	H	fixed at 0
Lg	gate inductance	H	fixed at 0
Ls	source inductance	H	fixed at 0
Cds	drain-source cap	F	0.0
Crf	used with RC to model frequency-dependent output conductance	F	10^{100}
Rc	used with CRC to model frequency-dependent output conductance (0 = infinity)	Ohm	0.5
Gsfwd	0 = none, 1 = linear, 2 = diode		linear

Table 3-8. Mesfet_Form Parameters (continued)

Parameter	Description	Unit	Default
Gdfwd	0 = none, 1 = linear, 2 = diode		none
Gsrev	0 = none, 1 = linear, 2 = diode, 3 = custom		none
Gdrev	gate junction forward bias warning		none
Vjr	breakdown junction potential		0.025
Is	gate-junction saturation current	A	1.0e-14
Ir	gate rev saturation current	A	1.0e-14
Imax	expression current	A	1.6
Xti	saturation current temperature exponent		3.0
N	gate junction emission coefficient		1
Eg	energy tap for temperature effect on IS		1.1.1
Vbr	gate junction reverse bias breakdown voltage (0 = infinity)	V	1e100
Vtotc	VTO temperature coefficient	V/deg. C	0.0
Rin	channel resistance	Ohm	0.0
Taumdl	use 2nd order Bessel polynomial to model tau effect in transient		no
Fnc	flicker noise corner frequency	Hertz	0.0
R	gate noise coefficient		0.5
C	gate-drain noise correlation coefficient		0.9
P	drain noise coefficient		1.0
wVgfwd	gate junction forward bias (warning	V	
wBvgs	gate-source reverse breakdown voltage (warning)	V	
wBvgd	gate-drain reverse breakdown voltage (warning)	V	
wBvds	drain-source breakdown voltage (warning)	V	
wIdsmax	maximum drain-source current (warning)	A	
wPmax	maximum power dissipation	W	
AllParams	DataAccessComponent for file-based model parameter values		

Notes/Equations References

1. The following equations are the default settings for some of the parameters:

   Ids = (100ma)×((1+_v2))^2)×tanh(_v1)\

   Qgs = (1pf)×(_v1) - (1pf) × ((_v2) -(_v1))×(_v1)

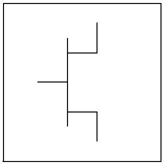
   Qgd = (1prf)×(_v1) - ((v2) -(v1))×(_v1)

   lgd = ramp ((10+(_v1))/10)

   lgs = ramp ((10+(_v1))/10)

Modified_Materka_Model (Modified Materka GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-9. Modified_Materka_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		8
Idss	saturation drain current	A	0
Vto	threshold voltage	V	−2
Beta2	coefficient for pinch-off change with respect to Vds	1/V	2
Ee	exponent defining dependence of saturation current	1/V	2
Ke	description of dependence on gate voltage	1/V	0
Kg	dependence on Vgs of drain slope in linear region	1/V	0
Sl	linear region slope of Vgs-0 drain characteristic	S	1
Ss	saturation region drain slope characteristic at vgs=0	S	0
Tau	transit time under gate	sec	0
Rgs	channel resistance	ohms	0
Rgd	gate drain resistance	ohms	0
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-9. Modified_Materka_Model Parameters (continued)

Parameter	Description	Unit	Default
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		
Cgs	zero bias gate-source junction capacitance	F	
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		
Cgd	zero bias gate-drain junction capacitance	F	
Rd	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds	drain-source capacitance	F	0.0
Gsfwd	0-none, 1=linear, 2=diode		
Gsrev	0-none, 1=linear, 2=diode		
Gdfwd	0-none, 1=linear, 2=diode		
Gdrev	0-none, 1=linear, 2=diode		
Vbi†	built-in gate potential	V	
Vjr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} < 0$)	V	0.025
Is	gate junction saturation current (diode model)	A	10^{-14}
Ir	gate reverse saturation current	A	10^{-14}
Imax	explosion current	A	1.6
N	gate junction emission coefficient (diode model)		1
Fnc	flicker noise corner frequency	Hz	0

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-9. Modified_Materka_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Lambda	channel length modulation	1/V	0
Vbr	reverse bias breakdown voltage	V	10^{100}
R	gate noise coefficient		0.5
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9
Taumdl	2nd order Bessel polynomial to model tau effect in transient simulation		no
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	
wPmax	maximum power dissipation warning	W	
AllParams	DataAccessComponent for file-based model parameter values		

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\, P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\, C_{gs}^2\, \omega^2\, R/g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\ C_{gs}\ \omega \sqrt{PR}\ C$$

3. The drain current in Modified_Materka_Model is computed with the following expression:

   Vp = Vto + Beta2 × Vds

   if (Vfc - Vp ≤ 0 or Vp ≥ 0)

   and Ids=0

   else

   $$power0 = \left(1 - \frac{Vgc}{Vp}\right)^{(Ee + Ke \times Vgc)}$$

   fi = Idss × power0

   gi= tanh (Sl × Vds/(Idss × (1-Kg × Vgc)))

   hi = 1 + Ss × Vds/Idss

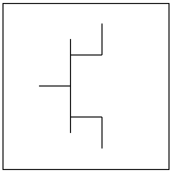
   Ids = fi × gi × hi

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

5. A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Statz_Model (Statz Raytheon GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-10. Statz_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel type		yes
PFET	P-channel type		no
Idsmod	Statz model		3
Vto††	threshold voltage	V	−2
Beta†, ††	transconductance	A/V^2	10^{-4}
Lambda	output conductance	1/V	0.0
Alpha	current saturation	1/V	2.0
B	controls I_{ds}-V_{gs} characteristic transition from quadratic to linear behavior (*b* in Statz's paper)	1/V	0.0
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Idstc	Ids temperature coefficient	A/Temp°C	0
Vbi††	built-in gate potential	V	0.85
Tau	transit time under gate	sec	0.0
Betatce	drain current exponential temperature coefficient	%/°C	0.0
Delta1	capacitance saturation transition voltage	V	0.3

† Parameter value scales with Area.

†† Parameter value varies with temperature based on model Tnom and device Temp.

††† Value of 0.0 is interpreted as infinity.

‡ Parameter value scales inversely with Area.

Table 3-10. Statz_Model Parameters (continued)

Parameter	Description	Unit	Default
Delta2	capacitance threshold transition voltage	V	0.2
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgs†, ††	zero bias gate-source junction capacitance	F	0.0
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgd†, ††	zero bias gate-drain junction capacitance	F	0.0
Rgd‡	gate drain resistance	ohms	0
Tqm	junction capacitance temperature coefficient		0.2
Vmax	maximum junction voltage before capacitance limiting	V	0.5
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Rd ‡	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs‡	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds†	drain-source capacitance	F	0
Crf†	used with Rc to model frequency dependent output conductance	F	0.0
Rc‡	used with Crf to model frequency dependent output conductance	ohms	infinity†††
Gsfwd	0-none, 1=linear, 2=diode		linear

† Parameter value scales with Area.

†† Parameter value varies with temperature based on model Tnom and device Temp.

††† Value of 0.0 is interpreted as infinity.

‡ Parameter value scales inversely with Area.

Table 3-10. Statz_Model Parameters (continued)

Parameter	Description	Unit	Default
Gsrev	0-none, 1=linear, 2=diode		none
Gdfwd	0-none, 1=linear, 2=diode		none
Gdrev	0-none, 1=linear, 2=diode		linear
Vjr	breakdown junction potential	V	0.025
Is†	gate junction saturation current (diode model)	A	10^{-14}
Ir†	gate reverse saturation current	A	10^{-14}
Imax	explosion current	A	1.6
Xti	temperature exponent for saturation current		3.0
N	gate junction emission coefficient		1
Eg	energy gap for temperature effect on Is	eV	1.11
Vbr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with V_{ds}<0)	V	10^{100}
Vtotc	Vto temperature coefficient	V/°C	0.0
Rin ‡	channel resistance	ohms	0.0
Taumdl	second order Bessel polynomial to model tau effect in transient		no
Fnc	flicker noise corner frequency	Hz	0
R	gate noise coefficient		0.5
C	gate-drain noise correlation coefficient		0.9
P	drain noise coefficient		1.0
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	

† Parameter value scales with Area.

†† Parameter value varies with temperature based on model Tnom and device Temp.

††† Value of 0.0 is interpreted as infinity.

‡ Parameter value scales inversely with Area.

Table 3-10. Statz_Model Parameters (continued)

Parameter	Description	Unit	Default
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	
wPmax	maximum power dissipation warning	W	
AllParams	DataAccessComponent for file-based model parameter values		

† Parameter value scales with Area.

†† Parameter value varies with temperature based on model Tnom and device Temp.

††† Value of 0.0 is interpreted as infinity.

‡ Parameter value scales inversely with Area.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Statz_Model implementation is based on the work of Statz et al [1].

   In particular, the expressions for drain source current and gate charge are implemented exactly as published in [1]. The Statz model also includes a number of features that (although not described in the Statz article) are generally accepted to be important features of a GaAsFET model. These include a gate delay factor (Tau), an input charging resistance (Ri), gate junction forward conduction and breakdown.
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

Equations/Discussion

Drain-Source Current

Statz_Model dc drain-source current is given by these expressions:

For $0 < V_{ds} < 3 / \alpha$

$$I_{ds} = \frac{\beta(V_{gs} - Vto)^2}{1 + \beta(V_{gs} - Vto)}\left[1 - \left[1 - \frac{\alpha V_{ds}}{3}\right]^3\right](1 + \lambda V_{ds})$$

where α is Alpha, β is Beta, Θ is B.

For $V_{ds} \geq 3/\alpha$

$$I_{ds} = \frac{\beta(V_{gs} - Vto)^2}{1 + \beta(V_{gs} - Vto)}(1 + \lambda V_{ds})$$

The current is set to zero for $V_{gs} < Vto$.

where α is Alpha, β is Beta, Θ is B.

Gate Charge

You are provided with two options in modeling the junction capacitance of a device. The first is to model the junction as a linear component (a constant capacitance). The second is to model the junction using a diode depletion capacitance model. If a non-zero value of Cgs is specified and Gscap is set to 1 (linear), the gate-source junction will be modeled as a linear component. Similarly, specifying a non-zero value for Cgd and Gdcap = 1 result in a linear gate-drain model. A non-zero value for either Cgs or Cgd together with Gscap =2 (junction) or Gdcap = 2 will force the use of the diode depletion capacitance model for that particular junction. Note, that each junction is modeled independent of the other and hence, it is possible to model one junction as a linear component while the other is treated nonlinearly. The junction depletion charge and capacitance equations are summarized below.

The gate charge in Statz_Model is given by,

for $V_{new} > V_{max}$,

$$Q_g = Cgs\left(2 \times Vbi\left(1 - \sqrt{1 - \frac{V_{max}}{Vbi}}\right) + \frac{V_{new} - V_{max}}{\sqrt{1 - \frac{V_{max}}{Vbi}}}\right) + Cgd \times V_{eff2}$$

for $V_{new} \leq V_{max}$

$$Q_g = Cgs \times 2 \times Vbi\left(1 - \sqrt{1 - \frac{V_{new}}{Vbi}}\right) + Cgd \times V_{eff2}$$

where

$V_{max} = \mathrm{Min}\ (Fc \times Vbi, V_{max})$

$$V_{new} = \frac{1}{2}\left(V_{eff1} + Vto + \sqrt{(V_{eff1} - Vto)^2 + Delta2^2}\right)$$

$$V_{eff1} = \frac{1}{2}\left\{V_{gc} + V_{gd} + \sqrt{(V_{gc} - V_{gd})^2 + Delta1^2}\right\}$$

and

$$V_{eff2} = \frac{1}{2}\left\{V_{gc} + V_{gd} - \sqrt{(V_{gc} - V_{gd})^2 + Delta1^2}\right\}$$

The inclusion of Ri requires that one of the controlling voltages be switched from V_{gs} to V_{gc}. This results in a symmetry between the d-c nodes instead of the d-s nodal symmetry described in the Statz paper (of course, if Ri is set to zero, the model reduces to the exact representation in the Statz paper).

To implement this model in a simulator, the gate charge must be partitioned between the g-c and g-d branches. Implementation of the Statz model partitions the gate charge according to the work of Divekar [2]. Under this partitioning scheme, the gate-source charge is given by:

for $V_{new} > V_{max}$,

$$Q_{gs} = Cgs\left(2 \times Vbi\left(1 - \sqrt{1 - \frac{V_{max}}{Vbi}}\right) + \frac{V_{new} - V_{max}}{\sqrt{1 - \frac{V_{max}}{Vbi}}}\right)$$

for $V_{new} \le V_{max}$

$$Q_{gs} = Cgs \times 2 \times Vbi\left(1 - \sqrt{1 - \frac{V_{new}}{Vbi}}\right)$$

while the gate-drain charge is

$$Q_{gd} = Cgd \times V_{eff2}$$

The small-signal capacitances (equations 16 and 17 in the Statz paper) are related to the charge partial derivatives through the following expressions:

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gc}} + \frac{\partial Q_{gd}}{\partial V_{gc}}$$

$$C_{gd} = \frac{\partial Q_{gs}}{\partial V_{gd}} + \frac{\partial Q_{gd}}{\partial V_{gd}}$$

Although the drain-source current model and the gate-conduction model (next section) are well behaved for negative V_{ds} (as well as the zero crossing), the charge model may cause convergence problems in the region $V_{ds} < 0.0$ V. The reason for this is that the charge partitioning is somewhat artificial in that Q_{gs} and Q_{gd} should *swap* roles for negative V_{ds} but don't. It is recommended that this model be used for positive V_{ds} only.

Gate forward conduction and breakdown

Implementation of Statz_Model places a diode model in both the gate-source and gate-drain junctions to model forward conduction current and reverse breakdown current. These currents are computed with these expressions:

Gate-Source Current

for $V_{gs} > -10 \times N \times v_t$

$$I_{gs} = Is \times \left[exp\left(\frac{V_{gs}}{N \times v_t} \right) - 1 \right]$$

for $-Vbr + 50 \times v_t < V_{gs} \leq -10 \times N \times v_t$

$$I_{gs} = Is \times [exp(-10) - 1] + g_{gs} \times (V_{gs} - 10 \times N \times v_t)$$

where

$$g_{gs} = Is \times \frac{exp(-10)}{N \times v_t}$$

for $V_{gs} \leq -Vbr + 50 \times v_t$

$$I_{gs} = -Is \times \exp\left(\frac{-Vbr + V_{gs}}{N \times v_t} \right) + Is \times [exp(-10) - 1] + g_{gs} \times (V_{gs} - 10 \times N \times v_t)$$

Gate-Drain Current

for $V_{gd} > -10 \times N \times v_t$

$$I_{gd} = Is \times \left[exp\left(\frac{V_{gd}}{N \times v_t} \right) - 1 \right]$$

for $-Vbr + 50 \times v_t < V_{gd} \leq -10 \times N \times v_t$

$$I_{gd} = Is \times [exp(-10) - 1] + g_{gd} \times (V_{gd} - 10 \times N \times v_t)$$

where

$$g_{gd} = Is \times \frac{exp-10}{N \times v_t}$$

for $V_{gd} \leq -Vbr + 50 \times v_t$

$$I_{gd} = -Is \times \exp\left(\frac{-(Vbr + V_{gd})}{N \times v_t} \right) Is \times [exp(-10) - 1] + g_{gd} \times (V_{gd} - 10 \times N \times v_t)$$

Time Delay

Like Curtice2_Model and Curtice3 _Model, Statz_Model uses an ideal time delay to model transit time effects under the gate. In the time domain, the drain source current for the ideal delay is given by:

$$I_{ds}(t) = I_{ds}(V_j(t-Tau), V_{ds}(t))$$

where $V_j = V_{gs}$ or $V_j = V_{gd}$ (depending on whether V_{ds} is positive or negative). In the frequency domain, only the transconductance is impacted by this delay and the familiar expression for transconductance is obtained

$$y_m = g_m \times \exp(-j \times \omega \times Tau)$$

High-Frequency Output Conductance

The series-RC network, Figure 3-7, is comprised of the parameters Crf and Rc and is included to provide a correction to the ac output conductance at a specific bias condition. At a frequency high enough such that Crf is an effective short, the output conductance of the device can be increased by the factor 1/Rc. (Also see [3].)

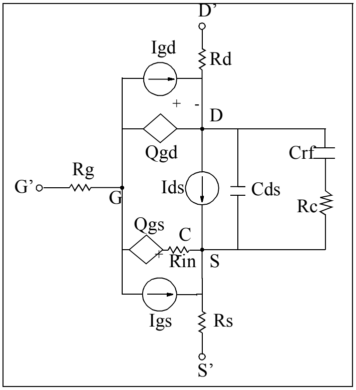


Figure 3-7. Statz_Model Schematic

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation current Is scales as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

The gate depletion capacitances Cgs and Cgd vary as:

$$Cgs^{NEW} = Cgs\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

$$Cgd^{NEW} = Cgd\left[\frac{1 + 0.5[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + 0.5[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Tnom}]}\right]$$

where *y* is a function of junction potential and energy gap variation with temperature.

The gate junction potential Vbi varies as:

$$Vbi^{NEW} = \frac{Temp}{Tnom} \times Vbi + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

where n_i is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage Vto varies as:

$$Vto^{NEW} = Vto + Vtotc(Temp - Tnom)$$

The transconductance Beta varies as:

$$Beta^{NEW} = Beta \times 1.01^{Betatce(Temp - Tnom)}$$

Noise Model

Thermal noise generated by resistors Rg, Rs, Rd and Rin is characterized by the spectral density:

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\, P(1 + f_{NC}/f)$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\, C_{gs}^2\, \omega^2\, R/g_m$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\, C_{gs}\, \omega \sqrt{PR}\, C$$

References

[1] H. Statz, P. Newman, I. Smith, R. Pucel and H. Haus. “GaAs FET device and circuit simulation in SPICE,” *IEEE Trans, on Electron Devices,* vol. ED-34, pp. 160-169, Feb. 1987.

[2] D. Divekar, *Comments on ‘GaAs FET device and circuit simulation in SPICE,’ IEEE Transactions on Electron Devices,* Vol. ED-34, pp. 2564-2565, Dec. 1987.

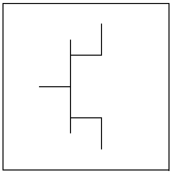
[3] C. Camacho-Penalosa and C.S. Aitchison. “Modelling frequency dependence of output impedance of a microwave MESFET at low frequencies,” *Electron. Lett.*, Vol. 21, pp. 528-529, June 6, 1985.

[4] P. Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE,* New York: McGraw-Hill, Second Edition 1993.

[5] A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques,* Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Tajima_Model (Tajima GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-11. Tajima_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Idsmod	Ids model		5
Vdss	drain current saturation voltage of this model	V	1
Vto	value of V1 below which Ids = Ids(V1=VT0,Vds)	V	–2
Beta2	coefficient for pinch-off change with respect to Vds	1/V	0
Ta	model 5: ‘a’ coefficient		–0.2
Tb	model 5: ‘b’ coefficient		0.6
Tm	model 5: ‘m’ coefficient		3.0
Idss	saturation drain current	A	0
Rin††	channel resistance	ohms	0
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Gscap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgs††	zero bias gate-source junction capacitance	F	0.0

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-11. Tajima_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Gdcap	0=none, 1=linear, 2=junction, 3=Statz charge, 5=Statz cap		linear
Cgd††	zero bias gate-drain junction capacitance	F	0.0
Rd	drain ohmic resistance	ohms	0.0
Rg	gate resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Ld	drain inductance	henry	0.0
Lg	gate inductance	henry	0.0
Ls	source inductance	henry	0.0
Cds††	drain-source capacitance	F	0.0
Crf††	used to model frequency-dependent output conductance	F	0.0
Rc†††	output resistance for RF operation	ohms	infinity‡
Gsfwd	0=none, 1=linear, 2=diode		linear
Gsrev	0=none, 1=linear, 2=diode		none
Gdfwd	0=none, 1=linear, 2=diode		none
Gdrev	0=none, 1=linear, 2=diode		linear
Vbi†	built-in gate potential	V	0.85
Is	gate junction reverse saturation current (diode model)	A	10^{-14}
Imax	explosion current	A	1.6
N	gate junction emission coefficient (diode model)		1
Fnc	flicker noise corner frequency	Hz	0
R	gate noise coefficient		0.5
P	drain noise coefficient		1
C	gate-drain noise correlation coefficient		0.9

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Table 3-11. Tajima_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Tnom	nominal ambient temperature	°C	25
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	
wPmax	maximum power dissipation warning	W	
AllParams	DataAccessComponent for file-based model parameter values		

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales with Area.

††† Parameter value scales inversely with Area.

‡ A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. This model supplies values for a GaAsFET device.
2. Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2 \rangle}{\Delta f} = 4kTg_m\, P(1 + f_{NC}/f) \tag{3-1}$$

$$\frac{\langle i_g^2 \rangle}{\Delta f} = 4kT\, C_{gs}^2\, \omega^2\, R/g_m \tag{3-2}$$

$$\frac{\langle i_g, i_d^* \rangle}{\Delta f} = 4kTj\, C_{gs}\, \omega \sqrt{PR}\, C \tag{3-3}$$

3. Following are additional parameter equations:

   $$\upsilon_p = \mathrm{Vto} - \mathrm{Beta}^2 \times \mathrm{Vds} - \mathrm{Vbi} \tag{3-4}$$

   $$\upsilon c = (\upsilon gs - \mathrm{Vbi} - \upsilon p)/\upsilon p \tag{3-5}$$

   If υ_p □□□□□□□□□□□□≥ 0 or $\upsilon_c \geq 0$, then ids = 0 (3-6)

   else

   $$id_1 = \left[\frac{(\exp(Tm \bullet \upsilon c)^{-1})}{Tm} - \upsilon c\right] \Big/ \left[1 - \frac{(1 - \exp(-Tm))}{Tm}\right] \tag{3-7}$$

   $$id_2 = Idss \bullet \left[1 - \exp\left(\left(\frac{\upsilon ds}{Vdss}\right) - Ta\left(\frac{\upsilon ds}{Vdss}\right)^2 - Tb\left(\frac{\upsilon ds}{Vdss}\right)^3\right)\right] \tag{3-8}$$

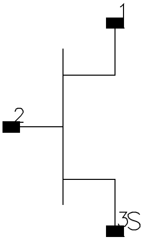
   $$\mathrm{ids} = \mathrm{id}_1 \times \mathrm{id}_2 \tag{3-9}$$

4. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). A nonlinear device model parameter value that is explicitly specified will override the value set by an AllParams association.

5. A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

TOM (TriQuint Scalable Nonlinear GaAsFET)

Symbol



Parameters

Model = name of a TOM_Model

W = new unit gate width, in length units (default 1.0)

N = new number of gate fingers (default: 1)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: linear or nonlinear (refer to Note 2)

_M = number of devices in parallel (default: 1)

Range of Usage

$W > 0$

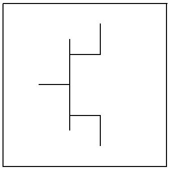
$N > 0$

Notes/Equations/References

1. W and N are used for scaling device instance; refer to the model for these descriptions.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. This device has no default artwork associated with it.

TOM_Model (TriQuint Scalable Nonlinear GaAsFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 3-12. TOM_Model Parameters

Parameter	**Description**	**Unit**	**Default**
Idsmod	Ids model		7
Vto[†]	nonscalable portion of threshold voltage	V	–2
Vtosc[††]	scalable portion of threshold voltage	V	0.0
Alpha	saturation voltage coefficient	1/V	2.0
Beta[†, †††]	transconductance coefficient	A/V^2	10^{-4}
Tqdelta[††]	output feedback coefficient	1/W	0
Tqgamma	dc drain pull coefficient		0.0
TggammaAc	AC pinchoff change with vds		0.0
Tnom	nominal ambient temperature at which these model parameters were derived	×°C	25
Q	power law exponent		2.0
Tau	gate transit time delay	sec	0.0
Vtotc	Vto temperature coefficient	V/°C	0.0
Betatce	drain current exponential temperature coefficient	%/°C	0.0

[†] Parameter value varies with temperature based on model Tnom and device Temp.
[††] Parameter value scales inversely with Area.
[†††] Parameter value scales with Area.
[‡] Value of 0.0 is interpreted as infinity.
[‡‡] Total gate resistance is Rg + Rgmet.

Table 3-12. TOM_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Cgs[†, †††]	zero-bias gate-source capacitance	F	0.0
Cgd[†, †††]	zero-bias gate-drain capacitance	F	0.0
Vbi	gate diode built-in potential	V	0.85
Tqm	temperature coefficient for TriQuint junction capacitance		0.2
Vmax	maximum junction voltage before capacitance limiting	V	
Fc	coefficient for forward bias depletion capacitance (diode model)		0.5
Delta1	capacitance saturation transition voltage	V	0.3
Delta2	capacitance threshold transition voltage	V	0.2
M	grading coefficient		0.5
Is[†, †††]	gate diode saturation current (diode model)	A	10^{-14}
N	gate diode emission coefficient (diode model)		1.0
Eg	energy gap for temperature effect on Is	eV	1.11
Xti	temperature exponent for saturation current		3.0
Vbr	gate-drain junction reverse bias breakdown voltage (gate-source junction reverse bias breakdown voltage with $V_{ds} = 0$)	V	infinity[‡]
Rg[‡‡]	gate resistance	ohms	0.0
Rd[††]	drain contact resistance	ohms	0.0
Rs[††]	source contact resistance	ohms	0.0
Trg1	linear temperature coefficient for Rg	1/°C	0
Trd1	linear temperature coefficient for Rd	1/°C	0
Trs1	linear temperature coefficient for Rs	1/°C	0

[†] Parameter value varies with temperature based on model Tnom and device Temp.

[††] Parameter value scales inversely with Area.

[†††] Parameter value scales with Area.

[‡] Value of 0.0 is interpreted as infinity.

[‡‡] Total gate resistance is Rg + Rgmet.

Table 3-12. TOM_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Cds†††	drain source capacitance	F	0.0
Rdb	R for frequency-dependent output conductance	Ohms	0.0
Cbs	C for frequency-dependent output capacitance	F	0.0
Rgmet‡‡	gate metal resistance	ohms	0.0
Ris††	source end channel resistance	ohms	0.0
Rid††	drain end channel resistance	ohms	0.0
Vgr	Vg (s,d) c includes voltage across Rg (s,d)		No
Imax	explosion current	A	1.6
Fnc	flicker noise corner efficiency	Hz	0
R	gate noise coefficient		0.5
P	drain noise coefficient		1
C	gate drain noise correlation coefficient		0.9
Taumdl	second order Bessel polynomial to model tau effect in transient simulation		no
Ugw	unit gate width of device	meter	1e-6
Ngf	number of device gate fingers		1
wVgfwd	gate junction forward bias warning	V	
wBvgs	gate-source reverse breakdown voltage warning	V	
wBvgd	gate-drain reverse breakdown voltage warning	V	
wBvds	drain-source breakdown voltage warning	V	
wIdsmax	maximum drain-source current warning	A	
wPmax	maximum power dissipation warning	W	

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value scales inversely with Area.

††† Parameter value scales with Area.

‡ Value of 0.0 is interpreted as infinity.

‡‡ Total gate resistance is Rg + Rgmet.

Table 3-12. TOM_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Gscap	0=none,1=linear,2=junction,3=Statz charge, 5=Statz cap		Statz
Gsfwd	0=none,1=linear,2=diode		diode

† Parameter value varies with temperature based on model Tnom and device Temp.
†† Parameter value scales inversely with Area.
††† Parameter value scales with Area.
‡ Value of 0.0 is interpreted as infinity.
‡‡ Total gate resistance is Rg + Rgmet.

Notes/Equations/References

1. This model supplies values for a TOM device.
2. Implementation of the TOM model is based on the work of McCaman et al, and also includes some features not covered in McCamans work. These enhancements include scaling with gate area and a seamless method for simulating with two different values for the parameters Tqgamma and TqgammaAc (one extracted at DC and the other adjusted to fit AC output conductance).
3. Model parameters such as Ls, Ld, Lg are not used by the TOM device in the simulator. Only those parameters listed in Table 3-12 are part of the TOM device. Extrinsic devices must be added externally by the user.
4. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally:

$Rd = 10^{-4}$ $Ris = 10^{-4}$

$Rs = 10^{-4}$ $Rid = 10^{-4}$

$Rg = 10^{-4}$ $Rgmet = 10^{-4}$

Other parameters are restricted to values > 0. If the user violates this restriction, the parameters will be internally fixed by the simulator:

$Vbi = 0.1$

$N = 1.0$

$Tqdelta= 0.0$

5. DC Drain-Source Current

The Tom DC drain-source current model is an enhanced version of the one published by McCamant et al. It includes the same features as the version implemented by TriQuint in PSPICE for their foundry customers (minus temperature effects). The TOM model DC drain-source current is given by the following expressions:

$$\text{Ids} = \frac{Idso}{1 + \delta \times Vds \times Idso}$$

where

$$\text{Idso} = \beta(V_{gs} - V_t)^Q \times \left[1 - \left[1 - \frac{\alpha Vds}{3}\right]^3\right] \quad \text{for } 0 < \text{Vds} < 3/\alpha$$

$$\text{Idso} = \beta(V_{gs} - V_t)^Q \quad \text{for Vds} \geq 3/\alpha$$

The threshold voltage V_t is given by:

Vt = (Vto + Vtosc) - Tqgamma × Vds

where δ is Tqdelta, α is Alpha, β is Beta and Vtosc represents the scalable portion of the zero-bias threshold voltage.

The current is set to zero for Vgs < Vt.

6. Gate Capacitances

The gate capacitances in the TOM model come from Statz et al.

The gate-source capacitance:

$$\frac{Cgs}{\sqrt{1 - \frac{Vn}{Vbi}}} \times \frac{1}{2}\left[1 + \frac{Veff - Vto}{\sqrt{(Veff - Vto)^2 + Delta2^2}}\right] \times \frac{1}{2}\left[1 + \frac{Vgs - Vgd}{\sqrt{(Vgs - Vgd)^2 + Delta^2}}\right] + Cgd \times \frac{1}{2}$$

$$\left[1 - \frac{Vgs - Vgd}{\sqrt{(Vgs - Vgd)^2 + Delta^2}}\right]$$

The gate-drain capacitance:

$$\frac{Cgs}{\sqrt{1 - \frac{Vn}{Vbi}}} \times \frac{1}{2}\left[1 + \frac{Veff - Vto}{\sqrt{(Veff - Vto)^2 + Delta2^2}}\right] \times \frac{1}{2}\left[1 - \frac{Vgs - Vgd}{\sqrt{(Vgs - Vgd)^2 + Delta^2}}\right] + Cgd \times \frac{1}{2}$$

$$\left[1 + \frac{Vgs - Vgd}{\sqrt{(Vgs - Vgd)^2 + Delta^2}}\right]$$

where

Delta = Delta1 if Delta1 is specified, otherwise Delta = $\frac{1}{Alpha}$

Veff = $\frac{1}{2}(Vgs + Vgd + \sqrt{(Vgs - Vgd)^2 + Delta^2})$

Vnew = $\frac{1}{2}(Veff + Vto + \sqrt{(Veff - Vto)^2 + Delta2^2})$

Vn = Vnew if Vnew < Min (Fc × Vbi, Vmax) otherwise Vn = Min (Fc × Vbi, Vmax)

7. **High-Frequency Output Conductance**

In their paper McCamant et al., discuss the effects of the parameter γ on the output conductance of the TOM model. Agilent's implementation permits the user to input both a DC (Tqgamma) and high frequency (TqgammaAc) value into the model. Given these two γ values, two separate values of the drain-source current function Ids can be computed, one for DC and one for AC:

Ids^{DC} = Ids (Vgs (t-Tau), Vds, Tqgamma)

Ids^{AC} = Ids (Vgs (t-Tau), Vds, TqgammaAc)

These two current functions can be seamlessly integrated into the nonlinear model by setting the current source in the equivalent circuit to the difference of these two functions:

Idb (Vgs (t-Tau), Vds) = Ids^{AC} - Ids^{DC}

The circuit elements Rdb and Cbs are both linear elements that are used to control the frequency at which the current source Idb becomes a factor. Note that at DC the source Idb has no impact on the response and the drain-source current is just the DC value. At very high frequency and with Rdb set to a very large quantity, the sources Ids and Idb add, giving the AC value for the drain-source current. The frequency at which the current (conductance) is midway between its two transitional extremes is

$f_o = \frac{1}{2\pi\tau_{disp}}$

where τ_{disp} = Rdb × Cbs

The user may select this transition frequency by setting the parameters Rdb and Cbs. However, it is recommended that Rdb be kept at a large value so it remains an effective open to the circuit.

8. **Dimensional Scaling Relations**

Scaling of TOM_Model parameters is accomplished through the use of the model parameters Ugw and Ngf (see Table 3-12) and the device parameters Ugw (same name as the model parameter) and N. From these four parameters, the following scaling relations can be defined:

$$sf = \frac{W \times N}{Ugw \times Ngf}$$

$$sfg = \frac{Ugw \times N}{W \times Ngf}$$

where W represents the device parameter Ugw, the *new* unit gate width.

Scaling will be disabled if N is not specified. The new parameters are computed internally by the simulator according to the following equations:

$$Beta^{new} = Beta \times sf$$

$$Tqdelta^{new} = \frac{Tqdelta}{sf}$$

$$Vtosc^{new} = \frac{Vtosc}{sf}$$

$$Is^{new} = Is \times sf$$

$$Ris^{new} = \frac{Ris}{sf}$$

$$Rid^{new} = \frac{Rid}{sf}$$

9. **Temperature Scaling Relations**

TOM_Model uses an extensive set of temperature scaling relations that permit the analysis of drain current, gate current, capacitances and even parasitic resistances over ambient temperature changes. The scaling relations assume the unscaled (nominal) parameters were extracted at Tnom. The parameters are scaled to an arbitrary operating ambient temperature (Temp) through the temperature scaling relations. Note that the user must specify the temperatures Temp and Tnom in °C—the program converts these temperatures to units of Kelvin. The equations that follow use temperature in Kelvin.

$$Vbi(Temp) = Vbi \times \left(\frac{Temp}{Tnom}\right) - 3V_t \log\left(\frac{Temp}{Tnom}\right)$$

$$- E_g(Tnom) \times \left(\frac{Temp}{Tnom}\right) + E_g(Temp)$$

$$Beta(Temp) = Beta \times 1.01^{Betatce \times (Temp - Tnom)}$$

$$Vto(Temp) = Vto + Vtotc \times (Temp - Tnom)$$

$$Is(Temp) = exp\left[\left(\frac{Temp}{Tnom} - 1\right) \times \frac{Eg}{V_t}\right] \times Is\left(\frac{Temp}{Tnom}\right)^{\frac{Xti}{N}}$$

$$Rd(Temp) = Rd \times (1 + Trd1 \times (Temp - Tnom))$$

$$Rs(Temp) = Rs \times (1 + Trs1 \times (Temp - Tnom))$$

$$Cgs(Temp) = Cgs\left[1 + Tqm \times \left[4.0 \times 10^{-4}(Temp - Tnom) + 1 - \frac{Vbi(Temp)}{Vbi}\right]\right]$$

$$Cgd(Temp) = Cgd\left[1 + Tqm \times \left[4.0 \times 10^{-4} \times \left((Temp - Tnom) + 1 - \frac{Vbi(Temp)}{Vbi}\right)\right]\right]$$

where

$$V_t = \frac{V \times Temp}{q}$$

$$E_g(T) = \frac{1.519 - 5.405 \times 10^{-4} T^2}{T + 204}$$

where

K = Boltzmann's constant = $8.62 \times 10^{-5} eV\ K^{-1}$

q = electron charge = $1.602 \times 10^{-19} C$.

10. **Noise Model**

Thermal noise generated by resistors Rg, Rs and Rd is characterized by the following spectral density.

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

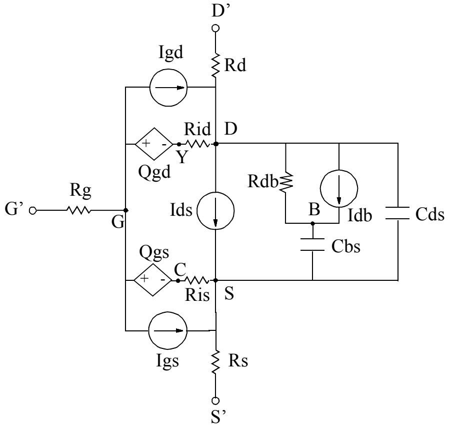
Parameters P, R, and C model drain and gate noise sources.

$$\frac{\langle i_d^2\rangle}{\Delta f} = 4kTg_m\,P(1+f_{NC}/f)$$

$$\frac{\langle i_g^2\rangle}{\Delta f} = 4kT\,C_{gs}^2\,\omega^2\,R/g_m$$

$$\frac{\langle i_g, i_d^*\rangle}{\Delta f} = 4kTj\,C_{gs}\,\omega\sqrt{PR}\,C$$

11. **Equivalent Circuit**



In this circuit illustration, Rdb and Cbs are shown. They are not available at the time of the initial release of this product version, but will be added in a future product patch or release.

12. A. McCaman, G. McCormack and D. Smith. “An Improved GaAs MESFET Model for SPICE”, *IEEE Trans. on Microwave Theory Tech*., vol. MTT-38, pp. 822-824, June 1990.
13. H. Statz, P. Newman, I. Smith, R. Pucel and H. Haus. “GaAs FET Device and Circuit Simulation in SPICE”, *IEEE Trans. on Electron Devices*, vol. ED-34, pp. 160-169, Feb. 1987.
14. A. Cappy, “Noise Modeling and Measurement Techniques,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No. 1, pp. 1-10, Jan. 1988.

Chapter 4: Devices and Models, JFET

Bin Model

The BinModel in the JFET library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

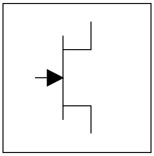
For information on the use of the binning feature, refer to the section *"Bin Model (Bin Model for Automatic Model Selection."* This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components.*

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

JFET_Model (Junction FET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 4-1. JFET_Model Parameters

Parameter	Description	Unit	Default
NFET	N-channel model		yes
PFET	P-channel model		no
Vto†	zero-bias threshold voltage	V	–2.0
Beta†, ††	transconductance parameter	A/V^2	10^{-4}
Lambda	channel-length modulation parameter	1/V	0.0
Rd††	drain ohmic resistance	ohms	0.0
Rs††	source ohmic resistance	ohms	0.0
Is†, ††	gate-junction saturation current	A	10^{-14}
Cgs†	zero-bias gate-source junction capacitance	F	0.0
Cgd†	zero-bias gate-drain junction capacitance	F	0.0
Pb†	gate-junction potential	V	1.0
Fc	forward-bias junction capacitance coefficient		0.5
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
Kf	flicker-noise coefficient		0.0
Af	flicker-noise exponent		1.0
Imax	explosion current	A	1.6

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Parameter value is scaled with Area specified with the JFET device.

Table 4-1. JFET_Model Parameters (continued)

Parameter	Description	Unit	Default
N	gate P-N emission coefficient		1.0
Isr[†]	gate P-N recombination current parameter	A	0.0
Nr	Isr emission coefficient		2.0
Alpha	ionization coefficient	1/V	0.0
Vk	ionization knee voltage	V	0.0
M	gate P-N grading coefficient		0.5
Vtotc	Vto temperature coefficient	V/°C	0.0
Betatce	Beta exponential temperature coefficient	%/°C	0.0
Xti	temperature coefficient		3.0
Ffe	flicker noise frequency exponent		1.0
wBvgs	gate-source reverse breakdown voltage (warning)	V	
wBvgd	gate-drain reverse breakdown voltage (warning)	V	
wBvds	drain-source breakdown voltage (warning)	V	
wIdsmax	maximum drain-source current (warning)	A	
wPmax	maximum power dissipation (warning)	W	
AllParams	DataAccessComponent-based parameters		

[†] Parameter value varies with temperature based on model Tnom and device Temp.

[††] Parameter value is scaled with Area specified with the JFET device.

Notes/Equations/References

1. This model supplies values for a JFET device.
2. JFET_Model equations are based on the FET model of Shichman and Hodges. For more information on JFET_Model, its parameters and equations, see [1].
3. The dc characteristics of a JFET_Model are defined by:
    - Vto and Beta: determine variation in drain current with respect to gate voltage.
    - Lambda: determines the output conductances
    - Is: saturation current of the two gate junctions.

4. Charge storage is modeled by nonlinear depletion layer capacitance for both gate junctions. These capacitances vary as 1/Sqrt (Junction Voltage) and are defined by Cgs, Cgd and Pb.
5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The saturation currents Is and Isr scale as:

$$Is^{NEW} = Is \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times N \times Temp} + \frac{Xti}{N} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

$$Isr^{NEW} = Isr \times exp\left[\left(\frac{Temp}{Tnom} - 1\right)\frac{q \times Eg}{k \times Nr \times Temp} + \frac{Xti}{Nr} \times ln\left(\frac{Temp}{Tnom}\right)\right]$$

The depletion capacitances Cgs and Cgd vary as:

$$Cgs^{NEW} = Cgs\left[\frac{1 + M[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cgd^{NEW} = Cgd\left[\frac{1 + M[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + M[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

where γ is a function of the junction potential and the energy gap variation with temperature.

The gate junction potential Pb varies as:

$$Pb^{NEW} = \frac{Temp}{Tnom} \times Pb + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

where n_i is the intrinsic carrier concentration for silicon, calculated at the appropriate temperature.

The threshold voltage Vto varies as:

$$Vto^{NEW} = Vto + Vtotc(Temp - Tnom)$$

The transconductance Beta varies as:

$$Beta^{NEW} = Beta \times 1.01^{Betatce(Temp - Tnom)}$$

Noise Model

Thermal noise generated by resistors Rs and Rd is characterized by the following spectral density:

$$\frac{<i^2>}{\Delta f} = \frac{4kT}{R}$$

Channel noise and flicker noise (Kf, Af, Ffe) generated by the dc transconductance g_m and current flow from drain to source is characterized by the following spectral density:

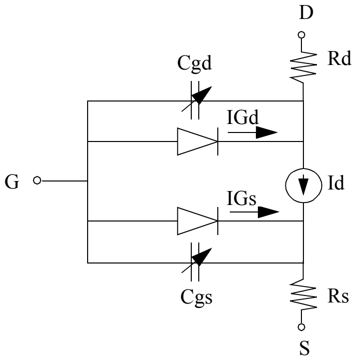
$$\frac{<i_{ds}^2>}{\Delta f} = \frac{8kTg_m}{3} + k_f \frac{I_{DS}^{a_f}}{f^{f_{fe}}}$$

In the above expressions, *k* is Boltzmann's constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, *kf*, *af*, and *ffe* are model parameters, *f* is the simulation frequency, and Δ*f* is the noise bandwidth.

References

[1] P. Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

Equivalent Circuit

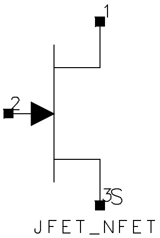


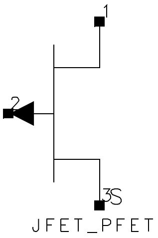
JFET (Nonlinear Junction Field-Effect Transistors)

JFET_NFET (Nonlinear Junction Field-Effect Transistor, N-Channel)

JFET_PFET (Nonlinear Junction Field-Effect Transistor, P-Channel

Symbol





Parameters

Model = name of a JFET_Model

Area = scaling factor that scales certain parameter values of the JFET_Model (default: 1)

Region = dc operating region: off, on, rev, ohmic (default: on)

Temp = device operating temperature, in °C (default: 25)

Mode = simulation mode for this device: linear or nonlinear (refer to Note 2) (default: nonlinear)

_M = number of devices in parallel (default: 1)

Range of Usage

N/A

Notes/Equations/References

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated JFET_Model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to JFET_Model to see which parameter values are scaled.
2. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
3. This device has no default artwork associated with it.

References

[1] *SPICE2: A Computer Program to Simulate Semiconductor Circuits,* University of California, Berkeley.

[2] P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE,* Second Edition, McGraw-Hill, Inc., 1993.

Chapter 5: Devices and Models, MOS

Bin Model

The BinModel in the MOS library allows you to sweep a parameter (usually a geometry, such as gate length), then enable the simulator to automatically select between different model cards. This alleviates the problem that one scalable model typically doesn't work for all sizes of a device.

For information on the use of the binning feature, refer to the section *"Bin Model (Bin Model for Automatic Model Selection."* This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components.*

Multiplicity (_M) Parameter

For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

Use of MOSFET Parameter Nlev

The MOSFET noise model is controlled by the model parameter Nlev. Table 5-1 shows which noise equations are used for each value of Nlev. These equations are always used for the BSIM1, BSIM2, LEVEL1, LEVEL2, LEVEL3 and LEVEL3_MOD models. For a BSIM3, these equations can be used to override the standard BSIM3v3 noise equations only when Nlev ≥ 1.

Table 5-1. Equations Used for Nlev parameter

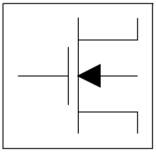
Nlev Value	Channel Noise	Flicker Noise	Default
-1	8/3k T g_m	$\frac{Kf\lvert I_{DS}\rvert^{Af}}{f^{Ffe}}$	ADS default (not usable with BSIM3v3)
0	8/3k T g_m	$\frac{Kf\lvert I_{DS}\rvert^{Af}}{f^{Ffe} C_{OX} L^2 Eff}$	Spice2G6 Hspice Nlev=0 (not usable with BSIM3v3)
1	8/3k T g_m	$\frac{Kf\lvert I_{DS}\rvert^{Af}}{f^{Ffe} C_{OX} W_{Eff\,LEff}}$	Hspice Nlev=1

Table 5-1. Equations Used for Nlev parameter (continued)

Nlev Value	Channel Noise	Flicker Noise	Default
2	8/3k T g_m	$\frac{Kfg_m^2}{f^{Ffe}C_{OX}W_{Eff}L_{Eff}}$	Hspice Nlev=2
3	$\frac{8}{3}kTB\langle V_{GS}-V_T\rangle\frac{1+a+a^2}{1+a}Gdsnoi$ 1 (pinchoff) a = 1 - V_{DS}/V_{DSAT} (linear) 0 (saturation)	$\frac{Kfg_m^2}{f^{Ffe}C_{OX}W_{Eff}L_{Eff}}$	Hspice Nlev=3

BSIM1_Model (BSIM1 MOSFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-2. BSIM1_Model Parameters

Parameter	Description	Unit	Default
NMOS	N-channel type model		yes
PMOS	P-channel type model		no
Idsmod	Ids model		4
Rsh	drain and source diffusion sheet resistance	ohms/sq	0.0
Js	bulk junction area saturation current	A/m^2	0.0
Temp	parameter measurement temperature	°C	25
Muz	zero-bias surface mobility	$cm^2/Vsec$	600
Dl	shortening of channel		0.0
Dw	narrowing of channel		0.0
Vdd	measurement drain bias range	V	5.0
Vfb	flat-band voltage	V	−0.3
Phi	surface potential at strong inversion	V	0.6
K1	body effect coefficient	√V	0.5
K2	drain/source depletion charge sharing coefficient		0.0
Eta	drain-induced barrier lowering coefficient		0.0
U0	transverse field mobility degradation coefficient	1/V	670.0
U1	zero-bias velocity saturation coefficient	µm/V	0.0
X2mz	sensitivity of mobility to substrate bias	cm^2/V^2	0.0
X2e	sensitivity of barrier lowering cf to substrate bias	1/V	-0.07

Table 5-2. BSIM1_Model Parameters (continued)

Parameter	Description	Unit	Default
X3e	sensitivity of barrier lowering cf to drain bias	1/V	0.0
X2u0	sensitivity of transverse field cf to substrate bias	$1/V^2$	0.0
X2u1	sensitivity of velocity saturation to substrate bias	µm/V^2	0.0
X3u1	sensitivity of velocity saturation to drain bias	µm/V^2	0.0
Mus	mobility at zero substrate bias at Vds=Vdd	cm$^{2/}$Vs	1082
X2ms	sensitivity of mobility to substrate bias	cm^2/V^{2s}	0.0
X3ms	sensitivity of mobility to drain bias at Vds=Vdd	cm^2/V^{2s}	0.0
N0	zero-bias subthreshold slope coefficient		0.5
Nb	sensitivity of subthreshold slope to substrate bias	1/V	0.0
Nd	sensitivity of subthreshold slope to drain bias	1/V	0.0
Tox	oxide thickness	µm	10^{-7}
Cj	zero-bias bulk junction bottom capacitance	F/m^2	0.0
Mj	bulk junction bottom grading coefficient		0.5
Cjsw	zero-bias bulk junction sidewall capacitance	F/m	0.0
Mjsw	bulk junction sidewall grading coefficient		0.33
Pb	bulk junction potential	V	0.8
Pbsw	built-in potential of source drain junction sidewall	V	1.0
Cgso	gate-source overlap capacitance, per channel width	F/m	0.0
Cgdo	gate-drain overlap capacitance, per channel width	F/m	0.0
Cgbo	gate-bulk overlap capacitance, per channel width	F/m	0.0
Xpart	coefficient of channel charge share		1.0
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0
Ffe	flicker noise frequency exponent		1.0

Table 5-2. BSIM1_Model Parameters (continued)

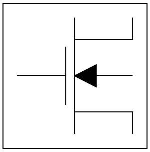
Parameter	Description	Unit	Default
Rg	gate resistance	ohms	0
N	bulk P-N emission coefficient		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

Notes/Equations/References

1. This model supplies values for a MOSFET device.
2. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

BSIM2_Model (BSIM2 MOSFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-3. BSIM2_Model Parameters

Parameter	Description	Unit	Default
NMOS	N-channel type model		yes
PMOS	P-channel type model		no
Idsmod	Ids model		5
Rsh	drain and source diffusion sheet resistance		0.0
Js	bulk junction saturation current, per junction area	A/m^2	0.0
Mu0	zero-bias surface mobility	$cm^2/V\text{-}s$	600
Dl	shortening of channel, in	µm	0.0
Dw	Narrowing of channel, in	µm	0.0
Vdd	measurement drain bias range	V	5.0
Vgg	measurement gate bias range	V	5.0
Vbb	measurement bulk bias range	V	-5.0
Temp	measurement temperature	^oC	25
Tox	oxide thickness	µm	10^{-7}
Cj	zero-bias bulk junction bottom capacitance	F/m^2	5.0
Mj	bulk junction bottom grading coefficient		0.5
Cjsw	zero-bias bulk junction sidewall capacitance	F/m	0.0
Mjsw	bulk junction sidewall grading coefficient		0.33
Pb	bulk junction potential	V	0.8

Table 5-3. BSIM2_Model Parameters

Parameter	Description	Unit	Default
Pbsw	built-in potential of source drain junction sidewall	V	1.0
Cgso	gate-source overlap capacitance, per channel width	F/m	0.0
Cgdo	gate-drain overlap capacitance, per channel width	F/m	0.0
Cgbo	gate-bulk overlap capacitance, per channel width		0.0
Xpart	coefficient of channel charge share		1.0
Vfb	flat-band voltage	V	-0.1
Phi	surface potential at strong inversion	V	0.6
K1	body effect coefficient	$\sqrt{V}$	0.5
K2	drain/source depletion charge sharing coefficient		0.0
Eta0	zero-bias drain-induced barrier lowering coefficient		0.08
Ua0	transverse field mobility degradation coefficient	1/V	670.0
U10	zero-bias velocity saturation coefficient	μm/V	0.0
Mu0b	sensitivity of mobility to substrate bias	cm^2/V^{2s}	0.0
Etab	sensitivity of barrier lowering cf to substrate bias	1/V	-0.07
Uab	sensitivity of transverse field cf to substrate bias	$1/V^2$	0.0
U1b	sensitivity of velocity saturation to substrate bias	$\mu m/V^2$	0.0
U1d	sensitivity of velocity saturation to drain bias	$\mu m/V^2$	0.0
Mus0	mobility at zero substrate bias at Vds=Vdd	cm^2/Vs	600.0
Musb	sensitivity of mobility to substrate bias	cm^2/V^{2s}	0.0
N0	zero-bias subthreshold slope coefficient		0.5
Nb	sensitivity of subthreshold slope to substrate bias	1/V	1.0
Nd	sensitivity of subthreshold slope to drain bias	1/V	0.0
Mu20	empirical parameter in beta 0 expression		0.0
Mu2b	sensitivity of Mu2 to Vbs	1/V	0.0
Mu2g	sensitivity of Mu2 to Vgs	1/V	0.0
Mu30	linear empirical parameter in beta 0 exp	cm^2/V^{2s}	0.0

Table 5-3. BSIM2_Model Parameters

Parameter	**Description**	**Unit**	**Default**
Mu3b	sensitivity of Mu3 to Vbs	cm^2/V^{3s}	0.0
Mu3g	sensitivity of Mu3 to Vgs	cm^2/V^{3s}	0.0
Mu40	quadratic empirical parameter in beta0 exp	cm^2/v^{3s}	0.0
Mu4b	sensitivity of Mu4 to Vbs	cm^2/v^{4s}	0.0
Ub0	mobility reduction to vertical field at Vbs=0	$1/V^2$	0.0
Ubb	sensitivity of mobility reduction to Vbs	$1/V^3$	0.0
Vof0	threshold voltage offset in the subthreshold region	V	0.0
Vofb	sensitivity of Vof to Vbs		0.0
Vofd	sensitivity of Vof to Vds		0.0
Ai0	pre-factor of hot-electron effect		0.0
Aib	sensitivity of Ai to Vbs	1/V	0.0
Bi0	exponential factor of hot-electron effect	V	0.0
Bib	sensitivity of Bi to Vbs		0.0
Vghigh	upper bound for the transition region	V	0.0
Vglow	lower bound for the transition region	V	-0.15
Lvglow	length dependence of Vglow	um*V	0.0
Wvglow	length dependence of Vglow	um*V	0.0
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0
Ffe	flicker noise frequency exponent		1.0
Rg	gate resistance		0
N	bulk P-N emission coefficient		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite

Table 5-3. BSIM2_Model Parameters

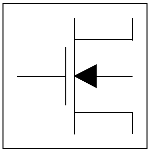
Parameter	Description	Unit	Default
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

Notes/Equations/References

1. This model supplies values for a MOSFET device.
2. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).
3. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

BSIM3_Model (BSIM3 MOSFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-4. BSIM3_Model Parameters

Parameter	Description	Units	Default
NMOS	N-channel type model		yes
PMOS	P-channel type model		no
Idsmod	Ids model		8
Version	model version		3.22
Mobmod	mobility model selector		1
Capmod	capacitance model selector		1
Noimod	noise model selector		1
Paramchk	model parameter checking selector		0
Binunit	bin unit selector		1
Rg	gate resistance	ohms	0
Rsh	drain and source diffusion sheet resistance	ohms/sq	0.0
Nj	bulk P-N emission coefficient		1.0
Xti	junction current temp. exponent		3.0
Js	gate saturation current	A/m^2	10^{-4}
Jsw	sidewall junction reverse saturation current	A/m^2	0.0
Lint	length offset fitting parameter (binning parameter; see Note 4)	m	0.0
Ll	coefficient of length dependence for length offset	m^{Lln}	0.0

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Lln	power of length dependence of length offset		1.0
Lw	coefficient of width dependence for length offset	m^{Lwn}	0.0
Lwn	power of width dependence of length offset		1.0
Lwl	coefficient of length and width cross term for length offset	$m^{(Lwn+Lln)}$	0.0
Wint	width offset fitting parameter (binning parameter; see Note 4)	m	0.0
Wl	coefficient of length dependence for width offset	m^{Wln}	0.0
Wln	power of length dependence of width offset		1.0
Ww	coefficient of width dependence for width offset	m^{Wwn}	0.0
Wwn	power of width dependence of width offset		1.0
Wwl	coefficient of length and width cross term for width offset	$m^{(Wwn+Wln)}$	0.0
Tnom	parameter measurement temp.	°C	25
Tox	oxide thickness	m	1.5×10^{-8}
Cj	zero-bias bulk junction bottom capacitance	F/m^2	5.0×10^{-4}
Mj	bulk junction bottom grading coefficient		0.5
Cjsw	zero-bias bulk junction sidewall capacitance	F/m	5.0×10^{-10}
Mjsw	bulk junction sidewall grading coefficient		0.33
Pb	bulk junction potential	V	1.0
Pbsw	sidewall junction potential	V	1.0
Xt	doping depth	m	1.55×10^{-7}
Vbm	maximum applied body bias	V	−5.0
Vbx	Vth transition body voltage	V	†

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Xj	metallurgical junction depth	m	1.5×10^{-7}
Dwg	coefficient of Weff's gate dependence (binning parameter; see Note 4)	m/V	0.0
Dwb	coefficient of Weff's body dependence (binning parameter; see Note 4)	$m/V^{(1/2)}$	0.0
Nch	channel doping concentration	$1/cm^3$	1.7×10^{17}
Nsub	substrate doping concentration	$1/cm^3$	6.0×10^{16}
Ngate	poly-gate doping concentration	$1/cm^3$	†
Gamma1	body effect coefficient near interface	$V^{(1/2)}$	†
Gamma2	body effect coefficient in the bulk	$V^{(1/2)}$	†
Alpha0	1st parameter of impact ionization current (binning parameter; see Note 4)	m/V	0.0
Beta0	2nd parameter of impact ionization current (binning parameter; see Note 4)	V	30.0
Vth0	zero-bias threshold voltage (binning parameter; see Note 4)	V	†
K1	first order body effect coefficient (binning parameter; see Note 4)	$V^{(1/2)}$	†
K2	second order body effect coefficient (binning parameter; see Note 4)		†
K3	narrow width effect coefficient (binning parameter; see Note 4)		80.0
K3b	body effect coefficient of K3 (binning parameter; see Note 4)	1/V	0.0
W0	narrow width effect W offset (binning parameter; see Note 4)	m	2.5×10^{-6}
Nlx	lateral non-uniform doping effect (binning parameter; see Note 4)	m	1.74×10^{-7}
Dvt0	short channel effect coefficient 0 (binning parameter; see Note 4)		2.2

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Dvt1	short channel effect coefficient 1 (binning parameter; see Note 4)		0.53
Dvt2	short channel effect coefficient 2 (binning parameter; see Note 4)	1/V	−0.032
Dvt0w	narrow width effect coefficient 0 (binning parameter; see Note 4)	1/m	0.0
Dvt1w	narrow width effect coefficient 1 (binning parameter; see Note 4)	1/m	5.3×10^{6}
Dvt2w	narrow width effect coefficient 2 (binning parameter; see Note 4)	1/V	−0.032
Cgso	gate-source overlap capacitance, per channel width	F/m	†
Cgdo	gate-drain overlap capacitance, per channel width	F/m	†
Cgbo	gate-bulk overlap capacitance, per channel length	F/m	0.0
Xpart	flag for channel charge partition		0.0
Drout	DIBL effect on Rout coefficient binning parameter; see Note 4)		0.56
Dsub	DIBL effect coefficient in subthreshold region binning parameter; see Note 4)		(fixed by Drout)
Ua	linear Vgs dependence of mobility (binning parameter; see Note 4)	m/V	2.25×10^{-9}
Ua1	temperature coefficient of Ua	m/V	4.31×10^{-9}
Ub	quadratic Vgs dependence of mobility (binning parameter; see Note 4)	$(m/V)^2$	5.87×10^{-19}
Ub1	temperature coefficient of Ub	$(m/V)^2$	-7.61×10^{-18}
Uc	body-bias dependence of mobility (binning parameter; see Note 4)	m/V^2 1/V	-4.65×10^{-11} Mobmod=1 ,2−0.0465 Mobmod=3
Uc1	temperature coefficient of Uc	m/V^2 1/V	-5.6×10^{-11} Mobmod=1,2 −0.056 Mobmod=3

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	**Description**	**Units**	**Default**
U0	low-field mobility at T=Tnom (binning parameter; see Note 4)	$cm^{2/Vs}$	670.0 NMOS 250.0 PMOS
Ute	temperature coefficient of mobility		−1.5
Rdsw	source drain resistance per width (binning parameter; see Note 4)	ohms × μm^{Wr}	0.0
Prwg	gate bias effect coefficient of Rdsw (binning parameter; see Note 4)	1/V	0.0
Prwb	body effect coefficient of Rdsw (binning parameter; see Note 4)	1/V	0.0
Wr	width dependence of Rds (binning parameter; see Note 4)		1.0
Prt	temperature coefficient of Rdsw	ohms × µm	0.0
Vsat	saturation velocity at T=Tnom (binning parameter; see Note 4)	m/s	8.0×10^4
At	temperature coefficient of Vsat	m/s	3.3×10^4
A0	bulk charge effect coefficient for channel length (binning parameter; see Note 4)		1.0
Keta	body-bias coefficient of bulk charge (binning parameter; see Note 4)	1/V	−0.047
Ags	gate bias coefficient of Abulk (binning parameter; see Note 4)	1/V	0.0
A1	first non-saturation factor for PMOS (binning parameter; see Note 4)	1/V	0.0
A2	second non-saturation factor for PMOS (binning parameter; see Note 4)		1.0
B0	bulk charge effect coefficient for channel width (binning parameter; see Note 4)	m	0.0
B1	bulk charge effect width offset (binning parameter; see Note 4)	m	0.0
Voff	threshold voltage offset (binning parameter; see Note 4)	V	-0.08

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Nfactor	subthreshold swing factor (binning parameter; see Note 4)		1.0
Cdsc	D/S and channel coupling capacitance (binning parameter; see Note 4)	F/m^2	2.4×10^{-4}
Cdscb	body-bias dependence of Cdsc (binning parameter; see Note 4)	F/V/m^2	0.0
Cdscd	drain-bias dependence of Cdsc (binning parameter; see Note 4)	F/V/m^2	0.0
Cit	interface state capacitance (binning parameter; see Note 4)	F/m^2	0.0
Eta0	subthreshold region DIBL coefficient (binning parameter; see Note 4)		0.08
Etab	body-bias coefficient for DIBL effect (binning parameter; see Note 4)	1/V	−0.07
Pclm	channel-length modulation coefficient (binning parameter; see Note 4)		1.3
Pdiblc1	first Rout DIBL effect coefficient		0.39
Pdiblc2	second Rout DIBL effect coefficient		0.0086
Pdiblcb	body effect coefficient of DIBL correction parameters	1/V	0
Pscbe1	first substrate current body effect	V/m	4.24×10^{8}
Pscbe2	second substrate current body effect	m/V	10^{-5}
Pvag	Vg dependence of Rout coefficient (binning parameter; see Note 4)		0.0
Delta	effective Vds parameter (binning parameter; see Note 4)	V	0.01
Kt1	temperature coefficient of Vth	V	−0.11
Kt1l	channel length sensitivity of Kt1	V×m	0.0
Kt2	body bias coefficient of Kt1		0.022

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Cgsl	light doped source-gate region overlap capacitance	F/m	0.0
Cgdl	light doped drain-gate region overlap capacitance	F/m	0.0
Ckappa	coefficient for lightly doped region overlap capacitance	F/m	0.6
Cf	fringing field capacitance	F/m	
Clc	constant term for short channel model	m	0.1×10^{-6}
Cle	exponential term for short channel		0.6
Dlc	length offset fitting parameter from C-V	m	Lint
Dwc	width offset fitting parameter from C-V	m	Wint
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1
Kf	flicker (1/f) noise coefficient		0.0
Af	flicker (1/f) noise exponent		1.0
Ef	flicker (1/f) noise frequency exponent		1.0
Em	flicker (1/f) noise parameter	V/m	4.1×10^{7}
Noia	noise parameter A		1.0×10^{20} NMOS 9.9×10^{18} PMOS
Noib	noise parameter B		5.0×10^{4} NMOS 2.4×10^{3} PMOS
Noic	noise parameter C		-1.4×10^{-12} NMOS 1.4×10^{12} PMOS
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
wIdsmax	maximum drain-source current (warning)	A	infinite
Toxm	gate oxide thickness tox value at which parameters are extracted	m	
Vfb	DC flat-band voltage	V	†
Noff	CV parameter in VgsteffCV for weak-to-strong inversion region		1.0
Voffcv	CV parameter in VgsteffCV for weak-to-strong inversion region		1.0
Ijth	diode limiting current	A	†
Alpha1	substrate current parameter	1/V	0.0
Acde	exponential coefficient for charge thickness in the accumulation and depletion regions (binning parameter; see Note 4)	m/V	1.0
Moin	coefficient for the gate-bias dependent surface potential (binning parameter; see Note 4)	$V^{(1/2)}$	15.0
Tpb	temperature coefficient of pb	V/K	0.0
Tpbsw	temperature coefficient of pbsw	V/K	0.0
Tpbswg	temperature coefficient of pbswg	V/K	0.0
Tcj	temperature coefficient of cj	1/K	0.0
Tcjsw	temperature coefficient of cjsw	1/K	0.0
Tcjswg	temperature coefficient of cjswg	1/K	0.0
Llc	coefficient of length dependence for CV channel length offset	m^{Lln}	DC Ll
Lwc	coefficient of width dependence for CV channel length offset	m^{Lwn}	DC Lw
Lwlc	coefficient of length and width cross-term for CV channel length offset	$m^{Lwn + LLn}$	DC Lwl
Wlc	coefficient of length dependence for CV channel width offset	m^{Wln}	DC Wl

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Wwc	coefficient of width dependence for CV channel width offset	m^{Wwn}	DC Ww
Wwlc	coefficient of length and width cross-term for CV channel width offset	$m^{Wln + Wwn}$	DC Wwl
wPmax	maximum power dissipation (warning)	W	infinite
Acm	area calculation method		10
Calcacm	flag to use Acm when Acm=12		-1
Hdif	length of heavily doped diffusion (ACM=2,3 only)	m	0
Ldif	length of lightly doped diffusion adjacent to gate (ACM=1,2)	m	0
Wmlt	width diffusion layer shrink reduction factor		1
Xw	accounts for masking and etching effects	m	0
Xl	accounts for masking and etching effects	m	0
Rdc	additional drain resistance due to contact resistance	Ohms	0
Rsc	additional source resistance due to contact resistance	Ohms	0
Vfbcv	flat-band voltage parameter for capmod=0 only	F/m	-1.0
B3qmod	BSIM3 charge model (0 for Berkeley, 1 for Hspice Capmod = 0)	...	0
Cjswg	S/D (gate side) sidewall junction capacitance	F/m	Cjsw
Pbswg	S/D (gate side) sidewall junction built in potential	V	Mjsw

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Mjswg	S/D (gate side) sidewall junction grading coefficient		Pbsw
Is	bulk junction saturation current	A	1e-14
Nqsmod	non-quasi-static model selector	···	0
Elm	non-quasi-static Elmore constant parameter	···	5.0
Rd	drain resistance	Ohms	0
Rs	source resistance	Ohms	0
Flkmod	flicker noise model selector	···	0
Tlev	temperature equation selector (0/1/2/3)	...	0
Tlevc	temperature equation selector for capacitance (0/1/2/3)	...	0
Eg	band gap	eV	1.16
Gap1	energy gap temperature coefficient alpha	V/°C	7.02e-4
Gap2	energy gap temperature coefficient beta	K	1108
Cta	Cj linear temperature coefficient	1/°C	0
Ctp	Cjsw linear temperature coefficient	1/°C	0
Pta	Vj linear temperature coefficnet	1/°C	0
Ptp	Vjsw linear temperature coefficient	1/°C	0
Trd	Rd linear temperature coefficient	1/°C	0
Trs	Rs linear temperature coefficient	1/°C	0
Wmin	binning minimum width (not used for binning; use BinModel)	m	0
Wmax	binning maximum width (not used for binning; use BinModel)	m	1
Lmin	binning minimum length (not used for binning; use BinModel)	m	0

† Calculated parameter

Table 5-4. BSIM3_Model Parameters (continued)

Parameter	Description	Units	Default
Lmax	binning maximum length (not used for binning; use BinModel)	m	1
AllParams	DataAccessComponent-based parameters		

† Calculated parameter

Notes/Equations/References

1. Nqsmod is also supported as an instance parameter. For simulation, only the Nqsmod instance parameter is used; the Nqsmod model parameter is not used. This is the way Berkeley defined Nqsmod in BSIM3v3.2. Hspice supports Nqsmod only as a model parameter.
2. This model supplies values for a MOSFET device. The default Version is 3.22. The previous version can be used by setting the Version parameter to 3.0, 3.1, 3.2, or 3.21.
3. BSIM1, BSIM2, and BSIM3 MOSFET models use the same parameters and parameter definitions as the BSIM models in SPICE3 (University of California-Berkeley).
4. Several DC, AC, and capacitance parameters can be binned. They are identified in the Description column of Table 5-4. All of these parameters follow this implementation:

   $$P = P_0 + \frac{P_L}{L_{eff}} + \frac{P_w}{W_{eff}} + \frac{P_p}{L_{eff} \times W_{eff}} \tag{5-1}$$

   For example, for the parameter k1, the following relationships exist: P_0 = k1, P_L = lkl, P_W = wkl, P_P=pkl. The Binunit parameter is a binning unit selector. If Binunit = 1, the units of L_{eff} and $W_{eff,}$ used in the preceding binning equation have the units of microns, otherwise in meters. For example, for a device with L_{eff} = 0.5υm and W_{eff} = 10υm, if Binunit = 1, the parameter values for vsat are le5, le4, 2e4, and 3e4 for vsat, lvsat, wvsat, and pvsat, respectively, Therefore, the effective value of vsat for this device is:

   vsat = 1e5 + 1e4/0.5 + 2e4/10 + 3e4/(0.5*10) = 1.28e5

   To get the same effective value of vsat for Binunit = 0, the values of vsat, lvsat, wvsat, and pvsat would be 1e5, le–2, 2e–2, 3e–8, respectively. Thus:

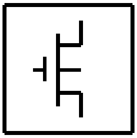
   vsat = 1e5 + 1e-2/0.5e6 + 2e–2/10e–6 + 3e –8/(0.5e-6 * 10e–6) = 1.28e5
5. The nonquasi-static (NQS) charge model is supported in versions 3.2 and later.

6. Model parameter U0 can be entered in meters or centimeters. U0 is converted to m^2/V sec as follows: if U0 > 1, it is multiplied by 10^{-4}.
7. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
8. DC operating point data is generated for this model. If a DC simulation is performed, device operating point data can be viewed for a component. The procedure for doing this is described in the *Circuit Simulation* manual. The device operating point information that is displayed for the BSIM3 model is:

Gmb	Small-signal Vbs to Ids transconductance, in Siemens
Gds	Small-signal drain source conductance, in Siemens
Vdsat	Saturation voltage, in Volts
Capbd	Small-signal bulk drain capacitance, in Farads
Capbs	Small-signal bulk source capacitance, in Farads
CgdM	Small-signal gate drain Meyer capacitance, in Farads
CgbM	Small-signal gate bulk Meyer capacitance, in Farads
CgsM	Small-signal gate source Meyer capacitance, in Farads
DqgDvgb	Small-signal transcapacitance dQg/dVg, in Farads
DqgDvdb	Small-signal transcapacitance dQg/dVd, in Farads
DqgDvsb	Small-signal transcapacitance dQg/dVs, in Farads
DqbDvgb	Small-signal transcapacitance dQb/dVg, in Farads
DqbDvdb	Small-signal transcapacitance dQb/dVd, in Farads
DqbDvsb	Small-signal transcapacitance dQb/dVs, in Farads
DqdDvgb	Small-signal transcapacitance dQd/dVg, in Farads
DqdDvdb	Small-signal transcapacitance dQd/dVd, in Farads
DqdDvsb	Small-signal transcapacitance dQd/dVs, in Farads

BSIM3SOI_Model (BSIM3 Silicon On Insulator MOSFET Model)

Symbol



Parameters

Model parameters must be specified in SI units. In some cases, parameters that are simply geometric variations of a listed parameter, such as L, W, or P, are not listed in this table.

Table 5-5. BSIM3SOI Parameters

Parameter	Description	Units	Default
NMOS	N-channel type model		yes
PMOS	P-channel type model		no
Capmod	short-channel capacitance model selector		2
Mobmod	mobility model selector		1
Noimod	noise model selector		1
Shmod	self-heating mode selector; 0 = no self-heating, 1 = self-heating		0
Ddmod	dynamic depletion mode selector		0
Igmod	gate current model selector		0
Paramchk	model parameter checking selector		0
Binunit	Bin unit selector		1
Version	model version		2.0
Tox	gate oxide thickness	m	1.0e-8)
Cdsc	drain, source, and channel coupling capacitance	F/m^2	2.4e-4
Cdsccb	body effect coefficient of Cdsc	F/(V*m^2)	0/0
Cdscd	drain bias dependence of Cdsc	F/(V*m^2	0.0
Cit	capacitance due to interface change	F/(V*m^2	1.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Nfactor	subthreshold swing factor (binning parameter; see Note 3)		0.0
Vsat	saturation velocity at temp, m/s (binning parameter; see Note 3)	m/s	8.0e4
At	temperature coefficient for saturation velocity (binning parameter; see Note 3)	m/s	3.3e4
A0	bulk change effect coefficient (binning parameter; see Note 3)		1.0
Ags	gate bulk coefficient of Abulk (binning parameter; see Note 3)	V^-1	0.0
A1	first saturation factor (binning parameter; see Note 3)	V^-1	0.0
A2	second non-saturation factor (binning parameter; see Note 3)		1.0
Keta	body-bias coefficient of the bulk charge effect (binning parameter; see Note 3)	V^-1	-0.6
Nsub	substrate doping concentration with polarity	cm	6.0e16
Nch	Channel doping concentration	cm^-3	17e17
Ngate	poly-gate doping concentration	cm^-3	0
Gamma1	body-effect coefficient near the interface	V^(1/2)	†
Gamma2	body-effect coefficient in the bulk	V^(1/2)	†
Vbx	Vth transition body voltage	V	†
Vbm	maximum body voltage	V	-3.0
Xt	doping depth	m	1.55e-7
K1	body-effect coefficient (binning parameter; see Note 3)	V^(1/2)	0.5
Kt1	temperature coefficient for threshold voltage,	V	-0.11
Kt11	channel length sensitivity of ktl	V+m	0.0
† Calculated parameter			

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Kt2	body-bias coefficient		0.022
K2	bulk effect coefficient 2 (binning parameter; see Note 3)		**0.0**
K3	narrow width coefficient (binning parameter; see Note 3)		**0.0**
K3b	body effect coefficient of K3 (binning parameter; see Note 3)	V^-1	0.0
WO	narrow width (binning parameter; see Note 3)		0.0
N1x	lateral non-uniform doping coefficient (binning parameter; see Note 3)	m	1.74e-7
Dvt0	first coefficient of short-channel effect on Vth (binning parameter; see Note 3)		2.2
Dvt1	first coefficient of short-channel effect on Vth (binning parameter; see Note 3)		0.53
Dvt2	body-bias coefficient of short-channel effect on Vth (binning parameter; see Note 3)	V^-1	-0.032
Dvt0w	first coefficient of narrow-width effect on Vth (binning parameter; see Note 3)		0.0
Dvt1w	first coefficient of narrow-width effect on Vth (binning parameter; see Note 3)	m^1	5.3e6
Dvt2w	second coefficient of narrow-width effect on Vth (binning parameter; see Note 3)	m^1	5.3e6
Drout	L depend (binning parameter; see Note 3)		0.56
Dsub	BL coefficient in sub-threshold region (binning parameter; see Note 3)		Drout
Vth0	zero-bias threshold voltage (binning parameter; see Note 3)		0.7 (NMOS), -0.7 (PMOS)
Ua	first-order mobility degradation coefficient (binning parameter; see Note 3)	m/V	2.25e-9

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Ua1	temperature coefficient of Ua	m/V	4.31e-9
Ub	second-order mobility degradation coefficient (binning parameter; see Note 3)	$(m/V)^2$	5.87e-19
Ub1	temperature coefficient of Ub	$(m/V)^2$	−7.61e-18
Uc	body-bias mobility degradation coefficient (binning parameter; see Note 3)	V^-1	**−0.0465**
Uc1	temperature coefficient of Uc	V^-1	-0.056
U0	low-field mobility at T=Tnom (binning parameter; see Note 3)	m^2/(V*s)	0.067 NMOS 0.025 PMOS
Ute	temperature coefficient of mobility		−1.5
Voff	Offset voltage in sub-threshold region (binning parameter; see Note 3)	V	0.08
Tnom	measurement temperature	C	25
Cgdo	G-D overlap capacitance per meter channel width	F/m	†
Xpart	coefficient of channel charge share		0.0
Delta	effective Vds (binning parameter; see Note 3)	V	0.01
Rsh	drain and source diffusion sheet resistance	Ohm/Sq	0.0
Rdsw	parasitic resistance per unit width (binning parameter; see Note 3)	Ohms*um^Wr	0.0
Prwg	gate bias effect on parasitic resistance (binning parameter; see Note 3)	V^-‘	0.0
Prwb	body effect on parasitic resistance (binning parameter; see Note 3)	V^-(1/2)	−0.047
Prt	temperature coefficient of parasitic resistance	Ohms*um	0.0
Eta0	sub-threshold region DIBL coefficient		0.08
Etab	second non-saturation factor for PMOS	V^-1	-0.07

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Pclm	channel-length modulation effect coefficient		1.3
Pdiblc1	drain induced barrier lowering effect coefficient 1		0.39
Pdiblc2	drain induced barrier lowering effect coefficient 1	V	-0.086
Pdiblc2b	body effect on drain induced barrier lowering	V^-1	0.0
Pvag	gate voltage dependence of Rout coefficient (binning parameter; see Note 3)		0.0
Tbox	back gate oxide thickness	m	3.0e-7
Tsi	silicon-on-insulator thickness	m	1.0e-7
Xj	metallurgical junction depth	m	Tsi
Rth0	self-heating thermal resistance	Ohms	0.0
Ctho	self-heating thermal capacitance	F	**0.0**
Ngidi	GIDL first parameter	V	1.2
Agidi	GIDL second parameter	Ohm^-1	0.0
Bgidi	GIDL third parameter	V/m	0.0
Ndiode	diode non-ideality factor (binning parameter; see Note 3)		1.0
Xbjt	temperature coefficient for Isbjt		1.0
Xdif	temperature coefficient for Isdif		1.0
Xrec	temperature coefficient for Isrec		1.0
Xtun	temperature coefficient for Istun		0.0
Pbswg	S/D (gate side) sidewall junction built-in potential	V	0.07
Mjswg	S/D (gate side) sidewall junction grading coefficient		0.5
Cjswg	S/D (gate side) sidewall junction capacitance	m	1.0e–10

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Lint	length reduction parameter (binning parameter; see Note 3)	m	0.0
L1	coefficient of length dependence for length offset	m	0.0
Lln	power of length dependence of length offset	m	1.0
Lw	coefficient of width dependence for length offset	m	0.0
Lwn	power of width dependence for length offset	m	1.0
Lwl	coefficient of lenth and width cross term length offset	m	0.0
Wr	width dependence of Rds (binning parameter; see Note 3)		1.0
Wint	width reduction parameter (binning parameter; see Note 3)	m	0.0
Dwg	coefficient of Weff's gate dependence (binning parameter; see Note 3)	m/V	0.0
Dwb	coefficient of Weff's substrate body bias dependence (binning parameter; see Note 3)	m/V^(-1/2)	0.0
W1	coefficient of length dependence for width offset	m	0.0
Win	power of length dependence for width offset		1.0
Ww	coefficient of width dependence for width offset	m	0.0
Wwn	power of width dependence for width offset		1.0
Wwl	coefficient of length and width cross term width of offset	m	0.0
BO	bulk charge coefficient for channel width (binning parameter; see Note 3)	m	0.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
B1	bulk charge effect width offset (binning parameter; see Note 3)	m	0.0
Cgsl	light doped source-gate region overlap capacitance	F/m	0.0
Ckappa	coefficient for light doped source-gate region overlap capacitance	F/m	0.0
Cf	fringing field capacitance	F/m	†
Clc	constant term for the short channel model	m	0.1e-7
Cle	exponential term for the short channel model		0.0
Dwc	width offset fitting parameter from C-V	m	Wint
Dlc	length offset fitting parameter from C-V	m	Lint
Alpha0	first parameter of impact ionization current (binning parameter; see Note 3)	m/V	0.0
Noia	noise parameter A		1.0e20 (NMOS), 9.9e18 (PMOS)
Noib	noise parameter B		5.0e4(NMOS), 2.4e3 (PMOS)
Noic	noise parameter C		-1,4e-12 (NMOS), -1,4e-12 (PMOS)
Em	flicker (l/f) noise parameter	V/m	4.1e-7
Ef	flicker (l/f) noise frequency exponent	V	1.0
Af	flicker (l/f) noise exponent		1.0
Kf	flicker (l/f) noise coefficient		0.0
Noif	floating body noise ideality factor		1.0
K1w1	first body effect with dependent parameter (binning parameter; see Note 3)	m	0.0
K1w2	second body effect with dependent parameter (binning parameter; see Note 3)	m	0.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	**Description**	**Units**	**Default**
Ketas	surface potential adjustment for bulk charge effect (binning parameter; see Note 3)	V	0.0
Dwbc	width offset for body contact isolation edge	m	0.0
Beta0	first Vds parameter of impact isolation current (binning parameter; see Note 3)	V^-1	0.0
Beta1	second Vds parameter of impact isolation current (binning parameter; see Note 3)		0.0
Beta2	third Vds parameter of impact isolation current (binning parameter; see Note 3)	V	0.0
VdsatiiO	nominal drain saturation voltage at threshold for impact ionization current	V	0.9
Tii	temperature dependent parameter for impact ionization (binning parameter; see Note 3)		0.0
Lii	channel length dependent parameter threshold for impact ionization (binning parameter; see Note 3)		0.0
Sii0	first Vgs dependent parameter for impact ionization current (binning parameter; see Note 3)	V^-1	0.5
Sii1	second Vgs dependent parameter for impact ionization current (binning parameter; see Note 3)	V^-1	0.1
Sii2	third Vgs dependent parameter for impact ionization current (binning parameter; see Note 3)	V^-1	0.1
Siid	Vgs dependent parameter for impact ionization current (binning parameter; see Note 3)	V^-1	0.1
Fbjtii	fraction of bipolar current affecting the impact ionization		0.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Esatii	saturation electric field for impact ionization (binning parameter; see Note 3)	V /m	1.0e7
Ntun	reverse tunneling new-ideality factor (binning parameter; see Note 3)		10.0
Nrecf0	recombination non-ideality factor at forward bias (binning parameter; see Note 3)		2.0
Nrecro	recombination non-ideality factor at reversed bias (binning parameter; see Note 3)		10.0
lsbjt	BJT injection saturation current (binning parameter; see Note 3)	A/m^2	1.0e-6
lsdif	Body to source/drain injection saturation current (binning parameter; see Note 3)	A/m^2	0.0
lsrec	recombination in depletion saturation current (binning parameter; see Note 3)	A/m^2	1.0e-6
lstun	reverse tunneling saturation current (binning parameter; see Note 3)	A/m^2	0.0
Ln	electron/hole diffusion length	m	2.0e-6
Vrec0	voltage dependent parameter for recombination current (binning parameter; see Note 3)	V	0.0
Vtun0	voltage dependent parameter for tunneling current (binning parameter; see Note 3)	V	0.0
Nbjt	power coefficient of channel length dependency for bipolar current (binning parameter; see Note 3)		1.0
Lbjt0	channel length for bipolar current (binning parameter; see Note 3)	m	0.2e-6
Ldif0	channel length dependency coefficient of diffusion cap		1.0
Vabjt	early voltage for bipolar current (binning parameter; see Note 3)	V	10.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Aely	channel length dependency of early voltage for bipolar current (binning parameter; see Note 3)	V/m	10.0
Ahli	high level injection parameter for bipolar current (binning parameter; see Note 3)		0.0
Rbody	intrinsic body sheet resistance	Ohm/m^2	0.0
Rbsh	extrinsic body sheet resistance	Ohm/m^2	0.0
Cgeo	capacitance per unit channel length	F/m	0/0
Tt	diffusion capacitance transit time coefficient	s	1.0e-12
Ndif	power coefficient of channel length dependency for diffusion capacitance		-1.0
Vsdfb	capacitance flatband voltage (binning parameter; see Note 3)	V	†
Vsdth	capacitance threshold voltage (binning parameter; see Note 3)	V	†
Csdmin	source/drain bottom diffusion minimum capacitance	F	†
Asd	source/drain bottom diffusion smoothing parameter		0.3
Cdesw	source/drain sidewall fringing capacitance per unit channel length	F/m	0/0
Ntrecf	temperature coefficient for Ncref		0.0
Ntrecr	temperature coefficient for Ncrer		0.0
Dlcb	length offset fitting parameter for body charge	m	Lint
Fbody	scaling factor for body charge		1.0
Tcjswg	temperature coefficient of Cjswg	K^-1	0.0
Tpbswg	temperature coefficient of Pbswg	V/K	0.0
Acde	exponential coefficient for finite charge thickness (binning parameter; see Note 3)	m/V	1.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Moin	coefficient for gate-bias dependent surface potential (binning parameter; see Note 3)	V^(1/2)	15.0
Delvt	threshold voltage adjust for CV, V (binning parameter; see Note 3)		0.0
Kb1	coefficient of Vbs0 dependency on Ves (binning parameter; see Note 3)		1.0
Dlbg	length offset fitting parameter for backgate charge	m	0.0
Toxqm	effective oxide thickness considering quantum effect	m	Tox
Wth0	minimum width for thermal resistance calculation	m	0.0
Rhalo	Body halo sheet resistance	Ohms	1.0e15
Ntox	power term of gate current		1.0
Toxref	target oxide thickness	m	2.5e-9
Ebg	effective bandgap in gate current calculation	V	1.2
Nevb	valence-band electron non-ideality factor	V	3.0
Alphagb1	first Vox dependent parameter for gate current in inversion		0.35
Betagb2	second Vox dependent parameter for gate current in inversion		0.03
Vgb1	third Vox dependent parameter for gate current in inversion		300.0
Necb	condition-band electron non-ideality factor		1.0
Alphagb2	first Vox dependent parameter for gate current in accumulation		0.43
Betagb2	second Vox dependent parameter for gate current in accumulation		0.05
Vgb2	third Vox dependent parameter for gate current in accumulation		17.0

† Calculated parameter

Table 5-5. BSIM3SOI Parameters (continued)

Parameter	Description	Units	Default
Voxh	limit of Vox in gate current calculation	V	5.0
Deltavox	Smoothing parameter in the Vox smoothing function	V	0.005
Gmin	minimum conductance added in parallel to the P-N junction	Siemens	1.0e-20
† Calculated parameter			

Notes

1. In the current ADS program version, this model is named BISIM3SOI, which is equivalent to the Berkeley model named BSIMSOI, a deep submicron, silicon-on-insulator MOSFET device model for SPICE engines. It was developed by the BSIM Group under the direction of Professor Chenming Hu in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. BSIMSOI is closely related to the industry standard bulk MOSFET model, BSIM.
2. BSIMPD2.2, used for this ADS release, is the new version of the Partial Depletion SOI MOSFET model, BSIMPD SOI. The gate-body tunneling (substrate current) is added in this release to enhance the model accuracy. BSIMPD2.2 information can be found on the BSIMSOI website (*http://www-device.eecs.berkeley.edu/~bsimsoi*).
3. Several DC, AC, and capacitance parameters can be binned. They are identified in the Description column of Table 5-5. All of these parameters follow this implementation:

   $$P = P_0 + \frac{P_L}{L_{eff}} + \frac{P_w}{W_{eff}} + \frac{P_p}{L_{eff} \times W_{eff}} \tag{5-2}$$

   For example, for the parameter k1, the following relationships exist: P_0 = k1, P_L = lkl, P_W = wkl, P_P=pkl. The Binunit parameter is a binning unit selector. If Binunit = 1, the units of L_{eff} and $W_{eff,}$ used in the preceding binning equation have the units of microns, otherwise in meters. For example, for a device with L_{eff} = 0.5υm and W_{eff} = 10υm, if Binunit = 1, the parameter values for vsat are le5, le4, 2e4, and 3e4 for vsat, lvsat, wvsat, and pvsat, respectively, Therefore, the effective value of vsat for this device is:

   vsat = 1e5 + 1e4/0.5 + 2e4/10 + 3e4/(0.5*10) = 1.28e5

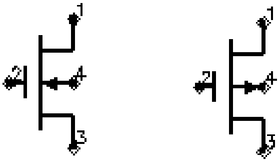
   To get the same effective value of vsat for Binunit = 0, the values of vsat, lvsat, wvsat, and pvsat would be 1e5, le–2, 2e–2, 3e–8, respectively. Thus:

$$vsat = 1e5 + 1e-2/0.5e6 + 2e-2/10e-6 + 3e-8/(0.5e-6 * 10e-6) = 1.28e5$$

BSIM3 Silicon On Insulator Transistor, Floating Body (NMOS and PMOS)

BSIM3SOI_NMOS (BSIM3 SOI Transistor (Floating Body), NMOS
BSIM3SOI_PMOS (BSIM3 SOI Transistor (Floating Body), PMOS,)

Symbol



Parameters

Model parameters must be specified in SI units

Model =model instance name

Length =channel length in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Width = channel width in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Ad = area of drain diffusion, in m^2 (default: 0.0)

As =area of source diffusion, in m^2 (default: 0.0)

Pd = perimeter of the drain junction, in m (default: 0.0)

Ps =perimeter of the drain junction, in m (default: 0.0)

Nrd = number of squares of the drain diffusion (default: 1.0)

Nrs =number of squares of the source diffusion (default: 1.0)

Nrb = number of squares in body (default:1.0)

Bjtoff = BJT on/off flag (yes = 1, no = 0; default: no)

Rth0 = instance thermal resistance in Ohms (default: model Rth0)

Cth0 =instance thermal resistance in F (default: model Cth0)

Nbc = number of body contact insulation edge (default: 0.0)

Nseg = number segments for width partitioning (default: 1.0)

Pdbcp =perimter length for bc parasitics at drain side (default: 0.0)

Psbcp =perimter length for bc parasitics at source side (default: 0.0)

Agbcp = gate to body overlap area for bc parasitics, in m^2 (default: 0.0)

Aebcp =substrate to body overlap area for bc parasitics, in m^2 (default: 0.0)

Vbsusr = Vbs specified by the user, in V (default: Vbs)

Temp = device operating temperature, Celsius (default: 25.0)

Mode = simulation mode for this device (default: nonlinear)

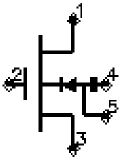
Noise =noise generation option (yes = 1, no = 0; default: yes)

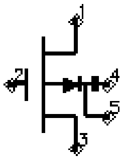
_M = number of devices in parallel (default: 1)

BSIM3 Silicon On Insulator Transistor with 5th Terminal, External Body Contact (NMOS and PMOS)

BSIM3SOI5_NMOS (BSIM3 SOI Transistor with 5th Terminal, NMOS)
BSIM3SOI5_PMOS (BSIM3 SOI Transistor with 5th Terminal, NMOS)

Symbol





Parameters

Model parameters must be specified in SI units

Model =model instance name

Length =channel length in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Width = channel width in um, mm, cm, meter, mil, or in (default: 5.0e-6)

Ad = area of drain diffusion, in m^2 (default: 0.0)

As =area of source diffusion, in t m^2 (default: 0.0)

Pd = perimeter of the drain junction, in m (default: 0.0)

Ps =perimeter of the drain junction, in m (default: 0.0)

Nrd = number of squares of the drain diffusion (default: 1.0)

Nrs =number of squares of the source diffusion (default: 1.0)

Nrb = number of squares in body (default:1.0)

Bjtoff = BJT on/off flag (yes = 1, no = 0; default: no)

Rth0 = instance thermal resistance in Ohms (default: model Rth0)

Cth0 =instance thermal resistance in F (default: model Cth0)

Nbc = number of body contact insulation edge (default: 0.0)

Nseg = number segments for width partitioning (default: 1.0)

Pdbcp =perimter length for bc parasitics at drain side (default: 0.0)

Psbcp =perimter length for bc parasitics at source side (default: 0.0)

Agbcp = gate to body overlap area for bc parasitics, in m^2 (default: 0.0)

Aebcp =substrate to body overlap area for bc parasitics, in m^2 (default: 0.0)

Vbsusr = Vbs specified by the user, in V (default: Vbs)

Temp = device operating temperature, Celsius (default: 25.0)

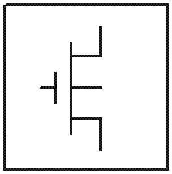
Mode = simulation mode for this device (default: nonlinear)

Noise =noise generation option (yes = 1, no = 0; default: yes)

_M = number of devices in parallel (default: 1)

BSIM4_Model (BSIM4 MOSFET Model)

Symbol



Parameters

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
LEVEL	SPICE3 model selector	14
VERSION	model version number	4.0.0
BINUNIT	binning unit selector	1
PARAMCHK	switch for parameter value check	1
MOBMOD	mobility model selector	0
RDSMOD	bias-dependant source/drain resistance model selector	0
IGCMOD	gate-to-channel tunneling current model selector	0
IGBMOD	gate-to-substrate tunneling current model selector	0
CAPMOD	capacitance model selector	2
RGATEMOD	gate resistance model selector	0 (no gate resist.)
RBODYMOD	substrate resistance network model selector	0 (network off)
TRNQSMOD	transient NQS model selector	0
ACNQSMOD	AC small-signal NQS model selector	0
FNOIMOD	flicker noise model selector	1
TNOIMOD	thermal noise model selector	0
DIOMOD	source/drain junction diode IV model selector	1
PERMOD	whether PS/PD (when given) includes the gate-edge perimeter	1 (including the gate-edge perimeter)
GEOMOD	geometry-dependent parasitics model selector - specifying how the end S/D diffusions are connected	0 (isolated)

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
RGEOMOD	source/drain diffusion resistance and contact model selector - specifying the end S/D contact type: point, wide or merged, and how S/D parasitics resistance is computed	0 (no S/D diffusion resistance)
EPSROX	gate dielectric constant relative to vacuum	3.9 (SiO_2)
TOXE	electrical gate equivalent oxide thickness	3.0e-9m
TOXP	physical gate equivalent oxide thickness	TOXE
TOXM	tox at which parameters are extracted	TOXE
DTOX	defined as (TOXE-TOXP)	0.0m
XJ	S/D junction depth	1.5e-7m
GAMMA1	body-effect coefficient near the surface	calculated
GAMMA2	body-effect coefficient in the bulk	calculated
NDEP	channel doping concentration at depletion edge for zero body bias	1.7e17cm^{-3}
NSUB	substrate doping concentration	6.0e16cm^{-3}
NGATE	Poly Si gate doping concentration	0.0cm^{-3}
NSD	source/drain doping concentration: fatal error if not positive	1.0e20cm^{-3}
VBX	V_{bs} at which the depletion region width equals XT	calculated
XT	doping depth	1.55e-7m
RSH	source/drain sheet resistance	0.0ohm/ square
RSHG	gate electrode sheet resistance	0.1ohm/ square
VTH0 or VTHO	long channel threshold voltage at V_{bs}= 0	0.7V(NMOS) -0.7V(PMOS)
VFB	Flat-voltage voltage	-1.0V
PHIN	Non-uniform vertical doping effect on surface potential	0.0V
K1	First-order body bias coefficient	0.5V$^{1/2}$
K2	Second-order body bias coefficient	0.0
K3	Narrow width coefficient	80.0
K3B	Body effect coefficient of K3	0.0V^{-1}
W0	Narrow width parameter	2.5e-6m

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
LPE0	Lateral non-uniform doping parameter at V_{bs} = 0	1.74e-7m
LPEB	Lateral non-uniform doping effect on K1	0.0m
VBM	Maximum applied body bias in VTH0 calculation	-3.0V
DVT0	First coefficient of short-channel effect on V_{th}	2.2
DVT1	Second coefficient of short-channel effect on V_{th}	0.53
DVT2	Body-bias coefficient of short-channel effect on V_{th}	-0.032V^{-1}
DVTP0	First coefficient of drain-induced V_{th} shift due to for long-channel pocket devices	0.0m
DVTP1	First coefficient of drain-induced V_{th} shift due to for long-channel pocket devices	0.0V^{-1}
DVT0W	First coefficient of narrow width effect on V_{th} for small channel length	0.0
DVT1W	Second coefficient of narrow width effect on V_{th} for small channel length	5.3e6m^{-1}
DVT2W	Body-bias coefficient of narrow width effect for small channel length	-0.032V^{-1}
U0	Low-field mobility	0.067 m^2/(Vs) (NMOS); 0.025 m^2/(Vs) PMOS
UA	Coefficient of first-order mobility degradation due to vertical field	1.0e-9m/V for MOBMOD = 0 and 1; 1.0e-15m/V for MOBMOD =2
UB	Coefficient of second-order mobility degradation due to vertical field	1.0e-19m^2/V^2
UC	Coefficient of mobility degradation due to body bias effect	-0.0465V^{-1} for MOBMOD = 1; -0.0465e-9 m/V^2 for MOBMOD = 0 and 2
EU	Exponent for mobility degradation of MOBMOD=2	1.67 (NMOS); 1.0 (PMOS)
VSAT	Saturation velocity	8.0e4m/s

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
A0	Coefficient of channel-length dependence of bulk charge effect	1.0
AGS	Coefficient of V_{gs} dependence of bulk charge effect	$0.0V^{-1}$
B0	Bulk charge effect coefficient for channel width	0.0m
B1	Bulk charge effect width offset	0.0m
KETA	Body-bias coefficient of bulk charge effect	$-0.047V^{-1}$
A1	First non-saturation effect parameter	$0.0V^{-1}$
A2	Second non-saturation factor	1.0
WINT	Channel-width offset parameter	0.0m
LINT	Channel-length offset parameter	0.0m
DWG	Coefficient of gate bias dependenc of W_{eff}	0.0m/V
DWB	Coefficient of body bias dependenc of W_{eff} bias dependence	$0.0m/V^{1/2}$
VOFF	Offset voltage in subthreshold region for large W and L	-0.08V
VOFFL	Channel-length dependence of VOFF	0.0mV
MINV	V_{gsteff} fitting parameter for moderate inversion condition	0.0
NFACTOR	Subthreshold swing factor	1.0
ETA0	DIBL coefficient in subthreshold region	0.08
ETAB	Body-bias coefficient for the subthreshold DIBL effect	$-0.07V^{-1}$
DSUB	DIBL coefficient exponent in subthreshold region	DROUT
CIT	Interface trap capacitance	$0.0F/m^2$
CDSC	coupling cpacitance between source/drain and channel	$2.4e-4F/m^2$
CDSCB	Body-bias sensitivity of Cdsc	$0.0F/(Vm^2)$
CDSCD	Drain-bias sensitivity if CDSC	$0.0F/(Vm^2)$
PCLM	Channel length modulation parameter	1.3
PDIBLC1	Parameter for DIBL effect on Rout	0.39
PDIBLC2	Parameter for DIBL effect on Rout	0.0086
PDIBLCB	Body bias coefficient of DIBL effect on Rout	$0.0V^{-1}$
DROUT	Channel-length dependence of DIBL effect on Rout	0.56

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
PSCBE1	First substrate current induced body-effect parameter	4.24e8V/m
PSCBE2	Second substrate current induced body-effect parameter	1.0e-5m/V
PVAG	Gate-bias dependence of Early voltage	0.0V
DELTA (δ in equation)	Parameter for DC V_{dseff}	0.01V
FPROUT	Effect of pocket implant on Rout degradation	$0.0\mathrm{V/m}^{0.5}$
PDITS	Impact of drain-induced V_{th} shift on Rout	$0.0\mathrm{V}^{-1}$
PDITSL	Channel-length dependence of drain-induced V_{th} shift for Rout	$0.0\mathrm{m}^{-1}$
PDITSD	V_{ds} dependence of drain-induced V_{th} shift for Rout	$0.0\mathrm{V}^{-1}$
RDSW	Zero bias LDD resistance per unit width for RDSMOD = 0	$200.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
RDSWMIN	LDD resistance per unit width at high V_{gs} and zero V_{bs} for RDSMOD = 0	$0.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
RDW	Zero bias lightly-doped drain resistance $R_d(V)$ per unit width for RDSMOD = 1	$100.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
RDWMIN	Lightly-doped drain resistance per unit width at high V_{gs} and zero V_{bs} for RDSMOD = 1	$0.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
RSW	Zero bias lightly-doped source resistance $R_s(V)$ per unit width for RDSMOD = 1	$100.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
RSWMIN	Lightly-doped source resistance per unit width at high V_{gs} and zero V_{bs} for RDSMOD = 1	$0.0\mathrm{ohm}\ (\mu\mathrm{m})^{WR}$
PRWG	Gate-bias dependence of LDD resistance	$1.0\mathrm{V}^{-1}$
PRWB	Body-bias dependence of LDD resistance	$0.0\mathrm{V}^{-0.5}$
WR	Channel-width dependence parameter of LDD resistance	1.0
NRS (instance parameter only)	Number of source diffusion squares	1.0
NRD (instance parameter only)	Number of drain diffusion squares	1.0
ALPHA0	First parameter of impact ionization current	0.0Am/V
ALPHA1	Isub parameter for length scaling	0.0A/V

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
BETA0	The second parameter of impact ionization current	30.0V
AGIDL	Pre-exponential coefficient for GIDL	0.0mho
BGIDL	Exponential coefficient for GIDL	2.3e9V/m
CGIDL	Parameter for body-bias effect on GIDL	$0.5V^3$
EGIDL	Fitting parameter for band bending for GIDL	0.8V
AIGBACC	Parameter for I_{gb} in accumulation	$0.43\ (Fs^2/g)^{0.5}m^{-1}$
BIGBACC	Parameter for I_{gb} in accumulation	$0.054\ (Fs^2/g)^{0.5}\ m^{-1}V^{-1}$
CIGBACC	Parameter for I_{gb} in accumulation	$0.075V^{-1}$
NIGBACC	Parameter for I_{gb} in accumulation	1.0
AIGBINV	Parameter for I_{gb} in inversion	$0.35\ (Fs^2/g)^{0.5}m^{-1}$
BIGBINV	Parameter for I_{gb} in inversion	$0.03\ (Fs^2/g)^{0.5}\ m^{-1}V^{-1}$
CIGBINV	Parameter for I_{gb} in inversion	$0.006V^{-1}$
EIGBINV	Parameter for I_{gb} in inversion	1.1V
NIGBINV	Parameter for I_{gb} in inversion	3.0
AIGC	Parameter for I_{ges} and I_{ged}	0.054 (NMOS) and 0.31 (PMOS) $(Fs^2/g)^{0.5}m^{-1}$
BIGC	Parameter for I_{ges} and I_{ged}	0.054 (NMOS) and 0.24 (PMOS) $(Fs^2/g)^{0.5}m^{-1}V^{-1}$
CIGC	Parameter for I_{ges} and I_{ged}	0.075 (NMOS) and 0.03 (PMOS) V^{-1}
AIGSD	Parameter for I_{gs} and I_{gd}	0.43 (NMOS) and 0.31 (PMOS) $(Fs^2/g)^{0.5}m^{-1}$
BIGSD	Parameter for I_{gs} and I_{gd}	0.054 (NMOS) and 0.24 (PMOS) $(Fs^2/g)^{0.5}m^{-1}V^{-1}$

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
CIGSD	Parameter for I_{gs} and I_{gd}	0.075 (NMOS) and 0.03 (PMOS) V^{-1}
DLCIG	Source/drain overlap length for I_{gs} and I_{gd}	LINT
NIGC	Parameter for I_{ges}, I_{ged}, I_{gs}, and I_{gd}	1.0
POXEDGE	Factor for the gate oxide thickness in source/drain overlap regions	1.0
PIGCD	V_{ds} dependence of I_{gcs} and I_{gcd}	1.0
NTOX	Exponent for the gate oxide ratio	1.0
TOXREF	Nominal gate oxide thickness for gate dielectric tunneling current model only	3.0e-9m
XPART	Charge partition parameter	0.0
CGSO	Non LDD region source-gate overlap capacitance per unit channel width	calculated (F/m)
CGDO	Non LDD region drain-gate overlap capacitance per unit channel width	calculated (F/m)
CGBO	Gate-bulk overlap capacitance per unit channel length	0.0
CGSL	Overlap capacitance between gate and lightly-doped source region	0.0F/m
CGDL	Overlap capacitance between gate and lightly-doped source region	0.0F/m
CKAPPAS	Coefficient of bias-dependent overlap capacitance for the source side	0.6V
CKAPPAD	Coefficient of bias-dependent overlap capacitance for the drain side	CKAPPAS
CF	Fringing field capacitance	calculated (F/m)
CLC	Constant term for the short channel model	1.0e-7m
CLE	Exponential term for the short channel model	0.6
DLC	Channel-length offset parameter for CV model	LINT (m)
DWC	Channel-width offset parameter for CV model	WINT (m)
VBFCV	Flat-band voltage parameter (for CAPMOD = 0 only)	-1.0V
NOFF	CV parameter in $V_{gsteff,CV}$ for weak to strong inversion	1.0

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
VOFFCV	CV parameter in $V_{gsteff,CV}$ for weak to strong inversion	0.0V
ACDE	Exponential coefficient for charge thickness in CAPMOD = 2 for accumulation and depletion regions	1.0m/V
MOIN	Coefficient for the gate-bias dependent surface potential	15.0
XRCRG1	Parameter for distributed channel-resistance effect for both intrinsic-input resistance and charge-deficit NQS models	12.0
XRCRG2	Parameter to account for the excess channel diffusion resistance for both instinsic input resistance and charge-deficit NQS models	1.0
RBPB (also an instance parameter)	Resistance connected between bNodePrime and bNode	50.0ohm
RBPD (also an instance parameter)	Resistance connected between bNodePrime and dbNode	50.0ohm
RBPS (also an instance parameter)	Resistance connected between bNodePrime and sbNode	50.0ohm
RBDB (also an instance parameter)	Resistance connected between dbNode and bNode	50.0ohm
RBSB (also an instance parameter)	Resistance connected between sbNode and bNode	50.0ohm
GBMIN	Conductance in parrallel with each of the five substrate resistances to avoid potential numerical instability due to unreasonably large a substrate resistance	1.0e-12mho
NOIA	Flicker noise parameter A	6.25e41 $(eV)^{-1}s^{1-EF}m^{-3}$ for NMOS; 6.188e40 $(eV)^{-1}s^{1-EF}m^{-3}$ for PMOS
NOIB	Flicker noise parameter B	3.125e26 $(eV)^{-1}s^{1-EF}m^{-1}$ for NMOS; 1.5e25 $(eV)^{-1}s^{1-EF}m^{-1}$ for PMOS
NOIC	Flicker noise parameter C	8.75 $(eV)^{-1}s^{1-EF}m$

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
EM	Saturation field	4.1e7V/m
AF	Flicker noise exponent	1.0
EF	Flicker noise frequency exponent	1.0
KF	Flicker noise coefficient	0.0 $A^{2-EF}s^{1-EF}F$
NTNOI	Noise factor for short-channel devices for TNOIMOD = 0 only	1.0
TNOIA	Coefficient for channel-length dependence of total channel thermal noise	1.5
TNOIB	Channel-length dependence parameter for channel thermal noise partitioning	3.5
DMCG	Distance from S/D contact center to the gate edge	0.0m
DMCI	Distance from S/D contact center to the isolation edge in the channel-length direction	DMCG
DMDG	Same as DMCG but for merged device only	0.0m
DMCGT	DMCG of test structures	0.0m
NF (instance parameter only)	Number of device fingers	1
DWJ	Offset of the S/D junction width	DWC (in CV model)
MIN (instance parameter only)	Whether to minimize the number of drain or source diffusions for even-number fingered device	0 (minimize the drain diffusion number)
XGW	Distance from the gate contact to the channel edge	0.0m
XGL	Offset of the gate length due to variations in patterning	0.0m
XL	Channel length offset due to mask/etch effect	0.0m
XW	Channel width offset due to mask/etch effect	0.0m
NGCON	Number of gate contacts	1
IJTHSREV IJTHDREV	Limiting current in reverse bias region	IJTHSREV = 0.1A IJTHDREV = IJTHSREV
IJTHSFWD IJTHDFWD	Limiting current in forward bias region	IJTHSFWD = 0.1A IJTHDFWD = IJTHSFWD

Table 5-6. BSIM4_Model Parameters

Parameter	**Description**	**Default**
XJBVS XJBVD	Fitting parameter for diode break-down	XJBVS = 1.0 XJBVD = XJBVS
BVS BVD	Breakdown voltage	BVS = 10.0V BVD = BVS
JSS JSD	Bottom junction reverse saturation current density	JSS = 1.0e-4A/m^2 JSD = JSS
JSWS JSWD	Isolation-edge sidewall reverse saturation current density	JSWS = 0.0A/m JSWD = JSWS
JSWGS JSWGD	Gate-edge sidewall reverse saturation current density	JSWGS = 0.0A/m JSWGD = JSWGS
CJS CJD	Bottom junction capacitance per unit area at zero bias	CJS = 5.0e-4F/m^2 CJD = CJS
MJS MJD	Bottom junction capacitance grating coefficient	MJS = 0.5 MJD = MJS
MJSWS MJSWD	Isolation-edge sidewall junction capacitance grading coefficient	MJSWS = 0.33 MJSWD = MJSWS
CJSWS CJSWD	Isolation-edge sidewall junction capacitance per unit area	CJSWS = 5.0e-10F/m CJSWD = CJSWS
CJSWGS CJSWGD	Gate-edge sidewall junction capacitance per unit length	CJSWGS = CJSWS CJSWGD = CJSWS
MJSWGS MJSWGD	Gate-edge sidewall junction capacitance grading coefficient	MJSWGS = MJSWS MJSWGD = MJSWS
PB	Bottom junction built-in potential	PBS = 1.0V PBD = PBS
PBSWS PBSWD	Isolation-edge sidewall junction built-in potential	PBSWS = 1.0V PBSWD = PBSWS
PBSWGS PBSWGD	Gate-edge sidewall junction built-in potential	PBSWGS = PBSWS PBSWGD = PBSWS
TNOM	Temperature at which parameters are extracted	27 degrees Celsius
UTE	Mobility temperature exponent	-1.5
KT1	Temperature coefficient for threshold voltage	-0.11V
KTIL	Channel length dependence of the temperature coefficient for threshold voltage	0.0Vm
KT2	Body-bias coefficient of Vth temperature effect	0.022

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
UA1	Temperature coefficient for UA	1.0e-9m/V
UB1	Temperature coefficient for UB	-1.0e-18(m/V)^2
UC1	Temperature coefficient for UC	0.056V^{-1} for MOBMOD = 1; 0.056e-9m/V^2 for MOBMOD = 0 and 2
AT	Temperature coefficient for saturation velocity	3.3e4m/s
PRT	Temperature coefficient for Rdsw	0.0ohm-m
NJS,NJD	Emission coefficients of junction for source and drain junctions, respectively	NJS = 1.0; NJD = NJS
XTIS,XTID	Junction current temperature exponents for source and drain junctions, respectively	XTIS = 3.0; XTID = XTIS
TPB	Temperature coefficient of PB	0.0V/K
TPBSW	Temperature coefficient of PBSW	0.0V/K
TPBSWG	Temperature coefficient of PBSWG	0.0V/K
TCJ	Temperature coefficient of CJ	0.0K^{-1}
TCJSW	Temperature coefficient of CJSW	0.0K^{-1}
TCJSWG	Temperature coefficient of CJSWG	0.0K^{-1}
WL	Coefficient of length dependence for width offset	0.0M^{WLN}
WLN	Power of length dependence of width offset	1.0
WW	Coefficient of width dependence for width offset	0.0M^{WWN}
WWN	Power of width dependence of width offset	1.0
WWL	Coefficient of length and width cross term dependence for width offset	0.0 m$^{WWN+WLN}$
LL	Coefficient of length dependence for length offset	0.0M^{LLN}
LLN	Power of length dependence of length offset	1.0
LW	Coefficient of width dependence for length offset	0.0m^{LWN}
LWN	Power of width dependence of length offset	1.0
LWL	Coefficient of length and width cross term dependence for length offset	0.0 m$^{LWN+LLN}$

Table 5-6. BSIM4_Model Parameters

Parameter	Description	Default
LLC	Coefficient of length dependence for CV channel length offset	LL
LWC	Coefficient of width dependence for CV channel length offset	LW
LWLC	Coefficient of length and width cross term dependence for CV channel length offset	LWL
WLC	Coefficient of length dependence for CV channel width offset	WL
WWC	Coefficient of width dependence for CV channel width offset	WW
WWLC	Coefficient of length and width cross term dependence for CV channel width offset	WWL
LMIN	Minimum channel length	0.0m
LMAX	Maximum channel length	1.0m
WMIN	Minimum channel width	0.0m
WMAX	Maximum channel width	1.0m

Range of Usage

N/A

Notes/Equations/References

1. Several DC, AC, and capacitance parameters can be binned. They are identified in the Description column of Table 5-6. All of these parameters follow this implementation:

$$P = P_0 + \frac{P_L}{L_{eff}} + \frac{P_w}{W_{eff}} + \frac{P_p}{L_{eff} \times W_{eff}} \tag{5-3}$$

For example, for the parameter k1, the following relationships exist: P_0 = k1, P_L = lkl, P_W = wkl, P_P=pkl. The Binunit parameter is a binning unit selector. If Binunit = 1, the units of L_{eff} and W_{eff}, used in the preceding binning equation have the units of microns, otherwise in meters. For example, for a device with L_{eff} = 0.5υm and W_{eff} = 10υm, if Binunit = 1, the parameter values for vsat are le5, le4, 2e4, and 3e4 for vsat, lvsat, wvsat, and pvsat, respectively, Therefore, the effective value of vsat for this device is:

vsat = 1e5 + 1e4/0.5 + 2e4/10 + 3e4/(0.5*10) = 1.28e5

To get the same effective value of vsat for Binunit = 0, the values of vsat, lvsat, wvsat, and pvsat would be 1e5, le–2, 2e–2, 3e–8, respectively. Thus:

vsat = 1e5 + 1e-2/0.5e6 + 2e–2/10e–6 + 3e –8/(0.5e-6 * 10e–6) = 1.28e5

2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
3. DC operating point data is generated for this model. If a DC simulation is performed, device operating point data can be viewed for a component. The procedure for doing this is described in the *Circuit Simulation* manual. The device operating point information that is displayed for the BSIM3 model is:

Gm	Small-signal Vgs to Ids transconductance, in Siemens
Gmb	Small-signal Vbs to Ids transconductance, in Siemens
Gds	Small-signal drain source conductance, in Siemens
Vth	Threshold voltage, in Volts
Vdsat	Saturation voltage, in Volts
DqgDvgb	Small-signal transcapacitance dQg/dVg, in Farads
DqgDvdb	Small-signal transcapacitance dQg/dVd, in Farads
DqgDvsb	Small-signal transcapacitance dQg/dVs, in Farads
DqbDvgb	Small-signal transcapacitance dQb/dVg, in Farads
DqbDvdb	Small-signal transcapacitance dQb/dVd, in Farads
DqbDvsb	Small-signal transcapacitance dQb/dVs, in Farads
DqdDvgb	Small-signal transcapacitance dQd/dVg, in Farads
DqdDvdb	Small-signal transcapacitance dQd/dVd, in Farads
DqdDvsb	Small-signal transcapacitance dQd/dVs, in Farads

4. If γ_1 is not given, it is calculated by $\gamma_1 = \frac{\sqrt{2q\varepsilon_{si}NDEP}}{C_{oxe}}$

   If γ_2 is not given, it is calculated by $\gamma_2 = \frac{\sqrt{2q\varepsilon_{si}NSUB}}{C_{oxe}}$

5. If *NDEP* is not given and γ_1 is given, *NDEP* is calculated from $NDEP = \frac{\gamma_1^2 C_{oxe}{}^2}{2q\varepsilon_{si}}$

   If both γ_1 and *NDEP* are not given, *NDEP* defaults to 1.7e17cm^{-3} and is calculated from *NDEP*

6. If *VBX* is not given, it is calculated by $\frac{qNDEP \times XT^2}{2\varepsilon_{si}} = (\Phi_s - VBX)$

7. If *VTH*0 is not given it is calculated by $VTH0 = VFB + \Phi_s + K1\sqrt{\Phi_s - V_{bs}}$ where *VFB* = -1.0

   If *VTH*0 is given, *VFB* defaults to $VFB = VTH0 - \Phi_s - K1\sqrt{\Phi_s - V_{bs}}$

8. If K_1 and K_2 are not given, they are calculated by

$$K1 = \gamma_2 - 2K2\sqrt{\Phi_s - VBM}$$

$$K2 = \frac{(\gamma_1 - \gamma_2)(\sqrt{\Phi_s - VBX} - \sqrt{\Phi_s})}{2\sqrt{\Phi_s}(\sqrt{\Phi_s - VBM} - \sqrt{\Phi_s}) + VBM}$$

9. If *CGSO* is not given, it is calculated by:

   If (*DLC* is given and > 0.0)

   $CGSO = DLC * C_{\mathrm{oxe}} - CGSL$

   if ($CGSO < 0.0$, $CGSO = 0.0$

   Else

   $CGSO = 0.6 * XJ * C_{\mathrm{oxe}}$

   If *CGDO* is not given, it is calculated by:

   If (*DLC* is given and > 0.0)

   $CGDO = DLC * C_{\mathrm{oxe}} - CGDL$

   if ($CGDO < 0.0$, $CGDO = 0.0$

   Else

   $CGDO = 0.6 * XJ * C_{\mathrm{oxe}}$

   If *CGBO* is not given, it is calculated by:

   $CGBO = 2 * DWC * C_{\mathrm{oxe}}$

10. If CF is not given, it is calculated by $CF = \frac{2 \times EPSROX \times \varepsilon_0}{\pi} \times \log\left(1 + \frac{4.0e-7}{TOXE}\right)$

11. For ***dioMod*** = 0, if XJBVS < 0.0, it is reset to 1.0

    For ***dioMod*** = 2, if XJBVS ≤ 0.0, it is reset to 1.0

    For ***dioMod*** = 0, if XJBVD < 0.0, it is reset to 1.0

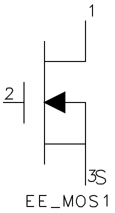
    For ***dioMod*** = 2, if XJBVD ≤ 0.0, it is reset to 1.0

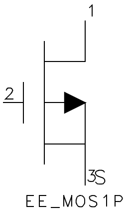
12. BSIM4 was developed by the Device Research Group of the Department of Electrical Engineering and Computer Science, University of California, Berkeley and copyrighted by the University of California.

EE_MOS (EEsof Nonlinear MOSFET)

EE_MOS1 (EEsof Nonlinear MOSFET, N-Channel)
EE_MOS1P (EEsof Nonlinear MOSFET, P-Chanel)

Symbol





Parameters

Model = name of an EE_MOS1_Model

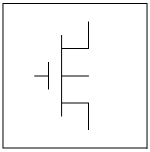
Temp = device operating temperature, in °C (default: 25)

Noise = noise generation (yes= 1; default) (no =0)

_M = number of devices in parallel (default: 1)

EE_MOS1_Model (EEsof Nonlinear MOSFET Model)

Symbol



Parameters

Table 5-7. EE_MOS1_Model Parameters

Name	Description	Unit	Default
Is	reverse saturation current	A	10^{-14}
N	junction ideality factor		1.0
Cdso	zero-bias output capacitance	F	0.0
Vbi	diode built-in potential	V	0.7
Mj	junction grading coefficient		0.5
Fc	depletion capacitance linearization point		10^{-4}
Vbr	drain-source voltage where breakdown current begins conducting	V	10^{-4}
Kbo	breakdown current coefficient		10^{-4}
Nbr	breakdown current exponent		2.0
Vinfl	inflection point in Cgs-Vgs characteristic	V	5.0
Deltds	linear region to saturation region transition	V	1.0
Deltgs	Cgs-Vgs transition voltage	V	1.0
Cgsmax	maximum value of Cgs	F	10^{-12}
Cgso	constant portion of gate-source capacitance	F	10^{-13}
Cgdo	constant portion of gate-drain capacitance	F	10^{-13}
Vgo	gate-source voltage where transconductance is a maximum	V	7.0
Vto	zero bias threshold voltage	V	1.0
Gamma	vds dependent threshold	1/V	0.0
Gmmax	peak transconductance	S	10×10^{-3}

Table 5-7. EE_MOS1_Model Parameters (continued)

Name	**Description**	**Unit**	**Default**
Delt	transconductance tail-off rate	V	2.0
Vbreak	voltage where transconductance tail-off begins	V	4.0
Lambda	output conductance parameter	1/V	0.0
Vsatm	maximum value of saturation voltage	V	10.0
Vgm	gate-source voltage where saturation voltage is Vsatm	V	5.0
Rdb	dispersion source output impedance	ohms	10^9
Cbs	dispersion source capacitance	F	1.6×10^{-13}
Gmmaxac	ac value of Gmmax	S	60×10^{-3}
Deltac	ac value of Delt	V	2.0
Vbreakac	ac value of Vbreak	V	4.0
Vgoac	ac value of Vgo	V	7
Lambdaac	ac value of Lambda	1/V	0.0
Vsatmac	maximum value of saturation voltage (ac)	V	10.0
Vgmac	gate-source voltage where saturation voltage is Vsatm (ac)	V	5.0
Gdbm	additional d-b branch conductance at Vdsm	S	0.0
Kdb	controls Vds dependence of D-B branch conductance		0.0
Vdsm	voltage where D-B branch conductance becomes constant	V	1.0
Rd	drain contact resistance	ohms	1.0
Rs	source contact resistance	ohms	1.0
Rg	gate metallization resistance	ohms	1.0
Ris	source end channel resistance	ohms	1.0
Rid	drain end channel resistance	ohms	1.0
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

Notes/Equations/References

1. This model supplies values for an EE_MOS device.
2. Model parameters such as Ls, Ld, Lg (as well as other package-related parameters that are included as part of the model file output from the EEMOS1 IC-CAP kernel) are not used by EE_MOS in the simulator. Only those parameters listed in Table 5-7 are part of EE_MOS. Any extrinsic devices must be added externally by the user.
3. To prevent numerical problems, the setting of some model parameters to 0 is trapped by the simulator. The parameter values are changed internally:

   Rd = 10^{-4}

   Rs = 10^{-4}

   Rg = 10^{-4}

   Ris = 10^{-4}

   Rid = 10^{-4}

   Vgm = 0.1

   Vgmac = 0.1

   Vsatm = 0.1

   Vsatmac = 0.1

   Deltds = 0.1
4. TEMP parameter is only used to calculate the noise performance of this model. Temperature scaling of model parameters is not performed.
5. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
6. This device has no default artwork associated with it.

Equations/Discussion:

EEMOS1 is an empirical analytic model that was developed by HP EEsof for the express purpose of fitting measured electrical behavior of 3-terminal n-channel MOSFETs intended for high-frequency analog applications. Unlike most physics-based MOSFET models found in SPICE programs, EEMOS1 contains no process or physical parameters. It does, however, accurately fit those electrical quantities that have direct bearing on the RF predictive abilities of the model, namely g_m vs. bias, g_{ds} vs. bias and, to a lesser degree, input and output capacitances vs. bias. The model includes the following features:

- Accurate drain-source current model fits measured current over gate and drain bias variations.
- Flexible transconductance formulation permits accurate fitting of g_m compression found in MOSFETs.
- Charge model that accurately tracks measured capacitance values.
- Dispersion model that permits simultaneous fitting of high-frequency conductances and dc characteristics.
- Well-behaved analytic expressions permit accurate extrapolations outside of the measurement range used to extract the model.

The model equations were developed concurrently with parameter extraction techniques to ensure the model would contain only parameters that were extractable from measured data. Although the model is amenable to automated parameter extraction techniques, it was designed to consist of parameters that are easily estimated (visually) from measured data such as $g_m{-}V_{gs}$ plots. Because the model equations are all well-behaved analytic expressions, EEMOS1 possesses no inherent limitations with respect to its usable power range. HP EEsof's IC-CAP program provides the user with the capability of extracting EEMOS1 models from measured data.

Channel Current

The channel current model in EEMOS1 is comprised of empirically derived analytic expressions and requires the specification of 9 parameter values. Because EEMOS1 is intended for large-signal analog applications, no attempt is made to characterize this channel current in the subthreshold or *weak* inversion region. The channel current expression is intended for use above V_t only. The equations were developed through examination of I_{ds} vs. bias and g_m vs. bias plots on a number of DMOS devices from various manufacturers. The equations are sufficiently flexible enough to handle either enhancement or depletion mode devices. The expressions below are given for $V_{ds}>0.0V$ although the model is equally valid for $V_{ds}<0.0V$. The model assumes the device is symmetrical; simply replace V_{gs} with V_{gd} and V_{ds} with $-V_{ds}$ obtain the reverse region ($V_{ds}<0.0V$) equations. The g_m, g_{ds} and I_{ds} equations take on take on two different forms depending on the value of V_{gs} relative to some of the model parameters. The I_{ds} expression is continuous through at least the second derivative everywhere except at V_t, where the second derivative is discontinuous.

The following voltages define regions of operation that are used in the current definitions:

$$V_t = Vto - Gamma \times V_{ds}$$

$$V_{gst} = V_{gs} - V_t \ .$$

for $V_{gst} \leq 0$

$$g_{mo} = 0.0$$

$$I_{dso} = 0.0$$

$$g_{dso} = 0.0$$

for $V_{gst} > 0$ and $V_{gs} \leq V_{break}$

$$g_{mo} = g_{mm}(V_{gs}, V_{ds})$$

$$I_{dso} = I_{dsm}(V_{gs}, V_{ds})$$

$$g_{dso} = g_{dsm}(V_{gs}, V_{ds})$$

for $V_{gst} > 0$ and $V_{gs} > V_{break}$

$$g_{mo} = a(V_{gs} - V_{asym})^{b}$$

$$I_{dso} = I_{dsm}(Vbreak, V_{ds}) + \frac{a}{b+1}[(V_{gs} - V_{asym})^{b+1} - Delt^{b+1}]$$

$$g_{dso} = g_{dsm}(Vbreak, V_{ds})$$

where:

$$g_{mm}(V, V_{ds}) = Gmmax\left[1 - \left(\frac{V - Vgo}{V_t - Vgo}\right)^2\right]$$

$$I_{dsm}(V,V_{ds}) = \left(Gmmax \times \left[(V - Vgo)\left(1 - \frac{1}{3}\left(\frac{V - Vgo}{V_t - Vgo}\right)^2\right) - \frac{2}{3}(V_t - Vgo)\right]\right)$$

$$g_{dsm}(V, V_{ds}) = Gmmax \times \left[\frac{2 \times Gamma}{3}\left(1 - \left(\frac{V - Vgo}{V_t - Vgo}\right)^3\right)\right]$$

$$m_{g_{mm}} = \left.\frac{\partial g_{mm}}{\partial V}\right|_{V = Vbreak}$$

$$= -\frac{2 \times Gmmax}{V_t - Vgo}\left(\frac{Vbreak - Vgo}{V_t - Vgo}\right)$$

$$V_{asym} = Vbreak - Delt$$

$$b = \frac{m_{g_{mm}} \times Delt}{g_{mm}(Vbreak, V_{ds})}$$

$$a = \frac{g_{mm}(Vbreak, V_{ds})}{Delt^{b}}$$

If b = −1, then the integral of g_{mo} (I_{dso}) is comprised of natural log functions:

$$I_{dso} = I_{dsm}(Vbreak, V_{ds}) + a[\log(V_{gs} - V_{asym}) - \log(Delt)]$$

The current saturation mechanism in EEMOS1 is described empirically through the parameters Vgm and Vsatm. The drain voltage where the channel current saturates is dependent on V_{gs} through the following relation:

$$V_{sat} = Vsatm \times \tanh\left[\frac{3(V_{gs} - V_t)}{Vgm}\right]$$

The preceding relations for I_{dso}, g_{mo} and g_{dso} can now be substituted in the following equations that model the current saturation and output conductance. This portion of the model is similar to an approach described by Curtice for modeling MESFETs [1].

$$I_{ds} = I_{dso}(1 + Lambda \times V_{ds})\tanh\left(\frac{3V_{ds}}{V_{sat}}\right)$$

$$g_m = \left[g_{mo}\tanh\left(\frac{3V_{ds}}{V_{sat}}\right) - I_{dso}\,\mathrm{sech}^2\left(\frac{3V_{ds}}{V_{sat}}\right) \times \left[\frac{3V_{ds}}{V_{sat}^2}\frac{\partial V_{sat}}{\partial V_{gs}}\right]\right]$$

$$\times (1 + Lambda \times V_{ds})$$

$$g_{ds} = \{g_{dso}(1 + Lambda \times V_{ds}) + I_{dso}Lambda\} \tanh\left(\frac{3V_{ds}}{V_{sat}}\right)$$

$$+ I_{dso} \times \frac{3\left(V_{sat} - V_{ds}\dfrac{\partial V_{sat}}{\partial V_{ds}}\right)(1 + Lambda \times V_{ds})}{V_{sat}^2} \operatorname{sech}^2\left(\frac{3V_{ds}}{V_{sat}}\right)$$

where

$$\frac{\partial V_{sat}}{\partial V_{gs}} = \frac{3 \times Vsatm}{Vgm} \operatorname{sech}^2\left(\frac{3(V_{gs} - V_t)}{Vgm}\right)$$

$$\frac{\partial V_{sat}}{\partial V_{ds}} = -\frac{3 \times Vsatm \times Gamma}{Vgm} \operatorname{sech}^2\left(\frac{3(V_{gs} - V_t)}{Vgm}\right)$$

Qualitatively, the operation of the channel current model can be described as follows.

The V_{ds} dependence of the equations is dominated by the parameters Vsatm, Vgm, Gamma, and Lambda. Output conductance is controlled by Gamma and Lambda. The parameter Vsatm represents the maximum drain-source voltage where the drain current saturates. Vgm is the gate voltage corresponding to the I-V trace where V_{sat}=Vsatm.

When Gamma = 0, Vsatm=0 and Lambda=0, EEMOS1 becomes dependent on V_{gs} only. Under these simplified conditions, the parameters describing the $g_m - V_{gs}$ dependence of the model are easily explained. Vto is the V_{gs} value where g_m becomes zero. The transconductance peaks at V_{gs}=VGO with a value of Gmmax. At V_{gs}=Vbreak, the model breaks from its quadratic g_m dependence and follows a hyperbolic dependence. The parameter Delt controls the voltage asymptote of this hyperbola. The shape of this tail-off region can be altered by tuning on the parameter Delt. EEMOS1 constrains the hyperbola to match the derivative of the quadratic function at V_{gs}=Vbreak. This ensures a continuous transition between the respective modeling regions for simulation. The parameter definitions are illustrated in Figure 5-1.

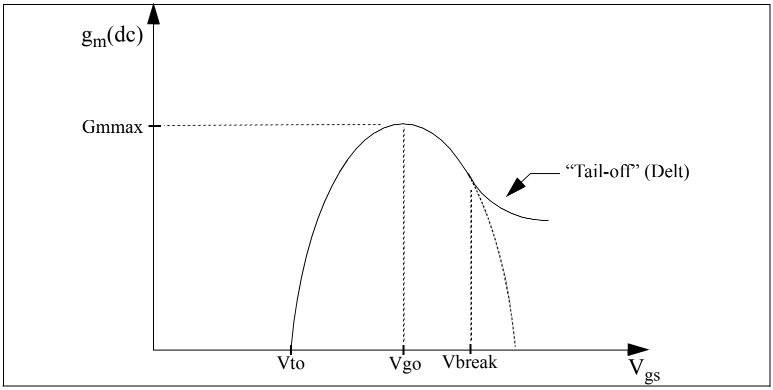


Figure 5-1. EEMOS1 g_m-V_{gs} Parameters

Dispersion Current (Idb)

The circuit used to model conductance dispersion consists of the elements Rdb, Cbs (these linear elements are also parameters) and the nonlinear source $I_{db}(V_{gs}, V_{ds})$. The model is a large-signal generalization of the dispersion model proposed by Golio et al. for MESFETs [2]. At dc, the drain-source current is just

the current I_{ds}. At high frequency (well above the transition frequency), the drain source current will be equal to I_{ds}(high frequency) = I_{ds}(dc) + I_{db}.

Linearization of the drain-source model yields the following expressions for y_{21} and y_{22} of the intrinsic EEMOS1 model:

$$y_{21} = g_{dsgs} + g_{dbgs} - \frac{g_{dbgs}}{1 + j\omega \times Cbs \times Rdb}$$

$$y_{22} = g_{dsds} + g_{dbds} + \frac{1}{Rdb} - \frac{\left(g_{dbds} + \frac{1}{Rdb}\right)}{1 + j\omega \times Cbs \times Rdb}$$

where

$$g_{dsgs} = \frac{\partial I_{ds}}{\partial V_{gs}}$$

$$g_{dsds} = \frac{\partial I_{ds}}{\partial V_{ds}}$$

$$g_{dbgs} = \frac{\partial I_{db}}{\partial V_{gs}}$$

$$g_{dbds} = \frac{\partial I_{db}}{\partial V_{ds}}$$

Evaluating these expressions at the frequencies ω=0 and ω=infinity, produces the following results for transconductance and output conductance:

For ω = 0,

$$Re[y_{21}] = g_m = g_{dsgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds}$$

For ω = infinity,

$$Re[y_{21}] = g_m = g_{dsgs} + g_{dbgs}$$

$$Re[y_{22}] = g_{ds} = g_{dsds} + g_{dbds} + \frac{1}{Rdb}$$

Between these two extremes, the conductances make a smooth transition, the abruptness of that is governed by the time constant τ_{disp} = Rdb × □□Cbs. The frequency f_0 at which the conductances are midway between these two extremes is defined as

$$f_0 = \frac{1}{2\pi\tau_{disp}}$$

The parameter Rdb should be set large enough so that its contribution to the output conductance is negligible. Unless the user is specifically interested in simulating the device near f_0, the default values of Rdb and Cbs specified in Table 5-7 will be adequate for most RF applications.

The EEMOS1 I_{ds} model can be extracted to fit either dc or ac characteristics. In order to simultaneously fit both dc I-Vs and ac conductances, EEMOS1 uses a simple scheme for modeling the I_{db} current source whereby different values of the same parameters can be used in the I_{ds} equations. The dc and ac drain-source currents can be expressed as follows:

$$I_{ds}^{dc}(Voltages, Parameters) = I_{ds}(Voltages, Vto, Gamma, Vgo, Gmmax, Delt, Vbreak, Lambda, Vsatm, Vgm$$

$$I_{ds}^{ac}(Voltages, Parameters) = I_{ds}(Voltages, Vto, Gamma, Vgoac, Gmmaxac, Deltac, Vbreakac, Lambdaac, Vsatmac, Vgmac$$

Parameters such as Vto that do not have an ac counterpart (there is no Vtoac parameter), have been found not to vary significantly between extractions using dc measurements versus those using ac measurements. The difference between the ac and dc values of I_{ds} plus an additional term that is a function of V_{ds} only gives the value of I_{db} for the dispersion model

$$I_{db}(V_{gs}, V_{ds}) = I_{ds}^{ac}(V_{gs}, V_{ds}) - I_{ds}^{dc}(V_{gs}, V_{ds}) + I_{dbp}(V_{ds})$$

where I_{dbp} and its associated conductance are given by:

for V_{ds} > Vdsm and $Kdb \neq 0$:

$$I_{dbp} = \sqrt{\frac{Gdbm}{Kdb}}\tan^{-1}((V_{ds} - Vdsm)\sqrt{Kdb \times Gdbm}) + Gdbm \times Vdsm$$

$$g_{dbp} = \frac{Gdbm}{(Kdb(Gdbm(V_{ds} - Vdsm)^2 + 1))}$$

for V_{ds} < –Vdsm and $Kdb \neq 0$:

$$I_{dbp} = \sqrt{\frac{Gdbm}{Kdb}}\tan^{-1}((V_{ds} + Vdsm)\sqrt{Kdb \times Gdbm}) - Gdbm \times Vdsm$$

$$g_{dbp} = \frac{Gdbm}{Kdb \times Gdbm((V_{ds} + Vdsm)^2 + 1)}$$

for $-Vdsm \leq V_{ds} \leq Vdsm$ or $Kdb = 0$:

$$I_{dsm} = Gdbm \times V_{ds}$$

$$g_{dbm} = Gdbm$$

By setting the seven high-frequency parameters equal to their dc counterparts, the dispersion model reduces to $I_{db} = I_{dbp}$. Examination of the I_{dbp} expression reveals that the additional setting of Gdbm to zero disables the dispersion model entirely. Because the I_{dbp} current is a function of V_{ds} only, it will impact output conductance only. However, the current function I_{ds}^{ac} will impact both g_m and g_{ds}. For this reason, the model is primarily intended to use g_m data as a means for tuning I_{ds}^{ac}. Once this *fitting* is accomplished, the parameters Gdbm, Kdb and Vdsm can be tuned to optimize the g_{ds} fit.

Charge Model

The EEMOS1 charge model consists of three separate charge sources that model channel charge and charge associated with the substrate (output) diode. The channel charge is partitioned between the two charge sources q_{gc} and q_{gy} such that symmetry is maintained relative to $V_{ds} = 0V$. These expressions were empirically developed by HP EEsof such that their derivatives would fit measured capacitance data. The channel charge expressions are:

$$q_{gc} = \frac{Cgsmax}{4}\left[V_{gc} - Vinfl + \sqrt{(V_{gc} - Vinfl)^2 + Deltgs^2}\right]$$

$$\text{'"} \times \left[1 + \tanh\left(\frac{3(V_{gc} - V_{gy})}{Deltds}\right)\right] + Cgso \times V_{gc}$$

$$q_{gy} = \frac{Cgsmax}{4}\left[V_{gy} - Vinfl + \sqrt{(V_{gy} - Vinfl)^2 + Deltgs^2}\right]$$

$$\times \left[1 - \tanh\left(\frac{3(V_{gy} - V_{gc})}{Deltds}\right)\right] + Cgdo \times V_{gy}$$

The output charge and its derivative are modeled using the standard junction diode depletion formula:

For $-V_{ds} < Fc \times Vbi$

$$q_{ds} = -\frac{Cdso \times Vbi}{1 - Mj}\left[1 - \left(1 + \frac{V_{ds}}{Vbi}\right)^{1 - Mj}\right]$$

$$C_{dsds} = \frac{\partial q_{ds}}{\partial V_{ds}} = \frac{Cdso}{\left[1 + \frac{V_{ds}}{Vbi}\right]^{Mj}}$$

For $-V_{ds} < -Fc \times Vbi$

the capacitance is extrapolated linearly from its value at Fc× Vbi according to the standard SPICE equation for a junction diode [3]. The charge derivatives are related to the small-signal capacitances through the following expressions:

$$C_{gs} \approx C_{gcgc} + C_{gygc}$$

$$C_{gd} \approx C_{gcgy} + C_{gygy}$$

$$C_{ds} \approx C_{dsds} - C_{gcgy}$$

where

$$C_{gcgc} = \frac{\partial q_{gc}}{\partial V_{gc}}$$

$$C_{gcgy} = \frac{\partial q_{gc}}{\partial V_{gy}}$$

$$C_{gygy} = \frac{\partial q_{gy}}{\partial V_{gy}}$$

$$C_{gygc} = \frac{\partial q_{gy}}{\partial V_{gc}}$$

Substrate Diode and Breakdown

When the drain-source voltage is reverse-biased, the substrate diode conducts according to the standard diode relation:

$$I_{for}(V_{ds}) = Is \times \left[e^{\frac{-qV_{ds}}{nkT}} - 1 \right]$$

where q is the charge on an electron, k is Boltzmann's constant, and T is the junction temperature.

The EEMOS1 breakdown model is based on a simple power law expression. The model consists of three parameters that are easily optimized to measured data. The breakdown current is given by:

For V_{ds} > Vbr,

$$I_{bkdn}(V_{ds}) = Kbo(V_{ds} - Vbr)^{Nbr}$$

For V_{ds} ≤ Vbr

$$I_{bkdn}(V_{ds}) = 0$$

Total current flowing through the substrate (body) diode from source to drain is given by:

$$I_{sub}(V_{ds}) = I_{for}(V_{ds}) - I_{bkdn}(V_{ds})$$

Noise Model

Thermal noise generated by resistors Rg, Rs, Rd, Ris, Rid, and Rdb is characterized by the following spectral density.

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

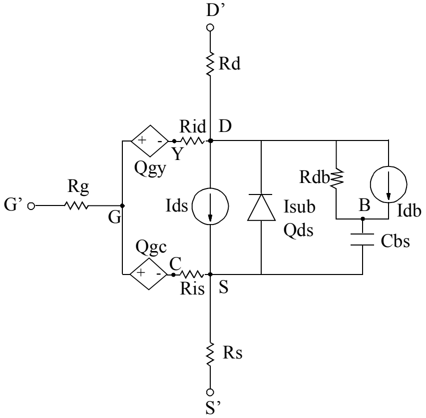
Channel noise generated by the dc transconductance g_m is characterized by the following spectral density:

$$\frac{< i_{ds}^2 >}{\Delta f} = \frac{8kTg_m}{3}$$

In the preceding expressions, *k* is Boltzmann's constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, and Δf is the noise bandwidth.

Flicker noise for this device is not modeled in this simulator version. However, the bias-dependent noise sources I_NoiseBD and V_NoiseBD (from the Sources library) can be connected external to the device to model flicker noise.

Equivalent Circuit



References

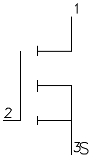
[1] W. R. Curtice, “A MESFET model for use in the design of GaAs integrated circuits,” *IEEE Transactions of Microwave Theory and Techniques,* Vol. MTT-28, pp. 448-456, May 1980.

[2] J. M. Golio, M. Miller, G. Maracus, D. Johnson. “Frequency dependent electrical characteristics of GaAs MESFETs,” *IEEE Trans. Elec. Devices*, vol. ED-37, pp. 1217-1227, May 1990.

[3] P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE,* Second Edition, McGraw-Hill, Inc., 1993.

HP_MOS (HP_Root MOS Transistor)

Symbol



Parameters

Model = name of an EE_MOS_Model

Wtot = total gate width, in length units (default: 10^{-4})

N = number of gate fingers (default: 1)

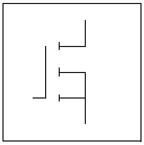
_M = number of devices in parallel (default: 1)

Notes/Equations/References

1. Wtot and N are optional scaling parameters that make it possible to scale the extracted model for different geometries.
2. Wtot is the *total* gate width—not the width per finger; N is the number of fingers. Therefore, the width per finger is Wtot / N. The scaling remains valid for ratios up to 5:1.
3. The parameters Ggs, Gds, Gmr, dQg_dVgs, and the rest are the small-signal parameters of the device evaluated at the dc operating point. To be displayed, they must be listed among the OUTPUT_VARS in the analysis component.

HP_MOS_Model (HP_Root MOS Transistor Model))

Symbol



Parameters

File = name of rawfile

Rs = source resistance

Rg = gate resistance

Rd = drain resistance

Ls = source inductance

Lg = gate inductance

Ld = drain inductance

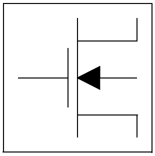
AllParams = DataAccessComponent-based parameters

Notes/Equations/References

1. The values of Rs, Rg, Rd, Ls, Lg, and Ld are meant to override the extracted values stored in the data file named in the File parameter. Generally, these parameters should not be used.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.
3. Because this model is measurement-based, extrapolation warning messages may occur if the Newton iteration exceeds the measurement range. If these messages occur frequently, check that the measurement data is within the simulation range.
4. For a list of HP Root Model references, refer to "HP_Diode_Model (HP_Root Diode Model)" on page 1-18.

LEVEL1_Model (MOSFET Level-1 Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-8. LEVEL1_Model Parameters

Parameter	Description	Unit	Default
NMOS	N-channel model		yes
PMOS	P-channel model		no
Idsmod	IDS model		1
Capmod	capacitance model selector		1
Vto[†]	zero-bias threshold voltage	V	0.0
Kp[†]	transconductance coefficient	A/m^2	2×10^{-5}
Gamma	bulk threshold	□√ V	0.0
Phi[†]	surface potential	V	0.6
Lambda	channel-length modulation parameter	1/V	0.0
Rd	drain ohmic resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Cbd[†]	zero-bias bulk-drain junction capacitance	F	0.0
Cbs[†]	zero-bias bulk-source junction capacitance	F	0.0
Is[†]	bulk junction saturation current	A	10^{-14}
Pb[†]	bulk junction potential	V	0.8
Cgso	gate-source overlap capacitance per meter of channel width	F/m	0.0

[†] Parameter value varies with temperature based on model Tnom and device Temp.

[††] Value of 0.0 is interpreted as infinity.

Table 5-8. LEVEL1_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Cgdo	gate-drain overlap capacitance per meter of channel width	F/m	0.0
Cgbo	gate-bulk overlap capacitance per meter of channel length	F/m	0.0
Rsh	drain and source diffusion sheet resistance	ohms/sq.	0.0
Cj†	zero-bias bulk junction bottom capacitance per square meter of junction area	F/m^2	0.0
Mj	bulk junction bottom grading coefficient		0.5
Cjsw†	zero-bias bulk junction periphery capacitance per meter of junction perimeter	F/m	0.0
Mjsw	bulk junction periphery grading coefficient		0.33
Js†	bulk junction saturation current per square meter of junction area	A/m^2	0.0
Tox	oxide thickness	m	10^{-7}
Nsub	substrate (bulk) doping density	$1/Cm^3$	0.0
Nss	surface state density	$1/Cm^2$	0.0
Tpg	gate material type: 0 = aluminum; −1 = same as bulk; 1 = opposite to bulk		1
Ld	lateral diffusion length	m	0.0
Uo†	surface mobility	$Cm^2/(V \times S)$	600.0
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1
Kf	flicker-noise coefficient		0.0
Af	flicker-noise exponent		1.0
Fc	bulk junction forward-bias depletion capacitance coefficient		0.5
Rg	gate ohmic resistance	ohms	0.0

† Parameter value varies with temperature based on model Tnom and device Temp.

†† Value of 0.0 is interpreted as infinity.

Table 5-8. LEVEL1_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Rds	drain-source shunt resistance	ohms	infinity[††]
Tnom	nominal ambient temp. at which model parameters were derived	°C	25
N	bulk P-N emission coefficient		1.0
Tt	bulk P-N transit time	sec	0.0
Ffe	flicker noise frequency exponent		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

[†] Parameter value varies with temperature based on model Tnom and device Temp.

[††] Value of 0.0 is interpreted as infinity.

Notes/Equations:

1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. MOSFET Level1_Model is Shichman-Hodges model derived from [1].
2. Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. The program will compute these parameters (except Lambda) if instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.
3. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.
4. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.

5. Diode parameters for the bottom junctions can be specified as absolute values (Is, Cbd and Cbs) or as per unit junction area values (Js and Cj).

   If Cbd = 0.0 and Cbs = 0.0, then Cbd and Cbs will be computed:

   Cbd = Cj × Ad, Cbs = Cj × As

   If Js > 0.0 and Ad > 0.0 and As > 0.0, then Is for drain and source will be computed:

   Is(drain) = Js × Ad, Is(source) = Js × As

6. Drain and source ohmic resistances can be specified as absolute values (Rd, Rs) or as per unit square value (Rsh).

   If Nrd ≠ 0.0 or Nrs ≠ 0.0, Rd and Rs will be computed:

   Rd = Rsh × Nrd, Rs = Rsh × Nrs

7. Charge storage in the MOSFET consists of capacitances associated with parasitics and intrinsic device.

   Parasitic capacitances consist of three constant overlap capacitances (Cgdo, Cgso, Cgbo) and the depletion layer capacitances for both substrate junctions (divided into bottom and periphery), that vary as Mj and Mjsw power of junction voltage, respectively, and are determined by the parameters Cbd, Cbs, Cj, Cjsw, Mj, Mjsw, Pb and Fc.

   The intrinsic capacitances consist of the nonlinear thin-oxide capacitance, which is distributed among the gate, drain, source, and bulk regions.

8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer's piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter TOX must be specified to invoke the Meyer model when Capmod is equal to 1 (default value). If Capmod = 0, no gate capacitances will be computed. If Capmod = 2, a smooth version of the Meyer model is used. If Capmod =3, the charge conserving first-order MOS charge model [2] that was used in Libra is used.

9. To include the thin-oxide charge storage effect, model parameter Tox must be > 0.0.

10. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances Cbd, Cbs, Cj, and Cjsw vary as:

$$Cbd^{NEW} = Cbd\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cbs^{NEW} = Cbs\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cj^{NEW} = Cj\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cjsw^{NEW} = Cjsw\left[\frac{1 + Mjsw[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mjsw[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

where γ is a function of the junction potential and the energy gap variation with temperature.

The surface potential Phi and the bulk junction potential Pb vary as:

$$Phi^{NEW} = \frac{Temp}{Tnom} \times Phi + \frac{2k \times Temp}{q} \ln\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

$$Pb^{NEW} = \frac{Temp}{Tnom} \times Pb + \frac{2k \times Temp}{q} \ln\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

The transconductance Kp and mobility Uo vary as:

$$Kp^{NEW} = Kp\left(\frac{Temp}{Tnom}\right)^{3/2}$$

$$Uo^{NEW} = Uo\left(\frac{Temp}{Tnom}\right)^{3/2}$$

The source and drain to substrate leakage currents Is and Js vary as:

$$Is^{NEW} = Is \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

$$Js^{NEW} = Js \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

where E_G is the silicon bandgap energy as a function of temperature.

The MOSFET threshold voltage variation with temperature is given by:

$$Vto^{NEW} = Vto + \gamma\left(\sqrt{Phi^{NEW}} - \sqrt{Phi}\right) + \frac{Phi^{NEW} - Phi}{2} - \frac{E_G^{Temp} - E_G^{Tnom}}{2}$$

Noise Model

Thermal noise generated by resistor Rg, Rs, Rd, and Rds is characterized by the following spectral density:

$$\frac{<i^2>}{\Delta f} = \frac{4kT}{R}$$

Channel and flicker noise (Kf, Af, Ffe) generated by dc transconductance g_m and current flow from drain to source is characterized by spectral density:

$$\frac{<i_{ds}^2>}{\Delta f} = \frac{8kTg_m}{3} + \mathrm{k}_f \frac{I_{DS}^{a_f}}{f^{f_{fe}}}$$

In the preceding expressions, *k* is Boltzmann's constant, `T` is operating temperature in Kelvin, *q* is electron charge, *kf*, a_f, and f_{fe} are model parameters, *f* is simulation frequency, and Δ*f* is noise bandwidth.

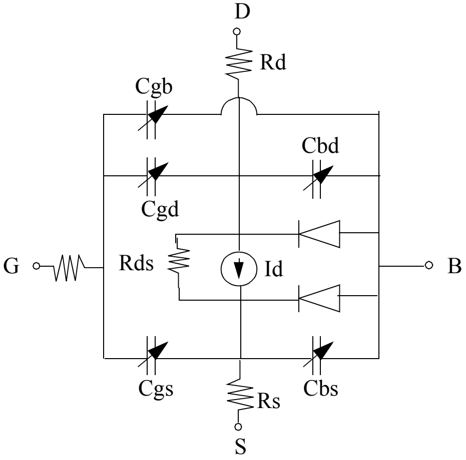
References

[1] H. Shichman and D. A. Hodges. “Modeling and simulation of insulated-gate field-effect transistor switching circuits,” *IEEE Journal of Solid-State Circuits,* SC-3, 285, Sept. 1968.

[2] Karen A. Sakallah, Yao-tsung Yen, and Steve S. Greenberg. “The Meyer Model Revisited: Explaining and Correcting the Charge Non-Conservation Problem,” *ICCAD*, 1987.

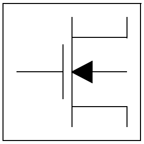
[3] P. Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

Equivalent Circuit



LEVEL2_Model (MOSFET Level-2 Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-9. LEVEL2_Model Parameters

Parameter	Description	Unit	Default
NMOS	N-channel model		yes
PMOS	P-channel model		no
Idsmod	IDS model		2
Capmod	capacitance model selector		1
Vto†	zero-bias threshold voltage	V	0.0
Kp†	transconductance coefficient	A/V^2	2×10^{-5}
Gamma	bulk threshold parameter	□√ V	0.0
Phi†	surface potential	V	0.6
Lambda	channel-length modulation parameter	1/V	0.0
Rd	drain ohmic resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Cbd†	zero-bias bulk-drain junction capacitance	F	0.0
Cbs†	zero-bias bulk-source junction capacitance	F	0.0
Is	bulk junction saturation current	A	10^{-14}
Pb†	bulk junction potential	V	0.8
Cgso	gate-source overlap capacitance per meter of channel width	F/m	0.0

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.

†† A value of 0.0 is interpreted as infinity.

Table 5-9. LEVEL2_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Cgdo	gate-drain overlap capacitance per meter of channel width	F/m	0.0
Cgbo	gate-bulk overlap capacitance per meter of channel length	F/m	0.0
Rsh	drain and source diffusion sheet resistance	ohms/sq	0.0
Cj†	zero-bias bulk junction bottom capacitance per square meter of junction area	F/m^2	0.0††
Mj	bulk junction bottom grading coefficient		0.5
Cjsw†	zero-bias bulk junction periphery capacitance per meter of junction perimeter	F/m	0.0
Mjsw	bulk junction periphery grading coefficient		0.33
Js†	bulk junction saturation current per square meter of junction area	A/m^2	0.0
Tox	oxide thickness	m	10^{-7}
Nsub	substrate (bulk) doping density	1/Cm^3	0.0
Nss	surface state density	1/Cm^2	0.0
Nfs	fast surface state density	1/Cm^2	0.0
Tpg	gate material type: 0 = aluminum; −1 = same as bulk; 1 = opposite to bulk		1
Xj	metallurgical junction depth	m	0.0
Ld	lateral diffusion length	m	0.0
Uo†	surface mobility	$Cm^2/(V \times s)$	600.0
Ucrit	critical field for mobility degradation	V/Cm	10^4
Uexp	critical field exponent in mobility degradation		0.0
Vmax	carriers maximum drift velocity	m/s	0.0
Neff	total channel charge coefficient		1.0

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.

†† A value of 0.0 is interpreted as infinity.

Table 5-9. LEVEL2_Model Parameters (continued)

Parameter	Description	Unit	Default
Xqc	fraction of channel charge attributed to drain		1.0
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0
Fc	bulk junction forward-bias depletion capacitance coefficient		0.5
Delta	width effect on threshold voltage		0.0
Rg	gate ohmic resistance	ohms	0.0
Rds	drain-source shunt resistance	ohms	infinity††
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
N	bulk P-N emission coefficient		1.0
Tt	bulk P-N transit time	sec	0.0
Ffe	flicker noise frequency exponent		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

† Parameter value varies with temperature based on Tnom of the model and Temp of the device.

†† A value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. LEVEL2_Model is a geometry-based, analytical model derived from [1].
2. LEVEL2_Model includes second order effects such as threshold voltage shift, mobility reduction, velocity saturation, channel length modulation, and subthreshold conduction.
3. Parameters Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. The program will compute these parameters (except Lambda) if, instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.
4. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.
5. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.
6. The diode parameters for the bottom junctions can be specified as absolute values (Is, Cbd and Cbs) or as per unit junction area values (Js and Cj).

   If Cbd = 0.0 and Cbs = 0.0, then Cbd and Cbs will be computed:

   Cbd = Cj × Ad,   Cbs = Cj × As

   If Js > 0.0 and Ad > 0.0 and As > 0.0, then Is for drain and source will be computed:

   Is(drain) = Js × Ad,   Is(source) = Js × As
7. Drain and source ohmic resistances can be specified as absolute values (Rd, Rs) or as per unit square value (Rsh).

   If Nrd ≠ 0.0 or Nrs ≠ 0.0, Rd and Rs will be computed:

   Rd = Rsh × Nrd,   Rs = Rsh × Nrs
8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer's piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter TOX must be specified to invoke the Meyer model when Capmod is equal to 1 (default value). If Capmod = 0, no gate capacitances will be computed. If Capmod = 2, a smooth version of the Meyer model is used. If Capmod =3, the charge conserving first-order MOS charge model [2] that was used in Libra is used.
9. The simulator uses Ward and Dutton [2] charge-controlled capacitance model if Xqc ≤ 0.5. If Xqc > 0.5, the charge-conserving first-order MOS charge model is used.

10. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances Cbd, Cbs, Cj, and Cjsw vary as:

$$Cbd^{NEW} = Cbd\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cbs^{NEW} = Cbs\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cj^{NEW} = Cj\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cjsw^{NEW} = Cjsw\left[\frac{1 + Mjsw[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mjsw[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

where γ is a function of the junction potential and the energy gap variation with temperature.

The surface potential Phi and the bulk junction potential Pb vary as:

$$Phi^{NEW} = \frac{Temp}{Tnom} \times Phi + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

$$Pb^{NEW} = \frac{Temp}{Tnom} \times Pb + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

The transconductance Kp and mobility Uo vary as:

$$Kp^{NEW} = Kp\left(\frac{Temp}{Tnom}\right)^{3/2}$$

$$Uo^{NEW} = Uo\left(\frac{Temp}{Tnom}\right)^{3/2}$$

The source and drain to substrate leakage currents Is and Js vary as:

$$Is^{NEW} = Is \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

$$Js^{NEW} = Js \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

where E_G is the silicon bandgap energy as a function of temperature.

The MOSFET threshold voltage variation with temperature is given by:

$$Vto^{NEW} = Vto + \gamma\left(\sqrt{Phi^{NEW}} - \sqrt{Phi}\right) + \frac{Phi^{NEW} - Phi}{2} - \frac{E_G^{Temp} - E_G^{Tnom}}{2}$$

Noise Model

Thermal noise generated by resistor Rg, Rs, Rd, and Rds is characterized by the following spectral density:

$$\frac{< i^2 >}{\Delta f} = \frac{4kT}{R}$$

Channel noise and flicker noise (Kf, Af, Ffe) generated by the dc transconductance g_m and current flow from drain to source is characterized by the following spectral density:

$$\frac{< i_{ds}^{2} >}{\Delta f} = \frac{8kTg_{m}}{3} + \mathrm{k}_{f}\frac{I_{DS}^{a_{f}}}{f^{f_{fe}}}$$

In the preceding expressions, *k* is Boltzmann's constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, *kf*, *af*, and *ffe* are model parameters, `f` is the simulation frequency, and Δf is the noise bandwidth.

References:

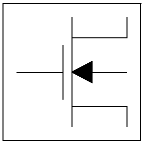
[1] Vladimirescu and S. Liu. The Simulation of MOS Integrated Circuits Using SPICE2, Memorandum No. M80/7, February 1980.

[2] D. E. Ward, and R. W. Dutton. "A Charge-Oriented Model for MOS Transistors Capacitances," *IEEE Journal on Solid-State Circuits*, SC-13, 1978.

[3] P. Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

LEVEL3_Model (MOSFET Level-3 Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-10. LEVEL3_Model Parameters

Parameter	Description	Unit	Default
NMOS	N-channel model		yes
PMOS	P-channel model		no
Idsmod	IDS model		3
Capmod	capacitance model selector		1
Vto[†]	zero-bias threshold voltage	V	0.0
Kp[†]	transconductance coefficient	A/V^2	2×10^{-5}
Gamma	bulk threshold	□√ V	0.0
Phi[†]	surface potential	V	0.6
Rd	drain ohmic resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Cbd[†]	zero-bias bulk-drain junction capacitance	F	0.0
Cbs[†]	zero-bias bulk-source junction capacitance	F	0.0
Is[†]	bulk junction saturation current	A	10^{-14}
Pb[†]	bulk junction potential	V	0.8
Cgso	gate-source overlap capacitance per meter of channel width	F/m	0.0

[†] Parameter value varies with temperature based on Tnom of model and Temp of device.

[††] Value of 0.0 is interpreted as infinity.

Table 5-10. LEVEL3_Model Parameters (continued)

Parameter	Description	Unit	Default
Cgdo	gate-drain overlap capacitance per meter of channel width	F/m	0.0
Cgbo	gate-bulk overlap capacitance per meter of channel length	F/m	0.0
Rsh	drain and source diffusion sheet resistance	ohms/sq	0.0
Cj†	zero-bias bulk junction bottom capacitance per square meter of junction area	F/m^2	0.0
Mj	bulk junction bottom grading coefficient		0.5
Cjsw†	zero-bias bulk junction periphery capacitance per meter of junction perimeter	F/m	0.0
Mjsw	bulk junction periphery grading coefficient		0.33
Js†	bulk junction saturation current per square meter of junction area	A/m^2	0.0
Tox	oxide thickness	m	10^{-7}
Nsub	substrate (bulk) doping density	$1/cm^3$	0.0
Nss	surface state density	$1/cm^2$	0.0
Nfs	fast surface state density	$1/cm^2$	0.0
Tpg	gate material type: 0=aluminum; −1=same as substrate; 1=opposite substrate		1
Xj	metallurgical junction depth	m	0.0
Ld	lateral diffusion length	m	0.0
Uo†	surface mobility	$cm^2/(V \times s)$	600.0
Vmax	carriers maximum drift velocity	m/s	0.0
Xqc	coefficient of channel charge share		1.0
Nlev	Noise model level		-1
Gdwnoi	Drain noise parameters for Nlev=3		1

† Parameter value varies with temperature based on Tnom of model and Temp of device.

†† Value of 0.0 is interpreted as infinity.

Table 5-10. LEVEL3_Model Parameters (continued)

Parameter	Description	Unit	Default
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0
Fc	bulk junction forward-bias depletion capacitance coefficient		0.5
Delta	width effect on threshold voltage		0.0
Theta	mobility modulation	1/V	0.0
Eta	static feedback		0.0
Kappa	saturation field factor		0.2
Rg	gate ohmic resistance	ohms	0.0
Rds	drain-source shunt resistance	ohms	infinity[††]
Tnom	nominal ambient temperature at which these model parameters were derived	°C	25
N	bulk P-N emission coefficient		1.0
Tt	bulk P-N transit time	sec	0.0
Ffe	Flicker noise frequency exponent		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

[†] Parameter value varies with temperature based on Tnom of model and Temp of device.

[††] Value of 0.0 is interpreted as infinity.

Notes/Equations/References

1. The simulator provides three MOSFET device models that differ in formulation of I-V characteristics. LEVEL3_Model is a semi-empirical model derived from [1].
2. LEVEL3_Model includes second order effects such as threshold voltage shift, mobility reduction, velocity saturation, channel length modulation, and subthreshold conduction.
3. Parameters Vto, Kp, Gamma, Phi, and Lambda determine the dc characteristics of a MOSFET device. Program will compute these parameters (except Lambda) if, instead of specifying them, you specify the process parameters Tox, Uo, Nsub, and Nss.
4. Vto is positive (negative) for enhancement mode and negative (positive) for depletion mode N-channel (P-channel) devices.
5. The p-n junctions between the bulk and the drain and the bulk and the source are modeled by parasitic diodes. Each bottom junction is modeled by a diode and each periphery junction is modeled by a depletion capacitance.
6. The diode parameters for the bottom junctions can be specified as absolute values (Is, Cbd and Cbs) or as per unit junction area values (Js and Cj).

   If Cbd=0.0 and Cbs=0.0, Cbd and Cbs will be computed:

   $$Cbd = Cj \times Ad \qquad Cbs = Cj \times As$$

   If Js>0.0 and Ad>0.0 and As>0.0, Is for drain and source will be computed:

   $$Is(drain) = Js \times Ad \qquad Is(source) = Js \times As$$

   Drain and source ohmic resistances can be specified as absolute values (Rd, Rs) or as per unit square value (Rsh).

   If Nrd≠0.0 or Nrs≠0.0, Rd and Rs will be computed:

   $$Rd = Rsh \times Nrd \qquad Rs = Rsh \times Nrs$$

7. Charge storage in the MOSFET consists of capacitances associated with parasitics and intrinsic device.

   The parasitic capacitances consist of three constant overlap capacitances (Cgdo, Cgso, Cgbo) and the depletion layer capacitances for both substrate junctions (divided into bottom and periphery) that vary as Mj and Mjsw power of junction voltage, respectively, and are determined by the parameters Cbd, Cbs, Cj, Cjsw, Mj, Mjsw, Pb and Fc.

   The intrinsic capacitances consist of the nonlinear thin-oxide capacitance, which is distributed among the gate, drain, source, and bulk regions.

8. Charge storage is modeled by fixed and nonlinear gate and junction capacitances. MOS gate capacitances, as a nonlinear function of terminal voltages, are modeled by Meyer's piece-wise linear model for levels 1, 2, and 3. The Ward charge conservation model is also available for levels 2 and 3, by specifying the XQC parameter to a value smaller than or equal to 0.5. For Level 1, the model parameter TOX must be specified to invoke the Meyer model when Capmod is equal to 1 (default value). If Capmod = 0, no gate capacitances will be computed. If Capmod = 2, a smooth version of the Meyer model is used. If Capmod =3, the charge conserving first-order MOS charge model [2] that was used in Libra is used.
9. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

Temperature Scaling

The model specifies Tnom, the nominal temperature at which the model parameters were calculated or extracted. To simulate the device at temperatures other than Tnom, several model parameters must be scaled with temperature. The temperature at which the device is simulated is specified by the device item Temp parameter. (Temperatures in the following equations are in Kelvin.)

The depletion capacitances Cbd, Cbs, Cj, and Cjsw vary as:

$$Cbd^{NEW} = Cbd\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cbs^{NEW} = Cbs\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cj^{NEW} = Cj\left[\frac{1 + Mj[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mj[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

$$Cjsw^{NEW} = Cjsw\left[\frac{1 + Mjsw[4 \times 10^{-4}(Temp - T_{REF}) - \gamma^{Temp}]}{1 + Mjsw[4 \times 10^{-4}(Tnom - T_{REF}) - \gamma^{Temp}]}\right]$$

where γ is a function of the junction potential and the energy gap variation with temperature.

The surface potential Phi and the bulk junction potential Pb vary as:

$$Phi^{NEW} = \frac{Temp}{Tnom} \times Phi + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

$$Pb^{NEW} = \frac{Temp}{Tnom} \times Pb + \frac{2k \times Temp}{q} 1n\left(\frac{n_i^{Tnom}}{n_i^{Temp}}\right)$$

The transconductance Kp and mobility Uo vary as:

$$Kp^{NEW} = Kp\left(\frac{Temp}{Tnom}\right)^{3/2}$$

$$Uo^{NEW} = Uo\left(\frac{Temp}{Tnom}\right)^{3/2}$$

The source and drain to substrate leakage currents Is and Js vary as:

$$Is^{NEW} = Is \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

$$Js^{NEW} = Js \times exp\left(\frac{q \times E_G^{Tnom}}{k \times Tnom} - \frac{q \times E_G^{Temp}}{k \times Temp}\right)$$

where E_G is the silicon bandgap energy as a function of temperature.

The MOSFET threshold voltage variation with temperature is given by:

$$Vto^{NEW} = Vto + \gamma\left(\sqrt{Phi^{NEW}} - \sqrt{Phi}\right) + \frac{Phi^{NEW} - Phi}{2} - \frac{E_G^{Temp} - E_G^{Tnom}}{2}$$

Noise Model

Thermal noise generated by resistor Rg, Rs, Rd, and Rds is characterized by the following spectral density:

$$\frac{\langle i^2 \rangle}{\Delta f} = \frac{4kT}{R}$$

Channel noise and flicker noise (Kf, Af, Ffe) generated by dc transconductance g_m and current flow from drain to source is characterized by the spectral density:

$$\frac{\langle i_{ds}^2 \rangle}{\Delta f} = \frac{8kTg_m}{3} + k_f \frac{I_{DS}^{a_f}}{f^{f_{fe}}}$$

In the preceding expressions, *k* is Boltzmann's constant, *T* is the operating temperature in Kelvin, *q* is the electron charge, *kf*, *af*, and *ffe* are model parameters, *f* is the simulation frequency, and Δf is the noise bandwidth.

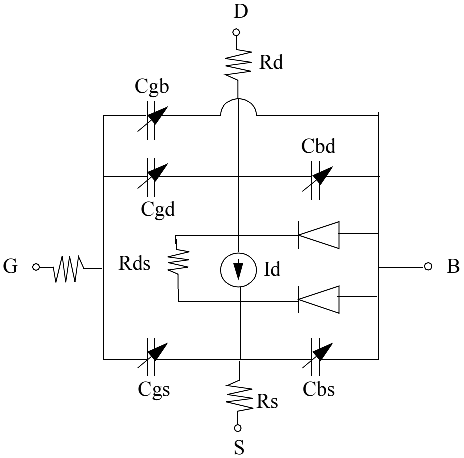
References

[1] Vladimirescu, and S. Liu. The Simulation of MOS Integrated Circuits Using SPICE2, Memorandum No. M80/7, February 1980.

[2] Karen A. Sakallah, Yao-tsung Yen, and Steve S. Greenberg. "The Meyer Model Revisited: Explaining and Correcting the Charge Non-Conservation Problem," *ICCAD*, 1987.

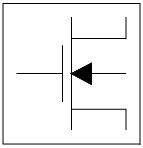
[3] P. Antognetti and G. Massobrio. *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, Second Edition 1993.

Equivalent Circuit



LEVEL3_MOD_Model (LEVEL 3 NMOD MOSFET Model)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-11. LEVEL3_MOD_Model Parameters

Parameter	**Description**	**Unit**	**Default**
NMOS	N-channel model		yes
PMOS	P-channel model		no
Idsmod	IDS model		6
Capmod	capacitance model selector		1
Vto†	zero-bias threshold voltage	V	0.0
Kp†	transconductance coefficient	A/V^2	0.0
Gamma	bulk threshold parameter	□√ V	0.0
Gamma2	bulk threshold parameter deep in substrate	√ V	0.0
Zeta	mobility modulation with substrate bias parameter		0.0
Phi†	surface potential	V	0.6
Rd	drain ohmic resistance	ohms	0.0
Rs	source ohmic resistance	ohms	0.0
Cbd†	zero-bias bulk-drain junction capacitance	F	0.0
Cbs†	zero-bias bulk-source junction capacitance	F	0.0
Is†	bulk junction saturation current	A	10^{-14}
Pb†	bulk junction potential	V	0.8
Cgso	gate-source overlap cap. per meter of channel width	F/m	0.0

† Parameter value varies with temperature based on Tnom of model and Temp of device.

†† Value of 0.0 is interpreted as infinity.

Table 5-11. LEVEL3_MOD_Model Parameters (continued)

Parameter	Description	Unit	Default
Cgdo	gate-drain overlap cap. per meter of channel width	F/m	0.0
Cgbo	gate-bulk overlap cap. per meter of channel length	F/m	0.0
Rsh	drain and source diffusion sheet resistance	ohms/sq.	0.0
Cj†	zero-bias bulk junction bottom capacitance per square meter of junction area	F/m^2	0.0
Mj	bulk junction bottom grading coefficient		0.5
Cjsw†	zero-bias bulk junction periphery capacitance per meter of junction perimeter	F/m	0.0
Mjsw	bulk junction periphery grading coefficient		0.33
Js†	bulk junction saturation current per square meter of junction area	A/m^2	0.0
Tox	oxide thickness	m	10^{-7}
Nsub	substrate (bulk) doping density	$1/cm^3$	0.0
Nss	surface state density	$1/cm^2$	0.0
Nfs	fast surface state density	$1/cm^2$	0.0
Tpg	gate material type: 0=aluminum; -1=same as substrate; 1=opposite substrate		1
Xj	metallurgical junction depth	m	0.0
Ld	lateral diffusion length	m	0.0
Uo†	surface mobility	$cm^2/(V\times S)$	600.0
Ucrit	critical field for mobility degradation	V/cm	10^{-4}
Uexp	field exponent in mobility degradation		0.0
Vmax	carriers maximum drift velocity	m/s	0.0
Xqc	coefficient of channel charge share		1.0
Kf	flicker noise coefficient		0.0
Af	flicker noise exponent		1.0

† Parameter value varies with temperature based on Tnom of model and Temp of device.

†† Value of 0.0 is interpreted as infinity.

Table 5-11. LEVEL3_MOD_Model Parameters (continued)

Parameter	**Description**	**Unit**	**Default**
Fc	bulk junction forward-bias depletion cap. coefficient		0.5
Delta	width effect on threshold voltage		0.0
Theta	mobility modulation	1/V	0.0
Eta	static feedback		0.0
Kappa	saturation field factor		0.2
Kappag	field correction factor gate drive dependence		0.0
Xmu	subthreshold fitting model parameter for NMOD		1.0
Rg	gate resistance	ohms	0.0
Rds	drain-source shunt resistance	ohms	infinity[††]
Tnom	nominal ambient temperature at which these model parameters were derived	×C	25
N	bulk P-N emission coefficient		1.0
Tt	bulk P-N transit time	sec	0.0
Ffe	flicker noise frequency exponent		1.0
Imax	explosion current	A	10.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

[†] Parameter value varies with temperature based on Tnom of model and Temp of device.

[††] Value of 0.0 is interpreted as infinity.

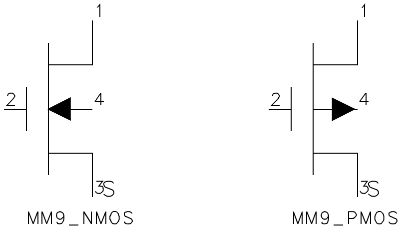
Notes/Equations/References

1. LEVEL3_MOD_Model is an enhanced version of the SPICE level 3 model. It exhibits smooth and continuous transitions in the weak to strong inversion region, and in the region between linear and saturation modes of device operation.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

MM9 (Philips MOS Model 9)

MM9_NMOS (Philips MOS Model 9, NMOS)
MM9_PMOS (Philips MOS Model 9, PMOS)

Symbol



Parameters

Model = name of a MOS_Model9

Length = channel length, in length units (default: 10^{-4})

Width = channel width, in length units (default: 10^{-4})

Ab = diffusion area (default: 10^{-12})

Ls = length of sidewall not under gate, in length units (default: 10^{-4})

Lg = length of sidewall under gate, in length units (default: 10^{-4})

Region = dc operating region: off, on, rev, sat (default: on)

Temp = device operating temperature, in °C (default: 27)

Mult = number of devices in parallel (default: 1)

Mode = device simulation mode: nonlinear, linear (default: nonlinear)

_M = number of devices in parallel (default: 1)

Notes/Equations/References

1. MOS Model 9 (version 902) is a compact MOS-transistor model intended for the simulation of circuit behavior with emphasis on analog applications. The model gives a complete description of all transistor action related quantities: nodal currents and charges, noise-power spectral densities and weak-avalanche currents. The equations describing these quantities are based on the gradual-channel approximation with a number of first-order corrections for small-size effects. The consistency is maintained by using the same

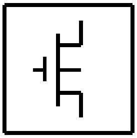
carrier-density and electrical-field expressions in the calculation of all model quantities. Model 9 provides a model for the intrinsic transistor only; junction charges and leakage currents are not included.

2. More information about the model can be obtained from:

   http://www.semiconductors.com/Philips_Models/mosmodel9.stm.html

MM30_Model (Philips MOS Model 30)

Symbol



Parameters

NMOS = NMOS Model Type; YES, NO (default: YES)

PMOS = PMOS Model Type; YES, NO (default: YES)

Ron = Ohmic resistance at zero-bias, Ohm (default: 1.0)

Rsat = space charge resistance at zero-bias in Ohms (default: 1.0)

Vsat = critical drain-source voltage for hot carrier, V (default: 10.0)

Psat = velocity saturation coefficient (default: 1.0)

Vp =pinch off voltage at zero gate and substrate voltages, V (default: -1.0)

Tox = gate oxide thickness, cm (default -1.0)

Dch = doping level channel, cm-3 (default: 1.0e+15)

Dsub = doping level substrate, cm-3 (default: 1.0e+15)

Vsub = substrate diffusion voltage, V (default: 0.6)

Cgate = gate capacitance at zero-bias, F (default: 0.0)

Csub = substrate capacitance at zero-bias, F (default: 0.0)

Tausc = space charge transit time of the channel, F (default: 0.0)

Tref = reference temperature on Celsius (default: 25.0)

Vgap = bandgap voltage channel, V (default: 1.2)

Ach = temperature coefficient resistivity of the channel (default: 0.0)

Kf = flicker noise coefficient (default: 0.0)

Af =flicker noise exponent (default: 1.0)

AllParams = Data Access Component (DAC) based parameters

Notes/Equations/References

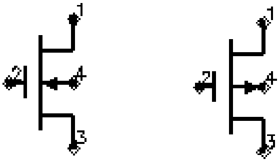
1. The Junction-Field-Effect Transistor (JFET) and the depletion mode Metal-Oxide (MOSFET) are semiconductor devices whose operation is achieved by depleting an already existing channel via a voltage controlled p-n junction (JFET) or a gate controlled surface depletion (MOSFET). These devices are often used as a load in high voltage MOS devices. This long channel JFET/MOSFET model is specially developed to describe the drift region of LDMOS, EPMOS and VDMOS devices. Please refer to the Philips report *The MOS model, level 3002.* The *pdf* file MOSModel 30.02 is downloadable at the following web site:

   http://www-us.semiconductors.com/Philips_Models/documentation/add_models/

Philips MOS Model 30 (NMOS and PMOS)

MM30_NMOS (Philips MOS Model 30, NMOS)
MM30_PMOS (Philips MOS Model 30, PMOS)

Symbol



Parameters

Model = Model instance name (can be file-based)

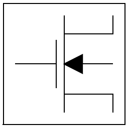
Temp = temperature in Celsius (default: 25.0)

Mult_ = Multiplication factor (default: 1.0)

_M = Number of devices in parallel (default: 1)

MOS_Model9_Process (Philips MOS Model 9, Process Based)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-12. MOS_Model9_Process

Parameter	Description	Units	Default
NMOS	N-channel type MOSFET		yes
PMOS	P-channel type MOSFET		no
Type	process-based model type		2
Ler	effective channel length of reference transistor	m	10^{-4}
Wer	effective channel width of reference transistor	m	10^{-4}
Lvar	difference between actual and programmed poly-silicon gate length	m	0.0
Lap	effective channel length reduction per side due to lateral diffusion of source/drain dopant ions	m	0.0
Wvar	difference between actual and programmed field-oxide opening	m	0.0
Wot	effective channel width reduction per side due to lateral diffusion of channel-stop dopant ions	m	0.0
Tr	temperature at which parameters have been determined	°C	27
Vtor	threshold voltage at zero back-bias	V	0.87505
Stvto	coefficient of temperature dependence of Vto	V/K	0.0
Slvto	coefficient of length dependence of Vto	V×m	0.0
Sl2vto	second coefficient of length dependence of Vto	$V\times m^2$	0.0
Swvto	coefficient of width dependence of Vto	V×m	0.0
Kor	low back-bias body factor	√ V	0.74368

Table 5-12. MOS_Model9_Process (continued)

Parameter	Description	Units	Default
Slko	coefficient of length dependence of Ko	√ V×m	0.0
Swko	coefficient of width dependence of Ko	√ V×m	0.0
Kr	high back-bias body factor	√ V	0.55237
Slk	coefficient of length dependence of K	√ V×m	0.0
Swk	coefficient of width dependence of K	√ V×m	0.0
Phibr	surface potential at strong inversion	V	0.65
Vsbxr	transition voltage for dual-k factor model	V	0.63304
Slvbsx	coefficient of length dependence of Vsbx	V×m	0.0
Swvbsx	coefficient of width dependence of Vsbx	V×m	0.0
Betsq	gain factor	A/V^2	0.12069×10^{-3}
Etabet	exponent of temperature dependence of gain factor		0.0
The1r	coefficient of mobility due to gate-induced field	1/V	0.99507×10^{-01}
Stthe1r	coefficient of temperature dependence of The1	1/V/K	0.0
Slthe1r	coefficient of length dependence of The1	m/V	0.0
Stlthe1	coefficient of temperature dependence of length dependence of The1	m/V/K	0.0
Swthe1	coefficient of width dependence of The1	m/V	0.0
Wdog	characteristic drain gate width below which dogboning appears	m	0.0
Fthe1	coefficient describing the width dependence of The1 for W < Wdog		0.0
The2r	coefficient of mobility due to back-bias	√ V	0.43225×10^{-1}
Stthe2r	coefficient of temperature dependence of The2	√ ς/K	0.0
Slthe2r	coefficient of length dependence of The2	m/√ V	0.0
Stlthe2	coefficient of temperature dependence of length dependence of The2	m/√ V/K	0.0
Swthe2	coefficient of width dependence of The2	m/√ V$^{)}$	0.0
The3r	coefficient of mobility due to lateral field	1/V	0.0

Table 5-12. MOS_Model9_Process (continued)

Parameter	Description	Units	Default
Stthe3r	coefficient of temperature dependence of The3	1/V/K	0.0
Slthe3r	coefficient of length dependence of The3	m/V	0.0
Stlthe3	coefficient of temperature dependence of length dependence of The3	m/V/K	0.0
Swthe3	coefficient of width dependence of The3	m/V	0.0
Gam1r	coefficient for drain-induced threshold shift for large gate drive	$V^{(1\text{-Etads})}$	0.38096×10^{-2}
Slgam1	coefficient of length dependence of Gam1	$V^{(1\text{-Etads})}m$	0.0
Swgam1	coefficient of width dependence of Gam1	$V^{(1\text{-Etads})}m$	0.0
Etadsr	exponent of Vds dependence of Gam1		0.6
Alpr	factor of channel-length modulation		0.1×10^{-1}
Etaalp	exponent of length dependence of Alp		0.0
Slalp	coefficient of length dependence of Alp	$m^{(\text{Etaalp})}$	0.0
Swalp	coefficient of width dependence of Alp	m	0.0
Vpr	characteristic voltage of channel length modulation	V	0.67876×10^{1}
Gamoor	coefficient of drain-induced threshold shift at zero gate drive		0.29702×10^{-4}
Slgamoo	coefficient of length dependence of Gamo	m^2	0.0
Etagamr	exponent of back-bias dependence of Gamo		2.0
Mor	factor of subthreshold slope		0.44
Stmo	coefficient of temperature dependence of Mo	1/K	0.0
Slmo	coefficient of length dependence of Mo	$\sqrt{m}$	0.0
Etamr	exponent of back-bias dependence of M		2.0
Zet1r	weak-inversion correction factor		0.2015×10^{1}
Etazet	exponent of length dependence of Zet1		0.0
Slzet1	coefficient of length dependence of Zet1	$m^{(\text{Etazet})}$	0.0

Table 5-12. MOS_Model9_Process (continued)

Parameter	**Description**	**Units**	**Default**
Vsbtr	limiting voltage of VSB dependence of M and Gamo	V	0.61268×10^{1}
Slvsbt	coefficient of length dependence of Vsbt	m×V	0.0
A1r	factor of weak-avalanche current		0.20348×10^{2}
Sta1	coefficient of temperature dependence of A1	1/K	0.0
Sla1	coefficient of length dependence of A1	m	0.0
Swa1	coefficient of width dependence of A1	m	0.0
A2r	exponent of weak-avalanche current	V	0.33932×10^{2}
Sla2	coefficient of length dependence of A2	m×V	0.0
Swa2	coefficient of width dependence of A2	m×V	0.0
A3r	factor of drain-source voltage above which weak-avalanche occurs		0.10078×10^{1}
Sla3	coefficient of length dependence of A3	m	0.0
Swa3	coefficient of width dependence of A3	m	0.0
Tox	thickness of oxide layer	m	10^{-6}
Col	gate overlap per unit channel width	F/m	0.0
Ntr	coefficient of thermal noise	J	0.0
Nfr	coefficient of flicker noise	V^{2}	0.0
Vr	voltage at which junction parameters have been determined	V	0.0
Jsgbr	bottom saturation current density due to electron-hole generation at V=Vr	A/m^{2}	10^{-14}
Jsdbr	bottom saturation current density due to diffusion from back contact	A/m^{2}	10^{-14}
Jsgsr	sidewall saturation current density due to electron-hole generation at V=Vr	A/m	10^{-14}
Jsdsr	sidewall saturation current density due to diffusion from back contact	A/m	10^{-14}

Table 5-12. MOS_Model9_Process (continued)

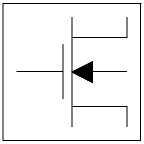
Parameter	**Description**	**Units**	**Default**
Jsggr	gate edge saturation current density due to electron-hole generation at V=Vr	A/m	10^{-14}
Jsdgr	gate edge saturation current density due to diffusion from back contact	A/m	10^{-14}
Cjbr	bottom junction capacitance at V=Vr	F/m^2	0.0
Cjsr	sidewall junction capacitance at V=Vr	F/m	0.0
Cjgr	gate edge junction capacitance at V=Vr	F/m	0.0
Vdbr	diffusion voltage of bottom junction at V=Vr	V	0.8
Vdsr	diffusion voltage of sidewall junction at V=Vr	V	0.8
Vdgr	diffusion voltage of gate edge junction at V=Vr	V	0.8
Pb	bottom-junction grading coefficient		0.5
Ps	sidewall-junction grading coefficient		0.5
Pg	gate-edge-junction grading coefficient		0.5
Nb	emission coefficient of bottom forward current		1.0
Ns	emission coefficient of sidewall forward current		1.0
Ng	emission coefficient of gate-edge forward current		1.0
AllParams	DataAccessComponent-based parameters		

Notes/Equations/References

1. This model supplies values for an MM9 device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

MOS_Model9_Single (Philips MOS Model 9, Single Device)

Symbol



Parameters

Model parameters must be specified in SI units.

Table 5-13. MOS_Model9_Single Parameters

Parameter	Description	Units	Default
NMOS	N-channel type MOSFET		yes
PMOS	P-channel type MOSFET		no
Type	single device type		1
Vto	threshold voltage at zero back-bias	V	0.87505
Ko	low-back-bias body factor	$V^{(1/2)}$	0.74368
K	high-back-bias body factor	$V^{(1/2)}$	0.55237
Phib	surface potential at strong inversion	V	0.65
Vsbx	transition voltage for dual-k factor model	V	0.63304
Bet	gain factor	A/V^2	0.12069×10^{-3}
The1	coefficient of mobility reduction due to gate-induced field	1/V	0.99507×10^{-1}
The2	coefficient of mobility reduction due to back-bias	$V^{(1/2)}$	0.43225×10^{-1}
The3	coefficient of mobility reduction due to lateral field	1/V	0.0
Gam1	coefficient for drain-induced threshold shift for large gate drive	$V^{(1\text{-}Etads)}$	0.38096×10^{-2}
Etads	exponent of VDS dependence of Gam1		0.6
Alp	factor of channel-length modulation		0.1×10^{-1}
Vp	characteristic voltage of channel length modulation	V	0.67876×10^{1}
Gamoo	coefficient of drain-induced threshold shift at zero gate drive		0.29702×10^{-4}

Table 5-13. MOS_Model9_Single Parameters

Parameter	**Description**	**Units**	**Default**
Etagam	exponent of back-bias dependence of Gamo		2.0
Mo	factor of subthreshold slope		0.44
Etam	exponent of back-bias dependence of M		2.0
Zet1	weak-inversion correction factor		0.20153×10^{1}
Vsbt	limiting voltage of vsb dependence of M and Gamo	V	$0.61268\times10^{+1}$
A1	factor of weak-avalanche current		0.20348×10^{2}
A2	exponent of weak-avalanche current	V	0.33932×10^{2}
A3	factor of drain-source voltage above which weak-avalanche occurs		0.10078×10^{1}
Cox	gate-to-channel capacitance	F	10^{-12}
Cgso	gate-source overlap capacitance	F	10^{-12}
Cgdo	gate-drain overlap capacitance	F	10^{-12}
Nt	coefficient of thermal noise	J	0.0
Nf	coefficient of flicker noise	V^{2}	0.0
Isgb	generation saturation current of bottom area AB	A	10^{-14}
Isdb	diffusion saturation current of bottom area AB	A	10^{-14}
Isgs	generation saturation current of locos-edge LS	A	10^{-14}
Isds	diffusion saturation current of locos-edge LS	A	10^{-14}
Isgg	generation saturation current of gate-edge LG	A	10^{-14}
Isdg	diffusion saturation current of gate-edge LG	A	10^{-14}
Cjb	bottom junction capacitance	F	10^{-15}
Cjs	sidewall junction capacitance	F	10^{-15}
Cjg	gate edge junction capacitance	F	10^{-15}
Vdb	diffusion voltage of bottom area Ab	V	1.0
Vds	diffusion voltage of Locos-edge Ls	V	1.0
Vdg	diffusion voltage of gate edge Lg	V	1.0

Table 5-13. MOS_Model9_Single Parameters

Parameter	**Description**	**Units**	**Default**
Pb	bottom-junction grading coefficient		0.8
Ps	sidewall-junction grading coefficient		0.8
Pg	gate-edge-junction grading coefficient		0.8
Nb	emission coefficient of bottom forward current		1.0
Ns	emission coefficient of sidewall forward current		1.0
Ng	emission coefficient of gate-edge forward current		1.0
wVsubfwd	substrate junction forward bias (warning)	V	infinite
wBvsub	substrate junction reverse breakdown voltage (warning)	V	infinite
wBvg	gate oxide breakdown voltage (warning)	V	infinite
wBvds	drain-source breakdown voltage (warning)	V	infinite
wIdsmax	maximum drain-source current (warning)	A	infinite
wPmax	maximum power dissipation (warning)	W	infinite
AllParams	DataAccessComponent-based parameters		

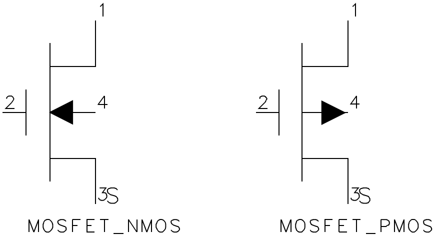
Notes/Equations/References

1. This model supplies values for an MM9 device.
2. Use AllParams with a DataAccessComponent to specify file-based parameters (refer to DataAccessComponent). Note that model parameters that are explicitly specified take precedence over those specified via AllParams. Set AllParams to the DataAccessComponent instance name.

MOSFET (Nonlinear, N-Channel and P-Channel)

MOSFET_NMOS (Nonlinear MOSFET, N-Channel)
MOSFET_PMOS (Nonlinear MOSFET, P-Channel)

Symbol



Parameters

Model = name of BSIM1_Model, BSIM2_Model, BSIM3_Model, LEVEL1_Model, LEVEL2_Model, LEVEL3_Model, or LEVEL3_MOD_Model

Length = channel length: um, mm, cm, meter, mil, in (default: 10^{-4} m)

Width = channel width: um, mm, cm, meter, mil, in (default: 10^{-4} m)

Ad = drain diffusion area, m^2 (default: 0.0)

As = source diffusion area, m^2 (default: 0.0)

Pd = drain junction perimeter: um, mm, cm, meter, mil, in (default: 0.0 m)

Ps = source junction perimeter: um, mm, cm, meter, mil, in (default: 0.0 m)

Nrd = number of equivalent squares in drain diffusion region (default: 1); Nrd is multiplied by Rsh (sheet resistance factor specified in Model) to get parasitic series drain resistance.

Nrs = number of equivalent squares in source diffusion region (default: 1) Nrs is multiplied by Rsh (sheet resistance factor specified in Model) to get parasitic series source resistance.

Region = dc operating region: off, on, rev, sat (default: on)

Temp = device operating temperature (refer to Note 1), in °C, (default: 25)

Mode = simulation mode for this device: nonlinear or linear (default: nonlinear) (refer to Note 3)

Nqsmod = turns on(1) or off(0) the Non-Quasi static charge model option

_M = number of devices in parallel (default:1)

Range of Usage

Length, Width, Ad, As, Pd, Ps > 0

Notes

1. The Temp parameter specifies the physical (operating) temperature of the device. If this is different than the temperature at which the model parameters are valid or extracted (specified by the Tnom parameter of the associated model) certain model parameters are scaled such that the device is simulated at its operating temperature. Refer to the appropriate model to see which parameter values are scaled.
2. The M_ parameter affects MOSFET channel width, diode leakage, capacitors, and resistors in the following manner.

   Width: Mult × Weff

   Areas and perimeters:

      Mult × Ad

      Mult × As

      Mult × Pd

      Mult × Ps

   Diode leakage:

      if (Js == 0), then Is = Mult × Is

   Capacitors:

      if (CJ == 0), then Cbd = Mult × Cbd, Cbs = Mult × Cbs

   Resistors:

      if (Nrs × Rsh == 0), then Rs = Rs/Mult; else Rs = (Nrs × Rsh)/Mult

      if (Nrd × Rsh == 0), then Rd = Rd/Mult; else Rd (Nrd × Rsh)/Mult

   Due to second-order effects in some models (BSIM3 for example), the use of the Mult parameter is not exactly equivalent to parallel multiple devices.
3. The Mode parameter is used only during harmonic balance, oscillator, or large-signal S-parameter analysis. By identifying devices that are operating in their linear region, the simulation time may be decreased. Devices with Mode=linear are linearized about their dc operating point.
4. This device has no default artwork associated with it.

References

[1] H. Shichman and D. A. Hodges. “Modeling and simulation of insulated-gate field-effect transistor switching circuits,” *IEEE Journal of Solid-State Circuits,* SC-3, 285, September 1968.

[2] A. Vladimirescu and S. Liu. *The Simulation of MOS Integrated Circuits Using SPICE2,* Memorandum No. M80/7, February 1980.

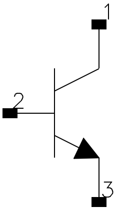
[3] P. Antognetti and G. Massobrio. *Semiconductor Device Modeling with SPICE,* McGraw-Hill, Inc., 1988.

[4] D. A. Divekar, *FET Modeling for Circuit Simulation*, Kluwer Academic Publishers, 1988.

Chapter 6: Linear Devices

BIP (Bipolar Transistor)

Symbol



Parameters

A = magnitude of current gain (alpha) at dc

T = time delay associated with current gain, in seconds

F = −3 dB frequency for current gain, in hertz

Cc = collector capacitance, in farads

Gc = collector conductance, in Siemens

Rb = base resistance, in ohms

Lb = base inductance, in henries

Ce = emitter capacitance, in farads

Re = emitter resistance, in ohms

Le = emitter inductance, in henrie

Range of Usage

$0 < A < 1.0$

Notes/Equations/References

1. $$A(f) = A \times \frac{e^{-(j2\pi fT)}}{1 + j\left(\frac{f}{F}\right)} \quad (\text{for } F > 0)$$

   $$A(f) = A \times e^{-(j\,2\,p\,f\,T)} \quad (\text{for } F = 0)$$

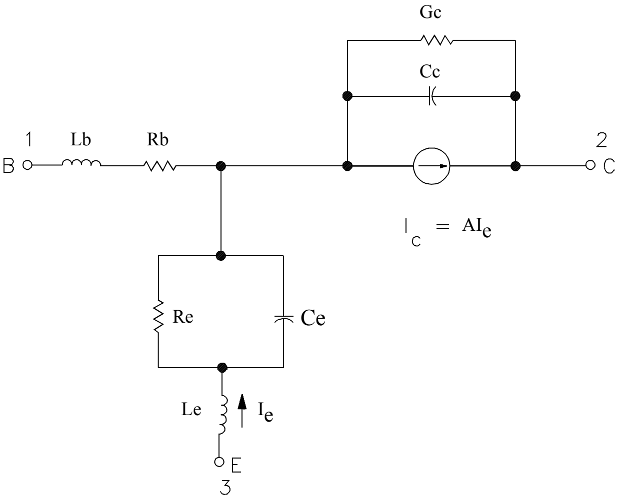
   where

   f= simulation frequency

F = reference frequency

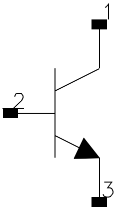
2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.
4. This component has no default artwork associated with it.

Equivalent Circuit



BIPB (Bipolar Transistor, ß Control)

Symbol



Parameters

B = magnitude of current gain (Beta) at dc

A = phase offset of current gain

T = time delay associated with current gain, in seconds

Cc = collector capacitance, in farads

Gc = collector conductance, in Siemens

Rb = base resistance, in ohms

Lb = base inductance, in henries

Ce = emitter capacitance, in farads

Re = emitter resistance, in ohms

Le = emitter lead inductance, in henries

Rel = emitter lead resistance, in ohms

Range of Usage

B > 0

Notes/Equations/References

1. $\beta(f) = B \times e^{-j(2\pi f T_{\sec} - A_{radians})}$

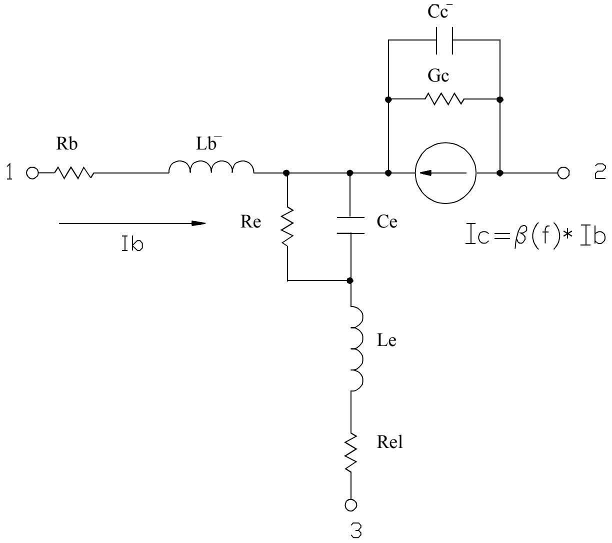
   where

   f = simulation frequency in hertz

2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.

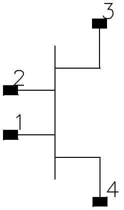
4. This component has no default artwork associated with it.

Equivalent Circuit



DFET (Dual-Gate Field Effect Transistor)

Symbol



Parameters

Gm1 = dc transconductance - gate 1, in Siemens

T1 = time delay of Gm1, in seconds

F1 = –3 dB frequency for Gm1

Cgs1 = gate-to-source capacitance - gate 1, in farads

Ri1 = input resistance - gate 1, in ohms

Cdg1 = drain-to-gate capacitance - gate 1, in farads

Cds1 = drain-to-source capacitance - gate 1, in farads

Rds1 = drain-to-source resistance - gate 1, in ohms

Rg1 = gate1 resistance, in ohms

Lg1 = gate1 inductance, in henries

Gm2 = dc transconductance - gate 2, in Siemens

T2 = time delay of Gm2, in seconds

F2 = –3 dB frequency for Gm2

Cgs2 = gate-to-source capacitance - gate 2, in farads

Ri2 = input resistance - gate 2, in ohms

Cdg2 = drain-to-gate capacitance - gate 2, in farads

Cds2 = drain-to-source capacitance - gate 2, in farads

Rds2 = drain-to-source resistance - gate 2, in ohms

Rg2 = gate 2 resistance, in ohms

Lg2 = gate 2 inductance, in henries

Rd = drain resistance, in ohms

Ld = drain inductance, in henries

Rs = source resistance, in ohms

Ls = source inductance, in henries

Cgls = gate1-to-source capacitance, in farads

Cgl2 = gate1-to-gate2 capacitance, in farads

Cgld = gate1-to-drain capacitance, in farads

Cg2d = gate2-to-drain capacitance, in farads

Cds = drain-to-source capacitance, in farads

R12 = resistance representing composite of resistance of drain 1 and source 2, in ohms

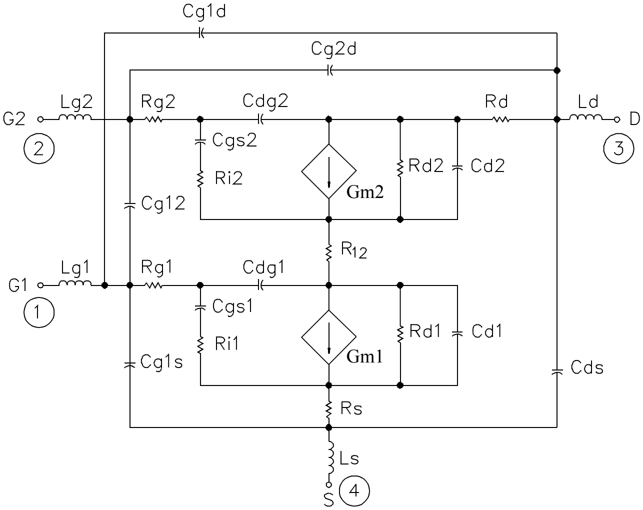
Range of Usage

N/A

Notes/Equations/References

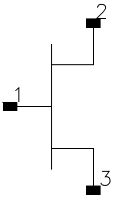
1. For time-domain analysis, the frequency-domain analytical model is used.
2. This component is assumed to be noiseless.
3. This component has no default artwork associated with it.

Equivalent Circuit



FET (Field Effect Transistor)

Symbol



Parameters

G = magnitude of transconductance at dc, in Siemens

T = time delay associated with transconductance, in seconds

F = transconductance roll-off frequency, in frequency units

Cgs = gate-to-source capacitance, in farads

Ggs = gate-to-source conductance, in Siemens

Ri = channel resistance, in ohms

Cdg = drain-to-gate capacitance, in farads

Cdc = dipole layer capacitance, in farads

Cds = drain-to-source capacitance, in farads

Rds = drain-to-source resistance, in ohms

Range of Usage

N/A

Notes/Equations/References

1. Setting F equal to zero gives constant transconductance magnitude with respect to frequency:

   $$\text{Transconductance} = G(f) = G \times \left(\frac{e^{-(j2\pi fT)}}{1 + j\frac{f}{F}}\right) \qquad (\text{for } F > 0)$$

   $$\text{Transconductance} = G(f) = G \times e^{-(j2\pi fT)} \qquad (\text{for } F = 0)$$

   where

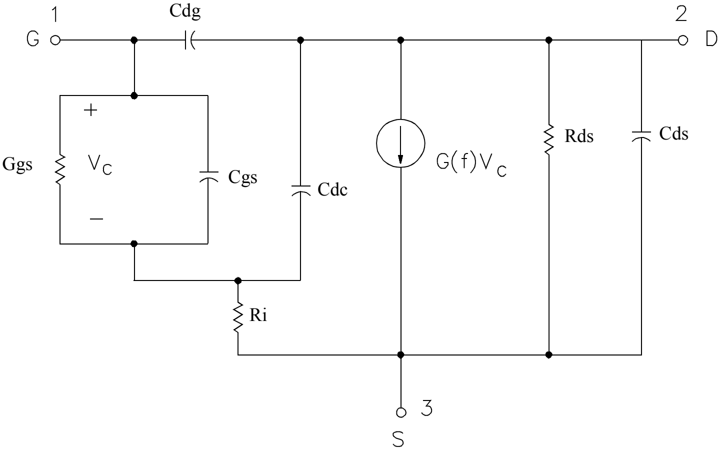
f = simulation frequency, in hertz

F = reference frequency, in hertz

T = time delay, in seconds

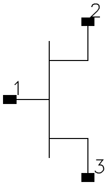
2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.
4. This component has no default artwork associated with it.

Equivalent Circuit



FET2 (Field Effect Transistor with Source Resistance)

Symbol



Parameters

G = magnitude of transconductance at dc, in Siemens

T = time delay associated with transconductance, in seconds

F = transconductance roll-off frequency, in frequency units

Cgs = gate-to-source capacitance, in farads

Ggs = gate-to-source conductance, in Siemens

Ri = channel resistance, in ohms

Cdg = drain-to-gate capacitance, in farads

Cdc = dipole layer capacitance, in farads

Cds = drain-to-source capacitance, in farads

Rds = drain-to-source resistance, in ohms

Rs = source resistance, in ohms

Range of Usage

N/A

Notes/Equations/References

1. Setting F equal to zero gives constant transconductance magnitude with respect to frequency:

$$\text{Transconductance} = G(f) = G \times \left(\frac{e^{-(j2\pi fT)}}{1 + j\frac{f}{F}}\right) \qquad (\text{for } F > 0)$$

$$\text{Transconductance} = G(f) = G \times e^{-(j2\pi fT)} \qquad (\text{for } F = 0)$$

where

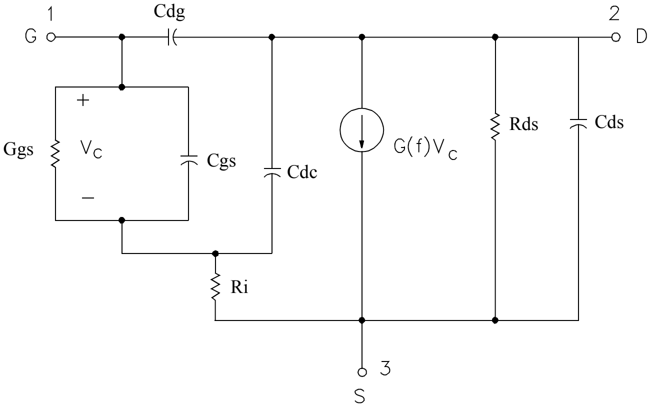
f = simulation frequency, in hertz

F = reference frequency, in hertz

T = time delay, in seconds

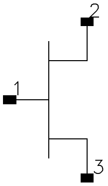
2. For time-domain analysis, the frequency-domain analytical model is used.
3. This component is assumed to be noiseless.
4. This component has no default artwork associated with it.

Equivalent Circuit



FETN1 (FET Noise Model (Van der Ziel))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rds = drain-to-source resistance, in ohms

P = noise parameter P (see references)

R = noise parameter R (see references)

C = noise parameter C (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by A. Van der Ziel) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN1 is determined by connecting appropriate circuit components externally to FETN1.
3. For time-domain analysis, the frequency-domain analytical model is used.
4. This component has no default artwork associated with it.

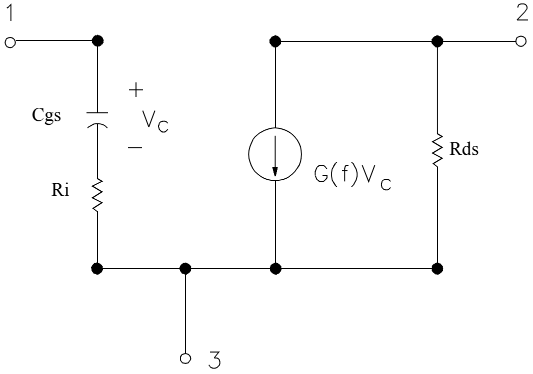
References

[1] C. Liechti "Microwave Field Effect Transistors—1976," *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-24, June 1976, pp. 279-300.

[2] A. Van der Ziel, “Gate Noise in Field Effect Transistors at Moderately High Frequencies,” *Proceedings of the IEEE,* Vol. 51, March 1963, pp. 461-467.

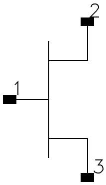
[3] A. Van der Ziel, “Thermal Noise in Field Effect Transistors,” *Proceedings of the IRE,* Vol. 50, August 1962, pp. 1808-1812.

Equivalent Circuit



FETN2 (FET Noise Model (Statz, et al))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rs = drain-to-source resistance, in ohms

Rg = gate resistance, in ohms

Kr = noise parameter Kr (see references)

Kc = noise parameter Kc (see references)

Kg = noise parameter Kg (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Statz, et al.) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN2 is determined by connecting appropriate circuit components externally to FETN2.
3. For time-domain analysis, the frequency-domain analytical model is used.
4. This component has no default artwork associated with it.

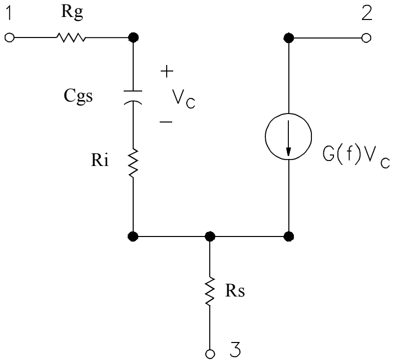
References

[1] R. Pucel, H. Haus, and H. Statz. “Signal and Noise Properties of Gallium Arsenide Microwave Field-Effect Transistors,” *Advances in Electronics and Electron Physics*, Vol. 38. New York: Academic Press, 1975, pp. 195-265.

[2] R. Pucel, D. Masse, and C. Krumm. “Noise Performance of Gallium Arsenide Field-Effect Transistors,” *IEEE Journal of Solid-State Circuits,* Vol. SC-11, April 1976, pp. 243-255.

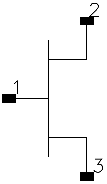
[3] H. Statz, H. Haus, and R. Pucel. “Noise Characteristics of Gallium Arsenide Field-Effect Transistors,” *IEEE Transactions on Electron Devices,* Vol. ED-21, September 1974, pp. 549-562.

Equivalent Circuit



FETN3 (FET Noise Model (Fukui))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rs = source resistance, in ohms

Rg = gate resistance, in ohms

K1 = noise parameter K1 (see references)

K2 = noise parameter K2 (see references)

K3 = noise parameter K3 (see references)

K4 = noise parameter K4 (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Fukui) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN3 is determined by connecting appropriate circuit components externally to FETN3.
3. The expressions that relate the noise parameters to the model components (G, Cgs, for example) and the K1-K4 parameters use the model components in specific units. The values of K1-K4 should conform to these units of the model components. (See references.)
4. For time-domain analysis, the frequency-domain analytical model is used.

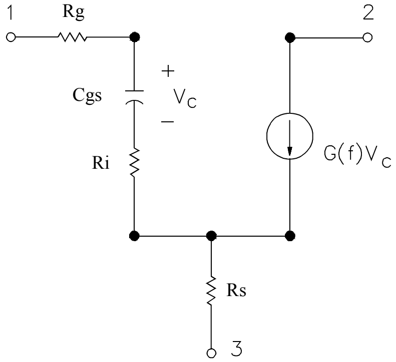
5. This component has no default artwork associated with it.

References

[1] H. Fukui, “Design of Microwave GaAs MESFET’s for Broad-Band Low-Noise Amplifiers,” *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-27, July 1979, pp. 643-650.

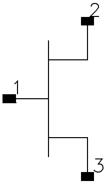
[2] H. Fukui, Addendum to “Design of Microwave GaAs MESFET’s for Broad-Band Low-Noise Amplifiers,” *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-29, October 1981.

Equivalent Circuit



FETN4 (FET Noise Model (Podell))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rs = source resistance, in ohms

Rg = gate resistance, in ohms

NFmin = minimum noise figure, in dB

FRef = frequency at which NFMin is measured, in hertz

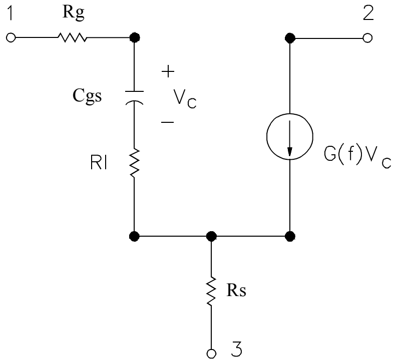
Range of Usage

N/A

Notes/Equations/References

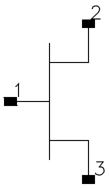
1. This component provides a linear bias-independent FET noise model (by Podell) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN4 is determined by connecting appropriate circuit components externally to FETN4.
3. For time-domain analysis, the frequency-domain analytical model is used.
4. This component has no default artwork associated with it.
5. A. Podell, “A Functional GaAs FET Noise Model,” *IEEE Transactions on Electron Devices*, Vol. ED-28, No. 5, May 1981, pp. 511-517.

Equivalent Circuit



FETN4a (FET Noise Model (Podell))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rs = source resistance, in ohms

Rg = gate resistance, in ohms

K = parameter related to the noise performance of this model (see references)

Range of Usage

N/A

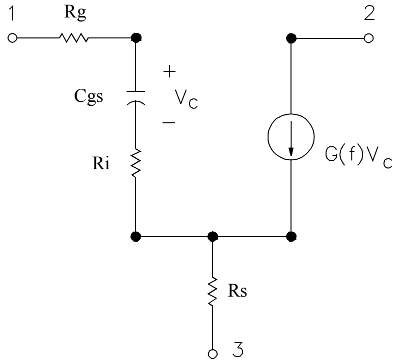
Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Podell) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. This model is the same as FETN4 except that the input parameter related to the noise performance for FETN4a is K, whereas those for FETN4 are NFMin and FRef. Specifying K instead of NFMin and FRef is an alternate way to describe the same model.
3. The effect of feedback or parasitics on the noise performance of FETN4a is determined by connecting appropriate circuit components externally to FETN4a.
4. For time-domain analysis, the frequency-domain analytical model is used.
5. This component has no default artwork associated with it.

References

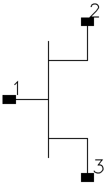
[1] A. Podell, “A Functional GaAs FET Noise Model,” *IEEE Transactions on Electron Devices,* Vol. ED-28, No. 5, May 1981, pp. 511-517.

Equivalent Circuit



FETN5 FET Noise Model (Gupta, et al))

Symbol



Parameters

G = magnitude of transconductance, in Siemens

T = = time delay associated with transconductance, in seconds

Cgs = gate-to-source capacitance, in farads

Ri = channel resistance, in ohms

Rds = drain-to-source resistance, in ohms

Rs = source resistance, in ohms

Rg = gate resistance, in ohms

Sio = power spectral density of output noise current, in picoamperes squared per hertz (see references)

Range of Usage

N/A

Notes/Equations

1. This component provides a linear bias-independent FET noise model (by Gupta, et al.) for use during a noise analysis. The signal performance of the component is determined by the equivalent circuit shown following these notes.
2. The effect of feedback or parasitics on the noise performance of FETN5 is determined by connecting appropriate circuit components externally to FETN5.
3. For time-domain analysis, the frequency-domain analytical model is used.
4. This component has no default artwork associated with it.

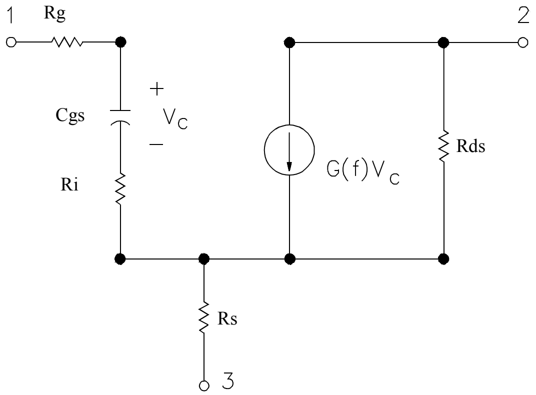
References

[1] M. Gupta, O. Pitzalis, S. Rosenbaum, and P. Greiling. “Microwave Noise Characterization of GaAs MESFET’s: Evaluation by On-Wafer Low-Frequency Output Noise Current

Measurement," *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-35, No. 12, December 1987, pp. 1208-1217.

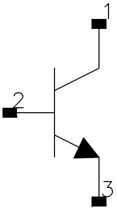
[2] M. Gupta and P. Greiling. "Microwave Noise Characterization of GaAs MESFET's: Determination of Extrinsic Noise Parameters," *IEEE Transactions on Microwave Theory and Techniques,* Vol. 36, No. 4, April 1988, pp. 745-751.

Equivalent Circuit



HYBPI (Hybrid-Pi Bipolar Transistor)

Symbol



Parameters

G = transconductance, in Siemens

T = transit time, in seconds

Cpi = base-emitter (pi) capacitance, in farads

Rpi = base-emitter (pi) resistance, in ohms

Cmu = base-collector (mu) capacitance, in farads

Rmu = base-collector (mu) resistance, in ohms

Rb = base resistance, in ohms

Rc = collector resistance, in ohms

Re = emitter resistance, in ohms

Range of Usage

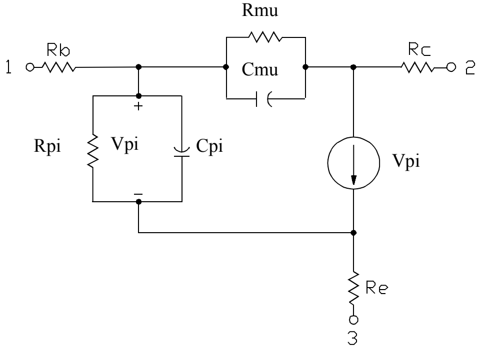
Rpi > 0

Rmu > 0

Notes/Equations/References

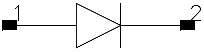
1. For time-domain analysis, the frequency-domain analytical model is used.
2. This component is assumed to be noiseless.
3. This component has no default artwork associated with it.

Equivalent Circuit



PIN (PIN Diode, Chip Model)

Symbol



Parameters

Cj = junction capacitance, in farads

Rj = junction resistance, in ohms

Rs = diode series resistance, in ohms

Ls = bond wire inductance, in henries

Cb = by-pass capacitance, in farads

Cg = capacitance of gap across which diode is connected, in farads

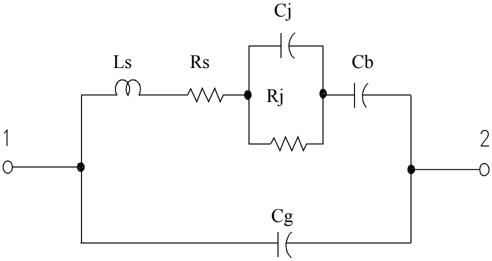
Range of Usage

N/A

Notes/Equations/References

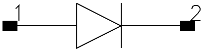
1. This component is assumed to be noiseless.
2. This component has no default artwork associated with it.

Equivalent Circuit



PIN2 (PIN Diode, Packaged Model)

Symbol



Parameters

Cj = junction capacitance, in farads

Rj = junction resistance, in ohms

Rs = series resistance, in ohms

Ls = series inductance, in henries

Cp = package capacitance, in farads

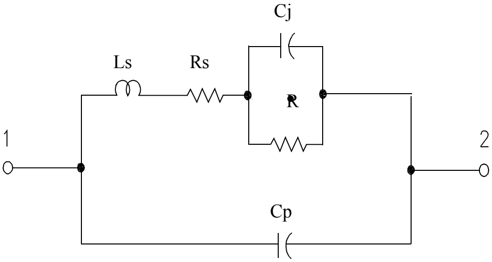
Range of Usage

N/A

Notes/Equations/References

1. This component is assumed to be noiseless.
2. This component has no default artwork associated with it.

Equivalent Circuit



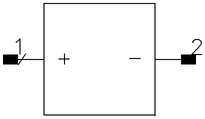
Chapter 7: Equation-Based Non-Linear Components

Multiplicity (_M) Parameter

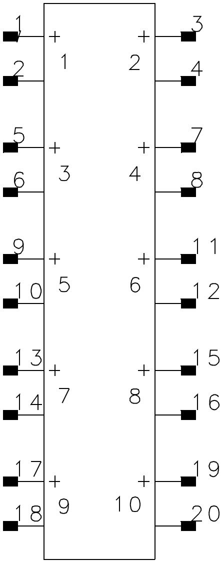
For more information on the use of the multiplicity feature (the _M parameter, which is available with several devices in this chapter), refer to the section "Multiplicity." This section appears in Chapter 1, Introduction, of *Circuit Components: Introduction and Simulation Components*.

FDD1P to FDD 10P (1- to 10-Port Frequency-Domain Defined Device)

Symbol



FDD1P



FDD10P

Parameters

I[i, j]] = current equation that describes spectral current. *i* refers to the port number. *j* refers to a frequency index.

V[i, j] = voltage equation that describes spectral voltage. *i* refers to the port number. *j* refers to a frequency index.

Freq[k] = carrier frequency, in hertz

Trig[k] = trigger event

Ce[k] = clock enable definiiton

Range of Usage

$0 \le i \le 10$

Notes/Equations/References

1. The frequency-domain defined device (FDD) enables you to create equation-based, user-defined, nonlinear components. The FDD is a multi-port device that describes current

and voltage spectral values in terms of algebraic relationships of other voltage and current spectral values. It is for developing nonlinear, behavioral models that are more easily defined in the frequency domain.

For complete information on how to use these devices and application examples, refer to *Circuit Simulation*.

2. Equations that relate the port spectral voltages and currents are described in the frequency domain. The two basic types of equations are current equations and voltage equations. Their format is:

   I[port, findex] = f(_sv(),_sv_d(),_si(),_si_d())

   V[port, findex] = f(_sv(),_sv_d(),_si(),_si_d())

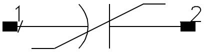
   where *port* is the port number and *findex* is a frequency index.

   The equations can be listed in any order, and more than one equation can be used for a single port, but each port must have at least one equation.

   The variables of interest at a given port are the port spectral voltages and port spectral currents. Spectral voltages and currents can be obtained using the functions *_sv(), _si()*, *_sv_d()*, and *_si_d().*
3. The *freq* parameter enables you to define one or more carrier frequencies.
4. The FDD enables you to define up to 31 trigger events. Anytime the value of the trigger expression is equal to a number other than zero, a trigger event is declared for the corresponding trigger.
5. Clock enables specify that the output of a given port can change only when a specified trigger, or a set of specified triggers, occurs.

NonlinC (Nonlinear Capacitor)

Symbol



Parameters

Coeff = list of coefficients that describe a polynomial that defines capacitance as a function of voltage v across the capacitor where

$$cap = Coeff[0] + Coeff[1] \times v + Coeff[2] \times v^2 + ... + Coeff[n] \times v^n$$

and coefficients are entered using the list function

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

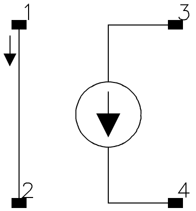
Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line.
2. Units of Coeff[0] = farads
   units of Coeff[1] = farads/volt
   units of Coeff[2] = farads/volt^2

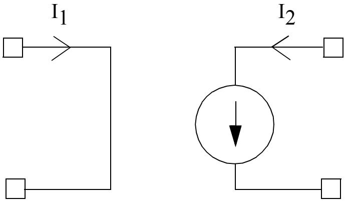
   Coefficients are entered using the list function. For example, if
   $C = 5V^2 + 4V^4$
   the parameter entry is
   Coeff = list(0,0,5,0,4)
3. The controlling voltage v is the voltage across the capacitor, with pin 1 (the one with the slash) being positive and pin 2 being negative.
4. This component has no default artwork associated with it.

NonlinCCCS (Nonlinear Current-Controlled Current Source)

Symbol



Illustration



Parameters

Coeff =list of coefficients that describe a polynomial that defines output current I_2 as a function of input current I_1:

if only one coefficient is specified

$I_2 = \text{Coeff}[0] \times I_1^2$

the coefficient is entered using the list function

Coeff = list(Coeff[0])

otherwise

$I_2 = \text{Coeff}[0] + \text{Coeff}[1] \times I_1 + \text{Coeff}[2] \times I_1^2 + \ldots + \text{Coeff}[n] \times I_1^n$

and coefficients are entered as

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line using the list function. For example, if

   $I_2 = 3 - 2I_1^2 + 5I_1^6$

   the parameter entry is

   Coeff = list(3,0,-2,0,0,0,5)

   If $I_2 = 5I_1$, then Coeff = list(5)

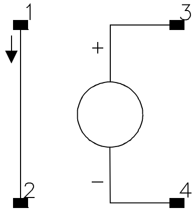
   If $I_2 = 5$, then Coeff = list(5,0)

2. This component has no default artwork associated with it.

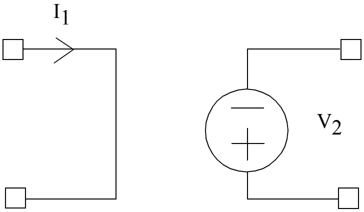
3. Output current is in Amperes.

NonlinCCVS (Nonlinear Current-Controlled Voltage Source)

Symbol



Illustration



Parameters

Coeff = a list of coefficients that describe a polynomial that defines output voltage V_2 as a function of input current I_1:

if only one coefficient is specified

V_2 = Coeff[0] × I_1

the coefficient is entered using the list function

Coeff = list(Coeff[0])

otherwise

V_2 = Coeff[0] + Coeff[1] × I_1 + Coeff[2] × I_1^2 +.. .+Coeff[n] × I_1^n

and coefficients are entered as

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line.Enter values for each coefficient in a single line using the list function. For example, if

   $V_2 = 3 - 2I_1^2 + 5I_1^6$

   the parameter entry is

   Coeff = list(3,0,-2,0,0,0,5)

   If $V_2 = 5I_1$, then Coeff = list(5)

   If $V_2 = 5$, then Coeff = list(5,0)

2. This component has no default artwork associated with it.
3. Output voltage is in Volts.

NonlinL (Nonlinear Inductor)

Symbol

Parameters

Coeff = a list of coefficients that describe a polynomial that defines inductance as a function of current through the inductor:

$$L = Coeff[0] + Coeff[1] \times I + Coeff[2] \times I^2 + . . . + Coeff[n] \times I^n$$

and coefficients are entered using the list function

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line.

   units of Coeff[0] =henries
   units of Coeff[1] =henries/amp
   units of Coeff[2] = henries/amp^2

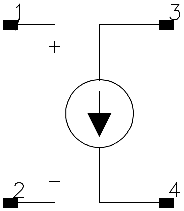
   Coefficients are entered using the list function. For example, if
   $L = 5I^2 + 4I^4$
   the parameter entry is
   Coeff = list(0,0,5,0,4)

2. The controlling circuit i is the current flowing from pin 1 (the one with the slash) to pin 2.

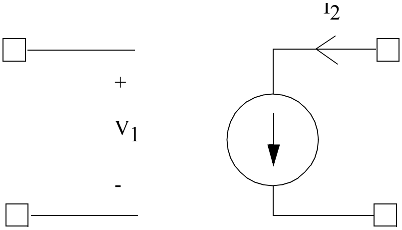
3. This component has no default artwork associated with it.

NonlinVCCS (Nonlinear Voltage-Controlled Current Source)

Symbol



Illustration



Parameters

Coeff = a list of coefficients that describe a polynomial that defines output current I_2 as a function of input voltage V_1:

if only one coefficient is specified

$I_2 = \text{Coeff}[0] \times V_1$

the coefficient is entered using the list function

Coeff = list(Coeff[0])

otherwise

$I_2 = \text{Coeff}[0] + \text{Coeff}[1] \times V_1 + \text{Coeff}[2] \times V_1^2 + \ldots + \text{Coeff}[n] \times V_1^n$

and coefficients are entered as

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line. Enter values for each coefficient in a single line using the list function. For example, if

   $I_2 = 3 - 2V_1^2 + 5V_1^6$

   the parameter entry is

   Coeff = list(3,0,-2,0,0,0,5)

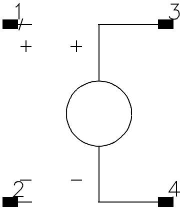
   If $I_2 = 5V_1$, then Coeff = list(5)

   If $I_2 = 5$, then Coeff = list(5,0)

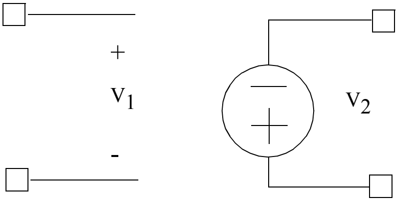
2. This component has no default artwork associated with it.
3. Output current is in Amperes.

NonlinVCVS (Nonlinear Voltage-Controlled Voltage Source)

Symbol



Illustration



Parameters

Coeff = a list of coefficients that describe a polynomial that defines output voltage V_2 as a function of input voltage V_1:

If only one coefficient is specified

$V_2 = \text{Coeff}\,[0] \times V_1$

the coefficient is entered using the list function

Coeff = list(Coeff[0])

otherwise,

$V_2 = \text{Coeff}[0] + \text{Coeff}[1] \times V_1 + \text{Coeff}[2] \times V_1{}^2 + \ldots + \text{Coeff}[n] \times V_1{}^n$

and coefficients are entered as

Coeff = list (Coeff[0], Coeff[1],Coeff[2],...,Coeff[n])

Range of Usage

N/A

Notes/Equations/References

1. The coefficients of polynomial are specified in the dialog box for this component. Enter values for each coefficient in a single line. Enter values for each coefficient in a single line using the list function. For example, if

   $V_2 = 3 - 2V_1^2 + 5V_1^6$

   the parameter entry is

   Coeff = list(3,0,-2,0,0,0,5)

   If $V_2 = 5V_1$, then Coeff = list(5)

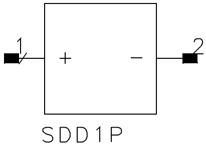
   If $V_2 = 5$, then Coeff = list(5,0)

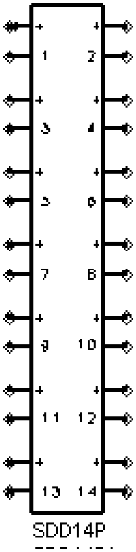
2. This component has no default artwork associated with it.

3. Output voltage is in Volts.

SDD1P to SDD14P (Symbolically Defined Device, 1-12 and 14 Ports)

Symbol





Parameters

I[i, j]] = explicit equation that describes port current in terms of voltage. *i* refers to the port number. *j* refers to the weighting function (0,1, or user defined).

F[i,j]] = implicit equation defining a nonlinear relationship of port voltages and port currents (or the currents of certain other devices) that is equal to 0. *i* refers to the port number. *j* refers to the weighting function (0, 1, or user defined).

H[k] = user-defined weighting function

C[l]] = controlling current

In[i,j] = equation that specifies the noise current squared. *i* refers to the port number. *j* refers to the weighting function (0, 1, or user-defined)

Nc[i,j] = complex noise correlation coefficient between ports *i* and *j*.

Range of Usage

$0 \le i \le 10$

$0 \le j$

$2 \leq k$

$1 \leq 1$

Notes/Equations/References

1. The symbolically-defined device (SDD) enables you to create equation based, user-defined, nonlinear components. The SDD is a multi-port device which is defined by specifying algebraic relationships that relate the port voltages, currents, and their derivatives, plus currents from certain other devices.
2. Devices SDD1P through SDD10P are available from the component palette and library browser. Two additional devices, SDD12P and SDD14P are only available by typing their exact names into the Component History box, pressing Enter, and moving the cursor to the drawing error to place the components.
3. The port index *i* can go from 1 to 14, not 0 to 10, and not 13.
4. Port variables, *_in* and *_vn*, contain the current and voltage values of a port, respectively. n specifies the port number, for example, the current and voltage variables for port one are *_i1* and *_v1*, respectively.
5. The equations that relate port currents and port voltages are specified in the time domain. These constitutive relationships may be specified in either *explicit* or *implicit* representations.

   With the *explicit* representation, the current at port *k* is specified as a function of port voltages:

   $$i_k = f(v_1, v_2, \dots v_n)$$

   The *implicit* representation uses an implicit relationship between any of the port currents and any of the port voltages:

   $$f_k(v_1, v_2, \dots v_n, i_1, i_2, \dots i_n) = 0$$

   Using the implicit representation, you can also reference current flowing in another device, by using controlling currents.

   Different types of expressions cannot be mixed—that is, a single port must be described by either implicit or explicit expressions. Every port must have at least one equation.

   By convention, a positive port current flows into the terminal marked +.
6. A *weighting function* is a frequency-dependent expression used to scale the spectrum of a port current.Weighting functions are evaluated in the frequency domain.

There are two predefined weighting functions. Weighting function 0 is defined to be identically one. It is used when no weighting is desired. Weighting function 1 is defined as *jw* and is used when a time derivative is desired. You can define other weighting functions, starting with 2.

7. An SDD can also be set up to reference the current flowing in another device. The devices that can be referenced are limited to either voltage sources or current probes in the same network. To specify a current as a control current, you enter the instance name of the device in the *C[k]* parameter of the SDD. These currents can then be referred to using the variable *_ck* for the *kth* referenced current. These variables *_ck* may be used in the SDD equations along with the SDD port voltages *_vn* and port currents *_in*.
8. In[] and Nc[] are used to specify the noise behavior of the SDD. In[*i,j*] specifies

$(i_i, i_i{*})$

the short-circuit noise current squared, in units of amperes squared at port *i*, with weighting function *j*.

Nc[*i,j*] specifies the complex noise correlation coefficient between ports *i* and *j*. It should be a complex number with a magnitude less than or equal to one, Nc[i,j] and Nc[j,i] should be complex conjugates of each other.

$$Nc\lceil i, j\rceil = \frac{(i_i,i_j{*})}{\sqrt{(i_i,i_i{*})(i_i,i_j{*})}}$$

9. For more information on how to use these devices and application examples, refer to *Circuit Simulation*.

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