Chapter 14

BJT Models

IThe bipolar-junction transistor (BJT) model in HSPICE is an adaptation of the integral charge control model of Gummel and Poon.

The HSPICE model extends the original Gummel-Poon model to include several effects at high bias levels. This model automatically simplifies to the Ebers-Moll model when certain parameters (VAF, VAR, IKF, and IKR) are not specified.

This chapter covers the following topics:

- Using the BJT Model
- Using the BJT Element
- Understanding the BJT Model Statement
- Using the BJT Models (NPN and PNP)
- Understanding BJT Capacitances
- Modeling Various Types of Noise
- Using the BJT Quasi-Saturation Model
- Using Temperature Compensation Equations
- Converting National Semiconductor Models

Using the BJT Model

The BJT model is used to develop BiCMOS, TTL, and ECL circuits. For BiCMOS devices, use the high current Beta degradation parameters, IKF and IKR, to modify high injection effects. The model parameter SUBS facilitates the modeling of both vertical and lateral geometrics.

Model Selection

To select a BJT device, use a BJT element and model statement. The element statement references the model statement by the reference model name. The reference name is given as MOD1 in the following example. In this case an NPN model type is used to describe an NPN transistor.

Example

```
Q3 3 2 5 MOD1 <parameters>
.MODEL MOD1 NPN <parameters>
```

Parameters can be specified in both element and model statements. The element parameter always overrides the model parameter when a parameter is specified as both. The model statement specifies the type of BJT, for example, NPN or PNP.

Control Options

Control options affecting the BJT model are: DCAP, GRAMP, GMIN, and GMINDC. DCAP selects the equation which determines the BJT capacitances. GRAMP, GMIN, and GMINDC place a conductance in parallel with both the base-emitter and base-collector pn junctions. DCCAP invokes capacitance calculations in DC analysis.

Table 14-1: BJT Options

capacitance	DCAP, DCCAP
conductance	GMIN, GMINDC, GRAMP

Override global depletion capacitance equation selection that uses the .OPTION DCAP=<*val*> statement in a BJT model by including DCAP=<val> in the BJT's .MODEL statement.

Convergence

Adding a base, collector, and emitter resistance to the BJT model improves its convergence. The resistors limit the current in the device so that the forward-biased pn junctions are not overdriven.

Using the BJT Element

The BJT element parameters specify the connectivity of the BJT, normalized geometric specifications, initialization, and temperature parameters.

Table 14-2: BJT Element Parameters

Type	**Parameters**
netlist	Qxxx, mname, nb, nc, ne, ns
geometric	AREA, AREAB, AREAC, M
initialization	IC (VBE, VCE), OFF
temperature	DTEMP

General form

```
Qxxx nc nb ne <ns> mname <aval> <OFF> <IC=vbeval,
vceval> <M=val> <DTEMP=val>
```

or

```
Qxxx nc nb ne <ns> mname <AREA=val> <AREAB=val>
<AREAC=val> <OFF> <VBE=val> + <VCE=val> <M=val>
<DTEMP=val>
```

Qxxx	BJT element name. Must begin with a “Q”, which can be followed by up to 15 alphanumeric characters.
nc	collector terminal node name
nb	base terminal node name
ne	emitter terminal node name
ns	substrate terminal node name, optional. Can be set in the model with BULK= Node name.
mname	model name reference
aval	value for AREA

OFF	sets initial condition to OFF for this element in DC analysis. Default=ON.
IC=vbeval,	initial internal base to emitter voltage (vbeval) or initial internal collector to
vceval	emitter voltage (vceval). Overridden by the .IC statement.
M	multiplier factor to simulate multiple BJTs. All currents, capacitances, and resistances are affected by M.
DTEMP	the difference between element and circuit temperature (default= 0.0)
AREA	emitter area multiplying factor that affects resistors, capacitors, and currents (default=1.0)
AREAB	base area multiplying factor that affects resistors, capacitors, and currents (default=AREA)
AREAC	collector area multiplying factor that affects resistors, capacitors, and currents (default=AREA)

Examples

```
Q100 CX BX EX QPNP AREA=1.5 AREAB=2.5 AREAC=3.0
Q23 10 24 13  QMOD IC=0.6,5.0
Q50A 11 265 4 20 MOD1
```

Scaling

Scaling is controlled by the element parameters AREA, AREAB, AREAC, and M. The AREA parameter, the normalized emitter area, divides all resistors and multiplies all currents and capacitors. AREAB and AREAC scale the size of the base area and collector area. Either AREAB or AREAC is used for scaling, depending on whether vertical or lateral geometry is selected (using the SUBS model parameter). For vertical geometry, AREAB is the scaling factor for IBC, ISC, and CJC. For lateral geometry, AREAC is the scaling factor. The scaling factor is AREA for all other parameters.

The scaling of the DC model parameters (IBE, IS, ISE, IKF, IKR, and IRB) for both vertical and lateral BJT transistors, is determined by the following formula:

$$Ieff = AREA \cdot M \cdot I$$

where I is either IBE, IS, ISE, IKF, IKR, or IRB.

For both the vertical and lateral the resistor model parameters, RB, RBM, RE, and RC are scaled by the following equation.

$$Reff = \frac{R}{AREA \cdot M}$$

where R is either RB, RBM, RE, or RC.

BJT Current Convention

The direction of current flow through the BJT is assumed for example purposes in Figure 13-1. Use either I(Q1) or I1(Q1) syntax to print the collector current. I2(Q1) refers to the base current, I3(Q1) refers to the emitter current, and I4(Q1) refers to the substrate current.

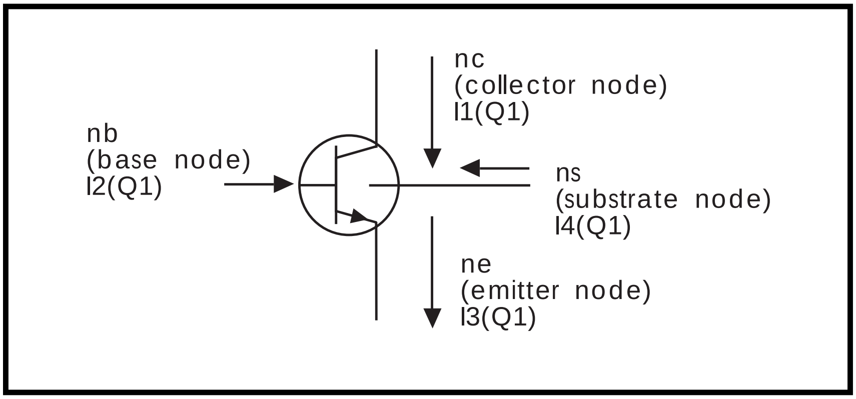

Figure 13-1 – BJT Current Convention

BJT Equivalent Circuits

HSPICE uses four equivalent circuits in the analysis of BJTs: DC, transient, AC, and AC noise circuits. The components of these circuits form the basis for all element and model equations. Since these circuits represent the entire BJT in HSPICE, every effort has been made to demonstrate the relationship between the equivalent circuit and the element/model parameters.

The fundamental components in the equivalent circuit are the base current (ib) and the collector current (ic). For noise and AC analyses, the actual ib and ic currents are not used. The partial derivatives of ib and ic with respect to the terminal voltages vbe and vbc are used instead. The names for these partial derivatives are:

Reverse Base Conductance

$$g\mu = \left.\frac{\partial ib}{\partial vbc}\right|_{vbe = const.}$$

Forward Base Conductance

$$g\pi = \left.\frac{\partial ib}{\partial vbe}\right|_{vbc = const.}$$

Collector Conductance

$$g_o = \left.\frac{\partial ic}{\partial vce}\right|_{vbe = const.} = -\left.\frac{\partial ic}{\partial vbc}\right|_{vbe = const.}$$

Transconductance

$$gm = \left.\frac{\partial ic}{\partial vbe}\right|_{vce\,=\,cons}$$

$$= \frac{\partial ic}{\partial vbe} + \frac{\partial ic}{\partial vbc}$$

$$= \frac{\partial ic}{\partial vbe} - g_o$$

The ib and ic equations account for all DC effects of the BJT.

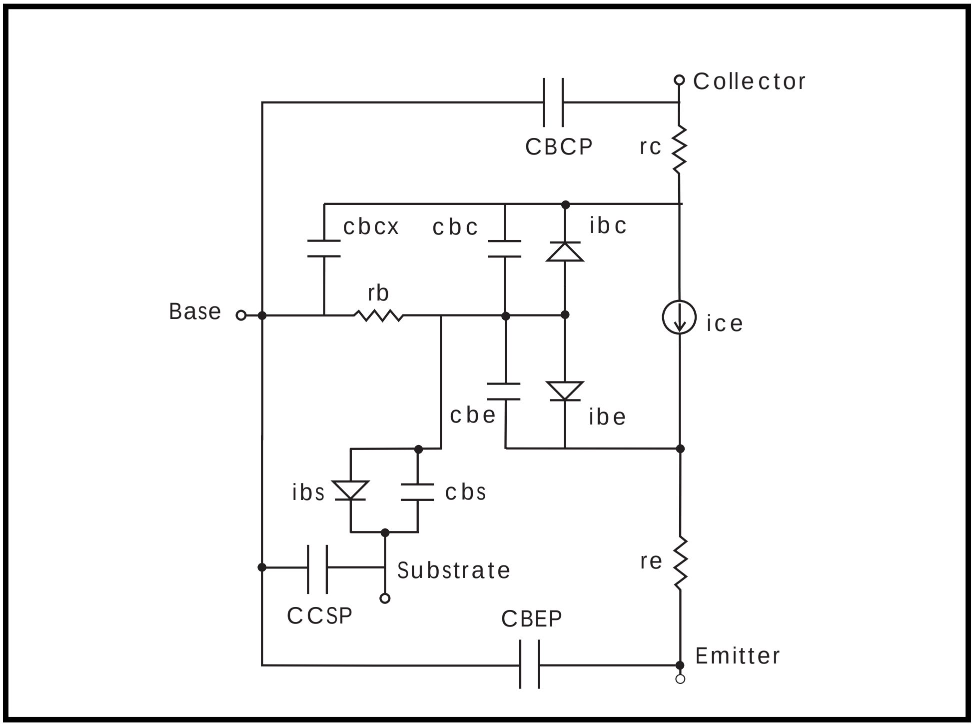

Figure 13-1: Lateral Transistor, BJT Transient Analysis

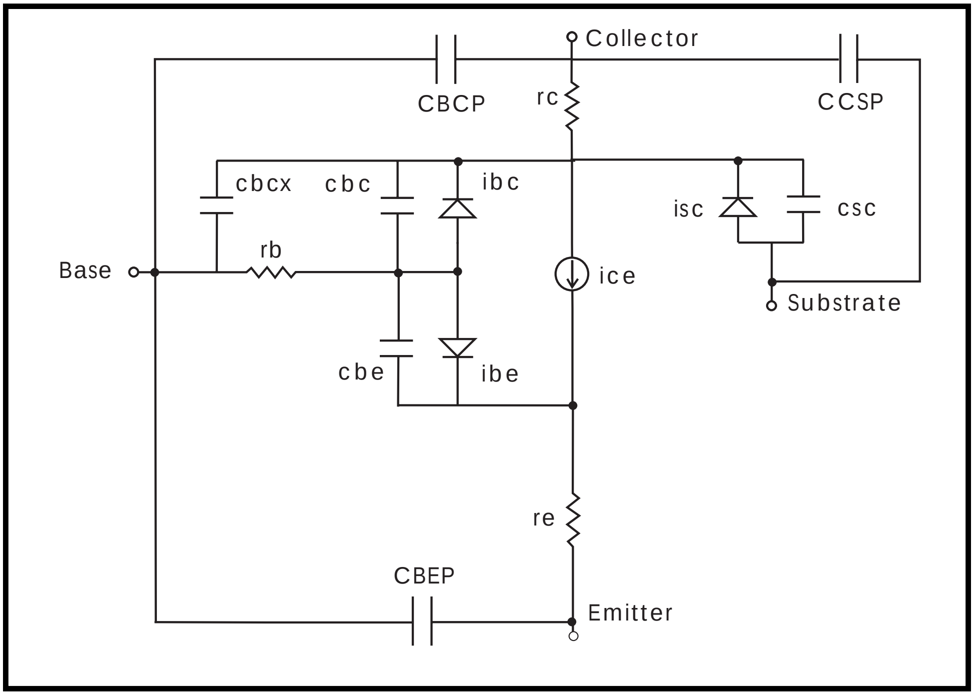

Figure 13-2: Vertical Transistor, BJT Transient Analysis

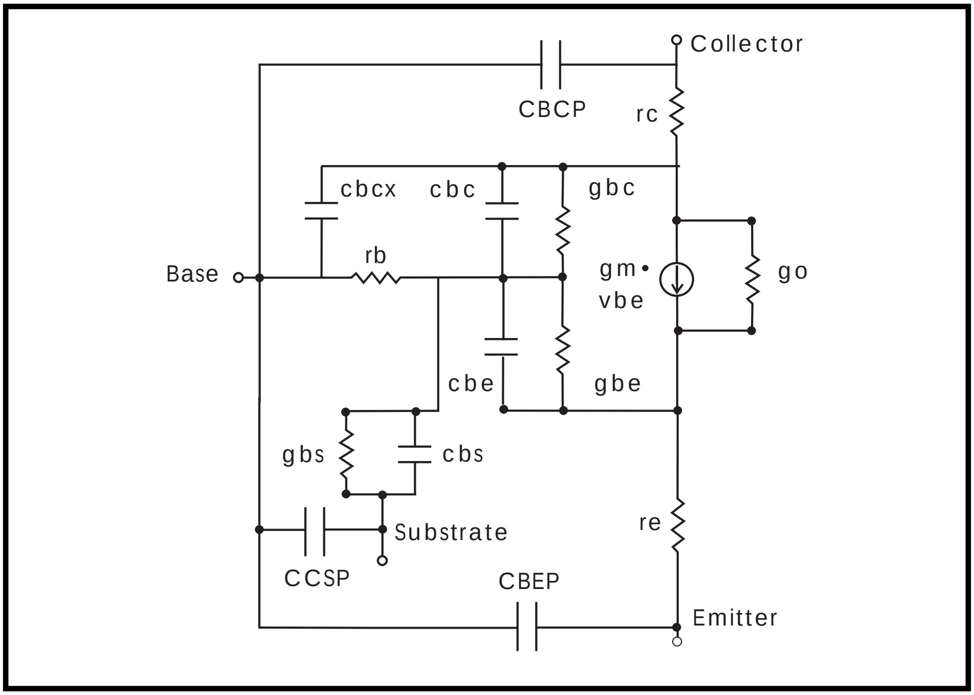

Figure 13-3: Lateral Transistor, BJT AC Analysis

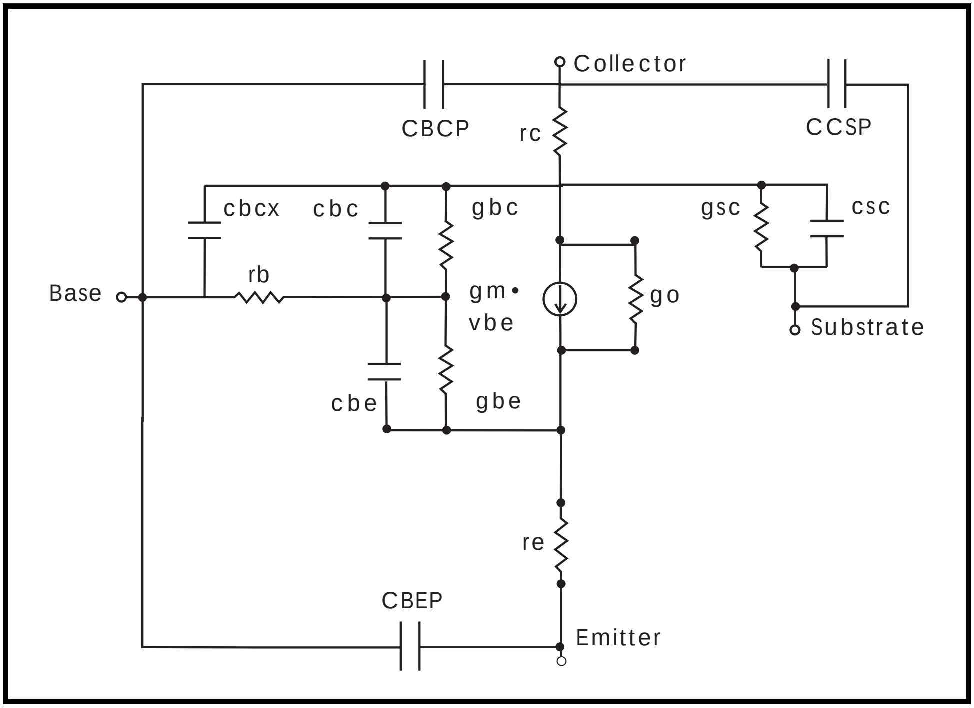

Figure 13-4: Vertical Transistor, BJT AC Analysis

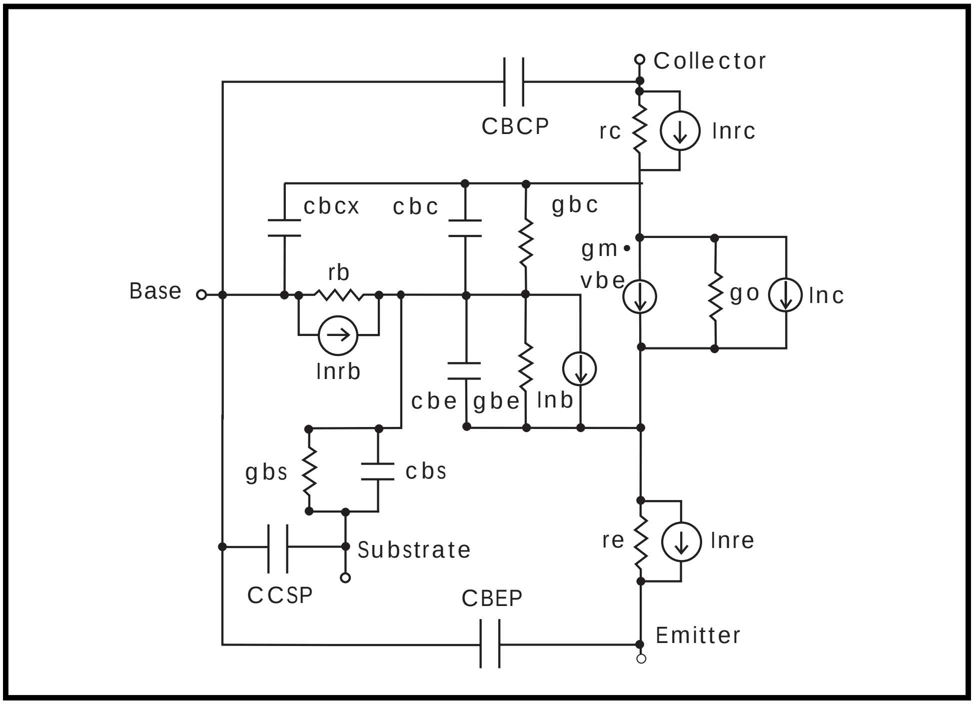

Figure 13-5: Lateral Transistor, BJT AC Noise Analysis

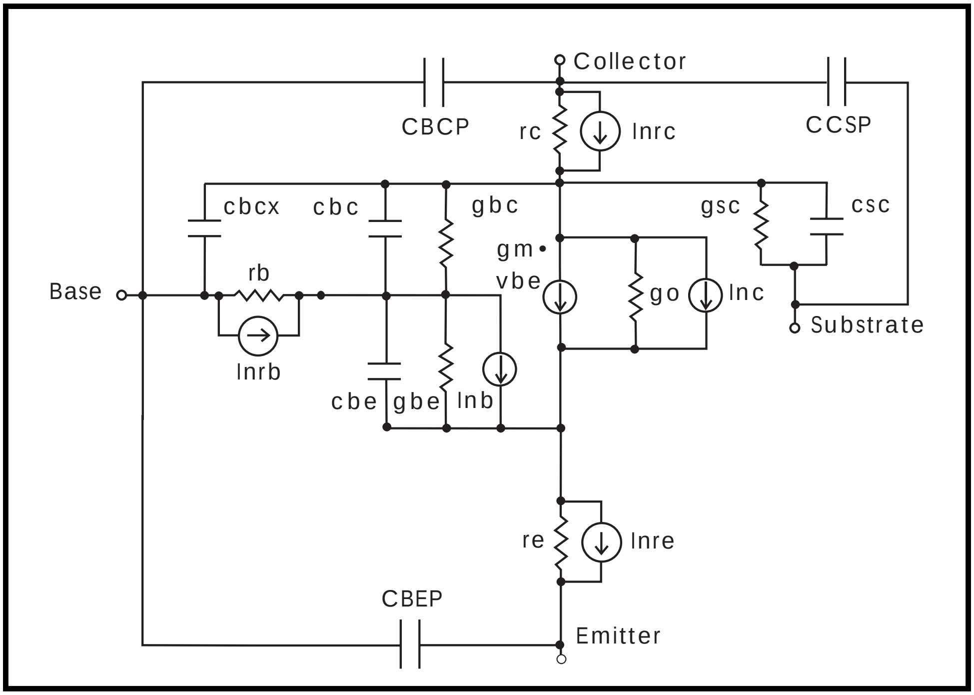

Figure 13-6: Vertical Transistor, BJT AC Noise Analysis

Table 13-2: Equation Variable Names

Variable	Definitions
cbc	internal base to collector capacitance
cbcx	external base to collector capacitance
cbe	internal base to emitter capacitance
csc	substrate to collector capacitance (vertical transistor only)
cbs	base to substrate capacitance (lateral transistor only)
f	frequency
gbc	reverse base conductance

Table 13-2: Equation Variable Names

Variable	Definitions
gbe	forward base conductance
gm	transconductance
gsc	substrate to collector conductance (vertical transistor only)
go	collector conductance
gbs	base to substrate conductance (lateral transistor only)
ib	external base terminal current
ibc	DC current base to collector
ibe	DC current base to emitter
ic	external collector terminal current
ice	DC current collector to emitter
inb	base current equivalent noise
inc	collector current equivalent noise
inrb	base resistor current equivalent noise
inrc	collector resistor equivalent noise
inre	emitter resistor current equivalent noise
ibs	DC current base to substrate (lateral transistor only)
isc	DC current substrate to collector (vertical transistor only)
qb	normalized base charge
rb	base resistance
rbb	short-circuit base resistance
vbs	internal base substrate voltage
vsc	internal substrate collector voltage

Table 13-3: Equation Constants

Quantities	**Definitions**
k	1.38062e-23 (Boltzmann’s constant)
q	1.60212e-19 (electron charge)
t	temperature in °Kelvin
Δt	t - tnom
tnom	tnom = 273.15 + TNOM in °Kelvin
vt(t)	k · t/q
vt(tmon)	k · tnom/q

Understanding the BJT Model Statement

General form

```
.MODEL mname NPN <(> <pname1 = val1> ... <)>
```

or

```
.MODEL mname PNP <pname1 = val1> ...
```

mname	model name. Elements refer to the model by this name.
NPN	identifies an NPN transistor model
pname1	Each BJT model can include several model parameters.
PNP	identifies a PNP transistor model

Example

```
.MODEL t2n2222a NPN
+ ISS=  0.          XTF=   1.          NS =   1.00000
+ CJS=  0.          VJS=   0.50000     PTF=   0.
+ MJS=  0.          EG =   1.10000     AF =   1.
+ ITF=  0.50000     VTF=   1.00000     F  = 153.40622
+ BR = 40.00000     IS =   1.6339e-14 VAF= 103.40529
+ VAR= 17.77498    IKF=   1.00000    IS =   4.6956e-15
+ NE =  1.31919    IKR=   1.00000    ISC=   3.6856e-13
+ NC =  1.10024     IRB=   4.3646e-05 NF =   1.00531
+ NR =  1.00688     RBM=   1.0000e-02 RB =  71.82988
+ RC =  0.42753     RE =   3.0503e-03 MJE=   0.32339
+ MJC=  0.34700     VJE=   0.67373     VJC=   0.47372
+ TF =  9.693e-10  TR = 380.00e-9    CJE=   2.6734e-11
+ CJC=  1.4040e-11 FC =   0.95000    XCJC=   0.94518
```

BJT Basic Model Parameters

To permit the use of model parameters from earlier versions of HSPICE, many of the model parameters have aliases, which are included in the model parameter list in “BJT Basic DC Model Parameters” on page 14-19. The new name is always used on printouts, even if an alias is used in the model statement.

BJT model parameters are divided into several groups. The first group of DC model parameters includes the most basic Ebers-Moll parameters. This model is effective for modeling low-frequency large-signal characteristics.

Low current Beta degradation effect parameters ISC, ISE, NC, and NE aid in modeling the drop in the observed Beta, caused by the following mechanisms:

- recombination of carriers in the emitter-base space charge layer
- recombination of carriers at the surface
- formation of emitter-base channels

Low base and emitter dopant concentrations, found in some BIMOS type technologies, typically use the high current Beta degradation parameters, IKF and IKR.

Use the base-width modulation parameters, that is, early effect parameters VAF and VAR, to model high-gain, narrow-base devices. The model calculates the slope of the I-V curve for the model in the active region with VAF and VAR. If VAF and VAR are not specified, the slope in the active region is zero.

The parasitic resistor parameters RE, RB, and RC are the most frequently used second-order parameters since they replace external resistors. This simplifies the input netlist file. All the resistances are functions of the BJT multiplier M value. The resistances are divided by M to simulate parallel resistances. The base resistance is also a function of base current, as is often the case in narrow-base technologies.

Transient model parameters for BJTs are composed of two groups: junction capacitor parameters and transit time parameters. The base-emitter junction is modeled by CJE, VJE, and MJE. The base-collector junction capacitance is modeled by CJC, VJC, and MJC. The collector-substrate junction capacitance is modeled by CJS, VJS, and MJS.

TF is the forward transit time for base charge storage. TF can be modified to account for bias, current, and phase, by XTF, VTF, ITF, and PTF. The base charge storage reverse transit time is set by TR. There are several sets of temperature equations for the BJT model parameters that you can select by setting TLEV and TLEVC.

Table 13-4: – BJT Model Parameters

DC	BF, BR, IBC, IBE, IS, ISS, NF, NR, NS, VAF, VAR
beta degradation	ISC, ISE, NC, NE, IKF, IKR
geometric	SUBS, BULK
resistor	RB, RBM, RE, RC, IRB
junction capacitor	CJC, CJE, CJS, FC, MJC, MJE, MJS, VJC, VJE, VJS, XCJC
parasitic capacitance	CBCP, CBEP, CCSP
transit time	ITF, PTF, TF, VT, VTF, XTF
noise	KF, AF

BJT Basic DC Model Parameters

Name(Alias)	Units	Default	Description
BF (BFM)		100.0	ideal maximum forward Beta
BR (BRM)		1.0	ideal maximum reverse Beta
BULK (NSUB)		0.0	sets the bulk node to a global node name. A substrate terminal node name (ns) in the element statement overrides BULK.
IBC	amp	0.0	reverse saturation current between base and collector. If both IBE and IBC are specified, HSPICE uses them in place of IS to calculate DC current and conductance, otherwise IS is used. $IBCeff = IBC \cdot AREAB \cdot M$ AREAC replaces AREAB, depending on vertical or lateral geometry.
EXPLI	amp	1e15	current explosion model parameter. The PN junction characteristics above the explosion current area linear, with the slope at the explosion point. This speeds up simulation and improves convergence. $EXPLIeff = EXPLI \cdot AREAeff$
IBE	amp	0.0	reverse saturation current between base and emitter. If both IBE and IBC are specified, HSPICE uses them in place of IS to calculate DC current and conductance, otherwise IS is used. $IBEeff = IBE \cdot AREA \cdot M$

Name(Alias)	Units	Default	Description
IS	amp	1.0e-16	transport saturation current. If both IBE and IBC are specified, HSPICE uses them in place of IS to calculate DC current and conductance, otherwise IS is used. $ISeff = IS \cdot AREA \cdot M$
ISS	amp	0.0	reverse saturation current bulk-to-collector or bulk-to-base, depending on vertical or lateral geometry selection $SSeff = ISS \cdot AREA \cdot M$
LEVEL		1.0	model selector
NF		1.0	forward current emission coefficient
NR		1.0	reverse current emission coefficient
NS		1.0	substrate current emission coefficient
SUBS			substrate connection selector: +1 for vertical geometry, -1 for lateral geometry default=1 for NPN, default=-1 for PNP
UPDATE		0	UPDATE = 1 selects alternate base charge equation

Low Current Beta Degradation Effect Parameters

ISC (C4, JLC)	amp	0.0	base-collector leakage saturation current. If ISC is greater than 1e-4, then: $ISC = IS \cdot ISC$ otherwise: $ISCeff = ISC \cdot AREAB \cdot M$ AREAC replaces AREAB, depending on vertical or lateral geometry.
ISE (C2, JLE)	amp	0.0	base-emitter leakage saturation current. If ISE is greater than 1e-4, then: $ISE = IS \cdot ISE$ otherwise: $ISEeff = ISE \cdot AREA \cdot M$
NC (NLC)		2.0	base-collector leakage emission coefficient
NE (NLE)		1.5	base-emitter leakage emission coefficient

Base Width Modulation Parameters

VAF (VA, VBF)	V	0.0	forward early voltage. Use zero to indicate an infinite value.
VAR (VB, VRB, BV)	V	0.0	reverse early voltage. Use zero to indicate an infinite value.

High Current Beta Degradation Effect Parameters

IKF IK,JBF)	amp	0.0	corner for forward Beta high current roll-off. Use zero to indicate an infinite value. $IKFeff = IKF \cdot AREA \cdot M$
IKR (JBR)	amp	0.0	corner for reverse Beta high current roll-off. Use zero to indicate an infinite value $IKReff = IKR \cdot AREA \cdot M$
NKF		0.5	exponent for high current Beta roll-off

Parasitic Resistance Parameters

IRB (JRB,IOB)	amp	0.0	base current, where base resistance falls half-way to RBM. Use zero to indicate an infinite value. IRBeff = IRB · AREA · M
RB	ohm	0.0	base resistance RBeff = RB / (AREA · M)
RBM	ohm	RB	minimum high current base resistance RBMeff = RBM / (AREA · M)
RE	ohm	0.0	emitter resistance REeff = RE / (AREA · M)
RC	ohm	0.0	collector resistance RCeff = RC / (AREA · M)

Junction Capacitor Parameters

CJC	F	0.0	base-collector zero-bias depletion capacitance Vertical: CJCeff = CJC · AREAB · M Lateral: CJCeff = CJC · AREAC · M

CJE	F	0.0	base-emitter zero-bias depletion capacitance (vertical and lateral): $CJEeff = CJE \cdot AREA \cdot M$
CJS (CCS, CSUB)	F	0.0	zero-bias collector substrate capacitance Vertical: $CJSeff = CJS \cdot AREAC \cdot M$ Lateral: $CJSeff = CJS \cdot AREAB \cdot M$
FC		0.5	coefficient for forward bias depletion capacitance formula for DCAP=1 DCAP Default=2 and FC is ignored
MJC (MC)		0.33	base-collector junction exponent (grading factor)
MJE (ME)		0.33	base-emitter junction exponent (grading factor)
MJS(ESUB)		0.5	substrate junction exponent (grading factor)
VJC (PC)	V	0.75	base-collector built-in potential
VJE (PE)	V	0.75	base-emitter built-in potential
VJS (PSUB)	V	0.75	substrate junction built in potential
XCJC (CDIS)		1.0	internal base fraction of base-collector depletion capacitance

Parasitic Capacitances

CBCP	F	0.0	external base-collector constant capacitance CBCPeff = CBCP · AREA · M
CBEP	F	0.0	external base-emitter constant capacitance CBEPeff = CBEP · AREA · M
CCSP	F	0.0	external collector substrate constant capacitance (vertical) or base substrate (lateral) CCSPeff = CCSP · AREA · M

Transit Time Parameters

ITF (JTF)	amp	0.0	TF high-current parameter ITFeff = ITF · AREA · M
PTF		0.0	frequency multiplier to determine excess phase
TF	s	0.0	base forward transit time
TR	s	0.0	base reverse transit time
VTF	V	0.0	TF base-collector voltage dependence coefficient. Use zero to indicate an infinite value.
XTF		0.0	TF bias dependence coefficient

Noise Parameters

AF	1.0	flicker-noise exponent
KF	0.0	flicker-noise coefficient

BJT LEVEL=2 Model Parameters

BRS		1.0	Reverse beta for substrate BJT.
GAMMA		0.0	epitaxial doping factor, $GAMMA = (2 \cdot ni / n)^2$ where n is epitaxial impurity concentration
NEPI		1.0	emission coefficient
QCO	Coul	0.0	epitaxial charge factor Vertical: $QCOeff=QCO \cdot AREAB \cdot M$ Lateral: $QCOeff=QCO \cdot AREAC \cdot M$
RC	ohm	0.0	resistance of the epitaxial region under equilibrium conditions $RCeff=RC/(AREA \cdot M)$
VO	V	0.0	carrier velocity saturation voltage. Use zero to indicate an infinite value.

BJT Model Temperature Effects

Several temperature parameters control derating of the BJT model parameters. They include temperature parameters for junction capacitance, Beta degradation (DC), and base modulation (Early effect) among others.

Table 13-5: – BJT Temperature Parameters

Function	**Parameter**
base modulation	TVAF1, TVAF2, TVAR1, TVAR2
capacitor	CTC, CTE, CTS
capacitor potentials	TVJC, TVJE, TVJS
DC	TBF1, TBF2, TBR1, TBR2, TIKF1, TIKF2, TIKR1, TIKR2, TIRB1, TIRB2, TISC1, TISC2, TIS1, TIS2, TISE1, TISE2, TISS1, TISS2, XTB, XTI
emission coefficients	TNC1, TNC2, TNE1, TNE2, TNF1, TNF2, TNR1, TNR2, TNS1, TNS2
energy gap	EG, GAP1, GAP2
equation selectors	TLEV, TLEVC
grading	MJC, MJE, MJS, TMJC1, TMJC2, TMJE1, TMJE2, TMJS1, TMJS2
resistors	TRB1, TRB2, TRC1, TRC2, TRE1, TRE2, TRM1, TRM2
transit time	TTF1, TTF2, TTR1, TTR2

Temperature Effect Parameters

Name(Alias)	**Units**	**Default**	**Description**
BEX		2.42	VO temperature exponent (Level 2 only)
BEXV		1.90	RC temperature exponent (Level 2 only)

Name(Alias)	Units	Default	Description
CTC	1/°	0.0	temperature coefficient for zero-bias base collector capacitance. TLEVC=1 enables CTC to override the default HSPICE temperature compensation.
CTE	1/°	0.0	temperature coefficient for zero-bias base emitter capacitance. TLEVC=1 enables CTE to override the default HSPICE temperature compensation.
CTS	1/°	0.0	temperature coefficient for zero-bias substrate capacitance. TLEVC=1 enables CTS to override the default HSPICE temperature compensation.
EG	eV		energy gap for pn junction for TLEV=0 or 1, default=1.11; for TLEV=2, default=1.16 1.17 - silicon 0.69 - Schottky barrier diode 0.67 - germanium 1.52 - gallium arsenide
GAP1	eV/°	7.02e-4	first bandgap correction factor (from Sze, alpha term) 7.02e-4 - silicon 4.73e-4 - silicon 4.56e-4 - germanium 5.41e-4 - gallium arsenide

Name(Alias)	Units	Default	Description
GAP2		1108	second bandgap correction factor (from Sze, beta term) 1108 - silicon 636 - silicon 210 - germanium 204 - gallium arsenide
MJC (MC)		0.33	base-collector junction exponent (grading factor)
MJE (ME)		0.33	base-emitter junction exponent (grading factor)
MJS (ESUB)		0.5	substrate junction exponent (grading factor)
TBF1	1/°	0.0	first order temperature coefficient for BF
TBF2	1/°^{2}	0.0	second order temperature coefficient for BF
TBR1	1/°	0.0	first order temperature coefficient for BR
TBR2	1/°^{2}	0.0	second order temperature coefficient for BR
TIKF1	1/°	0.0	first order temperature coefficient for IKF
TIKF2	1/°^{2}	0.0	second order temperature coefficient for IKF
TIKR1	1/°	0.0	first order temperature coefficient for IKR
TIKR2	1/°^{2}		second order temperature coefficient for IKR
TIRB1	1/°	0.0	first order temperature coefficient for IRB
TIRB2	1/°^{2}	0.0	second order temperature coefficient for IRB
TISC1	1/°	0.0	first order temperature coefficient for ISC TLEV=3 enables TISC1.
TISC2	1/°^{2}	0.0	second order temperature coefficient for ISC TLEV=3 enables TISC2.

Name(Alias)	**Units**	**Default**	**Description**
TIS1	1/°	0.0	first order temperature coefficient for IS or IBE and IBC TLEV=3 enables TIS1.
TIS2	1/°^{2}	0.0	second order temperature coefficient for IS or IBE and IBC TLEV=3 enables TIS2.
TISE1	1/°	0.0	first order temperature coefficient for ISE TLEV=3 enables TISE1.
TISE2	1/°^{2}	0.0	second order temperature coefficient for ISE TLEV=3 enables TISE2.
TISS1	1/°	0.0	first order temperature coefficient for ISS TLEV=3 enables TISS1.
TISS2	1/°^{2}	0.0	second order temperature coefficient for ISS TLEV=3 enables TISS2.
TITF1			first order temperature coefficient for ITF
TITF2			second order temperature coefficient for ITF
TLEV		1	temperature equation level selector for BJTs (interacts with TLEVC)
TLEVC		1	temperature equation level selector for BJTs, junction capacitances and potentials (interacts with TLEV)
TMJC1	1/°	0.0	first order temperature coefficient for MJC
TMJC2	1/°^{2}	0.0	second order temperature coefficient for MJC

Name(Alias)	Units	Default	Description
TMJE1	1/°	0.0	first order temperature coefficient for MJE
TMJE2	1/°^{2}	0.0	second order temperature coefficient for MJE
TMJS1	1/°	0.0	first order temperature coefficient for MJS
TMJS2	1/°^{2}	0.0	second order temperature coefficient for MJS
TNC1	1/°	0.0	first order temperature coefficient for NC
TNC2		0.0	second order temperature coefficient for NC
TNE1	1/°	0.0	first order temperature coefficient for NE
TNE2	1/°^{2}	0.0	second order temperature coefficient for NE
TNF1	1/°	0.0	first order temperature coefficient for NF
TNF2	1/°^{2}	0.0	second order temperature coefficient for NF
TNR1	1/°	0.0	first order temperature coefficient for NR
TNR2	1/°^{2}	0.0	second order temperature coefficient for NR
TNS1	1/°	0.0	first order temperature coefficient for NS
TNS2	1/°^{2}	0.0	second order temperature coefficient for NS
TRB1 (TRB)	1/°	0.0	first order temperature coefficient for RB
TRB2	1/°^{2}	0.0	second order temperature coefficient for RB
TRC1 (TRC)	1/°	0.0	first order temperature coefficient for RC
TRC2	1/°^{2}	0.0	second order temperature coefficient for RC
TRE1 (TRE)	1/°	0.0	first order temperature coefficient for RE
TRE2	1/°^{2}	0.0	second order temperature coefficient for RE
TRM1	1/°	TRB1	first order temperature coefficient for RBM
TRM2	1/°^{2}	TRB2	second order temperature coefficient for RBM
TTF1	1/°	0.0	first order temperature coefficient for TF
TTF2	1/°^{2}	0.0	second order temperature coefficient for TF

Name(Alias)	Units	Default	Description
TTR1	1/°	0.0	first order temperature coefficient for TR
TTR2	$1/°^2$	0.0	second order temperature coefficient for TR
TVAF1	1/°	0.0	first order temperature coefficient for VAF
TVAF2	$1/°^2$	0.0	second order temperature coefficient for VAF
TVAR1	1/°	0.0	first order temperature coefficient for VAR
TVAR2	$1/°^2$	0.0	second order temperature coefficient for VAR
TVJC	V/°	0.0	temperature coefficient for VJC. TLEVC=1 or 2 enables TVJC to override the default HSPICE temperature compensation.
TVJE	V/°	0.0	temperature coefficient for VJE. TLEVC=1 or 2 enables TVJE to override the default HSPICE temperature compensation.
TVJS	V/°	0.0	temperature coefficient for VJS. TLEVC=1 or 2 enables TVJS to override the default HSPICE temperature compensation.
XTB (TB, TCB)		0.0	forward and reverse Beta temperature exponent (used with TLEV=0, 1 or 2)
XTI		3.0	saturation current temperature exponent. Use XTI = 3.0 for silicon diffused junction. Set XTI = 2.0 for Schottky barrier diode.

Using the BJT Models (NPN and PNP)

This section describes the NPN and PNP BJT models.

Transistor Geometry — Substrate Diode

The substrate diode is connected to either the collector or the base depending on whether the transistor has a lateral or vertical geometry. Lateral geometry is implied when the model parameter SUBS=-1, and vertical geometry when SUBS=+1. The lateral transistor substrate diode is connected to the internal base and the vertical transistor substrate diode is connected to the internal collector. Vertical and lateral transistor geometries are illustrated in the following figures.

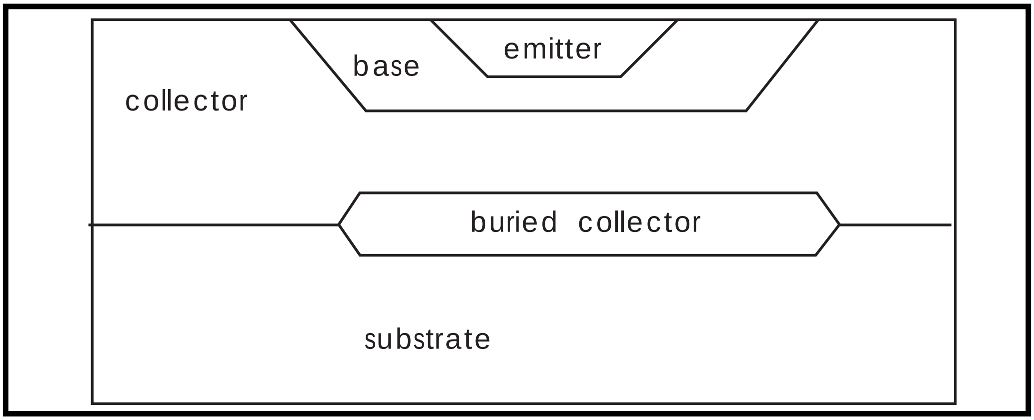

Figure 13-7: Vertical Transistor (SUBS = +1)

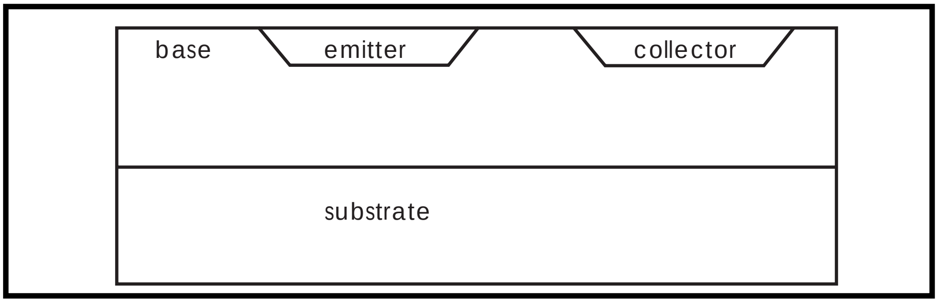

Figure 13-8: Lateral Transistor (SUBS = -1)

In Figure 13-10, the views from the top demonstrate how IBE is multiplied by either base area, AREAB, or collector area, AREAC.

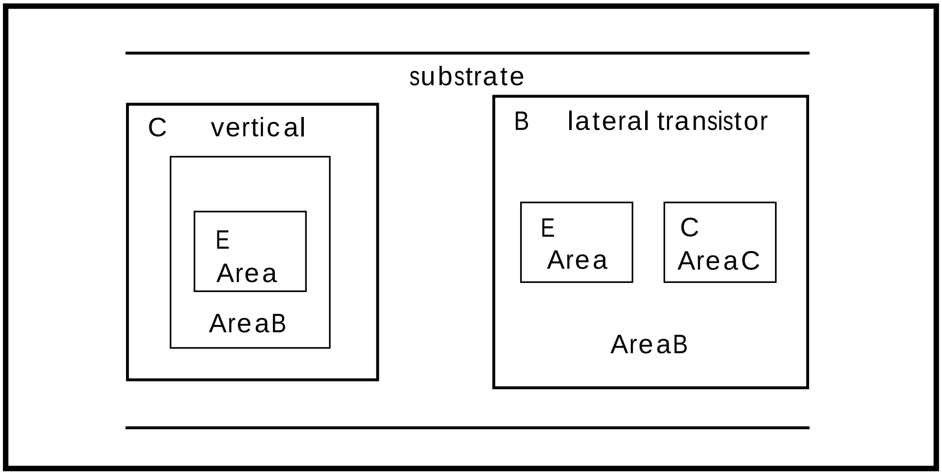

Figure 13-9: Base, AREAB, Collector, AREAC

DC Model Equations

These equations are for the DC component of the collector current (ic) and the base current (ib).

Current Equations - IS Only

If only IS is specified, without IBE and IBC:

$$ic = \frac{ISeff}{qb} \cdot \left(e^{\frac{vbe}{NF \cdot vt}} - e^{\frac{vbc}{NR \cdot vt}}\right) - \frac{ISeff}{BR} \cdot \left(e^{\frac{vbc}{NR \cdot vt}} - 1\right) - ISCeff \cdot \left(e^{\frac{vbc}{NC \cdot vt}} - 1\right)$$

$$= \frac{ISeff}{BF} \cdot \left(e^{\frac{vbe}{NF \cdot vt}} - 1\right) + \frac{ISeff}{BR} \cdot \left(e^{\frac{vbc}{NR \cdot vt}} - 1\right) + ISEeff \cdot \left(e^{\frac{vbe}{NE \cdot vt}} -\right.$$

$$\left. + ISCeff \cdot \left(e^{\frac{vbc}{NC \cdot vt}} - 1\right)\right.$$

Current Equations - IBE and IBC

If IBE and IBC are specified, instead of IS:

$$= \frac{IBEeff}{qb}\cdot\left(e^{\frac{vbe}{NF\cdot vt}}-1\right)-\frac{IBCeff}{qb}\cdot\left(e^{\frac{vbc}{NR\cdot vt}}-1\right)-\frac{IBCeff}{BR}\cdot\left(e^{\frac{vbc}{NR\cdot vt}}-\right.$$

$$-ISCeff\cdot\left(e^{\frac{vbc}{NC\cdot vt}}-1\right)$$

$$= \frac{IBEeff}{BF}\cdot\left(e^{\frac{vbe}{NF\cdot vt}}-1\right)+\frac{IBCeff}{BR}\cdot\left(e^{\frac{vbc}{NR\cdot vt}}-1\right)+ISEeff\cdot\left(e^{\frac{vbe}{NE\cdot vt}}-\right.$$

$$+ISCeff\cdot\left(e^{\frac{vbc}{NC\cdot vt}}-1\right)$$

$$IBCeff = IBC\cdot AREAB\cdot M \quad Vertical$$

$$IBCeff = IBC\cdot AREAC\cdot M \quad Lateral$$

$$IBEeff = IBE\cdot AREA\cdot M \quad Vertical\ or\ Lateral$$

$$ISCeff = ISC\cdot AREAB\cdot M \quad Vertical$$

$$ISCeff = ISC\cdot AREAC\cdot M \quad Lateral$$

$$ISEeff = ISE\cdot AREA\cdot M \quad Vertical\ or\ Lateral$$

The last two terms in the expression of the base current represent the components due to recombination in the base-emitter and base collector space charge regions at low injection.

Substrate Current Equations

The substrate current is substrate to collector for vertical transistors and substrate to base for lateral transistors.

Vertical Transistors

$$sc = ISSeff \cdot \left(e^{\frac{vsc}{NS \cdot vt}} - 1 \right. \qquad vsc > -10 \cdot NS \cdot vt$$

$$isc = -ISSeff \qquad vsc \leq -10 \cdot NS \cdot vt$$

Lateral Transistors

$$ibs = ISSeff \cdot \left(e^{\frac{vbs}{NS \cdot vt}} - 1 \right) \qquad vbs > -10 \cdot NS \cdot vt$$

$$ibs = -ISSeff \qquad vbs \leq -10 \cdot NS \cdot vt$$

If both IBE and IBC are *not* specified:

$$ISSeff = ISS \cdot AREA \cdot M$$

If both IBE and IBC are specified:

$$ISSeff = ISS \cdot AREAC \cdot M \quad \textit{vertical}$$

$$ISSeff = ISS \cdot AREAB \cdot M \quad \textit{lateral}$$

Base Charge Equations

VAF and VAR are, respectively, forward and reverse early voltages. IKF and IKR determine the high current Beta roll-off. ISE, ISC, NE, and NC determine the low current Beta roll-off with ic.

If UPDATE=0 or $\frac{vbc}{VAF} + \frac{vbe}{VAR} < 0$, then

$$q1 = \frac{1}{\left(1 - \frac{vbc}{VAF} - \frac{vbe}{VAR}\right)}$$

Otherwise, if UPDATE=1 and $\frac{vbc}{VAF} + \frac{vbe}{VAR} \geq 0$, then

$$q1 = 1 + \frac{vbc}{VAF} + \frac{vbe}{VAR}$$

$$q2 = \frac{ISEeff}{IKFeff} \cdot \left(e^{\frac{vbe}{NF \cdot vt}} - 1\right) + \frac{ISCeff}{IKReff} \cdot \left(e^{\frac{vbc}{NR \cdot vt}} - 1\right)$$

$$qb = \frac{q1}{2} \cdot [1 + (1 + 4 \cdot q2)^{NKF}]$$

Variable Base Resistance Equations

HSPICE provides a variable base resistance model consisting of a low-current maximum resistance set by RB and a high-current minimum resistance set by RBM. IRB is the current when the base resistance is halfway to its minimum value. If RBM is not specified, it is set to RB.

If IRB is not specified:

$$rbb = RBMeff + \frac{RBeff - RBMeff}{qb}$$

If IRB is specified:

$$rbb = RBMeff + 3 \cdot (RBeff - RBMeff) \cdot \frac{\tan(z) - z}{z \cdot \tan(z) \cdot \tan(z)}$$

$$z = \frac{-1 + [1 + 144 \cdot ib / (\pi^2 \cdot IRBeff)]^{1/2}}{\frac{24}{\pi^2} \cdot \left(\frac{ib}{IRBeff}\right)^{1/2}}$$

Understanding BJT Capacitances

This section describes BJT capacitances.

Base-Emitter Capacitance Equations

The base-emitter capacitance contains a complex diffusion term with the standard depletion capacitance formula. The diffusion capacitance is modified by model parameters TF, XTF, ITF, and VTF.

Determine the base-emitter capacitance cbe by the following formula:

$$cbe = cbediff + cbedep$$

where cbediff and cbedep are the base-emitter diffusion and depletion capacitances, respectively.

Note: When you run a DC sweep on a BJT, use .OPTIONS DCCAP to force the evaluation of the voltage-variable capacitances during the DC sweep.

Base-Emitter Diffusion Capacitance

Determine diffusion capacitance as follows:

ibe $\leq$ 0

$$cbediff = \frac{\partial}{\partial vbe}\left(TF \cdot \frac{ibe}{qb}\right)$$

ibe $>$ 0

$$cbediff = \frac{\partial}{\partial vbe}\left[TF \cdot (1 + argtf) \cdot \frac{ibe}{qb}\right]$$

where:

$$argtf = XTF \cdot \left(\frac{ibe}{ibe + ITF}\right)^2 \cdot e^{\frac{vbc}{1.44 \cdot VTF}}$$

The forward part of the collector-emitter branch current is determined as follows:

$$ibe = ISeff \cdot \left(e^{\frac{vbe}{NF \cdot vt}} - 1\right)$$

Base-Emitter Depletion Capacitance

There are two different equations for modeling the depletion capacitance. The proper equation is selected by specification of the option DCAP in the OPTIONS statement.

DCAP=1

The base-emitter depletion capacitance is determined as follows:

vbe < FC · VJE

$$cbedep = CJEeff \cdot \left(1 - \frac{vbe}{VJE}\right)^{-MJE}$$

vbe ≥ FC · VJE

$$cbedep = CJEeff \cdot \frac{1 - FC \cdot (1 + MJE) + MJE \cdot \frac{vbe}{VJE}}{(1 - FC)^{(1 + MJE)}}$$

DCAP=2

The base-emitter depletion capacitance is determined as follows:

vbe < 0

$$cbedep = CJEeff \cdot \left(1 - \frac{vbe}{VJE}\right)^{-MJE}$$

vbe ≥ 0

$$cbedep = CJEeff \cdot \left(1 + MJE \cdot \frac{vbe}{VJE}\right)$$

DCAP=3

Limits peak depletion capacitance to FC · CJCeff or FC · CJEeff, with proper fall-off when forward bias exceeds PB (FC ≥ 1).

Base Collector Capacitance

Determine the base collector capacitance cbc as follows:

$$cbc = cbcdiff + cbcdep$$

where cbcdiff and cbcdep are the base-collector diffusion and depletion capacitances, respectively.

Base Collector Diffusion Capacitance

$$cbcdiff = \frac{\partial}{\partial vbc}(TR \cdot ibc)$$

where the internal base-collector current ibc is:

$$ibc = ISeff \cdot \left(e^{\frac{vbc}{NR \cdot vt}} - 1\right)$$

Base Collector Depletion Capacitance

There are two different equations for modeling the depletion capacitance. Select the proper equation by specifying option DCAP in an .OPTIONS statement.

DCAP=1

Specify DCAP=1 to select one of the following equations:

vbc < FC · VJC

$$cbcdep = XCJC \cdot CJCeff \cdot \left(1 - \frac{vbc}{VJC}\right)^{-MJC}$$

vbc ≥ FC · VJC

$$cbcdep = XCJC \cdot CJCeff \cdot \frac{1 - FC \cdot (1 + MJC) + MJC \cdot \frac{vbc}{VJC}}{(1 - FC)^{(1 + MJC)}}$$

DCAP=2

Specify DCAP=2 to select one of the following equations:

vbc < 0

$$dep = XCJC \cdot CJCeff \cdot \left(1 - \frac{vbc}{VJC}\right)^{-}$$

vbc ≥ 0

$$cbcdep = XCJC \cdot CJCeff \cdot \left(1 + MJC \cdot \frac{vbc}{VJC}\right)$$

External Base — Internal Collector Junction Capacitance

The base-collector capacitance is modeled as a distributed capacitance when the model parameter XCJC is set. Since the default setting of XCJC is one, the entire base-collector capacitance is on the internal base node cbc.

DCAP=1

Specify DCAP=1 to select one of the following equations:

vbcx < FC · VJC

$$cbcx = CJCeff \cdot (1 - XCJC) \cdot \left(1 - \frac{vbcx}{VJC}\right)^{-MJC}$$

vbcx ≥ FC · VJC

$$cbcx = CJCeff \cdot (1 - XCJC) \cdot \frac{1 - FC \cdot (1 + MJC) + MJC \cdot \frac{vbcx}{VJC}}{(1 - FC)^{(1 + MJC)}}$$

DCAP=2

Specify DCAP=2 to select one of the following equations:

vbcx < 0

$$cbcx = CJCeff \cdot (1 - XCJC) \cdot \left(1 - \frac{vbcx}{VJC}\right)^{-MJC}$$

vbcx ≥ 0

$$cbcx = CJCeff \cdot (1 - XCJC) \cdot \left(1 + MJC \cdot \frac{vbcx}{VJC}\right)$$

where vbcx is the voltage between the external base node and the internal collector node.

Substrate Capacitance

The function of substrate capacitance is similar to that of the substrate diode. Switch it from the collector to the base by setting the model parameter, SUBS.

Substrate Capacitance Equation — Lateral

Base to Substrate Diode

Reverse Bias vbs < 0

$$cbs = CJSeff \cdot \left(1 - \frac{vbs}{VJS}\right)^{-MJS}$$

Forward Bias vbs ≥ 0

$$cbs = CJSeff \cdot \left(1 + MJS \cdot \frac{vbs}{VJS}\right)$$

Substrate Capacitance Equation — Vertical

Substrate to Collector Diode

Reverse Bias vsc < 0

$$csc = CJSeff \cdot \left(1 - \frac{vsc}{VJS}\right)^{-MJS}$$

Forward Bias vsc ≥ 0

$$csc = CJSeff \cdot \left(1 + MJS \cdot \frac{vsc}{VJS}\right)$$

Excess Phase Equation

The model parameter, PTF models excess phase. It is defined as extra degrees of phase delay (introduced by the BJT) at any frequency and is determined by the equation:

$$excess\ \ phase = \left(2 \cdot \pi \cdot PTF \cdot \frac{TF}{360}\right) \cdot (2 \cdot \pi \cdot f)$$

where f is in hertz, and you can set PTF and TF. The excess phase is a delay (linear phase) in the transconductance generator for AC analysis. Use it also in transient analysis.

Modeling Various Types of Noise

Equations for modeling BJT thermal, shot, and flicker noise are as follows.

Noise Equations

The mean square short-circuit base resistance noise current equation is:

$$inrb = \left(\frac{4 \cdot k \cdot t}{rbb}\right)^{1/2}$$

The mean square short-circuit collector resistance noise current equation is:

$$inrc = \left(\frac{4 \cdot k \cdot t}{RCeff}\right)^{1/2}$$

The mean square short-circuit emitter resistance noise current equation is:

$$inre = \left(\frac{4 \cdot k \cdot t}{REeff}\right)^{1/2}$$

The noise associated with the base current is composed of two parts: shot noise and flicker noise. Typical values for the flicker noise coefficient, KF, are 1e-17 to 1e-12. They are calculated as:

$$2 \cdot q \cdot fknee$$

where fknee is noise knee frequency (typically 100 Hz to 10 MHz) and q is electron charge.

$$inb^2 = (2 \cdot q \cdot ib) + \left(\frac{KF \cdot ib^{AF}}{f}\right)$$

$$inb^2 = shot\ \ noise^2 + flicker\ \ noise^2$$

$$shot\ \ noise = (2 \cdot q \cdot ib)^{1/2}$$

$$flicker\ \ noise = \left(\frac{KF \cdot ib^{AF}}{f}\right)^{1/2}$$

The noise associated with the collector current is modeled as shot noise only.

$$inc = (2 \cdot q \cdot ic)^{1/2}$$

Noise Summary Printout Definitions

RB, V^2/Hz	output thermal noise due to base resistor
RC, V^2/Hz	output thermal noise due to collector resistor
RE, V^2/Hz	output thermal noise due to emitter resistor
IB, V^2/Hz	output shot noise due to base current
FN, V^2/Hz	output flicker noise due to base current
IC, V^2/Hz	output shot noise due to collector current
TOT, V^2/Hz	total output noise: $TOT= RB + RC + RE + IB + IC + FN$

Using the BJT Quasi-Saturation Model

Use the BJT quasi-saturation model (Level=2), an extension of the Gummel-Poon model (Level 1 model), to model bipolar junction transistors which exhibit quasi-saturation or base push-out effects. When a device with lightly doped collector regions operates at high injection levels, the internal base-collector junction is forward biased, while the external base-collector junction is reversed biased; DC current gain and the unity gain frequency fT falls sharply. Such an operation regime is referred to as quasi-saturation, and its effects have been included in this model.

Figure 13-10: show the additional elements of the Level 2 model. The current source Iepi and charge storage elements Ci and Cx model the quasi-saturation effects. The parasitic substrate bipolar transistor is also included in the vertical transistor by the diode D and current source Ibs.

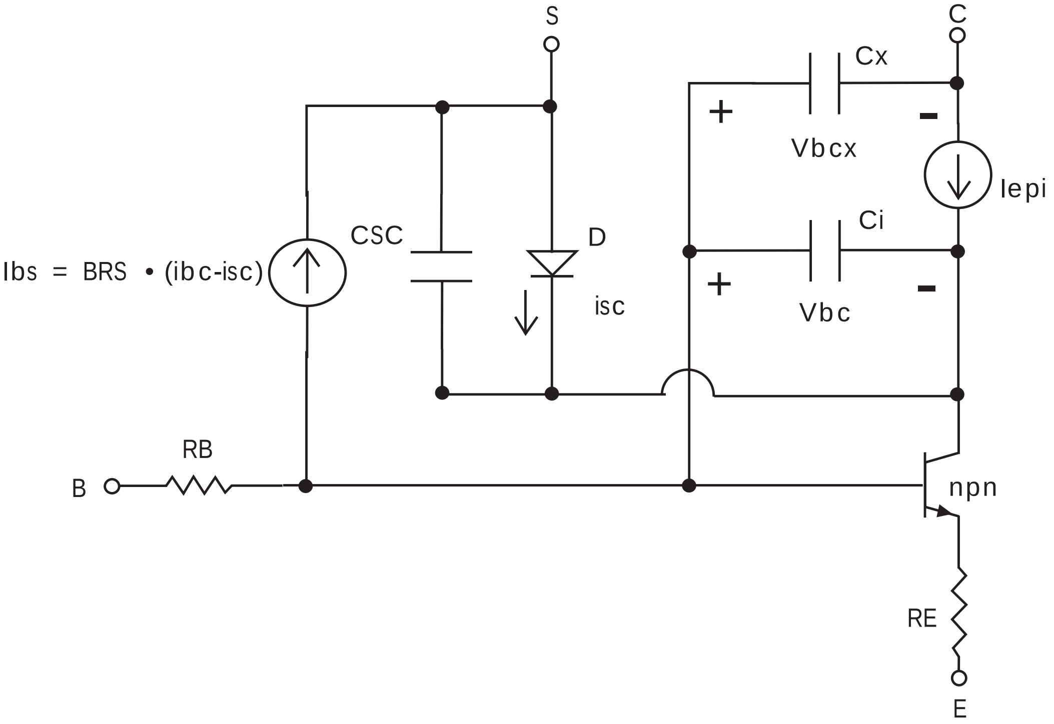

Figure 13-10: Vertical npn Bipolar Transistor (SUBS=+1)

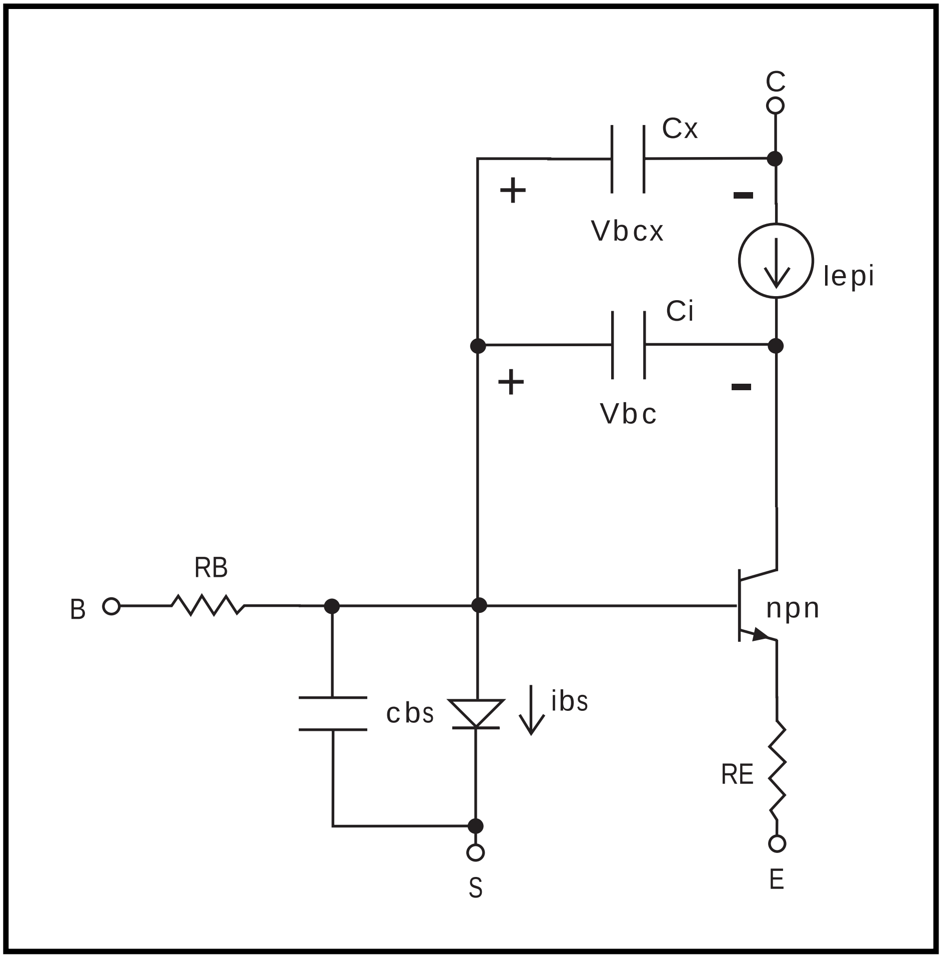

Figure 13-11: Lateral npn Bipolar Transistor (SUBS=-1)

Epitaxial Current Source Iepi

The epitaxial current value, Iepi, is determined by the following equation:

$$Iepi = \frac{ki - kx - \ln\left(\frac{1 + ki}{1 + kx}\right) + \frac{vbc - vbcx}{NEPI \cdot vt}}{\left(\frac{RCeff}{NEPI \cdot vt}\right) \cdot \left(1 + \frac{|vbc - vbcx|}{VO}\right)}$$

where

$$ki = [1 + GAMMA \cdot e^{vbc/(NEPI \cdot vt)}]^{1/2}$$

$$kx = [1 + GAMMA \cdot e^{vbcx/(NEPI \cdot vt)}]^{1/2}$$

In special cases when the model parameter GAMMA is set to zero, ki and kx become one and

$$Iepi = \frac{vbc - vbcx}{RCeff \cdot \left(1 + \frac{|vbc - vbcx|}{VO}\right)}$$

Epitaxial Charge Storage Elements Ci and Cx

The epitaxial charges are determined by:

$$qi = QCOeff \cdot \left(ki - 1 - \frac{GAMMA}{2}\right)$$

and

$$qx = QCOeff \cdot \left(kx - 1 - \frac{GAMMA}{2}\right)$$

The corresponding capacitances are calculated as following:

$$Ci = \frac{\partial}{\partial vbc}(qi) = \left(\frac{GAMMA \cdot QCOeff}{2 \cdot NEPI \cdot vt \cdot kx}\right) \cdot e^{vbc/(NEPI \cdot vt)}$$

and

$$Cx = \frac{\partial}{\partial vbcx}(qx) = \left(\frac{GAMMA \cdot QCOeff}{2 \cdot NEPI \cdot vt \cdot kx}\right) \cdot e^{vbcx/(NEPI \cdot vt)}$$

In the special case where GAMMA=0 the Ci and Cx become zero.

Example

```
*quasisat.sp comparison of bjt level1 and level2
model
.options nomod relv=.001 reli=.001 absv=.1u absi=1p
.options post
q11 10 11 0 mod1
q12 10 12 0 mod2
q21 10 21 0 mod1
q22 10 22 0 mod2
q31 10 31 0 mod1
q32 10 32 0 mod2
vcc 10 0 .7
i11 0 11 15u
i12 0 12 15u
i21 0 21 30u
i22 0 22 30u
i31 0 31 50u
i32 0 32 50u
.dc vcc 0 3 .1
.print dc vce=par('v(10)') i(q11)  i(q12)  i(q21)
i(q22) i(q31)  i(q32)
*.graph dc i(q11)  i(q12)  i(q21)  i(q22)
*.graph dc i(q11)  i(q12)
.MODEL MOD1 NPn IS=4.0E-16 BF=75 VAF=75
+  level=1 rc=500 SUBS=+1
.MODEL MOD2 NPn IS=4.0E-16 BF=75 VAF=75
+  level=2 rc=500 vo=1  qco=1e-10
```

```
+  gamma=1e-9  SUBS=+1
.end
```

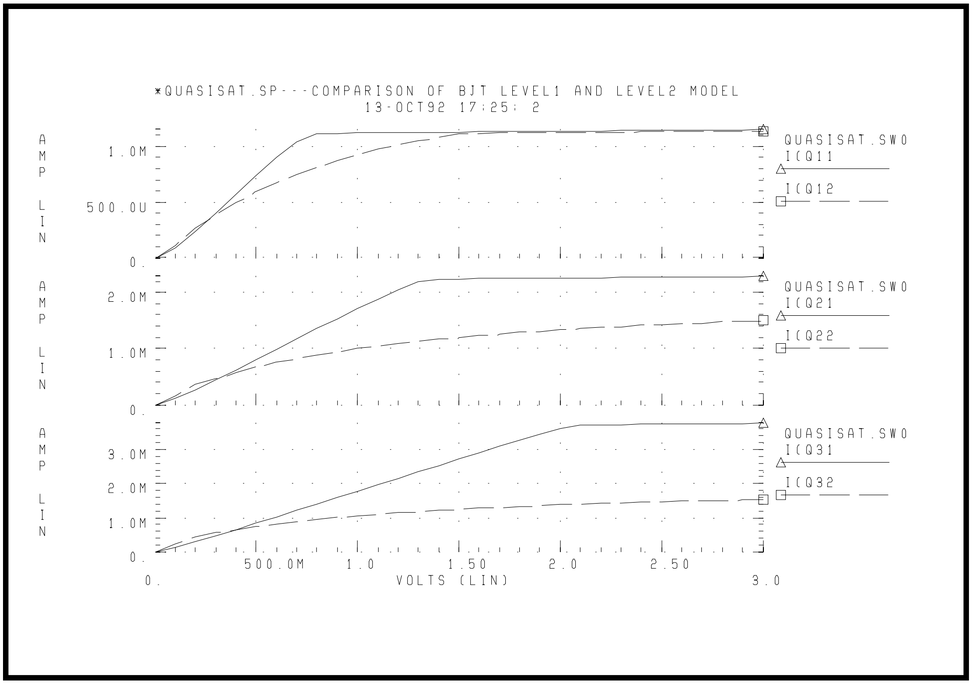

Figure 13-12: Comparison of BJT Level 1 and Level 2 Model

Using Temperature Compensation Equations

This section describes how to use temperature compensation equations.

Energy Gap Temperature Equations

To determine energy gap for temperature compensation, use the following equations:

TLEV = 0, 1 or 3

$$egnom = 1.16 - 7.02e{-4} \cdot \frac{tnom^2}{tnom + 1108.0}$$

$$eg(t) = 1.16 - 7.02e{-4} \cdot \frac{t^2}{t + 1108.0}$$

TLEV=2

$$egnom = EG - GAP1 \cdot \frac{tnom^2}{tnom + GAP2}$$

$$eg(t) = EG - GAP1 \cdot \frac{t^2}{t + GAP2}$$

Saturation and Beta Temperature Equations, TLEV=0 or 2

The basic BJT temperature compensation equations for beta and the saturation currents when TLEV=0 or 2 (default is SPICE style TLEV=0):

$$BF(t) = BF \cdot \left(\frac{t}{tnom}\right)^{XTB}$$

$$BR(t) = BR \cdot \left(\frac{t}{tnom}\right)^{XTB}$$

$$ISE(t) = \frac{ISE}{\left(\frac{t}{tnom}\right)^{XTB}} \cdot e^{\frac{facln}{NE}}$$

$$ISC(t) = \frac{ISC}{\left(\frac{t}{tnom}\right)^{XTB}} \cdot e^{\frac{facln}{NC}}$$

$$ISS(t) = \frac{ISS}{\left(\frac{t}{tnom}\right)^{XTB}} \cdot e^{\frac{facln}{NS}}$$

The parameter XTB usually should be set to zero for TLEV=2.

$$IS(t) = IS \cdot e^{facln}$$

$$IBE(t) = IBE \cdot e^{\frac{facln}{NF}}$$

$$BC(t) = IBC \cdot e^{\frac{facl}{NR}}$$

TLEV=0, 1 or 3

$$facln = \frac{EG}{vt(tnom)} - \frac{EG}{vt(t)} + XTI \cdot \ln\left(\frac{t}{tnom}\right)$$

TLEV=2

$$facln = \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)} + XTI \cdot \ln\left(\frac{t}{tnom}\right)$$

Saturation and Temperature Equations, TLEV=1

The basic BJT temperature compensation equations for beta and the saturation currents when TLEV=1:

$$BF(t) = BF \cdot (1 + XTB \cdot \Delta t)$$

$$BR(t) = BR \cdot (1 + XTB \cdot \Delta t)$$

$$ISE(t) = \frac{ISE}{1 + XTB \cdot \Delta t} \cdot e^{\frac{facln}{NE}}$$

$$ISC(t) = \frac{ISC}{1 + XTB \cdot \Delta t} \cdot e^{\frac{facln}{NC}}$$

$$ISS(t) = \frac{ISS}{1 + XTB \cdot \Delta t} \cdot e^{\frac{facln}{NS}}$$

$$IS(t) = IS \cdot e^{facln}$$

$$IBE(t) = IBE \cdot e^{\frac{facln}{NF}}$$

$$IBC(t) = IBC \cdot e^{\frac{facln}{NR}}$$

where

$$facln = \frac{EG}{vt(tnom)} - \frac{EG}{vt(t)} + XTI \cdot \ln\left(\frac{t}{tnom}\right)$$

TLEV=0, 1, 2

The parameters IKF, IKR, and IRB are also modified as follows:

$$IKF(t) = IKF \cdot (1 + TIKF1 \cdot \Delta t + TIKF2 \cdot \Delta t^2)$$

$$IKR(t) = IKR \cdot (1 + TIKR1 \cdot \Delta t + TIKR2 \cdot \Delta t^2)$$

$$IRB(t) = IRB \cdot (1 + TIRB1 \cdot \Delta t + TIRB2 \cdot \Delta t^2)$$

Saturation Temperature Equations, TLEV=3

The basic BJT temperature compensation equations for the saturation currents when TLEV=3

$$IS(t) = IS^{(1 + TIS1 \cdot \Delta t + TIS2 \cdot \Delta t^2)}$$

$$IBE(t) = IBE^{(1 + TIS1 \cdot \Delta t + TIS2 \cdot \Delta t^2)}$$

$$IBC(t) = IBC^{(1 + TIS1 \cdot \Delta t + TIS2 \cdot \Delta t^2)}$$

$$ISE(t) = ISE^{(1 + TISE1 \cdot \Delta t + TISE2 \cdot \Delta t^2)}$$

$$ISC(t) = ISC^{(1 + TISC1 \cdot \Delta t + TISC2 \cdot \Delta t^2)}$$

$$ISS(t) = ISS^{(1 + TISS1 \cdot \Delta t + TISS2 \cdot \Delta t^2)}$$

The parameters IKF, IKR, and IRB are also modified as follows:

$$IKF(t) = IKF^{(1 + TIKF1 \cdot \Delta t + TIKF2 \cdot \Delta t^2)}$$

$$IKR(t) = IKR^{(1 + TIKR1 \cdot \Delta t + TIKR2 \cdot \Delta t^2)}$$

$$IRB(t) = IRB^{(1 + TIRB1 \cdot \Delta t + TIRB2 \cdot \Delta t^2)}$$

The following parameters are also modified when corresponding temperature coefficients are specified, regardless of the TLEV value.

$$BF(t) = BF \cdot (1 + TBF1 \cdot \Delta t + TBF2 \cdot \Delta t^2)$$

$$BR(t) = BR \cdot (1 + TBR1 \cdot \Delta t + TBR2 \cdot \Delta t^2)$$

$$VAF(t) = VAF \cdot (1 + TVAF1 \cdot \Delta t + TVAF2 \cdot \Delta t^2)$$

$$VAR(t) = VAR \cdot (1 + TVAR1 \cdot \Delta t + TVAR2 \cdot \Delta t^2)$$

$$ITF(t) = ITF \cdot (1 + TITF1 \cdot \Delta t + TITF2 \cdot \Delta t^2)$$

$$TF(t) = TF \cdot (1 + TTF1 \cdot \Delta t + TTF2 \cdot \Delta t^2)$$

$$TR(t) = TR \cdot (1 + TTR1 \cdot \Delta t + TTR2 \cdot \Delta t^2)$$

$$NF(t) = NF \cdot (1 + TNF1 \cdot \Delta t + TNF2 \cdot \Delta t^2)$$

$$NR(t) = NR \cdot (1 + TNR1 \cdot \Delta t + TNR2 \cdot \Delta t^2)$$

$$NE(t) = NE \cdot (1 + TNE1 \cdot \Delta t + TNE2 \cdot \Delta t^2)$$

$$NC(t) = NC \cdot (1 + TNC1 \cdot \Delta t + TNC2 \cdot \Delta t^2)$$

$$NS(t) = NS \cdot (1 + TNS1 \cdot \Delta t + TNS2 \cdot \Delta t^2)$$

$$MJE(t) = MJE \cdot (1 + TMJE1 \cdot \Delta t + TMJE2 \cdot \Delta t^2)$$

$$MJC(t) = MJC \cdot (1 + TMJC1 \cdot \Delta t + TMJC2 \cdot \Delta t^2)$$

$$MJS(t) = MJS \cdot (1 + TMJS1 \cdot \Delta t + TMJS2 \cdot \Delta t^2)$$

Capacitance Temperature Equations

TLEVC=0

$$CJE(t) = CJE \cdot \left[1 + MJE \cdot \left(4.0e{-4} \cdot \Delta t - \frac{VJE(t)}{VJE} + 1\right)\right]$$

$$CJC(t) = CJC \cdot \left[1 + MJC \cdot \left(4.0e{-4} \cdot \Delta t - \frac{VJC(t)}{VJC} + 1\right)\right]$$

$$CJS(t) = CJS \cdot \left[1 + MJS \cdot \left(4.0e{-4} \cdot \Delta t - \frac{VJS(t)}{VJS} + 1\right)\right]$$

where

$$VJE(t) = VJE \cdot \frac{t}{tnom} - vt(t) \cdot \left[3 \cdot \ln\left(\frac{t}{tnom}\right) + \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)}\right]$$

$$VJC(t) = VJC \cdot \frac{t}{tnom} - vt(t) \cdot \left[3 \cdot \ln\left(\frac{t}{tnom}\right) + \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)}\right]$$

$$VJS(t) = VJS \cdot \frac{t}{tnom} - vt(t) \cdot \left[3 \cdot \ln\left(\frac{t}{tnom}\right) + \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)}\right]$$

TLEVC=1

$$CJE(t) = CJE \cdot (1 + CTE \cdot \Delta t)$$

$$CJC(t) = CJC \cdot (1 + CTC \cdot \Delta t)$$

$$CJS(t) = CJS \cdot (1 + CTS \cdot \Delta t)$$

and contact potentials determined as:

$$VJE(t) = VJE - TVJE \cdot \Delta t$$

$$VJC(t) = VJC - TVJC \cdot \Delta t$$

$$VJS(t) = VJS - TVJS \cdot \Delta t$$

TLEVC=2

$$CJE(t) = CJE \cdot \left(\frac{VJE}{VJE(t)}\right)^{MJE}$$

$$CJC(t) = CJC \cdot \left(\frac{VJC}{VJC(t)}\right)^{MJC}$$

$$CJS(t) = CJS \cdot \left(\frac{VJS}{VJS(t)}\right)^{MJS}$$

where

$$VJE(t) = VJE - TVJE \cdot \Delta t$$

$$VJC(t) = VJC - TVJC \cdot \Delta t$$

$$VJS(t) = VJS - TVJS \cdot \Delta t$$

TLEVC=3

$$CJE(t) = CJE \cdot \left(1 - 0.5 \cdot dvjedt \cdot \frac{\Delta t}{VJE}\right)$$

$$CJC(t) = CJC \cdot \left(1 - 0.5 \cdot dvjcdt \cdot \frac{\Delta t}{VJC}\right)$$

$$CJS(t) = CJS \cdot \left(1 - 0.5 \cdot dvjsdt \cdot \frac{\Delta t}{VJS}\right)$$

$$VJE(t) = VJE + dvjedt \cdot \Delta t$$

$$VJC(t) = VJC + dvjcdt \cdot \Delta t$$

$$VJS(t) = VJS + dvjsdt \cdot \Delta t$$

where for TLEV= 0, 1 or 3

$$dvjedt = -\frac{egnom + 3 \cdot vt(tnom) + (1.16 - egnom) \cdot \left(2 - \frac{tnom}{tnom + 1108}\right) - VJE}{tnom}$$

$$dvjcdt = -\frac{egnom + 3 \cdot vt(tnom) + (1.16 - egnom) \cdot \left(2 - \frac{tnom}{tnom + 1108}\right) - VJC}{tnom}$$

$$dvjsdt = -\frac{egnom + 3 \cdot vt(tnom) + (1.16 - egnom) \cdot \left(2 - \frac{tnom}{tnom + 1108}\right) - VJS}{tnom}$$

and for TLEV=2

$$dvjedt = -\frac{egnom + 3 \cdot vt(tnom) + (EG - egnom) \cdot \left(2 - \frac{tnom}{tnom + GAP2}\right) - VJE}{tnom}$$

$$dvjcdt = -\frac{egnom + 3 \cdot vt(tnom) + (EG - egnom) \cdot \left(2 - \frac{tnom}{tnom + GAP2}\right) - VJC}{tnom}$$

$$dvjsdt = -\frac{egnom + 3 \cdot vt(tnom) + (EG - egnom) \cdot \left(2 - \frac{tnom}{tnom + GAP2}\right) - VJS}{tnom}$$

Parasitic Resistor Temperature Equations

The parasitic resistors, as a function of temperature regardless of TLEV value, are determined as follows:

$$RE(t) = RE \cdot (1 + TRE1 \cdot \Delta t + TRE2 \cdot \Delta t^2)$$

$$RB(t) = RB \cdot (1 + TRB1 \cdot \Delta t + TRB2 \cdot \Delta t^2)$$

$$RBM(t) = RBM \cdot (1 + TRM1 \cdot \Delta t + TRM2 \cdot \Delta t^2)$$

$$RC(t) = RC \cdot (1 + TRC1 \cdot \Delta t + TRC2 \cdot \Delta t^2)$$

BJT LEVEL=2 Temperature Equations

The model parameters of BJT Level 2 model are modified for temperature compensation as follows:

$$GAMMA(t) = GAMMA \cdot e^{(facln)}$$

$$RC(t) = RC \cdot \left(\frac{t}{tnom}\right)^{BEX}$$

$$VO(t) = VO \cdot \left(\frac{t}{tnom}\right)^{BEXV}$$

Converting National Semiconductor Models

National Semiconductor's SNAP circuit simulator has a scaled BJT model that is not the same as that used by HSPICE. To use this model with HSPICE, make the following changes.

For a subcircuit that consists of the scaled BJT model, the subcircuit name must be the same as the name of the model. Inside the subcircuit there is a .PARAM statement that specifies the scaled BJT model parameter values. Put a scaled BJT model inside the subcircuit, then change the ".MODEL mname mtype" statement to a .PARAM statement. Ensure that each parameter in the .MODEL statement within the subcircuit has a value in the .PARAM statement.

Scaled BJT Subcircuit Definition

This subcircuit definition converts the National Semiconductor scaled BJT model to a form usable in HSPICE. The .PARAM parameter inside the .SUBCKT represents the .MODEL parameter in the National circuit simulator. Therefore, the ".MODEL mname" statement must be replaced by a .PARAM statement. The model name must be changed to SBJT.

Note: All the parameters used in the following model must have a value which comes either from a .PARAM statement or the subcircuit call.

Example

```
.SUBCKT SBJT NC NB NE SF=1 SCBC=1 SCBE=1 SCCS=1
SIES=1 SICS=1
+ SRB=1 SRC=1 SRE=1 SIC=0 SVCE=0 SBET=1
Q NC NB NE SBJT IC=SIC VCE=SVCE
.PARAM IES=110E-18 ICS=5.77E-18NE=1.02 NC=1.03
+ ME=3.61MC=1.24EG=1.12NSUB=0
+ CJE=1E-15CJC=1E-15 CSUB=1E-15EXE=0.501
+ EXC=0.222ESUB=0.709PE=1.16PC=0.37
+ PSUB=0.698 RE=75RC=0.0RB=1.0
+ TRE=2E-3 TRC=6E-3 TRB=1.9E-3VA=25
+ FTF=2.8E9 FTR=40E6 BR=1.5TCB=5.3E-3
```

```
+ TCB2=1.6E-6 BF1=9.93 BF2=45.7 BF3=55.1
+ BF4=56.5 BF5=53.5BF6=33.8
+ IBF1=4.8P IBF2=1.57N IBF3=74N
+ IBF4=3.13U IBF5=64.2U IBF6=516U
*
.MODEL SBJT NPN
+ IBE='IES*SF*SIES' IBC='ICS*SF*SICS'
+ CJE='CJE*SF*SCBE' CJC='CJC*SF*SCBC'
+ CJS='CSUB*SF*SCCS' RB='RB*SRB/SF'
+ RC='RC*SRC/SF' RE='RE*SRE/SF'
+ TF='1/(6.28*FTF)' TR='1/(6.28*FTR)'
+ MJE=EXE MJC=EXC
+ MJS=ESUB VJE=PE
+ VJC=PC VJS=PSUB
+ NF=NE NR=NC
+ EG=EG BR=BR VAF=VA
+ TRE1=TRE TRC1=TRC TRB1=TRB
+ TBF1=TCB TBF2=TCB2
+ BF0=BF1 IB0=IBF1
+ BF1=BF2 IB1=IBF2
+ BF2=BF3 IB2=IBF3
+ BF3=BF4 IB3=IBF4
+ BF4=BF5 IB4=IBF5
+ BF5=BF6 IB5=IBF6
+NSUB=0 sbet=sbet
+TLEV=1 TLEVC=1
+XTIR='MC*NC' XTI='ME*NE'
.ENDS SBJT
```

The BJT statement is replaced by:

```
 XQ1 1046 1047 8 SBJT SIES=25.5 SICS=25.5 SRC=3.92157E-2
+ SRE=3.92157E-2 SBET=3.92157E-2 SRB=4.8823E+2
SCBE=94.5234
+ SCBC=41.3745 SCCS=75.1679 SIC=1M SVCE=1
```

Chapter 14

Using JFET and MESFET Models

HSPICE contains three JFET/MESFET DC model levels. The same basic equations are used for both gallium arsenide MESFETs and silicon based JFETs. This is possible because special materials definition parameters are included in these models. These models have also proven useful in modeling indium phosphide MESFETs.

This chapter covers the following topics:

- Understanding JFETS
- Specifying a Model
- Understanding the Capacitor Model
- Using JFET and MESFET Element Statements
- Using JFET and MESFET Model Statements
- Generating Noise Models
- Using the Temperature Effect Parameters
- Understanding the TriQuint Model (TOM) Extensions to Level=3

Understanding JFETS

JFETs are formed by diffusing a gate diode between the source and drain, while MESFETs are formed by applying a metal layer over the gate region, creating a Schottky diode. Both technologies control the flow of carriers by modulating the gate diode depletion region. These field effect devices are referred to as bulk semiconductor devices and are in the same category as bipolar transistors. Compared to surface effect devices such as MOSFETs, bulk semiconductor devices tend to have higher gain because bulk semiconductor mobility is always higher than surface mobility.

Enhanced characteristics of JFETs and MESFETs, relative to surface effect devices, include lower noise generation rates and higher immunity to radiation. These advantages have created the need for newer and more advanced models.

Features for JFET and MESFET modeling include:

- Charge-conserving gate capacitors
- Backgating substrate node
- Mobility degradation due to gate field
- Computationally efficient DC model (Curtice and Statz)
- Subthreshold equation
- Physically correct width and length (ACM)

The HSPICE GaAs model Level=3 (See *A MESFET Model for Use in the Design of GaAs Integrated Circuits, IEEE Transactions on Microwave Theory*) assumes that GaAs device velocity saturates at very low drain voltages. The HSPICE model has been further enhanced to include drain voltage induced threshold modulation and user-selectable materials constants. These features allow use of the model for other materials such as silicon, indium phosphide, and gallium aluminum arsenide.

The Curtice model (See *GaAs FET Device and Circuit Simulation in SPICE, IEEE Transactions on Electron Devices Vluume ED-34*) in HSPICE has been revised and the TriQuint model (TOM) is implemented as an extension of the earlier Statz model.

Specifying a Model

To specify a JFET or MESFET model in HSPICE, use a JFET element statement and a JFET model statement. The model parameter Level selects either the JFET or MESFET model. LEVEL=1 and LEVEL=2 select the JFET, and LEVEL=3 selects the MESFET. Different submodels for the MESFET LEVEL=3 equations are selected using the parameter SAT.

LEVEL=1	SPICE model
LEVEL=2	modified SPICE model, gate modulation of LAMBDA
LEVEL=3	hyperbolic tangent MESFET model (Curtice, Statz, Meta, TriQuint Models)
SAT=0	Curtice model (Default)
SAT=1	Curtice model with user defined VGST exponent
SAT=2	cubic approximation of Curtice model with gate field degradation (Statz model)
SAT=3	Meta-Software variable saturation model

The model parameter CAPOP selects the type of capacitor model:

CAPOP=0	SPICE depletion capacitor model
CAPOP=1	charge conserving, symmetric capacitor model (Statz)
CAPOP=2	Meta improvements to CAPOP=1

CAPOP=0, 1, 2 can be used for any model level. CAPOP=1 and 2 are most often used for the MESFET Level 3 model.

The model parameter ACM selects the area calculation method:

ACM=0	SPICE method (default)
ACM=1	physically based method

Examples

```
J1 7 2 3 GAASFET
.MODEL GAASFET NJF LEVEL=3 CAPOP=1 SAT=1 VTO=-2.5
BETA=2.8E-3
+   LAMBDA=2.2M  RS=70 RD=70 IS=1.7E-14  CGS=14P
CGD=5P
+   UCRIT=1.5  ALPHA=2

J2 7 1 4 JM1
.MODEL JM1 NJF (VTO=-1.5, BETA=5E-3, CGS=5P, CGD=1P,
CAPOP=1  ALPHA=2)

J3 8 3 5 JX
.MODEL JX PJF (VTO=-1.2, BETA=.179M, LAMBDA=2.2M
+   CGS=100P CGD=20P CAPOP=1 ALPHA=2)
```

The first example selects the n channel MESFET model, LEVEL=3. It uses the SAT, ALPHA, and CAPOP=1 parameter. The second example selects an n-channel JFET and the third example selects a p-channel JFET.

Understanding the Capacitor Model

The SPICE depletion capacitor model (CAPOP=0) uses a diode-like capacitance between source and gate, where the depletion region thickness (and therefore the capacitance) is determined by the gate-to-source voltage. A similar diode model is often used to describe the normally much smaller gate-to-drain capacitance.

These approximations have serious shortcomings:

1. *Zero source-to-drain voltage:* The symmetry of the FET physics gives the conclusion that the gate-to-source and gate-to-drain capacitances should be equal, but in fact they can be very different.
2. *Inverse-biased transistor:* Where the drain acts like the source and the source acts like the drain. According to the model, the large capacitance should be between the original source and gate; but in this circumstance, the large capacitance is between the original drain and gate.

When low source-to-drain voltages inverse biased transistors are involved, large errors can be introduced into simulations. To overcome these limitations, use the Statz charge-conserving model by selecting model parameter CAPOP=1. The model selected by CAPOP=2 contains further improvements.

Model Applications

MESFETs are used to model GaAs transistors for high speed applications. Using MESFET models, transimpedance amplifiers for fiber optic transmitters up to 50 GHz can be designed and simulated.

Control Options

Control options that affect the simulation and design of both JFETs and MESFETs include:

DCAP	capacitance equation selector
GMIN, GRAMP, GMINDC	conductance options
SCALM	model scaling option

DCCAP	invokes capacitance calculation in DC analysis.

Table 14-1: JFET Options

Function	Control Options
capacitance	DCAP, DCCAP
conductance	GMIN, GMINDC, GRAMP
scaling	SCALM

Override a global depletion capacitance equation selection that uses the .OPTION DCAP=<*val*> statement in a JFET or MESFET model by including DCAP=<*val*> in the device's .MODEL statement.

Convergence

Enhance convergence for JFET and MESFET by using the GEAR method of computation (.OPTIONS METHOD=GEAR), when you include the transit time model parameter. Use the options GMIN, GMINDC, and GRAMP to increase the parasitic conductance value in parallel with pn junctions of the device.

Capacitor Equations

The option DCAP selects the equation used to calculate the gate-to-source and gate-to-drain capacitance for CAPOP=0. DCAP can be set to 1, 2 or 3. The default is 2.

Using JFET and MESFET Element Statements

The JFET and MESFET element statement contains netlist parameters for connectivity, the model reference name, dimensional geometric parameters, in addition to initialization and temperature parameters. The parameters are listed in Table 14-2.

Table 14-2: JFET Element Parameters

Function	Parameter
netlist	Jxxx, mname, nb, nd, ng, ns
geometric	AREA, L, M, W
initialization	IC=(vds, vgs), OFF
temperature	DTEMP

Syntax

```
Jxxx nd ng ns <nb> mname <AREA | W=val L=val> <OFF>
<IC=vdsval, vgsval> <M=val>
+    <DTEMP=val>
or
Jxxx nd ng ns mname <<AREA=val> | <W=val> <L=val>>
<M=val> <OFF> <DTEMP=val>
+    <VDS=vdsval> <VGS=vgsval>
```

Jxxx	JFET or MESFET element name. The name must begin with a “J” followed by up to 15 alphanumeric characters.
nb	bulk terminal node name or number
nd	drain terminal node name or number
ng	gate terminal node name or number
ns	source terminal node name or number

mname	model name. the name must reference a JFET or MESFET model.
AREA	the AREA multiplying factor. It affects the BETA, RD, RS, IS, CGS, and CGD model parameters. If AREA is not specified but Weff and Leff are greater than zero then: AREA=Weff/Leff, ACM=0 AREA=Weff · Leff, ACM=1 AREAeff=M · AREA Default = 1.0
W=val	FET gate width
L=val	FET gate length Leff = L · SCALE + LDELeff
OFF	sets initial condition to OFF for this element in DC analysis. Default = ON. Weff = W · SCALE + WDELeff
IC=vdsval,	initial condition for the drain-source voltage (vdsval), or for the gate-source
M=val	Multiplier factor to simulate multiple JFETs. All currents, capacitances, and resistances are affected by M.
vgsval	voltage (vgsval). This condition can be overridden by the IC statement.
DTEMP	device temperature difference with respect to circuit temperature. Default = 0.0.

Examples

```
J1 7 2 3 JM1
jmes xload gdrive common jmodel
```

Scaling

The AREA and M element parameters, together with the SCALE and SCALM control options, control scaling. For all three model levels, the model parameters IS, CGD, CGS, RD, RS, BETA, LDEL, and WDEL, are scaled using the same equations.

Scaled parameters A, L, W, LDEL, and WDEL, are affected by option SCALM. SCALM defaults to 1.0. To enter the parameter W with units in microns, for example, set SCALM to 1e-6, then enter W=5; HSPICE sets W=5e-6 meters, or 5 microns.

Override global scaling that uses the .OPTION SCALM=<val> statement in a JFET or MESFET model by including SCALM=<val> in the .MODEL statement.

JFET Current Convention

The direction of current flow through the JFET is assumed in the following diagram. Either I(Jxxx) or I1(Jxxx) syntax can be used when printing the drain current. I2 references the gate current and I3 references the source current. Jxxx is the device name.

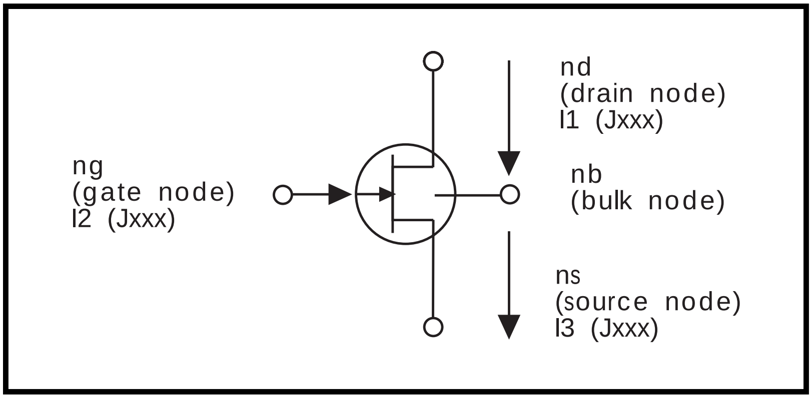

Figure 14-1: JFET Current Convention, N-Channel

Figure 14-1: represents the HSPICE current convention for an n channel JFET. For a p-channel device, the following must be reversed:

- Polarities of the terminal voltages vgd, vgs, and vds
- Direction of the two gate junctions
- Direction of the nonlinear current source id

JFET Equivalent Circuits

HSPICE uses three equivalent circuits in the analysis of JFETs: transient, AC, and noise circuits. The components of these circuits form the basis for all element and model equation discussion.

The fundamental component in the equivalent circuit is the drain to source current (ids). For noise and AC analyses, the actual ids current is not used. Instead, the partial derivatives of ids with respect to the terminal voltages, vgs, and vds are used. The names for these partial derivatives are:

Transconductance

$$gm = \left.\frac{\partial(ids)}{\partial(vgs)}\right|_{vds = const.}$$

Output Conductance

$$gds = \left.\frac{\partial(ids)}{\partial(vds)}\right|_{vgs = const.}$$

The ids equation accounts for all DC currents of the JFET. The gate capacitances are assumed to account for transient currents of the JFET equations. The two diodes shown in Figure 14-2: are modeled by these ideal diode equations:

$$igd = ISeff \cdot \left(e^{\frac{vgd}{N \cdot vt}} - 1\right) \qquad vgd > -10 \cdot N \cdot vt$$

$$igd = -ISeff \qquad vgd \le -10 \cdot N \cdot vt$$

$$igs = ISeff \cdot \left(e^{\frac{vgs}{N \cdot vt}} - 1\right) \qquad vgs > -10 \cdot N \cdot vt$$

$$igs = -ISeff \qquad vgs \le -10 \cdot N \cdot vt$$

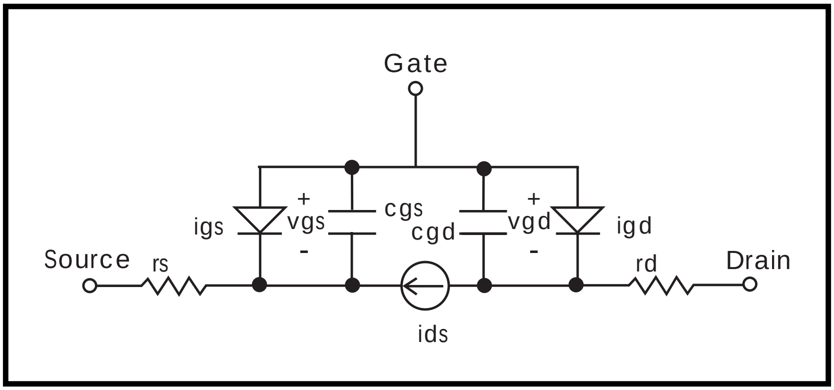

Figure 14-2: JFET/MESFET Transient Analysis

Note: For DC analysis, the capacitances are not part of the model.

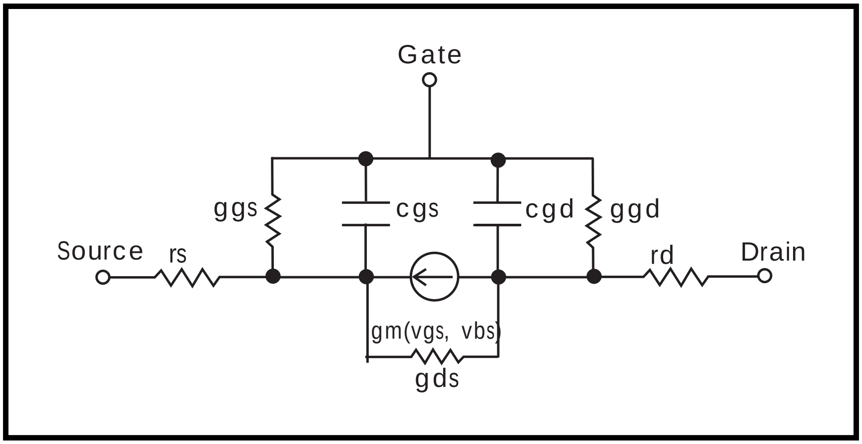

Figure 14-3: JFET/MESFET AC Analysis

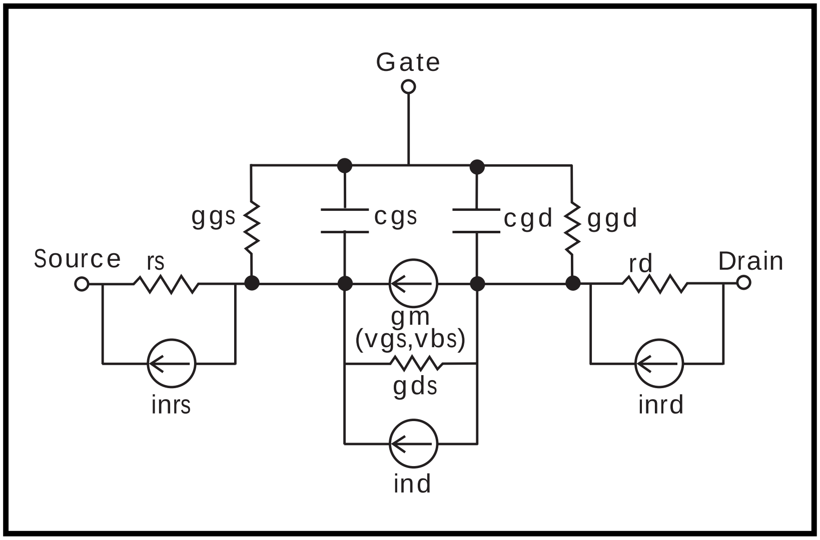

Figure 14-4: JFET/MESFET AC Noise Analysis

Table 14-3: Equation Variable Names and Constants

Variable/ Quantity	Definitions
cgd	gate to drain capacitance
cgs	gate to source capacitance
ggd	gate to drain AC conductance
ggs	gate to source AC conductance
gds	drain to source AC conductance controlled by vds
gm	drain to source AC transconductance controlled by vgs
igd	gate to drain current
igs	gate to source current
ids	DC drain to source current
ind	equivalent noise current drain to source
inrd	equivalent noise current drain resistor
inrs	equivalent noise current source resistor
rd	drain resistance
rs	source resistance
vgd	internal gate-drain voltage
vgs	internal gate-source voltage
f	frequency
ε_o	vacuum permittivity = 8.854e-12 F/m
k	1.38062e-23 (Boltzmann’s constant)
q	1.60212e-19 (electron charge)
t	temperature in °K
Dt	t - tnom

Table 14-3: Equation Variable Names and Constants

Variable/ Quantity	Definitions
tnom	nominal temperature of parameter measurements in °K (user-input in °C). Tnom = 273.15 + TNOM
vt(t)	$k \cdot t/q$
vt(tnom)	$k \cdot tnom/q$

Using JFET and MESFET Model Statements

General Form

.MODEL mname NJF <LEVEL = val> <pname1 = val1> ...

.MODEL mname PJF <LEVEL = val> <pname1 = val1> ...

mname	model name. Elements refer to the model by this name.
NJF	identifies an N-channel JFET or MESFET model
LEVEL	The LEVEL parameter selects different DC model equations.
pname1=val1	Each JFET or MESFET model can include several model parameters.
PJF	identifies a P-channel JFET or MESFET model

JFET and MESFET Model Parameters

DC characteristics are defined by the model parameters VTO and BETA. These parameters determine the variation of drain current with gate voltage. LAMBDA determines the output conductance, and IS, the saturation current, of the two gate junctions. Two ohmic resistances, RD and RS, are included. Charge storage is modeled by nonlinear depletion-layer capacitances for both gate junctions which vary as the -M power of junction voltage, and are defined by the parameters CGS, CGD, and PB.

Use parameters KF and AF to model noise, which is also a function of the series source and drain resistances (RS and RD), in addition to temperature. Use the parameters ALPHA and A to model MESFETs.

The AREA model parameter is common to both the element and model parameters. The AREA element parameter always overrides the AREA model parameter.

Table 14-4: JFET and MESFET Model Parameters

Model Parameters Common To All Levels	
geometric	ACM, ALIGN, AREA, HDIF, L, LDEL, LDIF, RD, RG, RS, RSH, RSHG, RSHL, W, WDEL
capacitance	CAPOP, CGD, CGS, FC, M, PB, TT
subthreshold	ND, NG
noise	AF, KF
Level=1 Model Parameters (JFET)	
DC	BETA, IS, LAMBDA, N, VTO
Level=2 Model Parameters (JFET)	
DC	BETA, IS, LAMBDA, LAM1, N, VTO
Level=3 Model Parameters (MESFET)	
DC	ALPHA, BETA, D, GAMDS, IS, N, K1, LAMBDA, NCHAN, SAT, SATEXP, UCRIT, VBI, VGEXP, VP, VTO

The following subsections provide information about:

- Gate Diode DC Parameters
- DC Model LEVEL 1 Parameters
- DC Model LEVEL 2 Parameters
- DC Model LEVEL 3 Parameters
- ACM (Area Calculation Method) Parameter Equations

Gate Diode DC Parameters

Name(Alias)	Units	Default	Description
ACM			area calculation method. This parameter allows the selection between the old SPICE unitless gate area calculations and the new HSPICE area calculations (see the ACM section). If W and L are specified, AREA becomes: ACM=0 AREA=Weff/Leff ACM=1 AREA=Weff · Leff
ALIGN	m	0	misalignment of gate
AREA			default area multiplier. This parameter affects the BETA, RD, RS, IS, CGS, and CGD model parameters. AREAeff=M · AREA Override this parameter using the element effective area.
HDIF	m	0	distance of the heavily diffused or low resistance region from source or drain contact to lightly doped region
IS	amp	1.0e-14	gate junction saturation current ISeff = IS · AREAeff

Name(Alias)	Units	Default	Description
L	m	0.0	default length of FET. Override this parameter using the element L. Leff = L · SCALM + LDELeff
LDEL	m	0.0	difference between drawn and actual or optical device length LDELeff = LDEL · SCALM
LDIF	m	0	distance of the lightly doped region from heavily doped region to transistor edge
N		1.0	emission coefficient for gate-drain and gate-source diodes
RD	ohm	0.0	drain ohmic resistance (see the ACM section) RDeff = RD /AREAeff, ACM=0
RG	ohm	0.0	gate resistance (see the ACM section) RGeff = RG · AREAeff, ACM=0
RS	ohm	0.0	source ohmic resistance (see the ACM section) RSeff = RS /AREAeff, ACM=0
RSH	ohm/sq	0	heavily doped region, sheet resistance
RSHG	ohm/sq	0	gate sheet resistance
RSHL	ohm/sq	0	lightly doped region, sheet resistance

Name(Alias)	Units	Default	Description
W	m	0.0	default width of FET. Override this parameter using the element W. $Weff = W \cdot SCALM + WDELeff$
WDEL	m	0.0	difference between drawn and actual or optical device width $WDELeff = WDEL \cdot SCALM$

Gate Capacitance LEVEL 1, 2 and 3 Parameters

Name(Alias)	Units	Default	Description
CAPOP		0.0	capacitor model selector: CAPOP=0 – default capacitance equation based on diode depletion layer CAPOP=1 – symmetric capacitance equations (Statz) CAPOP=2 – Meta-software improvement to CAPOP=1
CALPHA	ALPHA		saturation factor for capacitance model (CAPOP=2 only)
CAPDS	F	0	drain to source capacitance for TriQuint model $CAPDSeff = CAPDS \cdot \frac{Weff}{Leff} \cdot M$

Name(Alias)	**Units**	**Default**	**Description**
CGAMDS	GAMDS		threshold lowering factor for capacitance (CAPOP=2 only)
CGD	F	0.0	zero-bias gate-drain junction capacitance CGDeff = CGD · AREAeff Override this parameter by specifying GCAP.
CGS	F	0.0	zero-bias gate-source junction capacitance CGSeff = CGS · AREAeff Override this parameter by specifying GCAP
CRAT		0.666	source fraction of gate capacitance (used with GCAP)
GCAP	F		zero-bias gate capacitance. If specified, CGSeff = GCAP · CRAT · AREAeff and CGDeff = GCAP · (1-CRAT) · AREAeff
FC		0.5	coefficient for forward-bias depletion capacitance formulas (CAPOP=0 and 2 only)
CVTO	VTO		threshold voltage for capacitance model (CAPOP=2 only)
M (MJ)		0.50	grading coefficient for gate-drain and gate-source diodes (CAPOP=0 and 2 only) 0.50 - step junction 0.33 - linear graded junction

Name(Alias)	Units	Default	Description
PB	V	0.8	gate junction potential
TT	s	0	transit time – option METHOD=GEAR is recommended when using transit time for JFET and MESFET

Note: Many DC parameters (such as VTO, GAMDS, ALPHA) can also affect capacitance.

DC Model LEVEL 1 Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	Level=1 invokes SPICE JFET model
BETA	amp/ V^2	1.0e-4	transconductance parameter, gain $ETAeff = BETA \cdot \frac{Weff \cdot}{Leff}$
LAMBDA	1/V	0.0	channel length modulation parameter
ND	1/V	0.0	drain subthreshold factor (typical value=1)
NG		0.0	gate subthreshold factor (typical value=1)
VTO	V	-2.0	threshold voltage. If set, it overrides internal calculation. A negative VTO is a depletion transistor regardless of NJF or PJF. A positive VTO is always an enhancement transistor.

DC Model LEVEL 2 Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	level of FET DC model. Level=2 is based on modifications to the SPICE model for gate modulation of LAMBDA.
BETA	amp /V^2	1.0e-4	transconductance parameter, gain $ETAeff = BETA \cdot \frac{Weff \cdot}{Leff}$
LAMBDA	1/V	0.0	channel length modulation parameter
LAM1	1/V	0.0	channel length modulation gate voltage parameter
ND	1/V	0.0	drain subthreshold factor (typical value=1)

Name(Alias)	**Units**	**Default**	**Description**
NG		0.0	gate subthreshold factor (typical value=1)
VTO	V	-2.0	threshold voltage. When set, VTO overrides internal calculation. A negative VTO is a depletion transistor regardless of NJF or PJF. A positive VTO is always an enhancement transistor.

DC Model LEVEL 3 Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	level of FET DC model. Level=3 is the Curtice MESFET model.
A	m	0.5µ	active layer thickness
			Aeff = A · SCALM
ALPHA	1/V	2.0	saturation factor
BETA	amp/V^2	1.0e-4	transconductance parameter, gain
			$ETAeff = BETA \cdot \frac{Weff \cdot}{Leff}$
D		11.7	semiconductor dielectric constant: Si=11.7, GaAs=10.9
DELTA		0	Ids feedback parameter of TriQuint model
GAMDS *(GAMMA)*		0	drain voltage, induced threshold voltage lowering coefficient
LAMBDA	1/V	0.0	channel length modulation parameter
K1	$V^{1/2}$	0.0	threshold voltage sensitivity to bulk node
NCHAN	$atom/cm^3$	1.552e16	effective dopant concentration in the channel
ND	1/V	0.0	drain subthreshold factor
NG		0.0	gate subthreshold factor (typical value=1)

Name(Alias)	Units	Default	Description
SAT		0.0	saturation factor
			SAT=0 (standard Curtice model)
			SAT= (Curtice model with hyperbolic tangent coefficient)
			SAT=2 (cubic approximation of Curtice model (Statz))
SATEXP		3	drain voltage exponent
UCRIT	V/cm	0	critical field for mobility degradation
VBI		1.0	gate diode built-in voltage
VGEXP (Q)		2.0	gate voltage exponent
VP			dinch-off voltage (default is calculated)
VTO	V	-2.0	threshold voltage. If set, it overrides internal calculation. A negative VTO is a depletion transistor regardless of NJF or PJF. A positive VTO is always an enhancement transistor.

ACM (Area Calculation Method) Parameter Equations

The JFET model parameter ACM allows you to select between the SPICE unitless gate area calculations and the HSPICE area calculations. The ACM=0 method (SPICE) uses the ratio of W/L to keep AREA unitless. The ACM=1 model (HSPICE) requires parameters such as IS, CGS, CGD, and BETA to have proper physics-based units.

In the following equations, lower case “m” indicates the element multiplier.

ACM=0

$$AREAeff = \frac{Weff}{Leff} \cdot m$$

$$RDeff = \frac{RD}{AREAeff}$$

$$RSeff = \frac{RS}{AREAeff}$$

$$RGeff = RG \cdot \frac{AREAeff}{m^2}$$

ACM=1

$$AREAeff = Weff \cdot Leff \cdot m$$

$$RDeff = \frac{RD}{m}$$

Or if RD=0,

$$RDeff = RSH \cdot \frac{HDIF}{Weff \cdot m} + RSHL \cdot \frac{LDIF + ALIGN}{Weff \cdot m}$$

$$RGeff = \frac{RG}{m}$$

or if RG=0,

$$RGeff = RSHG \cdot \frac{Weff}{Leff \cdot m}$$

$$RSeff = \frac{RS}{m}$$

or if RS=0,

$$RSeff = RSH \cdot \frac{HDIF}{Weff \cdot m} + RSHL \cdot \frac{LDIF - ALIGN}{Weff \cdot m}$$

Resulting calculations

$$ISeff = IS \cdot AREAeff$$

$$CGSeff = CGS \cdot AREAeff$$

$$CGDeff = CGD \cdot AREAeff$$

$$BETAeff = BETA \cdot \frac{Weff}{Leff} \cdot m$$

Note: It is important to remember that the model parameter units for IS, CGS, CGD, are unitless in ACM=0 and per square meter for ACM=1.

Example

```
j1 10 20 0 40 nj_acm0  w=10u l=1u
j2a 10 20 0 41 nj_acm1  w=10u l=1u

.model nj_acm0 njf level=3 capop=1 sat=3  acm=0
+ is=1e-14  cgs=1e-15 cgd=.3e-15 $$$ note different
units for is,cgs,cgd
+ rs=100  rd=100 rg=5 beta=5e-4
+ vto=.3 n=1  ng=1.4 nd=1
+ k1=.2  vgexp=2 alpha=4 ucrit=1e-4 lambda=.1
satexp=2
+ eg=1.5 gap1=5e-4 gap2=200 d=13

.model nj_acm1 njf level=3 capop=1 sat=3 acm=1
+ is=1e-2  cgs=1e-3 cgd=.3e-3  $$$ note different
units for is,cgs,cgd
+ rs=100  rd=100 rg=5 beta=5e-4
+ vto=.3 n=1  ng=1.4 nd=1
+ k1=.2  vgexp=2 alpha=4 ucrit=1e-4 lambda=.1
satexp=2
+ eg=1.5 gap1=5e-4 gap2=200 d=13
```

JFET and MESFET Capacitances

Gate Capacitance CAPOP=0

The DCAP option switch selects the diode forward bias capacitance equation:

DCAP=1

Reverse Bias:

vgd < FC · PB

$$cgd = CGDeff \cdot \left(1 - \frac{vgd}{PB}\right)^{-M}$$

vgs < FC · PB

$$cgs = CGSeff \cdot \left(1 - \frac{vgs}{PB}\right)^{-M}$$

Forward Bias:

vgd FC· PB

$$cgd = TT \cdot \frac{\partial igd}{\partial vgd} + CGDeff \cdot \frac{1 - FC \cdot (1 + M) + M \cdot \frac{vgd}{PB}}{(1 - FC)^{M+1}}$$

vgs FC· PB

$$cgs = TT \cdot \frac{\partial igs}{\partial vgs} + CGSeff \cdot \frac{1 - FC \cdot (1 + M) + M \cdot \frac{vgs}{PB}}{(1 - FC)^{M+1}}$$

DCAP=2 (HSPICE Default)

Reverse Bias:

vgd < 0

$$cgd = CGDeff \cdot \left(1 - \frac{vgd}{PB}\right)^{-M}$$

vgs < 0

$$cgs = CGSeff \cdot \left(1 - \frac{vgs}{PB}\right)^{-M}$$

Forward Bias:

vgd 0

$$cgd = TT \cdot \frac{\partial igd}{\partial vgd} + CGDeff \cdot \left(1 + M \cdot \frac{vgd}{PB}\right)$$

vgs 0

$$cgs = TT \cdot \frac{\partial igs}{\partial vgs} + CGSeff \cdot \left(1 + M \cdot \frac{vgs}{PB}\right)$$

DCAP=3

Limits peak depletion capacitance to FC · CGDeff or FC · CGSeff, with proper fall-off when forward bias exceeds PB (FC ≥ 1).

Gate Capacitance CAPOP=1

Gate capacitance CAPOP=1 is a charge conserving symmetric capacitor model most often used for MESFET model Level 3.

$$Cgs = \frac{CGS}{4\sqrt{1-\frac{vnew}{PB}}} \cdot \left[1 + \frac{veff - vte}{\sqrt{(veff - vte)^2 + (0.2)^2}}\right] \cdot$$

$$+ \frac{vds}{\sqrt{vds^2 + \left(\frac{1}{ALPHA}\right)^2}} \Bigg| + \Bigg| \frac{CGD}{2} \cdot \Bigg| \Bigg(1 - \frac{vds}{\sqrt{vds^2 + \left(\frac{1}{ALPHA}\right)^2}}$$

$$Cgd = \left(\frac{CGS}{4\sqrt{1-\frac{vnew}{PB}}} \cdot \left[1 + \frac{veff - vte}{\sqrt{(veff - vte)^2 + (0.2)^2}}\right] \cdot \Bigg[1 - \frac{vds}{\sqrt{vds^2 + \Big(\frac{1}{ALP}}} \right.$$

$$\left. \left(\frac{CGD}{2} \cdot \left[1 + \frac{vds}{\sqrt{vds^2 + \left(\frac{1}{ALPHA}\right)^2}} \right] \right] \right)$$

where

$$vte = VTO + GAMDS \cdot vds + K1(vbs) = \text{effective threshold}$$

$$veff = \frac{1}{2}\left[vgs + vgd + \sqrt{vds^2 + \left(\frac{1}{ALPHA}\right)^2}\right]$$

and

$$vnew = \frac{1}{2}[veff + vte + \sqrt{(veff - vte)^2 + (0.2)^2}]$$

```
CGD = High -vds Cgd at vgs = 0
CGS = High -vds Cgs at vgs = 0
```

```
CGD - CGDeff
CGS - CGSeff
```

Gate Capacitance CAPOP=2

The Statz capacitance equations (See *H. Statz, P.Newman, I.W.Smith, R.A. Pucel, and H.A. Haus, GaAs FET Device and Circuit Simulation in Spice*) (CAPOP=1) contain some mathematical behavior that has been found to be problematic when trying to fit data.

- For vgs below the threshold voltage and Vds>0 (normal bias condition), Cgd is greater than Cgs and rises with Vds, while Cgs drops with Vds.
- Although Cgd properly goes to a small constant representing a sidewall capacitance, Cgs drops asymptotically to zero with decreasing Vgs.
- (For the behavior for Vds<0, interchange Cgs and Cgd and replace Vds with -Vds in the above descriptions.)
- It can be difficult to simultaneously fit the DC characteristics and the gate capacitances (measured by S-parameters) with the parameters that are shared between the DC model and the capacitance model.
- The capacitance model in the CAPOP=1implementation also lacks a junction grading coefficient and an adjustable width for the Vgs transition to the threshold voltage. The width is fixed at 0.2).
- Finally, an internal parameter for limiting forward gate voltage is set to 0.8 · PB in the CAPOP=1 implementation. This is not always consistent with a good fit.

The CAPOP=2 capacitance equations help to solve the problems described above.

CAPOP=2 Parameters

Parameter	**Default**	**Units**	**Description**
CALPHA	ALPHA		saturation factor for capacitance model
CGAMDS	GAMDS		threshold lowering factor for capacitance
CVTO	VTO		threshold voltage for capacitance model
FC	0.5		PB multiplier – typical value 0.9 gate diode limiting voltage=FC · PB.
M (MJ)	0.5		junction grading coefficient
VDEL	0.2		transition width for Vgs

Capacitance Comparison (CAPOP=1 and CAPOP=2)

The following figures show comparisons of CAPOP=1 and CAPOP=2. Note in Figure 14-5 that below threshold (-0.6 v) Cgs for CAPOP=2 drops towards the same value as Cgd, while for CAPOP=1,

$CGS \rightarrow 0.$

Note in Figure 14-6 how the Cgs-Cgd characteristic curve “flips over” below threshold for CAPOP=1, while for CAPOP=2, it is well-behaved.

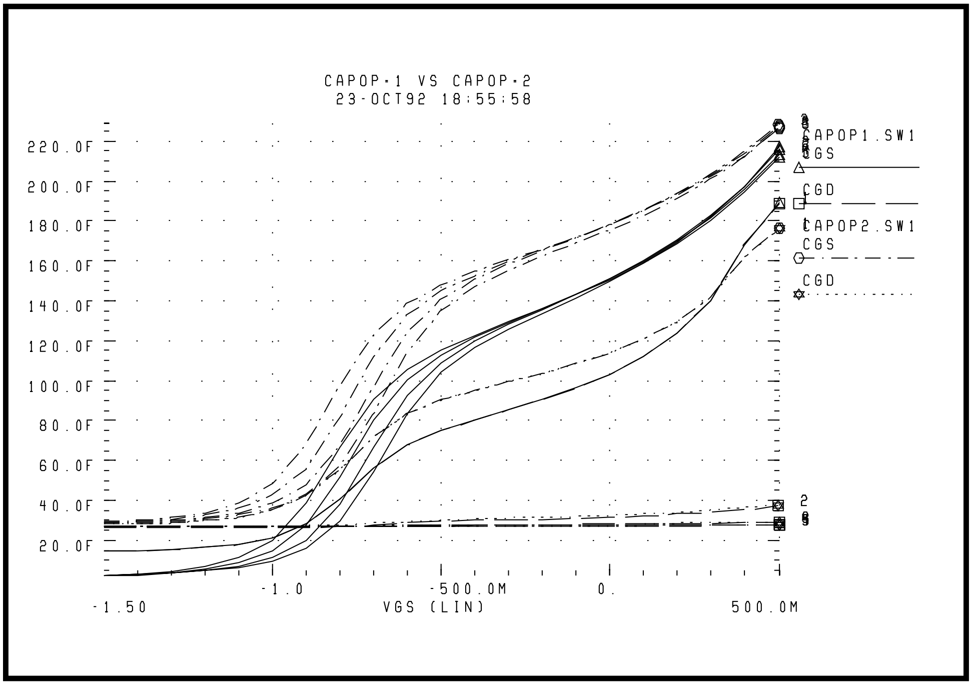

Figure 14-5: CAPOP=1 vs. CAPOP=2. Cgs, Cgd vs. Vgs for Vds=0, 1, 2, 3, 4

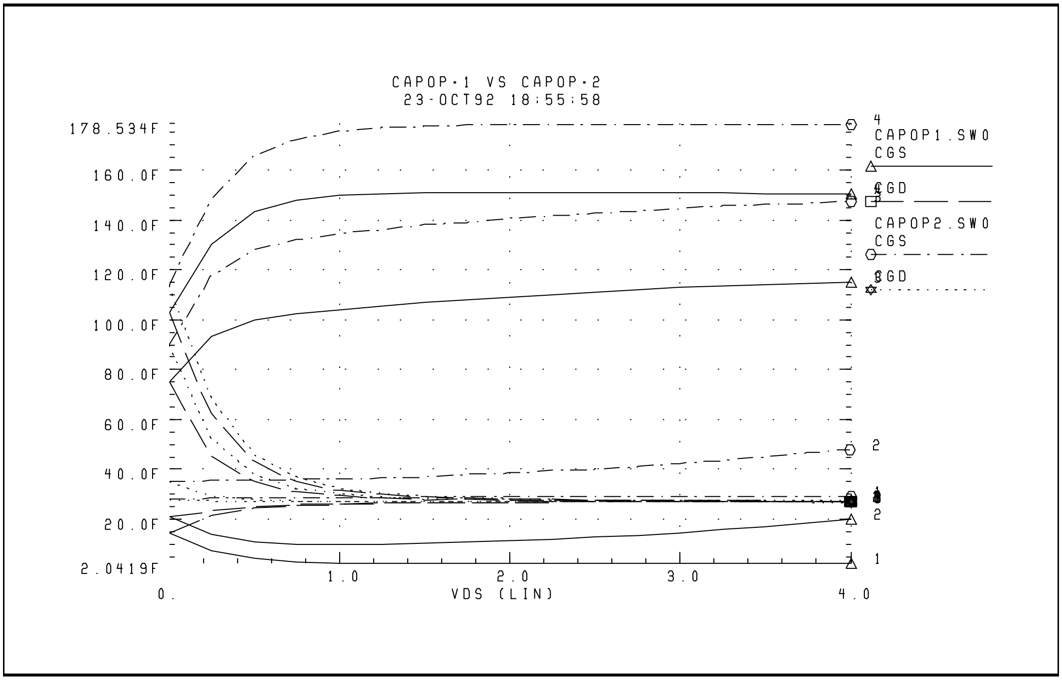

Figure 14-6: CAPOP=1 vs. CAPOP=2. Cgs, Cgd vs. Vds for Vgs = -1.5, -1.0, -0.5, 0

JFET and MESFET DC Equations

DC Model Level 1

JFET DC characteristics are represented by the nonlinear current source, ids. The value of ids is determined by the following equations.

$$vgst = vgs - VTO$$

vgst< 0 Channel pinched off

$$ids = 0$$

0<vgst<vds Saturated region

$$ids = BETAeff \cdot vgst^2 \cdot (1 + LAMBDA \cdot vds)$$

0<vds<vgst Linear region

$$ids = BETAeff \cdot vds \cdot (2 \cdot vgst - vds) \cdot (1 + LAMBDA \cdot vds)$$

The drain current at zero vgs bias (ids) is related to VTO and BETA by the equation:

$$idss = BETAeff \cdot VTO^2$$

At a given vgs, LAMBDA can be determined from a pair of drain current and drain voltage points measured in the saturation region where vgst<vds:

$$LAMBDA = \left(\frac{ids2 - ids1}{ids1 \cdot vds2 - ids2 \cdot vds1}\right)$$

DC Model Level 2

The DC characteristics of the JFET Level 2 model are represented by the nonlinear current source (ids). The value of ids is determined by the following equations:

$$vgst = vgs - VTO$$

vgst<0 Channel pinched off

$$ids = 0$$

0<vgst ≤ vds, vgs 0 Saturated region, forward bias

$$ids = BETAeff \cdot vgst^2 \cdot [1 + LAMBDA \cdot (vds - vgst) \cdot (1 + LAM1 \cdot vgs)$$

0<vgst<vds, vgs<0 Saturated region, reverse bias

$$ids = BETAeff \cdot vgst^2 \cdot \left[1 - LAMBDA \cdot (vds - vgst) \cdot \frac{vgst}{VTO}\right]$$

0<vds<vgst Linear region

$$ids = BETAeff \cdot vds(2 \cdot vgst - vds)$$

DC Model Level 3

The DC characteristics of the MESFET Level 3 model are represented by the nonlinear hyperbolic tangent current source (ids). The value of ids is determined by the following equations:

vds>0 Forward region

If model parameters VP and VTO are not specified they are calculated as follows:

$$VP = -\frac{q \cdot NCHAN \cdot Aeff^2}{2 \cdot D \cdot \varepsilon_o}$$

$$VTO = VP + VBI$$

then,

$$vgst = vgs - [VTO + GAMDS \cdot vds + K1(vbs)]$$

$$beteff = \frac{BETAeff}{(1 + UCRIT \cdot vgst)}$$

vgst<0 Channel pinched off

$$ids = idsubthreshold(N0, ND, vds, vgs)$$

vgst>0, SAT=0 On region

$$ids = beteff \cdot (vgst^{VGEXP}) \cdot (1 + LAMBDA \cdot vds) \cdot \tanh(ALPHA \cdot vds)$$

$$+ idsubthreshold(N0, ND, vds, vgs)$$

vgst>0, SAT=1 On region

$$ids = beteff \cdot (vgst^{VGEXP}) \cdot (1 + LAMBDA \cdot vds) \cdot \tanh\left(ALPHA \cdot \frac{vds}{vgst}\right)$$

$$+ idsubthreshold(N0, ND, vds, vgs)$$

vgst>0, SAT=2, vds<3/ALPHA On region

$$ids = beteff \cdot vgst^2 \cdot (1 + LAMBDA \cdot vds) \cdot \left[1 - \left(1 - ALPHA \cdot \frac{vds}{3}\right)^3\right]$$

$$+ idsubthreshold(N0, ND, vds, vgs)$$

vgst>0, SAT=2, vds>3/ALPHA On region

$$ids = beteff \cdot vgst^2 \cdot (1 + LAMBDA \cdot vds)$$

$$+ idsubthreshold(N0, ND, vds, vgs)$$

If vgst >0, SAT=3 is the same as SAT=2, except exponent 3 and denominator 3 are parameterized as SATEXP, and exponent 2 of vgst is parameterized as VGEXP.

Note: idsubthreshold is a special function that calculates the subthreshold currents given the model parameters N0 and ND.

Generating Noise Models

Noise Parameters

Name(Alias)	Units	Default	Description
AF		1.0	flicker noise exponent
KF		0.0	flicker noise coefficient. Reasonable values for KF are in the range 1e-19 to 1e-25 V^2 F.
NLEV		2.0	noise equation selector
GDSNOI		1.0	channel noise coefficient. Use with NLEV=3.

Noise Equations

The JFET noise model is shown in Figure 14-4:. Thermal noise generation in the drain and source regions (RD and RS resistances) is modeled by the two current sources, inrd and inrs. The units of inrd and inrs are:

$$inrd = \left(\frac{4 \cdot k \cdot t}{rd}\right)^{1/2}$$

$$inrs = \left(\frac{4 \cdot k \cdot t}{rs}\right)^{1/2}$$

Channel thermal and flicker noise are modeled by the current source ind and defined by the equation:

$$ind = channel\ thermal\ noise + flicker\ noise$$

If the model parameter NLEV is less than 3, then:

$$channel\ thermal\ noise = \left(\frac{8 \cdot k \cdot t \cdot gm}{3}\right)^{1/2}$$

The previous formula is used in both saturation and linear regions, which can lead to wrong results in the linear region. For example, at VDS=0, channel thermal noise becomes zero, because gm=0. This is physically impossible. If the NLEV model parameter is set to 3, HSPICE uses a different equation, which is valid in both linear and saturation regions (See *Tsivids, Yanis P., Operation and Modeling of the MOS Transistor, McGraw-Hill, 1987, p. 340*).

For NLEV=3

$$channel\ thermal\ noise\ =$$

$$\left(\frac{8kt}{3} \cdot BETAeff \cdot (vgs - VTO) \cdot \frac{1 + a + a^2}{a} \cdot GDSNOI\right)^{1/2}$$

where

$$\alpha\ =\ 1 - \frac{vds}{vgs - VTO}, \quad \textit{Linear region}$$

$$\alpha\ =\ 0 \qquad \textit{Saturation region}$$

The flicker noise is calculated as:

$$flicker\ noise\ =\ \left(\frac{KF \cdot ids^{AF}}{f}\right)^{1/2}$$

Noise Summary Printout Definitions

RD, V^2/HZ	output thermal noise due to drain resistor
RS, V^2/HZ	output thermal noise due to source resistor
RG, V^2/HZ	output thermal noise due to gate resistor
ID, V^2/HZ	output thermal noise due to channel
FN, V^2/HZ	output flicker noise
TOT, V^2/HZ	total output noise (TOT = RD + RS + RG + ID + FN)
ONOISE	output noise
INOISE	input noise

Using the Temperature Effect Parameters

Table 14-5: lists temperature effect parameters. The temperature effect parameters apply to Levels 1, 2, and 3. They include temperature parameters for the effect of temperature on resistance, capacitance, energy gap, and a number of other model parameters. The temperature equation selectors, TLEV and TLEVC, select different temperature equations for the calculation of energy gap, saturation current, and gate capacitance. TLEV can be either 0, 1, or 2 while TLEVC can be either 0, 1, 2, or 3.

Table 14-5: Temperature Parameters (Levels 1, 2, and 3)

Function	**Parameter**
capacitance	CTD, CTS
DC	M, TCV, XTI
energy gap	EG, GAP1, GAP2
equation selections	TLEV, TLEVC
grading	M
mobility	BEX
resistance	TRD, TRS

Temperature Effect Parameters

Name(Alias)	Units	Default	Description
BETATCE	1/°	0.0	Beta temperature coefficient for TriQuint model
BEX		0.0	mobility temperature exponent, correction for low field mobility
CTD	1/°	0.0	temperature coefficient for gate-drain junction capacitance. TLEVC=1 enables CTD to override the default temperature compensation.
CTS	1/°	0.0	temperature coefficient for gate-source junction capacitance. TLEVC=1 enables CTS to override the default temperature compensation.
EG	eV	1.16	energy gap for the gate to drain and gate to source diodes at 0 °K 1.17 - silicon 0.69 - Schottky barrier diode 0.67 - germanium 1.52 - gallium arsenide
GAP1	eV/°	7.02e-4	first bandgap correction factor, from Sze, alpha term 7.02e-4 - silicon 4.73e-4 - silicon 4.56e-4 - germanium 5.41e-4 - gallium arsenide

Name(Alias)	**Units**	**Default**	**Description**
GAP2		1108	second bandgap correction factor, from Sze, beta term 1108 - silicon 636 - silicon 210 - germanium 204 - gallium arsenide
M (MJ)		0.50	grading coefficient for gate-drain and gate-source diodes 0.50 - step junction 0.33 - linear graded junction
N		1.0	emission coefficient for gate-drain and gate-source diodes
TCV (VTOTC)	1/°	0.0	temperature compensation coefficient for VTO (threshold voltage)
TLEV		0.0	temperature equation selector for junction diodes. Interacts with the TLEVC parameter.
TLEVC		0.0	temperature equation selector for junction capacitances and potential. Interacts with the TLEV parameter.
TPB	V/°	0.0	temperature coefficient for PB. TLEVC=1 or 2 overrides the default temperature compensation.
TRD (TDR1)	1/°	0.0	temperature coefficient for drain resistance
TRG (TRG1)	1/°	0	temperature coefficient for gate resistance
TRS (TRS1)	1/°	0.0	temperature coefficient for source resistance

Name(Alias)	Units	Default	Description
XTI		0.0	saturation current temperature exponent XTI=3 for silicon diffused junction or XTI=2 for Schottky barrier diode

Temperature Compensation Equations

Energy Gap Temperature Equations

To determine energy gap for temperature compensation, use the following equation:

TLEV = 0 or 1

$$egnom = 1.16 - 7.02e{-4} \cdot \frac{tnom^2}{tnom + 1108.0}$$

$$eg(t) = 1.16 - 7.02e{-4} \cdot \frac{t^2}{t + 1108.0}$$

TLEV = 2

$$egnom = EG - GAP1 \cdot \frac{tnom^2}{tnom + GAP2}$$

$$eg(t) = EG - GAP1 \cdot \frac{t^2}{t + GAP2}$$

Saturation Current Temperature Equations

The saturation current of the gate junctions of the JFET varies with temperature according to the equation:

$$is(t) = IS \cdot e^{\frac{facln}{N}}$$

TLEV=0 or 1

$$facln = \frac{EG}{vt(tnom)} - \frac{EG}{vt(t)} + XTI \cdot \ln\left(\frac{t}{tnom}\right)$$

TLEV=2

$$facln = \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)} + XTI \cdot \ln\left(\frac{t}{tnom}\right)$$

Gate Capacitance Temperature Equations

There are temperature equations for the calculation of gate capacitances. The parameters CTS and CTD are the linear coefficients. If the TLEVC is set to zero, the SPICE equations are used. To achieve a zero capacitance variation, set the coefficients to a very small value such as 1e-6 and TLEVC=1 or 2.

TLEVC=0

$$CGS(t) = CGS \cdot \left[1 + M \cdot \left(4.0e\text{-}4 \cdot \Delta t - \frac{PB(t)}{PB} + 1\right)\right]$$

$$CGD(t) = CGD \cdot \left[1 + M \cdot \left(4.0e\text{-}4 \cdot \Delta t - \frac{PB(t)}{PB} + 1\right)\right]$$

where

$$PB(t) = PB \cdot \left(\frac{t}{tnom}\right) - vt(t) \cdot \left[3\ln\left(\frac{t}{tnom}\right) + \frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)}\right]$$

TLEVC=1

$$CGS(t) = CGS \cdot (1 + CTS \cdot \Delta t)$$

$$CGD(t) = CGD \cdot (1 + CTD \cdot \Delta t)$$

where

$$PB(t) = PB - TPB \cdot \Delta t$$

TLEVC=2

$$CGS(t) = CGS \cdot \left(\frac{PB}{PB(t)}\right)^{M}$$

$$CGD(t) = CGD \cdot \left(\frac{PB}{PB(t)}\right)^{M}$$

where

$$PB(t) = PB - TPB \cdot \Delta t$$

TLEVC=3

$$CGS(t) = CGS \cdot \left(1 - 0.5 \cdot dpbdt \cdot \frac{\Delta t}{PB}\right)$$

$$CGD(t) = CGD \cdot \left(1 - 0.5 \cdot dpbdt \cdot \frac{\Delta t}{PB}\right)$$

where

$$PB(t) = PB + dpbdt \cdot \Delta t$$

TLEV=0 or 1

$$dpbdt = \frac{-\left[egnom + 3 \cdot vt(tnom) + (1.16 - egnom) \cdot \left(2 - \frac{tnom}{tnom + 1108}\right) \cdot\right.}{tnom}$$

TLEV=2

$$dpbdt = \frac{-\left[egnom + 3 \cdot vt(tnom) + (EG - egnom) \cdot \left(2 - \frac{tnom}{tnom + GAP2}\right)\right.}{tnom}$$

Threshold Voltage Temperature Equation

The threshold voltage of the JFET varies with temperature according to the equation:

$$VTO(t) = VTO - TCV \cdot \Delta t$$

$$CVTO(t) = CVTO - TCV \cdot \Delta t$$

Mobility Temperature Equation

The mobility temperature compensation equation is updated as follows:

$$BETA(t) = BETA \cdot \left(\frac{t}{tnom}\right)^{BEX} \qquad \text{If BETATCE=0}$$

Otherwise (TriQuint model):

$$BETA(T) = BETA \cdot 1.01^{BETATCE(t - tnom)}$$

Parasitic Resistor Temperature Equations

The RD and RS resistances in JFET vary with temperature according to the following equations:

$$RD(t) = RD \cdot (1 + TRD \cdot \Delta t)$$

$$RS(t) = RS \cdot (1 + TRS \cdot \Delta t)$$

$$RG(t) = RG \cdot (1 + TRG \cdot \Delta t)$$

Understanding the TriQuint Model (TOM) Extensions to Level=3

TOM (“TriQuint’s Own Model” See A.J. McCamant, G.D. Mc Cormack,and D.H.Smith, An Improved GaAs MESFET Model for SPICE, IEEE) is implemented as part of the existing GaAs Level 3 model. See *W.Curtice, A MESFET Model For Use In the Design of GaAs Integrated Circuits, IEEE Tran, Microwave* and *H.Statz, P.Newman, I.W.Smith, R.A. Pucel, and H.A. Haus, ‘GaAs FET Device And Cicuit Simulation in SPICE’*.

There are a few differences from the original implementation. The HSPICE version of the TOM model takes advantage of existing Level 3 features to provide:

- subthreshold model (NG, ND)
- channel and source/drain resistances, geometrically derived from width and length (RD, RG, RS, RSH, RSHG, RSHL, HDIF, LDIF) (ACM=1)
- photolithographic compensation (LDEL, WDEL, ALIGN)
- substrate terminal
- geometric model with width and length specified in the element (ACM=1)
- automatic model selection as a function of width and length (WMIN, WMAX, LMIN, LMAX)
- user-defined band-gap coefficients (EG, GAP1, GAP2)

Several alias TOM parameters are defined for existing HSPICE Level 3 parameters to make the conversion easier. An alias allows the original name or the alias name to be used in the .MODEL statement. However, the model parameter printout is in the original name. Please note that in two cases, a sign reversal is needed, even when using the TOM parameter name.

Alias Hspice Printout Names

Table 14-6 shows the Hspice alias printout names.

Table 14-6: Alias Hspice Printout Names

Q	VGEXP	
GAMMA	GAMDS original	sign opposite of TriQuint’s
VTOTC	TCV original	sign opposite of TriQuint’s
TRG1	TRG	
TRD1	TRD	
TRS1	TRS	

TOM Model Parameters

Name(Alias)	Units	Default	Description
BETATCE			temperature coefficient for BETA If betatce is set to a nonzero value: $BETA(temp) = BETA(tnom) \cdot 1.01^{(BETATCE \cdot (}$ The more common HSPICE Beta temperature update is: $BETA(temp) = BETA(tnom) \cdot \left(\frac{temp}{tnom}\right)^{BE}$
DELTA			Ids feedback parameter of the TOM model. This parameter is not used if its value is zero. DELTA can be negative or positive. $i_{ds} \Rightarrow \frac{i_{ds}}{max[(-1 + v_{ntol}),(DELTA + v_{ds} \cdot i_{ds}}$
CAPDS			drain to source capacitance $CAPDSeff = CAPDS \cdot \frac{Weff}{Leff} \cdot M$

Note: In the original TOM implementation by TriQuint, parameters LAMBDA and UCRIT do not exist. Therefore they must remain zero (their default value) in HSPICE Level 3 in order to reproduce the TOM model. Use of nonzero values for these parameters with nonzero BETATCE, DELTA, or CAPDS results in a hybrid model.