HSPICE® Reference Manual: Elements and Device Models

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SYNOPSYS®

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Contents

About this Manual

This manual describes standard models that you can use when simulating your circuit designs in HSPICE:

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Conventions

The following typographical conventions are used in Synopsys HSPICE documentation.

Convention	Description
`Courier`	Indicates command syntax.
Italic	Indicates a user-defined value, such as *`object_name`*.
Bold	Indicates user input — text you type verbatim — in syntax and examples. For a graphical user interface, **Bold** indicates a GUI element.
[ ]	Denotes optional parameters, such as: `write_file [-f filename]`
( )	When shown, the parentheses ( ) are part of the syntax. For example: + LISTFREQ=(1k 100k 10meg)
...	Indicates that parameters can be repeated as many times as necessary: `pin1 pin2 ... pinN`
|	Indicates a choice among alternatives, such as `low	medium	high`

Convention	Description
+	Indicates a continuation of a command line.
/	Indicates levels of directory structure.
Edit > Copy	Indicates a path to a menu command, such as opening the Edit menu and choosing Copy.
Control-c	Indicates a keyboard combination, such as holding down the Control key and pressing c.

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Acknowledgments

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Overview of Models

Describes the elements and models you can use to create a netlist in HSPICE.

HSPICE ships many examples for your use; see Listing of Demonstration Input Files for paths to demo files.

A circuit *netlist* describes the basic functionality of an electronic circuit that you are designing. In HSPICE format, a netlist consists of a series of *elements* that define the individual components of the overall circuit. You can use your HSPICE-format netlist to simulate your circuit to help you verify, analyze, and debug your design, before you turn that design into an actual electronic circuit.

Your netlist can include several types of elements:

- Passive elements, see Chapter 2, Passive Device Models
  - Resistors
  - Capacitors
  - Inductors
  - Mutual Inductors
- Active elements:
  - Diodes, see Chapter 3, Diode Models
  - Junction Field Effect Transistors (JFETs), see Chapter 4, JFET and MESFET Models
  - Metal Semiconductor Field Effect Transistors (MESFETs), see Chapter 4, JFET and MESFET Models
  - Bipolar Junction Transistors (BJTs), see Chapter 5, BJT Models
- Transmission lines (see the HSPICE Signal Integrity Guide):
  - S element

  - T element
  - U element
  - W element
- Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), see the HSPICE MOSFET Models Manual.

This chapter discusses these topics:

Using Models to Define Netlist Elements

A series of standard models have been provided with the software. Each model is like a template that defines various versions of each supported element type used in an HSPICE-format netlist. Individual elements in your netlist can refer to these standard models for their basic definitions. When you use these models, you can quickly and efficiently create a netlist and simulate your circuit design.

Eight different versions (or *levels*) of JFET and MESFET models for use with HSPICE are supplied. An individual JFET or MESFET element in your netlist can refer to one of these models for its definition. That is, you do not need to define all of the characteristics (called *parameters*) of each JFET or MESFET element within your netlist.

Referring to standard models in this way reduces the amount of time required to:

- Create the netlist.
- Simulate and debug your circuit design.
- Turn your circuit design into actual circuit hardware.

Within your netlist, each element that refers to a model is known as an *instance* of that model. When your netlist refers to predefined device models, you reduce both the time required to create and simulate a netlist, and the risk of errors, compared to fully defining each element within your netlist.

Supported Models for Specific Simulators

This manual describes individual models that have been provided. HSPICE supports a specific subset of the available models. This manual describes the Synopsys device models for passive and active elements. You can include these models in HSPICE-format netlists.

Selecting Models

To specify a device in your netlist, use both an element and a model statement. The element statement uses the simulation device model name to reference the model statement. The following example uses the `MOD1` name to refer to a BJT model. The example uses an NPN model type to describe an NPN transistor.

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

You can specify parameters in both element and model statements. If you specify the same parameter in both an element and a model, then the element parameter (local to the specific instance of the model) always overrides the model parameter (global default for all instances of the model, if you do not define the parameter locally).

The model statement specifies the type of device — for example, a BJT, the device type might be NPN or PNP.

Subcircuits

`X`*<subcircuit_name>* adds an instance of a subcircuit to your netlist. You must already have defined that subcircuit in your netlist by using a `.MACRO` or `.SUBCKT` command.

If you initialize a non-existent subcircuit node, HSPICE generates a warning message. This can occur if you use an existing .ic file (initial conditions) to initialize a circuit that you modified since you created the *.ic* file.

Syntax

```
X [subcircuit_name] n1 [n2 n3 …] subnam
[parnam = val &] [M = val] [S=val] [DTEMP=val]
```

Argument	Definition
X *subcircuit_name*	Subcircuit element name. Must begin with an X, followed by up to 15 alphanumeric characters.
n1 …	Node names for external reference.
subnam	Subcircuit model reference name.
parnam	A parameter name set to a value (val) for use only in the subcircuit. It overrides a parameter value in the subcircuit definition, but is overridden by a value set in a `.PARAM` statement.
M	Multiplier. Makes the subcircuit appear as M subcircuits in parallel. You can use this multiplier to characterize circuit loading. HSPICE does not need additional calculation time to evaluate multiple subcircuits. Do not assign a negative value or zero as the M value.
S	Scales a subcircuit. For more information about the S parameter, see S (Scale) Parameter in the *HSPICE User Guide: Simulation and Analysis*. This keyword works only if you set `.OPTION HIER_SCALE`.
DTEMP	Element temperature difference with respect to the circuit temperature in Celsius. Default=0.0. This argument sets a different temperature in subcircuits than the global temperature. This keyword works only when the you set `.OPTION XDTEMP`.

Example 1

The following example calls a subcircuit model named `MULTI`. It assigns the `WN = 100` and `LN = 5` parameters in the `.SUBCKT` statement (not shown). The subcircuit name is `X1`. All subcircuit names must begin with `X`.

```
X1 2 4 17 31 MULTI WN = 100 LN = 5
```

Example 2

This example defines a subcircuit named `YYY`. The subcircuit consists of two 1 ohm resistors in series. The `.IC` statement uses the `VCC` passed parameter to initialize the `NODEX` subcircuit node.

```
.SUBCKT YYY NODE1 NODE2 VCC = 5V
.IC NODEX = VCC
   R1 NODE1 NODEX 1
   R2 NODEX NODE2 1
.EOM
XYYY 5 6 YYY VCC = 3V
```

Safe Operating Area Warnings

The following warning message is issued when terminal voltages of a device (MOSFET, BJT, Diode, Resistor, Capacitor, etc.) exceed their safe operating area (SOA):

```
**warning**(filename:line number) resulted during SOA check <node
voltage name> (=val) of <device/element name> has exceeded <node
voltage name>_max (=val)

To turn it off use .option WARN=0
```

See the following control options for details:

- .OPTION WARN
- .OPTION MAXWARN

Model LEVEL Parameter Must be a Constant Value

The LEVEL parameter may not be entered as an expression or by using single quotation marks. Such action results in the following error message:

```
**error** (inv.sp:31) level should be defined as a constant value
and it cannot be an expression or in single quotes.
```

Use of Example Syntax

To copy and paste proven syntax use the demonstration files shipped with your installation of HSPICE (see Listing of Demonstration Input Files). Attempting to copy and paste from the book or help documentation may present unexpected results, as text used in formatting may include hidden characters, white space, etc. for visual clarity.

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Passive Device Models

Describes passive devices you can include in an HSPICE netlist, including resistor, inductor, and capacitor models.

HSPICE ships hundreds of examples for your use; see Listing of Input Demonstration Files for paths to demo files.

You can use the set of passive model definitions in conjunction with element definitions to construct a wide range of board and integrated circuit-level designs. Passive device models let you include the following in any analysis:

- Transformers
- PC board trace interconnects
- Coaxial cables
- Transmission lines

The wire element model is specifically designed to model the RC delay and RC transmission line effects of interconnects, at both the IC level and the PC board level.

To aid in designing power supplies, a mutual-inductor model includes switching regulators, and several other magnetic circuits, including a magnetic-core model and element. To specify precision modeling of passive elements, you can use the following types of model parameters:

- Geometric
- Temperature
- Parasitic

These topics are covered in the following sections:

Resistor Device Model and Equations

The following section describes equations for Wire RC and Resistor models.

For a listing of output templates for resistor models see Element Template Listings (HSPICE Only), Table 33, in the *HSPICE User Guide: Basic Simulation and Analysis*.

Wire RC Model

You can use the `.MODEL` statement to include a Wire RC model in your HSPICE netlist and evaluate both thermal noise and flicker noise in HSPICE. For a general description of the `.MODEL` statement, see .MODEL in the *HSPICE and RF Command Reference*.

Syntax

```
.MODEL MNAME R KEYWORD=value [CRATIO=val]
```

The wire element RC model is a CRC (pi) model. Use the `CRATIO` wire model parameter to allocate the parasitic capacitance of the wire element (between the input capacitor and the output capacitor of the model). This allows for symmetric node impedance for bidirectional circuits, such as buses.

Parameter	Description
mname	Model name. Elements use this name to reference the model.
R	Specifies a wire model.
keyword	Any model parameter name.

Parameter	Description
CRATIO	Ratio to allocate the total wire element parasitic capacitance. This is the capacitance between the capacitor connected to the input node, and the capacitor connected to the output node of the wire element pi model. You can assign a value between 0 and 1 to CRATIO. Default=0.5 ■ 0 Assigns all of the parasitic capacitance (CAP_{eff}) to the output node. ■ 0.5 Assigns half of the parasitic capacitance to the input node, and half to the output node. ■ 1 Assigns all of the parasitic capacitance to the input node. ■ CRATIO values smaller than 0.5 assign more of the capacitance to the output node than to the input node. ■ Values greater than 0.5 assign more of the capacitance to the input node than to the output node. If you set a CRATIO value outside the 0 to 1.0 range, simulation shows a warning, sets CRATIO to 0.5, and continues the analysis.

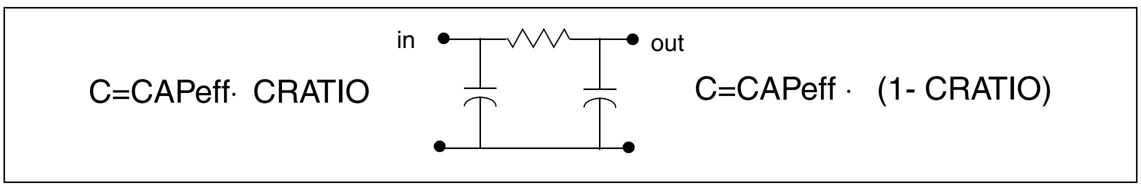


Figure 1 Wire Model Example

A wire-model resistor behaves like an elementary transmission line (see T-element (Ideal Transmission Lines) in the *HSPICE User Guide: Simulation and Analysis*, if the `.MODEL` statement specifies an optional capacitor (from the n2 node to a bulk or ground node). The bulk node functions as a ground plane for the wire capacitance.

A wire has a drawn length and a drawn width. The resistance of the wire is the effective length, multiplied by `RSH`, then divided by the effective width.

To avoid syntactic conflicts, if a resistor model uses the same name as a parameter for *rval* in the element statement, then the simulation uses the model name. In the following example, `R1` assumes that `REXX` refers to the model, and not to the parameter.

Resistor and Wire RC Model Parameter Example

```
.PARAMETER REXX=1
R1 1 2 REXX
.MODEL REXX R RES=1
```

Wire RC Model Parameter Syntax

```
Rxxx n1 n2 [mname Rval] [TC1 TC2 TC] [SCALE=val] [M=val]
+ [AC=val] [DTEMP=val] [L=val] [W=val] [C=val]
+ [NOISE=val]
Rxxx n1 n2 [mname] [R=]resistance [TC1=val]
+ [TC2=val] [TC=val] [SCALE=val] [M=val]
+ [AC=val] [DTEMP=val] [L=val] [W=val] [C=val]
+ [NOISE=val]
```

Table 1 Wire Model Parameters

Name (Alias)	Units	Default	Description
BULK	gnd		Default reference node for capacitance.
CAP	F	0	Default capacitance.
CAPSW	F/m	0	Sidewall fringing capacitance.
COX	F/m2	0	Bottomwall capacitance.
DI		0	Relative dielectric constant.
DLR	m	0	Difference between the drawn length and the actual length (for resistance calculation only). The capacitance calculation uses DW. $DLR_{eff}=DLR \cdot SCALM$
DW	m	0	Difference between the drawn width and the actual width. $DW_{eff}=DW \cdot SCALM$
L	m	0	Default length of the wire. $L_{scaled}=L \cdot SHRINK \cdot SCALM$
LEVEL			Model selector (not used).
RAC	ohm		Default AC resistance (the RACeff default is Reff).
RES	ohm	0	Default resistance.
RSH		0	Sheet resistance/square.
SHRINK		1	Shrink factor.
TC1C	1/deg	0	First-order temperature coefficient for capacitance.
TC2C	1/deg2	0	Second-order temperature coefficient for capacitance.
TC1R	1/deg	0	First-order temperature coefficient for resistance.

Table 1 Wire Model Parameters (Continued)

Name (Alias)	Units	Default	Description
TC2R	1/deg2	0	Second-order temperature coefficient for resistance.
VC1R	1/volt	0	First-order voltage-bias coefficient for resistance.
VC2R	1/volt^2	0	Second-order voltage-bias coefficient for resistance.
THICK	m	0	Dielectric thickness.
TREF	deg C	TNOM	Temperature reference for model parameters.
W	m	0	Default width of the wire. Wscaled=W · SHRINK · SCALM

Resistor Syntax

```
Rxxx n1 n2 mname [R=]resistance [TC1=val]
+ [TC2=val] [VC1=val] [VC2=val] [SCALE=val] [M=val] [AC=val]
+ [DTEMP=val] [L=val] [W=val] [C=val] [NOISE=val]
```

Supported instance parameters above include: `R`, `TC1`, `TC2`, `SCALE`, `M`, `AC`, `DTEMP`, `L`, `W`, `C`, and `NOISE`.

`TC1` and `TC2` are aliases for `TC1R` and `TC2R`. Resistor syntax is described in Resistor Elements in a HSPICE Netlist in the *HSPICE User Guide: Simulation and Analysis*.

Resistor Model Selector

For multiple resistor models, you can use the automatic model selector in HSPICE to find the proper model for each resistor.

The model selector syntax is based on a common model root name with a unique extension for each model.

Example

```
.model REXX.1 R LMIN=0.5 LMAX=0.7 WMIN=0.1 WMAX=0.5 RES=1.2
.model REXX.2 R LMIN=0.7 LMAX=0.9 WMIN=0.1 WMAX=0.5 RES=1.3
```

You can then use the standard resistor model call to map the models to an element declaration:

```
R1 1 2 REXX L=0.6 W=0.5
```

The resistor model selector uses the following criteria:

```
LMIN <= L < LMAX
WMIN <= W < WMAX
```

Resistor Model Equations

This section contains equations for different characteristics of resistors.

Wire Resistance Calculation

You can specify the wire width and length in both the element and model statements. The element values override the model values.

- To scale the element width and length, use `.OPTION SCALE` and the `SHRINK` model parameter.
- To scale the model width and length, use `.OPTION SCALM` and the `SHRINK` model parameter.

The following equations calculate the effective width and length:

$$Weff = Wscaled - 2 \cdot DWeff$$

$$Leff = Lscaled - 2 \cdot DLReff$$

If you specify element resistance:

$$Reff = \frac{R \cdot SCALE(element)}{M}$$

Otherwise, if

$$(Weff \cdot Leff \cdot RSH)$$

is greater than zero, then:

$$Reff = \frac{Leff \cdot RSH \cdot SCALE(element)}{M \cdot Weff}$$

If $(Weff \cdot Leff \cdot RSH)$ is zero, then:

$$Reff = \frac{RES \cdot SCALE(element)}{M}$$

If you specify `AC` resistance in the element, then:

$$RACeff = \frac{AC \cdot SCALE(element)}{M}$$

Otherwise, if the model specifies `RAC`, the RAC_{eff} equation uses `RAC`:

$$RACeff = \frac{RAC \cdot SCALE(element)}{M}$$

If the model does not specify either `AC` resistance or RAC, then the equation defaults to:

$$RACeff = Reff$$

If the resistance is less than the `RESMIN` option, then the RAC_{eff} equation resets it to the `RESMIN` value, and issues a warning message.

$$RESMIN = \frac{1}{GMAX \cdot 1000 \cdot M}$$

Wire Capacitance Calculation

The effective length is the scaled drawn length, less (`2 · DLeff`).

- L_{eff} represents the effective length of the resistor, from physical edge to physical edge.
- DW_{eff} is the distance from the drawn edge of the resistor to the physical edge of the resistor.

The effective width is the same as the width used in the resistor calculation.

$$Leff = Lscaled - 2 \Rightarrow DLeff$$

$$Weff = Wscaled - 2 \Rightarrow DWeff$$

If you specify the element capacitance, `C`:

$$CAPeff = C \cdot SCALE(element) \cdot M$$

Otherwise, the equation calculates the capacitance from the L_{eff}, W_{eff}, and `COX` values:

$$CAPeff = M \cdot SCALE(element) \cdot [Leff \cdot Weff \cdot COX] \\ + 2 \cdot (Leff + Weff) \cdot CAPSW]$$

Computing the bottom-wall capacitance, `COX`, is based on a hierarchy of defaults and specified values, involving:

- dielectric thickness (`THICK`)
- relative dielectric constant (`DI`)

Whether you specify a `COX` value affects how HSPICE uses the equation:

- If you specify `COX=`*value*, then the equation uses the *value*.
- If you do not specify `COX`, but you do specify a value other than zero for `THICK` (the dielectric thickness):
  - If you specify a non-zero value for `DI=`*value*, then:

    $$COX = \frac{DI \cdot \varepsilon o}{THICK}$$

  - If you do not specify a `DI` value or if the value is zero, then:

    $$COX = \frac{\varepsilon ox}{THICK}$$

    The following values apply to the preceding equation:

    $\varepsilon o = 8.8542149e\text{-}12$ F/meter

    $\varepsilon ox = 3.453148e\text{-}11$ F/meter

- If you do not specify COX, and THICK = 0, this is an error.
  - If you specify only the model capacitance (CAP), then:

    $$CAPeff = CAP \cdot SCALE(element) \cdot M$$

  - If you specify the capacitance, but you do not specify the bulk node, then the resistor model does not evaluate the capacitance, and issues a warning message.

Resistor Noise Equation

The following equation models the thermal noise of a resistor:

$$inr = \left(NOISE \cdot \frac{4kT}{Rval}\right)^{1/2}$$

In the preceding equation, NOISE is a model parameter (default=1). To eliminate the contribution of resistor noise, specify the NOISE parameter in a resistor model.

Parameter	Description
RX	Transfers the function of thermal noise to the output. This is not noise, but is a transfer coefficient, which reflects the contribution of thermal noise to the output. For example: V(output) = I(local)*rx(from local to output) Where V(output) is the noise voltage at the output port, I(local) is the local noise current in the specific noise element. It is clear that rx should have an unit of impedance, therefore we call it transimpedance. By summarizing all the contributions (power) from each independent noisy element, we can get the total noise contribution(power) at the output port.
TOT, V^2/Hz	Total output noise: $TOT = RX^2 \cdot inr^2$

Resistor Temperature Equations

You can use temperature values to set resistor and capacitor values:

$$R(t) = R \cdot (1.0 + TC1 \cdot \Delta t + TC2 \cdot \Delta t^2)$$

$$RAC(t) = RAC \cdot (1.0 + TC1 \cdot \Delta t + TC2 \cdot \Delta t^2)$$

$$C(t) = C \cdot (1.0 + TC1 \cdot \Delta t + TC2 \cdot \Delta t^2)$$

Parameter	Description
Δt	t - tnom
t	Element temperature in °K: t = circuit temp + DTEMP + 273.15
tnom	Nominal temperature in °K: tnom = 273.15 + TNOM

Noise Parameter for Resistors

Resistor models generate electrical thermal noise. However, some tasks, such as macro modeling, require noiseless resistor models.

- If you set *noise*=1 (default) or if you do not specify the noise parameter, HSPICE models a resistor that generates noise.
- If you do not want the resistor model to generate thermal noise, set *noise*=0 in the instance statement (noiseless resistor model).

Example

This example is located in the following directory:

$installdir/demo/hspice/apps/noise.sp

In this example, `rd` is a 1-ohm noiseless resistor that connects between node 1 and node 6.

Evaluating Flicker Noise of Resistors

The following section describes the flicker noise equation and parameters, and how to test for flicker noise in HSPICE.

The following equation supports the flicker noise model for resistors:

$$Noise(sid) = \frac{KF \times \left(I^{AF}\right)}{\left(Leff^{Lf}\right) \times \left(Weff^{Wf}\right) \times \left(f^{Ef}\right)}$$

Where

Parameter	Description	Unit
f	Frequency	HZ
I	Current	A
Leff	Effective length (Ldrawn - dL)	m
Noise(sid)	Noise spectrum density	A2 Hz

Parameter	Description	Unit
Weff	Effective width (Wdrawn - dw)	m

The following lists the parameters and descriptions for the flicker noise model

Parameter	Description	Unit	Default	Bin
AF	exponent of current (>0)	none	2	no
EF	exponent of frequency(>0)	none	1	no
KF	flicker noise coefficient(≥ 0)	$A^{(2-AF)} \times m^{(LF+WF)} \times Hz^{(EF-1)}$	0	no
LF	exponent of effective length (>0)	none	1	no
WF	exponent of effective width(>0)	none	1	no

Example of Using Flicker Noise Parameters

To use the flicker noise parameters in a resister model, specify the flicker noise parameters (KF, AF, LF, WF and EF) in the resistor model card. For example:

```
.model Res1 R  noise=1 kf=6.0e-28 af=2 lf=1 wf=1 ef=1 l=1u
    dlr=0.01u w=10u dw=0.01u
```

If these parameters are not specified, HSPICE uses their default values, and the flicker noise will be 0. Observe that these parameters all have limitations: KF ≥ 0, AF, LF, WF and EF >0. If their values exceed the limitations, HSPICE will issue warning messages.

The parameters l, w, dlr, dw must also be specified in the model card for HSPICE to evaluate the effective length and width. If these parameters are not specified, their default value is 0, so the effective length and width are 0, and there will be a divide-by-zero error in the evaluation of the flicker noise equation. HSPICE will abort and issue an error message.

Controlling the Evaluation of Noise

HSPICE uses the NOISE parameter in a model as a switch to control evaluation of thermal and flicker noise. Its value is 0 or 1. For example:

```
.model Res1 R  noise=1 kf=6.0e-28 af=2 lf=1 wf=1 ef=1    l=1u
dlr=0.01u w=10u dw=0.01u
 .model Res2 R  noise=0 kf=6.0e-28 af=2 lf=1 wf=1 ef=1    l=1u
dlr=0.01u w=10u dw=0.01u
R1 1  2 Res1 50
R2 2  3 Res2 50
```

In the above example, resistor R1 uses model Res1 which specifies noise=1, and resistor R2 uses model Res2 which specifies noise=0. The noise analysis, R1 has noise and R2 is noise-free. The default value of model parameter NOISE is 1.

Instance of Parameter NOISE: Noiseless Resistor

Sometimes a noiseless resistor is required. The resistor can be noiseless even if there are noise parameters set in the model. This is because the parameter NOISE can be both an instance parameter and a model parameter. If NOISE is set in both the instance and the model, the instance parameter will override the model parameter. For example:

```
.model Res1 R  noise=1 kf=6.0e-28 af=2 lf=1 wf=1 ef=1 l=1u
     dlr=0.01u w=10u dw=0.01u
.model Res2 R noise=0 kf=6.0e-28 af=2 lf=1 wf=1 ef=1 l=1u dlr=0.01u
     w=10u dw=0.01u
R1 1 2 Res1 50
R2 2 3 Res2 50
R3 3 4 Res1 50 noise=0
R4 4 5 Res2 50 noise=1
```

In the example, resistors R1 and R3 use model Res1 and resistors R2 and R4 use model Res2. R1 will have noise and R2 will be noiseless since these resistors will use the noise parameter defined in the model. Resistor R3 is noiseless and R4 will have the noise because the noise instance parameter is specified for each.

Test Case for Both Thermal and Flicker Noise

The following example uses the .noise analysis syntax to test for both thermal and flicker noise in a resistor.

```
v1 1 0 10 ac=1
R1 1 2 Res1 50  $noise=1
R2 2 3 Res2 50  $noise=1
R3 3 4 Res1 50  noise=0
R4 4 0 Res2 50  noise=1
.model Res1 R  noise=1 kf=6.0e-28 af=2 lf=1 wf=1 ef=1
+ l=1u dlr=0.01u w=10u dw=0.01u
 .model Res2 R  noise=0 kf=6.0e-28 af=2 lf=1 wf=1 ef=1
+ l=1u dlr=0.01u w=10u dw=0.01u
.model Res3 R  $noise=1
.model Res4 R  $noise=1
.options post list
.ac dec 10 10k 100k
.noise v(2,3) v1 10
.print noise inoise onoise
.op
 .end
```

In the *.list* file below, the output shows `rs` is thermal noise, `1/f` is flicker noise:

```
 **** resistor squared noise voltages (sq v/hz)
element     0:r1         0:r2         0:r3        0:r4
rs          5.145e-20    0.           0.          5.145e-20
1/f         5.924e-20    0.           0.          5.924e-20
total       1.107e-19    0.           0.          1.107e-19
rx         12.5000      37.5000      12.5000     12.5000
```

LEVEL2 CMC R2 Resistor Model

R2_CMC is a nonlinear 2-terminal resistor model. The model does not include parasitic capacitances. Optionally, the model can include self-heating. R2_CMC is well behaved and does not have the numerical problems that can arise in polynomial models. Although empirical, the form of the nonlinearity can model data reasonably well, especially for velocity saturation effects which are important in short resistors.

The CMC_R2 model is implemented as LEVEL=2 in the RESISTOR models.

LEVEL=2 Element Syntax

```
Rxxx n1 n2 mname [M=val] instanceParameters
.MODEL mname r LEVEL = 2 [keyword = val] ...
```

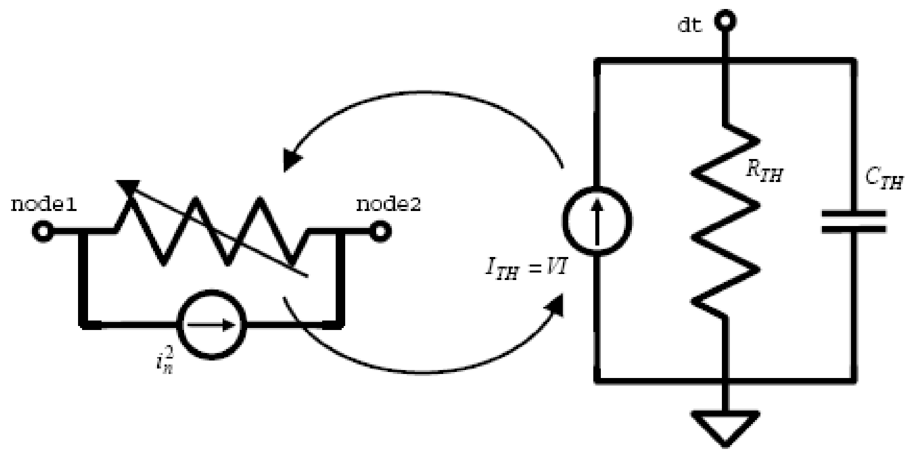


Figure 2 R2_CMC Model Equivalent Network (thermal sub-network is optional)

LEVEL 2 Model Parameters

Table 2 and Table 3 on page 21 describe instance and model parameters, respectively.

Table 2 Instance Parameters

Name	Default	Min.	Max.	Units	Description
m	1	0	∞		Multiplicity factor (number in parallel)
w	1.0e-6	0.0	∞	m	Design width of resistor body
l	1.0e-6	0.0	∞	m	Design length of resistor body
r	100.0	0.0	∞	Ω	Resistance (per segment, total resistance is r/m)
c1	1	0	1		Contact at terminal 1: 0=no 1=yes
c2	1	0	1		Contact at terminal 2: 0=no 1=yes
isnoisy	1	0	1		Switch for noise: 0=no 1=yes
sw_et	1	0	1		Switch for turning off self-heating: 0=exclude 1=include

Table 2 Instance Parameters (Continued)

Name	Default	Min.	Max.	Units	Description
trise	0.0			°C	Local temperature delta to ambient (before self-heating)

Table 3 Model Parameters

Name	Default	Min.	Max.	Units	Description
level	2				Model level
version					Model version
revision					Model revision (sub-version)
afn	2.0	0.0	∞		Flicker noise current exponent
bfn	1.0	0.0	∞		Flicker noise 1/f exponent
cth0	0.0	0.0	∞	sW/K	Thermal capacitance fixed component
ctha	0.0	0.0	∞	$(sW)/K\mu m^2$	Thermal capacitance area component
cthp	0.0	0.0	∞	$(sW)/K\mu m$	Thermal capacitance perimeter component
dxle	0.0			μm	Length delta for field calculation
gmin	1.0e-12	0.0	∞		
gth0	1.0e+6	0.0	∞	W/K	Thermal capacitance fixed component
gtha	0.0	0.0	∞	$W/K\mu m^2$	Thermal capacitance area component
gthp	0.0	0.0	∞	$W/K\mu m$	Thermal capacitance perimeter component
jmax	100.0	0.0		$A/\mu m$	Maximum current density
kfn	0.0	0.0	∞		Flicker noise coefficient (unit depends on afn)
lmax	9.9e99	0.0	∞	μm	Maximum allowed drawn length

Table 3 Model Parameters

Name	Default	Min.	Max.	Units	Description
lmin	0.0	0.0	∞	μm	Minimum allowed drawn length
p2	0.0	0.0	1.0-p3		Quadratic field coefficient factor: $E_{c2} = p2*p3/q3$
p3	0.0	0.0	1.0		Linear field coefficient factor: $E_{c2} = p2*p3/q3$
q2	0.0	0.0	∞	$\mu m/V$	1/field at which the quadratic field coefficient activates
q3	0.0	0.0	∞	$\mu m/V$	1/field at which the linear field coefficient activates
rsh	100.0	0.0	∞	$\Omega/\square$	Sheet resistance
rthresh	1.0e-3	0.0	∞	Ω	Threshold to switch to resistance form
scale	1.0	0.0	1.0		Scale factor for instance geometries
shrink	0.0	0.0	100.0	%	Shrink percentage for instance geometries
sw_efgeo	0	0	1		Switch for electric field geometry calculation: 0=design 1=effective
sw_fngeo	0				Switch for flicker noise geometry calculation: 0=design 1=effective
tc1	0.0			/K	Resistance linear TC
tc1kfn	0.0				Flicker noise coefficient linear TC
tc1l	0.0			$\mu m/K$	Resistance linear TC length coefficient
tc1w	0.0			$\mu m/K$	Resistance linear TC width coefficient
tc2	0.0			/K2	Resistance quadratic TC
tc2l	0.0			$\mu m/K^2$	Resistance quadratic TC length coefficient
tc2w	0.0			$\mu m/K^2$	Resistance quadratic TC width coefficient
tmax	500.0	27.0	1000.0	°C	Maximum ambient temperature

Table 3 Model Parameters

Name	Default	Min.	Max.	Units	Description
tmaxclip	500.0	27.0	1000.0	°C	Clip maximum temperature
tmin	-100.0	-250.0	27.0	°C	Minimum ambient temperature
tminclip	-100.0	-250.0	27.0	°C	Clip minimum temperature
tnom	27.0	-250	1000.0	°C	Nominal (reference) temperature
wmax	9.9e99	0.0	∞	μm	Maximum allowed drawn width
wmin	0.0	0.0	∞	μm	Minimum allowed drawn width
xl	0.0			μm	Length offset (total)
xw	0.0			μm	Width offset (total)

Usage

With Model Card:

```
rinstanceName (node1 node2) modelName instanceParameters
.model modelName r2_cmc modelParameters
```

Without Model Card:

```
rname (node1 node2) r=resistanceValue [tc1=tc1Value]
[tc2=tc2Value]
```

Example

```
r137 (n1 n2) rnpoly1 w=1u l=10u
.model rnpoly1 r2_cmc
+ rsh=100.0 xl=0.2u xw=-0.05u
+ p3=0.12 q3=1.63 p2=0.014 q2=3.79
r138 (n2 n3) r=110.0 tc1=1.0e-3
```

LEVEL 5 CMC R3 Resistor Model

R3_CMC model is a nonlinear 3-terminal resistor model that includes self-heating, velocity saturation, statistical variations, and parasitic capacitance and currents. The core depletion pinching model formulations is for p-n junctions of diffused resistors, but is also applicable for MOS behavior of polysilicon resistors. Since p-n junction pinching controls JFET device behavior, the R3_CMC model is also applicable to JFETs.

The CMC_R3 model is implemented as LEVEL=5 in the RESISTOR models.

LEVEL=5 Element Syntax

```
Rxxx n1 nc n2 mname [M=val] instanceParameters
.MODEL mname r LEVEL=5 [keyword = val] …
```

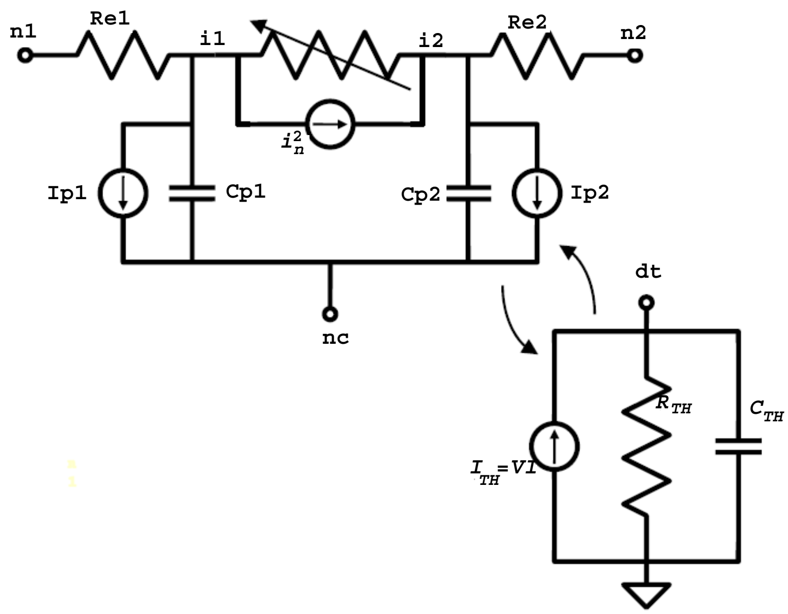


Figure 3 R3_CMC Model Equivalent Network (thermal sub-network is optional)

Level 5 Instance and Model Parameters

Table 4 on page 24, Table 5 on page 25, and Table 6 on page 27 describe instance, special model parameters, and model parameters respectively.

Table 4 CMC R3 Instance Parameters

Name	Default	Min.	Max.	Units	Description
a1	0.0	0.0	∞	m2	Area of node n1 partition

Table 4 CMC R3 Instance Parameters (Continued)

Name	Default	Min.	Max.	Units	Description
a2	0.0	0.0	∞	m2	Area of node n2 partition
c1	0	0	∞		# contacts at n1 terminal
c2	0	0	∞		# contacts at n2 terminal
l	1.0e-6	0.0	∞	m	Design length of resistor body
m	1	0	∞		Multiplicity factor (number in parallel)
nsmm_l	0.0				Number of standard deviations of local variation for l
nsmm_rsh	0.0				Number of standard deviations of local variation for rsh
nsmm_w	0.0				Number of standard deviations of local variation for w
p1	0.0	0.0	∞	m	Perimeter of node n1 partition
p2	0.0	0.0	∞	m	Perimeter of node n2 partition
sw_et	1	0	1		Switch for turning off self-heating: 0=exclude 1=include
sw_mman	0	0	1		Switch for mismatch analysis: 0=no and 1=yes
swnoise	1	0	1		Switch for noise: 0=no 1=yes
trise	0.0			°C	Local temperature delta to ambient (before self-heating)
w	1.0e-6	0.0	∞	m	Design width of resistor body
wd	0.0	0.0	∞	m	Dogbone width (total; not per side)

Table 5 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
version					Model version (major model change)
subversion					Model subversion (minor model change)

Table 5 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
revision					Model revision (implementation update)
level	5				Model level
gmin	1.0e-12	0.0	∞	S	Minimum conductance (for parasitic branches)
imax	1.0	0.0	∞		Current at which to linearize diode currents
jmax	100.0	0.0		$A/\mu m$	Maximum current density
lmax	9.9e99	lmin	∞	μm	Maximum allowed drawn length
lmin	0.0	0.0	∞	μm	Minimum allowed drawn length
rthresh	0.001	0.0	∞	Ω	Threshold to switch end resistance to V=I*R form
scale	1.0	0.0	1.0		Scale factor for instance geometries
shrink	0.0	0.0	100.0	%	Shrink percentage for instance geometries
tmax	500.0	27.0	1000.0	$^{\circ}C$	Maximum ambient temperature
tmaxclip	500.0	27.0	1000.0	$^{\circ}C$	Clip maximum temperature
tmin	-100.0	-250.0	27.0	$^{\circ}C$	Minimum ambient temperature
tminclip	-100.0	-250.0	27.0	$^{\circ}C$	Clip minimum temperature
type	-1	-1	+1		Resistor type: -1=n-body and +1=p-body
vmax	9.9e99	0.0	∞	V	Maximum voltage w.r.t. control node nc
wmax	9.9e99	wmin	∞	μm	Maximum allowed drawn length
wmin	0.0	0.0	∞	μm	Minimum allowed drawn length

Table 6 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
afn	2.0	0.0	∞		Flicker noise current exponent
aja	-0.5		∞	V	Smoothing parameter for cja
ajp	-0.5			V	Smoothing parameter for cjp
ats			∞		Saturation smoothing parameter
bfn	1.0	0.0	∞		Flicker noise 1/f exponent
ca	0.0	0.0	∞	$F/\mu m^2$	Fixed capacitance per unit area
cja	0.0	0.0	∞	$F/\mu m^2$	Depletion capacitance per unit area
cjp	0.0	0.0	∞	$F/\mu m$	Depletion capacitance per unit perimeter
cp	0.0	0.0	∞	$F/\mu m$	Fixed capacitance per unit perimeter
cth0	0.0	0.0	∞	sW/K	Thermal capacitance fixed component
ctha	0.0	0.0	∞	$(sW)/K\mu m^2$	Thermal capacitance area component
cthc	0.0	0.0		$(sW)/K\mu m$	Thermal capacitance contact component
cthp	0.0	0.0	∞	$(sW)/K\mu m$	Thermal capacitance perimeter component
dfinf	0.01	0.0001	10,0	$/\sqrt{V}$	Depletion factor for wide/long device
dfl	0.0			$\mu m/\sqrt{V}$	Depletion factor 1/l coefficient
dfw	0.0			$\mu m/\sqrt{V}$	Depletion factor 1/w coefficient
dfwl	0.0			$\mu m^2/\sqrt{V}$	Depletion factor 1/(w*l) coefficient
dp	2.0	0.1	1000.0	V	Depletion potential
du	0.02	0.0	1000.0		Mobility reduction at ecorn

Table 6 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
dxlsat	0.0			μm	Additional length offset for velocity saturation calculation
ea	1.12			V	Activation voltage for diode temperature dependence
ecorn	0.4	0.01	ecrit	V/μm	Velocity saturation corner field
ecrit	4.0	0.02	1000.0	V/μm	Velocity saturation critical field
fc	0.9	0.0	0.99		Depletion capacitance linearization factor
fdrw	1.0	0.0	∞	μm	Finite doping width offset reference width
fdxwinf	0.0			μm	Finite doping width offset width value for wide devices
gth0	1.0e+6	0.0	∞	W/K	Thermal capacitance fixed component
gtha	0.0	0.0	∞	$W/K\mu m^2$	Thermal capacitance area component
gthp	0.0	0.0	∞	$W/K\mu m$	Thermal capacitance perimeter component
ibv	1.0e-6	0.0	∞	A	Current at breakdown
isa	0.0	0.0	∞	$A/\mu m^2$	Diode saturation current per unit area
isp	0.0	0.0	∞	$A/\mu m$	Diode saturation current per unit perimeter
kfn	0.0	0.0	∞		Flicker noise coefficient (unit depends on afn)
ma	0.33	0.0	1.0		Grading coefficient for cja
mp	0.33	0.0	1.0		Grading coefficient for cjp
na	1.0	0.0	∞		Ideality factor for isa
nbv	1.0	0.0	∞		Ideality factor for breakdown current
np	1.0	0.0	∞		Ideality factor for isp

Table 6 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
nsig_l	0.0				Number of standard deviations of global variation for l
nsig_rsh	0.0				Number of standard deviations of global variation for rsh
nsig_w	0.0				Number of standard deviations of global variation for w
nst	1.0	0.1	5.0		Subthreshold slope parameter
nwxw	0.0			μm^2	Narrow width offset correction coefficient
pa	0.75	0.0	∞	V	Built-in potential for cja
pp	0.75	0.0	∞	V	Built-in potential for cjp
rc	0.0	0.0	∞	Ω	Resistance per contact
rcw	0.0	0.0	∞	$\Omega\mu m$	Width adjustment for contact resistance
rsh	100.0	0.0	∞	$\Omega/\square$	Sheet resistance
sig_l	0.0	0.0	∞	μm	Global variation standard deviation for l (absolute)
sig_rsh	0.0	0.0	∞	%	Local variation standard deviation for rsh (relative)
sig_w	0.0	0.0	∞	μm	Local variation standard deviation for w (absolute)
smm_l	0.0	0.0	∞	$\mu m^{1.5}$	Local variation standard deviation for l (absolute)
smm_rsh	0.0	0.0	∞	$\%\mu m$	local variation standard deviation for rsh (relative)
smm_w	0.0	0.0	∞	$\mu m^{1.5}$	Local variation standard deviation for rsh (relative)
sw_dfgeo	1	0	1		Switch for depletion factor geometry dependence: 0=drawn and 1=effective
sw_fngeo	0	0	1		Switch for flicker noise geometry calculation: 0=design 1=effective

Table 6 CMC R3 Special Model Parameters

Name	Default	Min.	Max.	Units	Description
sw_mmgeo	0	0	1		Switch for flicker noise geometry calculation: 0=drawnand 1=effective
tc1	0.0			/K	Resistance linear TC
tc1kfn	0.0			$/K$	Flicker noise coefficient linear TC
tc1l	0.0			$\mu m/K$	Resistance linear TC length coefficient
tc1nbv	0.0			$/K$	Breakdown ideality factor linear TC
tc1rc	0.0			$\mu m/K$	Contact resistance linear TC
tc1vbv	0.0			$/K$	Breakdown voltage linear
tc1w	0.0			$\mu m/K$	Resistance linear TC width coefficient
tc2	0.0			/K2	Resistance quadratic TC
tc2l	0.0			$\mu m/K^2$	Resistance quadratic TC length coefficient
tc2rc	0.0			$\mu m/K^2$	Contact resistance quadratic TC
tc2vbv	0.0			$/K^2$	Breakdown voltage quadratic TC
tc2w	0.0			$\mu m/K^2$	Resistance quadratic TC width coefficient
tnom	27.0	-250	1000.0	°C	Nominal (reference) temperature
vbv	0.0	0.0	∞	V	Breakdown voltage
wexw	0.0			μm	Webbing effect width offset correction coefficient (for dog-boned devices)
xis	3.0				Exponent for diode temperature dependence
xl	0.0			μm	Length offset (total)
xlw	0.0				Width dependence of length offset
xw	0.0			μm	Width offset (total)

CMC R3 Usage

With Model card:

```
rinstanceName ([node1 node2 node3) [mname]
   instanceParameters
.MODEL modelName r modelParameters
```

Without Model card

```
rname (node1 node2) r=resistanceValue [tc1=tc1Value]
   [tc2=tc2Value]
```

Example

```
r137   n1 n2 n3   rnpoly1  w=1u  l=10u
.model  rnpoly1  r
+ level=5   rsh=100.0
r138   n2 n3   r=110.0 tc1=1.0e-3
```

Capacitor Device Model and Equations

This section describes capacitor models and their equations.

For a listing of output templates for diode models see Element Template Listings (HSPICE Only), Table 34, in the *HSPICE User Guide: Basic Simulation and Analysis*.

Capacitance Model

You can use the `.MODEL` statement to include a capacitance model in your HSPICE netlist. For a general description of the `.MODEL` statement, see .MODEL in the *HSPICE Reference Manual: Commands and Control Options*.

Syntax

```
.MODEL mname C parameter=value
```

Parameter	Description
mname	Model name
C	Specifies a capacitance model

Parameter	Description
parameter	Any model parameter name

Table 7 Capacitance Parameters

Name (Alias)	Units	Default	Description
CAP	F	0	Default capacitance value.
CAPSW	F/m	0	Sidewall fringing capacitance.
COX	F/m^2	0	Bottomwall capacitance.
DEL	m	0	Difference between the drawn width and the actual width or length. $DEL_{eff} = DEL \cdot SCALM$
DI		0	Relative dielectric constant.
L	m	0	Default length of the capacitor. $L_{scaled} = L \cdot SHRINK \cdot SCALM$
SHRINK		1	Shrink factor.
TC1	1/deg	0	First temperature coefficient for capacitance.
TC2	$1/deg^2$	0	Second temperature coefficient for capacitance.
VC1	1/volt	0	First-order voltage-bias coefficient for capacitance.
VC2	$1/volt^2$	0	Second-order voltage-bias coefficient for capacitance.
THICK	m	0	Insulator thickness.
TREF	deg C	TNOM	Reference temperature.
W	m	0	Default width of the capacitor. $W_{scaled} = W \cdot SHRINK \cdot SCALM$

Parameter Limit Checking

If a capacitive element value exceeds 0.1 F, then the output listing file receives a warning message. This feature helps you to identify elements that are missing units or have incorrect values, particularly if the elements are in automatically-produced netlists.

Capacitor Device Equations

Capacitor equations include effective capacitance and capacitance temperature.

Effective Capacitance Calculation

You can associate a model with a capacitor. You can specify some of the parameters in both the element and the model descriptions. The element values override the model values.

- To scale the element width and length, use `.OPTION SCALE` and the `SHRINK` model parameter.
- To scale the model width and length, use `.OPTION SCALM` and the `SHRINK` model parameter.

The following equations calculate the effective width and length:

$$Weff = Wscaled - 2 \Rightarrow DELeff$$

$$Leff = Lscaled - 2 \Rightarrow DELeff$$

If you specify the element capacitance:

$$CAPeff = C \cdot SCALE(element) \cdot M$$

Otherwise, the equation calculates the capacitance from the L_{eff}, Weff, and COX values:

$$CAPeff = M \cdot SCALE(element) \cdot$$
$$[Leff \cdot Weff \cdot COX + 2 \cdot (Leff + Weff) \cdot CAPSW]$$

If you do not specify COX, but THICK is not zero, then:

$$COX = \frac{DI \cdot \varepsilon o}{THICK}$$ if `DI` not zero

$$COX = \frac{\varepsilon ox}{THICK}$$ if `DI`=0

The following values apply to the preceding equation:

$$\varepsilon o = 8.8542149e\text{-}12$$

$$\frac{F}{meter}$$

$$\varepsilon ox = 3.453148e\text{-}11$$

$$\frac{F}{meter}$$

If you specify only the model capacitance (CAP), then:

$$CAPeff = CAP \cdot SCALE(element) \cdot M$$

Capacitance Voltage Equation

The following equation calculates the capacitance as a function of voltage across a given capacitor:

$$C(v) = C \cdot (1 + V \cdot VC1 + V^2 \cdot VC2)$$

Capacitance Temperature Equation

The following equation calculates the capacitance as a function of temperature:

$$C(t) = C \cdot (1.0 + TC1 \cdot \Delta t + TC2 \cdot \Delta t^2)$$

Parameter	Description
Δt	t - tnom
t	Element temperature in degrees Kelvin. t=circuit_temp + DTEMP + 273.15
tnom	Nominal temperature in degrees Kelvin. tnom+273.15 + TNOM

Inductor Device Model and Equations

You can use several elements and models to analyze:

- Switching regulators
- Transformers
- Mutual inductive circuits

These elements include:

- Magnetic winding elements
- Mutual cores
- Magnetic core models

You can use the saturable core model for:

- Chokes
- Saturable transformers
- Linear transformers

To use the model, you must:

1. Provide a mutual core statement.
2. Use a `.MODEL` statement to specify the core parameters.
3. Use a magnetic winding element statement to specify the windings around each core element.

Inductor Core Models

Syntax

Magnetic Core

```
.MODEL mname L (<pname1 = val1>…)
```

Jiles-Atherton Ferromagnetic Core

```
.MODEL mname CORE (LEVEL=1 <pname1 = val1>…)
```

LEVEL=3 Resistor Model

```
.MODEL mname L LEVEL=3 <SCALE=val> <TNOM=val>
```

Example 1

```
.MODEL CHOKE L(BS=12K BR=10K HS=1 HCR=.2 HC=.3 AC=1. LC=3.)
```

To use this example, obtain the core model parameters from the manufacturer's data. Figure 4 on page 37 illustrates the required b-h loop parameters for the model.

The model includes:

- Core area
- Length
- Gap size
- Core growth time constant

Example 2

This example is located in the following directory:
$installdir/demo/hspice/mag/bhloop.sp

Table 8 Magnetic Core Model Parameters

Name (Alias)	Units	Default	Description
AC	cm^2	1.0	Core area.
BS	Gauss	13000	Magnetic flux density, at saturation.
BR	Gauss	12000	Residual magnetization.
HC	Oersted	0.8	Coercive magnetizing force.
HCR	Oersted	0.6	Critical magnetizing force.
HS	Oersted	1.5	Magnetizing force, at saturation.
LC	cm	3.0	Core length.
LG	cm	0.0	Gap length.
TC	s	0.0	Core growth time constant.

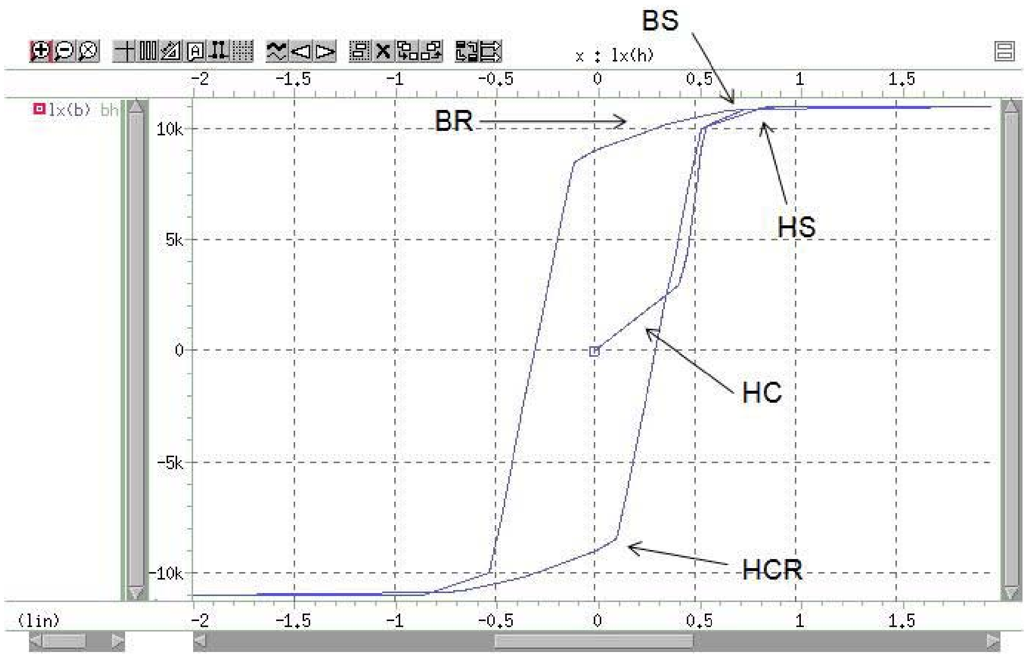


Figure 4 Magnetic Saturable Core Model

Table 9 Jiles-Atherton Core Model Parameters

Name (Alias)	Units	Default	Description
LEVEL		2	Model selector. ■ For the Jiles-Atherton model, LEVEL=1. ■ LEVEL=2 (default) selects the Pheno model, which is the original model.
A	amp/meter	1e3	Characterizes the shape of anhysteretic magnetization.
ALPHA		1e-3	Coupling between the magnetic domains.
AREA, (AC)	cm2	1	Mean of the cross section for the magnetic core. AC is an alias of AREA.
C		0.2	Domain flexing parameter.
K	amp/meter	500	Domain of an isotropy parameter.
MS	amp/meter	1e6	Magnetization saturation.

Table 9 Jiles-Atherton Core Model Parameters (Continued)

Name (Alias)	Units	Default	Description
PATH, (LC)	cm	3	Mean of the path length for the magnetic core. LC is an alias of PATH.

Table 10 Magnetic Core Element Outputs

Output Variable	Description
LX1	Magnetic field, h (oersted)
LX2	Magnetic flux density, b (gauss)
LX3	Slope of the magnetization curve, $\frac{dm}{dh}$
LX4	Bulk magnetization, m (amp/meter)
LX5	Slope of the anhysteretic magnetization curve, $\frac{dm_{an}}{dh}$
LX6	Anhysteretic magnetization, m_{an} (amp/meter)
LX7	Effective magnetic field, h_e (amp/meter)

Inductor Device Equations

This section contains equations for inductors.

Checking Parameter Limits

If an inductive element value exceeds 0.1 Henry, the output listing file receives a warning message. This feature helps you identify elements that are missing units or that have incorrect values, particularly if the elements are in automatically-produced netlists.

Inductor Temperature Equation

The following equation provides the effective inductance as a function of temperature:

$$L(t) = L \cdot (1.0 + TC1 \cdot \Delta t + TC2 \cdot \Delta t^2)$$

Parameter	Description
Δ t	t - tnom
t	Element temperature in degrees Kelvin.
	t=circuit_temp + DTEMP + 273.15
tnom	Nominal temperature in degrees Kelvin.
	tnom=273.15 + TNOM

To create coupling between inductors, use a separate coupling element.

To specify mutual inductance between two inductors, use the coefficient of coupling, kvalue. The following equation defines kvalue:

$$K = \frac{M}{(L_1 \cdot L_2)^{1/2}}$$

Parameter	Description
L1, L2	Inductances of the two coupled inductors.
M	Mutual inductance, between the inductors.

The linear branch relation for transient analysis, is:

$$v_1 = L_1 \cdot \frac{di_1}{dt} + M \cdot \frac{di_2}{dt}$$

$$v_2 = M \cdot \frac{di_1}{dt} + L_2 \cdot \frac{di_2}{dt}$$

The linear branch relation for `AC` analysis, is:

$$V_1 = (j \cdot \omega \cdot L_1) \cdot I_1 + (j \cdot \omega \cdot M) \cdot I_2$$

$$V_2 = (j \cdot \omega \cdot M) \cdot I_1 + (j \cdot \omega \cdot L_2) \cdot I_2$$

Note: If you do not use a mutual inductor statement to define an inductor reference, then an error message appears, and simulation terminates.

Jiles-Atherton Ferromagnetic Core Model

The Jiles-Atherton ferromagnetic core model is based on domain wall motion, including both bending and translation. A modified Langevin expression describes the hysteresis-free (anhysteretic) magnetization curve. This leads to:

$$m_{an} = M\dot{S} \cdot \left(\coth\left(\frac{h_e}{A}\right) - \frac{A}{h_e}\right)$$

$$h_e = h + ALPHA \cdot m_{an}$$

Parameter	Description
m_{an}	Magnetization level, if the domain walls could move freely.
h_e	Effective magnetic field.
h	Magnetic field.
MS	This model parameter represents the saturation magnetization.
A	This model parameter characterizes the shape of anhysteretic magnetization.
ALPHA	This model parameter represents the coupling between the magnetic domains.

The preceding equation generates anhysteretic curves, if the `ALPHA` model parameter has a small value. Otherwise, the equation generates some elementary forms of hysteresis loops, which is not a desirable result.

The following equation calculates the slope of the curve, at zero (0):

$$\frac{dm_{an}}{dh} = \frac{1}{3 \cdot \frac{A}{MS} - ALPHA}$$

The slope must be positive; therefore, the denominator of the above equation must be positive. If the slope becomes negative, an error message appears.

Anhysteretic magnetization represents the global energy state of the material, if the domain walls could move freely, but the walls are displaced and bent in the material.

If you express the bulk magnetization (m) as the sum of an irreversible component (due to wall displacement), and a reversible component (due to domain wall bending), then:

$$\frac{dm}{dh} = \frac{(m_{an} - m)}{K} + C \cdot \left(\frac{dm_{an}}{dh} - \frac{dm}{dh}\right)$$

-or-

$$\frac{dm}{dh} = \frac{(m_{an} - m)}{(1 + C) \cdot K} + \frac{C}{1 + C} \cdot \frac{dm_{an}}{dh}$$

Solving the above differential equation obtains the bulk magnetization value, m. The following equation uses m to compute the flux density (b):

$$b = \mu_0 \cdot (h + m)$$

The following values apply to the preceding equation:

- μ_0 The permeability of free space, is $4\pi \cdot 10^{-7}$
- The units of h and m are in amp/meter.
- The units of b are in Tesla (Wb/meter^2).

Example

This example demonstrates the effects of varying the `ALPHA`, `A`, and `K` model parameters, on the b-h curve.

- Figure 5 on page 42 shows b-h curves for three values of `ALPHA`.
- Figure 6 on page 42 shows b-h curves for three values of `A`.
- Figure 7 on page 43 shows b-h curves for three values of `K`.

Input File

This input file is located in the following directory:
`$installdir/demo/hspice/mag/jiles.sp`

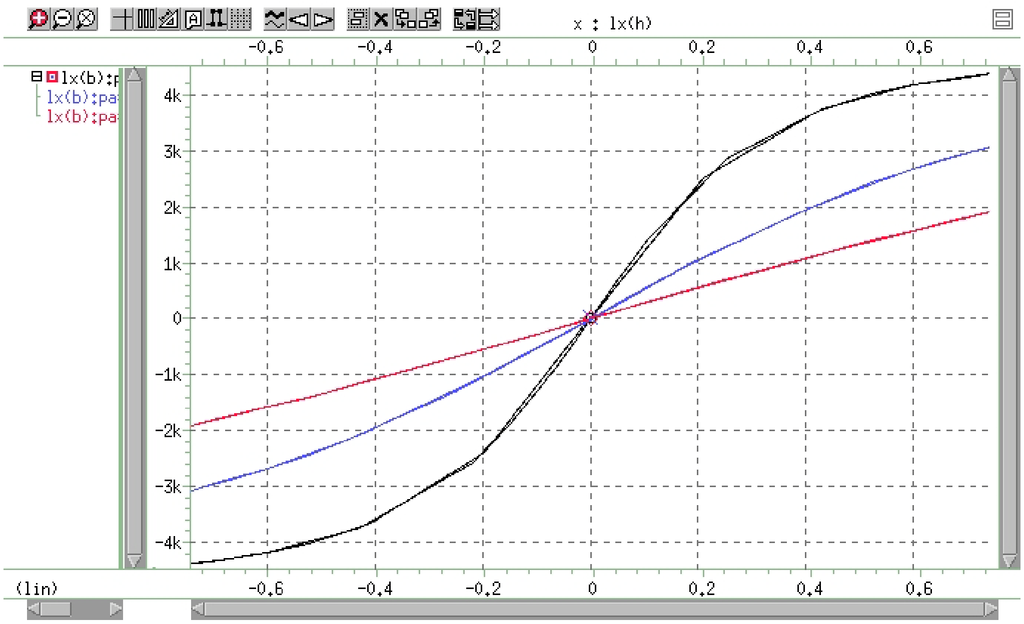


Figure 5 Anhysteretic b-h Curve Variation: Slope and ALPHA Increase

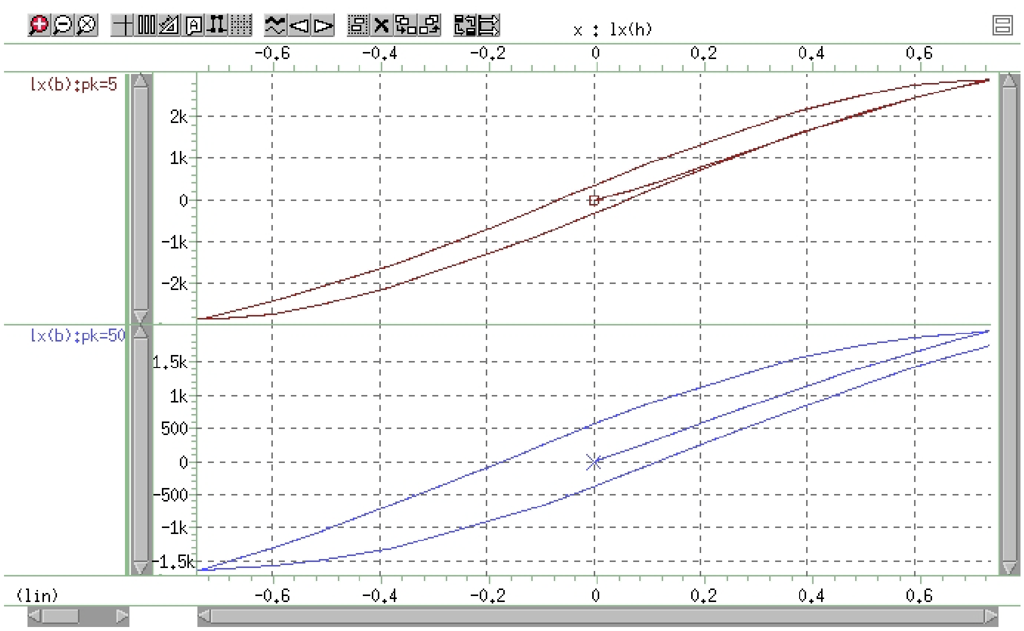


Figure 6 Anhysteretic b-h Curve Variation: Slope Decreases, A Increases

Discontinuities in Inductance Due to Hysteresis

This example creates multi-loop hysteresis b-h curves for a magnetic core. Discontinuities in the inductance, which are proportional to the slope of the b-h curve, can cause convergence problems. Figure 7 and Figure 8 on page 44 demonstrates the effects of hysteresis on the inductance of the core.

This input file is located in the following directory:
`$installdir/demo/hspice/mag/tj2b.sp`

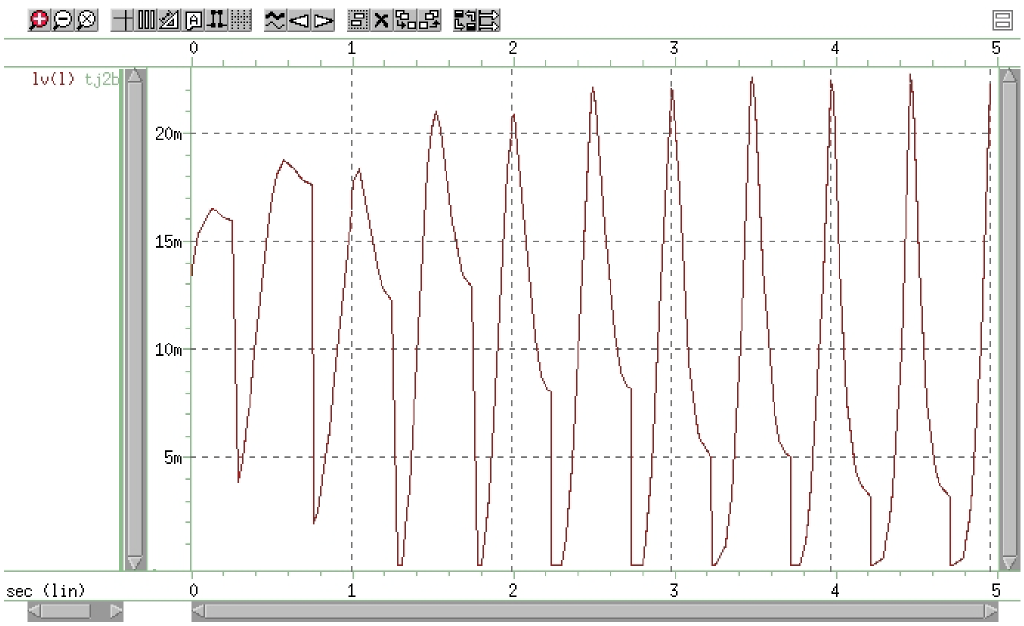


Figure 7 Inductance Curve

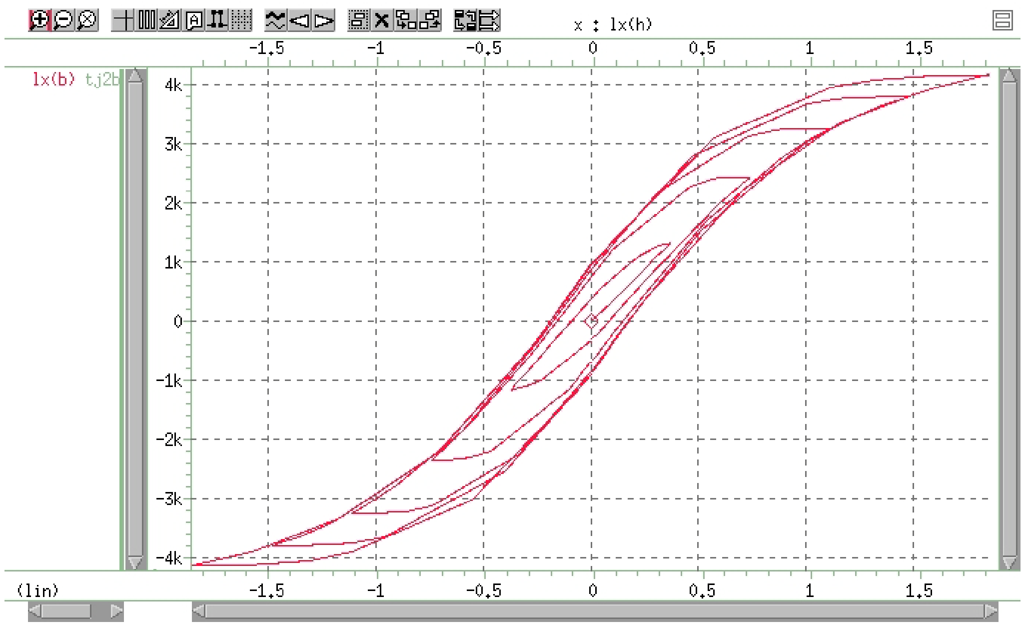


Figure 8 Hysteresis Curve

Optimizing the Extraction of Parameters

This example demonstrates how to optimize the process of extracting parameters from the Jiles-Atherton model. Figure 9 shows the plots of the core output, before and after optimization.

Input File

This input file is located in the following directory: $installdir/demo/hspice/mag/tj_opt.spThe tj_opt.sp file also contains the analysis results listing.

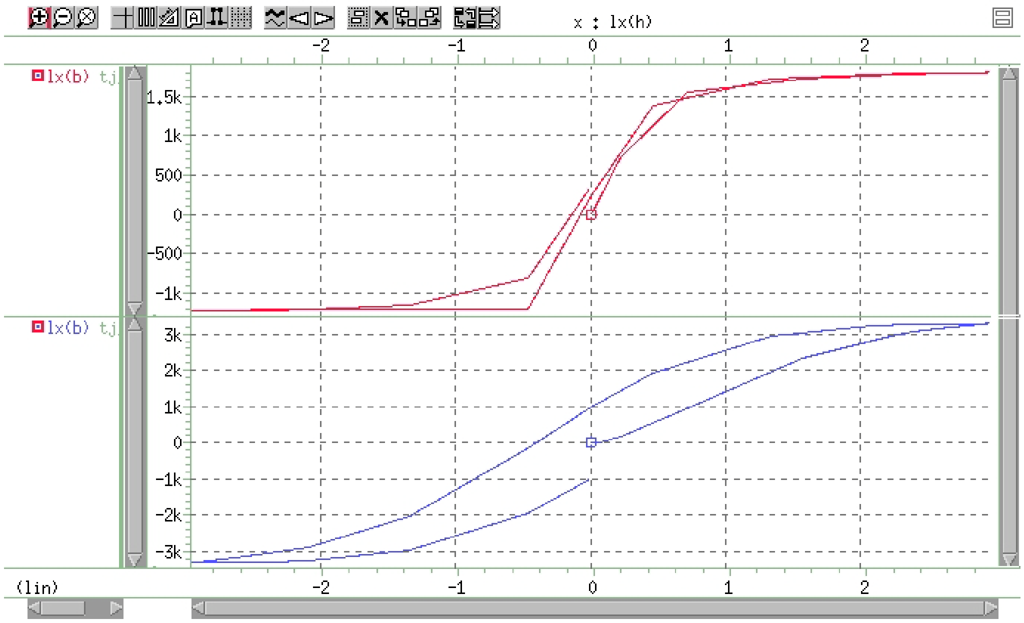


Figure 9 Output Curves, Before Optimization (top), and After Optimization (bottom)

3

Diode Models

Describes model parameters and scaling effects for geometric and nongeometric junction diodes.

HSPICE ships hundreds of examples for your use; see Listing of Demonstration Input Files for paths to demo files.

You use diode models to describe pn junction diodes within MOS and bipolar integrated circuit environments and discrete devices. You can use four types of models (as well as a wide range of parameters) to model standard junction diodes:

- Zener diodes
- Silicon diffused junction diodes
- Schottky barrier diodes
- Nonvolatile memory diodes (tunneling current)

  Note: See the MOSFET Diode Models in the *HSPICE Reference Manual: MOSFET Models* for other MOSFET and standard discrete diodes.

Diode model types include the junction diode model, and the Fowler-Nordheim model. Junction diode models have two variations: geometric and nongeometric.

For a listing of output templates for diode models see Element Template Listings (HSPICE Only), Table 43, in the *HSPICE User Guide: Basic Simulation and Analysis*.

These topics are discussed in the following sections:

- Diode Types
- Specifying Junction Diode Models

- Using the JUNCAP Models
- Using the Fowler-Nordheim Diode, Level 2
- Philips D500 Model (Advanced Diode Model), Level 5
- DIODE_CMC Model, Level 7
- Converting National Semiconductor Models
- DC Operating Point Output of Diodes

Diode Types

Use the geometric junction diode to model:

- IC-based, standard silicon-diffused diodes
- Schottky barrier diodes
- Zener diodes.

Use the geometric parameter to specify dimensions for pn junction poly and metal capacitance for a particular IC process technology.

Use the non-geometric junction diode to model discrete diode devices, such as standard and Zener diodes. You can use the non-geometric model to scale currents, resistances, and capacitances by using dimensionless area parameters.

The *Fowler-Nordheim* diode defines a tunneling current-flow, through insulators. The model simulates diode effects in nonvolatile EEPROM memory.

These topics are presented in the following sections:

- Using Diode Model Statements
- Setting Control Options

Using Diode Model Statements

Use model and element statements to select the diode models. Use the `LEVEL` parameter (in model statements) to select the type of diode model:

- LEVEL=1 selects the non-geometric, junction diode model
- LEVEL=2 selects the Fowler-Nordheim diode model
- LEVEL=3 selects the geometric, junction diode model.

To design Zener, Schottky barrier, and silicon diffused diodes, alter the model parameters for both LEVEL=1 and LEVEL=3. LEVEL=2 does not permit modeling of these effects. For Zener diodes, set the BV parameter for an appropriate Zener breakdown voltage.

If you do not specify the LEVEL parameter in the .MODEL statement, the model defaults to the non-geometric, junction diode model, LEVEL=1.

Use control options with the diode model, to:

- Scale model units
- Select diffusion capacitance equations
- Change model parameters.

Setting Control Options

To set control options, use the .OPTION statement.

Control options, related to the analysis of diode circuits and other models, include:

- DCAP
- DCCAP
- GMIN
- GMINDC
- SCALE
- SCALM

Bypassing Latent Devices (HSPICE only)

Use .OPTION BYPASS (latency) to decrease simulation time in large designs. To speed simulation time, this option does not recalculate currents, capacitances, and conductances, if the voltages at the terminal device nodes have not changed. .OPTION BYPASS applies to MOSFETs, MESFETs, JFETs, BJTs, and diodes. Use .OPTION BYPASS to set BYPASS.

BYPASS might reduce simulation accuracy for tightly-coupled circuits such as op-amps, high gain ring oscillators, and so on. Use .OPTION MBYPASS MBYPASS to set MBYPASS to a smaller value for more accurate results.

Setting Scaling Options

- Use the SCALE element option to scale LEVEL=2 and LEVEL=3 diode element parameters.
- Use the SCALM (scale model) option to scale LEVEL=2 and LEVEL=3 diode model parameters.

LEVEL=1 does not use SCALE or SCALM.

Include SCALM=<*val*> in the .MODEL statement (in a diode model) to override global scaling that uses the .OPTION SCALM=<*val*> statement.

Using the Capacitor Equation Selector Option — DCAP

- Use the DCAP option to select the equations used in calculating the depletion capacitance (LEVEL=1 and LEVEL=3).
- Use the DCCAP option to calculate capacitances in DC analysis.

Include DCAP=<*val*> in the .MODEL statement for the diode to override the global depletion capacitance equation that the .OPTION DCAP=<*val*> statement selects.

Using Control Options for Convergence

Diode convergence problems often occur at the breakdown voltage region when the diode is either overdriven or in the OFF condition.

To achieve convergence in such cases, do either of the following:

- Include a non-zero value in the model for the RS (series resistor) parameter.
- Increase GMIN (the parallel conductance that HSPICE automatically places in the circuit). You can specify GMIN and GMINDC in the .OPTION statement.

Table 11 shows the diode control options:

Table 11 Diode Control Options

Function	Control Options
Capacitance	DCAP, DCCAP

Table 11 Diode Control Options (Continued)

Function	Control Options
Conductance	GMIN, GMINDC
Geometry	SCALM, SCALE

Specifying Junction Diode Models

Use the diode element statement to specify the two types of junction diodes: geometric or non-geometric. Use a different element type format for the Fowler-Nordheim model.

Use the parameter fields in the diode element statement to define the following parameters of the diode model, specified in the `.MODEL` statement for the diode:

- Connecting nodes
- Initialization
- Temperature
- Geometric junction
- Capacitance parameters

Both `LEVEL=1` and `LEVEL=3` junction diode models share the same element parameter set. Poly and metal capacitor parameters of `LM`, LP, `WM` and `WP`, do not share the same element parameter.

Element parameters have precedence over model parameters, if you repeat them as model parameters in the `.MODEL` statement.

Parameters common to both element and model statements are:

`AREA, PJ, M, LM, LP, WM, WP, W, and L.`

Table 12 Junction Diode Element Parameters

Function	Parameters
Netlist	Dxxx, n+, n-, mname
Initialization	IC, OFF

Table 12 Junction Diode Element Parameters (Continued)

Function	Parameters
Temperature	DTEMP
Geometric junction	AREA, L, M, PJ, W
Geometric capacitance (LEVEL=3 only)	LM, LP, WM, WP

These topics are discussed in the following sections:

Using the Junction Model Statement

You can use the `.MODEL` statement to include a junction model in your HSPICE netlist. For a general description of the `.MODEL` statement, see the *HSPICE Command Reference*.

Syntax

```
.MODEL mname D <LEVEL = val> <keyword = val> ...
```

Parameter	Description
mname	Model name. The diode element uses this name to refer to the model.
D	Symbol that identifies a diode model.
LEVEL	Symbol that identifies a diode model.
	LEVEL=1 =junction diode. LEVEL=2 =Fowler-Nordheim diode. LEVEL=3 =geometric processing for junction diode.

Parameter	Description
keyword	Model parameter keyword, such as CJO or IS.

Example

```
.MODEL D D (CO=2PF, RS=1, IS=1P)
.MODEL DFOWLER D (LEVEL=2, TOX=100, JF=1E-10, EF=1E8)
.MODEL DGEO D (LEVEL=3, JS=1E-4, JSW=1E-8)
.MODEL d1n750a D
+ LEVEL=1  XP   =0.0  EG   =1.1
+ XOI   =0.0  XOM =0.0  XM   =0.0
+ WP    =0.0  WM  =0.0  LP   =0.0
+ LM    =0.0  AF  =1.0  JSW =0.0
+ PB    =0.65  PHP =0.8  M    =0.2994
+ FC    =0.95  FCS =0.4  MJSW=0.5
+ TT    =2.446e-9  BV   =4.65  RS   =19
+ IS    =1.485e-11  CJO =1.09e-9  CJP =0.0
+ PJ    =0.0  N    =1.615  IK   =0.0
+ IKR  =1.100e-2  IBV =2.00e-2
```

Using Junction Model Parameters

The diode element statement references the `.MODEL` statement. The `.MODEL` statement contains parameters that specify:

- Type of diode model (LEVEL=1, `2`, or `3`)
- DC
- Capacitance
- Temperature
- Resistance
- Geometry
- Noise

Table 13 Junction Diode Model Parameters (LEVEL=1 and 3)

Function	Parameters
model type	LEVEL

Table 13 Junction Diode Model Parameters (LEVEL=1 and 3) (Continued)

Function	Parameters
DC parameters	IBV, IK, IKR, IS, ISW, N, RS, VB, RS
geometric junction	AREA, M, PJ
geometric capacitance (LEVEL=3 only)	L, LM, LP, SHRINK, W, WM, WP, XM, XOJ, XOM, XP, XW
capacitance	CJ, CJP, FC, FCS, M, MJSW, PB, PHP, TT
noise	AK, KF

Table 14 Junction DC Parameters in LEVEL=1 and 3

Name (Alias)	Units	Default	Description
AREA		1.0	Junction area. ■ For LEVEL=1 AREAeff = AREA· M, unitless ■ For LEVEL=3 AREAeff=AREA· SCALM^2 · SHRINK^2 · ■ M unit = meter2 ■ If you specify W and L: AREAeff = Weff · Leff · M unit = meter2
EXPLI	amp/ AREAeff	0	Current-explosion model parameter. The PN junction characteristics (above the explosion current) are linear with the slope at the explosion point. This speeds up the simulation and improves convergence. EXPLIeff = EXPLI· AREAeff
EXPLIR	amp/ AREAeff	EXPLI	Reverse mode current explosion model parameter. EXPLIReff = EXPLIR· AREAeff
IBV	amp/ AREAeff	1.0e-3	Current, at breakdown voltage: For LEVEL=3: IBVeff = IBV· AREAeff / SCALM2
IK (IKF, JBF)	amp/ AREAeff	0.0	Forward-knee current (intersection of the high- and low-current asymptotes). IKeff = IK· AREAeff

Table 14 Junction DC Parameters in LEVEL=1 and 3 (Continued)

Name (Alias)	Units	Default	Description
IKR (JBR)	amp/ AREAeff	0.0	Reverse-knee current (intersection of the high- and low-current asymptotes). IKReff = IKR· AREAeff
IS (JS)	amp/ AREAeff	LEVEL 1= 1.0e-14 LEVEL 3= 0.0	Saturation current per unit area. If the IS value is less than EPSMIN, the program resets the value of IS to EPSMIN, and shows a warning message. EPSMIN default=1.0e-28 If the value of IS is too large, the program displays a warning. ■ For LEVEL=1: ISeff = AREAeff· IS ■ For LEVEL=3: ISeff = AREAeff · IS/SCALM2
JSW (ISP)	amp/ PJeff	0.0	Sidewall saturation current, per unit junction periphery. ■ For LEVEL=1: JSWeff = PJeff· JSW ■ For LEVEL=3: JSWeff = PJeff· JSW/SCALM
JTUN	amp/ AREAeff	0.0	Tunneling saturation current per area. ■ For LEVEL=1: JTUNeff = AREAeff· JTUN ■ For LEVEL=3: JTUNeff = AREAeff· JTUN/SCALM2
JTUNSW	amp/PJeff	0.0	Sidewall tunneling saturation current per unit junction periphery. ■ For LEVEL=1: JTUNSWeff = PJeff· JTUNSW ■ For LEVEL=3: JTUNSWeff = PJeff· JTUNSW/SCALM
L			Default length of the diode. Leff = L· SHRINK· SCALM + XWeff
LEVEL		1	Diode model selector. ■ LEVEL=1 or LEVEL=3 selects the junction diode model. ■ LEVEL=2 selects the Fowler-Nordheim model.
N		1.0	Emission coefficient.
NBV			N Breakdown emission coefficient (If not specified, NBV is set to N).

Table 14 Junction DC Parameters in LEVEL=1 and 3 (Continued)

Name (Alias)	Units	Default	Description
NTUN		30	Tunneling emission coefficient.
PJ		0.0	Junction periphery. ■ For LEVEL=1: PJeff = PJ· M, unitless ■ For LEVEL=3: PJeff = PJ· SCALM· M· SHRINK, meter ■ If you specify W and L: PJeff = (2· Weff + 2· Leff)· M, meter
RS	ohms or ohms/m^2 (see note below)	0.0	Ohmic series resistance. ■ For LEVEL=1: RSeff = RS/AREAeff ■ For LEVEL=3: RSeff= RS · SCALM2/AREAeff
SHRINK		1.0	Shrink factor.
VB (BV, VAR, VRB)	V	0.0	Reverse breakdown voltage. 0.0 indicates an infinite breakdown voltage.
XW			Accounts for masking and etching effects. XWeff = XW· SCALM

Note: If you use a diode model than does not specify an `AREA`, then `AREA` defaults to 1, and `RS` is in units of ohms. If you specify the `AREA` in square meters (m^2) in the netlist, then the units of `RS` are ohms/m^2.

Table 15 Junction Capacitance Parameters

Name (Alias)	Units	Default	Description
CJ (CJA, CJO)	F/ AREAeff	0.0	Zero-bias junction capacitance, per unit-junction bottomwall area. ■ For LEVEL=1: CJOeff = CJO· AREAeff ■ For LEVEL=3: CJeff = CJ · AREAeff/SCALM2

Table 15 Junction Capacitance Parameters

Name (Alias)	Units	Default	Description
CJP (CJSW)	F/PJeff	0.0	Zero-bias junction capacitance, per unit-junction periphery (PJ). ■ For LEVEL=1: CJPeff = CJP· PJeff ■ For LEVEL=3: CJPeff = CJP· PJeff/SCALM
FC		0.5	Coefficient for the formula that calculates the capacitance for the forward-bias depletion area
FCS		0,5	Coefficient for the formula that calculates the capacitance for the forward-bias depletion periphery.
M (EXA, MJ)		0.5	Grading coefficient at area junction.
MJSW (EXP)		0.33	Grading coefficient at periphery junction.
PB (PHI, VJ, PHA)	V	0.8	Contact potential at area junction.
PHP	V	PB	Contact potential at periphery junction.
TT	s	0.0	Transit time.

Table 16 Metal and Poly Capacitor Parameters, LEVEL=3

Name (Alias)	Units	Default	Description
LM	m	0.0	Default length of metal. Use this parameter if the element statement does not specify LM. LMeff = LM· SCALM· SHRINK
LP	m	0.0	Default length of polysilicon. Use this parameter if the element statement does not specify LP. LPeff = LP· SCALM· SHRINK
WM	m	0.0	Default width of metal. Use this parameter if the element statement does not specify WM. WMeff = WM· SCALM· SHRINK

Table 16 Metal and Poly Capacitor Parameters, LEVEL=3 (Continued)

Name (Alias)	Units	Default	Description
WP	m	0.0	Default width of polysilicon. Use this parameter if the element statement does not specify WP. WPeff = WP· SCALM· SHRINK
XM	m	0.0	Accounts for masking and etching effects in metal layer: XMeff = XM· SCALM
XOI		10k	Thickness of the poly to bulk oxide.
XOM	Å	10k	Thickness of the metal to bulk oxide.
XP	m	0.0	Accounts for masking and etching effects in poly layer: XPeff = XP· SCALM

Table 17 Noise Parameters for LEVEL=1 and 3

Name (Alias)	Units	Default	Description
AF		1.0	Flicker noise exponent.
KF		0.0	Flicker noise coefficient.

Geometric Scaling for Diode Models

LEVEL=1 Scaling

`LEVEL=1` uses the `AREA` and `M` Element parameters to scale the following element and model parameters: `IK`, `IKR`, `JS`, `CJO`, and `RS`.
For `AREA` and `M`, default=1.

This element is not geometric, because it uses dimensionless values to measure both the area (`AREA`) and the periphery (`PJ`). The `.OPTION SCALE` and `.OPTION SCALM` statements do not affect these parameters.

Here is the process:

- Diode models multiply the periphery junction parameter by `M` (the multiplier parameter) to scale a dimensionless periphery junction:

$PJ_{eff} = PJ \cdot M$

The diode models then use PJeff to scale `CJP` (the zero-bias junction capacitance), and the sidewall saturation current (`JSW`).

$CJP_{eff} = PJ_{eff} \cdot CJP$
$JSW_{eff} = PJ_{eff} \cdot JSW$

$JTUNSW_{eff} = PJ_{eff} \cdot JTUNSW$

The models use the `AREA` and `M` values to obtain $AREA_{eff}$.

$AREA_{eff} = AREA \cdot M$

Models multiply `CJO`, `IK`, `IKR`, `IBV`, and `IS` by $AREA_{eff}$ to obtain their effective scaled values. However, diode models divide `RS` by $AREA_{eff}$.

$IK_{eff} = AREA_{eff} \cdot IK$
$IKR_{eff} = AREA_{eff} \cdot IKR$
$IS_{eff} = AREA_{eff} \cdot IS$
$RS_{eff} = RS/AREA_{eff}$
$CJO_{eff} = CJO \cdot AREA_{eff}$

$JTUN_{eff} = JTUN \cdot AREA_{eff}$

LEVEL=3 Scaling

The `SCALM`, `SCALE`, `SHRINK`, and `M` parameters affect `LEVEL=3` scaling.

- `SCALE` affects the following `LEVEL=3` element parameters:

  ```
  AREA, LM, LP, PJ, WM, WP, W, L
  ```

- `SCALM` affects the following model parameters:

  ```
  AREA, IBV, IK, IKR, IS, PJ, JSW, RS, CJO, CJP, LM, LP,
  WP, XM, XP, W, L, XW, JTUN, JTUNSW
  ```

If you include `AREA` as either an element parameter or a model parameter, then the program uses `SCALE` or `SCALM`. The following equations use the `AREA` element parameter, instead of the `AREA` model parameter.

If you specified the `AREA` and `PJ` model parameters, but not the element, then use `SCALM` as the scaling factor, instead of `SCALE`.

The following equations determine the parameters of the scaled effective area, and of the periphery junction element:

$AREA_{eff} = AREA \cdot M \cdot SCALE^2 \cdot SHRINK^2$
$PJeff = PJ \cdot SCALE \cdot M \cdot SHRINK$

If you specified `W` and `L`:

$AREA_{eff} = W_{eff} \cdot L_{eff} \cdot M$
$PJ_{eff} = (2 \cdot W_{eff} + 2 \cdot L_{eff}) \cdot M$

The following values apply to the preceding equations:

$W_{eff} = W \cdot SCALE \cdot SHRINK + XW_{eff}$
$L_{eff} = L \cdot SCALE \cdot SHRINK + XW_{eff}$

To find the value of JSWeff and CJPeff, use the following formula:

$JSW_{eff} = PJ_{eff} \cdot (JSW/SCALM)$
$CJP_{eff} = PJ_{eff} \cdot (CJP/SCALM)$

$JTUNSW_{eff} = PJ_{eff} \cdot JTUNSW/SCALM$

To determine the polysilicon and metal capacitor dimensions, multiply each by `SCALE` or by `SCALM` if you used model parameters to specify these dimensions.

$LM_{eff} = LM \cdot SCALE \cdot SHRINK$
$WM_{eff} = WM \cdot SCALE \cdot SHRINK$
$LP_{eff} = LP \cdot SCALE \cdot SHRINK$
$WP_{eff} = WP \cdot SCALE \cdot SHRINK$
$XP_{eff} = XP \cdot SCALM$
$XM_{eff} = XM \cdot SCALM$

Use the following formulas to determine the effective scaled model parameters (IBeff, IKeff, IKReff, IBVeff, RSeff, and CJO):

$IK_{eff} = AREA_{eff} \cdot IK$
$IKR_{eff} = AREA_{eff} \cdot IKR$

$IBV_{eff} = IBV \cdot Area_{eff}/SCALM^2$

$IS_{eff} = IS \cdot (AREA_{eff}/SCALM^2)$

$RS_{eff} = RS/(AREA_{eff} \cdot SCALM^2)$

$CJO_{eff} = AREA_{eff} \cdot (CJO/SCALM^2)$

$JTUN_{eff} = AREA_{eff} \cdot (JTUN/SCALM^2)$

Defining Diode Models

This section describes diode current, and diode-equivalent circuits.

Diode Current

Figure 10 shows the direction of current flow through the diode. Use either `I(D1)` or `I1(D1)` syntax to print the diode current.

If the voltage on node1 is 0.6V greater than the voltage on node2, then the diode is forward biased or turned on. The anode is the p-doped side of a diode, and the cathode is the n-doped side.

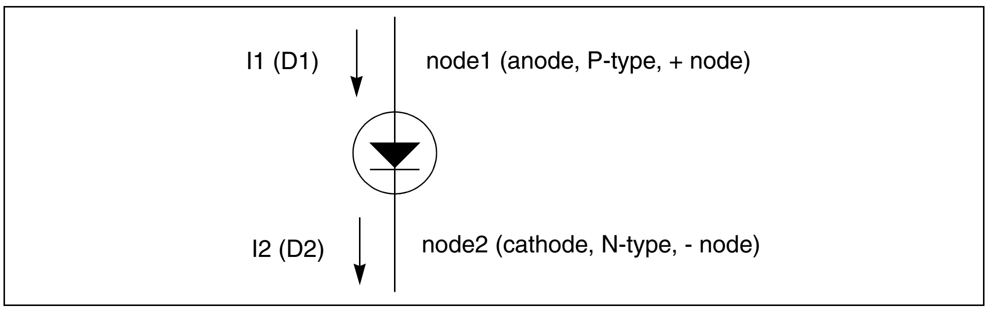


Figure 10   Diode Current Convention

Using Diode Equivalent Circuits

Synopsys diode device models provide three equivalent circuits for diode analysis: transient, AC, and noise circuits. Components of these circuits form the basis for all element and model equations.

The fundamental component in the DC-equivalent circuit is the DC diode current (`id`). Noise and AC analyses do not use the actual `id` current; instead, these analyses use the partial derivative of `id` with respect to the `vd` terminal voltage.

The conductance equation for this partial derivative is:

$$gd = \frac{\partial id}{\partial vd}$$

The drain current (`id`) equation accounts for all basic DC effects of the diodes. The diode device models assume that capacitance effects are separate from the `id` equations.

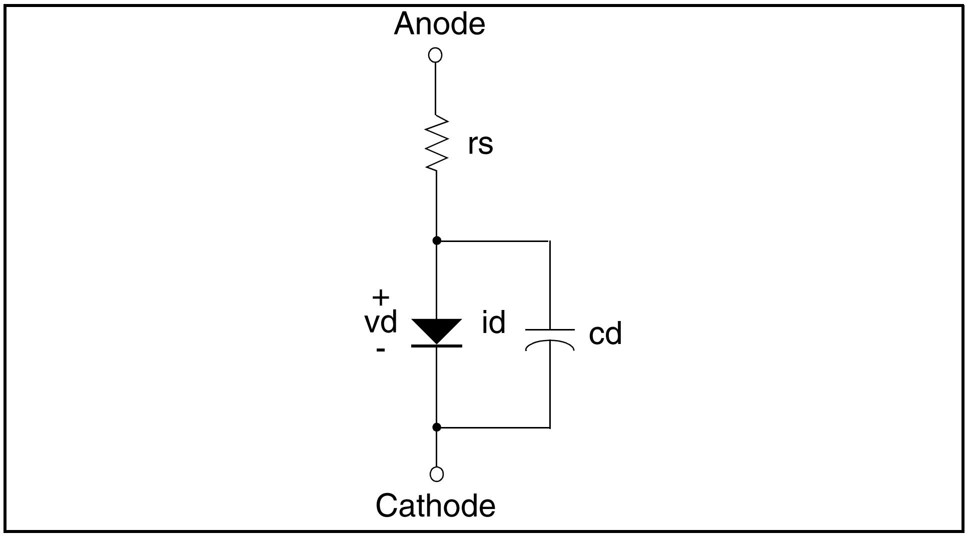


Figure 11 Equivalent Circuit for Diode in Transient Analysis

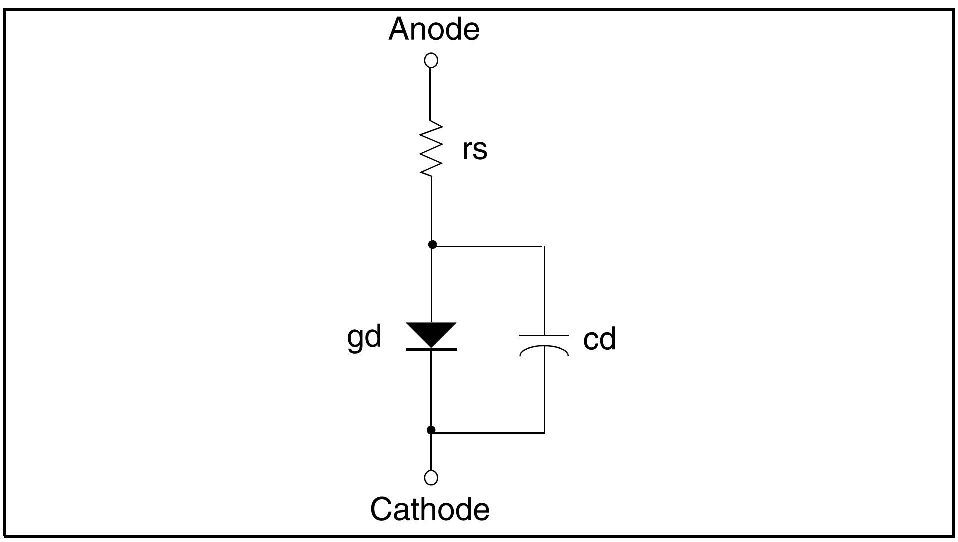


Figure 12 Equivalent Circuit for Diode in AC Analysis

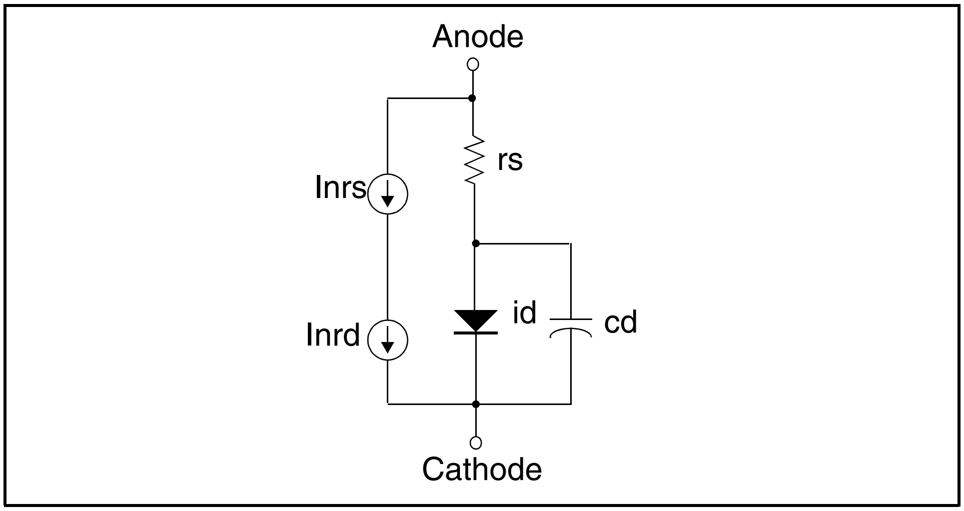


Figure 13 Equivalent Circuit for Diode in AC Noise Analysis

Determining Temperature Effects on Junction Diodes

`LEVEL=1` and `LEVEL=3` model statements contain parameters that calculate temperature effects. `TLEV` and `TLEVC` select different temperature equation to calculate temperature effects on:

- Energy gap
- Leakage current
- Breakdown voltage
- Contact potential
- Junction capacitance
- Grading

Table 18 Junction Diode Temperature Parameters (LEVEL=1 and 3)

Variable	Parameter
Resistance coefficient	TRS
Capacitance coefficient (area)	CTA
Capacitance coefficient (periphery)	CTP

Table 18 Junction Diode Temperature Parameters (LEVEL=1 and 3) (Continued)

Variable	Parameter
Energy gap (pn junction)	EG
Energy gap (bandgap corrections)	GAP1, GAP2
Transit time coefficient	TTT1, TTT2
Reference temperature	TREF
Temperature selectors	TLEV, TLEVC
Miscellaneous	TM1, TM2, TPB, TPHP
Saturation current temperature	XTI

Table 19 Junction Diode Temperature Effects, LEVEL=1 and 3

Name (Alias)	Units	Default	Description
CTA (CTC)	1/×	0.0	Temperature coefficient for area junction capacitance (CJ). If you set the TLEVC parameter to 1, CTAl overrides the default temperature coefficient.
CTP	1/×	0.0	Temperature coefficient for periphery junction capacitance (CJP). If you set TLEVC to 1, CTP overrides the default temperature coefficient.
EG	eV		Energy gap for pn junction diode. ■ For TLEV=0, 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
KEG	-	1	EG correction factor for tunneling
GAP1	eV/×	7.02e-4	First bandgap correction factor. From Sze, alpha term. 7.02e-4 - silicon (old value) 4.73e-4 - silicon 4.56e-4 - germanium 5.41e-4 - gallium arsenide

Table 19 Junction Diode Temperature Effects, LEVEL=1 and 3 (Continued)

Name (Alias)	Units	Default	Description
GAP2	×	1108	Second bandgap correction factor. From Sze, beta term. 1108 - silicon (old value) 636 - silicon 210 - germanium 204 - gallium arsenide
PT		3.0	PT is an alias for XTI.
TCV	1/×	0.0	Temperature coefficient of breakdown voltage.
TLEV		0.0	Diode temperature equation selector. Interacts with TLEVC.
TLEVC		0.0	Level selector for diode temperature, junction capacitances, and contact potentials. Interacts with TLEV.
TM1	1/×	0.0	First-order temperature coefficient for MJ.
TM2	1/° 2	0.0	Second-order temperature coefficient for MJ.
TPB (TVJ)	V/×	0.0	PB temperature coefficient. If you set the TLEVC parameter to 1 or 2, TPB overrides default temperature compensation.
TPHP	V/×	0.0	PHP temperature coefficient. If you set the TLEVC parameter to 1 or 2, TPHP overrides default temperature compensation.
TREF	×c	25.0	Model reference temperature (LEVEL=1 or 3 only).
TRS	1/×	0.0	Resistance temperature coefficient.
TTT1	1/×	0.0	First-order temperature coefficient for TT.
TTT2	1/° 2	0.0	Second-order temperature coefficient for TT.
XTI		3.0	Exponent for the saturation-current temperature. ■ Set XTI=3.0 for a silicon-diffused junction. ■ Set XTI=2.0 for a Schottky barrier diode. PT is an alias for XTI.
XTITUN		3.0	Exponent for the tunneling current temperature.

Using Junction Diode Equations

Table 20 shows the definitions of variables in diode equations.

Table 20 Equation Variable Definitions

Variable	Definition
cd	total diode capacitance
f	frequency
gd	diode conductance
id	diode DC current
id1	current, without high-level injection
ind	equivalent noise current for a diode
inrs	equivalent noise current for a series resistor
vd	voltage, across the diode

Table 21 shows the definitions of equation quantities.

Table 21 Equation Quantity Definition

Quantity	Definition
tox	3.453143e-11 F/m
k	1.3806226e-23 (Boltzmann's constant)
q	1.6021918e-19 (electron charge)
t	temperature in °Kelvin
Δt	t - tnom
tnom	nominal temperature of parameter measurements in °Kelvin
vt(t)	$k \cdot$ t/q: thermal voltage
vt(tnom)	$k \cdot$ tnom/q: thermal voltage

Using Junction DC Equations

A basic diode device model contains three regions:

- Forward bias
- Reverse bias
- Breakdown regions

For a forward-bias diode, the anode is more positive than the cathode. The diode is turned *on*, and conducts above 0.6 V. Set the `RS` model parameter to limit conduction current. As the forward-bias voltage increases past 0.6 V, the limiting resistor prevents the value of the diode current from becoming too high, and prevents the solution from converging.

Forward Bias: $vd \geq -10 \cdot vt$

$$id = ISeff \cdot \left(e^{\frac{vd}{N \cdot vt}} - 1\right)$$

$$vd = v_{node1} - v_{node2}$$

In reverse-bias, the anode (node1) is more negative than the cathode. The diode is turned *off* and conducts a small leakage current.

Reverse Bias: $BVeff < vd < -10 \cdot vt$

$$id = -ISeff - JTUNeff \cdot \left(e^{\frac{-vd}{NTUN \cdot vt}} - 1\right)$$

For breakdown, set the `BV` (`VB`) parameter, which induces reverse-breakdown (or avalanche). You can see this effect in Zener diodes. It occurs when anode-cathode voltage is less than the breakdown voltage (BV). To model this action, measure the voltage (`BV`) and the current (`IBV`), at the reverse-knee or at the onset of avalanche.

Note: `BV` must be a positive number.

Breakdown: $vd < -BV$

$$id = -ISeff \cdot e^{-\left(\frac{vd + BVeff}{NBV \cdot vt}\right)} - JTUNeff \cdot \left(e^{\frac{-vd}{NTUN \cdot vt}} - 1\right)$$

The device model adjusts the `BV` parameter to obtain $BVeff$:

$$ibreak = -ISeff \cdot \left(e^{\frac{-BV}{NBV \cdot vt}} - 1\right)$$

If $IBVeff > ibreak$, then:

$$BVeff = BV - NBV \times vt \times ln\left(\frac{IBVeff}{ibreak}\right)$$

Otherwise:

$$IBVeff = ibreak$$

Most diodes do not behave as ideal diodes. The `IK` and `IKR` parameters are called *high-level injection* parameters. They tend to limit the exponential increase in current.

Note: Diode models use the exponential equation in both the forward and reverse regions.

Forward Bias

$$id = \frac{id1}{1 + \left(\frac{id1}{IKeff}\right)^{1/2}}$$

Reverse Bias

$$id = \frac{id1}{1 + \left(\frac{id1}{IKReff}\right)^{1/2}}$$

For $vd \geq -BVeff$:

$$id1 = ISeff \cdot \left(e^{\frac{vd}{N \cdot vt}} - 1\right) - JTUNeff \cdot \left(e^{\frac{-vd}{NTUN \cdot vt}} - 1\right)$$

Otherwise:

$$id1 = -ISeff \cdot \left(e^{\frac{vd}{N \cdot vt}} - 1\right) - ISeff \cdot e^{-\left(\frac{vd + BVeff}{NBV \cdot vt}\right)} - JTUNeff \cdot \left(e^{\frac{-vd}{NTUN \cdot vt}} - 1\right)$$

From DC measurements of the forward-biased diode characteristics, you can estimate:

- Reverse-saturation current (`IS`)
- Emission coefficient (`N`)
- Model parameter (`RS`)

You can determine `N` from the slope of the diode characteristic in the ideal region. In most cases, the emission coefficient is the value of the unit, but is closer to 2 for MOS diodes.

At higher bias levels, the diode current deviates from the ideal exponential characteristic, due to ohmic resistance in the diode, and the effects of high-level injection. The deviation of the actual diode voltage (from the ideal exponential characteristic), at a specific current, determines the value of `RS`. In practice, simulation of diode device models estimates `RS` at several values of `id`, and averages them, because the value of `RS` depends upon diode current.

Using Diode Capacitance Equations

In Figure 11 on page 62, *cd* models the diode capacitance. The `cd` capacitance is a combination of diffusion (cdiff), depletion (cdep), metal (cmetal), and poly (cpoly) capacitances.

$$cd = cdiff + cdep + cmetal + cpoly$$

Using Diffusion Capacitance Equations

The transit time (`TT`) models the diffusion capacitance, caused by injected minority carriers. In practice, simulation of diode models estimates `TT`, from pulsed time-delay measurements.

$$cdiff = TT \cdot \frac{\partial id}{\partial vd}$$

Using Depletion Capacitance Equations

To model depletion capacitance, diode device models use the junction bottom and junction periphery capacitances. The formula for both bottom area and periphery capacitances is similar, but each has its own model parameters. To select either of the two equations for forward-bias junction capacitance, use `.OPTION DCAP`.

DCAP = 1

The capacitance formula for the junction bottom area is:

$$vd < FC \cdot PB$$

$$cdepa = CJeff \cdot \left(1 - \frac{vd}{PB}\right)^{-MJ}$$

$$vd \geq FC \cdot PB$$

$$cdepa = CJeff \cdot \frac{1 - FC \cdot (1 + MJ) + MJ \cdot \dfrac{vd}{PB}}{(1 - FC)^{(1 + MJ)}}$$

The capacitance formula for the junction periphery is: $vd < FCS \cdot PHP$

$$cdepp = CJPeff \cdot \left(1 - \frac{vd}{PHP}\right)^{-MJSW}$$

$$vd \geq FCS \cdot PHP$$

$$cdepp = CJPeff \cdot \frac{1 - FCS \cdot (1 + MJSW) + MJSW \cdot \dfrac{vd}{PHP}}{(1 - FCS)^{(1 + MJSW)}}$$

$$cdep = cdepa + cdepp$$

DCAP = 2 (default)

The capacitance formula for the total depletion is:

$$vd < 0$$

$$cdep = CJeff \cdot \left(1 - \frac{vd}{PB}\right)^{-MJ} + CJPeff \cdot \left(1 - \frac{vd}{PHP}\right)^{-MJSW}$$

$$vd \geq 0$$

$$cdep = CJeff \cdot \left(1 + MJ \cdot \frac{vd}{PB}\right) + CJPeff \cdot \left(1 + MJSW \cdot \frac{vd}{PHP}\right)$$

DCAP = 3

Limits peak depletion capacitance to $FC \cdot CGSeff$ or $FC \cdot CGSeff$ with proper fall-off when the forward bias exceeds `PB` (`FC`> 1).

Metal and Poly Capacitance Equations (LEVEL=3 Only)

To determine the metal and poly capacitances, use the following equations:

$$cmetal = \left(\frac{\varepsilon_{ox}}{XOI}\right) \cdot (WPeff + XPeff) \cdot (LPeff + XPeff) \cdot M$$

$$cpoly = \left(\frac{\varepsilon_{ox}}{XOM}\right) \cdot (WMeff + XMeff) \cdot (LMeff + XMeff) \cdot M$$

Using Noise Equations

Figure 13 on page 63 shows the noise model for a diode. An independent current source (`inrs`) in parallel with the resistor, models the thermal noise that a resistor generates. To determine the value of `inrs`, use:

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

The unit of `inrs` is Amp/(Hz)$^{1/2}$.

The `ind` current source models the shot and flicker noise of the diode. The following equation defines `ind`:

$$ind = \left(2 \cdot q \cdot id + \frac{KF \cdot id^{AF}}{f}\right)^{1/2}$$

Temperature Compensation Equations

This section describes the temperature-compensation equations.

Energy Gap Temperature Equations

The equations below determine the energy gap for temperature compensation.

TLEV = 0 or 1

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

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

TLEV = 2

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

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

Leakage Current Temperature Equations

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

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

TLEV = 0 or 1

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

TLEV = 2

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

Tunneling Current Temperature Equations

TLEV = 0 or 1

$$faclnt = KEG \cdot \left(\frac{EG}{vt(tnom)} - \frac{EG}{vt(t)}\right) + XTITUN \cdot \ln\left(\frac{t}{tnom}\right)$$

TLEV = 2

$$faclnt = KEG \cdot \left(\frac{egnom}{vt(tnom)} - \frac{eg(t)}{vt(t)}\right) + XTITUN \cdot \ln\left(\frac{t}{tnom}\right)$$

Breakdown-Voltage Temperature Equations

TLEV = 0

$$BV(t) = BV - TCV \Rightarrow \Delta t$$

TLEV = 1 or 2

$$BV(t) = BV \cdot (1 - TCV \Rightarrow \Delta t)$$

$$JTUN(t) = JTUN \cdot e^{facInt}$$

$$JTUNSW(t) = JTUNSW \cdot e^{facInt}$$

Transit-Time Temperature Equations

$$TT(t) = TT \cdot (1 + TTT1 \cdot \Delta t + TTT2 \cdot \Delta t^2)$$

Junction Built-in Potential Temperature Equations

TLEVC = 0

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

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

TLEVC = 1 or 2

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

$$PHP(t) = PHP - TPHP \Rightarrow \Delta t$$

TLEVC = 3

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

$$PHP(t) = PHP + dphpdt \cdot \Delta t$$

If **TLEVC = 3** and **TLEV = 0 or 1**, then:

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

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

If **TLEV = 2**:

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

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

Junction Capacitance Temperature Equations

TLEVC = 0

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

$$CJSW(t) = CJSW \cdot \left[1 + MJSW \cdot \left(4.0e\text{-}4 \Rightarrow \Delta t - \frac{PHP(t)}{PHP} + 1\right)\right]$$

TLEVC = 1

$$CJ(t) = CJ \cdot (1 + CTA \cdot \Delta t)$$

$$CJSW(t) = CJSW \cdot (1 + CTP \cdot \Delta t)$$

TLEVC = 2

$$CJ(t) = CJ \cdot \left(\frac{PB}{PB(t)}\right)^{MJ}$$

$$CJSW(t) = CJSW \cdot \left(\frac{PHP}{PHP(t)}\right)^{MJSW}$$

TLEVC = 3

$$CJ(t) = CJ \cdot \left(1 - 0.5 \Rightarrow dpbdt\ \text{Þ} \frac{\Delta t}{PB}\right)$$

$$CJSW(t) = CJSW \cdot \left(1 - 0.5 \cdot dphpdt \cdot \frac{\Delta t}{PHP}\right)$$

Grading Coefficient Temperature Equation

$$MJ(t) = MJ \cdot (1 + TM1 \cdot \Delta t + TM2 \cdot \Delta t^2)$$

Resistance Temperature Equations

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

Using the JUNCAP Models

This section describes the JUNCAP (junction capacitance) diode models: JUNCAP1 and JUNCAP2. These diodes models have been implemented in HSPICE as

- Level 4 = JUNCAP1
- Level 6 = JUNCAP2

For a full description of the JUNCAP models, see http://www.semiconductors.philips.com/Philips_Models/.

You can use the .MODEL statement to include a JUNCAP (junction capacitance) model in your HSPICE netlist. For a general description, see the , see the .MODEL statement in the *HSPICE Reference Manual: Commands and Control Options*.

Input Syntax

```
Dxxx na nb modelname [area=val] [pj=val] [pgate=val]
+ [m=>val] [dtemp=val] [off=val] [IC=val]
.OPTION list
```

Parameter	Description
Dxxx	Diode element name. Must begin with D, followed by up to 1023 alphanumeric characters.
na	Positive terminal (anode) node name. The series resistor for the equivalent circuit is attached to this terminal.
nb	Negative terminal (cathode) node name.
mname	Diode model name reference.
area	Diode area. In the model card, AB can use this value.
pj	Length of the side-wall in the AB diffusion area, which is not under the gate. In the model card, LS uses this value.
pgate	Length of the side-wall in the AB diffusion area, which is under the gate. In the model card, LG uses this value.
m	Multiplier to simulate multiple diodes in parallel. The M setting affects all currents, capacitances, and resistances. The default is 1.
dtemp	The difference between the element temperature and the circuit temperature in degrees celsius. The default is DTA.
off	Sets initial conditions for this element to OFF in DC analysis. Default=ON.
ic	Initial voltage across a diode element. Use this value when you specify the UIC option in the .TRAN statement. The .IC statement overrides this value.
.OPTION list	Prints the updated temperature parameters for the JUNCAP diode model.

These topics are discussed in the following sections:

- JUNCAP1 Model
- JUNCAP2 Model - Level 6

JUNCAP1 Model

To use this model, specify:

```
.MODEL mname D LEVEL=4 [keyword=val]
```

Parameter	Description
mname	Model name. The diode element uses this name to refer to the model.
D	Symbol that identifies a diode model.
LEVEL	Symbol that identifies a diode model.
keywords	Model parameter keywords.

Example

```
.model MD D LEVEL=4
+ AB=2E-12 LS=2E-6 LG=1.3E-6 DTA=0 TR=30 VR=0.3 JSGBR=1.2e-3
+ JSDBR=1.3e-3 JSGSR=1.1e-3 JSDSR=1.3e-3 JSGGR=1.4e-3
+ JSDGR=1.4e-3 NB=1.6 NS=1.3 NG=1.3 VB=0.9 CJBR=1.2e-12
+ CJSR=1.2e-12 CJGR=1.3e-12 VDBR=1.6 VDSR=1.3 VGDR=1.2 PB=0.5
+ PS=0.6 PG=0.4
```

Model Parameters

The JUNCAP1 model parameters are listed in Table 22.

Table 22 JUNCAP1 Model Parameters

Name	Unit	Default	Min.	Description
AB	m^2	1e-12	0.0	Diffusion area.
CJBR	Fm-2	1.0E-12	0.0	Bottom junction capacitance, at V=VR.
CJGR	Fm-2	1.0E-12	0.0	Gate-edge junction capacitance, at V=VR.
CJSR	Fm-2	1.0E-12	0.0	Sidewall junction capacitance, at V=VR.

Table 22 JUNCAP1 Model Parameters (Continued)

Name	Unit	Default	Min.	Description
DTA	°C	0.0		Temperature offset of Juncap element with respect to TA.
JSDBR	Am-2	1.0e-3	0.0	Bottom saturation-current density, due to diffusion from back-contact.
JSDGR	Am-2	1.0e-3	0.0	Gate-edge saturation-current density, due to diffusion from back-contact.
JSDSR	Am-2	1.0e-3	0.0	Sidewall saturation-current density, due to diffusion from back-contact.
JSGBR	Am-2	1.0e-3	0.0	Bottom saturation-current density, due to generating electron holes at V=VR.
JSGGR	Am-2	1.0e-3	0.0	Gate-edge saturation-current density, due to generating electron holes at V=VR.
JSGSR	Am-2	1.0e-3	0.0	Sidewall saturation-current density, due to generating electron holes at V=VR
LG	m	0.0	0.0	Length of the side-wall for the AB diffusion area, which is under the gate. (Default deviates from Philips JUNCAP =1.0e-6).
LS	m	0.0	0.0	Length of the side-wall for the AB diffusion area, which is not under the gate. (Default deviates from Philips JUNCAP =1.0e-8).
NB		1.0	0.1	Emission coefficient of the bottom forward current.
NG		1.0	0.1	Emission coefficient of the gate-edge forward current.
NS		1.0	0.1	Emission coefficient of the sidewall forward current.
PB		0.40	0.05	Grading coefficient of the bottom junction.
PG		0.40	0.05	Grading coefficient of the gate-edge junction.
PS		0.40	0.05	Grading coefficient of the sidewall junction.
TR	°C	25	-273.15	Temperature at which simulation finds parameter values.
VB	V	0.9		Reverse breakdown voltage.
VDBR	V	1.00	0.05	Diffusion voltage of the bottom junction, at T=TR.
VDGR	V	1.00	0.05	Diffusion voltage of the gate-edge junction.

Table 22 JUNCAP1 Model Parameters (Continued)

Name	Unit	Default	Min.	Description
VDSR	V	1.00	0.05	Diffusion voltage of the sidewall junction, at T=TR.
VR	V	0.0		Voltage at which simulation finds parameter values.

Theory

This section summarizes the elementary physics of a junction diode. Refer to semiconductor literature for additional information.

You can represent the current voltage characteristics as follows:

$$J = \{J_d(n_i^2 + (J_g(n_i, \ V))\} \cdot \left[\exp\left(\frac{qv}{kT}\right) - 1\right]$$

$$ni \ T^{\frac{3}{2}} \cdot \ \exp\left(\frac{-E_g}{2kT}\right)$$

Quantity	Units	Description
J	Am-2	Total reverse-current density.
Jd	Am-2	Diffusion saturation-current density.
Jg	Am-2	Generation-current density.
ni	m-3	Intrinsic carrier concentration.
V	V	Voltage, across the diode.
Eg	J	Energy gap.
k	JK-1	Boltzmann constant.
T	K	Temperature.

For $V<V_D$, this equation describes the charge of the junction capacitance:

$$Q = Q_j\left[1 - \left(1 - \frac{V}{V_D}\right)^{1-P}\right]$$

Quantity	Units	Description
Q	C	Total diode-junction charge.
Qj	C	Junction charge, at built-in voltage.
V	V	Voltage, across the diode.
Vd	V	Diffusion voltage at the junction.
P		Grading coefficient for the junction.

JUNCAP Model Equations

The JUNCAP model describes reverse-biasing of source, drain or well-to-bulk junction devices. Similar to the MOS model, this model uses quasi-static approximations (in charge equations) to formulate current equations and to model AC effects.

To include the effects from differences in the sidewall, bottom, and gate-edge junction profiles, the JUNCAP model calculates these three contributions separately.

JUNCAP also models both the diffusion and the generation currents, each with individual temperature and voltage dependence.

In the JUNCAP model, the gate-edge junction (very close to the surface) provides a part of the total charge. The MOS model charge equations also includes this charge so simulation counts it twice. However, this results in only a very minor error.

The next section shows the model equations. For the model to operate correctly in a circuit simulator environment, you must specify some numerical additions (see the Nomenclature section). You must include any fixed capacitance that is present on a node (such as metal-1-to-substrate capacitance) in either a fixed capacitor statement or INTCAP. These capacitances are not part of the JUNCAP model as they were in the old NODCAP model.

Nomenclature

Table 23 lists the electrical variable parameters:

Table 23 JUNCAP Model Electrical Variable Parameters

No.	Variable	Program Name	Units	Description
1	Va	VA	V	Potential, applied to the anode.
2	Vk	VK	V	Potential, applied to the cathode.
3	Ia	IA	A	DC current, into the anode.
4	Ik	IK	A	DC current, into the cathode.
5	Qa	QA	C	Charge in a device, attributed to the anode.
6	Qk	QK	C	Charge in a device, attributed to the cathode.

Note: The model card lists the parameters. See JUNCAP model syntax earlier in this chapter.

Table 24 lists internal variables and parameters:

Table 24 JUNCAP Model Internal Variables and Parameters

No.	Variable or Parameter	Program Name	Units	Description
1	Vdb	VDB	V	Diffusion voltage of the AB bottom area.
2	Vds	VDS	V	Diffusion voltage of the LS Locos-edge.
3	Vdg	VDG	V	Diffusion voltage of the LG gate-edge.
4	Cjb	CJB	F	Capacitance of the AB bottom area.
5	Cjs	CJS	F	Capacitance of the LS Locos-edge.
6	Cjg	CJG	F	Capacitance of the LG gate-edge.
7	Isdb	ISDB	A	Diffusion saturation current of AB bottom area.
8	Isds	ISDS	A	Diffusion saturation current of LS Locos-edge.
9	Isdg	ISDG	A	Diffusion saturation current of LG gate-edge.

Table 24 JUNCAP Model Internal Variables and Parameters (Continued)

No.	Variable or Parameter	Program Name	Units	Description
10	Isgb	ISGB	A	Generation saturation current of AB bottom area.
11	Isgs	ISGS	A	Generation saturation current of LS Locos-edge.
12	Isgg	ISGG	A	Generation saturation current of LG gate-edge.
13	Ta	TA	C	Ambient circuit temperature.
14	Tkd	TKD	K	Absolute temperature of the junction/device.
15	V	V	V	Diode bias voltage (V=VA - VK).
16	I	I	A	Total DC current, from anode to cathode: (I = IA = -IK)
17	Q	Q	C	Total junction charge: (Q = QA = - QK)

ON/OFF Condition

Solving a circuit involves successive calculations. The calculations start from a set of initial guesses for the electrical quantities of the non-linear elements. The devices start in the default state.

DC Operating Point Output

The output of a DC operating point calculation contains information about the state of a device, at its operation point.

Note: G min conductance connects in parallel to the G conductance. This conductance influences the DC operating output.

Temperature, Geometry and Voltage Dependence

The general scaling rules, which apply to all three components of the JUNCAP model, are:

$$T_{KR} = T_0 + T_R$$

$$T_{KD} = T_0 + T_A + DT_A$$

$$V_{TR} = k \cdot \frac{T_{KR}}{q}$$

$$V_{TD} = K \cdot \frac{T_{KD}}{q}$$

$$V_{gR} = 1.16 - \frac{(7.02 \cdot 10e-4 \cdot T_{KR} \cdot T_{KR})}{(1108.0 + T_{KR})}$$

$$V_{gD} = 1.16 - \frac{(7.02 \cdot 10e-4 \cdot T_{KR} \cdot T_{KD})}{(1108.0 + T_{KD})}$$

$$F_{TD} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{V_{gR}}{(2 \cdot V_{TR})} - \frac{V_{gD}}{(2 \cdot V_{TD})}\right)$$

Internal Reference

The following equations specify the internal reference parameters for the bottom component:

$$\left(V_{DB} = \frac{V_{DBR} \cdot T_{KD}}{T_{KR} - 2 \cdot V_{TD} \cdot 1nF_{TD}}\right)$$

$$C_{JB} = C_{JBR} \cdot A_B \cdot \left(\frac{(V_{DBR} - V_R)}{V_{DB}}\right)^{P_B}$$

$$I_{SGB} = J_{SGBR} \cdot F_{TD} \cdot A_B \cdot \left(\frac{V_{DB}}{(V_{DBR} - V_R)}\right)^{P_B}$$

$$I_{SDB} = J_{SDBR} \cdot F_{TD} \cdot F_{TD} \cdot A_B$$

Locos-edge and gate-edge components use similar formulations:

- Replace the `B` (bottom) index with `S` (locos-edge) or `G` (gate-edge).
- Replace the `AB` (bottom) area with `LS` (locos-edge) or `LG` (gate-edge).

For the locos-edge:

$$V_{DS} = \frac{V_{DSR} \cdot T_{KR}}{T_{KR} - 2 \cdot V_{TD} \cdot 1nF_{TD}}$$

$$C_{JS} = C_{JSR} \cdot \; L_S \cdot \; \left(\frac{(V_{DSR} - V_R)}{V_{DS}}\right)^{P_S}$$

$$I_{SGS} = J_{SGSR} \cdot \; F_{TD} \cdot \; L_S \cdot \; \left(\frac{V_{DS}}{(V_{DSR} - V_R)}\right)^{P_S}$$

$$I_{SDS} = J_{SDSR} \cdot \; F_{TD} \cdot \; F_{TD} \cdot \; L_S$$

For the gate-edge:

$$V_{DG} = \frac{V_{DGR} \cdot \; T_{KD}}{T_{KR} - 2 \cdot \; V_{TD} \cdot \; 1nF_{TD}}$$

$$C_{JG} = C_{JGR} \cdot \; L_G \cdot \; \left(\frac{(V_{DGR} - V_R)}{V_{DG}}\right)^{P_G}$$

$$I_{SGS} = J_{SGGR} \cdot \; F_{TD} \cdot \; L_G \cdot \; \left(\frac{V_{DG}}{(V_{DGR} - V_R)}\right)^{P_G}$$

$$I_{SDS} = J_{SDGR} \cdot \; F_{TD} \cdot \; F_{TD} \cdot \; L_G$$

Note: The remainder of this section shows the equations only for the bottom component.

JUNCAP Capacitor and Leakage Current Model

The charge description defines the following internal parameter:

$$Q_{JDB} = C_{JB} \cdot \; V_{DB}(1 - P_B)$$

To prevent an unlimited increase in the voltage derivative of the charge, the charge description consists of two parts:

- Original power function
- Supplemented quadratic function

The cross-over point between these regions (indicated as VI) defines the following parameters:

$$F_{CB} = 1 - \left(\frac{(1 + P_B)}{3}\right)^{\frac{1}{P_B}}$$

$$V_{LB} = F_{CB} \cdot \; V_{DB}$$

$$C_{LB} = C_{JB}(1 - F_{CB})^{-P_B}$$

$$Q_{LB} = Q_{JDB}(1 - (1 - F_{CB})^{(1 - P_B)})$$

$$Q_{JBV} = Q_{JCB} \cdot \left(\frac{(1 - (1 - V))}{V_{DB}}\right)^{(1 - P_B)} \quad \mathrm{V} < \mathrm{V}_{LB}$$

$$Q_{LB} + C_{LB}(V - V_{LB}) \cdot \left(\frac{1 + (P_B(V - V_{LB}))}{2 \cdot \ V_{DB} \cdot \ (1 - F_{CB})}\right) \quad \mathrm{V} >= \mathrm{V}_{LB} \quad (12.63)$$

Use similar expressions for the locos-edge (Q_{JSV}) and gate-edge (Q_{JGV}) charges.

The following equation describes the total charge characteristic:

$$Q = Q_{JBV} + Q_{JSV} + Q_{JGV}$$

From Equation 12.63 (above), you can use elementary mathematics to derive simple equations for the capacitance of the bottom area:

$$C_{JBV} = C_{JB} \cdot \left(1 / \left(\frac{1 - v}{V_{DB}}\right)\right)^{P_B} \quad V < V_{LB}$$

$$C_{LB} + C_{LB} \cdot \ P_B \cdot \left(\frac{(V - V_{LB})}{V_{DB} \cdot \ (1 - F_{CB})}\right) \quad V \geq V_{LB}$$

Similar expressions exist for C_{JSV} and C_{JGV}.

Total capacitance:

$$C = C_{JBV} + C_{JSV} + C_{JGV}$$

Diffusion and Generation Currents

Using the scaled parameters from the preceding section, you can express the diffusion and generation current components as:

$$I_{DB} = I_{SDB} \cdot \ \exp\left(\frac{V}{(N_B \cdot \ V_{TD})} - 1\right)$$

$$I_{GB} = I_{SGB} \cdot \left(\frac{(V_{DB} - V)}{V_{DB}}\right)^{P_B} \cdot \left(\exp\left(\left(\frac{V}{N_B \cdot \ V_{TD}}\right) - 1\right)\right) \quad V \leq V_{DB}$$

$$0 \quad V > V_{DB}$$

- The first relation, concerning the diffusion component, is valid over the whole operating range.
- The second relation, describing the generation current, shows an unlimited increase in the derivative of this function, at $V=V_{DB}$.

Therefore, the power function merges at V=0.0 with a hyperbolic function in the forward-bias range. Simulating the model then divides the exponential part by $\exp(V/(N_B \cdot V_{TD}))$. This enables a gradual decrease in the generation-current component.

This calculation uses the hyperbolic function:

$$I_{HYP} = F_{SB}(V + V_{AB})^{-B}$$

The *B* parameter controls the decrease in current for voltages V>0.0 for all generation components. The model sets *B* to a fixed value of 2. The continuity constraints of the function and derivative in the merge point lead to the following relations for F_{SB} and V_{AB}:

$$V_{AB} = B \cdot \frac{V_{DB}}{P_B}$$

$$F_{SB} = I_{SGB} \cdot V_{AB}B$$

The generation current voltage characteristic in the forward region, becomes:

$$I_{GB} = F_{SB}/((V + V_{AB})^B) \cdot (1 - \exp(-v)/(N_B \cdot V_{TD}))$$

Final Model Equations

The final model equations for the currents of the bottom area, are:

$$I_{DB} = I_{SDB} \cdot (\exp(V/(N_B \cdot V_{TD})) - 1)$$

$$I_{GB} = I_{SGB} \cdot \left(\frac{V_{DB} - V}{V_{DB}}\right)^{P_B} \cdot \exp\left(\frac{V}{(N_B \cdot V_{TD})}\right) - 1 \quad V \le 0$$

$$Isgb \cdot \left(\frac{Vab}{(V + Vab)}\right)^B \cdot \left(1 - \exp\left(\frac{-V}{(Nb \cdot Vtd)}\right)\right) \quad V > 0.0$$

Use similar expressions for the locos-edge and gate-edge components.

The following equation expresses the total junction current:

$$I = (I_{DB} + I_{GB}) + (I_{DS} + I_{GS}) + (I_{DG} + I_{GG})$$

JUNCAP2 Model - Level 6

The JUNCAP2 model is a compact MOS model intended to describe the behavior of the diodes that are formed by the source, drain, or well-to-bulk junctions in MOSFETs. It is the successor to the JUNCAP1 model, and was developed by Koninklijke Philips Electronics N.V.

Physical Effects

The following physical effects have been included in the JUNCAP2 model:

- Geometrical scaling
- Depletion capacitance
- Ideal current
- Shockley-Read-Hall current
- Trap-assisted tunneling current
- Band-to-band tunneling current
- Avalanche breakdown
- Noise

For a full description of the JUNCAP2 model, see http://www.semiconductors.philips.com/Philips_Models/.

JUNCAP2 Model Updates

JUNCAP Model 200.3.3 Update

Fixed bug in FJUNQ-based selection-criterion in JUNCAP-express charge model.

JUNCAP Model 200.3.0 Update

The newly introduced express-option of the JUNCAP2 model, invoked by setting SWJUNEXP=1, allows the user to trade some simulation accuracy for simulation speed. In transient analyses, a simulation time reduction of up to a factor of 5 (of the simulation time associated with JUNCAP2) has been demonstrated with a very limited loss of accuracy. This is achieved by a creating a strongly simplified IV-model, combined with a more extensive initialization code.

JUNCAP Model 200.2.0 Update

- The band-to-band tunneling equations have been modified. At temperatures lower than the reference temperature, Vj can become lower than VBIR. This caused numerical problems in the model, which, in turn, sometimes resulted in convergence problems in the simulator. An alternative formulation of the equations has been implemented that avoids these problems.
- Minor bug fixes.

Usage in HSPICE

The JUNCAP2 model is `LEVEL=6` in the Synopsys diode models. Each version can be identified with model parameter `VERSION`.

To use this model, specify:

```
.MODEL mname D LEVEL=6 [keyword=val]
```

Parameter	Description
mname	Model name. The diode element uses this name to refer to the model.
D	Symbol that identifies a diode model.
LEVEL	Symbol that identifies a diode model.
keywords	Model parameter keywords.

Example

```
.MODEL NDIO D  LEVEL=6 VERSION=200.33
+ TYPE=1.000E+00 TRJ=21.000E+00 DTA=0.000E+00 IMAX=1.000E+03
+ CJORBOT=1.000E-03 CJORSTI=1.000E-09 CJORGAT=1.000E-09
+ VBIRBOT=1.000E+00 VBIRSTI=1.000E+00 VBIRGAT=1.000E+00
+ PBOT=500.000E-03 PSTI=500.000E-03 PGAT=500.000E-03
+ PHIGBOT=1.160E+00 PHIGSTI=1.160E+00 PHIGGAT=1.160E+00
+ IDSATRBOT=1.000E-12 IDSATRSTI=1.000E-18 IDSATRGAT=1.000E-18
+ CSRHBOT=100.000E+00 CSRHSTI=100.000E-06 CSRHGAT=100.000E-06
+ XJUNSTI=100.000E-09 XJUNGAT=100.000E-09 CTATBOT=100.000E+00
+ CTATSTI=100.000E-06 CTATGAT=100.000E-06 MEFFTATBOT=250.000E-03
+ MEFFTATSTI=250.000E-03 MEFFTATGAT=250.000E-03
+ CBBTBOT=1.000E-12 CBBTSTI=1.000E-18 CBBTGAT=1.000E-18
+ FBBTRBOT=1.000E+09 FBBTRSTI=1.000E+09 FBBTRGAT=1.000E+09
+ STFBBTBOT=-1.000E-03 STFBBTSTI=-1.000E-03 STFBBTGAT=-1.000E-03
+ VBRBOT=10.000E+00 VBRSTI=10.000E+00 VBRGAT=10.000E+00
+ PBRBOT=4.000E+00 PBRSTI=4.000E+00 PBRGAT=4.000E+00
```

Model Parameters

Table 25 lists the JUNCAP2 model parameters.

Table 25 JUNCAP2 Model Parameters

Name	Unit	Default	Description
LEVEL	-	1	Diode model level
TYPE	-	1	Switch (-1 or 1) to select P-N and N- P junction
VERSION	-	200.33	Version number for model update
DTA	°C	0	Temperature offset with respect to ambient temperature
IMAX	A	1000	Maximum current up to which forward current behaves exponentially
TRJ	°C	21	Reference temperature
Capacitance parameters			
CJORBOT	F/m^2	1e-3	Zero-bias capacitance per unit-of area of bottom component
CJORGAT	F/m	1e-9	Zero-bias capacitance per unit-of length of gate-edge component
CJORSTI	F/m	1e-9	Zero-bias capacitance per unit-of length of STI-edge component
PBOT	-	0:5	Grading coefficient of bottom component
PGAT	-	0:5	Grading coefficient of gate-edge component
PSTI	-	0:5	Grading coefficient of STI-edge component
VBIRBOT	V	1	Built-in voltage at the reference temperature of bottom component
VBIRGAT	V	1	Built-in voltage at the reference temperature of gate-edge component
VBIRSTI	V	1	Built-in voltage at the reference temperature of STI-edge component
Ideal-current parameters			
IDSATRBOT	A/m^2	1e-12	Saturation current density at the reference temperature of bottom component
IDSATRGAT	A/m	1e-18	Saturation current density at the reference temperature of gate-edge component
IDSATRSTI	A/m	1e-18	Saturation current density at the reference temperature of STI-edge component

Table 25 JUNCAP2 Model Parameters (Continued)

Name	Unit	Default	Description
PHIGBOT	V	1.16	Zero-temperature bandgap voltage of bottom component
PHIGGAT	V	1.16	Zero-temperature bandgap voltage of gate-edge component
PHIGSTI	V	1.16	Zero-temperature bandgap voltage of STI-edge component
Shockley-Read-Hall parameters			
CSRHBOT	A/m^3	1e+2	Shockley-Read-Hall prefactor of bottom component
CSRHGAT	A/m^2	1e-4	Shockley-Read-Hall prefactor of gate-edge component
CSRHSTI	A/m^2	1e-4	Shockley-Read-Hall prefactor of STI-edge component
XJUNGAT	m	1e-7	Junction depth of gate-edge component
XJUNSTI	m	1e-7	Junction depth of STI-edge component
Trap-assisted tunneling parameters			
CTATBOT	A/m^3	1e+2	Trap-assisted tunneling prefactor of bottom component
CTATGAT	A/m^2	1e-4	Trap-assisted tunneling prefactor of gate-edge component
CTATSTI	A/m^2	1e-4	Trap-assisted tunneling prefactor of STI-edge component
MEFFTATBOT	-	0:25	Effective mass (in units of m_0) for trap-assisted tunneling of bottom component
MEFFTATGAT	-	0:25	Effective mass (in units of m_0) for trap-assisted tunneling of gate-edge component
MEFFTATSTI	-	0:25	Effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component
Band-to-band tunneling parameters			
CBBTBOT	AV^{-3}	1e-12	Band-to-band tunneling prefactor of bottom component
CBBTGAT	$AV^{-3}m$	1e-18	Band-to-band tunneling prefactor of gate-edge component
CBBTSTI	$AV^{-3}m$	1e-18	Band-to-band tunneling prefactor of STI-edge component

Table 25 JUNCAP2 Model Parameters (Continued)

Name	Unit	Default	Description
FBBTRBOT	Vm^{-1}	1e+9	Normalization field at the reference temperature for band-to-band tunneling of bottom component
FBBTRGAT	Vm^{-1}	1e+9	Normalization field at the reference temperature for band-to-band tunneling of gate-edge component
FBBTRSTI	Vm^{-1}	1e+9	Normalization field at the reference temperature for band-to-band tunneling of STI-edge component
STFBBTBOT	K^{-1}	-1e-3	Temperature scaling parameter for band-to-band tunneling of bottom component
STFBBTGAT	K^{-1}	-1e-3	Temperature scaling parameter for band-to-band tunneling of gate edge component
STFBBTSTI	K^{-1}	-1e-3	Temperature scaling parameter for band-to-band tunneling of STI-edge component
Avalanche and breakdown parameters			
PBRBOT	V	4	Breakdown onset tuning parameter of bottom component
PBRGAT	V	4	Breakdown onset tuning parameter of gate-edge component
PBRSTI	V	4	Breakdown onset tuning parameter of STI-edge component
VBRBOT	V	10	Breakdown voltage of bottom component
VBRGAT	V	10	Breakdown voltage of gate-edge component
VBRSTI	V	10	Breakdown voltage of STI-edge component

Using the Fowler-Nordheim Diode, Level 2

The `LEVEL=2` diode model parameter selects the Fowler-Nordheim model. Fowler-Nordheim diodes can be either a metal-insulator-semiconductor or a semiconductor-insulator-semiconductor layer device. The insulator is sufficiently thin (100 Angstroms) to permit tunneling of carriers. It models:

- Electrically-alterable memory cells
- Air-gap switches
- Other insulation-breakdown devices

These topics are discussed in the following sections:

- Fowler-Nordheim Diode Model Parameters LEVEL=2
- Using Fowler-Nordheim Diode Equations
- Fowler-Nordheim Diode Capacitances

Fowler-Nordheim Diode Model Parameters LEVEL=2

Table 26 shows the Fowler-Nordheim diode model parameters for `LEVEL=2`.

Table 26 Fowler-Nordheim Diode Model Parameters

Name (alias)	Units	Default	Description
EF	V/cm	1.0e8	Forward critical electric field.
ER	V/cm	EF	Reverse critical electric field.
JF	amp/V2	1.0e-10	Forward current coefficient for Fowler-Nordheim.
JR	amp/V2	JF	Reverse current coefficient for Fowler-Nordheim.
L	m	0.0	Length of the diode for calculating the current in Fowler-Nordheim. Leff = L · SCALM · SHRINK + XWeff
TOX	Å	100.0	Thickness of the oxide layer.
W	m	0.0	Width of the diode for calculating the current in Fowler-Nordheim. Weff = W · SCALM · SHRINK + XWeff
XW	m	0.0	XWeff = XW · SCALM

Using Fowler-Nordheim Diode Equations

The following forward and reverse non-linear current source equations model the DC characteristics of the Fowler-Nordheim diode. In these equations:

$$AREAeff = Weff \cdot Leff \cdot M$$

Forward Bias

$vd \geq 0$

$$id = AREAeff \cdot JF \cdot \left(\frac{vd}{TOX}\right)^2 \cdot e^{\frac{-EF \cdot TOX}{vd}}$$

Reverse Bias

$vd < 0$

$$id = -AREAeff \cdot JR \cdot \left(\frac{vd}{TOX}\right)^2 \cdot e^{\frac{ER \cdot TOX}{vd}}$$

Fowler-Nordheim Diode Capacitances

The Fowler-Nordheim diode capacitance is a constant, derived from:

$$cd = AREAeff \cdot \frac{\varepsilon_{ox}}{TOX}$$

Philips D500 Model (Advanced Diode Model), Level 5

The Diode 500 model provides a detailed description of the diode currents in forward and reverse biased Si-diodes. It is meant to be used for DC, transient and AC analysis. The Philips D500 model is available as Level 5 in the Synopsys Diode models.

For more information about the D500 model, see:

http://www.nxp.com/Philips_Models/additional/advanced_diode/

These topics are discussed in the following sections:

- Using the Philips D-500 Model
- Equivalent Circuits and Equations

Using the Philips D-500 Model

Set level=5 to identify the model as Philips D500 Model. You can use DTEMP with this model to increase the temperature of individual elements, relative to the circuit temperature. Set DTEMP on the element line.

The general syntax for the Diode element is the same as the other standard diode models.

The available parameters are described in Table 27.

Table 27 Description of Philips D500 Parameters

Name	Units	Default	Clip low	Clip high	Description
Level	-	5	-	-	Model level
AF	-	1.0	0.01	-	Flickernoise exponent
CBBT	A/V	3.255	0.0	-	Band to band tunneling
CJ	F	7.0E-12	0.0	-	Zero-bias depletion capacitance
CSRH	A/cm	7.44E-7	0.0	-	Shockley-Read-Hall generation
CTAT	A/cm	3.31E-6	-	0.0	Trap assisted tunneling
IS	A	7.13E-13	0.0	-	Saturation current
KF	-	0.0	0.0	-	Flickernoise coefficient
N	-	0.1	1.044	-	Junction emission coefficient
P	-	0.40	0.05	0.99	Grading coefficient
PTRS	-	0.0	-	-	Power for temperature dependence of RS
RS	Ohm	0.0	0.0	-	Series resistance
TAU	S	500.0E-12	0.0	-	Transit time
TREF	25.0		-273.15	-	Reference temperature
V/cm	EMVBR	1.36E6	1.0	-	Electric field at breakdown
VBR	V	7.459	0.1	-	Breakdown voltage
VD	V	0.90	-	0.05	Diffusion voltage
VG	V	1.206	0.1	-	Bandgap voltage
VLC	V	0.0	-	-	Voltage dependence at low forward current

Equivalent Circuits and Equations

A full description of D-level-500 for diode is provided below. The DC/transient and AC equivalent circuits are shown in Figure 14 and Figure 15 on page 100, respectively.

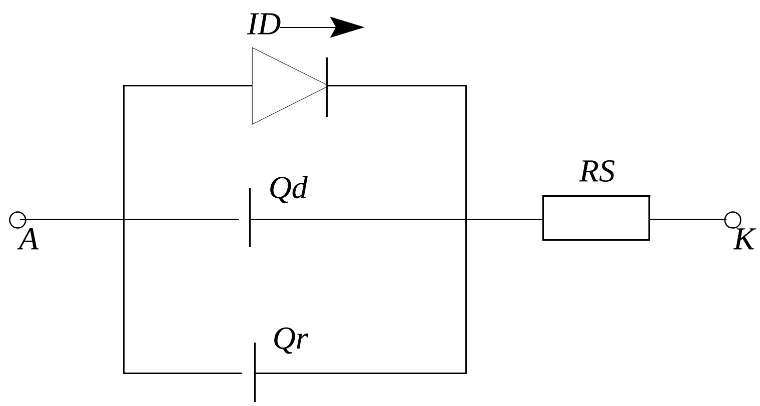


Figure 14 DC/Transient Circuit for Diode

Temperature Effects

The actual simulation temperature is denoted by *TEMP* (in °C). The temperature at which the parameters are determined is specified by *TREF* (in °C.)

- Conversion to Kelvins

$$TK = TEMP + 273.15 + DTA$$

$$TRK = TREF + 273.15$$

- Thermal Voltages

$$k = 1.3806226 \cdot 10^{-23} JK^{-1}$$

$$q = 1.6021918 \cdot 10^{-19} C$$

$$V_T = \left(\frac{k}{q}\right) \cdot T_K$$

$$V_{TR} = \left(\frac{k}{q}\right) \cdot T_{RK}$$

- Depletion Capacitances

$$F = \left(\frac{T_K}{T_{RK}}\right)^3 \cdot \exp\left[VG \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right]$$

$$VD_T = \left[\frac{VD}{V_{TR}} - \ln(F)\right] \cdot V_T$$

$$CJ_T = CJ \cdot \left(\frac{VD}{VD_T}\right)^P$$

- Transit Times

$$TAU_T = TAU\left(\frac{T_K}{T_{RK}}\right)^{1.8}$$

- Saturation Current

$$IS_T = IS \cdot \left(\frac{T_K}{T_{RK}}\right)^{1.8} \cdot \exp\left[\frac{VG}{N} \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right]$$

- Shockley-Read-Hall generation and trap assisted tunneling

$$T_{up} = \left(\frac{T_K}{T_{RK}}\right)^{3/2} \cdot \exp\left[\frac{VG + VLC}{2} \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right]$$

$$CSRH_T = CSRH \cdot T_{up}$$

$$CTAT_T = CTAT \cdot T_{up}$$

$$ETAT_T = 70.8 \cdot T_K^{3/2}$$

- Band-to-Band Tunneling

$$CBBT_T = CBBT \text{ (temperature independent)}$$

$$F0 = 1.9 \cdot 10^7 \cdot \left(1.04 - \frac{4.21 \cdot 10^{-4} \cdot T_K^2}{636 + T_K}\right)$$

- Avalanche Multiplication

$$dT = TEMP + DTA - 25° C$$

$$Bn = 1.23 \cdot 10^6$$

$$Bn_T = Bn \cdot \; 1 + 7.2 \cdot \; 10^{-4} \cdot \; dT - 1.6 \cdot \; 10^{-6} \cdot \; dT^2$$

- Breakdown

$$VBR_T = VBR \cdot \left(\frac{T_K}{T_{RK}}\right)^{0.1}$$

$$EMVBR_T = EMVBR \cdot \left(\frac{VD_T + VBR_T}{VD + VBR}\right)^{1-P}$$

- Resistance

$$RS_T = RS \cdot \left(\frac{T_K}{T_{RK}}\right)^{PTRS}$$

Model Constants and Parameter-Related Constants

$$K = 0.01$$

$$KET = 0.1$$

$$ETM = 3$$

- Maximum Electric Field and Depletion Layer width at zero bias:

$$E_0 = \frac{EMVBR_T}{\left(1 + \frac{VBR_T}{VD_T}\right)^{1-P}}$$

$$W_0 = \frac{VD_T}{E_0 \cdot \; (1-P)}$$

Diode Currents

First, the maximum reverse junction voltage is defined.

- Above this voltage the current will be extrapolated on a logarithmic scale.

$$V_j = \begin{cases} -0.99 \cdot \; VBR_T, & V_{AK1} < -0.99 \cdot \; VBR_T \\ V_{AK1}, & V_{AK1} \geq -0.99 \cdot \; VBR_T \end{cases}$$

- Ideal Forward Current

$$Id_f = IS_T \left\{ \exp\left(\frac{V_j}{N \cdot \; V_T}\right) - 1 \right\}$$

- Maximum Electric Field and Depletion Layer Width

$$VD_j = \frac{\sqrt{\left\{\left(1 - \frac{V_j}{VD_T}\right)^2 + \left(\frac{V_j}{VD_T} \cdot K\right)\right\} \cdot \left(1 - \frac{V_j}{VD_T}\right)}}{2}$$

$$E_m = E_0 \cdot VD_j^{(1-P)}$$

$$W_d = W_0 \cdot VD_j^P$$

- Shockley-Read-Hall Generation

$$I_{srh} = CSRH_T \cdot (W_d - W_0)$$

- Trap-Assisted Tunneling

$$ET_0 = \frac{\frac{E_0}{ETAT_T} + ETM - \sqrt{\left(\frac{E_0}{ETAT_T} - ETM\right)^2 + KET}}{2}$$

$$ET = \frac{\frac{E_m}{ETAT_T} + ETM - \sqrt{\left(\frac{E_m}{ETAT_T} - ETM\right)^2 + KET}}{2}$$

$$I_{tat} = CTAT_T \cdot W_d \cdot \left\{\frac{\exp(ET^2) - \exp(ET_0^2)}{\frac{E_m}{ETAT_T}}\right\}$$

- Non-Ideal Forward Current including Tunneling

$$Is_{lf} = CSRH_T \cdot \left\{6.28 + 38.58 \cdot \left(\frac{E_m}{ETAT_T}\right) \cdot \exp(ET_0^2)\right\} \cdot \frac{V_T}{E_m}$$

$$I_{lf} = Is_{lf} \cdot \frac{\exp\left(\frac{V_j}{N \cdot V_T}\right) - 1}{4 \cdot \exp\left(\frac{V_j}{2 \cdot N \cdot V_T}\right) + \exp\left(\frac{VLC}{2 \cdot N \cdot V_T}\right)} \cdot \exp\left(\frac{VLC}{2 \cdot N \cdot V_T}\right)$$

- Band-to Band-Tunneling

$$I_{bbt} = \frac{-CBBT_T \cdot V_j}{\left(\frac{F0}{E_m}\right)^{1.5} \cdot \exp\left(\frac{F0}{E_m}\right)}$$

- Avalanche Multiplication

$$\mu = 0.3295 \cdot \left(\frac{E_m}{EMVBR_T}\right)^2 \cdot \exp\frac{Bn_T}{EMVBR_T} - \frac{Bn_T}{E_m}$$

- Total Diode Current

$$I_d = \frac{(Id_f + I_{lf} - I_{srh}) \cdot \frac{1 + \exp(-2 \cdot \mu)}{2} - I_{bbt} + I_{tat} \cdot \exp(-\mu)}{1 - 2 \cdot \mu \cdot \{1 + \exp(-2 \cdot \mu)\}}$$

- Extrapolation of the Reverse Current

$$I_{dBR} = I_d \qquad \text{at } V_j = -0.99VBR_T$$

$$G_{dBR} = \frac{dI_d}{dV_j} \qquad \text{at } V_j = -0.99VBR_T$$

$$ID = \begin{cases} I_d & V_{AK1} \geq -0.99VBR_T \\ I_{dBR} \cdot \exp\left[\left(\frac{V_{AK1} + -0.99VBR_T}{I_{dBR}}\right)G_{dBR}\right] & V_{AK1} < -0.99VBR_T \end{cases}$$

Transient Model

Transient behavior is modeled using the DC equations.

- Diffusion charge

$$Q_D = TAU_T \cdot Id_f$$

- Depletion charge

$$FC = 1 - \left(\frac{1 + P}{3}\right)^{\left(\frac{1}{P}\right)}$$

$$Q_{AT} = CJ_T \cdot \left(\frac{VD_T}{1 - P}\right)$$

$$V_L = FC \cdot VD_T$$

$$C_L = CJ_T \cdot (1 - FC)^{-P}$$

$$Q_L = Q_{AT} \cdot \{1 - (1 - FC)^{(1-P)}\}$$

Then, if $V_{AK1} < V_L$

$$Q_T = Q_{AT} \cdot \left[1 - \left\{1 - \left(\frac{V_{AK1}}{VD_T}\right)\right\}^{(1-P)}\right]$$

Or, if $V_{AK1} \geq V_L$

$$Q_T = V_L + C_L \cdot (V_{AK'1} - V_L) - \left\{1 + \frac{P \cdot (V_{AK'1} - V_L)}{2 \cdot VD_T \cdot (1 - FC)}\right\}$$

AC Linearized model

Using the appropriate definitions for the various circuit elements leads to the following equations:

$$R_D = \frac{1}{dID/ \ dV_{AK1}}$$

Where $dID/ \ dV_{AK1}$ is the first derivative of the total diode current with respect to the Internal voltage Internal voltage V_{AK1}.

The capacitances are defined as:

$$C_T = CJ_T \cdot \left\{1 - \left(\frac{V_{AK1}}{VD_T}\right)\right\}^{-P} \qquad \text{for } V_{AK1} < V_L$$

$$C_T = C_L \cdot \left\{1 + \frac{P \cdot (V_{AK1} - V_L)}{VD_T \cdot (1 - FC)}\right\} \qquad \text{for } V_{AK1} \geq V_L$$

$$C_1 = C_T + TAU_T \cdot \left(\frac{Id_f + IS_T}{N \cdot V_T}\right)$$

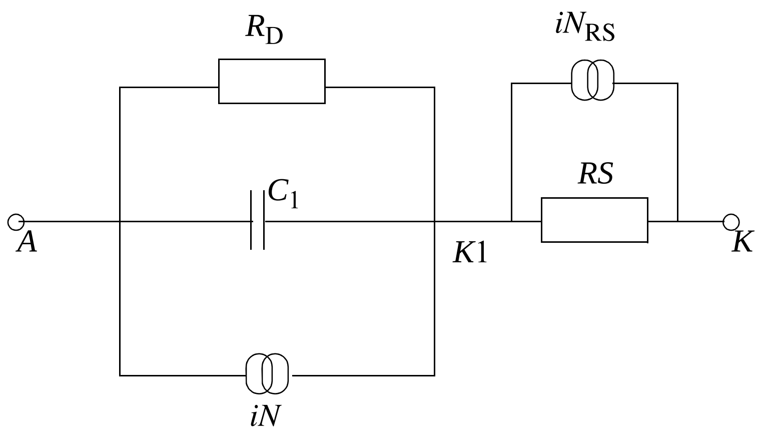


Figure 15 AC equivalent circuit for Diode, including Noise Sources

Noise Model

For noise analysis, noise sources are added to the small signal model as shown in Figure 15. In these equations f represents the operation frequency of the transistor and is the Δf

bandwidth. When Δf is taken as 1 Hz, a noise density is obtained.

- Thermal noise

$$\overline{iN_{RS}^{\,2}} = \frac{4 \cdot K \cdot T_K \cdot \Delta f}{RS_T}$$

- Current noise (shot noise and 1/f noise)

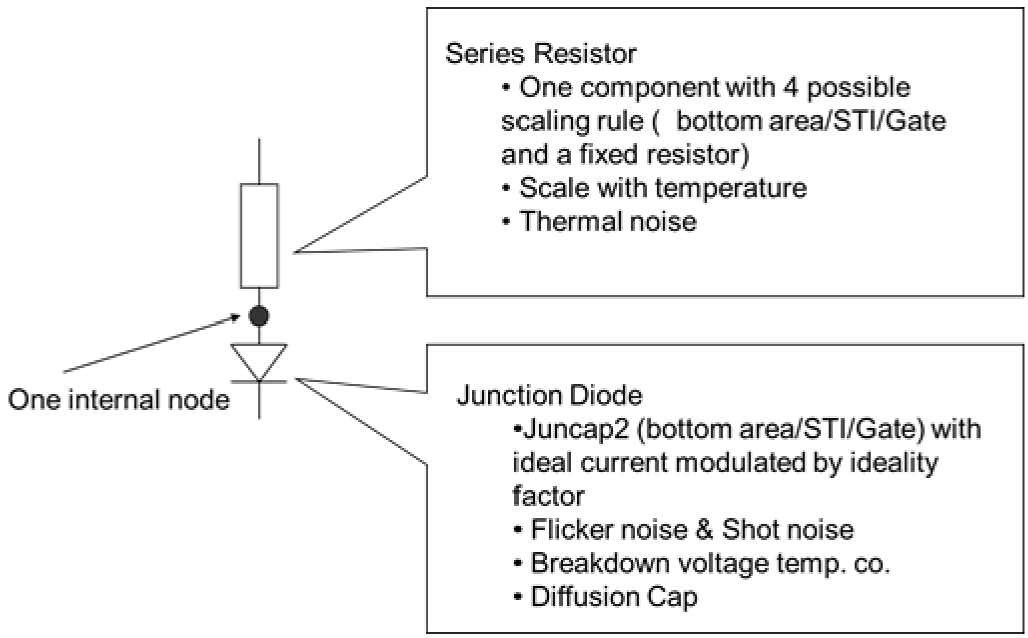
$$\overline{iN^2} = 2 \cdot q \cdot |Id_f| \cdot \Delta f + KF + MULT \cdot \left|\frac{Id_f}{MULT}\right|^{AF} \cdot \frac{\Delta f}{f}$$

DIODE_CMC Model, Level 7

The DIODE_CMC model includes following enhancement beyond JUNCAP2:

- Series resistor
- Diffusion cap
- Breakdown voltage temperature coefficient

- Ideality factor
- Noise
- Instance parameter LG default value change
- Alias parameters for AB,LS,MULT
- Min-max parameters for warning purpose



Set level=7 to identify the diode model as DIODE_CMC.

This section covers the following topics:

- Instance Parameters
- Model Parameters

Instance Parameters

Name	Unit	Default	Min	Max	Description
AB	m^2	1.00E-12	0	-	Junction area
AREA	m^2	1.00E-12	0	-	alias of AB
LS	m	1.00E-06	0	-	STI-edge part of junction perimeter
PERIM	m	1.00E-06	0	-	alias of LS
PJ	m	1.00E-06	0	-	alias of LS
LG	m	0	0	-	Gate-edge part of junction perimeter
MULT	-	1	0	-	Number of devices in parallel

Model Parameters

Name	Unit	Default	Min	Max	Description
VERSION	-	1	-	-	Model version
SUBVERSION	-	0	-	-	Model subversion
REVISION	-	0	-	-	Model revision
TYPE	-	1	-1	1	Type parameter, in output value 1 reflects n-type, -1 reflects p-type
DTA	C	0	-	-	Temperature offset with respect to ambient temperature

This section covers the following topics:

- DIODE_CMC - Reduced Parameters
- JUNCAP2 - Express Parameters

DIODE_CMC - Reduced Parameters

Name	Unit	Default	Min	Max	Description
IMAX	A	1000	1.00E-12	-	Maximum current up to which forward current behaves exponentially
TRJ	C	21	-250	-	Reference temperature
CJORBOT	Fm^-2	1.00E-03	1.00E-12	-	Zero-bias capacitance per unit-of-area of bottom component
CJORSTI	Fm^-1	1.00E-09	1.00E-18	-	Zero-bias capacitance per unit-of-length of STI-edge component
CJORGAT	Fm^-1	1.00E-09	1.00E-18	-	Zero-bias capacitance per unit-of-length of gate-edge component
VBIRBOT	V	1	0.05	-	Built-in voltage at the reference temperature of bottom component
VBIRSTI	V	1	0.05	-	Built-in voltage at the reference temperature of STI-edge component
VBIRGAT	V	1	0.05	-	Built-in voltage at the reference temperature of gate-edge component
PBOT	-	0.5	0.05	0.95	Grading coefficient of bottom component
PSTI	-	0.5	0.05	0.95	Grading coefficient of STI-edge component
PGAT	-	0.5	0.05	0.95	Grading coefficient of gate-edge component
PHIGBOT	V	1.16	-	-	Zero-temperature bandgap voltage of bottom component
PHIGSTI	V	1.16	-	-	Zero-temperature bandgap voltage of STI-edge component
PHIGGAT	V	1.16	-	-	Zero-temperature bandgap voltage of gate-edge component
IDSATRBOT	Am^-2	1.00E-12	0	-	Saturation current density at the reference temperature of bottom component

Name	Unit	Default	Min	Max	Description
IDSATRSTI	Am^-1	1.00E-18	0	-	Saturation current density at the reference temperature of STI-edge component
IDSATRGAT	Am^-1	1.00E-18	0	-	Saturation current density at the reference temperature of gate-edge component
CSRHBOT	Am^-3	1.00E+02	0	-	Shockley-Read-Hall prefactor of bottom component
CSRHSTI	Am^-2	1.00E-04	0	-	Shockley-Read-Hall prefactor of STI-edge component
CSRHGAT	Am^-2	1.00E-04	0	-	Shockley-Read-Hall prefactor of gate-edge component
XJUNSTI	m	1.00E-07	1.00E-09	-	Junction depth of STI-edge component
XJUNGAT	m	1.00E-07	1.00E-09	-	Junction depth of gate-edge component
CTATBOT	Am^-3	1.00E+02	0	-	Trap-assisted tunneling prefactor of bottom component
CTATSTI	Am^-2	1.00E-04	0	-	Trap-assisted tunneling prefactor of STI-edge component
CTATGAT	Am^-2	1.00E-04	0	-	Trap-assisted tunneling prefactor of gate-edge component
MEFFTATBOT	-	0.25	0.01	-	Effective mass (in units of m0) for trap-assisted tunneling of bottom component
MEFFTATSTI	-	0.25	0.01	-	Effective mass (in units of m0) for trap-assisted tunneling of STI-edge component
MEFFTATGAT	-	0.25	0.01	-	Effective mass (in units of m0) for trap-assisted tunneling of gate-edge component
CBBTBOT	AV^-3	1.00E-12	0	-	Band-to-band tunneling prefactor of bottom component
CBBTSTI	AV^-3m	1.00E-18	0	-	Band-to-band tunneling prefactor of STI-edge component

Name	Unit	Default	Min	Max	Description
CBBTGAT	AV^-3m	1.00E-18	0	-	Band-to-band tunneling prefactor of gate-edge component
FBBTRBOT	Vm^-1	1.00E+09	-	-	Normalization field at the reference temperature for band-to-band tunneling of bottom component
FBBTRSTI	Vm^-1	1.00E+09	-	-	Normalization field at the reference temperature for band-to-band tunneling of STI-edge component
FBBTRGAT	Vm^-1	1.00E+09	-	-	Normalization field at the reference temperature for band-to-band tunneling of gate-edge component
STFBBTBOT	K^-1	-1.00E-03	-	-	Temperature scaling parameter for band-to-band tunneling of bottom component
STFBBTSTI	K^-1	-1.00E-03	-	-	Temperature scaling parameter for band-to-band tunneling of STI-edge component
STFBBTGAT	K^-1	-1.00E-03	-	-	Temperature scaling parameter for band-to-band tunneling of gate-edge component
VBRBOT	V	10	0.1	-	Breakdown voltage of bottom component
VBRSTI	V	10	0.1	-	Breakdown voltage of STI-edge component
VBRGAT	V	10	0.1	-	Breakdown voltage of gate-edge component
PBRBOT	V	4	0.1	-	Breakdown onset tuning parameter of bottom component
PBRSTI	V	4	0.1	-	Breakdown onset tuning parameter of STI-edge component
PBRGAT	V	4	0.1	-	Breakdown onset tuning parameter of gate-edge component
RSBOT	VA^-1m^2	0	0	-	Series resistance per unit-of-area of bottom component
RSSTI	VA^-1m	0	0	-	Series resistance per unit-of-length of STI-edge component

Name	Unit	Default	Min	Max	Description
RSGAT	VA^-1m	0	0	-	Series resistance per unit-of-length of gate-edge component
RSCOM	ohm	0	0	-	Common series resistance, no scaling
STRS	-	0	0	-	Temperature scaling parameter for series resistance
KF	-	0	0	-	KF parameter for flicker noise
AF	-	1	0.1	-	AF parameter for flicker noise
TT	s	0	0	-	Transit time
STVBRBOT1	1/K	0	-	-	Temp. co of breakdown voltage bottom component
STVBRBOT2	1/K^2	0	-	-	Temp. co of breakdown voltage bottom component
STVBRSTI1	1/K	0	-	-	Temp. co of breakdown voltage STI-edge component
STVBRSTI2	1/K^2	0	-	-	Temp. co of breakdown voltage STI-edge component
STVBRGAT1	1/K	0	-	-	Temp. co of breakdown voltage gate-edge component
STVBRGAT2	1/K^2	0	-	-	Temp. co of breakdown voltage gate-edge component
NFABOT	-	1	0.1	-	ideality factor bottom component
NFASTI	-	1	0.1	-	ideality factor STI-edge component
NFAGAT	-	1	0.1	-	ideality factor gate-edge component
ABMIN	m^2	0	0	-	minimum allowed junction area
ABMAX	m^2	1	0	-	maximum allowed junction area
LSMIN	m	0	0	-	minimum allowed junction STI-edge
LSMAX	m	1	0	-	maximum allowed junction STI-edge
LGMIN	m	0	0	-	minimum allowed junction gate-edge

Name	Unit	Default	Min	Max	Description
LGMAX	m	1	0	-	maximum allowed junction gate-edge
TEMPMIN	C	-55	-250	-	minimum allowed junction temp
TEMPMAX	C	155	-250	-	maximum allowed junction temp
VFMAX	V	0	0	-	maximum allowed forward junction bias
VRMAX	V	0	0	-	maximum allowed reverse junction bias
XTI	-	3	0.1	-	Temp. co of saturation current
PT	-	3	0.1	-	alias of XTI
SCALE	-	1	0	1	Scale parameter
SHRINK	-	0	0	100	Scale parameter

JUNCAP2 - Express Parameters

Name	Unit	Default	Min	Max	Description
SWJUNEXP	-	0	0	1	Flag for JUNCAP-express; 0=full model, 1=express model
VJUNREF	-	2.5	0.5	-	Typical maximum junction voltage; usually about 2*VSUP
FJUNQ	-	0.03	0	-	Fraction below which junction capacitance components are considered negligible

Converting National Semiconductor Models

National Semiconductor's circuit simulator provides a scaled diode model, which is not the same as the diode device model. To use National Semiconductor circuit models, do the following:

1. For a subcircuit that consists of the scaled diode model, make sure that the subcircuit name is the same as the model name.

The `.PARAM` statement, inside the subcircuit, specifies the parameter values for the scaled diode model.

2. Add a scaled diode model inside the subcircuit, then change the `.MODEL` *mname mtype* statement to a `.PARAM` statement.
3. Ensure that the letter X precedes the names of all scaled diode elements.
4. Check that every parameter used in the `.MODEL` statement, inside the subcircuit, also has a value in the `.PARAM` statement.

Using the Scaled Diode Subcircuit Definition

The scaled diode subcircuit definition converts the National Semiconductor scaled diode model to a model that you can use in HSPICE. The `.PARAM` parameter, inside the `.SUBCKT`, represents the `.MODEL` parameter in the National circuit simulator.

To use this definition:

1. Replace the `.MODEL mname` statement with a `.PARAM` statement.
2. Change the model name to `SDIODE`.

The following is an example of a scaled-diode subcircuit definition:

```
.SUBCKT SDIODE NP NN SF=1 SCJA=1 SCJP=0 SIS=1 SICS=1
+ SRS=1
D NP NN SDIODE
.PARAM IS=1.10E-18 N=1.03 EG=0.8 RS=20.7E3
+ CJA=0.19E-15 PHI=0.25 CJP=0.318E-15
+ EXA=0.5 EXP=0.325 CTC=6E-4
+ TRS=2.15M M=2
*
.MODEL SDIODE D
+ IS='IS*SIS*SF' CJA='CJA*SF*SCJA' CJP='CJP*SF*SCJP'
+ RS='RS*SRS/SF' EXA=EXA EXP=EXP
+ N=N CTA=CTC CTP=CTC
+ TRS=TRS TLEV=1 TLEVC=1 xti='m*n'
.ENDS SDIODE
```

You must define the values for all parameters used in this model in either a `.PARAM` statement or the `.SUBCKT` call. Circuit simulation then replaces the diode statements with the call to the `SDIODE` subcircuit; for example,

```
XDS 14 1048 SDIODE SIS=67.32 SCJA=67.32 SRS=1.2285E-2
```

DC Operating Point Output of Diodes

`id`: current across the diode.
`vd`: voltage across the diode.
`req`: equivalent resistance (1 / equivalent conductance).

`cap`: total diode capacitance.

4

JFET and MESFET Models

Describes how to use JFET and MESFET models in HSPICE circuit simulations.

HSPICE ships hundreds of examples for your use; see Listing of Demonstration Input Files for paths to demo files.

Three JFET/MESFET DC model levels have been provided for IC circuit simulation. These models use the same equations for gallium arsenide MESFETs and silicon-based JFETs. This is possible because these models include materials definition parameters. You can also use these models to model indium phosphide MESFETs.

Overview of JFETs

JFETs form by diffusing a gate diode between the source and drain. MESFETs form by applying a metal layer over the gate region, and creating a Schottky diode. To control the flow of carriers, both technologies modulate the gate diode depletion region. These field effect devices are called bulk semiconductors and are in the same category as bipolar transistors. Compared to surface effect devices such as MOSFETs, bulk semiconductors 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`)

GaAs model `LEVEL=3`[1] assumes that GaAs device velocity saturates at very low drain voltages. This model includes drain voltage induced threshold modulation and user-selectable materials constants. These features let you use the model for other materials, such as silicon, indium phosphide, and gallium aluminum arsenide. The models that have been provided include a revised Curtice model[2], and a TriQuint model (TOM) that extends the earlier Statz model.

For a listing of output templates for JFET models see Element Template Listings (HSPICE Only), Table 45, in the *HSPICE User Guide: Basic Simulation and Analysis*.

Specifying a Model

To specify a JFET or MESFET model, 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`.

Bypassing Latent Devices (HSPICE Only)

Use the `BYPASS` (latency) option to decrease simulation time in large designs. To speed simulation time, this option does not recalculate currents, capacitances, and conductances, if the voltages at the terminal device nodes have not changed. The `BYPASS` option applies to MOSFETs, MESFETs, JFETs, BJTs, and diodes. Use `.OPTION BYPASS` to set `BYPASS`.

`BYPASS` might reduce simulation accuracy for tightly-coupled circuits such as op-amps, high gain ring oscillators, and so on. Use `.OPTION MBYPASS` to set `MBYPASS` to a smaller value for more accurate results.

Parameter	Description
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	HSPICE variable saturation model

The `CAPOP` model parameter selects the type of capacitor model:\

Parameter	Description
CAPOP=0	SPICE depletion capacitor model
CAPOP=1	Charge conserving, symmetric capacitor model (Statz)
CAPOP=2	HSPICE improvements to CAPOP=1

You can use `CAPOP=0`, `1`, `2` for any model level. `CAPOP=1` and `2` are most often used for the MESFET `LEVEL=3` model.

The `ACM` model parameter selects the area calculation method:

JFET / MESFET Selection Parameters	
Parameter	**Description**
ACM=0	SPICE method (default)
ACM=1	Physically based method

Example 1

The following example selects the n channel MESFET model, `LEVEL=3`. It uses the `SAT`, `ALPHA`, and `CAPOP=1` parameter:

```
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
```

Example 2

The following example selects an n-channel JFET:

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

Example 3

The following example selects a p-channel JFET:

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

Overview of 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 such as:

- 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 they can be very different.
- 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 might 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

Use MESFETs 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 Option	Description
DCAP	Capacitance equation selector
GMIN, GRAMP, GMINDC	Conductance options: transient or DC analysis, DC auto-convergence
SCALM	Model scaling option Note: SCALM is ignored in Level 49 and higher.
DCCAP	Invokes capacitance calculation in DC analysis

Table 28 JFET Options

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

To override a global depletion capacitance equation selection that uses the `.OPTION DCAP = ` *<val>* statement in a JFET or MESFET model, include `DCAP=`*<val>* in the device's `.MODEL` statement.

Convergence

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

Capacitor Equations

The DCAP option 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. Default is 2.

JFET and MESFET Equivalent Circuits

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.

The SCALM option affects A, L, W, LDEL, and WDEL scaled parameters. SCALM defaults to 1.0. For example, to enter the W parameter with micron units, set SCALM to 1e-6 then enter W=5. The default setting is W=5e-6 meters or 5 microns.

To override global scaling that uses the .OPTION SCALM = *<val>* statement in a JFET or MESFET model, include SCALM=*<val>* in the .MODEL statement.

JFET Current Conventions

Figure 16 on page 117 assumes the direction of current flow through the JFET. You can use either I(Jxxx) or I1(Jxxx) syntax when printing the drain current. I2 references the gate current and I3 references the source current. Jxxx is the device name. Figure 16 on page 117 represents the current convention for an n channel JFET.

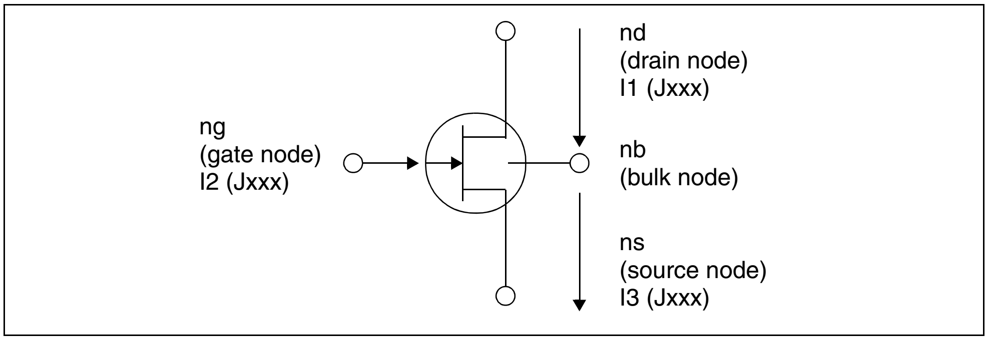


Figure 16 JFET Current Convention, N-Channel

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

Circuit simulation uses three equivalent circuits to analyze 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. Gate capacitances are assumed to account for transient currents of the JFET equations. The two diodes shown in Figure 17 are modeled by these ideal diode equations:

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

$$vgd > -10 \cdot N \cdot vt$$

$$igd = -ISeff$$

$$vgd \leq -10 \cdot N \cdot vt$$

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

$$vgs > -10 \cdot N \cdot vt$$

$$igs = -ISeff$$

$$vgs \leq -10 \cdot N \cdot vt$$

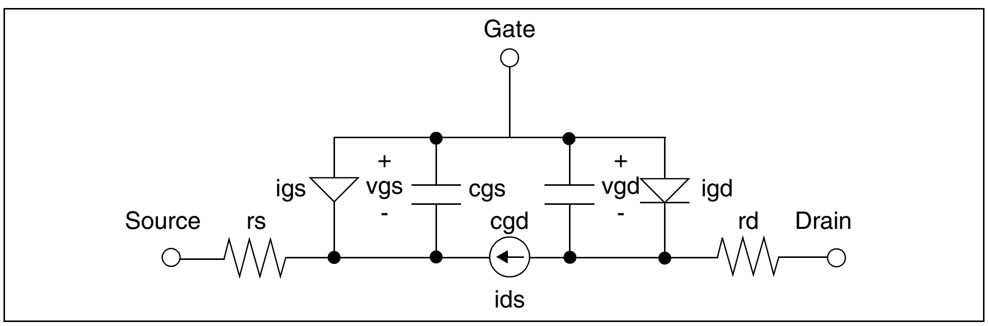


Figure 17   JFET/MESFET Transient Analysis

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

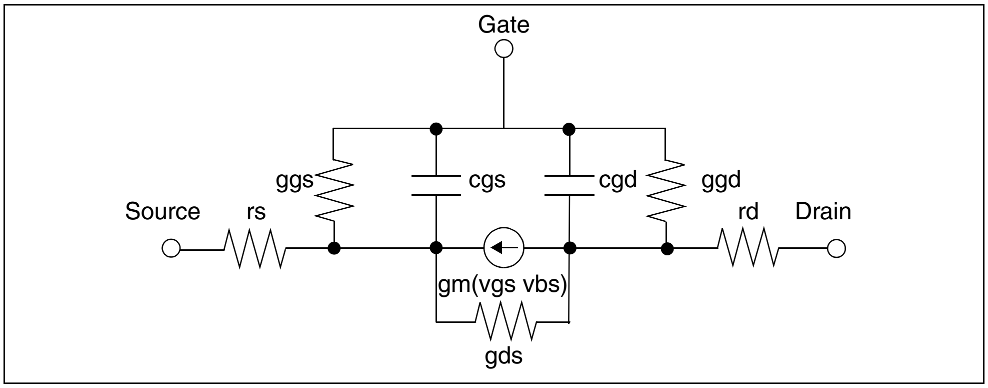


Figure 18 JFET/MESFET AC Analysis

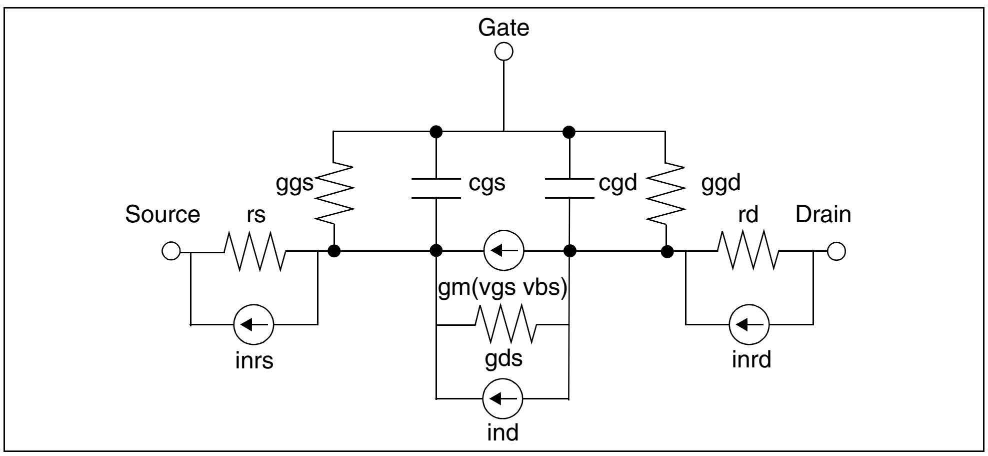


Figure 19 JFET/MESFET AC Noise Analysis

Table 29 Equation Variable Names and Constants

Variable/ Quantity	Definitions
ε_o	Vacuum permittivity = 8.854e-12 F/m
cgd	Gate to drain capacitance
cgs	Gate to source capacitance
Dt	t - tnom

Table 29 Equation Variable Names and Constants (Continued)

Variable/ Quantity	Definitions
f	Frequency
gds	Drain to source AC conductance controlled by vds
ggd	Gate to drain AC conductance
ggs	Gate to source AC conductance
gm	Drain to source AC transconductance controlled by vgs
ids	DC drain to source current
igd	Gate to drain current
igs	Gate to source current
ind	Equivalent noise current drain to source
inrd	Equivalent noise current drain resistor
inrs	Equivalent noise current source resistor
k	1.38062e-23 (Boltzmann's constant)
q	1.60212e-19 (electron charge)
rd	Drain resistance
rs	Source resistance
t	Temperature in °K
tnom	Nominal temperature of parameter measurements in °K (user-input in °C). Tnom = 273.15 + TNOM
vgd	Internal gate-drain voltage
vgs	Internal gate-source voltage
vt(t)	$k \cdot t/q$
vt(tnom)	$k \cdot tnom/q$

Table 30 JFET DC Operating Point Output

Quantities	Definitions
cgd	G-D capacitance
cgs	G-S capacitance
gds	Drain-source transconductance
gm	transconductance
gmbs	drain-body (backgate) transconductance
ids	D-S current
igd	G-D current
igs	G-S current
vds	D-S voltage
vgs	G-S voltage

JFET and MESFET Model Statements

You can use the `.MODEL` statement to include a JFET or MESFET model in your HSPICE netlist. For a general description of the `.MODEL` statement, see the *HSPICE Command Reference*.

Syntax

```
.MODEL <mname> NJF [LEVEL=val] <pname1=val1> ...
.MODEL mname PJF [LEVEL=val] [pname1=val1] ...
```

Parameter	Description
mname	Model name. Elements refer to the model by this name.
NJF	Identifies an N-channel JFET or MESFET model.
LEVEL	Selects different DC model equations.
pname1=val1	Each JFET or MESFET model can include several model parameters.

Parameter	Description
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. The charge storage is modeled by nonlinear depletion-layer capacitances for both gate junctions that vary as the -M power of junction voltage, and are defined by the parameters CGS, CGD, and PB.

KF and AF parameters 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 element and model parameters. The AREA element parameter always overrides the AREA model parameter.

Table 31 JFET and MESFET Model Parameters

Model Parameters Common to All Levels	
Capacitance	CAPOP, CGD, CGS, FC, M, PB, TT
Geometric	ACM, ALIGN, AREA, HDIF, L, LDEL, LDIF, RD, RG, RS, RSH, RSHG, RSHL, W, WDEL
Noise	AF, KF
Subthreshold	ND, NG
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 tables provide information about:

- Gate Diode DC Parameters (Table 32)
- Gate Capacitance LEVEL=1, 2, and 3 Parameters (Table 33
- DC Model LEVEL=1 Parameters (Table 34
- DC Model LEVEL=2 Parameters (Table 35
- DC Model LEVEL=3 Parameters (Table 36

Table 32 provides information about gate diode DC parameters.

Table 32 Gate Diode DC Parameters

Name (Alias)	Units	Default	Description
ACM			Area calculation method. Use this parameter to select between traditional SPICE unitless gate area calculations and the newer style of area calculations (see the ACM section). If W and L are specified, AREA becomes: ACM=0 AREA=W_{eff}/L_{eff} ACM=1 AREA=$W_{eff} \cdot$ Leff
ALIGN	m	0	Misalignment of gate
AREA			Default area multiplier. This parameter affects the BETA, RD, RS, IS, CGS, and CGD model parameters. $AREA_{eff}=M \cdot AREA$ 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 $IS_{eff} = IS \cdot AREA_{eff}$
L	m	0.0	Default length of FET. Override this parameter using the element L. $L_{eff} = L \cdot SCALM + LDEL_{eff}$
LDEL	m	0.0	Difference between drawn and actual or optical device length $LDEL_{eff} = LDEL \cdot SCALM$

Table 32 Gate Diode DC Parameters (Continued)

Name (Alias)	Units	Default	Description
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) $RD_{eff} = RD / AREA_{eff}$, ACM=0
RG	ohm	0.0	Gate resistance (see the ACM section) $RG_{eff} = RG \cdot AREA_{eff}$, ACM=0
RS	ohm	0.0	Source ohmic resistance (see the ACM section) $RS_{eff} = RS/AREA_{eff}$, 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
W	m	0.0	Default FET width. The We element overrides this parameter. $W_{eff} = W \cdot SCALM + WDEL_{eff}$
WDEL	m	0.0	Difference between drawn and actual or optical device width $WDEL_{eff} = WDEL \cdot SCALM$

Table 33 provides information about gate capacitance level 1, 2, and 3 parameters.

Table 33 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 – HSPICE improvement to CAPOP=1
CALPHA	ALPHA		Saturation factor for capacitance model (CAPOP=2 only)

Table 33 Gate Capacitance LEVEL=1, 2, and 3 Parameters (Continued)

Name (Alias)	Units	Default	Description
CAPDS	F	0	Drain to source capacitance for TriQuint model CAPDSeff=CAPDS $\cdot \frac{Weff}{Leff} \cdot M$
CGAMDS	GAMDS		Threshold lowering factor for capacitance (CAPOP=2 only)
CGD	F	0.0	Zero-bias gate-drain junction capacitance $CGD_{eff} = CGD \cdot AREA_{eff}$ Override this parameter by specifying GCAP.
CGS	F	0.0	Zero-bias gate-source junction capacitance $CGS_{eff} = CGS \cdot AREA_{eff}$ Override this parameter by specifying GCAP
CRAT		0.666	Source fraction of gate capacitance (used with GCAP)
GCAP	F		Z ero-bias gate capacitance. If specified, $CGS_{eff} = GCAP \cdot CRAT \cdot AREA_{eff}$ $CGD_{eff} = GCAP \cdot (1\text{-}CRAT) \cdot AREA_{eff}$
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
PB	V	0.8	Gate junction potential
TT	s	0	Transit time – use option METHOD=GEAR when using transit time for JFET and MESFET

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

Table 34 provides information about DC model `LEVEL=1` parameters.

Table 34 DC Model LEVEL=1 Parameters

Name (Alias)	Units	Default	Description
LEVEL		1.0	LEVEL=1 invokes the SPICE JFET model
BETA	amp/ V^2	1.0e-4	Transconductance parameter, gain $BETAeff = BETA \cdot \frac{Weff \cdot M}{Leff}$
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 the internal calculation. A negative VTO is a depletion transistor, regardless of NJF or PJF. A positive VTO is always an enhancement transistor.

Table 35 provides information about DC model `LEVEL=2` parameters.

Table 35 DC Model LEVEL=2 Parameters

Name (Alias)	Units	Default	Description
LEVEL		1.0	Level of FET DC model. LEVEL=2 is a modification of the SPICE model for gate modulation of LAMBDA.
BETA	amp /V^2	1.0e-4	Transconductance parameter, gain $BETAeff = BETA \cdot \frac{Weff \cdot M}{Leff}$
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)
NG		0.0	Gate subthreshold factor (typical value=1)

Table 35 DC Model LEVEL=2 Parameters (Continued)

Name (Alias)	Units	Default	Description
VTO	V	-2.0	Threshold voltage. When set, VTO overrides the internal calculation. A negative VTO is a depletion transistor, regardless of NJF or PJF. A positive VTO is always an enhancement transistor.

Table 36 provides information about DC model level 3 parameters.

Table 36 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	0.5m	Active layer thickness: $A_{eff} = A \cdot$ SCALM
ALPHA	1/V	2.0	Saturation factor
BETA	amp /V ^{2}	1.0e-4	Transconductance parameter, gain $BETAeff = BETA \cdot \frac{Weff \cdot M}{Leff}$
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)

Table 36 DC Model LEVEL=3 Parameters (Continued)

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			Pinch-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

Use the `ACM` model parameter to select between traditional SPICE unitless gate area calculations and the newer style of area calculations.

- The `ACM=0` method (SPICE) uses the ratio of W/L to keep `AREA` unitless.
- The `ACM=1` (HSPICE) model requires that parameters (such as `IS`, `CGS`, `CGD`, and `BETA`) have proper physics-based units.

In the following equations, *m* indicates the element multiplier.

ACM=0

SPICE model, parameters determined by element areas.

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

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

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

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

ACM=1

`ASPEC` model, parameters function of element width.

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

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

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:

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

ACM=2

HSPICE model, combination of `ACM=0,1` and provisions for lightly doped drain technology.

ACM=3

Extends `ACM=2` model to deal with stacked devices (shared source/drains) and source/drain periphery capacitance along a gate edge.

Resulting calculations:

$$ISeff = IS \cdot AREAeff$$

$$CGSeff = CGS \cdot AREAeff$$

$$CGDeff = CGD \cdot AREAeff$$

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

Note: The model parameter units for `IS`, `CGS`, and `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:

$vgd < FC \cdot PB$

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

$vgs < FC \cdot PB$

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

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 (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` · CGD_{eff} or `FC` · CGS_{eff} 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`.

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

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

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

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

The following equations calculate values for the preceding equations:

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

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

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

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

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

`CGD` - CGD_{eff}

`CGS` - CGS_{eff}

Gate Capacitance CAPOP=2

Statz capacitance equations[3] (`CAPOP=1`) contain mathematical behavior that might 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`.
- `Cgd` properly goes to a small constant representing a sidewall capacitance. However, as `Vgs` decreases, the `Cgs` curve drops along an asymptote line to zero.
- (For the behavior for `Vds`<0, interchange `Cgs` and `Cgd` and replace `Vds` with `-Vds` in the preceding descriptions.)
- It may 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=1` implementation 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.

`CAPOP=2` capacitance equations help to solve the previously-described problems.

Parameter	Default	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)

Figure 20 and Figure 21 on page 135 show comparisons of `CAPOP=1` and `CAPOP=2`. In Figure 20 on page 134, below the (-0.6 v) threshold, Cgs for `CAPOP=2` drops towards the same value as Cgd, while for `CAPOP=1`, `CGS` →0.

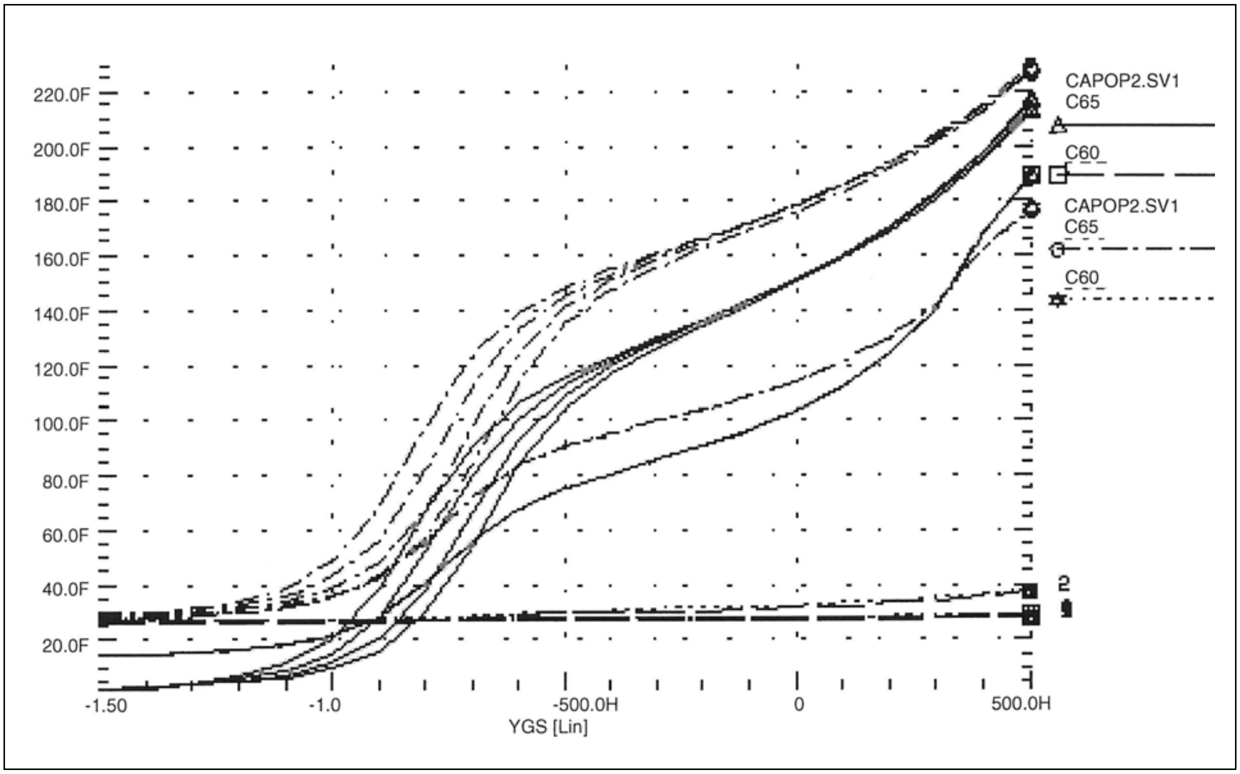


Figure 20 CAPOP=1 vs. CAPOP=2. Cgs, Cgd vs. Vgs for Vds=0, 1, 2, 3, 4

In Figure 21 on page 135, the Cgs-Cgd characteristic curve “flips over” below the threshold for `CAPOP=1`, whereas for `CAPOP=2`, it is does not.

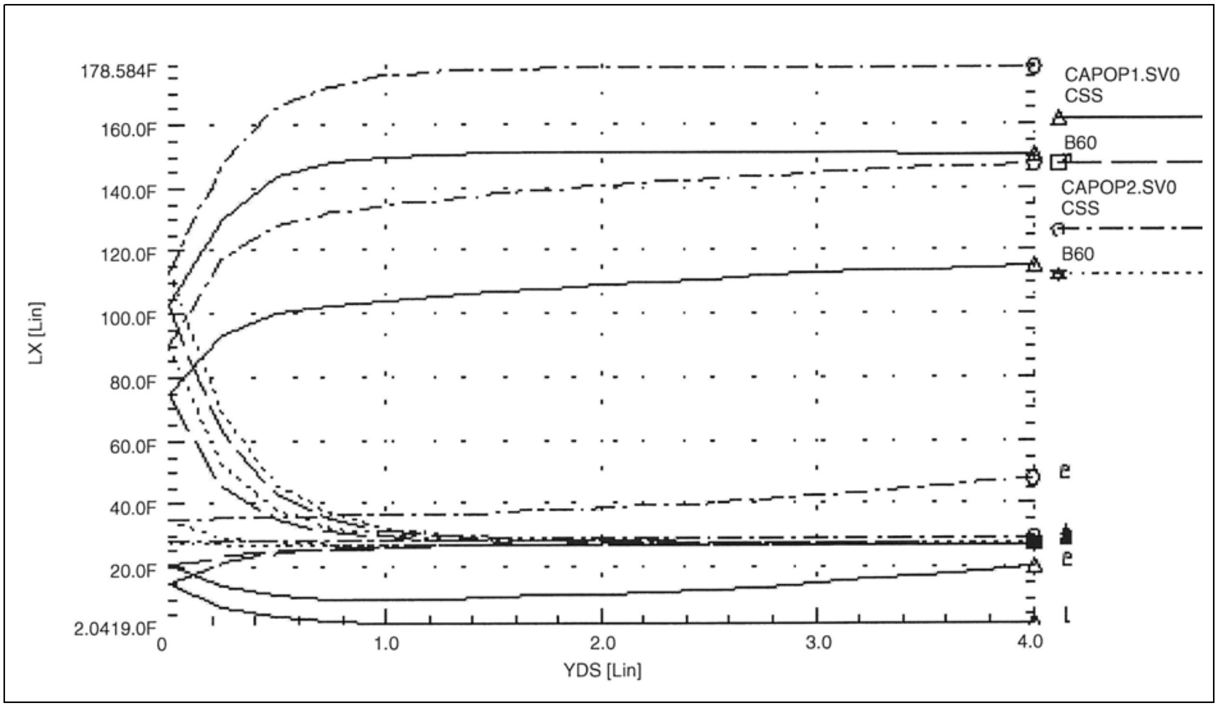


Figure 21 CAPOP=1 vs. CAPOP=2. Cgs, Cgd vs. Vds for Vgs=-1.5, -1.0, -0.5, 0

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 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` may 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 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 equations:

vds>0   Forward region

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

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

$$VTO = VP + VBI$$

then:

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

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

vgst<0 Channel pinched off

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

vgst>0, SAT=0 On region

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

$$idsubthreshold(NG, ND, vds, vgs)$$

vgst>0, SAT=1 On region

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

$$idsubthreshold(NG, ND, vds, vgs)$$

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

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

$$idsubthreshold(NG, ND, vds, vgs)$$

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 from the N0 and ND model parameters

JFET and MESFET Noise Models

Name (Alias)	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

Figure 19 on page 119 shows the JFET noise model. Thermal noise generation in the drain and source regions (`RD` and `RS` resistances) is modeled by the two current sources, `inrd` and `inrs`. The `inrd` and `inrs` units 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:

$$ind = channelthermalnoise + flickernoise$$

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

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

The previous formula, used in both saturation and linear regions, might lead to wrong results in the linear region. For example, at `VDS=0`, channel thermal noise is 0, because `gm=0`. This is physically impossible. If you set the `NLEV` parameter to 3, simulation uses an equation that is valid in both linear and saturation regions.[4]

For NLEV = 3

Linear Region:

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

$$\alpha = 1 - \frac{vds}{vgs - VTO}$$

Saturation Region:

$$channelthermalnoise = \left(\frac{8kt}{3} \cdot BETAeff \cdot (vgs - VTO) \cdot GDSNOI\right)$$

The flicker noise is calculated as:

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

Parameter	Description
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

JFET and MESFET Temperature Equations

Table 37 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` is either 0, 1, or 2 while `TLEVC` is either 0, 1, 2, or 3.

Table 37 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

Table 38 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

Table 38 Temperature Effect Parameters (Continued)

Name (Alias)	Units	Default	Description
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
GAP2	x	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
XTI		0.0	Saturation current temperature exponent XTI=3 for silicon diffused junction or XTI=2 for Schottky barrier diode

Temperature Compensation Equations

The following subsections described various types of temperature equations for JFET/MESFET models.

Energy Gap Temperature Equations

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

TLEV = 0 or 1

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

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

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

Temperature equations calculate the gate capacitances. The `CTS` and `CTD` parameters are the linear coefficients. If you set `TLEVC` to zero, simulation uses these equations. To achieve a zero capacitance variation, set the coefficients to a very small value (such as 1e-6), and set `TLEVC=1` or `2`.

TLEVC = 0

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

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

The next equation calculates values for the preceding equations:

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

TLEVC = 1

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

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

The next equation calculates values for the preceding equations:

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

TLEVC = 2

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

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

The next equation calculates values for the preceding equations:

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

TLEVC = 3

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

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

The next equation calculates values for the preceding equations:

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

TLEV = 0 or 1

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

TLEV = 2

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

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:

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

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 equations:

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

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

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

TriQuint (TOM) Extensions to LEVEL=3

TOM “TriQuint’s Own Model”[5] is implemented as part of the existing GaAs `LEVEL=3` model.[6] It has 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 `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	Printout Name	Note
Q	VGEXP	
GAMMA	GAMDS	sign opposite of TriQuint’s original
VTOTC	TCV	sign opposite of TriQuint’s original
TRG1	TRG	
TRD1	TRD	
TRS1	TRS	

Table 39 TOM Model Parameters

Name (Alias)	Description
BETATCE	Temperature coefficient for beta. If BETATCE is set to a nonzero value: $BETA(temp) = BETA(tnom) \cdot 1.01^{(BETATCE \cdot (temp - tnom))}$ The more common beta temperature update is: $BETA(temp) = BETA(tnom) \cdot \left(\frac{temp}{tnom}\right)^{BEX}$
DELTA	Ids feedback parameter of the TOM model. This parameter is not used if its value is zero. DELTA may 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: $CAPDSeff = CAPDS \cdot \frac{Weff}{Leff} \cdot M$

In the original TriQuint TOM implementation, `LAMBDA` and `UCRIT` parameters do not exist. Therefore, they must remain zero (their default value) in `LEVEL=3` to reproduce the TOM model. Using non-zero values for these parameters with nonzero `BETATCE`, `DELTA`, or `CAPDS`, results in a hybrid model.

LEVEL=7 TOM3 (TriQuint's Own Model III)

TOM3 (TriQuint's Own Model III) is available as the JFET/MESFET `LEVEL=7` device model. TriQuint developed it to improve the accuracy of capacitance equations by using quasi-static charge conservation in the implanted layer of a MESFET.

Using the TOM3 Model

Follow these steps to use the TOM3 model:

1. Set `LEVEL=7` to identify the model as TOM3.
2. The default room temperature is 25 in HSPICE, but is 27 in most other simulators. When comparing to other simulators, set the simulation temperature to 27 by using either `.TEMP 27` or `.OPTION TNOM=27`.

3. The set of model parameters must include the model reference temperature, `TNOM`, which corresponds to `TREF` in other levels in the JFET/ MESFET device models. The default for `TR` is 25.
4. TOM3 has its own charge-based capacitance model so it ignores the capacitance model set in the `CAPOP` parameter.
5. The model uses analytical derivatives for conductances. This model ignores the DERIV parameter, which selects the finite difference method.
6. You can use `DTEMP` with this model. `DTEMP` increases the temperature of individual elements, relative to the circuit temperature. Set `DTEMP` on the element line.
7. The general syntax for this element is the same as the other standard JFET/ MESFET models.
8. The model is defined by a specific sub-circuit, and a set of device equations. The topology uses local feedback, decreasing the DC output conductance to model drain, model dispersion, and self-heating effects.

   Note: For more informations, refer to "TOM3 Equations, Revised: 2 December 1999" by Robert B. Hallgren and David S. Smith.

Model Description

This section describes the DC and Capacitance equations for the HSPICE `LEVEL=7` JFET model.

DC Equations

The DC equations for the HSPICE `LEVEL=7` JFET model are:

Drain to Source Current (I_{DS})

$$I_{DS} = I_O \cdot (1 + LAMBDA \cdot V_{DS})$$

$$I_O = \beta \cdot V_G^Q \cdot f_K$$

$$f_K = \frac{\alpha \cdot V_{DS}}{[1 + (\alpha \cdot V_{DS})^K]^{1,1/\mathrm{K}}}$$

$$V_G = Q \cdot V_{ST} \cdot \log[\exp(u) + 1]$$

$$u = \frac{V_{GS} - V_{TO} + \gamma \cdot V_{DS}}{Q \cdot V_{ST}}$$

$$V_{ST} = V_{STO} \cdot (1 + M_{STO} \cdot V_{DS})$$

Transconductance

$$G_M = \left(\frac{Q \cdot \beta \cdot f_K \cdot V_G^{Q-1}}{1 + \exp(-u)}\right) \cdot (1 + LAMBDA \cdot V_{DS})$$

Output Conductance

$$G_{DS} = LAMBDA \cdot I_0 + G_M \cdot \gamma - \left(\frac{(V_{GS} - V_{TO} + \gamma \cdot V_{DS}) \cdot M_{ST0}}{1 + M_{ST0} \cdot V_{DS}}\right)$$

$$\left[\left(\frac{Q \cdot I_0 \cdot M_{ST0}}{1 + M_{ST0} \cdot V_{DS}}\right) + \left(\frac{\alpha \cdot \beta \cdot V_G^Q}{[1 + (\alpha \cdot V_{DS})^K]^{1+1/K}}\right)\right] \cdot (1 + LAMBDA \cdot V_{DS})$$

Gate Leakage Diode Current

`ILK` and `PLK` have no temperature dependence.

$$I_{LS} = ILK \cdot \left(1 - \exp\frac{-V_{GS}}{PLK}\right)$$

$$G_{LS} = \left(\frac{ILK}{PLK}\right) \cdot \left(\exp\frac{-V_{GS}}{PLK}\right)$$

$$I_{LD} = ILK \cdot \left(1 - \exp\frac{-V_{GD}}{PLK}\right)$$

$$G_{LD} = \left(\frac{ILK}{PLK}\right) \cdot \left(\exp\frac{-V_{GD}}{PLK}\right)$$

Temperature and Geometry Dependence

$$\beta = AREA \cdot BETA \cdot 1.01^{BETATCE \cdot (T - T_{NOM})}$$

$$\alpha = ALPHA \cdot 1.01^{ALPHATCE \cdot (T - T_{NOM})}$$

$$V_{TO} = VTO + VTOC \cdot (T - T_{NOM})$$

$$\gamma = GAMMA + GAMMATC \cdot (T - T_{NOM})$$

$$V_{ST0} = VST + VSTTC \cdot (T - T_{NOM})$$

$$V_{MT0} = MST + MSTTC \cdot (T - T_{NOM})$$

Capacitance Equations

The capacitance equations for the HSPICE `LEVEL=7` JFET model are:

Combined Gate Charge

$$Q_{GG} = Q_{GL} \cdot f_T + Q_{GH} \cdot (1 - f_T) + QGG0 \cdot (V_{GSI} + V_{GDI})$$

$$C_{GS} = C_{GSL} \cdot f_T + C_{GSH} \cdot (1 - f_T) + (Q_{GL} - Q_{GH}) \cdot \frac{\partial f_T}{\partial V_{GSI}} + QGG0$$

$$C_{GD} = C_{GDL} \cdot f_T + C_{GDH} \cdot (1 - f_T) + (Q_{GL} - Q_{GH}) \cdot \frac{\partial f_T}{\partial V_{GDI}} + QGG0$$

$$f_T = \exp(-QGGB \cdot I_{DS} \cdot V_{DS})$$

$$\frac{\partial f_T}{\partial V_{GDI}} = -QGGB \cdot [I_{DS} + (g_m + g_{ds}) \cdot V_{DS}] \cdot f_T$$

$$\frac{\partial f_T}{\partial V_{GD}} = -QGGB \cdot [I_{DS} + g_{ds} \cdot V_{DS}] \cdot f_T$$

Lower Power Gate Charge

$$Q_{GL} = qgI + QGCL \cdot (V_{GS} + V_{GD})$$

$$qgl = QGQL \cdot \exp[QGAG \cdot (V_{GS} + V_{GD})] \cdot \cosh(QGAD \cdot V_{DS})$$

$$C_{GSL} = qgl \cdot [QGAG + QGAD \cdot \tanh(QGAD \cdot V_{DS})] + QGCL$$

$$C_{GDL} = qgl \cdot [QGAG + QGAD \cdot \tanh(QGAD \cdot V_{DS})] + QGCL$$

High Power Gate Charge

$$Q_{GH} = QGQH \cdot \log\left(1 + \frac{I_{DS}}{QGI0}\right) + QGSH \cdot V_{GS} + QGDH \cdot V_{GD}$$

$$C_{GSH} = (G_M + G_{DS}) \cdot \left(\frac{QGQH}{I_{DS} + QGI0}\right) + QGSH$$

$$C_{GDH} = G_{DS} \cdot \left(\frac{QGQH}{I_{DS} + QGI0}\right) + QGDH$$

Table 40 TOM3 Parameters

Name (Alias)	Units	Default	Description
LEVEL	-	1	Model Index (7 for TOM3)
TNOM		25	Reference temperature
AF	-	1	Flicker noise exponent
ALPHA	1/V	2	Saturation factor
ALPHATCE	K-1	0	Alpha temperature coefficient (exponential)
BETA	A/V-Q	0.1	Transconductance parameter
BETATCE	K-1	0	Linear temperature coefficient for beta
CDS	F	1E-12	Drain to source capacitance
CGDTCE	K-1	0	Linear temperature coefficient for CGD
CGSTCE	K-1	0	Linear temperature coefficient for CGS
EG	V	1.11	Barrier height at 0K(used for capacitance model)
GAMMA	-	0	Drain voltage-induced threshold voltage lowering coefficient
GAMMATC	K-1	0	Linear temperature coefficient for GAMMA
ILK	A	0	Leakage diode current parameter
IS	A	1E-14	Forward gate diode saturation current
K	-	2	Knee-function parameter
KF	-	0	Flicker noise coefficient
LAMBDA	1/V	0	Channel length modulation parameter
MST	V-1	0	Sub-threshold slope – drain parameter
MSTTC	V^{-1}K-1	0	Linear temperature coefficient for MST

Table 40 TOM3 Parameters (Continued)

Name (Alias)	Units	Default	Description
N	-	1	Forward gate diode ideality factor
PLK	V	1	Leakage diode potential parameter
Q	-	2	Parameter Q to model non-square-law of drain current
QGAD	V-1	1	Charge parameter
QGAG	V-1	1	Charge parameter
QGCL	F	2E-16	Charge parameter
QGDH	F	0	Sidewall capacitance
QGG0	F	0	Charge parameter
QGGB	$A^{-1}V^{-1}$	100	Charge parameter
QGI0	A	1E-6	Charge parameter
QGQH	FV	-2E-16	Charge parameter
QGQL	FV	5E-16	Charge parameter
QGSH	F	1E-16	Sidewall capacitance
VBI	V	1	Gate diode built-in potential
VBITC	VK-1	0	Linear temperature coefficient for VBI
VST	V	1	Sub-threshold slope
VSTTC	VK-1	0	Linear temperature coefficient of VST
VTO	V	-2	Threshold voltage
VTOTC	V/K	0	Threshold voltage temperature coefficient
XTI	-	0	Diode saturation current temperature coefficient

LEVEL=8 Materka Model

This section describes the JFET/MESFET `LEVEL=8` device model.

For more information about this model, see Compact dc Model of GaAs FETs for Large-Signal Computer Calculation, *IEEE Journal of Solid-State Circuits*, Vol, SC-18, No.2, April 1983, and Computer Calculation of Large-Signal GaAs FET Amplifier Characteristics, *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-33, No. 2, February 1985.

Using the Materka Model

Follow these steps to use the Materka model:

1. Set `LEVEL=8`.
2. The default room temperature is 25 in HSPICE, but is 27 in most other simulators. When comparing to other simulators, set the simulation temperature to 27 by using either `.TEMP 27` or `.OPTION TNOM=27`.
3. The model has its own charge-based capacitance model. This model ignores the `CAPOP` parameter, which selects difference capacitance.
4. The `ACM` parameter is not supported.

DC Model

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \tanh\left(\frac{\alpha 1 * V_{DS}}{V_{GS} - V_P}\right)$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = I_{DSS}\left[-\frac{2}{V_P}\left(1 - \frac{V_{GS}}{V_P}\right) \cdot \tanh\left(\frac{\alpha 1 \cdot V_{DS}}{V_{GS} - V_P}\right)\right.$$

$$\left.\left(1 - \frac{V_{GS}{}^2}{V_P}\right) \cdot \operatorname{sech}^2\left(\frac{\alpha 1 \cdot V_{DS}}{V_{GS} - V_P}\right) \cdot \frac{-\alpha 1 \cdot V_{DS}}{V_{GS} - V_P{}^2}\right]$$

$$g_{DS} = \frac{\partial I_D}{\partial V_{DS}} = I_{DSS} \cdot \left(1 - \frac{V_{GS}}{V_P}\right) \cdot \left[-\frac{2\gamma V_{GS}}{V_P{}^2} \cdot \tanh\left(\frac{\alpha 1 \cdot V_{DS}}{V_{GS} - V_P}\right)\right.$$

$$\left(1-\frac{V_{GS}}{V_P}\right)\cdot\ \ \sec h^2\left(\frac{\alpha 1\cdot\ \ V_{DS}}{V_{GS}-V_P}\right)\cdot\ \ \frac{\alpha 1\cdot\ \ (V_{GS}-V_{PO})}{(V_{GS}-V_P)^2}\Bigg]$$

$$V_P\ =\ V_{TO}+\gamma\,V_{DS}$$

Table 41 DC Model Parameters

Name (Alias)	Units	Default	Description
LEVEL		1.0	LEVEL=8 is the Materka MESFET model.
ALPHA1			Empirical constant
GAMMA	1/V	0.0	Voltage slope parameter of pinch-off voltage
IDSS	A	0.1	Drain saturation current for Vgs=0
VP	V		Pinch-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.

Gate Capacitance Model

$$C_{GS}\ =\ \frac{CGS}{\sqrt[4]{1-\dfrac{vnew}{PB}}}\left[1+\frac{veff-vte}{\sqrt{(veff-vte)^2+(0.2)^2}}\right]\cdot\ \left[1+\frac{vds}{\sqrt{vds^2+\left(\dfrac{1}{ALPHA1}\right)^2}}\right]$$

$$\left[\frac{CGD}{2}\left(1-\frac{vds}{\sqrt{vds^2+\left(\dfrac{1}{ALPHA1}\right)^2}}\right)\right]$$

$$C_{GD} = \frac{CGS}{\sqrt[4]{1 - \frac{vnew}{PB}}}\left[1 + \frac{veff - vte}{\sqrt{(veff - vte)^2 + (0.2)^2}}\right] \cdot \left[1 - \frac{vds}{\sqrt{vds^2 + \left(\frac{1}{ALPHA1}\right)^2}}\right]$$

$$\left[\frac{CGD}{2}\left(1 + \frac{vds}{\sqrt{vds^2 + \left(\frac{1}{ALPHA1}\right)^2}}\right)\right]$$

$$vte = VTO + GAMMA \cdot \ vds = effective \text{ threshold}$$

$$veff = \frac{1}{2}\left[vgs + vgd + \sqrt{vds^2 + \left(\frac{1}{ALPHA1}\right)^2}\right]$$

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

Table 42 Gate Capacitance Model Parameters

Name (Alias)	Units	Default	Description
CGS	F	0.0	Zero-bias gate-source junction capacitance
CGD	F	0.0	Zero-bias gate-drain junction capacitance
PB	V	0.8	Gate Junction Potential
N		1.0	Emission coefficient for gate-drain and gate-source diodes

Noise Model

Two current sources model the thermal noise generation in the drain and source regions (`RD` and `RS` resistances):

- `inrd`
- `inrs`

`inrd` and `inrs` are modeled by:

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

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

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

`ind` = channel thermal noise+ flicker noise

$$channel\ \text{thermal noise} = \left(\frac{8kt \cdot g_m}{3}\right)^{1/2}$$

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

Table 43 Noise Model 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 V2 F.

Example

```
.MODEL  NCH   NJF   LEVEL =8
+ IDSS = 69.8e-3   VTO = -2  GAMMA = 0
+ ALPHA1 = 1   RS = 0   RD = 0
+ CGS = 1e-15   CGD = 2e-16   PB  = 0.8
+ IS = 5e-16   AF = 1   KF  = 0
+ FC = 0.5
.END
```

References

[1] GaAs FET Device and Circuit Simulation in SPICE, *IEEE Transactions on Electron Devices*, Vol. ED-34.

[2] A MESFET Model for Use in the Design of GaAs Integrated Circuits, *IEEE Transactions on Microwave Theory*, Vol. MTT-28 No. 5.

[3] H. Statz, P.Newman, I.W.Smith, R.A. Pucel, and H.A. Haus, *GaAs FET Device and Circuit Simulation in Spice*.

[4] Tsivids, Yanis P., *Operation and Modeling of the MOS Transistor*, McGraw-Hill, 1987, p. 340.

[5] A.J. McCamant, G.D. Mc Cormack, and D.H.Smith, *An Improved GaAs MESFET Model for SPICE*, IEEE.

[6] 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 Circuit Simulation in SPICE”.

5

BJT Models

Describes how to use BJT models in HSPICE circuit simulations.

HSPICE ships hundreds of examples for your use; see Listing of Demonstration Input Files for paths to demo files.

The bipolar-junction transistor (BJT) model is an adaptation of the integral charge control model of Gummel and Poon.The HSPICE BJT model extends the original Gummel-Poon model to include several effects at high bias levels. This model automatically simplifies to the Ebers-Moll model if you do not specify the `VAF`, `VAR`, `IKF`, and `IKR` parameters.

These topics are discussed in the following sections:

- LEVEL=6 Philips Bipolar Model (MEXTRAM Level 503)
- LEVEL=8 HICUM Model
- HICUM Model Advantages
- LEVEL=9 VBIC99 Model
- LEVEL=9 Model Parameters
- LEVEL=10 Philips MODELLA Bipolar Model
- LEVEL=11 UCSD HBT Model
- LEVEL=13 HICUM/L0 Model

Overview of BJT Models

You can use the BJT model to develop BiCMOS, TTL, and ECL circuits.

Note: To modify high-injection effects for BiCMOS devices, use the `IKF` and `IKR` high-current Beta degradation parameters.

The `SUBS` model parameter facilitates the modeling of both vertical and lateral geometrics.

For a listing of output templates for BJT models see Element Template Listings (HSPICE Only), Table 44, in the *HSPICE User Guide: Basic Simulation and Analysis*.

The following topics are discussed in these sections:

- Selecting Models
- BJT Model Statement
- BJT Basic Model Parameters
- BJT Model Temperature Effects
- BJT Device Equivalent Circuits
- BJT Current Conventions
- BJT Equivalent Circuits

Selecting Models

To select a BJT device, use a BJT element and model statement. The element statement uses the name of the simulation device model to reference the model statement. The following example uses the reference name MOD1. This example uses an NPN model type to describe an NPN transistor.

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

You can specify parameters in both element and model statements. If you specify the same parameter in both an element and a model, then the element parameter (local to the specific instance of the model) always overrides the model parameter (global default for all instances of the model, if you did not define the parameter locally). The model statement specifies the type of device—for example, for a BJT, the device type might be NPN or PNP.

BJT Control Options

The following control options affect the BJT model:

DCAP	Selects the equation that determines the BJT capacitances
DCCAP	Invokes capacitance calculations in DC analysis
GRAMP GMIN GMINDC	Place a conductance in parallel with both the base-emitter and the base-collector pn junctions

You can override global depletion capacitance equation selection that uses the `.OPTION DCAP=<val>` statement in a BJT model by including `DCAP=<val>` in the BJTs `.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.

BJT Model Statement

You can use the `.MODEL` statement to include a BJT model in your HSPICE netlist. For a general description of the `.MODEL` statement, see the *HSPICE Command Reference*.

Syntax

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

Parameter	Description
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
+ BR =40.00000  IS = 1.6339e-14  VAF=103.40529
+ VAR=17.77498  IKF= 1.00000
+ 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 model parameters have aliases, which are included in the model parameter list in BJT Basic Model Parameters on page 160. The new name is always used on printouts, even if the model statement uses an alias.

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

Bypassing Latent Devices (HSPICE Only)

Use the `BYPASS` (latency) option to decrease simulation time in large designs. To speed simulation time, this option does not recalculate currents, capacitances, and conductances, if the voltages at the terminal device nodes have not changed. The `BYPASS` option applies to MOSFETs, MESFETs, JFETs, BJTs, and diodes. Use `.OPTION BYPASS` to set `BYPASS`.

`BYPASS` might reduce simulation accuracy for tightly-coupled circuits such as op-amps, high gain ring oscillators, and so on. Use `.OPTION MBYPASS` to set `MBYPASS` to a smaller value for more-accurate results.

Parameters

Transient model parameters for BJTs are composed of two groups: junction capacitor parameters and transit time parameters.

- `CJE`, `VJE`, and `MJE` model the base-emitter junction.
- `CJC`, `VJC`, and `MJC` model base-collector junction capacitance.
- `CJS`, `VJS`, and `MJS` model the collector-substrate junction capacitance.

`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`. To select from several sets of temperature equations for the BJT model parameters, set `TLEV` and `TLEVC`.

Table 44 BJT Model Parameters

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

Table 45 DC Parameters for BJT Models

Name (Alias)	Unit	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.
EXPLI	amp	0	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. $EXPLI_{eff} = EXPLI \cdot AREA_{eff}$
IBC	amp	0.0	Reverse saturation current between base and collector. If you specify both IBE and IBC, simulation uses them in place of IS to calculate DC current and conductance; otherwise, the simulator uses IS. $IBC_{eff} = IBC \cdot AREAB \cdot M$ AREAC replaces AREAB, depending on vertical or lateral geometry.

Table 45 DC Parameters for BJT Models (Continued)

Name (Alias)	Unit	Default	Description
IBE	amp	0.0	Reverse saturation current between base and emitter. If you specify both IBE and IBC, simulation uses them in place of IS to calculate DC current and conductance; otherwise, the simulator uses IS. $IBE_{eff} = IBE \cdot AREA \cdot M$
IS	amp	1.0e-16	Transport saturation current. If you specify both IBE and IBC, simulation uses them in place of IS to calculate DC current and conductance; otherwise, simulation uses IS. $IS_{eff} = IS \cdot AREA \cdot M$
ISS	amp	0.0	Reverse saturation current bulk-to-collector or bulk-to-base, depending on vertical or lateral geometry selection. $SS_{eff} = ISS \cdot AREA \cdot M$
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 uses alternate base charge equation.

Table 46 Low-Current Beta Degradation Parameters

Name (Alias)	Unit	Default	Description
ISC (C4, JLC)	amp	0.0	Base-collector leakage saturation current. If ISC is greater than 1e-4, then: $ISC = IS \cdot ISC$ otherwise: $ISC_{eff} = ISC \cdot AREAB \cdot M$ 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: $ISE_{eff} = ISE \cdot AREA \cdot M$
NC (NLC)		2.0	Base-collector leakage emission coefficient.
NE (NLE)		1.5	Base-emitter leakage emission coefficient.

Table 47 Base Width Modulation Parameters

Name (Alias)	Unit	Default	Description
VAF (VA, VBF)	V	0.0	Forward early voltage. Zero=infinite value.
VAR (VB, VRB, BV)	V	0.0	Reverse early voltage. Zero=infinite value.

Table 48 High-Current Beta Degradation Parameters

Name (Alias)	Unit	Default	Description
IKF (IK, JBF)	amp	0.0	Corner for forward Beta high-current roll-off. Use zero to indicate an infinite value. $IKF_{eff} = IKF \cdot AREA \cdot M$

Table 48 High-Current Beta Degradation Parameters (Continued)

Name (Alias)	Unit	Default	Description
IKR (JBR)	amp	0.0	Corner for reverse Beta high-current roll-off. Use zero to indicate an infinite value. $IKR_{eff} = IKR \cdot AREA \cdot M$
NKF		0.5	Exponent for high-current Beta roll-off.

Table 49 Parasitic Resistance Parameters

Name (Alias)	Unit	Default	Description
IRB (JRB, IOB)	amp	0.0	Base current, where base resistance falls half-way to RBM. Use zero to indicate an infinite value. $IRB_{eff} = IRB \cdot AREA \cdot M$
RB	ohm	0.0	Base resistance: $RB_{eff} = RB / (AREA \cdot M)$
RBM	ohm	RB	Minimum high-current base resistance: $RBM_{eff} = RBM / (AREA \cdot M)$
RE	ohm	0.0	Emitter resistance: $RE_{eff} = RE / (AREA \cdot M)$
RC	ohm	0.0	Collector resistance: $RC_{eff} = RC / (AREA \cdot M)$

Table 50 Junction Capacitor Parameters

Name (Alias)	Unit	Default	Description
CJC	F	0.0	Base-collector zero-bias depletion capacitance ■ Vertical: $CJC_{eff} = CJC \cdot AREAB \cdot M$ ■ Lateral: $CJC_{eff} = CJC \cdot AREAC \cdot M$ if you specify a value other than zero for ibc and ibe.
CJE	F	0.0	Base-emitter zero-bias depletion capacitance (vertical and lateral): $CJE_{eff} = CJE \cdot AREA \cdot M$

Table 50 Junction Capacitor Parameters (Continued)

Name (Alias)	Unit	Default	Description
CJS (CCS, CSUB)	F	0.0	Zero-bias collector substrate capacitance ■ Vertical: $CJS_{eff} = CJS \cdot AREAC \cdot M$ ■ Lateral: $CJS_{eff} = CJS \cdot AREAB \cdot M$ If you specify a value other than zero for ibc and ibe.
FC		0.5	Coefficient for forward bias depletion capacitance formula for DCAP=1 DCAP Default=2 and FC are 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.

Table 51 Parasitic Capacitances Parameters

Name (Alias)	Unit	Default	Description
CBCP	F	0.0	External base-collector constant capacitance: $CBCP_{eff} = CBCP \cdot AREA \cdot M$
CBEP	F	0.0	External base-emitter constant capacitance: $CBEP_{eff} = CBEP \cdot AREA \cdot M$
CCSP	F	0.0	External collector substrate constant capacitance (vertical) or base substrate (lateral): $CCSP_{eff} = CCSP \cdot AREA \cdot M$

Table 52 Transit Time Parameters

Name (Alias)	Unit	Default	Description
ITF (JTF)	amp	0.0	TF high-current parameter: $ITF_{eff} = ITF \cdot AREA \cdot M$
PTF	x	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. Zero indicates an infinite value.
XTF		0.0	TF bias dependence coefficient.

Table 53 Noise Parameters

Name (Alias)	Unit	Default	Description
AF		1.0	Flicker-noise exponent.
KF		0.0	Flicker-noise coefficient.

Table 54 LEVEL=2 Parameters

Name (Alias)	Unit	Default	Description
BRS		1.0	Reverse beta for substrate BJT.
GAMMA		0.0	Epitaxial doping factor: $GAMMA = (2 \cdot ni / n)2$ In this equation, *n* is epitaxial impurity concentration.
NEPI		1.0	Emission coefficient.

Table 54 LEVEL=2 Parameters (Continued)

Name (Alias)	Unit	Default	Description
QCO	Coul	0.0	Epitaxial charge factor: ▪ Vertical: $QCO_{eff} = QCO \cdot AREAB \cdot M$ ▪ Lateral: $QCO_{eff} = QCO \cdot AREAC \cdot M$ if you specify a value other than zero for ibc and ibe.
RCO (RC)	ohm	0.0	Resistance of epitaxial region under equilibrium conditions: $RC_{eff} = RC/(AREA \cdot M)$
RCC	ohm	0.0	Collector resistance
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 55 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

Table 55 BJT Temperature Parameters (Continued)

Function	Parameter
transit time	TTF1, TTF2, TTR1, TTR2

Table 56 Temperature Effect Parameters

Name (Alias)	Unit	Default	Description
BEX		2.42	VO temperature exponent (LEVEL=2 only).
BEXV		1.90	RC temperature exponent (LEVEL=2 only).
CTC	1/×	0.0	Temperature coefficient for zero-bias base collector capacitance. TLEVC=1 enables CTC to override the default temperature compensation.
CTE	1/×	0.0	Temperature coefficient for zero-bias base emitter capacitance. TLEVC=1 enables CTE to override the default temperature compensation.
CTS	1/×	0.0	Temperature coefficient for zero-bias substrate capacitance. TLEVC=1 enables CTS to override the default temperature compensation.
EG	eV		Energy gap for pn junction diode 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
GAP2	x	1108	Second bandgap correction factor (Sze, beta term): ■ 1108 - silicon ■ 636 - silicon ■ 210 - germanium ■ 204 - gallium arsenide
MJC(MC)		0.33	Base-collector junction exponent (grading factor).

Table 56 Temperature Effect Parameters (Continued)

Name (Alias)	Unit	Default	Description
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.
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.

Table 56 Temperature Effect Parameters (Continued)

Name (Alias)	Unit	Default	Description
TITF1			First-order temperature coefficient for ITF.
TITF2			Second-order temperature coefficient for ITF.
TLEV		0.0	Temperature equation level selector for BJTs (interacts with TLEVC).
TLEVC		0.0	Temperature equation level selector: 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.
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.

Table 56 Temperature Effect Parameters (Continued)

Name (Alias)	Unit	Default	Description
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	Firs-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.
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	VJC temperature coefficient. TVJC uses TLEVC= 1 or 2 to override default temperature compensation.
TVJE	V/×	0.0	VJE temperature coefficient. TVJE uses TLEVC= 1 or 2 to override default temperature compensation.
TVJS	V/×	0.0	VJS temperature coefficient. TVJS uses TLEVC= 1 or 2 to override default temperature compensation.
XTB(TBTCB)		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.

BJT Device Equivalent Circuits

This section describes BJT scaling, current conventions, and equivalent circuits.

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 following formula scales the DC model parameters (IBE, IS, ISE, IKF, IKR, and IRB) for both vertical and lateral BJT transistors:

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

In the preceding equation, I can be 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.

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

In the preceding equation, *R* can be RB, RBM, RE, or RC.

BJT Current Conventions

The example in Figure 22 on page 174 assumes the direction of current flow through the BJT. 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.
- I4(Q1) refers to the substrate current.

  Note: The above terminal currents account both DC and charge induced currents.

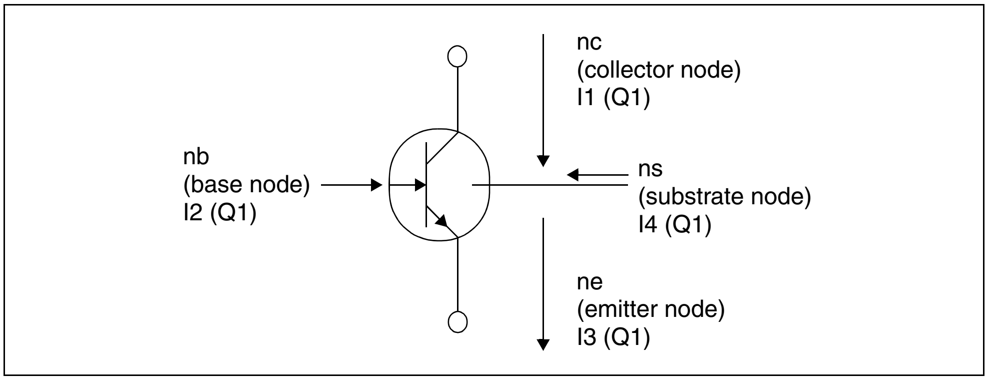


Figure 22 BJT Current Convention

BJT Equivalent Circuits

IC circuit simulation uses four equivalent circuits to analyze BJTs: DC, transient, AC, and AC noise circuits. The components of these circuits form the basis for all element and model equations. Because these circuits represent the entire BJT during simulation, 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. Instead, the partial derivatives of `ib` and `ic` with respect to the terminal voltages `vbe` and `vbc` are used. 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

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

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

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

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

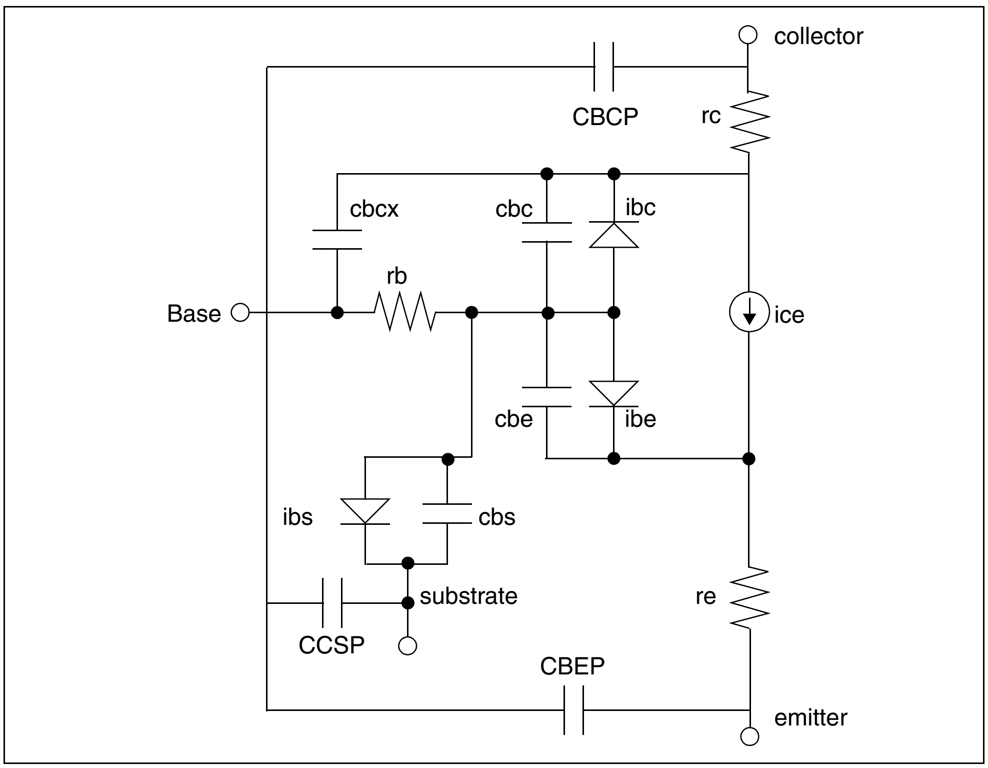


Figure 23 Lateral Transistor, BJT Transient Analysis

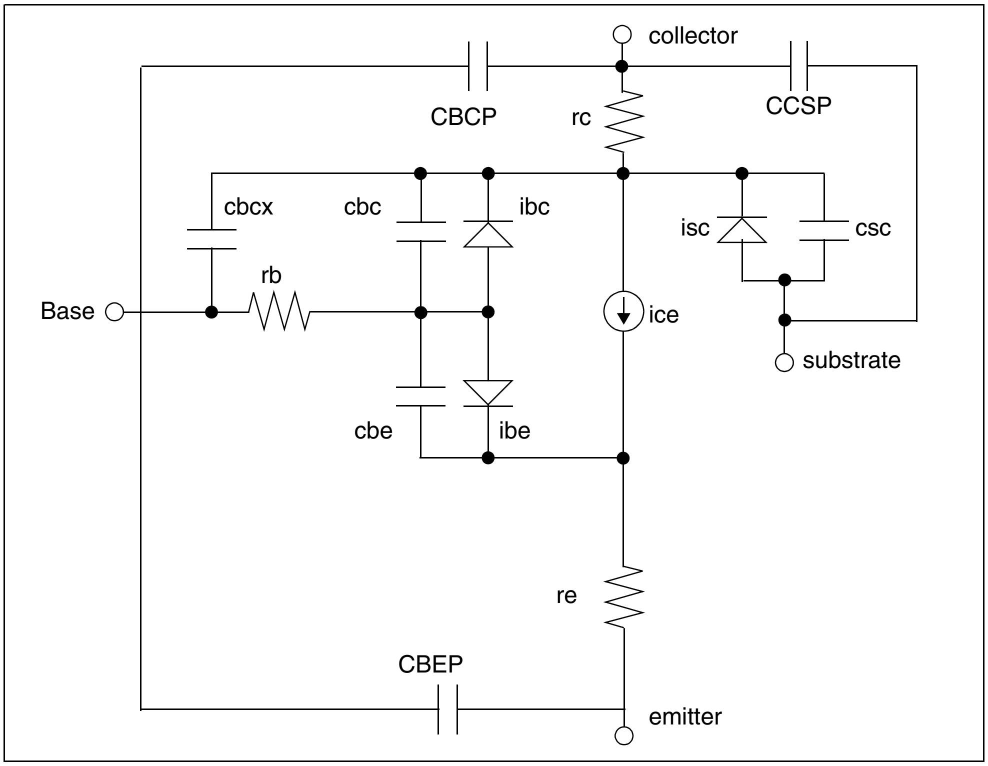


Figure 24 Vertical Transistor, BJT Transient Analysis

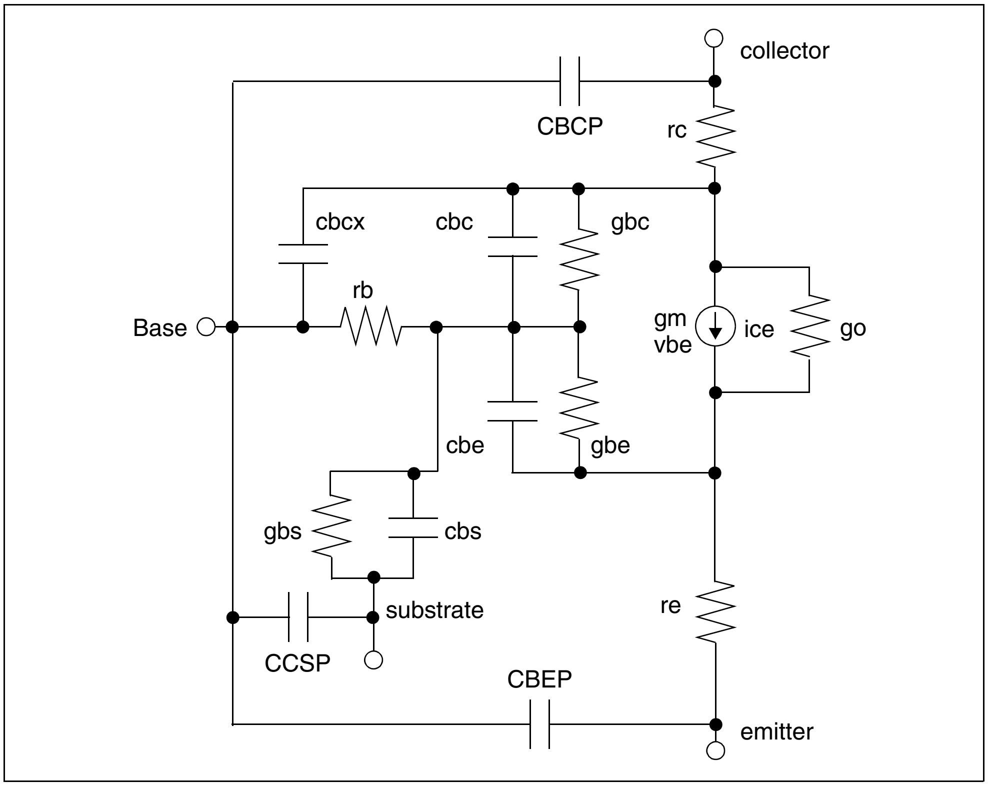


Figure 25   Lateral Transistor, BJT AC Analysis

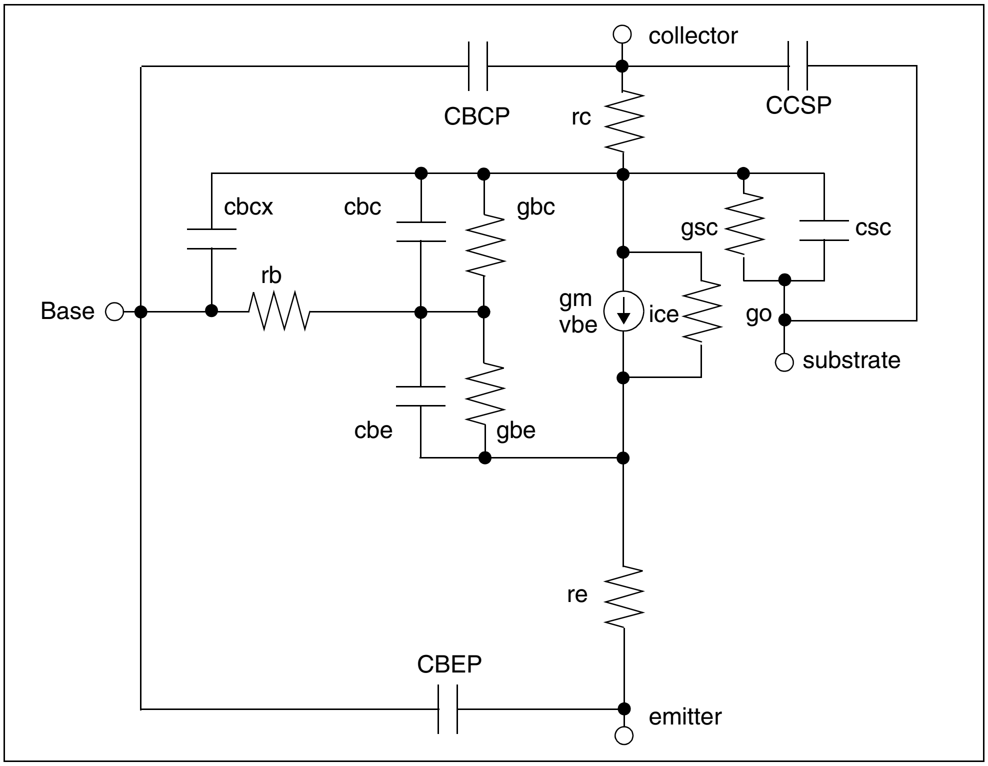


Figure 26 Vertical Transistor, BJT AC Analysis

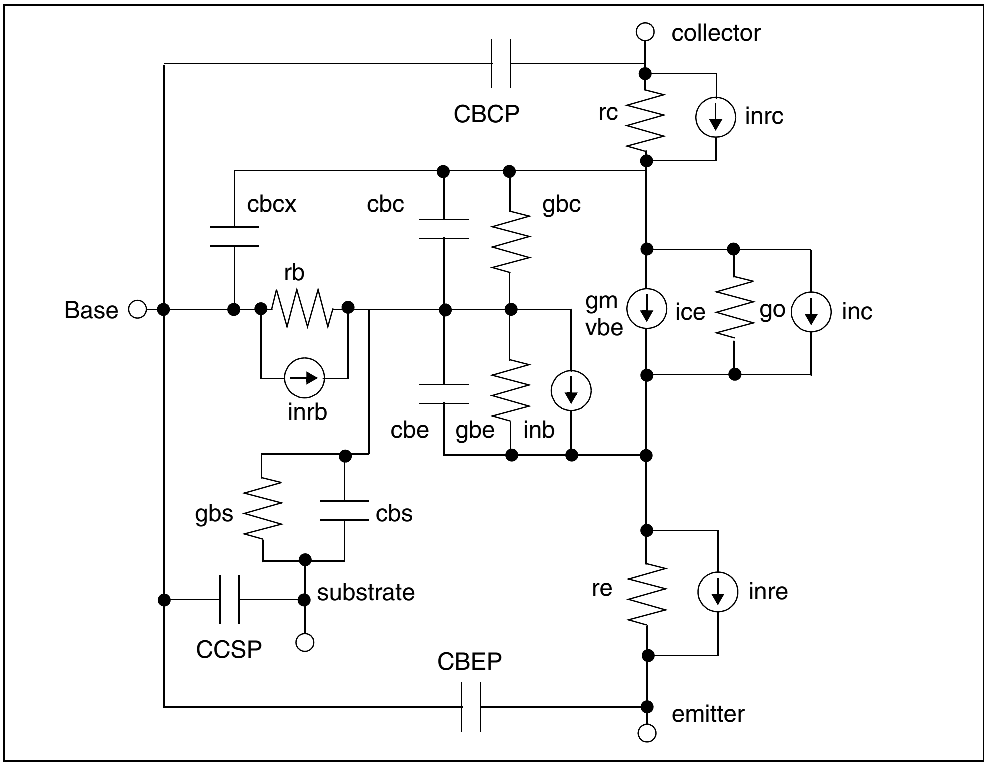


Figure 27   Lateral Transistor, BJT AC Noise Analysis

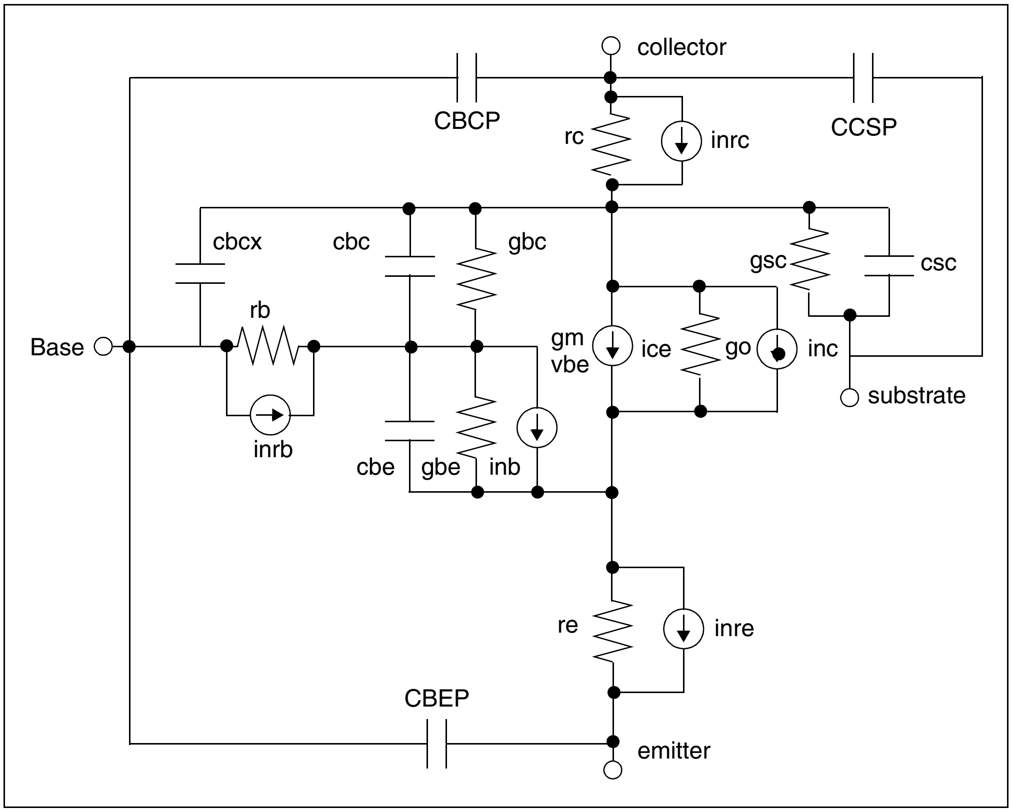


Figure 28 Vertical Transistor, BJT AC Noise Analysis

Table 57 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 57 Equation Variable Names (Continued)

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 58 Equation Constants

Quantities	Definitions
k	1.38062e-23 (Boltzmann's constant)
q	1.60212e-19 (Electron charge)
t	Temperature in degrees Kelvin
Δt	t - tnom
tnom	tnom =273.15 + TNOM in degrees Kelvin
vt(t)	$k \cdot t/q$
vt(tmon)	$k \cdot tnom/q$

Table 59 BJT DC Operating Point Output

Quantities	Definitions
ib	base current
ic	collector current
is	substrate current
vbe	B-E voltage
vbc	B-C voltage
vcs	C-S voltage
vs	substrate voltage
power	power
betad(betadc)	beta for DC analysis
gm	transconductance
rpi	B-E input resistance

Table 59 BJT DC Operating Point Output (Continued)

Quantities	Definitions
rmu(rmuv)	B-C input resistance
rx	base resistance
ro	collector resistance
cpi	internal B-E capacitance
cmu	internal B-C capacitance
cbx	external B-C capacitance
ccs	C-S capacitance
cbs	B-S capacitance
cxs	external substrate capacitance
betaac	beta for AC analysis
ft	unity gain bandwidth
*tolcc	Collector current tolerance
*tolcb	Base current tolerance

BJT Model Equations (NPN and PNP)

This section describes the NPN and PNP BJT models.

The following topics are discussed in these sections:

- Transistor Geometry in Substrate Diodes

Transistor Geometry in Substrate Diodes

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. Figure 29 and Figure 30 show vertical and lateral transistor geometries.

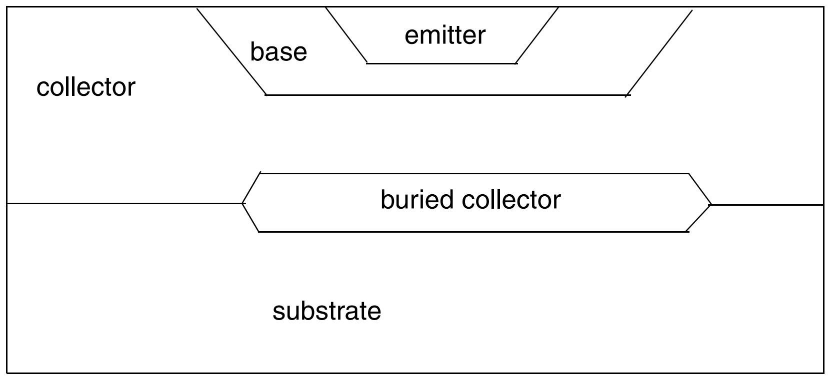


Figure 29   Vertical Transistor (SUBS =+1)

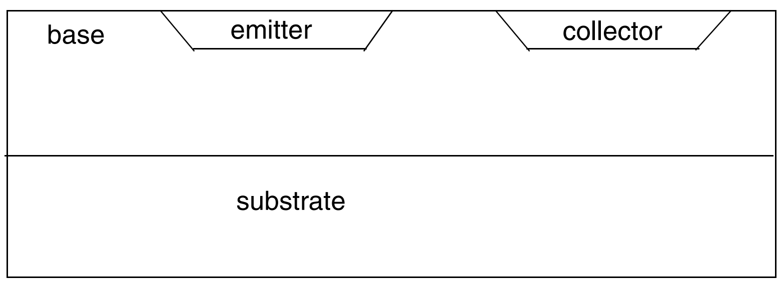


Figure 30   Lateral Transistor (SUBS =-1)

In Figure 31, the views from the top demonstrate how `IBE` is multiplied by either base area, AREAB or collector area, AREAC.

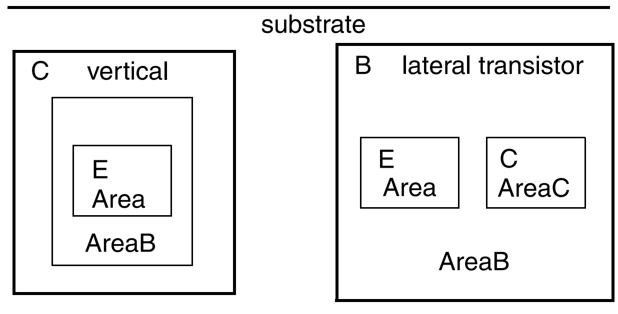


Figure 31 Base, AREAB, Collector, AREAC

DC Model Equations

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

Current Equations: IS Only

If you specify only `IS`, without `IBE` and `IBC`:

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

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

Current Equations: IBE and IBC

If you specify `IBE` and `IBC`, instead of `IS`:

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

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

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

Vertical

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

Lateral

$$IBEeff = IBE \cdot AREA \cdot M$$

Vertical or Lateral

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

Vertical

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

Lateral

$$ISEeff = ISE \cdot AREA \cdot M$$

Vertical or Lateral

The last two base-current terms represent components, due to recombining 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

$$isc = ISSeff \cdot \left(e^{\frac{vsc}{NS \cdot vt}} - 1\right)$$

$$vsc > -10 \cdot NS \cdot vt$$

$$isc = -ISSeff$$

$$vsc \leq -10 \cdot NS \cdot vt$$

Lateral Transistors

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

$$vbs > -10 \cdot NS \cdot vt$$

$$ibs = -ISSeff$$

$$vbs \leq -10 \cdot NS \cdot vt$$

If you do not specify either `IBE` or `IBC`:

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

If you specify both IBE and IBC:

$$ISSeff = ISS \cdot AREAC \cdot M$$

vertical

$$ISSeff = ISS \cdot AREAB \cdot M$$

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

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

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

With IBE and IBC, the preceding equation is:

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

In the preceding equation:

- `IBE=IS` if `IBE=0`
- `IBC=IS` if `IBC=0`

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

Variable Base Resistance Equations

A variable base resistance BJT model consists of a low-current maximum resistance (set using `RB`), and a high-current minimum resistance (set using `RBM`). `IRB` is the current when the base resistance is halfway to its minimum value. If you do not specify `RBM`, it is set to `RB`.

If you do not specify `IRB`:

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

If you specify `IRB`:

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

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

BJT Capacitance Equations

This section describes BJT capacitances.

The following topics are discussed in these sections:

- Base-Emitter Capacitance Equations
- Substrate Capacitance

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:

$$cbe = cbediff + cbedep$$

In the preceding equation, *cbediff* is the base-emitter diffusion, and *cbedep* is the depletion capacitance.

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

The following topics are discussed in these sections:

- Determining Base-Emitter Diffusion Capacitance
- Determining Base-Emitter Depletion Capacitance
- Determining Base Collector Capacitance
- Determining Base Collector Diffusion Capacitance
- Determining Base Collector Depletion Capacitance
- External Base — Internal Collector Junction Capacitance

Determining Base-Emitter Diffusion Capacitance

Determine diffusion capacitance as follows:

ibe ≤0

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

ibe > 0

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

The following equation calculates the *argtf* value for the preceding equation:

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

The forward part of the collector-emitter branch current is determined as follows (`IBE=IS` if `IBE=0`):

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

Determining Base-Emitter Depletion Capacitance

There are two different equations for modeling the depletion capacitance. Select the proper equation by specifying `.OPTION DCAP`.

DCAP=1

The base-emitter depletion capacitance is determined as follows:

$vbe < FC \cdot VJE$

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

$vbe \geq FC \cdot VJE$

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

DCAP=2

The base-emitter depletion capacitance is determined as follows:

$vbe < 0$

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

$vbe \geq 0$

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

DCAP=3

Limits peak depletion capacitance to `FC` $\cdot$ CJC_{eff} or `FC` $\cdot$ CJE_{eff} with proper fall-off when forward bias exceeds `PB` (`FC` $\geq$ 1).

Determining Base Collector Capacitance

Determine the base collector capacitance `cbc` as follows:

$$cbc = cbcdiff + cbcdep$$

In the preceding equation, cbcdiff is the base-collector diffusion, and cbcdep is the depletion capacitance.

Determining Base Collector Diffusion Capacitance

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

In the preceding equation, the internal base-collector current (`ibc`) is (`IBC=IS` if `IBC=0`):

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

Determining Base Collector Depletion Capacitance

There are two different equations for modeling the depletion capacitance. Select the proper equation by specifying `.OPTION DCAP`.

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

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

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

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

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

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

In the preceding equation, *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. To switch it from the collector to the base, set the `SUBS` model parameter.

The following section present these topics:

- Substrate Capacitance Equation: Lateral
- Substrate Capacitance Equation: Vertical
- Excess Phase Equation

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

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

Forward Bias vsc ≥ 0

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

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:

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

In the preceding equation, 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.

Defining BJT Noise Equations

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

Defining 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:

$$2 \cdot q \cdot fknee$$

In the preceding equation, fknee is the noise knee frequency (typically 100 Hz to 10 MHz), and *q* is electron charge.

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

$$inb^2 = \text{shot noise}^2 + \text{flicker noise}^2$$

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

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

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

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

Parameter	Description
RB, V2/Hz	output thermal noise due to base resistor
RC, V2/Hz	output thermal noise due to collector resistor
RE, V2/Hz	output thermal noise due to emitter resistor
IB, V2/Hz	output shot noise due to base current
FN, V2/Hz	output flicker noise due to base current
IC, V2/Hz	output shot noise due to collector current
TOT, V2/Hz	total output noise: TOT=RB + RC + RE + IB + IC + FN

BJT Temperature Compensation Equations

This section describes temperature compensation equations.

Energy Gap Temperature Equations

To determine energy gap for temperature compensation, use these equations:

TLEV =0, 1 or 3

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

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

TLEV=2

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

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

Saturation/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 `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`.

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

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

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

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`:

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

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

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

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

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

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

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

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

The following equation calculates the *facln* value for the preceding equations:

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

TLEV=0, 1, 2

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

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

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

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

Saturation Temperature Equations, TLEV=3

The basic BJT temperature compensation equations for the saturation currents when `TLEV=3` are as follows:

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

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

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

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

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

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

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

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

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

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

The following model parameters will be modified only according to the following equations whenever you specify corresponding non-zero temperature coefficients, 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

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

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

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

The following equations calculate values for the preceding equations:

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

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

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

TLEVC=1

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

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

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

The following equations calculate the built-in potentials:

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

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

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

TLEVC=2

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

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

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

The following equations calculate values for the preceding equations:

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

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

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

TLEVC=3

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

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

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

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

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

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

If `TLEV=0`, 1, or 3, then:

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

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

If `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 following equations determine the parasitic resistors as a function of temperature regardless of the `TLEV` value:

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

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

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

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

BJT LEVEL=2 Temperature Equations

The model parameters of BJT `LEVEL=2` model are modified for temperature compensation as:

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

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

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

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 that 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 reverse 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 32 and Figure 33 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.

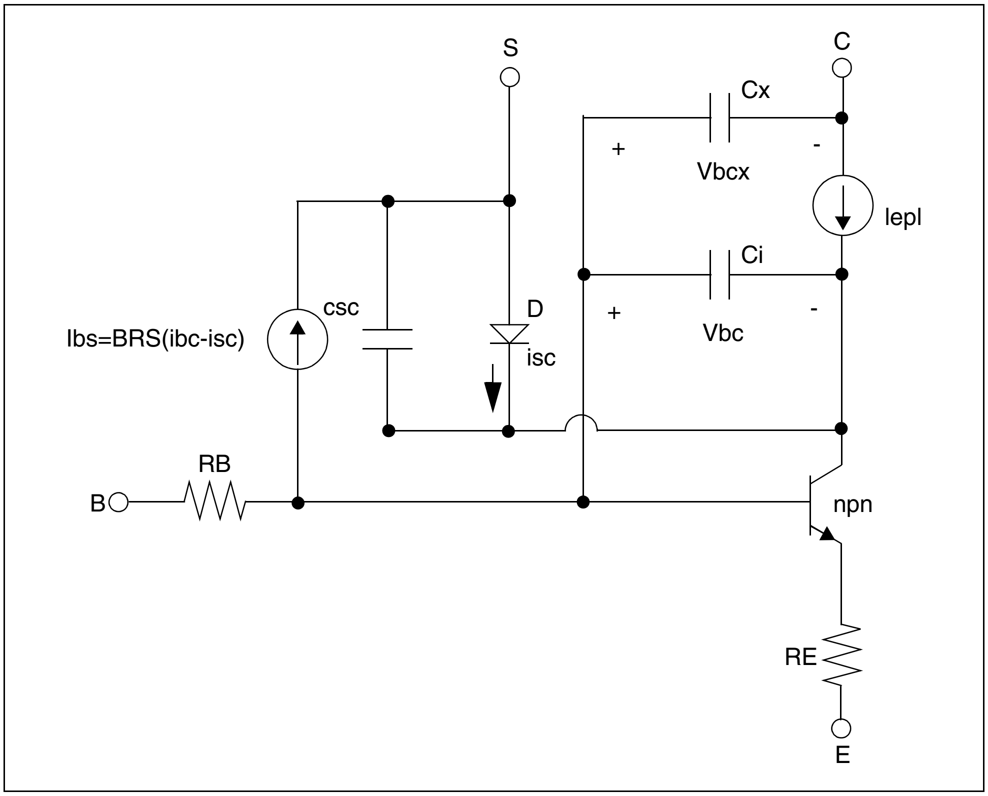


Figure 32 Vertical npn Bipolar Transistor (SUBS=+1)

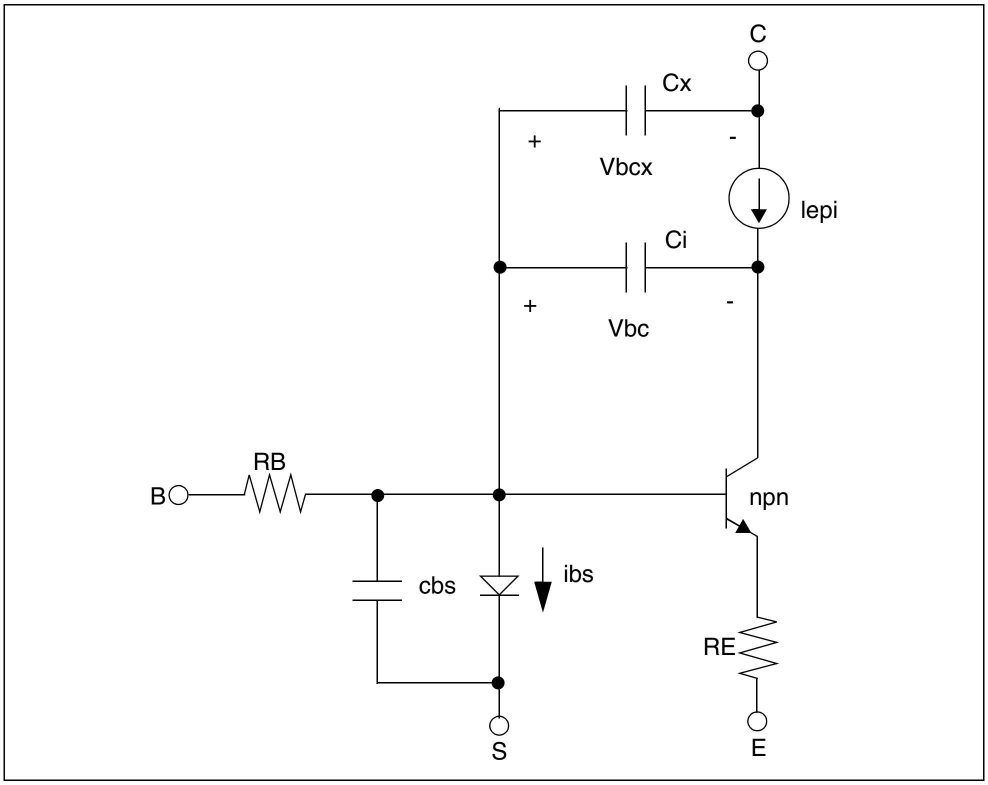


Figure 33 Lateral npn Bipolar Transistor (SUBS=-1)

Defining 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:

$$2 \cdot q \cdot fknee$$

In the preceding equation, fknee is the noise knee frequency (typically 100 Hz to 10 MHz), and *q* is electron charge.

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

$$inb^2 = \text{shot noise}^2 + \text{flicker noise}^2$$

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

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

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

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

Parameter	Description
RB, V2/Hz	output thermal noise due to base resistor
RC, V2/Hz	output thermal noise due to collector resistor
RE, V2/Hz	output thermal noise due to emitter resistor
IB, V2/Hz	output shot noise due to base current
FN, V2/Hz	output flicker noise due to base current
IC, V2/Hz	output shot noise due to collector current
TOT, V2/Hz	total output noise: TOT=RB + RC + RE + IB + IC + FN

Epitaxial Current Source Iepi

The following equation determines the epitaxial current value, Iepi:

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

The following equations calculate values for the preceding equations:

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

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

If you set the `GAMMA` model parameter to zero, then the ki and kx values both become one, and:

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

Epitaxial Charge Storage Elements Ci and Cx

The following equations calculate the epitaxial charges:

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

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

The corresponding capacitances are calculated as:

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

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

If `GAMMA=0`, then the `Ci` and `Cx` values become zero.

Example

This example is based on demonstration netlist quasisat.sp, which is available in directory $<installdir>/demo/hspice/bjt:

```
*quasisat.sp comparison of bjt Level1 and Level2
```

```
*model
.OPTION nomod relv=.001 reli=.001 absv=.1u absi=1p
.OPTION 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)
.probe dc i(q11) i(q12) i(q21) i(q22)
.probe 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 rco=500 rcc=2.599 vo=1 qco=1e-10
+ gamma=1e-9 SUBS=+1
.end
```

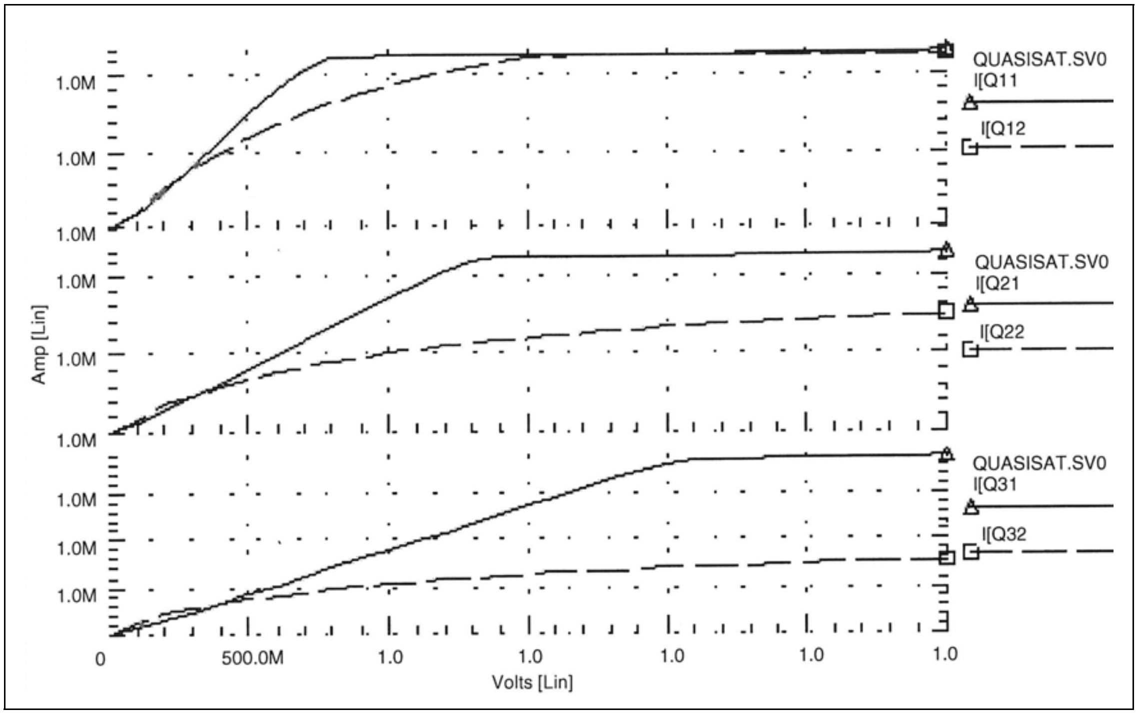


Figure 34 Comparing BJT LEVEL=1 and LEVEL=2 Models

Converting National Semiconductor Models

National Semiconductor's SNAP circuit simulator has a scaled BJT model that is not the same as the HSPICE BJT models. To use this model, 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.

Defining Scaled BJT Subcircuits

The following 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, replace the `.MODEL mname` statement with a `.PARAM` statement. Change the model name to SBJT.

Note: All parameter values in the following model must come from either a `.PARAM` statement or the subcircuit call.

Example

The following is a subcircuit definition that converts the National Semiconductor scaled BJT model to a form usable in HSPICE.

```
.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=1.10E-18    ICS=5.77E-18   NE=1.02   NC=1.03
+ ME=3.61   MC=1.24   EG=1.12   NSUB=0
+ CJE=1E-15   CJC=1E-15   CSUB=1E-15   EXE=0.501
+ EXC=0.222   ESUB=0.709   PE=1.16   PC=0.37
+ PSUB=0.698    RE=75   RC=0.0   RB=1.0
+ TRE=2E-3    TRC=6E-3   TRB=1.9E-3   VA=25
+ FTF=2.8E9    FTR=40E6    BR=1.5   TCB=5.3E-3
+ TCB2=1.6E-6    BF1=9.93    BF2=45.7    BF3=55.1
+ BF4=56.5    BF5=53.5   BF6=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 following replaces the BJT statement:

```
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
```

VBIC Bipolar Transistor Model

The VBIC (Vertical Bipolar Inter-Company) model is a bipolar transistor model. To use VBIC, specify the `LEVEL=4` parameter for the bipolar transistor model.

VBIC addresses many problems of the Gummel-Poon model:

- More accurate modeling of Early effect
- Parasitic substrate transistor
- Modulation of collector resistance
- Avalanche multiplication in collector junction, parasitic capacitances of base-emitter overlap in double poly BJTs, and self heating.

Defining 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:

$$2 \cdot q \cdot fknee$$

In the preceding equation, fknee is the noise knee frequency (typically 100 Hz to 10 MHz), and *q* is electron charge.

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

$$inb^2 = \text{shot noise}^2 + \text{flicker noise}^2$$

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

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

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

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

Parameter	Description
RB, V2/Hz	output thermal noise due to base resistor
RC, V2/Hz	output thermal noise due to collector resistor
RE, V2/Hz	output thermal noise due to emitter resistor
IB, V2/Hz	output shot noise due to base current
FN, V2/Hz	output flicker noise due to base current
IC, V2/Hz	output shot noise due to collector current
TOT, V2/Hz	total output noise: TOT=RB + RC + RE + IB + IC + FN

History of VBIC

VBIC was developed by engineers at several companies. The detailed equations for all elements are given in the referenced publication. Recent information and source code can be found on the web site:

http://www.designers-guide.org/VBIC/

The HSPICE implementation complies with standard VBIC. Starting in release 2001.4 of the VBIC model, self-heating and excess phase have been implemented or enabled.

The large signal equivalent circuit for VBIC is shown in Figure 35. Capacitors `CBCO`, `CBEO` and resistors `RCX`, `RBX`, `RE`, and `RS` are linear elements, all other elements of the equivalent circuit are nonlinear.

VBIC Parameters

Figure 35 lists the parameters that you can set for the model, and shows the default values for each parameter. The same parameter names are used in the table and the previous referenced publication.

Starting in Version 2003.03, the BJT `LEVEL=4` model prints FT in the `.OP` output.

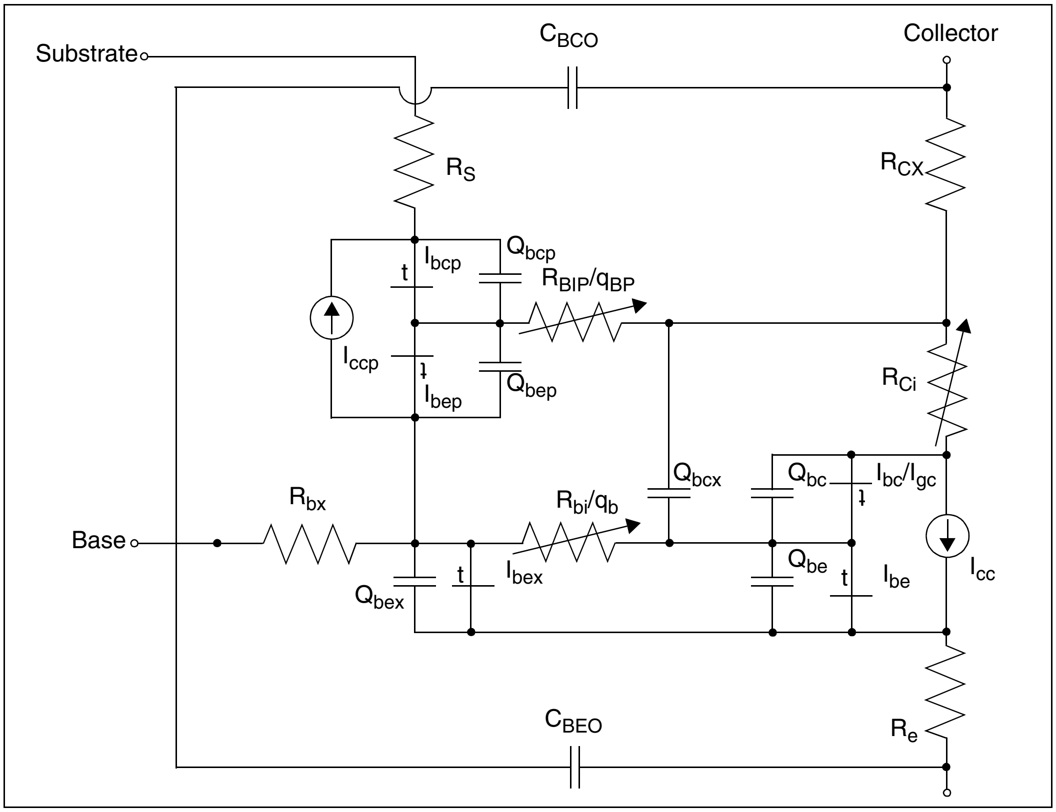


Figure 35 Transient Analysis

If values of parameters given by the user are beyond their ranges, those parameters will be reset to new values and warnings will be printed unless you set `.OPTION NOWARN`.

Table 60 BJT LEVEL=4 Default Model Parameters

Name (Alias)	Unit	Default	Description
AFN		1	Flicker noise exponent for current
AJC		-0.5	Base-collector capacitance switching parameter
AJE		-0.5	Base-emitter capacitance switching parameter
AJS		-0.5	Substrate-collector capacitance switching parameter

Table 60 BJT LEVEL=4 Default Model Parameters (Continued)

Name (Alias)	Unit	Default	Description
AVC1	V-1	0	Base-collector weak avalanche parameter 1
AVC2	V-1	0	Base-collector weak avalanche parameter 2
BFN		1	Flicker noise exponent for 1/f dependence
CBCO (CBC0)	F	0	Extrinsic base-collector overlap capacitance
CBEO (CBE0)	F	0	Extrinsic base-emitter overlap capacitance
CJC	F	0	Base-collector intrinsic zero bias capacitance
CJCP	F	0	Substrate-collector zero bias capacitance
CJE	F	0	Base-emitter zero bias capacitance
CJEP	F	0	Base-collector extrinsic zero bias capacitance
CTH	J/K	0	Thermal capacitance
EA	eV	1.12	Activation energy for IS
EAIC	eV	1.12	Activation energy for IBCI/IBEIP
EAIE	eV	1.12	Activation energy for IBEI
EAIS	eV	1.12	Activation energy for IBCIP
EANC	eV	1.12	Activation energy for IBCN/IBENP
EANE	eV	1.12	Activation energy for IBEN
EANS	eV	1.12	Activation energy for IBCNP
FC		0.9	Forward bias depletion capacitance limit
GAMM		0	Epi doping parameter
HRCF		1	High-current RC factor
IBCI	A	1e-16	Ideal base-collector saturation current
IBCIP	A	0	Ideal parasitic base-collector saturation current
IBCN	A	1e-15	Non-ideal base-collector saturation current

Table 60 BJT LEVEL=4 Default Model Parameters (Continued)

Name (Alias)	Unit	Default	Description
IBCNP	A	0	Non-ideal parasitic base-collector saturation current
IBEI	A	1e-18	Ideal base-emitter saturation current
IBEIP	A	0	Ideal parasitic base-emitter saturation current
IBEN	A	1e-15	Non-ideal base-emitter saturation current
IBENP	A	0	Non-ideal parasitic base-emitter saturation current
IKF	A	2e-3	Forward knee current
IKP	A	2e-4	Parasitic knee current
IKR	A	2e-4	Reverse knee current
IS	A	1e-16	Transport saturation current
ISMIN	A	1.0e-19	Parameter for extending the minimum value of is
ISP	A	1e-16	Parasitic transport saturation current
ISPMIN	A	1.0e-19	Parameter for extending the minimum value of isp
ITF	A	1e-3	Coefficient of TF dependence in Ic
KFN		0	Base-emitter flicker noise constant
MC		0.33	Base-collector grading coefficient
MCMIN	-	1.0d-2	Parameter for extending the minimum value of mc
ME		0.33	Base-emitter grading coefficient
MEMIN	-	1.0d-2	Parameter for extending the minimum value of me
MS		0.33	Substrate-collector grading coefficient
MSMIN	-	1.0d-2	Parameter for extending the minimum value of ms
NCI		1	Ideal base-collector emission coefficient
NCIP		1	Ideal parasitic base-collector emission coefficient
NCN		2	Non-ideal base-collector emission coefficient

Table 60 BJT LEVEL=4 Default Model Parameters (Continued)

Name (Alias)	Unit	Default	Description
NCNP		2	Non-ideal parasitic base-collector emission coefficient
NEI		1	Ideal base-emitter emission coefficient
NEN		2	Non-ideal base-emitter emission coefficient
NF		1	Forward emission coefficient
NFP		1	Parasitic forward emission coefficient
NR		1	Reverse emission coefficient
PC	V	0.75	Base-collector built-in potential
PE	V	0.75	Base-emitter built-in potential
PS	V	0.75	Substrate-collector built-in potential
QCO (QC0)	C	0	Epi charge parameter
QTF		0	Variation of TF with base-width modulation
RBI	Ohm	1e-1	Intrinsic base resistance
RBP	Ohm	1e-1	Parasitic base resistance
RBPMIN	A	1.0e-3	Parameter for extending the minimum value of rbp.
RBX	Ohm	1e-1	Extrinsic base resistance
RCI	Ohm	1e-1	Intrinsic collector resistance
RCX	Ohm	1e-1	Extrinsic collector resistance
RE	Ohm	1e-1	Emitter resistance
RS	Ohm	1e-1	Substrate resistance
RTH	K/W	0	Thermal resistance
TAVC	1/K	0	Temperature coefficient of AVC2
TD	s	0	Forward excess-phase delay time
TF	s	1e-11	Forward transit time

Table 60 BJT LEVEL=4 Default Model Parameters (Continued)

Name (Alias)	Unit	Default	Description
TNF	1/K	0	Temperature coefficient of NF
TR	s	1e-11	Reverse transit time
TREF (TNOM)	^{o}C	27	Nominal measurement temperature of parameters (do not use TNOM alias)
VEF	V	0	Forward Early voltage
VER	V	0	Reverse Early voltage
VO (V0)	V	0	Epi drift saturation voltage
VTF	V	0	Coefficient of TF dependence on Vbc
WBE		1	Portion of IBEI from Vbei, 1-WBE from Vbex
WSP		1	Portion of ICCP from Vbep, 1-WSP from Vbci
XII		3	Temperature exponent of IBEI/IBCI/IBEIP/IBCIP
XIN		3	Temperature exponent of IBEN/IBCN/IBENP/IBCNP
XIS		3	Temperature exponent of IS
XRB		1	Temperature exponent of base resistance
XRC		1	Temperature exponent of collector resistance
XRE		1	Temperature exponent of emitter resistance
XRS		1	Temperature exponent of substrate resistance
XTF		0	Coefficient of TF bias dependence
XVO (XV0)		0	Temperature exponent of VO

Noise Analysis

The following sources of noise are taken into account:

- The thermal noise of resistors `RBX`, `RCX`, `RE`, `RS`, `RBP`, `RCI`, `RBI`
- Shot noise of currents `IBE`, IBEP, ICC, ICCP
- Flicker noise due to currents `IBE`, IBEP

Noise due to IBEX and IGC is not included.

Defining 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:

$$2 \cdot q \cdot fknee$$

In the preceding equation, fknee is the noise knee frequency (typically 100 Hz to 10 MHz), and *q* is electron charge.

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

$$inb^2 = \text{shot noise}^2 + \text{flicker noise}^2$$

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

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

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

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

Parameter	Description
RB, V2/Hz	output thermal noise due to base resistor
RC, V2/Hz	output thermal noise due to collector resistor
RE, V2/Hz	output thermal noise due to emitter resistor
IB, V2/Hz	output shot noise due to base current
FN, V2/Hz	output flicker noise due to base current
IC, V2/Hz	output shot noise due to collector current
TOT, V2/Hz	total output noise: TOT=RB + RC + RE + IB + IC + FN

Self-heating and Excess Phase

After a self-heating effect is accounted for, the device element syntax becomes:

```
Qxxx nc nb ne [ns] [nt] mname [regular parameters] [tnodeout]
```

In the preceding syntax, `nt` is the temperature node. If you specify this node, but not `ns`, then you must specify the `tnodeout` parameter to indicate that the fourth node is the temperature node and not the substrate node. To turn on self-heating in addition to specifying the temperature node, the `RTH` (thermal resistance) model parameter must be not zero in the model card.

Excess phase affects only AC and transient characteristics analysis. To turn on this effect, the `TD` (forward excess-phase delay time) model parameter must be non-zero. But for transient analysis, turning on excess phase is not recommended, because the model's convergence is very sensitive to the `TD` value.

Example 1

This example with a no self-heating effect is located in the following directory: $installdir/demo/hspice/bjt/vbic.sp

Example 2

This example with self-heating effects is located in the following directory: $installdir/demo/hspice/bjt/self_heat.sp

In the preceding example, v(t) uses the T node to print the device temperature.

Notes on Using VBIC

1. If `LEVEL=4`, the model is a VBIC bipolar junction transistor.
2. The `LEVEL=4` model supports Area and M factor scaling.
3. Setting these parameters to zero infers a value of infinity: `HRCF`, `IKF`, `IKP`, `IKR`, `ITF`, `VEF`, `VER`, `VO`, `VTF`.
4. The `CBC0`, `CBE0`, `QC0`, `TNOM`, `V0`, and `XV0` parameters are aliases for `CBCO`, `CBEO`, `QCO`, `TREF`, `VO`, and XVO, respectively. Do not use `TNOM` as a model parameter name, because it is the name of the default room temperature.
5. The default room temperature is 25 degrees in HSPICE, but is 27 in some other simulators. If you set the VBIC bipolar junction transistor model parameters to 27 degrees, add `TREF=27` to the model so that simulation correctly interprets the model parameters.To set the nominal simulation temperature to 27, add `.OPTION TNOM=27` to the netlist. Do this when testing HSPICE versus other simulators that use 27 as the default room temperature.
6. Pole-zero simulation of this model is not supported.
7. For this version of implementation, all seven internal resistors should have values greater than or equal to 1.0e-3. Values smaller than this will be reassigned a value of 1.0e-3.

LEVEL=6 Philips Bipolar Model (MEXTRAM Level 503)

The Philips bipolar model (MEXTRAM Level 503) is the BJT `LEVEL=6` model. See also: LEVEL=6 Philips Bipolar Model (MEXTRAM Level 504). MEXTRAM includes effects that are not included in some other BJT models (such as in the original Gummel-Poon model):

- Temperature
- Charge storage
- Substrate
- Parasitic PNP
- High-injection
- Built-in electric field in base region
- Bias-dependent Early effect

- Low-level, non-ideal base currents
- Hard- and quasi-saturation
- Weak avalanche
- Hot carrier effects in the collector epilayer
- Explicit modeling of inactive regions
- Split base-collector depletion capacitance
- Current crowding and conductivity modulation for base resistance
- First order approximation of distributed high frequency effects in the intrinsic base (high frequency current crowding and excess phase shift)

You can use either of the following two parameters to specify the difference between the circuit temperature and the ambient temperatures in the MEXTRAM model:

- `DTEMP` instance parameter as specified in the element statement.
- `DTA` (difference between the device temperature and the ambient analysis temperature) global model parameter.

`DTA` and `DTEMP` both default to zero. `DTEMP` overrides `DTA` locally, if you specify both. Simulation uses the value of `DTEMP` to de-rate the temperature in model equations and other parameters.

- If you do not specify either the `DTEMP` or the `DTA` parameter, then `DTEMP=0.0`.
- If you specify `DTA` but not `DTEMP`, then `DTEMP` uses the `DTA` value.
- If you specify `DTEMP`, then simulation uses the `DTEMP` value, and ignores the `DTA` value.

For a description of the MEXTRAM model, refer to:

http://www-us.semiconductors.com/Philips_Models/

Defining 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:

$$2 \cdot q \cdot fknee$$

In the preceding equation, fknee is the noise knee frequency (typically 100 Hz to 10 MHz), and *q* is electron charge.

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

$$inb^2 = \text{shot noise}^2 + \text{flicker noise}^2$$

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

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

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

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

Parameter	Description
FN, V2/Hz	output flicker noise due to base current
IB, V2/Hz	output shot noise due to base current
IC, V2/Hz	output shot noise due to collector current
RB, V2/Hz	output thermal noise due to base resistor
RC, V2/Hz	output thermal noise due to collector resistor
RE, V2/Hz	output thermal noise due to emitter resistor
TOT, V2/Hz	total output noise: TOT=RB + RC + RE + IB + IC + FN

LEVEL=6 Element Syntax

```
Qxxx nc nb ne [ns] [nt] mname [AREA=val]
+ [OFF] [VBE=val] [VCE=val] [M=val] [DTEMP=val] tnodeout

Qxxx nc nb ne nt mname [AREA=val]
+ [OFF] [VBE=val] [VCE=val] [M=val] [DTEMP=val] tnodeout
```

Parameter	Description
Qxxx	BJT element name. Starts with Q, followed by up to 1023 alphanumeric characters.
nc	Collector terminal node name or number.
nb	Base node name or number.
ne	Emitter terminal node name or number.
ns	Substrate node name or number.
nt	Self-heating temperature node name or number. In the second form, nt is used as a self-heating node, but no substrate node is defined.
mname	BJT model name reference.
AREA	Normalized emitter area.
OFF	Sets initial condition to OFF for this element in DC analysis.
VBE	Initial internal base to emitter voltage.
VCE	Initial internal collector to emitter voltage.
M	Multiplier to simulate multiple BJTs in parallel (alias in an instance for the MULT model parameter). If you use MULT, set m to zero. ■ If (MULT > 0.0 and MULT != 1.0) and (m == 1), then HSPICE uses the MULT model parameter and displays a warning message. ■ Otherwise, HSPICE uses the m instance parameter and displays a warning message: MULT=1, m=1 (no warning messages) MULT=1, m=3 MULT=2, m=3 and so on...
DTEMP	Difference between element and circuit temperature.
tnodeout	Identify self heating node from substrate node.

LEVEL=6 Model Parameters

This section lists MEXTRAM `LEVEL=6` model parameters, including parameter names, descriptions, units, default values, and notes.

Table 61 BJT LEVEL=6 MEXTRAM 503 Flags

Name (Alias)	Unit	Default	Description
LEVEL	-	-	LEVEL=6 for MEXTRAM
EXAVL	-	0	Flag for extended modeling of avalanche currents
EXMOD	-	0	Flag for extended modeling of the reverse current gain
EXPHI	-	1	Flag for distributed high frequency effects
SUBS	-	-	Flag for switching substrate effect
OUTFLAG			

Table 62 BJT LEVEL=6 MEXTRAM 503 Basic Parameters

Name (Alias)	Unit	Default	Description
TREF	oC	0.0	Model nominal temperature
AB	-	1.35	Temperature coefficient resistivity of the base
AC	-	0.4	Temperature coefficient resistivity of the buried layer
AEPI	-	2.15	Temperature coefficient resistivity of the epilayer
AEX	-	1.	Temperature coefficient resistivity of the extrinsic base
AF	-	1.0	Flicker noise exponent
AS	-	2.15	For a closed buried layer: AS=AC For an open buried layer: AS=AEPI
AVL	-	50.	Weak avalanche parameter
BF	A	140.0	Ideal forward current gain
BRI	-	16.0	Ideal reverse current gain

Table 62 BJT LEVEL=6 MEXTRAM 503 Basic Parameters (Continued)

Name (Alias)	Unit	Default	Description
CJC	F	1.3e-13	Zero bias collector-base depletion capacitance
CJE	F	2.5e-13	Zero bias collector-base depletion capacitance
CJS	F	1.e-12	Zero bias collector-substrate depletion capacitance
EFI	-	0.7	Electric field intercept (with EXAVL=1)
ER	-	2.E-3	Temperature coefficient of VLF and VLR
ETA	-	4.0	Factor of the built-in field of the base
IBF	A	2.0E-14	Saturation current of the non-ideal forward base current
IBR	A	8.0e-15	Saturation current of the non-ideal reverse base current
IHC	A	3.e-3	Critical current for hot carriers
IK	A	15.E-3	High-injection knee current
IKS	A	5.E-6	Knee current of the substrate
IS	A	5.E-17	Collector-emitter saturation current
ISS	A	6.E-16	Base-substrate saturation current
KF	-	2.E-16	Flicker noise coefficient ideal base current
KFN	-	2.E-16	Flicker noise coefficient non-ideal base current
MC	-	0.5	Collector current modulation coefficient
MTAU	-	1.18	Non-ideality factor of the neutral and emitter charge
NA	cm^-3	3.0E17	Maximum base dope concentration
PC	-	0.4	Collector-base grading coefficient variable part
PE	-	0.33	Emitter-base grading coefficient
PS	-	0.33	Collector-substrate grading coefficient
QBO	C	1.2e-12	Base charge at zero bias
RBC	ohm	50.	Constant part of the base resistance

Table 62 BJT LEVEL=6 MEXTRAM 503 Basic Parameters (Continued)

Name (Alias)	Unit	Default	Description
RBV	ohm	100.	Variable part of the base resistance at zero bias
RCC	ohm	25.	Constant part of the collector resistance
RCV	ohm	750.	Resistance of the unmodulated epilayer
RE	ohm	2.0	Emitter series resistance
SCRCV	ohm	1000.0	Space charge resistance of the epilayer
SFH	-	0.6	Current spreading factor epilayer
TAUNE	s	3.e-10	Minimum delay time of neutral and emitter charge
VDC	V	0.6	Collector-base diffusion voltage
VDE	V	0.9	Emitter-base diffusion voltage
VDS	V	0.5	Collector-substrate diffusion voltage
VGB	V	1.18	Band-gap voltage of the base
VGC	V	1.205	Band-gap voltage of the collector
VGE	V	1.01	Band-gap voltage of the emitter
VGJ	V	1.1	Band-gap voltage recombination emitter-base junction
VGS	V	1.15	Band-gap voltage of the substrate
VI	V	0.040	Ionization voltage base dope
VLF	V	0.5	Cross-over voltage of the non-ideal forward base current
VLR	V	0.5	Cross-over voltage of the non-ideal reverse base current
XCJC	-	0.1	Fraction of the collector-base depletion capacitance under the emitter area
XCJE	F	0.5	Fraction of the emitter-base depletion capacitance that belongs to the sidewall
XEXT	-	0.5	Part of I EX,Q EX, Q TEX. and I SUB that depends on the base-collector voltage VBC1
XIBI	-	0.0	Fraction of ideal base current that belongs to the sidewall

Table 62 BJT LEVEL=6 MEXTRAM 503 Basic Parameters (Continued)

Name (Alias)	Unit	Default	Description
XP	F	0.2	Constant part of CJC

Example

This example is located in the following directory:
$*installdir*/demo/hspice/bjt/mextram.sp

LEVEL=6 Philips Bipolar Model (MEXTRAM Level 504)

Level 504 of the MEXTRAM model is also available as BJT `LEVEL=6` as is Level 503 of MEXTRAM. Use the `VERS` parameter to choose MEXTRAM level 503 or 504. The default value of the `VERS` parameter is 504. See Mextram 504 Update Releases for brief descriptions of version 504 updates.

For first-order and higher-order characteristic derivatives, MEXTRAM 504 returns better results than MEXTRAM 503. This effect is noticeable in output-conductance, cut-off frequency, and low-frequency third-order distortion.

MEXTRAM Level 504 models several effects that are not included in the original Gummel-Poon model.

These effects include:

- Temperature
- Charge storage
- Substrate
- Parasitic PNP
- High-injection
- Bias-dependent early effect
- Low-level, non-ideal base currents
- Hard- and quasi-saturation (including Kirk Effect)
- Weak avalanche (optionally including snap-back behavior)
- Explicit modeling of inactive regions
- Split base-collector and base-emitter depletion capacitance

- Current crowding and conductivity modulation of the base resistance
- First order approximation of distributed high frequency effects in the intrinsic base (high frequency current crowding and excess phase shift)
- Ohmic resistance of epilayer
- Velocity saturation effects on the resistance of the epilayer
- Recombination in the base (meant for SiGe transistors)
- Early effects in the case of a graded bandgap (SiGe)
- Thermal noise, shot noise, and 1/f-noise
- Self-heating

You can use either of two parameters to specify the difference between the circuit temperature and the ambient temperatures in the MEXTRAM model:

- `DTEMP` instance parameter as specified in the element statement
- `DTA` (difference between the device temperature and the ambient analysis temperature) global model parameter.

`DTA` and `DTEMP` both default to zero. `DTEMP` overrides `DTA` locally, if you specify both. Simulation uses the value of `DTEMP` to de-rate the temperature in model equations and other parameters.

- If you do not specify either the `DTEMP` or the `DTA` parameter, then `DTEMP=0.0`.
- If you specify `DTA` but not `DTEMP`, then `DTEMP` uses the `DTA` value.
- If you specify `DTEMP`, then simulation uses the `DTEMP` value, and ignores the `DTA` value.

This model is described at:

http://www.semiconductors.philips.com/Philips_Models/newsflashmextram504

The following topics are covered:

- Notes on Using MEXTRAM 503 or 504 Devices
- LEVEL=6 Model Parameters (504)
- Mextram 504 Update Releases

Notes on Using MEXTRAM 503 or 504 Devices

The following information applies to the HSPICE device model for the MEXTRAM 503 or 504 device:

- Set `LEVEL=6` to identify the model as a MEXTRAM bipolar junction transistor model.
- Set `VERS` parameter to 503 to use MEXTRAM 503 and to 504 to use MEXTRAM 504.
- All internal resistors are limited to greater than or equal to 1.0e-6.
- Reference temperature, `TREF`, is equal to 25 degrees.
- MEXTRAM does not contain extensive geometrical or process scaling rules (it has a multiplication factor to put transistors in parallel).
- MEXTRAM does not contain a substrate resistance.
- Constant overlap capacitances are not modelled within MEXTRAM.
- MEXTRAM 504 has better convergence than 503.
- MEXTRAM is more complex than Gummel-Poon (the computation time is longer and the convergence is less).
- No reverse emitter-base breakdown mechanism.
- Models the forward current of the parasitic PNP transistor.
- Output conductance dIc/dVce at the point where hard saturation starts seems to be too abrupt for high current levels, compared to measurements.
- Clarity of extrinsic current model describing Xiex and Xisub is improved by adding an extra node and an extra contact base resistance. In this case, parameter extraction would be more difficult.
- Starting in Release 2002.2:
  - Self-heating is now enabled for the MEXTRAM 504 model. You can use the `RTH` (thermal resistance) and `CTH` (thermal capacitance) model parameters, which had no effect in previous releases.
  - The `CBEO` capacitance parameter in MEXTRAM 504 models extrinsic B-E charge and capacitance effects. Also, the `CBCO` capacitance parameter models extrinsic B-C charge and capacitance effects.
  - The `SUBS` flag models the parasitic substrate effect when set to 1 (the default); `SUBS=0` does not model this effect. Both the MEXTRAM 503 and 504 models support the `SUBS` flag.

   - The MEXTRAM 504 model supports HSPICE-specific area-scaling and multiplicity (`M` factor) features.
   - The MEXTRAM 503 model includes `KN` and `KFN` noise parameters.
- Starting in Release 2003.03, the Mextram BJT (`LEVEL=6`) model supports Philips modelkit 4.3.
- Starting in Release X-2005.09, support for avalanche current shot noise source parameters `Iavl_cc`, `Iavl_bb`, and `Iavl_bc` was added.

LEVEL=6 Model Parameters (504)

The following tables describe MEXTRAM 504 as `LEVEL=6` model parameters, including parameter names, units, default values, descriptions, and notes.

- `TAUNE` in MEXTRAM 503 acts as `TAUE` in the 504 model.
- Parameters noted with an asterisk (*) are not used in the DC model.

The following parameters used in MEXTRAM 503 are deleted in MEXTRAM 504:

- QBO
- NA
- VGE
- ETA
- VLF
- ER
- VI
- EFI
- AVL

The following parameters have been added to MEXTRAM 504:

- VEF
- TAUB
- DVGBR
- VAVL
- XREC
- TAUE
- DVGBF
- WAVL
- DEG
- CTH
- AE
- MLF
- TAUR
- RTH
- VER
- TEPI
- DVGTE
- AXI

Table 63 BJT LEVEL=6 MEXTRAM 504 Flags

Name (Alias)	Unit	Default	Description
LEVEL	-	6	Model level
VERS	-	504	Flag to select between Mextram 503 and Mextram 504 models. Note: to set specific Mextram504 versions, such as 504.5, 504.6, 504.7, 504.8, refer to the INTVERS parameter

Table 63 BJT LEVEL=6 MEXTRAM 504 Flags (Continued)

Name (Alias)	Unit	Default	Description
INTVERS	-	4.61	Flag for choosing specific Mextram 504 version Note: supported versions include 4.3, 4.4, 4.5, 4.6, 4.61. 4.7 and 4.8.
EXMOD	-	1	Flag for extended modeling, reverse current gain
EXPHI	-	1	*Flag for distributed high frequency effects in transient
EXAVL	-	0	Flag for extended modeling of avalanche currents
TREF	^oC	25.0	Reference temperature
SUBS	-	-	Flag for switching substrate effect

Table 64 BJT LEVEL=6 MEXTRAM 504 Basic Parameters

Name (Alias)	Unit	Default	Description
BF	-	215.0	Ideal forward current gain
BRI	-	7.0	Ideal reverse current gain
IBF	A	2.7e-15	Saturation current, non-ideal forward base current
IBR	A	1.0e-15	Saturation current, non-ideal reverse base current
IK	A	0.1	Collector-emitter high injection knee current
IS	A	2.2e-17	Collector-emitter saturation current
MLF	V	2.0	Non-ideal factor of non-ideal forward base current
VEF		44.0	Forward early voltage
VER		2.5	Reverse early voltage
VLR	V	0.2	Cross-over voltage, non-ideal reverse base current
XEXT	-	0.63	Part of Iex, Qex, Qtex, and Isub that depends on the base-collector voltage Vbc1
XIBI	-	0.0	Fraction of ideal base current for the sidewall

Table 65 BJT LEVEL=6 MEXTRAM 504 Avalanche Model Parameters

Name (Alias)	Unit	Default	Description
SFH	-	0.3	Current spreading factor of avalanche model (if EXAVL=1)
VAVL	V	3.0	Voltage, determines avalanche-current curvature
WAVL	m	1.1e-6	Epilayer thickness in weak-avalanche model

Table 66 BJT LEVEL=6 MEXTRAM 504 Base-Emitter Capacitances

Name (Alias)	Unit	Default	Description
CJE	F	7.3e-14	*Zero bias emitter-base depletion capacitance
PE	-	0.4	Emitter-base grading coefficient
VDE	V	0.95	Emitter-base diffusion voltage
XCJE	-	0.4	*Sidewall portion of emitter-base depletion capacitance

Table 67 BJT LEVEL=6 MEXTRAM 504 Base-Collector Capacitances

Name (Alias)	Unit	Default	Description
CJC	F	7.8e-14	*Zero bias collector-base depletion capacitance
MC	-	0.5	Coefficient for the current modulation of the collector-base depletion capacitance
PC	-	0.5	Collector-base grading coefficient
VDC	V	0.68	Collector-base diffusion voltage
XCJC	-	3.2e-2	*Fraction of the collector-base depletion capacitance under the emitter
XP	-	0.35	Constant part of CJC

Table 68 BJT LEVEL\=6 MEXTRAM 504 Transit Time Parameters

Name (Alias)	Unit	Default	Description
DEG	EV	0.0	Bandgap difference over the base
MTAU	-	1.0	*Non-ideality of the emitter stored charge
TAUB	S	4.2e-12	*Transit time of stored base charge
TAUE	S	2.0e-12	*Minimum transit time of stored emitter charge
TAUR	S	5.2e-10	*Transit time, reverse extrinsic stored base charge
TEPI	S	4.1e-11	*Transit time of stored epilayer charge
XREC	-	0.0	Pre-factor of the recombination part of Ib1

Table 69 BJT LEVEL=6 MEXTRAM 504 Temperature Parameters

Name (Alias)	Unit	Default	Description
AB	-	1.0	Temperature coefficient of resistivity of base
AC	-	2.0	Temperature coefficient of resistivity, buried layer
AE	-	0.0	Temperature coefficient of emitter resistivity
AEPI	-	2.5	Temperature coefficient of resistivity of epilayer
AEX	-	0.62	Temperature coefficient of resistivity, extrinsic base
AQBO	-	0.3	Temperature coefficient, zero-bias base charge
ATH	-	0	Temperature coefficient of the thermal resistance
CVGBR	V	4.5e-2	Bandgap voltage difference, reverse current gain
DAIS	-	0	Parameter for fine tuning of temperature dependence for collector-emitter saturation current
DVGBF	V	5.0e-2	Bandgap voltage difference, forward current gain
DVGTE	V	0.05	*Bandgap voltage difference, emitter stored charge

Table 69 BJT LEVEL=6 MEXTRAM 504 Temperature Parameters (Continued)

Name (Alias)	Unit	Default	Description
VGB	V	1.17	Bandgap voltage of the base
VGC	V	1.18	Bandgap voltage of the collector
VGJ	V	1.15	Recombined bandgap voltage, emitter-base junction

Table 70 BJT LEVEL=6 MEXTRAM 504 Noise Parameters

Name (Alias)	Unit	Default	Description
AF	-	2.0	Exponent of the flicker-noise
KAVL	-	0	Switch for white noise contribution due to avalanche
KF	-	2.0e-11	Flicker-noise coefficient for ideal base current
KFN	-	2.0e-11	Flicker-noise coefficient, non-ideal base current

Table 71 BJT LEVEL=6 MEXTRAM 504 Substrate Parameters

Name (Alias)	Unit	Default	Description
CJS	F	3.15e-13	*Zero bias collector-substrate depletion capacitance
IKS	A	2.5e-4	Base-substrate high injection knee current
ISS	A	4.8e-17	Base-substrate saturation current
AS	-	1.58	For a closed buried layer: AS=AC For an open buried layer: AS=AEPI
PS	-	0.34	*Collector-substrate grading coefficient
VDS	V	0.62	*Collector-substrate diffusion voltage
VGS	V	1.2	Bandgap voltage of the substrate

Table 72 BJT LEVEL=6 MEXTRAM 504 Self-Heating Parameters

Name (Alias)	Unit	Default	Description
RTH	$^oC/W$	0	Thermal (self-heating) resistance
CTH	$J/^oC$	0	Thermal (self-heating) capacitance

Table 73 BJT LEVEL=6 MEXTRAM 504 Extrinsic Capacitance Parameters

Name (Alias)	Unit	Default	Description
CBEO	F	0	extrinsic Base-Emitter capacitance
CBCO	F	0	extrinsic Base-Collector capacitance

BJT LEVEL=6 MEXTRAM 504 DC OP Analysis Example

This example is located in the following directory:
$*installdir*/demo/hspice/bjt/mextram_dc.sp

BJT LEVEL=6 MEXTRAM 504 Transient Analysis Example

This example is located in the following directory:
$*installdir*/demo/hspice/bjt/mextram_tran.sp

BJT LEVEL=6 MEXTRAM 504 AC Analysis Example

This example is located in the following directory:

$*installdir*/demo/hspice/bjt/mextram_ac.sp

Table 74 BJT LEVEL=6 MEXTRAM504 Noise Parameters

Name	Unit	Default	Description
ABT	-	0	Temperature coefficient of the base-emitter tunneling current parameter
AET	-	0	Temperature coefficient for the base-emitter tunneling current parameter

Table 74 BJT LEVEL=6 MEXTRAM504 Noise Parameters (Continued)

Name	Unit	Default	Description
ALB	V	0	Exponential coefficient for the base-emitter tunneling current
BTJE	AV^{-2}	0	Pre-factor of the base-emitter tunneling current

Table 75 BJT LEVEL=6 MEXTRAM 504 Output Templates

Name	Alias	Description
VB2E1	LX26	Internal base-emitter bias
VB2C2	LX27	Internal base-collector bias
VB2C1	LX28	Internal base-collector bias including epilayer
VB1 C1	LX29	External base-collector bias without contact resistances
VE1E	LX30	Bias over emitter resistance
IN	LX31	Main current
IC1C2	LX32	Epilayer current
IB1B2	LX33	Pinched base current
IB1	LX34	Ideal forward base current
ISB1	LX35	Ideal side-wall base current
IB2	LX36	Non-ideal forward base current
IB3	LX37	Non-ideal reverse base current
IBET	LX38	Base-emitter tunneling current
IAVL	LX39	Avalanche current
IEX	LX40	Extrinsic reverse base current
XIEX	LX41	Extrinsic reverse base current
XISUB	LX42	Substrate current
ISF	LX43	Substrate failure current

Table 75 BJT LEVEL=6 MEXTRAM 504 Output Templates (Continued)

Name	Alias	Description
IRE	LX44	Current through emitter resistance
IRBC	LX45	Current through constant base resistance
IRCC	LX46	Current through constant collector resistance
QE	LX47	Emitter charge or emitter neutral charge
QTE	LX48	Base-emitter depletion charge
QSTE	LX49	Sidewall base-emitter depletion charge
QTC	LX50	Base-collector depletion charge
QEPI	LX51	Epilayer diffusion charge
QB1B2	LX52	AC current crowding charge
QTEX	LX53	Extrinsic base-collector depletion charge
XQTEX	LX54	Extrinsic base-collector depletion charge
QEX	LX55	Extrinsic base-collector diffusion charge
XQEX	LX56	Extrinsic base-collector diffusion charge
QTS	LX57	Collector-substrate depletion charge
GX	LX58	Forward transconductance
GY	LX59	Reverse transconductance
GZ	LX60	Reverse transconductance
GSPI	LX61	Conductance side-wall base-emitter junction
GPIX	LX62	Conductance floor base-emitter junction
GPIY	LX63	Early effect on recombination base current
GPIZ	LX64	Early effect on recombination base current
GMUX	LX65	Early effect on avalanche current limiting
GMUY	LX66	Conductance of avalanche current

Table 75 BJT LEVEL=6 MEXTRAM 504 Output Templates (Continued)

Name	Alias	Description
GUMZ	LX67	Conductance of avalanche current
GMUEX	LX68	Conductance of extrinsic base-collector junction
XGMUEX	LX69	Conductance of extrinsic base-collector junction
GRCVY	LX70	Conductance of epilayer current
GRCVZ	LX71	Conductance of epilayer current
RBV	LX72	Base resistance
GRBVX	LX73	Early effect on base resistance
GRBVY	LX74	Early effect on base resistance
GRBVZ	LX75	Early effect on base resistance
RE	LX76	Emitter resistance
RBC	LX77	Constant base resistance
RCC	LX78	Constant collector resistance
GS	LX79	Conductance parasitic PNP transistor
XGS	LX80	Conductance parasitic PNP transistor
GSF	LX81	Conductance substrate failure current
CSBE	LX82	Capacitance sidewall base-emitter junction
CBEX	LX83	Capacitance floor base-emitter junction
CBEY	LX84	Early effect on base-emitter diffusion charge
CBEZ	LX85	Early effect on base-emitter diffusion charge
CBCX	LX86	Early effect on base-collector diffusion charge
CBCY	LX87	Capacitance floor base-collector junction
CBCZ	LX88	Capacitance floor base-collector junction
CBCEX	LX89	Capacitance extrinsic base-collector junction

Table 75 BJT LEVEL=6 MEXTRAM 504 Output Templates (Continued)

Name	Alias	Description
XCBCEX	LX90	Capacitance extrinsic base-collector junction
CB1B2	LX91	Capacitance AC current crowding
CB1B2X	LX92	Cross-capacitance AC current crowding
CB1B2Y	LX93	Cross-capacitance AC current crowding
CB1B2Z	LX94	Cross-capacitance AC current crowding
CTS	LX95	Capacitance substrate-collector junction
GOUT	LX96	Output conductance
GMU	LX97	Feedback transconductance
CBE	LX98	Base-emitter capacitance
CBC	LX99	Base-collector capacitance
IQS	LX100	Current at onset of quasi-saturation
XIWEPI	LX101	Thickness of injection layer
VB2C2STA	LX102	Physical value of internal base-collector bias
PDISS	LX103	Dissipation
TK	LX104	Actual temperature
ISUBO	LX105	Substrate current
QBEI	LX106	Base-emitter diffusion charge
QBCI	LX107	Base- collector diffusion charge

Mextram 504 Update Releases

See the The following upgrades were made to the Mextram 504 model:

- Mextram 504, version 3 (504.3)
    - MULT has been moved in list of parameters

   - Lower clipping value of T_{ref} changed to -273°C
   - Added I_C, I_B and β_{dc} to operating point information
- Mextram 504, version 4 (504.4): Noise of collector epilayer has been removed
- Mextram 504, version 5 (504.5)
   - Addition of temperature dependence of thermal resistance
   - Addition of noise due to avalanche current
- Mextram 504, version 6 (504.6)
   - Added parameter dA_{I_s} for fine tuning of temperature dependence of I_{sT}
   - “G_{EM} = 0" added to equation (4.66)
   - Upper clipping value 1.0 of K_{avl} introduced
- Mextram 504, version 7 (504.7)
   - Added resistances of buried layer R_{Cblx} and R_{Cbli}, and their temperature scaling parameter A_{Cbl}.
   - Lower clipping value of resistances R_E, R_{BC}, R_{BV}, R_{Cc}, R_{Cv}, SCR_{Cv} increased to 1mΩ
   - Bug fix high temperature limit B_{nT}
- Mextram 504, version 8 (504.8)
   - Zener tunneling current in emitter-base junction— Parameters: $I_{zEB}$and N_{zEB}.
   - Material constants, implemented as parameters: V_{gzEB}, A_{VgzEB}, and T_{VgEB}.
- Mextram 504, version 10 (504.10) (F-2011-09-SP1)
   - Collector-substrate model: Physics-based temperature scaling ideal collector-substrate current; Parameters — ICSS, ASUB
   - Parasitic Base-Collector-Substrate (BCS) transistor model; Parameter — EXSUB

For detailed description of Mextram updates go to: http://mextram.ewi.tudelft.nl

LEVEL=8 HICUM Model

The HIgh CUrrent Model (HICUM) is an advanced transistor model for bipolar transistors with a primary emphasis on circuit design for high-speed/high-frequency applications. HICUM development was spurred by the SPICE Gummel-Poon model's (SGPM) inadequate level of accuracy for high-speed, large-signal transient applications and the required high-collector current densities. Other major disadvantages of the SGPM are:

- A lack of sufficient physical background
- Poor descriptions of base resistance and junction capacitances in the regions of interest
- Inadequate description of both Si- and III-V material-based HBTs.

The HICUM model is implemented as `LEVEL=8` in the BJT models and currently HSPICE supports HICUM v 2.32. The new parameters for version 2.32, 2.31and 2.3 are listed in Table 101 on page 259. The parameters for version 2.2 include those of version 2.1 are in Table 77 on page 248.

These topics are covered in the following sections:

HICUM Model Advantages

Major features of HICUM are:

- Accurate description of the high-current operating region (including quasi-saturation and saturation).
- Distributed modeling of external base-collector region.
- Proper handling of emitter periphery injection and charge storage.
- Internal base resistance as a function of operating point (conductivity modulation and emitter current crowding), and emitter geometry.
- Sufficiently physical model equations allowing predictions of temperature and process variations, as well as scalability, even at high current densities.

- Parasitic capacitances, independent on operating point, are available in the equivalent circuit, representing base-emitter and base-collector oxide overlaps, that become significant for small-size transistors.
- Weak avalanche breakdown is available.
- Self-heating effects are included. Non-quasi-static effects, resulting in a delay of collector current AND stored minority charge, are modelled as function of bias.
- Collector current spreading is included in minority charge and collector current formulation.
- Extensions for graded-base SiGe HBTs have been derived using the Generalized Integral Charge-Control Relation (GICCR); the GICCR also permits modelling of HBTs with (graded) bandgap differences within the junctions.
- Base-emitter tunneling model is available (for example, for simulation of varactor leakage).
- Simple parasitic substrate transistor is included in the equivalent circuit.
- Simple parallel RC network taking into account the frequency dependent coupling between buried layer and substrate terminal.
- Parameter extraction is closely related to the process enabling parametric yield simulation; parameter extraction procedure and list of test structures are available; HICUM parameters can be determined using standard measurement equipment and mostly simple, decoupled extraction procedures.
- Simple equivalent circuit and numerical formulation of model equations result in easy implementation and relatively fast execution time.
- Vertical NQS effects have been implemented in HICUM through “additional delay times” for both minority charge and forward transfer current.
- The correlation between base and collector noise is included in the HICUM compact model.

If you use these features with easily-measurable basic variables (such as junction capacitances and transit time), the results are more accurate than if you use SGPM. This improved accuracy applies to digital circuit, small-signal high-frequency, and especially high-speed large-signal transient simulation. Also, you can laterally scale HICUM over a wide range of emitter widths and lengths, up to high collector current densities. The scaling algorithm is generic, and has been applied to the SGPM (within its validity limits).

In summary, HICUM's major advantages over other bipolar compact models are:

- Scalability
- Process-based and relatively simple parameter extraction
- Predictive capability in terms of process and layout variations
- Fairly simple numerical formulation facilitating easy implementation and resulting in still reasonable simulation time compared to the (too) simple SGPM at high current densities

HSPICE HICUM Model vs. Public HICUM Model

The HSPICE `LEVEL=8` model is based on version 2.2 of the public HICUM model. There are two versions: version 2.1 and 2.2.

- Version 2.1, based on the Technology University of Dresden's HICUM standalone model kit source code
- Version 2.2, based on the Technology University of Dresden's HICUM Verilog-A code (current version 2.24)

To maintain flexibility, the `LEVEL=8` HICUM model uses `IS`, `MCF`, and `ZETACX` as additional model parameters. For more information on these parameters, see Table 100 on page 259.

For a complete description of HICUM model, see http://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_doc.html

LEVEL=8 Element Syntax

This section provides the syntax for BJT `LEVEL=8`, and an example of an input netlist and output format.

Syntax

```
Qxxx nc nb ne ns> <nt> mname[area] [M=val] [DTEMP=val]
+ [tnodeout]
```

Parameter	Description
Qxxx	BJT element name
nc	Collector terminal node

Parameter	Description
nb	Base terminal node, connected to 1 => 2
ne	Emitter terminal node, connected to 1 => 0
ns	Substrate terminal node
nt	Temperature node
mname	BJT model name reference
area	Emitter area multiplying factor. Affects current, resistance, capacitance. The default is 1.
M	Multiplier to simulate multiple BJTs in parallel. The default is 1.
DTEMP	Difference between the element temperature and the circuit temperature in degrees Celsius. The default is 0.0.
tnodeout	Identify self heating node from substrate node.

Example

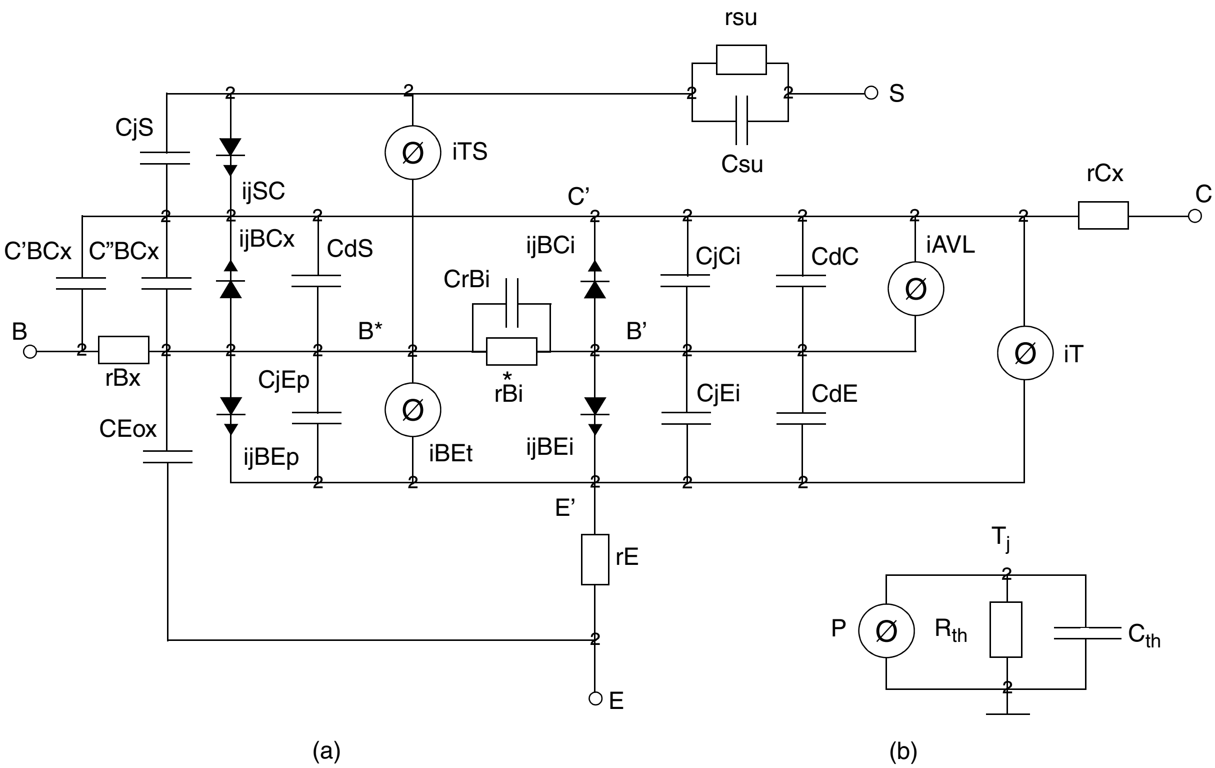
The following is an example of a BJT Q1 model:

```
Q1 1 2 0 4 QM area=1*0.5*5 dtemp=0.002
```

The preceding example includes the following connections:

- Collector is connected to node 1.
- Base is connected to node 2.
- Emitter is connected to node 0.
- Substrate is connected to node 4.
- QM references the name of the BJT model.

HICUM LEVEL=2 Circuit Diagram



Notes:
(a) The external BC capacitance consists of a depletion and a bias-independent capacitance (for example, oxide) capacitance with the ratio C'BCx / C"BCx being adjusted with respect to proper modeling of the HF behavior.
(b) Thermal network used for self-heating calculation.

Figure 36 Large-signal HICUM LEVEL=2 equivalent circuit

Input Netlist

```
.DATA test_data vbe vce vsub
0.0 0.0 0.0
0.1 0.0 0.0
0.2 0.0 0.0
0.3 0.0 0.0
0.4 0.0 0.0
0.5 0.0 0.0
0.6 0.0 0.0
0.7 0.0 0.0
0.8 0.0 0.0
0.9 0.0 0.0
1.0 0.0 0.0
.ENDDATA

.OPTION
.TEMP 26.85
VIN 2 0 vbe
VC 1 0 vce
VS 4 0 vsub
VE 3 0 0
Q1 1 2 3 4 hicum
.DC data=test_data
.PRINT DC I(VIN) i2(q1) I(VC) i1(q1) I(VCS) i4(q1)
.MODEL hicum NPN Level=8
+ tref =26.85
+ c10=.3760000E-31 qp0=.2780000E-13 ich=.2090000E-01
+ hfc=.1000000E+01
+ hfe=1.0000000E+00 hjei=.000000E+00
+ hjci=.100000E+01 tr=1.00000000E-9
+ cjei0=.81100E-14 vdei=.950000E+00 zei=.5000000E+00
+ aljei=.18000E+01
+ cjci0=.11600E-14 vdci=.800000E+00 zci=.3330000E+00
+ vptci=.41600E+03
+ rci0=.127800E+03 vlim=.700000E+00 vpt=.5000000E+01
+ vces=.100000E+00
+ t0=.47500000E-11 dt0h=.210000E-11 tbvl=.400000E-11
+ tef0=.180000E-11 gtfe=.140000E+01 thcs=.300000E-10
+ alhc=.750000E+00
+ fthc=.600000E+00
+ latb=.376500E+01 latl=.342000E+00 fqi=.9055000E+00
+ alit=.450000E+00 alqf=.225000E+00
+ favl=.118600E+01 qavl=.111000E-13 alfav=.82500E-04
+ alqav=.19600E-03
+ ibeis=.11600E-19 mbei=.101500E+01 ibeps=.10000E-29
+ mbep=.200000E+01
+ ireis=.11600E-15 mrei=.200000E+01 ireps=.10000E-29
+ mrep=.200000E+01
```

```
+ rbi0=.000000E+00 fdqr0=.00000E+00 fgeo=.730000E+00
+ fcrbi=.00000E+00
+ cjep0=.00000E+00 vdep=.105000E+01 zep=.4000000E+00
+ aljep=.24000E+01
+ ceox=.000000E+00
+ cjcx0=.00000E+00 vdcx=.700000E+00 zcx=.3330000E+00
+ vptcx=.10000E+03
+ ccox=.000000E+00 fbc=.1526000E+00
+ ibcxs=.10000E-29 mbcx=.200000E+01 ibcis=.11600E-19
+ mbci=.101500E+01
+ cjs0=.000000E+00 vds=.6000000E+00 zs=.44700000E+00
+ vpts=.100000E+04
+ rcx=.0000000E+00 rbx=.0000000E+00 re=.00000000E+00
+ kf=.00000000E+00 af=.00000000E+00
+ vgb=.1170000E+01 alb=.6300000E-02 alt0=.000000E+00
+ kt0=.0000000E+00
+ zetaci=.1600E+01 alvs=.100000E-02 alces=.40000E-03
+ zetarbi=0.5880E+00       zetarcx=0.2230E+00
+ zetarbx=0.2060E+00         zetare=0.0000E+00
+ rth=0.0 cth=0.0
+ ibets=.00000E+00 abet=.000000E+00
+ itss=.000000E+00 msf=.0000000E+00 tsf=0.000000E+00
+ iscs=.000000E+00
+ msc=.0000000E+00
+ rsu=.0000000E+00 csu=.0000000E+00
.END
```

LEVEL=8 Model Parameters

This section lists the HICUM `LEVEL=8` model parameters, internal transistor parameters, peripheral element parameters, and external element parameters for version 2.1. The parameters for version 2.2 include those of version 2.1 and new parameters listed in Table 77. This includes parameter names, descriptions, units, default values, factors, and notes.

Table 76   BJT LEVEL=8 Model Parameters

Name (Alias)	Unit	Default	Description
LEVEL	-	8	HICUM BJT level
TREF	C	26.85	Temperature in simulation
SYNOPSYS_UPDATE	-	1	Flag for bug fixing. ■ 1: bug fixed by Synopsys ■ 0: no bug fix

Table 76 BJT LEVEL=8 Model Parameters (Continued)

Name (Alias)	Unit	Default	Description
CDCI_UPDATE		1	Flag for CDCI equation; This flag can be used for SYNOPSY_UPDATE = 1 ■ 1=latest equation ■ 0=old equation
VERSION	-	2.24	HICUM version

Table 77 BJT LEVEL=8 Parameters Added in Version 2.2

Name	Unit	Default	Factor	Description
CBEPAR	-	1.0		Total parasitic BE capacitance (spacer and metal)
F1VG	V/K	1.02377e-4		Coefficient K1 in T dependent bandgap equation
F2VG	V/K	4.3215e-4		Coefficient K2 in T dependent bandgap equation
FBEPAR	-	0		Partitioning factor of parasitic BE capacitance
FLSH	-	0	M	Self-heating flag, also has instance parameter. If FLSH is not 0 and RTH>0, ON; otherwise OFF.
TBHREC	ps	0		BC recombination time constant at the BC barrier for high forward injection
TUNODE	-	1		Tunneling flag (1=on peripheral node; 0=on internal node)
VGC	V	1.17		Effective collector bandgap voltage V_gC_{eff}
VGE	V	1.17		Effective emitter bandgap voltage V_gE_{eff}
VGS	V	1.17		Effective substrate bandgap voltage V_gS_{eff}
ZETABET	-	5		Exponent coefficient in BE junction current temperature dependence
ZETACT	-	4.5		Exponent coefficient in transfer current temperature dependence

The default parameter values for HICUM version 2.2 are as follows:

****

```
.DATA test_data vbe vce vsub
0.0 0.0 0.0
0.1 0.0 0.0
0.2 0.0 0.0
0.3 0.0 0.0
0.4 0.0 0.0
0.5 0.0 0.0
0.6 0.0 0.0
0.7 0.0 0.0
0.8 0.0 0.0
0.9 0.0 0.0
1.0 0.0 0.0
.ENDDATA
.OPTION post
.TEMP 26.85
VIN 2 0 vbe
VC 1 0 vce
VS 4 0 vsub
VE 3 0 0
Q1 1 2 3 4 hicum
.DC data= test_data
.PRINT DC I(VIN) i2(q1) I(VC) i1(q1) I(VCS) i4(q1)
.MODEL hicum NPN Level=8
+ tref = 26.85
+ c10=.3760000E-31 qp0=.2780000E-13 ich=.2090000E-01
+ hfc=.1000000E+01
+ hfe=1.0000000E+00 hjei=.000000E+00
+ hjci=.100000E+01 tr=1.00000000E-9
+ cjei0=.81100E-14 vdei=.950000E+00 zei=.5000000E+00
+ aljei=.18000E+01
+ cjci0=.11600E-14 vdci=.800000E+00 zci=.3330000E+00
+ vptci=.41600E+03
+ rci0=.127800E+03 vlim=.700000E+00 vpt=.5000000E+01
+ vces=.100000E+00
+ t0=.47500000E-11 dt0h=.210000E-11 tbvl=.400000E-11
+ tef0=.180000E-11 gtfe=.140000E+01 thcs=.300000E-10
+ alhc=.750000E+00
+ fthc=.600000E+00
+ latb=.376500E+01 latl=.342000E+00 fqi=.9055000E+00
+ alit=.450000E+00 alqf=.225000E+00
+ favl=.118600E+01 qavl=.111000E-13 alfav=.82500E-04
+ alqav=.19600E-03
+ ibeis=.11600E-19 mbei=.101500E+01 ibeps=.10000E-29
+ mbep=.200000E+01
+ ireis=.11600E-15 mrei=.200000E+01 ireps=.10000E-29
+ mrep=.200000E+01
+ rbi0=.000000E+00 fdqr0=.00000E+00 fgeo=.730000E+00
+ fcrbi=.00000E+00
```

```
+ cjep0=.00000E+00 vdep=.105000E+01 zep=.4000000E+00
+ aljep=.24000E+01
+ ceox=.000000E+00
+ cjcx0=.00000E+00 vdcx=.700000E+00 zcx=.3330000E+00
+ vptcx=.10000E+03
+ ccox=.000000E+00 fbc=.1526000E+00
+ ibcxs=.10000E-29 mbcx=.200000E+01 ibcis=.11600E-19
+ mbci=.101500E+01
+ cjs0=.000000E+00 vds=.6000000E+00 zs=.44700000E+00
+ vpts=.100000E+04
+ rcx=.0000000E+00 rbx=.0000000E+00 re=.00000000E+00
+ kf=.00000000E+00 af=.00000000E+00
+ vgb=.1170000E+01 alb=.6300000E-02 alt0=.000000E+00
+ kt0=.0000000E+00
+ zetaci=.1600E+01 alvs=.100000E-02 alces=.40000E-03
+ zetarbi=0.5880E+00 zetarcx=0.2230E+00
+ zetarbx=0.2060E+00 zetare=0.0000E+00
+ rth=0.0 cth=0.0
+ ibets=.00000E+00 abet=.000000E+00
+ itss=.000000E+00 msf=.0000000E+00 tsf=0.000000E+00
+ iscs=.000000E+00
+ msc=.0000000E+00
+ rsu=.0000000E+00 csu=.0000000E+00
.END
```

Internal Transistors

This section lists the HICUM `LEVEL=8` internal transistor parameters. This includes parameter names, descriptions, units, default values, factors, and notes.

Table 78 BJT LEVEL=8 Transfer Current Parameters

Name (Alias)	Unit	Default	Factor	Description
C10	A^{2s}	2e-30	M^2	Constant. The IS setting determines the C10 parameter value. If IS > 0, then C10=IS * QP0; otherwise, C10=C10. IS=1.0e-16; C10=2.0e-30.
QP0	As	2e-14		Zero-bias hole charge
ICH	A	1e+20		High-current correction for 2D/3D
HFC	-	1		Weighting factor for Qfc (mainly for HBTs)
HFE	-	1		Weighting factor for Qef in HBTs

Table 78 BJT LEVEL=8 Transfer Current Parameters (Continued)

Name (Alias)	Unit	Default	Factor	Description
HJCI	-	1		Weighting factor for Qjci in HBTs
HJEI	-	1		Weighting factor for Qjei in HBTs

Table 79 BJT LEVEL=8 BE Depletion Capacitance Parameters

Name (Alias)	Unit	Default	Factor	Description
ALJEI (AJEI)	-	2.5		Ratio of max. to zero-bias value
CJEI0	F	0		Zero-bias value
VDEI	V	0.9		Built-in voltage
ZEI	-	0.5		Exponent coefficient

Table 80 BJT LEVEL=8 BC Depletion Capacitance Parameters

Name (Alias)	Unit	Default	Factor	Description
ALJEP (AJEP)	-	2.5		Ratio of max. to zero-bias value
CJCI0	F	0	M	Zero-bias value
VDCI	V	0.7		Built-in voltage
ZCI	-	0.4		Exponent coefficient
VPTCI	V	1e+20		Punch-through voltage (=q Nci w^2ci /(2epsilion))

Table 81 BJT LEVEL=8 Forward Transit Time Parameters

Name (Alias)	Unit	Default	Factor	Description
ALHC	-	0.1		Smoothing factor for current dep. C and B transit time
ALQF	-	0		Factor for additional delay time of Q_f

Table 81 BJT LEVEL=8 Forward Transit Time Parameters (Continued)

Name (Alias)	Unit	Default	Factor	Description
DT0H	s	0		Time constant for base and BC SCR width modulation
FLNQS	-	0		NQS flag (NQS supported in V2.23); also has instance parameter
FTHC	-	0		Partitioning factor for base and collection portion
GTFE	-	1		Exponent factor for current dep. emitter transit time
T0	s	0		Low current transit time at V_{BC}=0
TBVL	s	0		Voltage for modeling carrier jam at low VC'E'
TEF0	s	0		Storage time in neutral emitter
THCS	s	0		Saturation time constant at high current densities

Table 82 BJT LEVEL=8 Critical Current Parameters

Name (Alias)	Unit	Default	Factor	Description
RCI0	Ohm	150	1/M	Low-field resistance of internal collector region
VLIM	V	0.5		Voltage separating ohmic and SCR regime
VPT	V	1e+20		Epi punch-through vtg. of BC SCR
VCES	V	0.1		Internal CE sat. vtg.

Table 83 BJT LEVEL=8 Inverse Transit Time Parameter

Name (Alias)	Unit	Default	Factor	Description
TR	s	0		Time constant for inverse operation

Table 84 BJT LEVEL=8 Base Current Component Parameters

Name (Alias)	Unit	Default	Factor	Description
IBEIS	A	1e-18	M	BE saturation current
MBEI	-	1		BE saturation current
IREIS	A	0	M	BE recombination saturation current
MREI	-	2		BE recombination non-ideality factor
TBHREC	ps	0		BC recombination time constant at the BC barrier for high forward injection
IBCIS	A	1e-16	M	BC saturation current
MBCI	-	1		BC non-ideality factor

Table 85 BJT LEVEL=8 Weak BC Avalanche Breakdown Parameters

Name (Alias)	Unit	Default	Factor	Description
FAVL	1/V	0		Prefactor for CB avalanche effect
QAVL	C	0	M	Exponent factor for CB avalanche effect

Table 86 BJT LEVEL=8 Internal Base Resistance Parameters

Name (Alias)	Unit	Default	Factor	Description
FCRBI	-	0		Ratio of HF shunt to total internal capacitance.
FDQR0	-	0		Correction factor for BE and BC SCR modulation
FGEO	-	0.6557		Geometry factor (corresponds to long emitter stripe)
FQI	-	1.0		Ratio of internal to total minority charge
RBI0	Ohm	0	1/M	Value at zero-bias

Table 86 BJT LEVEL=8 Internal Base Resistance Parameters (Continued)

Name (Alias)	Unit	Default	Factor	Description
RBX	Ohm	0	1/M	External base series resistance
RCX	Ohm	0	1/M	External collector series resistance
RE	Ohm	0	1/M	Emitter series resistance

Table 87 BJT LEVEL=8 Lateral Scaling

Name (Alias)	Unit	Default	Factor	Description
LATB	-	0		Scaling factor for Qfc in l_E ("l" is the letter L—not the number 1)
LATL	-	0		Scaling factor for Qfc in l_E direction ("l" is the letter L—not the number 1)

Peripheral Elements

This section lists the HICUM `LEVEL=8` model peripheral element parameters. This includes parameter names, descriptions, units, default values, factors, and notes.

Table 88 BJT LEVEL=8 BE Depletion Capacitance

Name (Alias)	Unit	Default	Factor	Description
ALJEP	-	2.5		Ratio of max. to zero-bias value
CJEP0	F	0	M	Zero-bias value
VDEP	V	0.9		Built-in voltage
ZEP	-	0.5		Depletion coeff

Table 89 BJT LEVEL=8 Base Current

Name (Alias)	Unit	Default	Factor	Description
IBEPS	A	0	M	Saturation current
IREPS	A	0	M	Recombination saturation factor
MBEP	-	1		Non-ideality factor
MREP	-	2		Recombination non-ideality factor

Table 90 BJT LEVEL=8 BE Tunneling

Name (Alias)	Unit	Default	Factor	Description
ABET	-	40		Exponent coefficient
IBETS	A	0	M	Saturation current
TUNODE	-	1		Tunneling flag (1=on peripheral node; 0=on internal node)

External Elements

This section lists the HICUM `LEVEL=8` model external element parameters. This includes parameter names, descriptions, units, default values, factors, and notes.

Table 91 BJT LEVEL=8 BC Capacitance

Name (Alias)	Unit	Default	Factor	Description
CBEPAR	-	1.0		Total parasitic BE capacitance (spacer and metal)
CCOX (CBCPAR)	F	0	M	Collector oxide capacitance
CJCX0	F	0	M	Zero-bias depletion value
FBC (FDCPAR)	-	0		Partitioning factor for C_BCX =C’_BCx+C”_BCx
FBEPAR	-	0		Partitioning factor of parasitic BE capacitance
VDCX	V	0.7		Built-in voltage

Table 91 BJT LEVEL=8 BC Capacitance (Continued)

Name (Alias)	Unit	Default	Factor	Description
VPTCX	V	1e+20		Punch-through voltage
ZCX	-	0.4		Exponent coefficient

Table 92 BJT LEVEL=8 BC Base Current Component

Name (Alias)	Unit	Default	Factor	Description
IBCXS	A	0	M	Saturation current
MBCX	-	1		Non-ideality factor

Table 93 BJT LEVEL=8 Other External Elements

Name (Alias)	Unit	Default	Factor	Description
RBX	Ohm	0	1/M	External base series resistance
RE	Ohm	0	1/M	Emitter series resistance
RCX	Ohm	0	1/M	External collector series resistance

Table 94 BJT LEVEL=8 Substrate Transistor Parameters

Name (Alias)	Unit	Default	Factor	Description
ISCS	A	0	M	Saturation current of CS diode
ITSS	A	0	M	Transfer saturation current
MSC	-	1		Non-ideality factor of CS diode
MSF	-	1		Non-ideality factor (forward transfer current)
TSF	s	0		Minority charge storage transit time

Table 95 BJT LEVEL=8 Collector-Substrate Depletion Capacitance

Name (Alias)	Unit	Default	Factor	Description
CJS0	F	0	M	Zero-bias value of CS depletion cap
VDS	V	0.6		Built-in voltage
VPTS	V	1e+20		Punch-through voltage
ZS	-	0.5		Exponent coefficient

Table 96 BJT LEVEL=8 Substrate Coupling Network

Name (Alias)	Unit	Default	Factor	Description
RSU	Ohm	0	1/M	Substrate series resistance
CSU	F	0		Substrate capacitance from permittivity of bulk material

Table 97 BJT LEVEL=8 Noise Parameters

Name (Alias)	Unit	Default	Factor	Description
KF	-	0	M^{1-AF}	Flicker noise factor (no unit only for AF=2!)
AF	-	2		Flicker noise exponent factor

Table 98 BJT LEVEL=8 Temperature Dependence Parameters

Name (Alias)	Unit	Default	Factor	Description
ALCES	1/K	0		Relative temperature coefficient of VCES
ALFAV	1/K	0		Relative temperature coefficient for avalanche breakdown

Table 98 BJT LEVEL=8 Temperature Dependence Parameters (Continued)

Name (Alias)	Unit	Default	Factor	Description
ALQAV	1/K	0		Relative temperature coefficient for avalanche breakdown
ALT0	1/K	0		First-order relative temperature coefficient, TEF0
ALVS	1/K	0		Relative temperature coefficient of saturation drift velocity
F1VG	V/K	1.02377e-4		Coefficient K1 in T dependent bandgap equation
F2VG	V/K	4.3215e-4		Coefficient K2 in T dependent bandgap equation
KT0	$1/K^2$	0		Second-order relative temperature coefficient, TEF0
VGB	V	1.17		Bandgap voltage
VGC	V	1.17		Effective collector bandgap voltage V_gC_{eff}
VGE	V	1.17		Effective emitter bandgap voltage V_gE_{eff}
VGS	V	1.17		Effective substrate bandgap voltage V_gS_{eff}
ZETABET	-	5		Exponent coefficient in BE junction current temperature dependence
ZETACT	-	4.5		Exponent coefficient in transfer current temperature dependence
ZETARBI	-	0		Temperature exponent factor of RBI0
ZETARBX	-	0		Temperature exponent factor of RBX
ZETARCX	-	0		Temperature exponent factor of RCX
ZETARE	-	0		Temperature exponent factor of RE

To use the self-heating HICUM feature (in BJT `LEVEL=8`), set `VERS=2.1` and set an `RTH` parameter value other than 0. If you use vers=2.0 or `RTH=0`, then self-heating is OFF.

The self-heating effect also applies to the circuit temperature as an increased self-heating temperature. T=Tckt(circuit temperature) + Tsh(self heating temperature) + dtemp (difference between circuit temperature and ambient temperature).

Table 99 BJT LEVEL=8 Self-Heating Parameters

Name (Alias)	Unit	Default	Factor	Description
RTH	K/W	0	1/M	Thermal resistance (not supported in v2000.4)
CTH	Ws/K	0	M	Thermal resistance (not supported in v2000.4)
FLSH	-	0	M	Self-heating flag, also has instance parameter. If FLSH is not 0 and RTH>0, ON; otherwise OFF.

Table 100 BJT LEVEL=8 Other Parameters

Name (Alias)	Unit	Default	Factor	Description
IS	A	-1.0		Ideal saturation current
MCF	-	1.0		Non-ideal factor of reverse current between base and collector. VT=VT*MCF
ZETACX	-	1.0		Temperature exponent factor (epi-layer)

HICUM v2.3 Added Parameters

Table 101 BJT LEVEL=8 Version 2.32, 2.31 and 2.3 Added Parameters

Name (Alias)	Unit	Default	Description
DELCK	-	1	Fitting factor for *ICK*
AHJEI	-	0	Parameter describing the slope of *hjEi(VBE)*
RHJEI	-	1	Smoothing parameter for *hjEi(VBE)* at high voltage
DVGBE	V	0	Bandgap difference between base and BE-junction, used for *hjEi0* and *hf0*.
ZETAHJEI	-	1	Temperature coefficient for *ahjEi*
ZETAVGBE	-	1	Temperature coefficient for *hjEi0*
HF0	-	1	Weight factor for the low current minority charge
VCBAR	V	0	Barrier voltage

Table 101 BJT LEVEL=8 Version 2.32, 2.31 and 2.3 Added Parameters (Continued)

Name (Alias)	Unit	Default	Description
ACBAR	-	1	Smoothing parameter for barrier voltage
ICBAR	A	1	Normalization parameter
ZETARTH	K/W	1	Temperature coefficient for R*th*
KFRE	-	0	*RE*flicker noise coefficient
AFRE	-	2	*RE*flicker noise exponent factor

LEVEL=9 VBIC99 Model

The VBIC 95 (Vertical Bipolar Inter-Company Model) for Motorola bipolar transistor device is installed in the device models as BJT `LEVEL=4`. VBIC99 is a newer version of the VBIC model, and is implemented in the device models as BJT `LEVEL=9`.

To use the VBIC99 model, set the `LEVEL` parameter to 9 for the bipolar transistor model.

The VBIC99 model includes several effects that are improved compared to the VBIC95 model.

- In VBIC99, the temperature coefficients of the base and collector resistances are split.
- The temperature dependence of the built-in potential is also improved.

The following topics are discussed in these sections:

- Level 9 Usage Notes
- LEVEL=9 Element Syntax
- Effects of VBIC99
- Model Implementation
- LEVEL=9 Model Parameters

Level 9 Usage Notes

The following information applies to the HSPICE device model for the VBIC99 device:

- Set `LEVEL` to 9 to identify the model as a VBIC99 bipolar junction transistor model.
- The reference temperature, `TREF`, equals 27 degrees.
- The VBIC99 model supports `AREA` and `M` factor scaling.
- This model supports self-heating. Model parameters are `RTH` and `CTH`.

LEVEL=9 Element Syntax

```
Qxxx nc nb ne [ns] mname [AREA=val] [OFF] [VBE=val] [VCE=val]
+ [M=val] [DTEMP=val]
```

Parameter	Description
Qxxx	BJT element name. Must begin with Q, followed by up to 1023 alphanumeric characters.
Nc	Collector terminal node name or number.
Nb	Base terminal node name and number.
Ne	Emitter terminal node name or number.
Ns	Substrate node name or number.
t	Self heating node name or number.
Mname	BJT model name reference.
AREA	The normalized emitter area. VBIC99 LEVEL=9 model has no area effect. Default value=1. Area is used only as an alias of the multiplication factor (M).
OFF	Sets the initial condition to OFF for this element in DC analysis. You cannot use OFF with VBE or VCE.
VBE	Initial internal base-emitter voltage.
VCE	Initial internal collector-emitter voltage.
M	Multiplier to simulate multiple BJTs in parallel.

Parameter	Description
DTEMP	The temperature difference between the element and circuit.

Effects of VBIC99

The VBIC99 model includes several effects that are improved compared to the VBIC95 model:

- Addition of temperature dependency for several parameters.
- Base-emitter breakdown model.
- Reach-through model for base-collector depletion capacitance.
- High-current beta rolloff effect.
- Fixed collector-substrate capacitance,
- Reverse transport saturation current.

Model Implementation

The following parameters were added to the VBIC99 model and are not in the VBIC95 model.

ISRR	IKF	VRT	ART	QBM
DEAR	EAP	VBBE	NBBE	IBBE
TVBBE1	TVBBE2	TNBBE	EBBE	CCSO
XRCX	XRBX	XRBP	XIXF	XISR

LEVEL=9 Model Parameters

These tables describe VBIC99 as HSPICE BJT `LEVEL=9` model parameters, including parameter names, descriptions, units, default values, and notes. Parameters with an asterisk (*) are not used in the DC model.

Table 102 LEVEL=9 VBIC99 Basic Parameters

Parameter	Unit	Default	Description
LEVEL	-	9	Model level
TREF	W	27.0	Nominal measurement temperature of parameters
ART	-	0.1	*smoothing parameter for reach-through
AVC1	1/V	0.0	Base-collector avalanche parameter 1
AVC2	1/V	0.0	Base-collector avalanche parameter 2
DEAR	-	0.0	*delta activation energy for ISRR
EA	EV	1.12	Activation energy for IS
EAIC	EV	1.12	Activation energy for IBCI/IBEIP
EAIE	EV	1.12	Activation energy for IBEI
EAIS	EV	1.12	Activation energy for IBCIP
EANC	EV	1.12	Activation energy for IBCN/IBENP
EANE	EV	1.12	Activation energy for IBEN
EANS	EV	1.12	Activation energy for IBCNP
EAP	-	1.12	*activation energy for ISP
EBBE	-	0.0	exp(-VBBE/(NBBE*Vtv))
GAMM	-	0.0	Epi doping parameter
HRCF	-	0.0	High current RC factor
IBBE	-	1.0e-6	* base-emitter breakdown current
IBCI	A	1.0e-16	Ideal base-collector saturation current
IBCIP	A	0.0	Ideal parasitic base-collector saturation current

Table 102 LEVEL=9 VBIC99 Basic Parameters (Continued)

Parameter	Unit	Default	Description
IBCN	A	0.0	Non-Ideal base-collector saturation current
IBCNP	A	0.0	Non-Ideal base-collector saturation current
IBEI	A	1.0e-18	Ideal base-emitter saturation current
IBEIP	A	0.0	Ideal parasitic base-emitter saturation current
IBEN	A	0.0	Non-Ideal base-emitter saturation current
IBENP	A	0.0	Non-Ideal parasitic base-emitter saturation current
IKF	A	0.0	Forward knee current, zero means infinity
IKP	A	0.0	Parasitic knee current, zero means infinity
IKR	A	0.0	Reverse knee current, zero means infinity
IS	A	1.0e-16	Transport saturation current
ISP	A	0.0	Parasitic transport saturation current
ISRR	A	1.0	*Reverse transport saturation current
ITF	A	0.0	Coefficient of TF dependence on Ic
MC	-	0.33	Base-collector Grading coefficient
ME	-	0.33	Base-emitter Grading coefficient
MS	-	0.33	Substrate-collector Grading coefficient
NBBE	-	1.0	* base-emitter breakdown emission coefficient
NCI	-	1.0	Ideal base-collector emission coefficient
NCIP	-	1.0	Ideal parasitic base-collector emission coefficient
NCN	-	2.0	Non-ideal base-collector emission coefficient
NCNP	-	2.0	Ideal parasitic base-collector emission coefficient
NEI	-	1.0	Ideal base-emitter emission coefficient
NEN	-	2.0	Non-ideal base-emitter emission coefficient

Table 102 LEVEL=9 VBIC99 Basic Parameters (Continued)

Parameter	Unit	Default	Description
NF	-	1.0	Forward emission coefficient
NFP	-	1.0	Parasitic forward emission coefficient
NKF	-	0.5	*High current beta roll off parameter
NR	-	1.0	Reverse emission coefficient
PC	V	0.75	Base-collector built-in potential
PE	V	0.75	Base-emitter built-in potential
PS	V	0.75	Substrate-collector built-in potential
QBM	-	0.0	*base charge model selection
QTF	-	0.0	Variation of TF with base-width modulation
RBI	W	0.0	Intrinsic collector Resistance
RBP	W	0.0	Parasitic base Resistance
RBX	W	0.0	Extrinsic collector Resistance
RCI	W	0.0	Intrinsic collector Resistance
RCX	W	0.0	Extrinsic collector Resistance
RE	W	0.0	Emitter Resistance
RS	W	0.0	Substrate Resistance
TF	S	0.0	Forward transit time
TNBBE	-	0.0	*temperature coefficient of NBBE
TR	S	0.0	Reverse transit time
TVBBE1	-	0.0	*linear temperature coefficient of VBBE
TVBBE2	-	0.0	*quadratic temperature coefficient of VBBE
VBBE	-	0.0	*base-emitter breakdown voltage
VEF	V	0.0	Forward early voltage, zero means infinity

Table 102 LEVEL=9 VBIC99 Basic Parameters (Continued)

Parameter	Unit	Default	Description
VER	V	0.0	Reverse early voltage, zero means infinity
VO	V	0.0	Epi drift saturation voltage
VRT	V	0.0	*reach-through voltage for Cbc limiting
VTF	V	0.0	Coefficient of TF dependence on Vbc
WBE	-	1.0	Portion of IBEI from Vbei, 1-WBE from Vbex
WSP	-	1.0	Portion of ICCP from Vbep, 1-WBE from Vbci
XTF	-	0.0	Coefficient of TF bias dependence

Table 103 LEVEL=9 VBIC99 Capacitance/Charge Parameters

Parameter	Unit	Default	Description
AJC	-	-0.5	Base-collector cap smoothing factor
AJE	-	-0.5	Base-emitter cap. Smoothing factor
AJS	-	-0.5	Substrate-collector cap. Smoothing factor
CBCO	F	0.0	Extrinsic base-collector overlap cap
CBEO	F	0.0	Extrinsic base-emitter overlap cap
CCSO	F	0.0	*Fixed collector-substrate capacitance
CJC	F	0.0	Base-collector zero bias cap
CJCP	F	0.0	Substrate-collector zero bias cap
CJE	F	0.0	Base-emitter zero bias cap
CJEP	F	0.0	Base-collector extrinsic zero bias cap
FC	-	0.9	Forward bias depletion cap limit
QCO	Coul	0.0	Epi charge parameter

Table 104 LEVEL=9 VBIC99 Temperature Coefficients

Parameter	Unit	Default	Description
TAVC	1/K	0.0	Temperature coefficient of AVC2
TNF	1/K	0.0	Temperature exponent of NF
XII	-	3.0	Temperature exponent of IBEI/IBCI/IBEIP/IBCIP
XIKF	-	0.0	*Temperature exponent of IKF
XIN	-	3.0	Temperature exponent, IBEN/IBCN/IBENP/IBCNP
XIS	-	3.0	Temperature exponent of IS
XISR	-	0.0	*Temperature exponent of ISRR
XRBI	-	0.0	Temperature exponent of intrinsic base resistance
XRBP	-	0.0	*Temperature exponent of parasitic base resistance
XRBX	-	0.0	*Temperature exponent, extrinsic collector resistance
XRCI	-	0.0	Temperature exponent, intrinsic collector resistance
XRCX	-	0.0	*Temperature exponent of extrinsic base resistance
XRE	-	0.0	Temperature exponent of emitter resistance
XRS	-	0.0	Temperature exponent of substrate resistance
XVO	-	0.0	Temperature exponent of VO

Table 105 LEVEL=9 VBIC99 Noise Parameters

Parameter	Unit	Default	Description
AFN	-	1.0	Base-emitter Flicker noise exponent
KFN	-	0.0	Base-emitter Flicker noise constant
BFN	-	1.0	Base-emitter Flicker noise 1/f dependence

Table 106 LEVEL=9 VBIC99 Self-heating Parameters

Parameter	Unit	Default	Description
RTH	K/W	0.0	Thermal resistance
CTH	J/K	0.0	Thermal capacitance

Table 107 LEVEL=9 VBIC99 Excess Phase Parameter

Parameter	Unit	Default	Description
TD	S	0.0	Forward excess-phase delay time

VBIC99 LEVEL=9 AC Analysis Example

The VBIC99 level9 AC test example is located in the following directory:
$*installdir*/demo/hspice/bjt/vbic99_ac.sp

VBIC99 LEVEL=9 DC Analysis Example

The VBIC99 level9 DC test example is located in the following directory:
$*installdir*/demo/hspice/bjt/vbic99_dc.sp

VBIC99 LEVEL=9 TRAN Analysis Example

The VBIC99 level9 transient test example is located in the following directory:
$*installdir*/demo/hspice/bjt/vbic99_tran.sp

LEVEL=10 Philips MODELLA Bipolar Model

The Philips MODELLA `LEVEL=10` provides a highly-accurate compact model for lateral pnp integrated circuit transistors. This model is based directly on device physics. It uses a physical modelling approach where the main currents and charges are independently related to bias-dependent minority carrier concentrations. It also models current crowding effects, high injection effect, and a bias-dependent output impedance. Table 108 describes the transistor parameters for this model.

Table 108 BJT LEVEL=10 Transistor Parameters

Name (Alias)	Unit	Default	Description
LEVEL		10	Model level
AE		4.48	Temperature coefficient of BF
AF		1.00	Flicker noise exponent
BF		131.00	Ideal forward common-emitter current gain
BR		25.00	Ideal reverse common-emitter current gain
CJC	F	3.90e-13	Zero-bias collector-base depletion capacitance
CJE	F	6.10e-14	Zero-bias emitter-base depletion capacitance
CJS	F	1.30e-12	Zero-bias substrate-base depletion capacitance
DTA	oC	0.00	Difference between the device temperature and the ambient analysis temperature
EAFL	V	20.50	Early voltage of the lateral forward current component at zero collector-base bias
EAFV	V	75.00	Early voltage of the vertical forward current component at zero collector-base bias
EARL	V	13.10	Early voltage of the lateral reverse current component at zero emitter-base bias
EARV	V	104.00	Early voltage of the vertical reverse current component at zero emitter-base bias
EXPHI		0.00	rad Excess phase shift
IBF	A	2.60e-14	Saturation current of non-ideal forward base current
IBR	A	1.20e-13	Saturation current of non-ideal reverse base current
IK	A	1.10e-4	High injection knee current
IS	A	1.80e-16	Collector-emitter saturation current
ISS	A	4.00e-13	Saturation current of substrate-base diode
KF		0.00	Flicker noise coefficient

Table 108 BJT LEVEL=10 Transistor Parameters (Continued)

Name (Alias)	Unit	Default	Description
PC		0.36	Collector-base grading coefficient
PE		0.30	Emitter-base grading coefficient
PS		0.35	Substrate-base grading coefficient
RBCC	W	10.00	Constant part of the base resistance RBC
RBCV	W	10.00	Variable part of the base resistance RBC
RBEC	W	10.00	Constant part of the base resistance RBE
RBEV	W	50.00	Variable part of the base resistance RBE
RCEX	W	5.00	External part of the collector resistance
RCIN	W	47.00	Internal part of the collector resistance
REEX	W	27.00	External part of the emitter resistance
REIN	W	66.00	Internal part of the emitter resistance
RSB	W	1.00e15	Substrate-base leakage resistance
SNB		2.60	Temperature coefficient of epitaxial base electron mobility
SNBN		0.30	Temperature coefficient, buried layer electron mobility
SPB		2.853	Temperature coefficient, epitaxial base hole mobility
SPC		0.73	Temperature coefficient of collector hole mobility
SPE		0.73	Temperature coefficient of emitter hole mobility
SX		1.00	Temperature coefficient of combined minority carrier mobilities in emitter and buried layer
TFN	S	2.00e-10	Low injection forward transit time due to charge stored in emitter, and buried layer under the emitter
TFVR	S	3.00e-8	Low injection forward transit time due to charge stored in the epilayer under the emitter
TLAT	S	2.40e-9	Low injection (forward/reverse) transit time of charge stored in epilayer between emitter and collector

Table 108 BJT LEVEL=10 Transistor Parameters (Continued)

Name (Alias)	Unit	Default	Description
TREF	oC	25.00	Reference temperature of the parameter set
TRN	S	3.00e-9	Low injection reverse transit time due to charge stored in collector, and buried layer under collector
TRVR	S	1.00e-9	Low injection reverse transit time due to charge stored in the epilayer under the collector
VDC	V	0.57	Collector-base diffusion voltage
VDE	V	0.52	Emitter-base diffusion voltage
VDS	V	0.52	Substrate-base diffusion voltage
VGB	V	1.206	Bandgap voltage, base between emitter and collector
VGCB	V	1.206	Bandgap voltage of collector-base depletion region
VGE	V	1.206	Bandgap voltage of the emitter
VGEB	V	1.206	Bandgap voltage of the emitter-base depletion region
VGJE	V	1.123	Bandgap voltage recombination emitter-base junction
VGSB	V	1.206	Bandgap voltage of substrate-base depletion region
VLF	V	0.54	V Cross-over voltage, non-ideal forward base current
VLR	V	0.48	Cross-over voltage of non-ideal reverse base current
XCS		3.00	Ratio between the saturation current of c-b-s transistor and c-b-e transistor
XES		2.70e-3	Ratio between saturation current of e-b-s transistor and e-b-c transistor
XHCS		1.00	Fraction of substrate current of c-b-s transistor subject to high injection
XHES		0.70	Fraction of substrate current of e-b-s transistor subject to high injection
XIFV		0.43	Vertical fraction of forward current
XIRV		0.43	Vertical fraction of reverse current

The following topics are discussed in these sections:

- Equivalent Circuits
- DC Operating Point Output
- Model Equations
- Temperature Dependence of Parameters

Equivalent Circuits

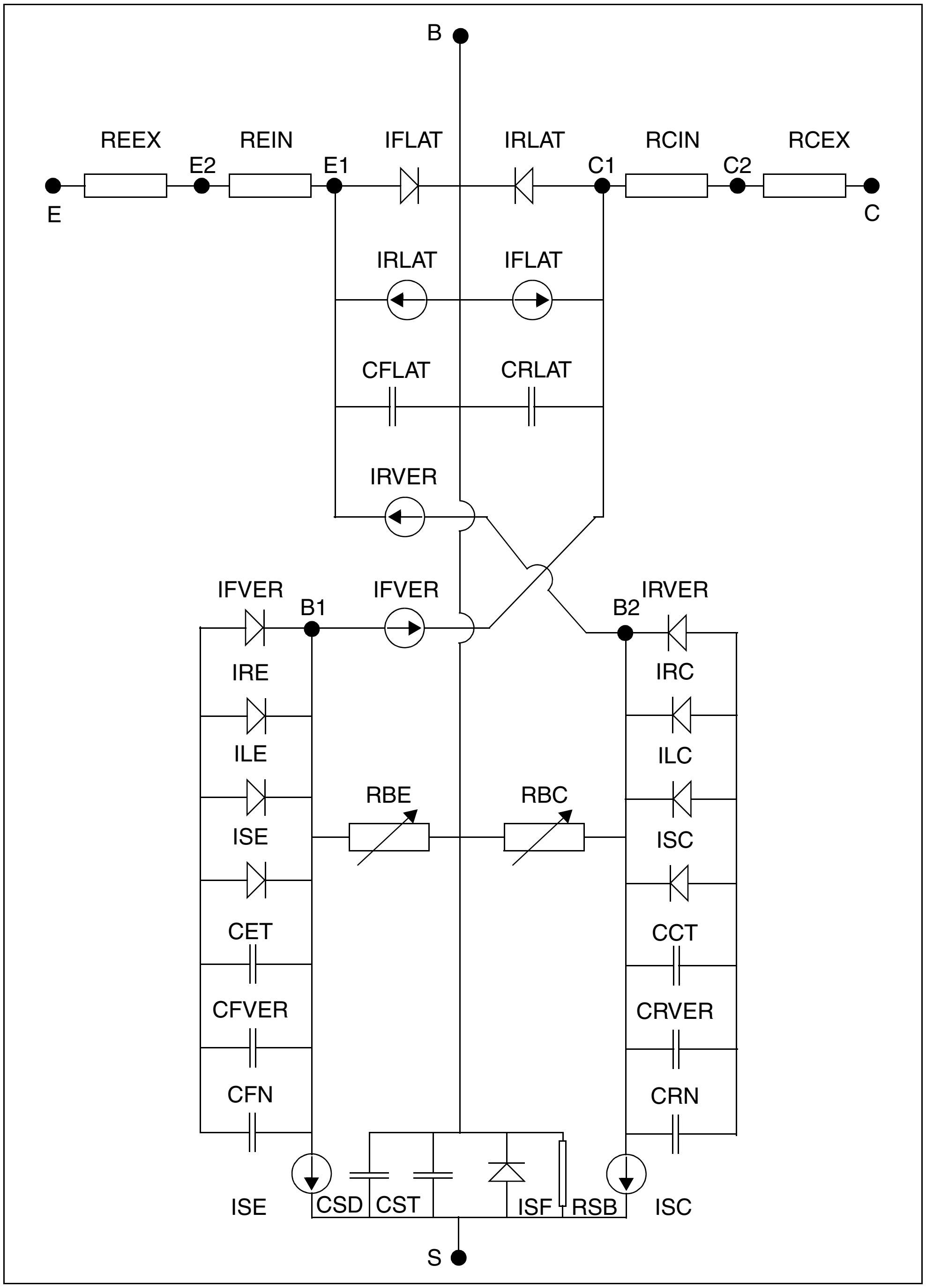


Figure 37 Large-signal Equivalent Circuit

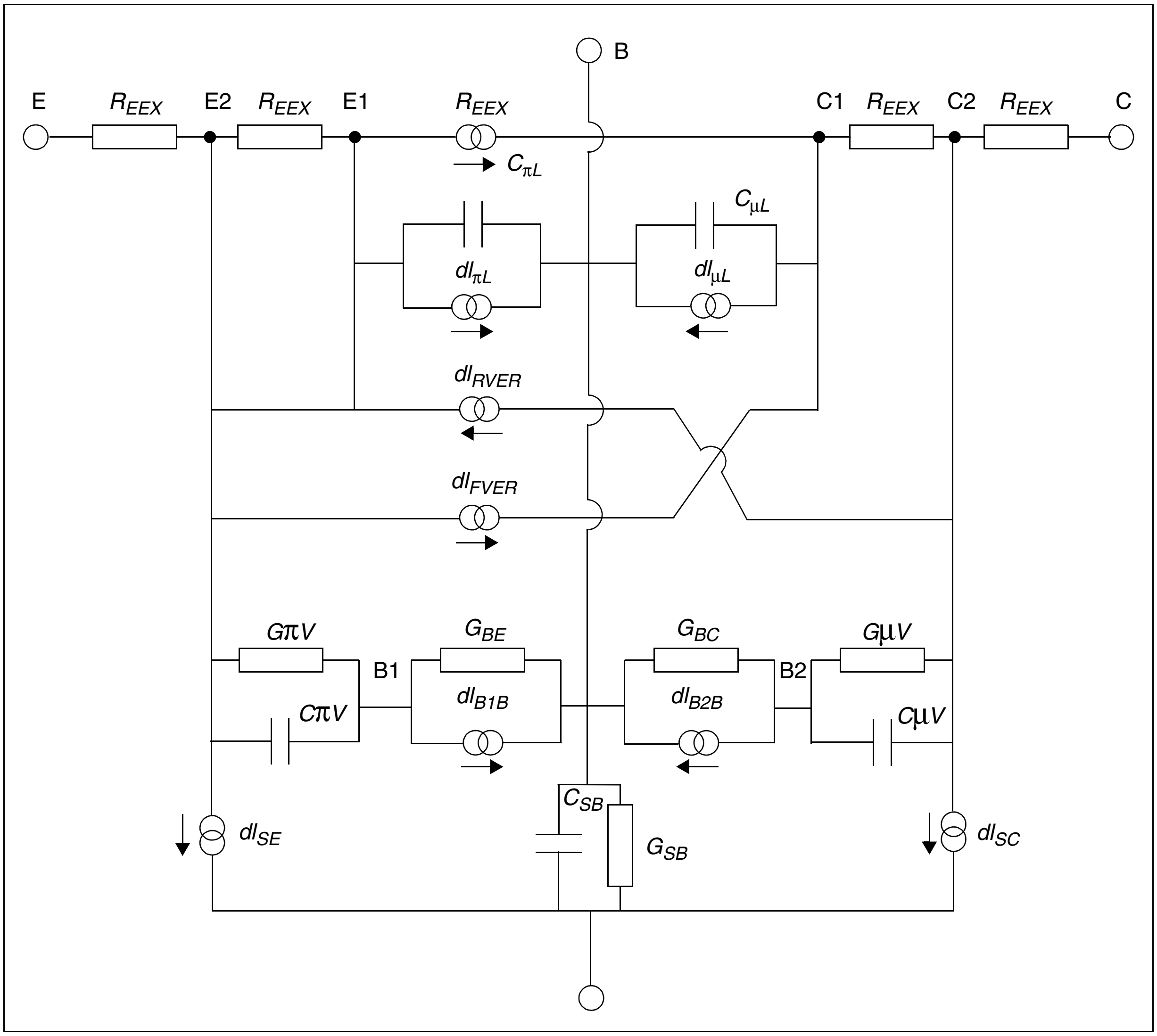


Figure 38 Small-signal Equivalent Circuit

DC Operating Point Output

The DC operating point output facility gives information on the state of a device at its operation point. Figure 1 shows the DC large signal equivalent circuit. Figure 38 shows the small signal equivalent circuit. `REEX`, `REIN`, `RCIN` and `RCEX` are constant resistors.

$$dI_{LAT} = g_{fL} \times dV_{E1B} - g_{rL} \times dV_{C1B}$$

$$dI_{FVER} = g_{11} \times dV_{E2B1} + g_{12} \times dV_{C1B}$$

$$dI_{RVER} = g_{21} \times dV_{E1B} + g_{22} \times dV_{C2B2}$$

$$dI_{B1B} = G_{IBE} \times dV_{E2B1}$$

$$dI_{B2B} = G_{IBC} \times dV_{C2B2}$$

$$dI_{PL} = jw \times C_{IPL} \times dV_{C1B}$$

$$dI_{mL} = jw \times C_{ImL} \times dV_{E1B}$$

$$dI_{SE} = G_{ISE} \times dV_{E2B1}$$

$$dI_{SC} = G_{ISC} \times dV_{C2B2}$$

Table 109 BJT LEVEL=10, DC Operating Point Parameters

Name (Alias)	**Description**
CMUL	Reverse diffusion capacitance, lateral path: $\partial Q_{RLAT} / \partial V_{C1B}$
CMUV	Reverse total capacitance, vertical path: $\partial (Q_{tc} + Q_{rver} + Q_{rn}) / \partial V_{C2B2}$
CPIL	Forward diffusion cap., lateral path: $\partial Q_{FLAT} / \partial V_{E1B}$
CPIV	Forward total capacitance, vertical path: $\partial (Q_{TE} + Q_{FVER} + Q_{FN}) / \partial V_{E2B1}$
CSB	Total capacitance s-b junction: $\partial Q_{TS} / \partial V_{SB} + \partial Q_{SD} / \partial V_{SB}$
G11	Forward conductance, vertical path.: $\partial I_{FVER} / \partial V_{E2B1}$
G12	Collector Early-effect on I_{FVER}: $\partial I_{FVER} / \partial V_{C1B}$
G21	Emitter Early-effect on I_{RVER}: $\partial I_{RVER} / \partial V_{E1B}$
G22	Reverse conductance, vertical path.: $\partial I_{RVER} / \partial V_{C2B2}$
GFL	Forward conductance, lateral path.: $\partial I_{FLAT} / \partial V_{E1B1}$
GMU	Conductance c-b junction: $\partial (I_{RC} + I_{LC}) / \partial V_{C2B2}$
GPI	Conductance e-b junction: $\partial (I_{RE} + I_{LE}) / \partial V_{E2B1}$
GRL	Reverse conductance, lateral path.: $\partial I_{RLAT} / \partial V_{C1B}$
GSB	Conductance s-b junction: $\partial I_{SF} / \partial V_{SB} + 1/R_{SB}$

Model Equations

Early Factors

The Early factors for the components of the main current I p are derived from the variation of the depletion widths in the base relative to the base width itself.

Early factor of the lateral current components

$$FLAT = hyp_1\left\{1 - \left(\frac{\sqrt{\left(1 - \frac{V}{VD}\right) + \delta}}{1 + \frac{EARL}{2VD}} - \frac{\sqrt{\left(1 - \frac{V_1}{VD}\right)^2 + \delta}}{1 + \frac{EAFL}{2VD}}\right) \cdot \ \delta_E\right\}$$

Early factor of the forward vertical current component

$$FFVR = hyp_1\left\{1 - \left(\frac{\sqrt[4]{\left(1 - \frac{V_{E2B1}}{VD_T}\right)^2 + \delta}}{1 + \frac{EARV}{2VD_T}} - \frac{\sqrt[4]{\left(1 - \frac{V_{CLB}}{VD_T}\right)^2 + \delta}}{1 + \frac{EAFV}{2VD_T}}\right) \cdot \ \delta_E\right\}$$

Early factor of the reverse vertical current component

$$FRVER = hyp_1\left\{1 - \left(\frac{\sqrt[4]{\left(1 - \frac{V_{E1B}}{VD_T}\right)^2 + \delta}}{1 + \frac{EARV}{2VD_T}} - \frac{\sqrt[4]{\left(1 - \frac{V_{C2B2}}{VD_T}\right)^2 + \delta}}{1 + \frac{EAFV}{2VD_T}}\right) \cdot \ \delta_E\right\}$$

Model Parameters

- `EAFL`
- `EAFV`
- `EARL`
- `EARV`

Currents

The ideal diode equations are as follows.

$$\text{If }1 = I_S(e^{\text{Ve1b/Vt}} - 1)$$

$$\text{If }2 = I_S(e^{\text{Ve2b1/Vt}} - 1)$$

$$\text{Ir }1 = I_S(e^{\text{Vc1b/Vt}} - 1)$$

$$\text{Ir }2 = I_S(e^{\text{Vc2b2/Vt}} - 1)$$

model parameter: Is

The Ip main current is as follows.

$$Ip = I_{flat} + I_{fver} - I_{rlat} - I_{rver}$$

Forward currents—Iflat and Ifver

The main forward current is separated into lateral and vertical components, originating from the emitter-base junction sidewall and bottom, respectively. These formulations include Early and high injection effects. Because the two currents depend on different internal emitter-base junction voltages, emitter current crowding is also modelled.

The lateral forward current component (Iflat) is:

$$I_{flat} = \left(\frac{4 \times (1 - Xifv) \times \text{If }1}{3 + \sqrt{1 + 16 \times \frac{\text{If }1}{Ik}}}\right) \div Flat$$

The vertical forward current component (I_{fver}) is:

$$I_{fver} = \left(\frac{4 \times Xifv \times \text{If }2}{3 + \sqrt{1 + 16 \times \frac{\text{If }2}{Ik}}}\right) \div Ffver$$

Model parameters:

- `Xifv`
- `Ik`

Reverse currents—Irlat and Irver

The main reverse current contains lateral and vertical components, originating from the collector-base junction sidewall and bottom, respectively. These formulations include Early and high injection effects. The two currents depend on different internal collector-base junction voltages, collector current crowding is also modelled.

The lateral reverse current component (Irlat) is:

$$I_{rlatt} = \left(\frac{4 \times (1 - Xirv) \times \mathrm{Ir}\,1}{3 + \sqrt{1 + 16 \times \dfrac{\mathrm{Ir}\,1}{Ik}}} \right) \div Flat$$

The vertical reverse current component (Irver) is:

$$I_{rver} = \left(\frac{4 \times Xirv \times \mathrm{Ir}\,2}{3 + \sqrt{1 + 16 \times \dfrac{\mathrm{Ir}\,2}{Ik}}} \right) \div Frver$$

Model parameter: `Xirv`

Base Current

Forward components

The total forward base current is composed of an ideal and a non-ideal component. Both components depend on the bottom part of the emitter-base junction.

Ideal component:

$$Ire = \frac{\mathrm{If}\,2}{Bf}$$

Non-ideal component:

$$Ile = \frac{Ibf \times (e^{\mathrm{Ve2b1/Vt}} - 1)}{e^{\mathrm{Ve2b1/Vt}} + e^{\mathrm{Vlf/2Vt}}}$$

Model parameters:

- `Bf`
- `Ibf`
- `Vif`

Reverse components

The total reverse base current is composed of an ideal and a non-ideal component. Both components depend on the bottom part of the collector-base junction.

Ideal component:

$$Irc = \frac{\mathrm{Ir}\,2}{Br}$$

Non-ideal component:

$$Ilc = \frac{Ibr \times (e^{\mathrm{Vc2b2/Vt}} - 1)}{e^{\mathrm{Vc2b2/2Vt}} + e^{\mathrm{Vlt/2Vt}}}$$

Model parameters:

- `Br`
- `Ibr`
- `Vlr`

Substrate current

Forward components

The forward substrate component depends on the bottom part of the emitter-base junction. It consists of an ideal component, and a component subject to high injection effects. The `XHES` parameter determines the fraction that is subject to high injection.

$$Ise = (1 - Xhes) \times Xes \times \mathrm{If}\,2 + \frac{4 \times Xhes \times Xes \times \mathrm{If}\,2}{3 + \sqrt{1 + 16 \times \frac{\mathrm{If}\,2}{Ik}}}$$

Model parameters:

- `Xes`
- `Xhes`

Reverse components

The reverse substrate component depends on the bottom part of the collector-base junction. It consists of an ideal component, and a component subject to high injection effects. The XHCS parameter determines the fraction that is subject to high injection.

$$Isc = (1 - Xhcs) \times Xcs \times \mathrm{Ir}\,2 + \frac{4 \times Xhcs \times Xcs \times \mathrm{Ir}\,2}{3 + \sqrt{1 + 16 \times \frac{\mathrm{Ir}\,2}{Ik}}}$$

Model parameters:

- Xcs
- Xhcs

Additional Substrate and Base current

An ideal diode models the substrate-base junction. You can use the reverse leakage current of this junction to model the zero-crossover phenomena, sometimes observed in the base current at low bias conditions and high temperatures.

$$Isf = Iss \times (e^{\mathrm{Vsb/Vt}} - 1)$$

Model parameter: Iss

Charges

Depletion Charges

The Poon-Gummel formulation models the depletion charges.

Emitter-base depletion charge

$$Qte = \frac{-Cje}{1 - Pe} \times \left\{ \frac{Vde - Ve2b1}{\left[\left(1 - \frac{Ve2b1}{Vde}\right)^2 + \delta\right]^{\frac{Pe}{2}}} \right\}$$

Model parameters:

- `Cje`
- `Vde`
- `Pe`

Collector-base depletion charge

$$Qtc = \frac{-Cjc}{1-Pc} \times \left\{ \frac{Vdc - Vc2b2}{\left[\left(1 - \frac{Vc2b2}{Vdc}\right)^2 + \delta\right]^{\frac{Pc}{2}}} \right\}$$

Model parameters:

- `Cjc`
- `Vdc`
- `Pc`

Substrate-base depletion charge

$$Qts = \frac{-Cjs}{1-Ps} \times \left\{ \frac{Vds - Vsb}{\left[\left(1 - \frac{Vsb}{Vds}\right)^2 + \delta\right]^{\frac{Ps}{2}}} \right\}$$

Model parameters:

- `Cjs`
- `Vds`
- `Ps`

Forward Stored Charges

Storing forward-active charges consists of three main components.

- Charge stored in epitaxial base region between emitter and collector:

$$Qflat = Tlat \times Ik \times \left(\sqrt{1 + 16 \times \frac{\mathrm{If}1}{Ik}} - 1\right) \times \frac{Flat}{8}$$

- Charge stored in epitaxial base region under emitter:

$$Qfver = Tfvr \times Ik \times \left(\sqrt{1 + 16 \times \frac{\mathrm{If}\,2}{Ik}} - 1\right) \times \frac{1}{8}$$

- Charge stored in emitter and buried layer under emitter:

  $$Qfn = Tfn \times \mathrm{If}\,2$$

Reverse Stored Charges

Storing reverse-active charges consists of three main components.

- Charge stored in epitaxial base region between emitter and collector:

  $$Qrlat = Tlat \times Ik \times \left(\sqrt{1 + 16 \times \frac{\mathrm{Ir}\,1}{Ik}} - 1\right) \times \frac{Flat}{8}$$

- Charge stored in epitaxial base region under collector:

  $$Qrver = Trvr \times Ik \times \left(\sqrt{1 + 16 \times \frac{\mathrm{Ir}\,2}{Ik}} - 1\right) \times \frac{1}{8}$$

- Charge stored in collector and buried layer under collector:

  $$Qrn = Trn \times \mathrm{Ir}\,2$$

Substrate-base Stored Charge

Charge stored in the substrate and base, due to the substrate-base junction. This charge storage occurs only when the substrate-base junction is forward biased:

$$Qsd = Tsd \times Isf$$

Note: Tsd is a constant.

Series Resistances

The emitter includes the following series resistance:

- Reex—constant
- Rein—constant

The collector includes the following series resistance:

- Rcex—constant
- Rcin—constant

The conductivity modulation of the base resistances is derived from the fact that the voltage drop across the epitaxial layer, is inversely proportional to the electron concentration under the emitter and collector.

Base resistance under the emitter:

$$Rbe = Rbec + \frac{2 \times Rbev}{\sqrt{1 + 16 \times \frac{\mathrm{If}\,2}{Ik}}}$$

Base resistance under the collector:

$$Rbc = Rbcc + \frac{2 \times Rbcv}{\sqrt{1 + 16 \times \frac{\mathrm{Ir}\,2}{Ik}}}$$

The Rb resistance models the ohmic leakage, across the substrate-base junction.

Noise Equations

For noise analysis current sources are added to the small signal equivalent circuit. In these equations:

- f represents the operation frequency of the transistor.
- Df is the bandwidth.

When measured at 1 Hz, a noise density is obtained.

Thermal Noise

$$\overline{iN^2{}_{REEX}} = \frac{4 \cdot k \cdot Tk}{REEX} \cdot \Delta f$$

$$\overline{iN^2{}_{REIN}} = \frac{4 \cdot k \cdot Tk}{REIN} \cdot \Delta f$$

$$\overline{iN^2{}_{RCIN}} = \frac{4 \cdot k \cdot Tk}{RCIN} \cdot \Delta f$$

$$\overline{iN^2{}_{RCEX}} = \frac{4 \cdot k \cdot Tk}{RCEX} \cdot \Delta f$$

$$\overline{iN^2{}_{RBE}} = \frac{4 \cdot k \cdot Tk}{RBE} \cdot \Delta f$$

$$\overline{iN^2}_{RBC} = \frac{4 \cdot k \cdot Tk}{RBC} \cdot \Delta f$$

$$\overline{iN^2}_{RSB} = \frac{4 \cdot k \cdot Tk}{RSB} \cdot \Delta f$$

Lateral Collector Current Shot Noise

$$\overline{iN^2}_{CLAT} = 2 \cdot q \cdot |I_{FLAT} - I_{RLAT}| \cdot \Delta f$$

Vertical Collector Current Shot Noise

$$\overline{iN^2}_{CVER} = 2 \cdot q \cdot |I_{FVER} - I_{RVER}| \cdot \Delta f$$

Forward-base Current Shot Noise and 1/f Noise

$$\overline{iN^2}_{B} = 2 \cdot q \cdot |I_{RE} - I_{LE}| \cdot \Delta f + \frac{KF \cdot MULTI^{1-AF} \cdot |I_{RE} \cdot I_{LE}|^{AF}}{f} \cdot \Delta f$$

Temperature Dependence of Parameters

$$Tk = Tref + 273.16$$

$$Tn = \frac{Temp}{Tref + 273.16}$$

$$Ti = \frac{1}{Tref + 273.16} - \frac{1}{Temp}$$

Series Resistance

$$RCIN_T = RCIN \times T_N^{SPC}$$

$$RBCC_T = RBCC \times T_N^{SNBN}$$

$$RBCV_T = RBCV \times T_N^{SNB}$$

$$RBEC_T = RBEC \times T_N^{SNBN}$$

$$RBEV_T = RBEV \times T_N^{SNB}$$

The BJT `LEVEL=10` model assumes that `REEX` and `RCEX` are temperature independent.

Depletion Capacitances

$$VDxt = -3k\frac{TEMP}{q} \cdot \; 1n(T_N) + VDx \cdot \; T_N + (1 - T_N) \cdot \; Vgap$$

$$CJ_{XT} = CJx \cdot \; \left(\frac{VDx}{VD_{XT}}\right)^{PX}$$

Emitter-base Junction

Vgap=VGEB, x=E

Collector-base Junction

Vgap=VGCB, x=C

Substrate-base Junction

Vgap=VGSB, x=S

Temperature Dependence of Other Parameters

$$VD_T = -3k\frac{TEMP}{q} \cdot \; 1n(T_N) + VD \cdot \; T_N + (1 - T_N) \cdot \; VGB$$

$$EAFL_T = EAFL \cdot \; \sqrt{\frac{VD_T}{VD}}$$

$$EARL_T = EARL \cdot \; \sqrt{\frac{VD_T}{VD}}$$

$$EAFV_T = EAFV \cdot \; \sqrt{\frac{VD_T}{VD}}$$

$$EARV_T = EARV \cdot \; \sqrt{\frac{VD_T}{VD}}$$

$$IS_T = IS \cdot \; T_N^{(4.0 - SPB)} \cdot \; \exp(q \cdot \; VGB \cdot \; {}^{T_I}/\; k)$$

$$BF_T = BF \cdot \; T_N^{(AE - SPB)} \cdot \; \exp\{q \cdot \; (VGB - VGE) \cdot \; {}^{T_I}/\; k\}$$

$$IBF_T = IBF \cdot T_N^{2} \cdot \exp\{q \cdot (VGJE/2) \cdot T_I / k\}$$

$$IK_T = IK \cdot T_N^{(1 - SPB)}$$

$$BR_T = BR \cdot \frac{BF_T}{BF}$$

$$IBR_T = IBR \cdot \frac{IBF_T}{IBF}$$

$$ISS_T = ISS \cdot T_N^{2} \cdot \exp\{q \cdot VGSB \cdot T_I / k\}$$

$$TLAT_T = TLAT \cdot T_N^{(SPB - 1.0)}$$

$$TFVR_T = TFVR \cdot \frac{TLAT_T}{TLAT}$$

$$TFN_T = TFN \cdot T_N^{(SX - 1.0)}$$

$$TRVR_T = TRVR \cdot \frac{TLAT_T}{TLAT}$$

$$TRN_T = TRN \cdot \frac{TFN_T}{TFN}$$

All other model parameters are temperature-independent.

LEVEL=11 UCSD HBT Model

The UCSD High Speed Devices Group in collaboration with the HBT Model Working Group, has been developing better SPICE models for heterojunction bipolar transistors (HBTs). The HSPICE implementation of the UCSD HBT MODEL is based on the website: http://hbt.ucsd.edu

- Usage Notes
- LEVEL=11 Element Syntax
- Model Equations

- Equivalent Circuit
- Example Model Statement for BJT LEVEL=11

Usage Notes

The following information applies to the HSPICE device model for the UCSD HBT device:

1. Set BJT `LEVEL=11`.
2. The default room temperature is 25o C in the HSPICE, but is 27o C in most other simulators. When comparing to other simulators, do one of the following:
   - set the simulation temperature to 27, or
   - set `TEMP 27`, or
   - set `.OPTION TNOM=27`
3. The set model parameter should always include the model reference temperature, `TREF`. The default value for `TREF` is 27.
4. You can use `DTEMP` with this model to increase the temperature of individual elements, relative to the circuit temperature. Set its value on the element line.
5. The HBT (BJT `LEVEL=11`) model includes self-heating effects. If you turn on self-heating, then set `RTH` to more than zero and `SELFT` to 1 in the model card.

LEVEL=11 Element Syntax

```
Qxxx nc nb ne [ns] mname [AREA=val] [OFF] [VBE=val]
   + [VCE=val] [M=val] [DTEMP=val]
```

Parameter	Description
Qxxx	BJT element name. Must begin with Q, which can be followed by up to 1023 alphanumeric characters.
nc	Collector terminal node name or number.
nb	Base terminal node name and number.

Parameter	Description
ne	Emitter terminal node name or number.
ns	Substrate node name or number.
t	Self-heating node name or number.
mname	BJT model name reference.
AREA	Normalized emitter area.
OFF	Sets initial condition to OFF for this element in DC analysis. You cannot use OFF with VBE or VCE.
VBE	Initial internal base-emitter voltage.
VCE	Initial internal collector-emitter voltage.
M	Multiplier to simulate multiple BJTs in parallel.
DTEMP	Difference between the temperature of the element and circuit.

Table 110 BJT LEVEL=11 Parameters

Parameter	Unit	Default	Description
AFN	-	1	BE flicker noise exponent for current
BF	-	10000	Forward ideal current gain
BFN	-	1	BE flicker noise exponent for frequency
BKDN	logic	false	Flag indicating to include BC breakdown
BR	-	10000	Reverse ideal current gain
BVC	V	1000	Collector-base breakdown voltage BVcbo
CCMIN	F	0	Minimum value of intrinsic BC Cj
CEMIN	F	0	Minimum BE capacitance
CJC	F	0	Intrinsic BC depletion capacitance at zero bias
CJCX	F	0	Extrinsic BC depletion capacitance at zero bias

Table 110 BJT LEVEL=11 Parameters (Continued)

Parameter	Unit	Default	Description
CJE	F	0	BE depletion capacitance at zero bias
CJS	F	0	Collector-substrate depletion capacitance (0 bias)
CTH	C/Joule	0	Thermal capacitance of device.
CXMIN	F	0	Minimum extrinsic Cbc
EAA	V	0	Added activation energy, ISE temp dependence
EAB	V	0	Added activation energy, ISC temp dependence
EAC	V	0	Activation energy, ISB temperature dependence
EAE	V	0	Activation energy, ISA temperature dependence
EAX	V	0	Added activation energy, ISEX temp dependence
EG	V	1.5	Activation energy for IS temperature dependence
FA	-	0.9	Factor for specification of avalanche voltage
FC	-	0.8	Factor for start of high bias BC Cj approximation
FCE	-	0.8	Factor for start of high bias BE Cj approximation
FEX	-	0	Factor to determine excess phase
ICRIT0	A	1e3	Critical current for intrinsic Cj variation
ICS	A	1e-30	Saturation value for collector-substrate current
IK	A	1e10	Knee current for dc high injection effect
IKRK	A	1e3	Characteristic current for Kirk effect
IS	A	1e-25	Saturation value for forward collector current
ISA	A	1e10	Collector current EB barrier limiting current
ISB	A	1e10	Collector current BC barrier limiting current
ISC	A	1e-30	Saturation value for intrinsic bc junction current
ISCX	A	1e-30	Saturation value for extrinsic bc junction current

Table 110 BJT LEVEL=11 Parameters (Continued)

Parameter	Unit	Default	Description
ISE	A	1e-30	Saturation value for non-ideal base current
ISEX	A	1e-30	Saturation value for emitter leakage diode
ITC	A	0	Characteristic current for TFC
ITC2	A	0	Characteristic current for TFC
KFN	-	0	BE flicker noise constant
MJC	-	0.33	Exponent for voltage variation of Intrinsic BC Cj
MJCX	-	0.33	Exponent for voltage variation, Extrinsic BC Cj
MJE	-	0.5	Exponent for voltage variation of BE Cj
MJS	-	0.5	Exponent for voltage variation of CS Cj
NA	-	2	Collector current EB barrier ideality factor
NB	-	2	Collector current BC barrier ideality factor
NBC	-	8	Exponent for BC multiplication factor vs voltage
NC	-	2	Ideality factor for intrinsic bc junction current
NCS	-	2	Ideality factor for collector-substrate current
NCX	-	2	Ideality factor for extrinsic bc junction current
NE	-	2	Ideality factor for non-ideal forward base current
NEX	-	2	Ideality factor for emitter leakage diode
NF	-	1	Forward collector current ideality factor
NR	-	1	Reverse current ideality factor
RBI	ohm	0	Intrinsic base resistance
RBX	ohm	0	Extrinsic base resistance
RCI	ohm	0	Intrinsic collector resistance
RCX	ohm	0	Extrinsic collector resistance

Table 110 BJT LEVEL=11 Parameters (Continued)

Parameter	Unit	Default	Description
RE	ohm	0	Emitter resistance
REX	ohm	0	Extrinsic emitter leakage diode series resistance
RTH	C/W	0	Thermal resistance, device to thermal ground
SELFT	-	0	Flag. Indicates whether to use self-heating. 0 (default) does not use self-heating. 1 turns on the self-heating feature.
TBCXS	S	0	Excess BC heterojunction transit time
TBEXS	S	0	Excess BE heterojunction transit time
TFB	S	0	Base transit time
TFC0	S	0	Collector forward transit time
TKRK	S	0	Forward transit time for Kirk effect
TNC	-	0	Coefficient for NC temperature dependence
TNE	-	0	Coefficient for NE temperature dependence
TNEX	-	0	Coefficient for NEX temperature dependence
TR	S	0	Reverse charge storage time, intrinsic BC diode
TREF	C	27	Temperature at which model parameters are given
TRX	S	0	Reverse charge storage time, extrinsic BC diode
TVJC	V/C	0	Coefficient for VJC temperature dependence
TVJCX	V/C	0	Coefficient for VJCX temperature dependence
TVJE	V/C	0	Coefficient for VJE temperature dependence
TVJS	V/C	0	Coefficient for VJS temperature dependence
VAF	V	1000	Forward Early voltage
VAR	V	1000	Reverse Early voltage

Table 110 BJT LEVEL=11 Parameters (Continued)

Parameter	Unit	Default	Description
VJC	V	1.4	Intrinsic BC diode built-in potential for Cj estimation
VJCX	V	1.4	Extrinsic BC diode built-in potential for Cj estimation
VJE	V	1.6	BE diode built-in potential for Cj estimation
VJS	V	1.4	CS diode built-in potential for Cj estimation
VKRK	V	1e3	Characteristic Voltage for Kirk effect
VTC	V	1e3	Characteristic voltage for TFC
XCJC	-	1	Factor for partitioning extrinsic BC Cj
XRB	-	0	Exponent for RB temperature dependence
XRC	-	0	Exponent for RC temperature dependence
XRE	-	0	Exponent for RE temperature dependence
XREX	-	0	Exponent for REX temperature dependence
XTB	-	2	Exponent for beta temperature dependence
XTI	-	2	Exponent for IS temperature dependence
XTIKRK	-	0	Exponent for IKRK temperature dependence
XTITC	-	0	Exponent for ITC temperature dependence
XTITC2	-	0	Exponent for ITC2 temperature dependence
XTTF	-	0	Exponent for TF temperature dependence
XTTKRK	-	0	Exponent for TKRK temperature dependence
XTVKRK	-	0	Exponent for VKRK temperature dependence

Model Equations

This section describes the model equations for the HSPICE BJT `LEVEL=11` model.

Current Flow

There are seven different current flow calculations for the BJT `LEVEL=11` device model.

- Intrinsic collector current contributions. This model computes the electron flow between Ei and Ci nodes by using equations similar to the Gummel-Poon model with modifications to take into account the potential spike that can appear at the base-emitter or base-collector junctions of HBTs. This model separates the electron current into forward and reverse components, Icf and Icr.

  Icf=IS * [exp(qVbei/NF/KT) - 1] / D
  Icr=IS * [exp(qVbci/NR/KT) -1] / D

  In these equations:

  D= qb + IS* exp(qVbei/NA/KT) / ISA + IS*exp(qVbci/NB/KT)/ISB

  `ISA`, `ISB`, `NA` and `NB` are new parameters. `ISA` and `ISB` approximate the transition currents, from base-transport controlled to potential-barrier controlled, current flow.

  `qb` partially retains the standard BJT model form (a fractional increase in the base charge associated with the bias changes).

  qb= q1/2 * [1+(1+4*q2)0.5]
  q1=1/ [1 - Vbci/VAF -Vbei/VAR]
  q2=IS/IK*[exp(qVbei/NF/KT)-1]

  In the preceding equations, `qb` omits the reverse knee current contribution. As noted in the following, `qb` is not used to define the ac model in the fashion of the Gummel-Poon model.

  The total collector current Icc is:

  Icc=Icf - Icr

  This formulation uses the `IS`, `NF`, `VAF`, `VAR`, and `IK` parameters, established in the SPICE BJT model in addition to the `ISA`, `ISB`, `NA`, and `NB` parameters described above.

- Intrinsic Base-Emitter Diode. Ideal and non-ideal components are included:

  Ibei= Icf / BF + ISE * [exp (q Vbei/ NE /KT) - 1]

- Extrinsic Base-Emitter Diode. The `LEVEL=11` model includes a diode connected between the Ex and E nodes, and an associated series resistance (Rex). You can use the diode and its resistance to model contributions from emitter edges.

Ibex=ISEX * [exp (q Vbex/ NEX /KT) - 1]

- Intrinsic Base-Collector Diode. Ideal and non-ideal components are included:

  Ibci=Icr / BR + ISC * [exp (q Vbci/ NC /KT) - 1]

- Intrinsic Base-Collector Breakdown Current. Ibk is current between the collector and base nodes, generated due to avalanche breakdown of the base-collector junction. If you set the `BKDN` parameter to true, then Ibk is determined according to:

  Ibk= (Mf -1) * Icf
  Otherwise, Ibk=0

  The preceding equations use the following definitions:

  - Mf is the multiplication factor associated with the BC junction at the specified voltage.
  - Icf is the forward electron current (as computed above in the absence of multiplication).

    Mf is calculated with a physically based expression, modified to avoid the singularity at Vbci=-`BVC`.

    Mf depends exclusively on the intrinsic base-intrinsic collector voltage, Vbci. If -Vbci closely approaches or exceeds `BVC` (-Vbci>FA*`BVC` with `FA` typically chosen to be 0.95), then the multiplication factor is computed according to a constant slope expression.

    Mf=1 / [1- (-Vbci/BVC)^NBC] for KTop/q< -Vbci < FA*BVC
    Mf=1 for -Vbci > KTop/q
    Mf=Mfl + gl *(-Vbci-FA*BVC) for -Vbci > FA*BVC

    In the preceding equations, Mfl and gl are the values of Mf and its derivative with respect to voltage, evaluated at the voltage -Vbci=FA*`BVC`:

    Mfl=1 / (1-FA^NBC)
    gl=Mfl*(Mfl-1)*NBC/(FA*BVC)

- Extrinsic Base-Collector Diode. This diode has customary I-V characteristics with its own saturation current and ideality factor.

Ibcx= ISCX * [exp(q Vbcx/ NCX /KTop) - 1]

- Substrate-Extrinsic Collector Diode. This diode allows for conducting substrates. Use it primarily for SiGe HBTs.

  Ics= ICS * [exp(-q Vcs/ NCS /KTop) - 1]

  In accordance with the model topology, the external currents through the E,B, and C nodes are:

  Ib= Ibei + Ibex - Ibk + Ibci + Ibcx
  Ic= Icc + Ibk -Ibci-Ibcx - Ics

Charge Storage

This section describes the following different charge storage calculations for the HSPICE BJT `LEVEL=11` device model.

- Base-Emitter Charge. The overall charge stored at the base-emitter junction has components associated with the base-emitter depletion layer:
  - Qbej, which is current-independent.
  - Qbediff, a collector current-dependent charge. Qbediff corresponds to a portion of the base charge, and the (collector current-dependent) base-collector charge.

    Qbe= Qbej + Qbediff

- Base-Emitter Depletion Charge, Qbej. The depletion charge, Qbej, follows equations standard for SPICE, modified to allow specification of a minimum capacitance `CEMIN` (corresponding to reach-through to an n+ layer).

  As studied by Chris Grossman, there is often an extra component of charge storage at the base-emitter heterojunction of HBTs, associated with a minimum in the conduction band energy profile.

  Qbej is computed using DepletionCapMod.

  Define:

  Vmin= VJE*[1-(CJE/CEMIN)(1/MJE)]

  (the critical voltage for attaining the minimum capacitance value)

  If Vbei<FCE*VJE and Vbei<Vmin:

  Qbej=CEMIN*(Vbei-VJE)+CEMIN*VJE*MJE/(MJE-1) *
  (CJE/CEMIN)(1/MJE)

  Cbej=dQbej/dVbei=CEMIN

If Vbei<FCE*VJE and Vbei>Vmin:

Qbej= -CJE*VJE*(1-Vbei/VJE)(1-MJE) / (1-MJE)

Cbej= CJE*(1-Vbei/VJE)(-MJE)

If Vbei>FCE*VJE, and CJE>CEMIN*(1-FCE)MJE:

Qbej=-CJE*VJE/(1-FCE)MJE*[(1-FCE)/(1-MJE)+FCE-Vbei/VJE

-MJE*(FCE-Vbei/VJE)2/2/(1-FCE)]

Cbej=CJE/(1-FCE)MJE*[1+MJE*(Vbei/VJE-FCE)/(1-FCE)]

If Vbei>FCE*VJE, and CJE<CEMIN*(1-FCE)MJE,

Qbej=CEMIN*(Vbei-VJE)+CEMIN*VJE*MJE/(MJE-1)

*(CJE/CEMIN)(1/MJE)+CJE*VJE*(Vbei/VJE-FCE)2*MJE/2/(1-FCE)(MJE+1)

Cbej=CEMIN + CJE*VJE*MJE*(Vbei/VJE-FC)/(1-FCE)(MJE+1)

- Base-Emitter Diffusion Charge, Qbediff. The diffusion charge in HBTs is associated with contributions from minority carriers in the base, and from mobile charge in the collector depletion region. In homojunction transistors, diffusion charge storage in the emitter is also present. The `LEVEL=11` model evaluates the base and collector-depletion region contributions separately (if necessary, the emitter charge storage can be associated with the base contribution).
  - Specify the base charge through the base transit time, `TFB`. This transit time varies with bias through several mechanisms:
  - The Early effect causes a change in transit time with junction voltage.
  - In heterojunction transistors, there is frequently a minimum in the conduction band, on the base side of the base-emitter (and potentially base-collector) heterojunction. Minority carriers tend to accumulate in these potential wells.

    The stored charge adds to the base charge (to a good approximation). In the lowest order, the charge stored is directly proportional to the collector current, and thus contributes to `TFB`. For a greater degree of accuracy, the depth of the potential well on the emitter side varies with Vbe. Similarly, the amount of charge stored at the base-collector side varies with Vbc.

    The equations used to describe the effects are:

TFBt=TFB*(1+Vbei/VAR+Vbci/VAF) +
TBEXS*exp(-q(Vbei-VJE)/NA/KTop) +
TBCXS*exp(q(Vbci-VJC)/NB/KTop)

Note: Different signs are associated with the BE and BC junction effects. The value of the T temperature to describe these effects is assumed to be Top.

You can use any of these methods to specify collector charge:

- A part is specified by the `TFC0` transit time parameter, modified by the qcc velocity modulation factor to account for voltage and current dependences.
- A part of the mobile charge is specified in the calculation of base-collector depletion region charge. To calculate this part, Qbcm, an expression for the collector current-dependent base-collector depletion charge is developed. Then the current-independent part is subtracted off (as discussed in the next section).
- A separate charge term, Qkrk, is associated with the Kirk effect.

Qfdiff=Icf*ftt*(TFBt + TFC0/qcc) + Qbcm + Qkrk

ftt=rTXTTF

qcc is a factor describing bias dependence of electron velocity in the BC depletion region:

qcc= [1 + (Icf/ITC)2] / [1 + (Icf/ITC2)3 + (VJCI-Vbci)/VTC]

- `ITC` is the threshold current for the velocity profile modulation effect.
- `ITC2` is a higher current at which the velocity profile modulation peaks (and the cutoff frequency begins to roll-off).
- `VTC` provides a voltage (or electric field) dependence of the carrier velocity.

ITC=ITC@Tnom* rTXTITC
ITC2=ITC2@Tnom* rTXTITC2

The following expression calculates the charge storage associated with the Kirk effect:

Qkrk=TKRK*Icf*exp[Vbci/VKRK+Icf/IKRK]

To account for excess phase, a fraction (1-`FEX`) of the current-dependent forward charge (Qfdiff) is associated with the BE junction, while the remainder is associated with the intrinsic BC junction.

Qbediff= (1-FEX)*Qfdiff

Note: Qfdiff (and thus Qbediff) depends on Vbci, through the terms involving Icf, qcc, Qkrk and Qbcm. As a result, a trans-capacitance is implied in the ac model. Similarly, Qbcdiff depends on Vbei, implying another trans-capacitance.

- Intrinsic Base-Collector Charge, Qbci. Charge stored at the intrinsic base-collector junction includes:
  - Depletion charge from the junction region.
  - Diffusion charge associated with normal operation of the transistor.
  - Diffusion charge associated with reverse operation of the device.

  Qbci=Qbcj + TRI* Icr + FEX*Qfdiff

  Although the charge in the depletion region depends on Ic, this section describes the portion corresponding to the Ic=0 condition. Subsequently, the proper Ic dependent contribution is considered, and included in Qbcm (a charge that is part of Qfdiff).
- Intrinsic base-collector depletion charge, Qbcj. When Ic=0, the depletion charge is calculated using the same algorithm as applied to Qbej (which accounts for a minimum of capacitance when the n- collector is depleted).
- Intrinsic base-collector diffusion charge. For reverse operation, a diffusion capacitance is implied by the TRI term in the Qbci equation. Here TRI is the effective reverse transit time, which is assumed to be bias-independent. The associated reverse diffusion capacitance is:

  Cbcrdiff= TRI* dIbci/dVbci

  For operation also includes diffusion capacitance in a manner similar to base-emitter capacitance with a partitioning specified by the excess phase factor, `FEX`.

  The terms associated with Icf*ftt*(TFB + TFC0/qcc) + Qkrk have already been discussed above for calculating Qbediff. The next section describes the Qbcm portion.

- Qbcm. This charge is the difference between the "proper" Icf-dependent charge in the BCi depletion region (called Qbcf), and the BCi depletion charge computed above (Qbcj), assuming that `Icf=0`.

  Qbcm=Qbcf - Qbcj

  To properly compute Qbcf, a formulation of the depletion region charge (similar to that used above) is used with the modification that the `CJ` parameter (zero bias capacitance) can depend on the Icf collector current. This corresponds to the physical phenomenon of varying charge density in the depletion region as a result of the mobile electron charge in that region.

  The current-dependent `CJ` parameter is termed `CJCH`; its form is:

  CJCH=CJC*sign(1-Icf/ICRIT)*ABS(1-Icf/ICRIT)MJC

  In this equation, `ICRIT` is a critical current, at which the effective charge density in the BC depletion region vanishes (and the capacitance Cbci drops dramatically). `ICRIT` is dependent on temperature and bias conditions, according to:

  ICRIT=ICRIT0*qcc/ftt

  In the preceding equation, ftt and qcc are the temperature-dependence, and Icf and Vcb are the dependence parameters described above.

  Using this formulation, the current dependence of the BC capacitance is included (although it is partially assigned to the BE junction charge, and partially to the BC junction, through the `FEX` excess-phase parameter).

  You can extract `ICRIT` and associated parameters from measurements of Cbc versus Ic.

  Note: These parameters also control some of the components of the forward transit time.

  A delay time is associated with specifying ICRIT:

  TFC1=CJC*VJC*MJC/(MJC-1)/ICRIT

  Use the `ICRIT` parameter carefully, generally in conjunction with selecting `TFC0` and `CJCI` in such a way that the sum `TFB` + `TFC0` + `TFC1` provide a reasonable estimate of charge storage, similar to `TF` in Gummel-Poon SPICE.

- Extrinsic Base-Collector Charge, Qbcx. The Qbcx stored charge consists of a depletion charge and a diffusion charge.

Standard SPICE does not use the diffusion charge component. However, this component can be an important contribution to saturation stored-charge in many HBTs (in addition to the contribution associated with the intrinsic base-collector junction).

The corresponding charge storage time, `TRX`, might be different from the intrinsic time, TRI. This difference occurs because of implant-induced recombination, surfaces, or other structural changes.

The depletion charge corresponds to a standard depletion region expression (without considering charge density modulation due to current), modified to allow for a minimum value of capacitance under a reach-through condition.

Furthermore, as indicated in the following, if you assign a value other than unity to the `XCJC` variable, then the depletion charge is partitioned between the Bx-Cx capacitance and the B-Cx capacitance.

Qbcx= TRX*Ibcx + XCJC*Qbcxo

In the preceding equation, Qbcxo is the depletion charge.

As a result the dependences of Ibcx on Vbcx, a diffusion capacitance results from the formulation:

Cbcxdiff= TRX* dIbcx/dVbcx

Base-Extrinsic Collector Charge (Qbcxx), and Treatment of `XCJC`

In standard SPICE, `XCJC` indicates the fraction of overall Cbc depletion capacitance that should be associated with the intrinsic base node. The remaining fraction (`1-XCJC`) is attached to the base terminal. HBT Spice uses a similar assignment: the depletion charge associated with the extrinsic base-collector junction is partitioned between the Bx node and the B node:

Qbcx= TRX*Ibcx + XCJC* Qbcxo

has been defined above, between the Bx and Cx nodes, and charge

Qbcxx= (1-XCJC)*Qbcxxo

is assigned between the B and Cx nodes. The Qbcxxo charge is computed with the same algorithm as for Qbcxo by using Vbcxx (rather than Vbcx) as the voltage.

- Collector-Substrate Charge, Qcs. This corresponds to a depletion charge, formulated in the standard SPICE fashion:

  For Vcs>-FC*VJS,

  Qcs= - CJS*VJS*(1+Vcs/VJS)(1-MJS) / (1-MJS)
  Ccs=CJS*(1+Vcs/VJS)(-MJS)

  For Vcs<-FC*VJS,

  Qcs= -CJS*VJS/(1-FC)MJS*
  [(1-FC)/(1-MJS) + FC +Vcs/VJS -MJS/2/(1-FC) *(FC+Vcs/VJS)2]

  Ccs=CJS*(1-FC)(-MJS)*[1-MJS/(1-FC)*(FC+Vcs/VJS)}

Noise

The `LEVEL=11` model includes noise current generators, similar to those in standard Spice. The noise current generators have magnitudes in units of A2/ Hz, and are computed based on 1Hz bandwidth. The noise sources are placed in parallel with corresponding linearized elements in the small signal model. Sources of 1/f noise have magnitudes that vary with the frequency (f); you can use a `BFN` exponent, if you do not see the exact f-1 behavior.

```
inc2=2*q*Icc
inb2= 2 * q *Ibe + KFN * IbeAFN / f BFN
inre2= 4 * K* Td / RE
inrbx2= 4 * K * Td / RBX
inrbi2= 4 * K * Td / RBI
inrcx2= 4 * K * Td / RCX
inrci2= 4 * K * Td / RCI
inrex2= 4 * K * Td / REX
```

Equivalent Circuit

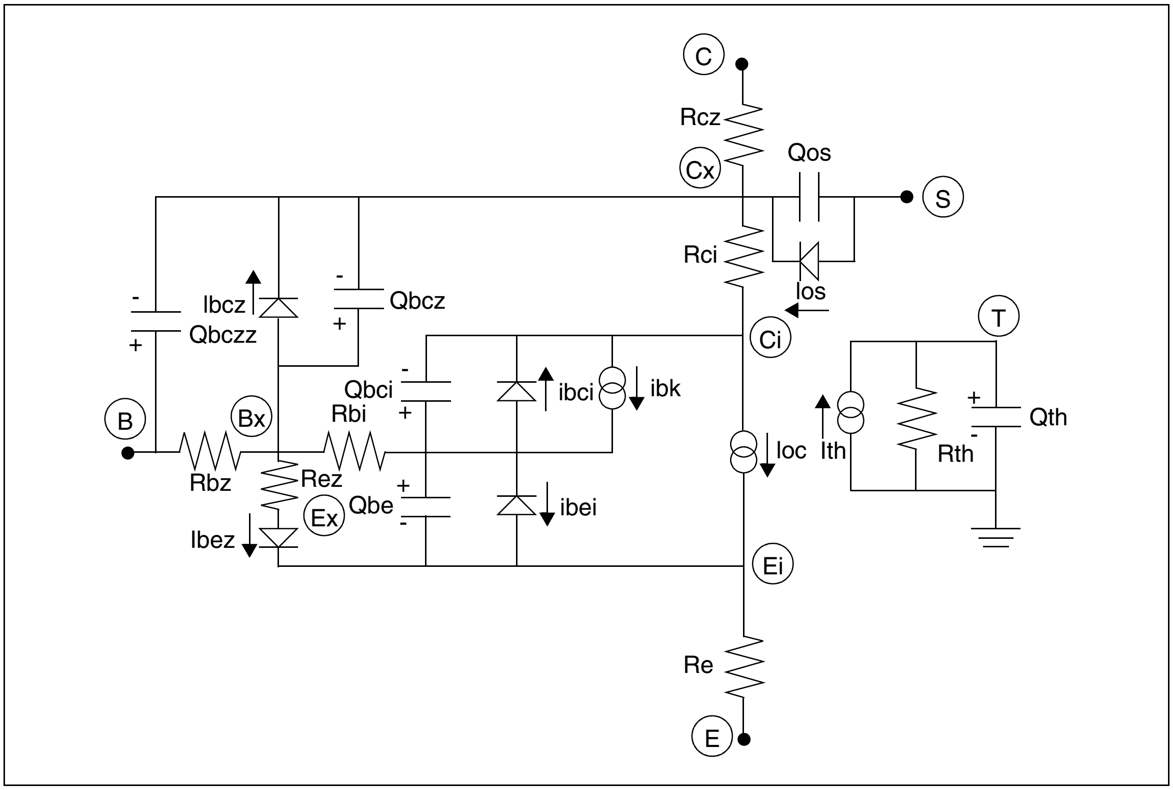


Figure 39 Circuit Diagram for Large-signal HBT Model

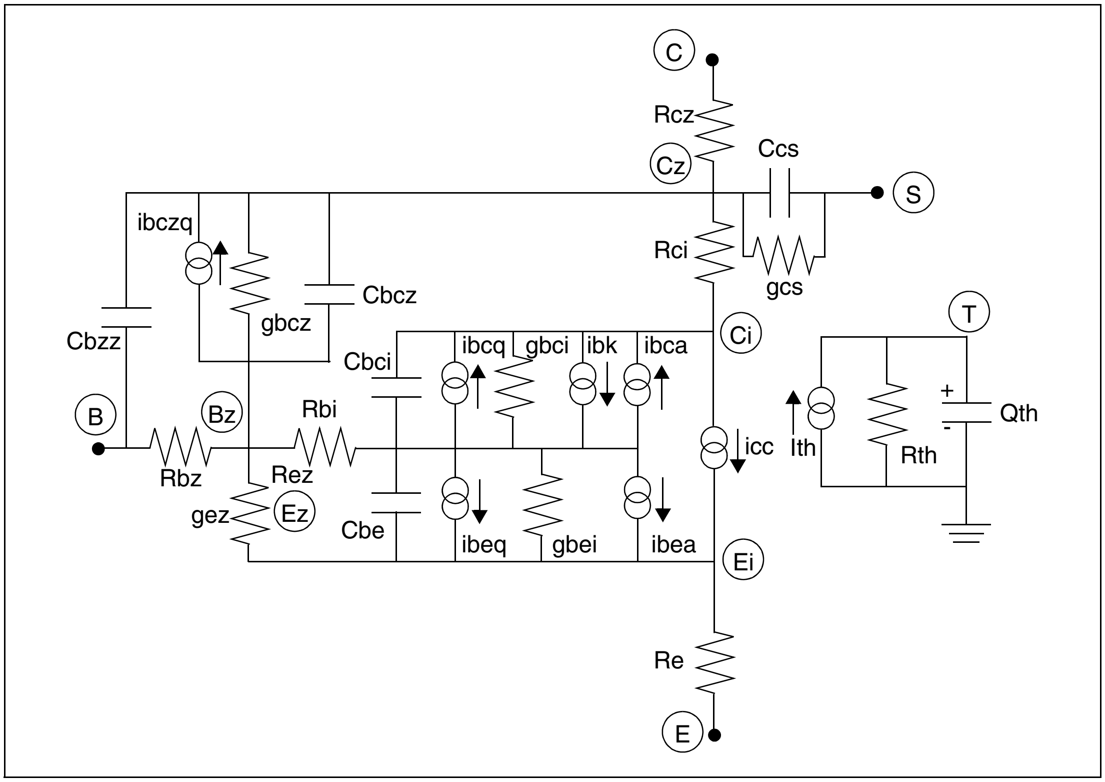


Figure 40 Circuit Diagram for Small-signal HBT Model

Example Model Statement for BJT LEVEL=11

```
.model hbt npn level=11
+ IS=1.2E-18  NF=1  NR=1  BF=200
+ BR=5  VAF=60  VAR=20  ISE=1E-17
+ NE=1.4  ISEX=4E-24  NEX=1.3  ISCX=1E-14
+ NCX=2  ISC=1E-16  NC=2  NA=10
+ ISA=2.18E-10  NB=10  ISB=1E10  RE=16
+ REX=20  RBI=20  BVC=28  NBC=6
+ FA=0.995  RCX =30  RCI=20  CJE=1.8E-14
+ VJE=1.45  CXMIN=1E-16  MJE=0.5  FC=0.8
+ ICRIT0=0.23  CCMIN=3E-15  TR=3.5E-10  VJCX=1.4
+ CJCX=8E-15  MJCX=0.35  XCJC=1  VJS=1.4
+ CJS=5E-16  MJS=0.01  CTH=1E-6  RTH=0
+ EG=1.645  XTI=0  XTB=-1.8  EAA=-0.495
+ EAB=-0.1  EAE=0.105  TNE=0  EAC=0.34
+ XTTF=1.5  ICS=1E-30  NCS=2  CEMIN=1E-15
+ FCE=0.8  TFB=2E-12  TFC0=2.5E-11  TBEXS=1E-14
+ ITC=7E-3  ITC2=0.014  VTC=40  TKRK=5E-13
+ VKRK=10  IKRK=0.012  TRX=3.5E-10  FEX=0
+ XTITC=1.5  XTITC2=1  TREF=25  CJC=7E-15
+ VJC=1.4  MJC=0.35
```

LEVEL=13 HICUM/L0 Model

HICUM/L0 is a simplified bipolar transistor model that combines the simplicity of the SPICE Gummel-Poon Model (SGPM) with various improvements from HICUM. The HICUM/L0 model is implemented as `LEVEL=13` in the HSPICE BJT models.

- HICUM/L0 Model Advantages
- HICUM/L0 Model vs. HICUM LEVEL=2 Model
- HICUM/L0 Version 1.3 Updates
- LEVEL=13 Element Syntax
- LEVEL=13 Model Parameters

HICUM/L0 Model Advantages

Major features of HICUM/L0 are:

- strongly circuit-design oriented and easy to understand for circuit designers
- sufficiently accurate for many applications
- computationally efficient and fast
- allows a fast parameter extraction for single transistors
- makes use of the advanced capabilities of HICUM `LEVEL=2` and the related knowledge base for generating geometry scalable and statistical models
- offers an easy migration path from a conventional, single-transistor-based, to a process-based geometry scalable parameter extraction and model usage to meet today's requirements for advanced integrated circuit design.

The model parameters have a clear (physical) meaning and many of them are similar to HICUM `LEVEL=2` parameters.

HICUM/L0 Model vs. HICUM LEVEL=2 Model

The following are the differences between HICUM/L0 and HICUM `LEVEL=2`:

- The perimeter base node has been eliminated by properly merging the respective internal and external counterparts of the BE depletion capacitance (C_{JE}), the base resistance (R_B), the BC depletion capacitance (C_{JC}), and the base current components across the BE and BC junction
- BE tunneling current, substrate coupling network, parasitic substrate transistor, and capacitance for modeling AC emitter current crowding in HICUM `LEVEL=2` have been omitted.

HICUM/L0 Version 1.3 Updates

The following changes were made with the release of v1.3.:

- Improvement to transfer current, including bias and temperature dependences.
- Bug fixes, as follows:

  Fixing of model parameter typos:

  - AHQ was given proper Spice name "AHQ"
- ZETAIQF was given proper Spice name "ZETAIQF"

- Addition of "gmin" (=1e-12) between internal collector emitter node of transfer current iT for convergence enhancement in case of reverse biased junctions
- The CC function is defined as *cc= cjci0_t_ii/cjcii*, which may cause numerical instability; Solution: a conditional loop as in L2 model.

```
if(cjcii > 0.0 && cjci0_t_ii > 0.0) begin
     cc= cjci0_t_ii/cjcii;
     qjci= qjci/cjci0_t_ii;
end else begin
     cc = 1.0;
     qjci = 0;
end
```

- Calculation for base resistance conductivity modulation
  - In the previous L0v1.2 model the calculation was done using DC charge (qje), which is physically incorrect => AC charge is being used.
  - "QJMODF" macro has been re-evaluated with AC parameters only.
  - Could lead to version incompatibility problem
- Limitation of junction related charge qj
  - junction related charge qj could go negative at vbe<0 with the typically low VER values
  - Solution: Smoothing function as in L2 model has been applied to limit the charge

```
qj    = (1+qjci/vef+qjei/ver);
a_bpt = 0.05;
b_q   = qj/a_bpt-1;
qj_2  = 0.025*(1+(b_q +sqrt(b_q*b_q+1.921812))/2);
```

For complete details, see *Improving HICUM L0 v1.2 transfer current, including bias and temperature dependences* at http://www.iee.et.tu-dresden.de/iee/eb/comp_mod.html

LEVEL=13 Element Syntax

Syntax

```
Qxxx nc nb ne [ns][nt] mname [area] [M=val] [DTEMP=val]
```

Parameter	Description
Qxxx	BJT element name
nc	Collector terminal node name or number
nb	Base terminal node name or number
ne	Emitter terminal node name or number
ns	Substrate terminal node name or number
nt	Self-heating node name or number
mname	BJT model name reference
area	Emitter area multiplying factor. Affects current, resistance, capacitance. Default is 1.
M	Multiplier to simulate multiple BJTs in parallel. Default is 1.
DTEMP	Difference between the element temperature and the circuit temperature in degrees Celsius. Default is DTA (difference between the device temperature and the ambient analysis temperature). If you do not specify DTEMP, then DTEMP uses the DTA value.

LEVEL=13 Model Parameters

Table 111 lists the HICUM/L0 `LEVEL=13` model parameters.

Table 111 BJT LEVEL=13 Model Parameters

Parameter	Unit	Default	Description
IS	A	1e-16	Transform saturation current
MCF	-	1	Non-ideality coefficient of forward collector current
MCR	-	1	Non-ideality coefficient of inverse collector current
VEF	V	∞	Forward Early voltage

Table 111 BJT LEVEL=13 Model Parameters (Continued)

Parameter	Unit	Default	Description
IQF	A	∞	Forward DC high-injection roll-off current
IQR	A	∞	Inverse DC high-injection roll-off current
IQFH	A	∞	High-injection correction current
TFH	-	∞	High-injection correction factor
CJE0	F	0	BE zero-bias depletion capacitance
VDE	V	0.9	BE built-in voltage
ZE	-	0.5	BE exponent factor
AJE	-	2.5	BE ratio of maximum to zero-bias value
CJCI0	F	0	BC total zero-bias depletion capacitance
VDCI	V	0.7	BC built-in voltage
ZCI	-	0.4	BC exponent factor
VPTCI	V	1e+20	BC punch-through voltage
T0	sec	0	Low current transit time at V_{BC}=0
DT0H	sec	0	Base width modulation contribution
TBVL	sec	0	SCR width modulation contribution
TEF0	sec	0	Storage time in neutral emitter
GTE	-	1	Exponent factor for emitter transit time
THCS	sec	0	Saturation time at high current densities
AHC	-	0.1	Smoothing factor for current dependence
TR	sec	0	Storage time at inverse operation
RCI0	Ohm	150	Low-field collector resistance under emitter
VLIM	V	0.5	Voltage dividing ohmic and saturation region
VPT	V	∞	Punch-through voltage
VCES	V	0.1	Saturation voltage
IBES	A	1e-18	BE saturation current
MBE	-	1	BE non-ideality factor
IRES	A	0	BE recombination saturation current
MRE	-	2	BE recombination non-ideality factor

Table 111 BJT LEVEL=13 Model Parameters (Continued)

Parameter	Unit	Default	Description
IBCS	A	0	BC saturation current
MBC	-	1	BC non-ideality factor
KAVL	-	0	Avalanche prefactor
EAVL	-	1	Avalanche exponent factor
RBI0	Ohm	0	Internal base resistance value at zero-bias
VR0E	V	2.5	Forward Early voltage (normalization voltage)
VR0C	V	∞	Reverse Early voltage (normalization voltage)
FGEO	-	0.656	Geometry factor
RBX	Ohm	0	External base series resistance
CJCX0	F	0	Zero-base external BC depletion capacitance
VDCX	V	0.7	External BC built-in voltage
ZCX	-	0.4	External BC exponent factor
VPTX	V	1e+20	Punch-through voltage
FBC	-	1	Split factor=C_{JCI0}/C_{JC0}
RE	Ohm	0	Emitter series resistance
RCX	Ohm	0	External collector series resistance
CBEPAR(CEOX)	F	0	Emitter-base isolation (overlap) capacitance
CBCPAR(CCOX)	F	0	Collector-base oxide capacitance
ISCS	A	0	SC saturation current
AF	-	2	Flicker noise exponent factor
AHQ	-	0	Smoothing factor for the d.c. injection width
ALB	1/K	0	Relative temperature coefficient of forward current gain
ALCES	1/K	0	Relative temperature coefficient of VCES
ALEAV	1/K	0	Temperature coefficient of avalanche exponent factor
ALKAV	1/K	0	Temperature coefficient of avalanche prefactor
ALT0	1/K	0	First-order relative temperature coefficient of T0
ALVS	1/K	0	Relative temperature coefficient of saturation drift velocity
CJS0	F	0	Zero-bias SC depletion capacitance

Table 111 BJT LEVEL=13 Model Parameters (Continued)

Parameter	Unit	Default	Description
CTH	Ws/K	0	Thermal capacitance
DT	°C	0	Temperature change for particular transistor
F1VG	V/K	-8.46e-5	Coefficient K1 in temperature-dependent bandgap equation
F2VG	V/K	3.042e-4	Coefficient K2 in temperature-dependent bandgap equation
FIQF	-	0	Flag to turn on voltage dependence of base-related critical current
KF	M^{1-AF}	0	Flicker noise coefficient (no unit only if AF=2)
KT0	1/K	0	Second-order relative temperature coefficient of T0
MSC	-	1	SC non-ideality factor
RTH	K/W	0	Thermal resistance
TNOM	°C	27	Temperature for which parameters are valid
VDS	V	0.3	SC built-in voltage
VER	V	∞	Reverse Early voltage
VGB	V	1.2	Bandgap voltage
VGC	V	1.2	Effective collector bandgap voltage
VGE	V	1.2	Effective emitter bandgap voltage
VGS	V	1.2	Effective substrate bandgap voltage
VPTS	V	1e+20	SC punch-through voltage
ZETABET	-	5	Exponent coefficient in BE junction current temperature dependence
ZETACI	-	0	Temperature coefficient of epi-collector diffusivity
ZETACT	-	4.5	Exponent coefficient in transfer current temperature dependence
ZETARBI	-	0	Temperature coefficient of internal base resistance
ZETARBX	-	0	Temperature coefficient of external base resistance
ZETARCX	-	0	Temperature coefficient of external collector resistance
ZETARE	-	0	Temperature coefficient of emitter resistance
ZS	-	0.3	External SC exponent factor
VDEDC	V	0.9	BE charge built-in voltage for d.c. transfer current
ZEDC	-	0.5	BE charge exponent factor for d.c. transfer current

Table 111 BJT LEVEL=13 Model Parameters (Continued)

Parameter	Unit	Default	Description
AJEDC	-	2.5	BE capacitance ratio (maximum to zero-bias value) for d.c. transfer current
ZETAIQF	-	0.0	Temperature coefficient of IQF
ZETARTH	-	0.0	Exponent factor for temperature dependent thermal resistance

For a complete description of the HICUM/L0 model, see:

http://www.iee.et.tu-dresden.de/iee/eb/comp_mod.html

References

[1] C. McAndrew, J. Seitchik, D. Bowers, M. Dunn, M. Foisy, I. Getreu, M. McSwain, S. Moinian, J. Parker, D. Roulston, M. Schroter, P. van Wijnen, and L. Wagner, “VBIC95: The vertical bipolar intercompany model,” *IEEE Journal of Solid State Circuits*, vol.31, p.1476-1483, 1996.

A

Finding Device Libraries

Lists device libraries you can use in HSPICE.

HSPICE ships hundreds of examples for your use; see Listing of Input Demonstration Files for paths to demo files.

For libraries with multiple models of a specific active or passive device element, you can use the automatic model selector in HSPICE to automatically find the proper model for each transistor size.

This chapter lists device libraries that you can use. It includes the following topics:

- Overview of Library Listings
- Analog Device Models
- Behavioral Device Models
- Bipolar Transistor Models
- Diode Models
- JFET and MESFET Models

Overview of Library Listings

The following sections list the names of the models provided with HSPICE. Models are stored by type in directories named after the model type, such as *dio* for diodes and *bjt* for bipolar junction transistors. The directory path is shown for each model type. You specify the directory path in the `.OPTION SEARCH` statement, as in the following example:

```
.OPTION SEARCH '$installdir/96/parts/dio'
```

In the preceding syntax, `$installdir` is the environment variable set to the path to the software installation directory and `96` is the HSPICE release number. All model directories are under the `parts` directory.

Analog Device Models

The search path for analog device models is:

`$installdir/parts/ad`

Table 112 Analog Model Names

AD581	ad581j	ad581k	ad581l	ad581s
ad581t	ad581u	ad584	ad584j	ad584k
ad584l	ad584s	ad584t	ad587	ad587j
ad587k	ad587l	ad587s	ad587t	ad587u
ad600	ad600j	ad602	ad602j	ad620
ad620a	ad620b	ad620s	ad624	ad624a
ad624b	ad624c	ad624s	ad630	ad630a
ad630b	ad630j	ad630k	ad630s	ad633
ad633j	ad645	ad645a	ad645b	ad645j
ad645k	ad645s	ad704	ad704a	ad704b
ad704j	ad704k	ad704t	ad705	ad705a
ad705b	ad705j	ad705k	ad705t	ad706
ad706a	ad706b	ad706j	ad706k	ad706t
ad711	ad711a	ad711b	ad711c	ad711j
ad711k	ad711s	ad711t	ad712	ad712a
ad712b	ad712c	ad712j	ad712k	ad712s
ad712t	ad713	ad713a	ad713b	ad713j

Table 112 Analog Model Names (Continued)

ad713k	ad713s	ad713t	ad734	ad734a
ad734b	ad734s	ad743	ad743a	ad743b
ad743j	ad743k	ad743s	ad744	ad744a
ad744b	ad744c	ad744j	ad744k	ad744s
ad744t	ad745	ad745a	ad745b	ad745j
ad745k	ad745s	ad746	ad746a	ad746b
ad746j	ad746s	ad780	ad780a	ad780b
ad780s	ad797	ad797a	ad797b	ad797s
ad810	ad810a	ad810s	ad811	ad812
ad812a	ad813	ad813a	ad817	ad817a
ad818	ad818a	ad820	ad826	ad826a
ad828	ad828a	ad829	ad829a	ad829j
ad829s	ad830	ad830a	ad830j	ad830s
ad840	ad840j	ad840k	ad840s	ad843
ad843a	ad843b	ad843j	ad843k	ad843s
ad844	ad844a	ad844b	ad844s	ad845
ad845a	ad845b	ad845j	ad845k	ad845s
ad846	ad846a	ad846b	ad846s	ad847
ad847a	ad847j	ad847s	ad848	ad848a
ad848j	ad848s	ad9617	ad9618	ad9621
ad9622	ad9623	ad9624	ad9630	adg411
adg411b	adg411t	adg412	adg412b	adg412t
adg413	adg413b	adg413t	amp01	amp02
buf04	mat02	mat03	mat04	mlt04

Table 112 Analog Model Names (Continued)

mlt04g	op160	op160a	op160f	op160g
op176	op176g	op177	op177a	op177b
op177e	op177f	op177g	op20	op200
op200a	op200e	op200f	op200g	op20b
op20c	op20f	op20g	op20h	op21
op213	op215	op215a	op215b	op215c
op215e	op215f	op215g	op21a	op21e
op21f	op21g	op21h	op220	op220a
op220c	op220e	op220f	op220g	op221
op221a	op221b	op221c	op221e	op221g
op249	op249a	op249e	op249f	op249g
op260	op27	op275	op275g	op27a
op27b	op27c	op27e	op27f	op27g
op282	op282g	op283	op285	op285g
op290	op290a	op290e	op290f	op290g
op292	op295	op297	op297a	op297e
op297f	op297g	op37	op37a	op37b
op37c	op37e	op37f	op37g	op400
op400a	op400e	op400f	op400g	op400h
op41	op41a	op41b	op41e	op41f
op41g	op42	op420	op420b	op420c
op420f	op420g	op420h	op421	op421b
op421c	op421f	op421g	op421h	op42a
op42e	op42f	op42g	op43	op43a

Table 112 Analog Model Names (Continued)

op43b	op43e	op43f	op43g	op44
op467	op467g	op470	op482	op482g
op490	op490a	op490e	op490f	op490g
op492	op497	op497a	op497b	op497c
op497f	op497g	op61	op64	op77
op77a	op77b	op77e	op77f	op77g
op80	op80b	op80e	op80f	op80g
op90	op90a	op90e	op90f	op90g
op97	op97a	op97e	op97f	pm1012
ref01	ref01a	ref01c	ref01e	ref01h
ref02	ref02a	ref02c	ref02d	ref02e
ref02h	ref05	ref05a	ref05b	ref10
ref10a	ref10b	ssm2017	ssm2017p	ssm2131
ssm2210	ssm2220			

Behavioral Device Models

The search path for behavioral device models is:

`$installdir/parts/behave`

The required element syntax is:

`Xyyyyy in- in+ out` *`vcc vee modelname`*

Optional parameters are:

vos=value, ibos=value, av=value

Table 113 Behavioral Model Names

ad4bit	ad8bit	alf155	alf156	alf157
alf255	alf347	alf351	alf353	alf355
alf356	alf357	alf3741	alm101a	alm107
alm108	alm108a	alm111	alm118	alm124
alm124a	alm139a	alm1458	alm1558	alm158
alm158a	alm201a	alm207	alm208	alm208a
alm224	alm258	alm258a	alm2901	alm2902
alm2904	alm301a	alm307	alm308	alm308a
alm318	alm324	alm3302	alm339	alm358
alm358a	alm725	alm741	alm747	alm747c
amc1458	amc1536	amc1741	amc1747	ane5534p
anjm4558	anjm4559	anjm4560	aop04	aop07
aop14	aop15b	aop16b	at094cns	atl071c
atl072c	atl074c	atl081c	atl082c	atl084c
atl092cp	atl094cn	aupc1251	aupc358	ga201
rcfilt	tline			

Bipolar Transistor Models

The search path for bipolar transistor models is:

`$installdir/parts/bjt`

The required element syntax is:

`Xyyyy` *coll base emit modelname*

Optional parameters are:

betaf=value, tauf=value

Table 114 Bipolar Transistor Model Names

t2n1132a	t2n2102	t2n2219a	t2n2222	t2n2222a
t2n2369	t2n2369a	t2n2501	t2n2605	t2n2642
t2n2857	t2n2894	t2n2904	t2n2904a	t2n2905
t2n2905a	t2n2906	t2n2907	t2n2907a	t2n2945a
t2n3013	t2n3227	t2n3250	t2n3250a	t2n3251
t2n3251a	t2n3467	t2n3501	t2n3546	t2n3637
t2n3742	t2n3743	t2n3866	t2n3904	t2n3906
t2n3946	t2n3947	t2n3962	t2n4261	t2n4449
t2n5058	t2n5059	t2n5179	t2n6341	t2n6438
t2n706	t2n708	t2n869	t2n869a	t2n918
t2n930	t2sa1015	t2sa950	t2sa965	t2sa970
t2sc1815	t2sc1923	t2sc2120	t2sc2235	t2sc2669
tmps6595	tne741	tne901		

Diode Models

The search path for diode models is:

`$installdir/parts/dio`

The required element syntax is:

`Xyyyyy` *anode cathode modelname*

Optional parameters are:

isat=value, tt=value

Table 115 Diode Model Names

d12bg11	d12bh11	d12dg11	d12dh11	d12fg11

Table 115 Diode Model Names (Continued)

d12fh11	d12gg11	d12gh11	d12jg11	d12jh11
d1n3016	d1n3017	d1n3018	d1n3019	d1n3020
d1n3021	d1n3022	d1n3023	d1n3024	d1n3025
d1n3026	d1n3027	d1n3028	d1n3029	d1n3030
d1n3031	d1n3032	d1n3033	d1n3034	d1n3035
d1n3036	d1n3037	d1n3038	d1n3039	d1n3040
d1n3041	d1n3042	d1n3043	d1n3044	d1n3045
d1n3046	d1n3047	d1n3048	d1n3049	d1n3050
d1n3051	d1n3821	d1n3822	d1n3823	d1n3824
d1n3825	d1n3826	d1n3827	d1n3828	d1n3829
d1n3830	d1n4001	d1n4002	d1n4003	d1n4004
d1n4005	d1n4006	d1n4007	d1n4148	d1n4149
d1n4150	d1n4370	d1n4371	d1n4372	d1n4446
d1n4447	d1n4448	d1n4449	d1n4728	d1n4729
d1n4730	d1n4731	d1n4732	d1n4733	d1n4734
d1n4735	d1n4736	d1n4737	d1n4738	d1n4739
d1n4740	d1n4741	d1n4742	d1n4743	d1n4744
d1n4745	d1n4746	d1n4747	d1n4748	d1n4749
d1n4750	d1n4751	d1n4752	d1n4753	d1n4754
d1n4755	d1n4756	d1n4757	d1n4758	d1n4759
d1n4760	d1n4761	d1n4762	d1n4763	d1n4764
d1n5221	d1n5222	d1n5223	d1n5224	d1n5225
d1n5226	d1n5227	d1n5228	d1n5229	d1n5230
d1n5231	d1n5232	d1n5233	d1n5234	d1n5235

Table 115 Diode Model Names (Continued)

d1n5236	d1n5237	d1n5238	d1n5239	d1n5240
d1n5241	d1n5242	d1n5243	d1n5244	d1n5245
d1n5246	d1n5247	d1n5248	d1n5249	d1n5250
d1n5251	d1n5252	d1n5253	d1n5254	d1n5255
d1n5256	d1n5257	d1n5258	d1n5259	d1n5260
d1n5261	d1n5262	d1n5263	d1n5264	d1n5265
d1n5266	d1n5267	d1n5268	d1n5269	d1n5270
d1n5271	d1n5272	d1n5333	d1n5334	d1n5335
d1n5336	d1n5337	d1n5338	d1n5339	d1n5340
d1n5341	d1n5342	d1n5343	d1n5344	d1n5345
d1n5346	d1n5347	d1n5348	d1n5349	d1n5350
d1n5351	d1n5352	d1n5353	d1n5354	d1n5355
d1n5356	d1n5357	d1n5358	d1n5359	d1n5360
d1n5361	d1n5362	d1n5363	d1n5364	d1n5365
d1n5366	d1n5367	d1n5368	d1n5369	d1n5370
d1n5371	d1n5372	d1n5373	d1n5374	d1n5375
d1n5376	d1n5377	d1n5378	d1n5379	d1n5380
d1n5381	d1n5382	d1n5383	d1n5384	d1n5385
d1n5386	d1n5387	d1n5388	d1n5817	d1n5818
d1n5819	d1n5913	d1n5914	d1n5915	d1n5916
d1n5917	d1n5918	d1n5919	d1n5920	d1n5921
d1n5922	d1n5923	d1n5924	d1n5925	d1n5926
d1n5927	d1n5928	d1n5929	d1n5930	d1n5931
d1n5932	d1n5933	d1n5934	d1n5935	d1n5936

Table 115 Diode Model Names (Continued)

d1n5937	d1n5938	d1n5939	d1n5940	d1n5941
d1n5942	d1n5943	d1n5944	d1n5945	d1n5946
d1n5947	d1n5948	d1n5949	d1n5950	d1n5951
d1n5952	d1n5953	d1n5954	d1n5955	d1n5956
d1n746	d1n747	d1n748	d1n749	d1n750
d1n751	d1n752	d1n753	d1n754	d1n755
d1n756	d1n757	d1n758	d1n759	d1n914
d1n957	d1n958	d1n959	d1n960	d1n961
d1n962	d1n963	d1n964	d1n965	d1n966
d1n967	d1n968	d1n969	d1n970	d1n971
d1n972	d1n973	d1n974	d1n975	d1n976
d1n977	d1n978	d1n979	d1n980	d1n981
d1n982	d1n983	d1n984	d1n985	d1n986
d1s1585	d1s1586	d1s1587	d1s1588	d1sv147
d1sv149	dmbr115p	dmbr120p	dmbr130p	dmbr140p
dsk4a3				

JFET and MESFET Models

The search path for JFET and MESFET models is:

`$installdir/parts/fet`

The required element syntax is:

`Xyyyy` *`drain gate source modelname`*

Optional parameters are:

vt=value, betaf=value

Table 116 FET Model Names

J108	J109	J110	J111	J112
j113	j2n3330	j2n3460	j2n3824	j2n4391
j2n4392	j2n4393	j2n4856	j2n4857	j2n5457
j2n5458	j2n5459	j2n5460	j2n5461	j2n5462
j2n5463	j2n5465	j309	j511	j557
jsj74	jsk170	m2n6755	m2n6756	m2n6757
m2n6758	m2n6759	m2n6760	m2n6761	m2n6762
m2n6763	m2n6764	m2n6765	m2n6766	m2n6767
m2n6768	m2n6769	m2n6770	m2n6787	m2n6788
m2n6789	m2n6790	m2n6791	m2n6792	m2n6793
m2n6794	m2n6795	m2n6796	m2n6797	m2n6798
m2n6799	m2n6800	m2n6801	m2n6802	mbuz10
mbuz20	mbuz23	mbuz24	mbuz32	mbuz35
mbuz36	mbuz42	mbuz45	mbuz46	mbuz60
mbuz63	mbuz64	mbuz71	mbuz72a	mbuz74
mbuz76	mirf120	mirf121	mirf122	mirf123
mirf130	mirf131	mirf132	mirf133	mirf140
mirf141	mirf142	mirf143	mirf150	mirf151
mirf152	mirf153	mirf220	mirf221	mirf222
mirf223	mirf230	mirf231	mirf232	mirf233
mirf240	mirf241	mirf242	mirf243	mirf250
mirf251	mirf252	mirf253	mirf320	mirf321
mirf322	mirf323	mirf330	mirf331	mirf332

Table 116 FET Model Names (Continued)

mirf333	mirf340	mirf341	mirf342	mirf343
mirf350	mirf351	mirf352	mirf353	mirf420
mirf421	mirf422	mirf423	mirf430	mirf431
mirf432	mirf433	mirf440	mirf441	mirf442
mirf443	mirf450	mirf451	mirf452	mirf453
mirf510	mirf511	mirf512	mirf513	mirf520
mirf521	mirf522	mirf523	mirf530	mirf531
mirf532	mirf533	mirf540	mirf541	mirf542
mirf543	mirf610	mirf611	mirf612	mirf613
mirf620	mirf621	mirf622	mirf623	mirf630
mirf631	mirf632	mirf633	mirf640	mirf641
mirf642	mirf643	mirf710	mirf711	mirf712
mirf713	mirf720	mirf721	mirf722	mirf723
mirf730	mirf731	mirf732	mirf733	mirf740
mirf741	mirf742	mirf743	mirf810	mirf811
mirf812	mirf813	mirf820	mirf821	mirf822
mirf823	mirf830	mirf831	mirf832	mirf833
mirf840	mirf841	mirf842	mirf843	mirf9020
mirff110	mirff111	mirff112	mirff113	mirff120
mirff121	mirff122	mirff123	mirff130	mirff131
mirff132	mirff133	mirff210	mirff211	mirff212
mirff213	mirff220	mirff221	mirff222	mirff223
mirff230	mirff231	mirff232	mirff233	mirff310
mirff311	mirff312	mirff313	mirff320	mirff321

Table 116 FET Model Names (Continued)

mirff322	mirff323	mirff330	mirff331	mirff332
mirff333	mirff430	mirff431	mirff432	mirff433

Transmission Line Models

Table 117 lists the Transmission Line models that you can use in HSPICE.

Search path: `$installdir/parts/tline`

Table 117 Transmission Line Model Names

rcfilt	rg11_u	rg11a_u	rg15_u	rg180b_u
rg188a_u	rg53_u	rg54a_u	rg58a_u	rg58c_u
rg59b_u	rg62_u	rg62b_u	rg71_u	rg71b_u
rg9_u	rg9b_u	tw_sh_u	tw_un_u	

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