Chapter 13

Using Diodes

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 and 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 Chapter 15, Introducing MOSFET; Chapter 16, Selecting a MOSFET Model; and Chapter 22, Performing Behavioral Modeling for other MOSFET and standard discrete diodes.

Diode model types include the junction diode model and the Fowler-Nordheim model. The junction diode model has two variations: geometric and nongeometric.

This chapter provides an overview of element and model parameters and scaling effects for the geometric and nongeometric junction diodes.The following topics are covered in this chapter:

- Understanding the Diode Types
- Using Model and Element Statements
- Specifying Junction Diodes
- Calculating Temperature Effects
- Using Diode Equations
- Using the Fowler-Nordheim Diode
- Converting National Semiconductor Models

Understanding the Diode Types

Use the geometric junction diode to model IC based standard silicon diffused diodes, Schottky barrier diodes, and Zener diodes. Use the geometric parameter to specify pn junction poly and metal capacitance dimensions for a particular IC process technology.

Use the nongeometric junction diode to model discrete diode devices such as standard and Zener diodes. The nongeometric model allows you to scale currents, resistances, and capacitances using dimensionless area parameters.

The Fowler-Nordheim diode defines tunneling current flow through insulators. Use it to model diode effects in nonvolatile EEPROM memory.

Using Model and Element Statements

Use model and element statements to select the diode models. The model statement's LEVEL parameter selects the type of diode model used:

- LEVEL=1 selects the nongeometric junction diode model
- LEVEL=2 selects the Fowler-Nordheim diode model
- LEVEL=3 selects the geometric junction diode model

You can design Zener, Schottky barrier, and silicon diffused diodes by altering model parameters for both Level 1 and Level 3. Level 2 does not permit modeling of these effects. For Zener diodes, the BV parameter is set for an appropriate Zener breakdown voltage.

If you do not specify the LEVEL parameter in the .MODEL statement, the model defaults to the nongeometric junction diode model, Level 1.

Use control options with the diode model to scale model units, select diffusion capacitance equations, and change model parameters.

Control Options

Control options related to the analysis of diode circuits, as well as other models, include DCAP, DCCAP, GMIN, GMINDC, SCALE, and SCALM. Specify these models using the .OPTIONS statement.

Scaling Options

Use the scale element option, SCALE, to scale Levels 2 and 3 diode element parameters. Use the scale model option, SCALM, to scale Levels 2 and 3 diode model parameters. Level 1 does not use SCALE or SCALM.

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

Capacitor Equation Selector Option — DCAP

The DCAP option selects the equations used in calculating the depletion capacitance (Level 1 and Level 3). The option DCCAP invokes calculation of capacitances in DC analysis.

Include the DCAP=<val> in the diode's .MODEL statement to override the global depletion capacitance equation selection with the .OPTIONS DCAP=<val> statement.

Convergence

Diode convergence problems often occur at the breakdown voltage region when the diode is overdriven or in the OFF condition. To achieve convergence in such cases, include a nonzero value in the model for the series resistor parameter RS, or increase GMIN (the parallel conductance Hspice automatically places in the circuit). You can specify GMIN and GMINDC in the .OPTIONS statement.

The diode control options follow:

Capacitance	DCAP, DCCAP
Conductance	GMIN, GMINDC
Geometry	SCALM, SCALE

Specifying Junction Diodes

Use the diode element statement to specify the two types of junction diodes, geometric and nongeometric. Use a different element type format for the Fowler-Nordheim model.

The diode element statement parameter fields define the connecting nodes, initialization, temperature, geometric junction, and capacitance parameters of the diode model selected in the diode .MODEL statement. 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 take precedence over model parameters, if repeated in the .MODEL statement as model parameters.

Parameters common to both element and model statements are: `AREA, PJ, M, LM, LP, WM, WP, W, and L.`

Table 13-1: – Junction Diode Element Parameters

Function	Parameters
netlist	Dxxx, n+, n-, mname
initialization	IC, OFF
temperature	DTEMP
geometric junction	AREA, L, M, PJ, W
geometric capacitance (Level=3 only)	LM, LP, WM, WP

Diode Element

General form

```
Dxxx nplus nminus mname <AREA=val> <PJ=val> <WP=val>
<LP=val> + <WM=val> <LM=val> <OFF> <IC=vd> <M=val>
<DTEMP=val>
```

or

```
Dxxx nplus nminus mname <area_val <periphery_val>> <OFF>
<IC=vd> <M=val>
```

or

```
Dxxx nplus nminus mname <W=val> <L=val> <WP=val> <LP=val>
+    <WM=val> <LM=val> <OFF> <IC=vd> <M=val> <DTEMP=val>
```

AREA	Area of the diode. It modifies saturation currents, capacitances, and resistances. Area factor for LEVEL=1 model is not affected by the option SCALE. Default=1.0. Affects IK, IKR, JS, CJO, and RS.
	`For LEVEL=3,`
	`AREAeff = AREA   M   SCALE2 SHRINK2, or`
	`AREAeff = Weff   Leff   M`
	The effective area overrides model parameter AREAeff calculated from model parameter AREA. If unspecified, AREA is calculated from W, L.

DTEMP	The difference between element temperature and the circuit temperature. Default=0.0.
Dxxx	Diode element name. Must begin with a **D**, which can be followed by a maximum of 15 alphanumeric characters.

IC=vd	Initial voltage across the diode element. Interacts with the UIC option in the .TRAN statement and is overridden by the .IC statement.
L	Length of diode in meters (Level 3 only)
	`Leff = L   SCALE   SHRINK + XWeff`
LM	Length of metal capacitor in meters (Level 3 only). Overrides model parameter LM in the model. Default=0.0.
	`LMeff = LM   SCALE   SHRINK.`
LP	Length of polysilicon capacitor in meters (Level 3 only). Overrides model parameter LP in model. Default=0.0.
	`LPeff = LP   SCALE   SHRINK.`
M	Multiplier factor to simulate multiple diodes. All currents, capacitances, and resistances are affected by M=val. Default=1.
mname	Model name. It can be up to 16 characters long.
nplus	Positive terminal (anode) node name. It can be up to 16 characters long. Series resistor is attached to this terminal.
nminus	Negative terminal (cathode) node name. It can be up to 16 characters long.
OFF	Switch that sets initial condition to OFF for the element in DC analysis. Default=ON.
PJ	Periphery of junction. Overrides PJ in model. Calculated from W, L if specified. Affects JSW and CJP model parameters. Default=0.0.
	For LEVEL=1,

	`PJeff = PJ   M`
	For LEVEL=3,
	`PJeff = PJ   SCALE   M   SHRINK`
	`PJeff = (2   Weff + 2   Leff)   M`

W	Width of diode in meters (Level 3 only) `Weff = W   SCALE   SHRINK + XWeff`
WM	Width of metal capacitor (Level 3 only). Overrides WM in the model. Default=0.0 `WMeff = WM   SCALE   SHRINK`
WP	Width of polysilicon capacitor in meter (Level 3 only). Overrides WP in model. Default=0.0 `WPeff = WP   SCALE   SHRINK`

Examples

The following example shows how to connect a diode called DCLMMMP between node 3 and substrate. The diode has a voltage of 0.2 V at timepoint 0 in a transient analysis. The model statement with the model reference name DMOD contains the diode model parameters.

```
DCLMMMP 3 substrate DMOD 3 IC=0.2
```

LEVEL=1 Scaling

Scaling for Level 1 involves the use of the AREA and M element parameters. The element and model parameters scaled with AREA and M include:
`IK, IKR, JS, CJO, and RS. For AREA and M, default=1`

This element is not a geometric model because both the area (AREA) and periphery (PJ) are measured in dimensionless values. These parameters are not affected by the SCALE and SCALM options.

The periphery junction parameter is multiplied by M, the multiplier parameter, to scale the dimensionless periphery junction.

$$PJeff = PJ \cdot M$$

PJeff is then used to scale CJP, the zero-bias junction capacitance, and the sidewall saturation current, JSW.

$$CJPeff = PJeff \cdot CJP$$

$$JSWeff = PJeff \cdot JSW$$

AREA and M are used to obtain AREAeff.

$$AREAeff = AREA \cdot M$$

CJO, IK, IKR, IBV, and IS are multiplied by AREAeff to obtain their effective scaled values. RS, however, is divided by AREAeff.

$$IKeff = AREAeff \cdot IK$$

$$IKReff = AREAeff \cdot IKR$$

$$IBVeff = AREAeff \cdot IBV$$

$$ISeff = AREAeff \cdot IS$$

$$RSeff = RS / AREAeff$$

$$CJOeff = CJO \cdot AREAeff$$

LEVEL=3 Scaling

Level 3 scaling is affected by SCALM, SCALE, SHRINK, and M.

The Level 3 element parameters affected by SCALE include:

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

The model parameters affected by SCALM include:

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

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

If the AREA and PJ model parameters are specified and the element is not, use SCALM as the scaling factor instead of SCALE. The scaled effective area and periphery junction element parameters are determined by:

$$\mathrm{AREAeff} = \mathrm{AREA} \cdot \mathrm{M} \cdot \mathrm{SCALE}^2 \cdot \mathrm{SHRINK}^2$$

$$\mathrm{PJeff} = \mathrm{PJ} \cdot \mathrm{SCALE} \cdot \mathrm{M} \cdot \mathrm{SHRINK}$$

or, if W and L are specified,

$$\mathrm{AREAeff} = \mathrm{Weff} \cdot \mathrm{Leff} \cdot \mathrm{M}$$

$$\mathrm{PJeff} = (2 \cdot \mathrm{Weff} + 2 \cdot \mathrm{Leff}) \cdot \mathrm{M}$$

where

$$\mathrm{Weff} = \mathrm{W} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK} + \mathrm{XWeff}$$

$$\mathrm{Leff} = \mathrm{L} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK} + \mathrm{XWeff}$$

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

$$\mathrm{JSWeff} = \mathrm{PJeff} \cdot (\mathrm{JSW}/\mathrm{SCALM})$$

$$\mathrm{CJPeff} = \mathrm{PJeff} \cdot (\mathrm{CJP}/\mathrm{SCALM})$$

To determine the polysilicon and metal capacitor dimensions, multiply each by SCALE or by SCALM if specified as model parameters.

$$\mathrm{LMeff} = \mathrm{LM} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK}$$

$$\mathrm{WMeff} = \mathrm{WM} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK}$$

$$\mathrm{LPeff} = \mathrm{LP} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK}$$

$$\mathrm{WPeff} = \mathrm{WP} \cdot \mathrm{SCALE} \cdot \mathrm{SHRINK}$$

$$\mathrm{XPeff} = \mathrm{XP} \cdot \mathrm{SCALM}$$

$$\mathrm{XMeff} = \mathrm{XM} \cdot \mathrm{SCALM}$$

You can determine the effective scaled model parameters, IBeff, IKeff, IKReff, IBVeff, RSeff, and CJO as follows:

$$\mathrm{IKeff} = \mathrm{AREAeff} \cdot \mathrm{IK}$$

$$\mathrm{IKReff} = \mathrm{AREAeff} \cdot \mathrm{IKR}$$

$$\mathrm{IBVeff} = (\mathrm{AREAeff} \cdot \mathrm{IBV}) / \mathrm{SCALM}^2$$

$$\mathrm{ISeff} = \mathrm{IS} \cdot (\mathrm{AREAeff} / \mathrm{SCALM}^2)$$

$$\mathrm{RSeff} = \mathrm{RS} / (\mathrm{AREAeff} \cdot \mathrm{SCALM}^2)$$

$$\mathrm{CJOeff} = \mathrm{AREAeff} \cdot (\mathrm{CJO} / \mathrm{SCALM}^2)$$

Diode Current

Figure 13-1 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, 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.

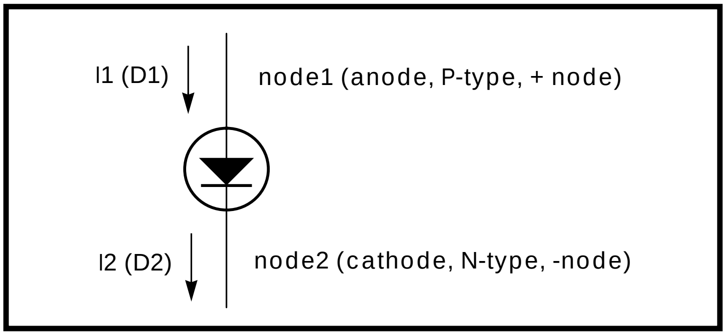

Figure 13-1: Diode Current Convention

Diode Equivalent Circuits

HSPICE uses three equivalent circuits in 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). For noise and AC analyses, the actual id current is not used. The partial derivative of id with respect to the terminal voltage vd is used instead. The name for this partial derivative is:

Conductance

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

The drain current (id) equation accounts for all basic DC effects of the diodes. Hspice assumes capacitance effects to be separate from the id equations.

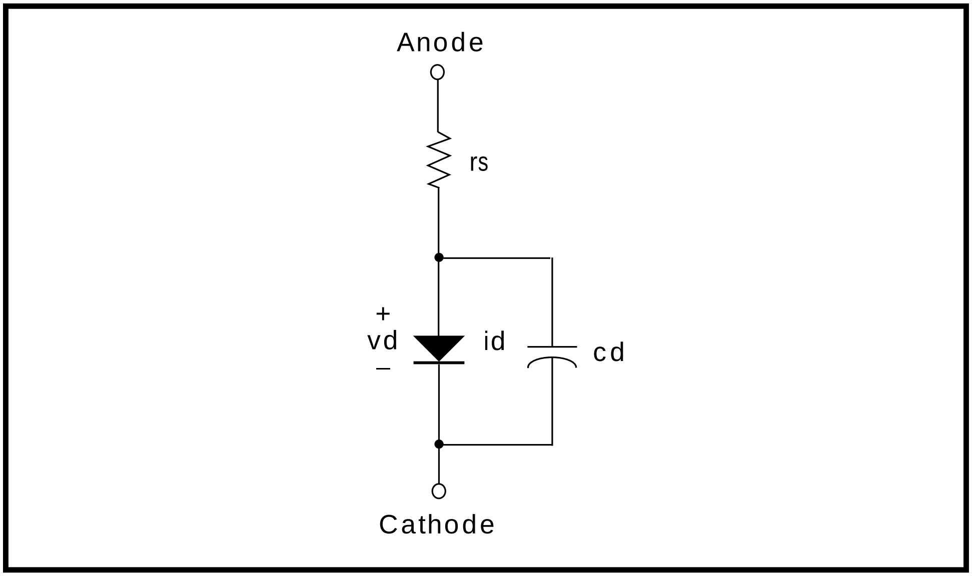

Figure 13-2: Equivalent Circuit, Diode Transient Analysis

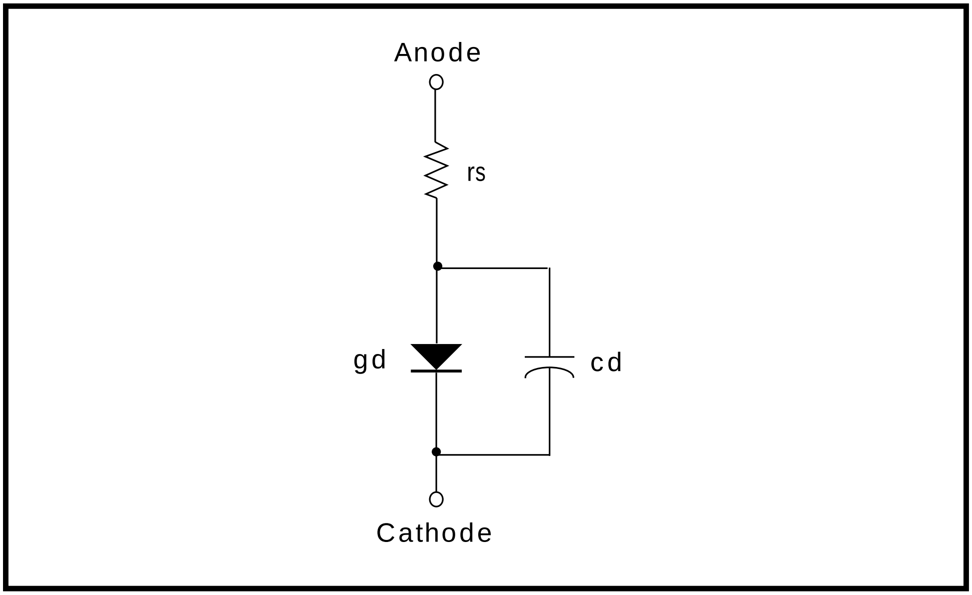

Figure 13-3: Equivalent Circuit, Diode AC Analysis

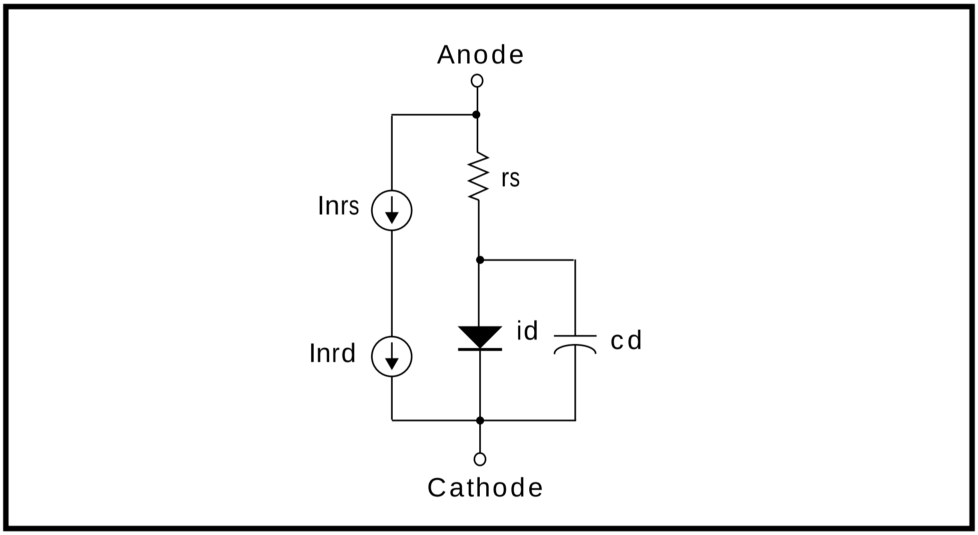

Figure 13-4: Equivalent Circuit, Diode AC Noise Analysis

Using the Junction Model Statement

This section describes how to use the junction model statement.

Format

The format of the junction model statement is:

```
.MODEL mnameD <LEVEL = val> <keyword = val> ...
```

mname	Model name. The diode element refers to the model by this name.
D	Symbol that identifies a diode model
LEVEL	Type of diode. The diode model includes three diode types: LEVEL=1 = junction diode LEVEL=2 = Fowler-Nordheim LEVEL=3 = geometric processing for junction diode
keyword	Model parameter keyword such as CJO or IS

Examples

Examples of the jumction model statements are:

```
.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=1XP  =0.0EG  =1.1
+ XOI  =0.0XOM =0.0XM  =0.0
+ WP   =0.0WM  =0.0LP  =0.0
+ LM   =0.0AF  =1.0JSW =0.0
+ PB   =0.65PHP =0.8M   =0.2994
+ FC   =0.95FCS =0.4MJSW=0.5
```

```
+ TT   =2.446e-9BV  =4.65RS  =19
+ IS   =1.485e-11CJO =1.09e-9CJP =0.0
+ PJ   =0.0N   =1.615IK  =0.0
+ IKR  =1.100e-2IBV =2.00e-2
```

Junction Model Parameters

The .MODEL statement is referenced by the diode element statement. The .MODEL statement contains parameters that specify the type of diode model used (Level 1, 2, or 3), as well as DC, capacitance, temperature, resistance, geometric, and noise parameters.

Table shows the junction diode model parameters and their function.)

Table 13-2: Junction Diode Model Parameters (Level 1 and Level 3

Function	Parameters
model type	LEVEL
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

Junction DC Parameters Level 1 and 3

Table shows the junction DC parameters for Levels one and three:

Table 13-3: Junction DC parameters for Level 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 = meter^2 If you specify W and L: AREAeff = Weff · Leff · M unit = meter^2
EXPLI	amp/ AREAeff	1e15	Current explosion model parameter. The PN junction characteristics above the explosion current are linear, with the slope at the explosion point, which increases simulation speed and improves convergence. EXPLIeff = EXPLI · AREAeff
IB	amp	1.0e-3	Current at breakdown voltage For LEVEL=3 IBVeff = IBV · AREAeff / SCALM^2
IBV	amp	1.0e-3	Current at breakdown voltage For LEVEL=3 IBVeff = IBV · AREAeff / SCALM^2
IK (IKF, JBF)	amp/ AREAeff	0.0	Forward knee current (intersection of the high- and low-current asymptotes) IKeff = IK · AREAeff.
IKR (JBR)	amp/ AREAeff	0.0	Reverse knee current (intersection of the high- and low-current asymptotes) IKReff = IKR · AREAeff.

Table 13-3: Junction DC parameters for Level and 3

Name(Alias)	Units	Default	Description
IS (JS)	amp/ AREAeff	1.0e-14	If you use an IS value less than EPSMIN, the program resets the value of IS to EPSMIN and displays 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/SCALM^2
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
L			Default length of diode Leff = L · SHRINK · SCALM+ XWeff
LEVEL		1	Diode model selector LEVEL=1 or LEVEL=3 selects junction diode model LEVEL=2 selects Fowler-Nordheim model
N		1.0	Emission coefficient
PJ		0.0	Junction periphery For LEVEL=1 PJeff = PJ · M, unitless For LEVEL=3 PJeff = PJ · SCALM · M · SHRINK, meter If W and L are specified PJeff = (2 · Weff + 2 · Leff) · M, meter

Table 13-3: Junction DC parameters for Level and 3

Name(Alias)	Units	Default	Description
RS	ohms or ohms/m^2 See Note.	0.0	Ohmic series resistance For LEVEL=1 RSeff = RS/AREAeff For LEVEL=3 RSeff= RS·SCALM^2/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 for which the AREA is not specified, AREA defaults to 1; then RS has units of Ohms. If AREA is specified in the netlist in m^2*, then the units of RS are Ohms/m*^{2}*.*

Junction Capacitance Parameters

Table 13-4 shows the junction capacitance parameters:

Table 13-4: 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 $CJeff = CJ \cdot AREAeff/SCALM^2$
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 forward-bias depletion area capacitance formula
FCS		0.5	Coefficient for the forward-bias depletion periphery capacitance formula
M (EXA,)MJ		0.5	Area junction grading coefficient
MJSW (EXP)		0.33	Periphery junction grading coefficient
PB (PHI, VJ, PHA)	V	0.8	Area junction contact potential

Table 13-4: Junction Capacitance Parameters

Name(Alias)	Units	Default	Description
PHP	V	PB	Periphery junction contact potential
TT	s	0.0	Transit time

Metal and Poly Capacitor Parameters Level=3

Table 13-5 shows the metal and poly capacitor parameters for Level 3:

Table 13-5: Metal and Poly Capacitor Parameters for Level 3

Name(Alias)	Units	Default	Description
LM	m	0.0	Use this parameter when LM is not specified in the element statement. $LMeff = LM \cdot SCALM \cdot SHRINK$
LP	m	0.0	Use this parameter if LP is not specified in the element statement. $LPeff = LP \cdot SCALM \cdot SHRINK$
WM	m	0.0	Use this parameter if WM is not specified in the element statement. $WMeff = WM \cdot SCALM \cdot SHRINK$
WP	m	0.0	Use this parameter if WP is not specified in the element statement. $WPeff = WP \cdot SCALM \cdot SHRINK$
XM	m	0.0	XM accounts for masking and etching effects: $XMeff = XM \cdot SCALM$.
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 $XPeff = XP \cdot SCALM$

Noise Parameters LEVEL=1 and 3

Table 13-5 shows the metal and poly capacitor parameters for Level 3

Table 13-6: Noise Parameters Level 1 and 3

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

Calculating Temperature Effects

Level 1 and Level 3 model statements contain parameters for the calculation of temperature effects. TLEV and TLEVC select different temperature equations for the calculation of temperature effects on energy gap, leakage current, breakdown voltage, contact potential, junction capacitance, and grading.

Table 13-7: Junction Diode Temperature Parameters (Level 1 and 3

Variable	Parameter
resistance coefficient	TRS
capacitance coefficient	CTA, CTP
energy gap	EG, GAP1, GAP2
transit time coefficient	TTT1, TTT2
reference temperature	TREF
temperature selectors	TLEV, TLEVC
miscellaneous	TM1, TM2, TPB, TPHP
saturation current	XT1

Temperature Effect Parameters LEVEL=1 and 3

Table 13-8: Temperature Effect Parameters

Name(Alias)	Units	Default	Description
CTA (CTC)	1/°	0.0	Temperature coefficient for area junction capacitance (CJ). Set parameter TLEVC to 1 to enable CTAl to override default temperature coefficient.
CTP	1/°	0.0	Temperature coefficient for periphery junction capacitance (CJP). Set TLEVC to 1 to enable CTP to override default temperature coefficient.

Table 13-8: Temperature Effect Parameters

Name(Alias)	Units	Default	Description
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
GAP1	eV/°	7.02e-4	7.02e-4 - silicon (old value) 4.73e-4 - silicon 4.56e-4 - germanium 5.41e-4 - gallium arsenide
GAP2		1108	1108 - silicon (old value) 636 - silicon 210 - germanium 204 - gallium arsenide
TCV	1/°	0.0	Breakdown voltage temperature coefficient
TLEV		0.0	Temperature equation selector for diode; 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	Temperature coefficient for PB. Set parameter TLEVC to 1 or 2 to enable TPB to override default temperature compensation.
TPHP	V/°	0.0	Temperature coefficient for PHP. Set parameter TLEVC to 1 or 2 to enable TPHP to override default temperature compensation.
TREF		25.0	Model reference temperature (Level 1 or 3 only)

Table 13-8: Temperature Effect Parameters

Name(Alias)	Units	Default	Description
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	Saturation current temperature exponent. Set XTI=3.0 for silicon-diffused junction. Set XTI=2.0 for Schottky barrier diode.

Using Diode Equations

Table 13-9 shows the diode equation variable definition:

Table 13-9: 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	diode equivalent noise current
inrs	series resistor equivalent noise current
vd	voltage across the diode

Table 13-10 shows the equation quantity definition:

Table 13-10: Equation Quantity Definition

Quantity	Definition
tox	3.453143e-11 F/m
k	1.38062e-23 (Boltzmann’s constant)
q	1.60212e-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

Junction DC Equations

The basic diode is modeled in 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 volts. Set the model parameter RS to limit conduction current. As the forward bias voltage increases past 0.6 volts, the limiting resistor prevents the value of the diode current from becoming too high and the solution from converging.

Forward Bias: vd > -10 · vt

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

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

For 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 · vt

$$id = -ISeff$$

For breakdown, the parameter BV (VB) is set, inducing reverse breakdown or avalanche. This effect is seen in Zener diodes and occurs when the anode-cathode voltage is less than BV. Model this action by measuring the voltage (BV) and the current (IBV) at the reverse knee or onset of avalanche.

Note: BV is always described as a positive number.

Breakdown: vd < - BVeff

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

The BV parameter is adjusted as follows to obtain BVeff:

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

If IBVeff > ibreak, then,

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

Otherwise,

$$IBVeff = ibreak$$

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

Note: The exponential equation is used in both the forward and reverse regions.

Forward Bias

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

Reverse Bias

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

where id1 is

For vd $\geq$ -BV$_{eff}$:

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

Otherwise:

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

You can estimate the reverse saturation current IS, emission coefficient N, and model parameter RS from DC measurements of the forward biased diode characteristics. 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 unit, but is closer to 2 for MOS diodes.

In practice, at higher levels of bias, the diode current deviates from the ideal exponential characteristic. This deviation is due to the presence of ohmic resistance in the diode as well as high-level injection effects. The deviation of the actual diode voltage from the ideal exponential characteristic at a specific current determines the value of RS. In practice, RS is estimated at several values of id and averaged, since the value of RS depends upon diode current.

Diode Capacitance Equations

The diode capacitance is modeled by cd in Figure 13-4. The capacitance, cd, is a combination of diffusion capacitance, (cdiff), depletion capacitance, (cdep), metal, (cmetal), and poly capacitances, (cpoly).

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

Diffusion Capacitance Equations

The transit time (TT) models the diffusion capacitance, caused by injected minority carriers. In practice, TT is estimated from pulsed time-delay measurements.

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

Depletion Capacitance Equations

The depletion capacitance is modeled by junction bottom and junction periphery capacitances. The formula for both bottom area and periphery capacitances is similar, except each has its own model parameters. There are two equations for forward bias junction capacitance which are selected using .OPTIONS DCAP.

DCAP=1

The junction bottom area capacitance formula is:

$\boldsymbol{vd < FC \cdot PB}$

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

$\boldsymbol{vd \;\; FC \cdot PB}$

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

The junction periphery capacitance formula is:

$\boldsymbol{vd < FCS \cdot PHP}$

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

$\boldsymbol{vd \;\; FCS \cdot PHP}$

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

then,

$$cdep = cdepa + cdepp$$

DCAP=2 (default)

The total depletion capacitance formula is:

vd < 0

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

vd 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 · CGDeff or FC · CGSeff, with proper fall-off when forward bias exceeds PB (FC ≥ 1).

Metal and Poly Capacitance Equations (LEVEL=3 Only)

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

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

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

Noise Equations

Figure 13-4 shows the noise model for a diode. An independent current source, inrs, in parallel with the resistor models the thermal noise generated by a resistor. To determine the value of inrs, use the equation:

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

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

The shot and flicker noise of the diode are modeled by the current source ind, which is defined by:

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

Temperature Compensation Equations

This section describes the temperature compensation equations.

Energy Gap Temperature Equations

Use the following equations to determine energy gap for temperature compensation.

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

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

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

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

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

Breakdown Voltage Temperature Equations

TLEV=0

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

TLEV=1 or 2

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

Transit Time Temperature Equations

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

Contact Potential Temperature Equations

TLEVC=0

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

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

TLEVC=1 or 2

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

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

TLEVC=3

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

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

where TLEV=0 or 1

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

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

and 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

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

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

TLEVC=1

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

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

TLEVC=2

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

Note: In the above equation MJ is not MJ(t).

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

TLEVC=3

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

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

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 Fowler-Nordheim Diode

The diode model parameter LEVEL=2 selects the Fowler-Nordheim model. Fowler- Nordheim diodes are formed as a metal-insulator-semiconductor or as 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, and other insulation breakdown devices.

Fowler-Nordheim Diode Element

The format of the Fowler-Nordheim diode element is:

```
Dxxx nplus nminus mname <W=val <L=val>> <OFF> <IC=vd>
<M=val>
```

Dxxx	Diode element name. Must begin with the letter **D**, and can be followed by a maximum of 15 alphanumeric characters.
nplus	Positive (anode) terminal node name (can be up to 16 characters)
nminus	Negative (cathode) terminal node name (can be up to 16 characters)
mname	Model name. Must reference a LEVEL=2 model for a Fowler- Nordheim diode element.
W	Width of diode in units of meter. Overrides W in the LEVEL=2 model. Default=0.0. `Weff = W · SCALE · SHRINK + XWeff`
L	Length of diode in units of meter. Overrides L in the LEVEL=2 model. Default=0.0. `Leff = L · SCALE · SHRINK + XWeff`

OFF	Sets initial condition to OFF for this element in DC analysis. Default=ON.
IC=vd	Initial voltage across this diode element. Interacts with the UIC option on the .TRAN statement and overridden by the .IC statement.
M	Multiplier factor to simulate multiple diodes. M affects all currents and capacitances. Default=1.0.

Example

```
*FILE: /TUN.SP
.OPTION GMINDC=1E-22 GMIN=1E-22 PIVTOL=1E-23
D1 1 0 TMOD   W=5E-4   L=5E-4
.MODEL TMOD D LEVEL=2 EF=3E8 JF=2E-6  TOX=100
.TRAN .2 5S
VD 1 0 PL 5V 0S    10V 5S
.PRINT V(1) I(D1)
.END
```

The SCALE element parameter scales the length and width of Fowler-Nordheim diode models.

SCALM is used as the scaling factor if length and width are specified as model parameters.

If both element and model parameters are specified, the element parameter is used along with the SCALE scaling factor. The effective area is then determined as the product of the scaled effective length and width.

Fowler-Nordheim Diode Model Parameters LEVEL=2

Table 13-11 shows the Fowler-Nordheim diode model parameters for Level 2:

Table 13-11: 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/V^2	1.0e-10	Forward Fowler-Nordheim current coefficient
JR	amp/V^2	JF	Reverse Fowler-Nordheim current coefficient
L	m	0.0	Length of diode for calculation of Fowler-Nordheim current Leff = L · SCALM · SHRINK + XWeff
TOX	Å	100.0	Thickness of oxide layer
W	m	0.0	Width of diode for calculation of Fowler-Nordheim current Weff = W · SCALM · SHRINK + XWeff
XW	m	0.0	XWeff = XW · SCALM

Fowler-Nordheim Diode Equations

The DC characteristics of the Fowler-Nordheim diode are modeled by the following forward and reverse nonlinear current source equations. In the following equations:

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

Forward Bias: vd 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:

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

Converting National Semiconductor Models

National Semiconductor's circuit simulator has a scaled diode model that is not the same as that used by HSPICE. To use National Semiconductor circuit models, do the following:

For a subcircuit that consists of the scaled diode model, the subcircuit name must be the same as the name of the model.

The .PARAM statement inside the subcircuit specifies the scaled diode model parameter values. Add a scaled diode model inside the subcircuit, then change the `.MODEL mname mtype` statement to a .PARAM statement.

Ensure that all the scaled diode elements are preceded by the character X.

Check that every parameter used in the .MODEL statement inside the subcircuit has a value in the .PARAM statement.

Scaled Diode Subcircuit Definition

The scaled diode subcircuit definition converts the National Semiconductor scaled diode model to a form a model usable in HSPICE. The .PARAM parameter inside the .SUBCKT represents the .MODEL parameter in the National circuit simulator. Replace the .MODEL mname statement by a .PARAM statement. Change the model name to SDIODE.

Example

An example of scaled diode subcircuit definition is:

```
.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
```

Note: All the parameters used in the following model must have a value which comes from either a .PARAM statement or the .SUBCKT call. The diode statements are then replaced by the call to the subcircuit SDIODE:

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