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>
<thead>
<tr>
<th>Function</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>netlist</td>
<td>Dxxx, n+, n-, mname</td>
</tr>
<tr>
<td>initialization</td>
<td>IC, OFF</td>
</tr>
<tr>
<td>temperature</td>
<td>DTEMP</td>
</tr>
<tr>
<td>geometric junction</td>
<td>AREA, L, M, PJ, W</td>
</tr>
<tr>
<td>geometric capacitance (Level=3 only)</td>
<td>LM, LP, WM, WP</td>
</tr>
</tbody>
</table>
### 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,

\[
\text{AREAeff} = \text{AREA} \times \text{M} \times \text{SCALE}^2 \times \text{SHRINK}^2, \text{ or}
\]

\[
\text{AREAeff} = \text{Weff} \times \text{Leff} \times \text{M}
\]

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.
## Using Diodes

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

For LEVEL=1,
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.

\[
P_{\text{Jeff}} = P_J \cdot M
\]

\( P_{\text{Jeff}} \) is then used to scale \( C_{\text{JP}} \), the zero-bias junction capacitance, and the sidewall saturation current, \( J_{\text{SW}} \).

\[
C_{\text{JPeff}} = P_{\text{Jeff}} \cdot C_{\text{JP}}
\]

\[
J_{\text{Sweff}} = P_{\text{Jeff}} \cdot J_{\text{SW}}
\]

\( \text{AREA} \) and \( M \) are used to obtain \( \text{AREAeff} \).

\[
\text{AREAeff} = \text{AREA} \cdot M
\]

\( C_{\text{JO}}, I_K, I_{KR}, I_{BV}, \) and \( I_{S} \) are multiplied by \( \text{AREAeff} \) to obtain their effective scaled values. \( R_S \), however, is divided by \( \text{AREAeff} \).

\[
I_{Keff} = \text{AREAeff} \cdot I_K
\]

\[
I_{KR eff} = \text{AREAeff} \cdot I_{KR}
\]

\[
I_{BV eff} = \text{AREAeff} \cdot I_{BV}
\]

\[
I_{S eff} = \text{AREAeff} \cdot I_{S}
\]

\[
R_{S eff} = R_S / \text{AREAeff}
\]

\[
C_{J O eff} = C_{J O} \cdot \text{AREAeff}
\]

**LEVEL=3 Scaling**

Level 3 scaling is affected by \( \text{SCALM}, \text{SCALE}, \text{SHRINK}, \) and \( M \).

The Level 3 element parameters affected by \( \text{SCALE} \) include:

\( \text{AREA}, \text{LM}, \text{LP}, P_J, WM, WP, W, L \)

The model parameters affected by \( \text{SCALM} \) include:


If you include the \( \text{AREA} \) as either an element parameter or a model parameter, the program uses \( \text{SCALE} \) or \( \text{SCALM} \). The following equations use the \( \text{AREA} \) *element* parameter, instead of the \( \text{AREA} \) *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:

\[
\text{AREA}_{\text{eff}} = \text{AREA} \cdot M \cdot \text{SCALE}^2 \cdot \text{SHRINK}^2 \\
\text{PJ}_{\text{eff}} = \text{PJ} \cdot \text{SCALE} \cdot M \cdot \text{SHRINK}
\]

or, if W and L are specified,

\[
\text{AREA}_{\text{eff}} = W_{\text{eff}} \cdot L_{\text{eff}} \cdot M \\
\text{PJ}_{\text{eff}} = (2 \cdot W_{\text{eff}} + 2 \cdot L_{\text{eff}}) \cdot M
\]

where

\[
W_{\text{eff}} = W \cdot \text{SCALE} \cdot \text{SHRINK} + X_{\text{Weff}} \\
L_{\text{eff}} = L \cdot \text{SCALE} \cdot \text{SHRINK} + X_{\text{Leff}}
\]

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

\[
J_{\text{SWeff}} = \text{PJ}_{\text{eff}} \cdot (\text{JSW} / \text{SCALM}) \\
C_{\text{JPeff}} = \text{PJ}_{\text{eff}} \cdot (\text{CJP} / \text{SCALM})
\]

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

\[
L_{\text{Meff}} = L_M \cdot \text{SCALE} \cdot \text{SHRINK} \\
W_{\text{Meff}} = W_M \cdot \text{SCALE} \cdot \text{SHRINK} \\
L_{\text{Peff}} = L_P \cdot \text{SCALE} \cdot \text{SHRINK} \\
W_{\text{Peff}} = W_P \cdot \text{SCALE} \cdot \text{SHRINK} \\
X_{\text{Peff}} = X_P \cdot \text{SCALM} \\
X_{\text{Meff}} = X_M \cdot \text{SCALM}
\]
You can determine the effective scaled model parameters, $I_{Beff}$, $I_{Keff}$, $I_{KReff}$, $I_{BVeff}$, $R_{Seff}$, and $C_{JOeff}$ as follows:

\[
\begin{align*}
I_{Keff} &= A_{REAeff} \cdot I_K \\
I_{KReff} &= A_{REAeff} \cdot I_{KR} \\
I_{BVeff} &= (A_{REAeff} \cdot I_{BV}) / SCALM^2 \\
I_{Seff} &= I_S \cdot (A_{REAeff}/SCALM^2) \\
R_{Seff} &= R_S / (A_{REAeff} \cdot SCALM^2) \\
C_{JOeff} &= A_{REAeff} \cdot (C_{JO}/SCALM^2)
\end{align*}
\]

**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](image-url)
**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 \( i_d \). For noise and AC analyses, the actual \( i_d \) current is not used. The partial derivative of \( i_d \) with respect to the terminal voltage \( v_d \) is used instead. The name for this partial derivative is:

*Conductance*

\[
g_d = \frac{\partial i_d}{\partial v_d}
\]

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

---

*Figure 13-2: Equivalent Circuit, Diode Transient Analysis*
Using Diodes

Figure 13-3: Equivalent Circuit, Diode AC Analysis

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

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 junction 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 dln750a 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
```
Using Diodes

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)

<table>
<thead>
<tr>
<th>Function</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>model type</td>
<td>LEVEL</td>
</tr>
<tr>
<td>DC parameters</td>
<td>IBV, IK, IKR, IS, ISW, N, RS, VB, RS</td>
</tr>
<tr>
<td>geometric junction</td>
<td>AREA, M, PJ</td>
</tr>
<tr>
<td>geometric capacitance</td>
<td>L, LM, LP, SHRINK, W, WM, WP, XM, XOJ, XOM, XP, XW</td>
</tr>
<tr>
<td>capacitance</td>
<td>CJ, CJP, FC, FCS, M, MJSW, PB, PHP, TT</td>
</tr>
<tr>
<td>noise</td>
<td>AK, KF</td>
</tr>
</tbody>
</table>
**Junction DC Parameters Level 1 and 3**

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

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA</td>
<td>1.0</td>
<td>Junction area</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>For LEVEL=1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AREAeff = AREA \cdot M, unitless</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>For LEVEL=3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AREAeff/Area \cdot SCALM^2 \cdot SHRINK^2 \cdot M unit = meter^2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>If you specify W and L:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AREAeff = Weff \cdot Leff \cdot M unit = meter^2</td>
<td></td>
</tr>
<tr>
<td>EXPLI</td>
<td>amp/AREAeff</td>
<td>1e15</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EXPLIeff = EXPLI \cdot AREAeff</td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>amp</td>
<td>1.0e-3</td>
<td>Current at breakdown voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For LEVEL=3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBVeff = IBV \cdot AREAeff / SCALM^2</td>
<td></td>
</tr>
<tr>
<td>IBV</td>
<td>amp</td>
<td>1.0e-3</td>
<td>Current at breakdown voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For LEVEL=3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBVeff = IBV \cdot AREAeff / SCALM^2</td>
<td></td>
</tr>
<tr>
<td>IK (IKF, JBF)</td>
<td>amp/AREAeff</td>
<td>0.0</td>
<td>Forward knee current (intersection of the high- and low-current asymptotes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IKeff = IK \cdot AREAeff.</td>
<td></td>
</tr>
<tr>
<td>IKR (JBR)</td>
<td>amp/AREAeff</td>
<td>0.0</td>
<td>Reverse knee current (intersection of the high- and low-current asymptotes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IKReff = IKR \cdot AREAeff.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 13-3: Junction DC parameters for Level 1 and 3

<table>
<thead>
<tr>
<th>Name (Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS (JS)</td>
<td>amp/</td>
<td>1.0e-14</td>
<td>If you use an IS value less than EPSMIN, the program resets the value of IS to EPSMIN and displays a warning message.</td>
</tr>
<tr>
<td></td>
<td>AREAeff</td>
<td></td>
<td>EPSMIN default=1.0e-28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>If the value of IS is too large, the program displays a warning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For LEVEL=1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ISeff = AREAeff \cdot IS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For LEVEL=3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ISeff = AREAeff \cdot IS/SCALM^2</td>
</tr>
</tbody>
</table>

| JSW (ISP)    | amp/  | 0.0    | Sidewall saturation current per unit junction periphery |
|              | PJeff |        | For LEVEL=1 |
|              |        |        | JSWeff = PJeff \cdot JSW |
|              |        |        | For LEVEL=3 |
|              |        |        | JSWeff = PJeff \cdot JSW/SCALM |

| L            |       | Default length of diode |
|              |       | Leff = L \cdot SHRINK \cdot SCALM + XWeff |

| LEVEL        |       | 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 \cdot M, unitless |
|              |       | For LEVEL=3 |
|              |       | PJeff = PJ \cdot SCALM \cdot M \cdot SHRINK, meter |
|              |       | If W and L are specified |
|              |       | PJeff = (2 \cdot Weff + 2 \cdot Leff) \cdot M, meter |
Specifying Junction Diodes

Table 13-3: Junction DC parameters for Level 1 and 3

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>ohms</td>
<td>0.0</td>
<td>Ohmic series resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For LEVEL=1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RSeff = RS/AREAeff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For LEVEL=3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RSeff = RS · SCALM²/AREAeff</td>
</tr>
<tr>
<td></td>
<td>ohms/m²</td>
<td></td>
<td>See Note.</td>
</tr>
<tr>
<td>SHRINK</td>
<td></td>
<td>1.0</td>
<td>Shrink factor</td>
</tr>
<tr>
<td>VB (BV, VAR, VRB)</td>
<td>V</td>
<td>0.0</td>
<td>Reverse breakdown voltage. 0.0 indicates an infinite breakdown voltage</td>
</tr>
<tr>
<td>XW</td>
<td></td>
<td></td>
<td>Accounts for masking and etching effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>XWeff = XW · SCALM</td>
</tr>
</tbody>
</table>

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 m², then the units of RS are Ohms/m².
## Junction Capacitance Parameters

Table 13-4 shows the junction capacitance parameters:

### Table 13-4: Junction Capacitance Parameters

<table>
<thead>
<tr>
<th>Name (Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CJ (CJA, CJO)</td>
<td>F/AREAe</td>
<td>0.0</td>
<td>Zero-bias junction capacitance per unit junction bottomwall area</td>
</tr>
</tbody>
</table>
| | | | For LEVEL=1  
| | | | CJo_{eff} = CJO \cdot AREA_{eff} |
| | | | For LEVEL=3  
| | | | CJ_{eff} = CJ \cdot AREA_{eff}/SCALM^{2} |
| CJP (CJSW) | F/PJeff | 0.0 | Zero-bias junction capacitance per unit junction periphery (PJ) |
| | | | For LEVEL=1  
| | | | CJ_{peff} = CJP \cdot PJeff |
| | | | For LEVEL=3  
| | | | CJ_{peff} = CJP \cdot PJeff/SCALM |
| FC | F | 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, V) | | 0.8 | Area junction contact potential |

VJ, PHA |
### Table 13-4: Junction Capacitance Parameters

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHP</td>
<td>V</td>
<td>PB</td>
<td>Periphery junction contact potential</td>
</tr>
<tr>
<td>TT</td>
<td>s</td>
<td>0.0</td>
<td>Transit time</td>
</tr>
</tbody>
</table>

### 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

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
</table>
| LM          | m     | 0.0     | Use this parameter when LM is not specified in the element statement.  
LMeff = LM ⋅ SCALM ⋅ SHRINK |
| LP          | m     | 0.0     | Use this parameter if LP is not specified in the element statement.  
LPeff = LP ⋅ SCALM ⋅ SHRINK |
| WM          | m     | 0.0     | Use this parameter if WM is not specified in the element statement.  
WMeff = WM ⋅ SCALM ⋅ SHRINK |
| WP          | m     | 0.0     | Use this parameter if WP is not specified in the element statement.  
WPeff = WP ⋅ SCALM ⋅ SHRINK |
| XM          | m     | 0.0     | XM accounts for masking and etching effects:  
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  
XPeff = XP ⋅ 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**

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>1.0</td>
<td></td>
<td>flicker noise exponent</td>
</tr>
<tr>
<td>KF</td>
<td>0.0</td>
<td></td>
<td>flicker noise coefficient</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistance coefficient</td>
<td>TRS</td>
</tr>
<tr>
<td>capacitance coefficient</td>
<td>CTA, CTP</td>
</tr>
<tr>
<td>energy gap</td>
<td>EG, GAP1, GAP2</td>
</tr>
<tr>
<td>transit time coefficient</td>
<td>TTT1, TTT2</td>
</tr>
<tr>
<td>reference temperature</td>
<td>TREF</td>
</tr>
<tr>
<td>temperature selectors</td>
<td>TLEV, TLEVC</td>
</tr>
<tr>
<td>miscellaneous</td>
<td>TM1, TM2, TPB, TPHP</td>
</tr>
<tr>
<td>saturation current</td>
<td>XT1</td>
</tr>
</tbody>
</table>

Temperature Effect Parameters LEVEL=1 and 3

Table 13-8: Temperature Effect Parameters

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTA (CTC)</td>
<td>1/°</td>
<td>0.0</td>
<td>Temperature coefficient for area junction capacitance (CJ). Set parameter TLEVC to 1 to enable CTAI to override default temperature coefficient.</td>
</tr>
<tr>
<td>CTP</td>
<td>1/°</td>
<td>0.0</td>
<td>Temperature coefficient for periphery junction capacitance (CJP). Set TLEVC to 1 to enable CTP to override default temperature coefficient.</td>
</tr>
</tbody>
</table>
### Table 13-8: Temperature Effect Parameters

<table>
<thead>
<tr>
<th>Name (Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG</td>
<td>eV</td>
<td></td>
<td>Energy gap for pn junction diode</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For TLEV=0, 1, default=1.11, for TLEV=2, default=1.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.17 - silicon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.69 - Schottky barrier diode</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.67 - germanium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.52 - gallium arsenide</td>
</tr>
<tr>
<td>GAP1</td>
<td>eV/°</td>
<td>7.02e-4</td>
<td>7.02e-4 - silicon (old value)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.73e-4 - silicon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.56e-4 - germanium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.41e-4 - gallium arsenide</td>
</tr>
<tr>
<td>GAP2</td>
<td>1108</td>
<td></td>
<td>1108 - silicon (old value)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>636 - silicon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>210 - germanium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>204 - gallium arsenide</td>
</tr>
<tr>
<td>TCV</td>
<td>1/°</td>
<td>0.0</td>
<td>Breakdown voltage temperature coefficient</td>
</tr>
<tr>
<td>TLEV</td>
<td>0.0</td>
<td></td>
<td>Temperature equation selector for diode; interacts with TLEVC</td>
</tr>
<tr>
<td>TLEVC</td>
<td>0.0</td>
<td></td>
<td>Level selector for diode temperature, junction capacitances and contact potentials; interacts with TLEV</td>
</tr>
<tr>
<td>TM1</td>
<td>1/°</td>
<td>0.0</td>
<td>First order temperature coefficient for MJ</td>
</tr>
<tr>
<td>TM2</td>
<td>1/°²</td>
<td>0.0</td>
<td>Second order temperature coefficient for MJ</td>
</tr>
<tr>
<td>TPB (TVJ)</td>
<td>V/°</td>
<td>0.0</td>
<td>Temperature coefficient for PB. Set parameter TLEVC to 1 or 2 to enable TPB to override default temperature compensation.</td>
</tr>
<tr>
<td>TPHP</td>
<td>V/°</td>
<td>0.0</td>
<td>Temperature coefficient for PHP. Set parameter TLEVC to 1 or 2 to enable TPHP to override default temperature compensation.</td>
</tr>
<tr>
<td>TREF</td>
<td>25.0</td>
<td></td>
<td>Model reference temperature (Level 1 or 3 only)</td>
</tr>
</tbody>
</table>
Calculating Temperature Effects

Table 13-8: Temperature Effect Parameters

<table>
<thead>
<tr>
<th>Name(Alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRS</td>
<td>(^{1/0})</td>
<td>0.0</td>
<td>Resistance temperature coefficient</td>
</tr>
<tr>
<td>TTT1</td>
<td>(^{1/0})</td>
<td>0.0</td>
<td>First order temperature coefficient for TT</td>
</tr>
<tr>
<td>TTT2</td>
<td>(^{1/0^2})</td>
<td>0.0</td>
<td>Second order temperature coefficient for TT</td>
</tr>
<tr>
<td>XTI</td>
<td>3.0</td>
<td></td>
<td>Saturation current temperature exponent. Set XTI=3.0 for silicon-diffused junction. Set XTI=2.0 for Schottky barrier diode.</td>
</tr>
</tbody>
</table>
Using Diode Equations

Table 13-9 shows the diode equation variable definition:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>cd</td>
<td>total diode capacitance</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
</tr>
<tr>
<td>gd</td>
<td>diode conductance</td>
</tr>
<tr>
<td>id</td>
<td>diode DC current</td>
</tr>
<tr>
<td>id1</td>
<td>current without high level injection</td>
</tr>
<tr>
<td>ind</td>
<td>diode equivalent noise current</td>
</tr>
<tr>
<td>inrs</td>
<td>series resistor equivalent noise current</td>
</tr>
<tr>
<td>vd</td>
<td>voltage across the diode</td>
</tr>
</tbody>
</table>

Table 13-10 shows the equation quantity definition:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>tox</td>
<td>3.453143e-11 F/m</td>
</tr>
<tr>
<td>k</td>
<td>1.38062e-23 (Boltzmann's constant)</td>
</tr>
<tr>
<td>q</td>
<td>1.60212e-19 (electron charge)</td>
</tr>
<tr>
<td>t</td>
<td>temperature in °Kelvin</td>
</tr>
<tr>
<td>Δt</td>
<td>t - tnom</td>
</tr>
<tr>
<td>tnom</td>
<td>nominal temperature of parameter measurements in °Kelvin</td>
</tr>
<tr>
<td>vt(t)</td>
<td>k \cdot t/q; thermal voltage</td>
</tr>
<tr>
<td>vt(tnom)</td>
<td>k \cdot tnom/q; thermal voltage</td>
</tr>
</tbody>
</table>
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:** \( v_d > -10 \cdot v_t \)

\[
\begin{align*}
    id &= I_{Seff} \cdot \left( \frac{v_d}{e^{N \cdot v_t}} - 1 \right) \\
    v_d &= v_{\text{node}1} - v_{\text{node}2}
\end{align*}
\]

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:** \( BV_{eff} < v_d < -10 \cdot v_t \)

\[
    id = -I_{Seff}
\]

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:** \( v_d < -BV_{eff} \)

\[
    id = -I_{Seff} \cdot e^{\left(\frac{v_d + BV_{eff}}{N \cdot v_t}\right)}
\]
Using Diodes

The BV parameter is adjusted as follows to obtain BVeff:

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

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 \( vd \geq -BVeff \):

\[ id1 = ISeff \cdot \left( \frac{vd}{e^{N \cdot vt}} - 1 \right) \]
Using Diode Equations

Otherwise:

\[ id1 = IS_{eff} \cdot \left( e^{\frac{vD}{N \cdot vT}} - 1 \right) - IS_{eff} \cdot \left[ e^{\left(\frac{vD + BV_{eff}}{N \cdot vT}\right)} - 1 \right] \]

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:

\[ v_d < FC \cdot PB \]

\[ c_{depa} = C_{Jeff} \cdot \left(1 - \frac{v_d}{PB}\right)^{MJ} \]

\[ v_d = FC \cdot PB \]

\[ c_{depa} = C_{Jeff} \cdot \frac{1 - FC \cdot (1 + MJ) + MJ \cdot \frac{v_d}{PB}}{(1 - FC)^{(1 + MJ)}} \]

The junction periphery capacitance formula is:

\[ v_d < FCS \cdot PHP \]

\[ c_{depp} = C_{JPeff} \cdot \left(1 - \frac{v_d}{PHP}\right)^{MJSW} \]

\[ v_d = FCS \cdot PHP \]

\[ c_{depp} = C_{JPeff} \cdot \frac{1 - FCS \cdot (1 + MJSW) + MJSW \cdot \frac{v_d}{PHP}}{(1 - FCS)^{(1 + MJSW)}} \]

then,

\[ c_{dep} = c_{depa} + c_{depp} \]
DCAP=2 (default)

The total depletion capacitance formula is:

\[ \text{vd} < 0 \]

\[ c_{dep} = CJeff \cdot \left(1 - \frac{\text{vd}}{PB}\right)^{-MJ} + CJPeff \cdot \left(1 - \frac{\text{vd}}{PHP}\right)^{-MJSW} \]

\[ \text{vd} \geq 0 \]

\[ c_{dep} = CJeff \cdot \left(1 + MJ \cdot \frac{\text{vd}}{PB}\right) + CJPeff \cdot \left(1 + MJSW \cdot \frac{\text{vd}}{PHP}\right) \]

DCAP=3

Limits peak depletion capacitance to \( FC \cdot CGEff \) or \( FC \cdot CGSeff \), with proper fall-off when forward bias exceeds PB (\( FC \geq 1 \)).

Metal and Poly Capacitance Equations (LEVEL=3 Only)

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

\[ c_{metal} = \left(\frac{\varepsilon_{ox}}{XOI}\right) \cdot (WPeff + XPeff) \cdot (LPeff + XPeff) \cdot M \]

\[ c_{poly} = \left(\frac{\varepsilon_{ox}}{XOM}\right) \cdot (WMeff + XMeff) \cdot (LMeff + XMeff) \cdot M \]

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:

\[ inrs = \left(\frac{4 \cdot k \cdot t}{RS_{eff}}\right)^{1/2} \]

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:

\[
ind = \left(2 \cdot q \cdot id + \frac{KF \cdot id_A^F}{f}\right)^{1/2}
\]

**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 \( 1 \)

\[
eganom = 1.16 - 7.02e^{-4} \cdot \frac{tnom^2}{tnom + 1108.0}
\]

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

\( TLEV=2 \)

\[
eganom = EG - GAP1 \cdot \frac{tnom^2}{tnom + GAP2}
\]

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

**Leakage Current Temperature Equations**

\[
JS(t) = JS \cdot e^{\frac{facin}{N}}
\]

\[
JSW(t) = JSW \cdot e^{\frac{facin}{N}}
\]
Using Diode Equations

**TLEV=0 or 1**

\[
\text{facln} = \frac{EG}{vt(t_{\text{nom}})} - \frac{EG}{vt(t)} + XTI \cdot \ln \left(\frac{t}{t_{\text{nom}}}\right)
\]

**TLEV=2**

\[
\text{facln} = \frac{eg_{\text{nom}}}{vt(t_{\text{nom}})} - \frac{eg(t)}{vt(t)} + XTI \cdot \ln \left(\frac{t}{t_{\text{nom}}}\right)
\]

**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**

**TLEV=0**

\[
PB(t) = PB \cdot \left(\frac{t}{t_{\text{nom}}}\right) - \frac{vt(t)}{VT(t)} \cdot \left[3 \cdot \ln \left(\frac{t}{t_{\text{nom}}}\right) + \frac{eg_{\text{nom}}}{vt(t_{\text{nom}})} - \frac{eg(t)}{vt(t)}\right]
\]

\[
PHP(t) = PHP \cdot \frac{t}{t_{\text{nom}}} - \frac{vt(t)}{VT(t)} \cdot \left[3 \cdot \ln \left(\frac{t}{t_{\text{nom}}}\right) + \frac{eg_{\text{nom}}}{vt(t_{\text{nom}})} - \frac{eg(t)}{vt(t)}\right]
\]

**TLEV=1 or 2**

\[
PB(t) = PB - TPB \cdot \Delta t
\]

\[
PHP(t) = PHP - TPHP \cdot \Delta t
\]
Using Diodes

**TLEVC=3**

\[ PB(t) = PB + \frac{dpbdt}{\Delta t} \]

\[ PHP(t) = PHP + \frac{dphpdt}{\Delta t} \]

where TLEV=0 or 1

\[
\frac{dpbdt}{\Delta t} = \frac{-\left[ egnom \cdot 3 \cdot vt(t_{nom}) + (1.16 - egnom) \cdot \left( 2 - \frac{t_{nom}}{t_{nom} + 1108} \right) - PB \right]}{t_{nom}}
\]

\[
\frac{dphpdt}{\Delta t} = \frac{-\left[ egnom \cdot 3 \cdot vt(t_{nom}) + (1.16 - egnom) \cdot \left( 2 - \frac{t_{nom}}{t_{nom} + 1108} \right) - PHP \right]}{t_{nom}}
\]

and TLEV=2

\[
\frac{dpbdt}{\Delta t} = \frac{-\left[ egnom \cdot 3 \cdot vt(t_{nom}) + (EG - egnom) \cdot \left( 2 - \frac{t_{nom}}{t_{nom} + GAP2} \right) - PB \right]}{t_{nom}}
\]

\[
\frac{dphpdt}{\Delta t} = \frac{-\left[ egnom \cdot 3 \cdot vt(t_{nom}) + (EG - egnom) \cdot \left( 2 - \frac{t_{nom}}{t_{nom} + GAP2} \right) - PHP \right]}{t_{nom}}
\]

**Junction Capacitance Temperature Equations**

**TLEVC=0**

\[ CJ(t) = CJ \cdot \left[ 1 + MJ \cdot \left( 4.0 \cdot 10^{-4} \cdot \Delta t - \frac{PB(t)}{PB} + 1 \right) \right]\]

\[ CJSW(t) = CJSW \cdot \left[ 1 + MJSW \cdot \left( 4.0 \cdot 10^{-4} \cdot \Delta t - \frac{PHP(t)}{PHP} + 1 \right) \right]\]
Using Diode Equations

**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 Diodes

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.
  
  \[ W_{eff} = W \cdot \text{SCALE} \cdot \text{SHRINK} + X_{Weff} \]

- **L**: Length of diode in units of meter. Overrides L in the LEVEL=2 model. Default=0.0.
  
  \[ L_{eff} = L \cdot \text{SCALE} \cdot \text{SHRINK} + X_{Leff} \]
Using the Fowler-Nordheim Diode

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>
<thead>
<tr>
<th>Name (alias)</th>
<th>Units</th>
<th>Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF</td>
<td>V/cm</td>
<td>1.0e8</td>
<td>Forward critical electric field</td>
</tr>
<tr>
<td>ER</td>
<td>V/cm</td>
<td>EF</td>
<td>Reverse critical electric field</td>
</tr>
<tr>
<td>JF</td>
<td>amp/V^2</td>
<td>1.0e-10</td>
<td>Forward Fowler-Nordheim current coefficient</td>
</tr>
<tr>
<td>JR</td>
<td>amp/V^2</td>
<td>JF</td>
<td>Reverse Fowler-Nordheim current coefficient</td>
</tr>
<tr>
<td>L</td>
<td>m</td>
<td>0.0</td>
<td>Length of diode for calculation of Fowler-Nordheim current</td>
</tr>
<tr>
<td>TOX</td>
<td>Å</td>
<td>100.0</td>
<td>Thickness of oxide layer</td>
</tr>
<tr>
<td>W</td>
<td>m</td>
<td>0.0</td>
<td>Width of diode for calculation of Fowler-Nordheim current</td>
</tr>
<tr>
<td>XW</td>
<td>m</td>
<td>0.0</td>
<td>XWeff = XW ⋅ SCALM</td>
</tr>
</tbody>
</table>

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:

\[ \text{AREAeff} = \text{Weff} \cdot \text{Leff} \cdot M \]

Forward Bias: \( vd < 0 \)

\[ id = \text{AREAeff} \cdot \text{JF} \cdot \left( \frac{vd}{\text{TOX}} \right)^2 \cdot e^{-\frac{EF \cdot \text{TOX}}{vd}} \]
Reverse Bias:  \( v_d < 0 \)

\[
id = -A_{\text{REAl}} \cdot J_R \cdot \left(\frac{v_d}{\text{TOX}}\right)^2 \cdot e^{\frac{E_R \cdot \text{TOX}}{v_d}}
\]

**Fowler-Nordheim Diode Capacitances**

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

\[
c_d = A_{\text{REAl}} \cdot \frac{\varepsilon_{\text{ox}}}{\text{TOX}}
\]
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
```