3 Diode Model - Level 500

3.1 Introduction

The Diode level-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.

For **Pstar** and **Spectre** users it is available as a built-in model.

3.2 Simulator specific items

3.2.1 Pstar

d_n (a, k) level=500, <parameters>

n	:	occurrence indicator
<parameters>	:	list of model parameters

a and k are anode (+) and cathode (-) terminals respectively.

3.2.2 Spectre

model modelname dio500 <modpar>
componentname a k modelname <inpar>

modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters[1]
<inpar>	:	list of instance parameters[1]

a and k are anode and cathode terminals respectively.

1. For more details of these Spectre parameters see also Cadence Spectre Circuit Simulator Reference, version 4.4.6 or 5.0.

3.3 Survey of modeled effects

In the diode model level-500 the non-ideal forward current and the reverse DC current is significantly improved compared to the diode model level-1. The charge and noise models are basically the same as in the diode model level-1.

Diode model level-500 includes:

- Forward biasing

– ideal current
– non-ideal current including tunneling

- Reverse biasing

– Trap assisted tunneling
– Shockley-Read-Hall generation
– Band-to-band tunneling
– Avalanche multiplication

- Breakdown
- Series resistances
- Charge storage effects
- Temperature scaling rules
- Noise model for *RS* and the ideal forward current

The model does not include:

- Noise from the non-ideal forward and reverse diode currents

3.4 Parameters

The parameters for D-level-500 are listed in the table below.

Pos.	Parameter name	Units	Description
1	LEVEL	-	Model level, must be set to 500
2	IS	A	Saturation current
3	N	-	Junction emission coefficient
4	VLC	V	Voltage dependence at low forward currents
5	VBR	V	Breakdown voltage
6	EMVBR	V/cm	Electric field at breakdown
7	CSRH	A/cm	Shockley-Read-Hall generation
8	CBBT	A/V	Band to band tunneling
9	CTAT	A/cm	Trap assisted tunneling
10	RS	Ω	Series resistance
11	TAU	s	Transit time
12	CJ	F	Zero-bias depletion capacitance
13	VD	V	Diffusion voltage
14	P	-	Grading coefficient
15	TREF	°C	Reference temperature
16	VG	V	Bandgap voltage
17	PTRS	-	Power for temperature dependence of RS
18	KF	-	Flickernoise coefficient
19	AF	-	Flickernoise exponent
20	DTA	K	Difference between device temperature and ambient temperature
21	MULT	-	Multiplication factor

The parameter *N* should be close to unity and is not intended to simulate a current other than the usual injection of holes/electrons.

Parameter *MULT*

This parameter may be used to put several diodes in parallel.

The following parameters are multiplied by *MULT*:

IS *CSRH* *CBBT* *CTAT* *CJ*

Divided by *MULT* are:

RS

Default and clipping values

The default values and clipping values are listed below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
1	LEVEL	-	500	-	-
2	IS	A	7.13×10^{-13}	0.0	-
3	N	-	1.044	0.1	-
4	VLC	V	0.0	-	-
5	VBR	V	7.459	0.1	-
6	EMVBR	V/cm	1.36×10^{6}	1.0	-
7	CSRH	A/cm	7.44×10^{-7}	0.0	-
8	CBBT	A/V	3.255	0.0	-
9	CTAT	A/cm	3.31×10^{-6}	0.0	-
10	RS	Ω	0.0	0.0	-
11	TAU	s	500.0×10^{-12}	0.0	-
12	CJ	F	7.0×10^{-12}	0.0	-
13	VD	V	0.90	0.05	-
14	P		0.40	0.05	0.99
15	TREF	°C	25.0	-273.15	-
16	VG	V	1.206	0.1	-
17	PTRS	-	0.0	-	-
18	KF	-	0.0	0.0	-
19	AF	-	1.0	0.01	-
20	DTA	K	0.0	-	-
21	MULT	-	1.0	0.0	-

3.4.1 Pstar specific items

3.4.2 The ON/OFF condition

The solution of a circuit involves a process of successive calculations. The calculations are started from a set of ‘initial guesses’ for the electrical quantities of the nonlinear elements. A simplified DCAPPROX mechanism for devices using ON/OFF keywords is mentioned in [56]. By default the devices start in the default state.

Diode level 500			
	Default	ON	OFF
V_{AK1}	0.7	0.7	0.0

3.4.3 Numerical Adaptation

To implement the model in a circuit simulator, care must be taken of the numerical stability of the simulation program. A small non-physical conductance, G_{min}, is connected between the nodes A and $K1$. The value of the conductance is 10^{-15} [1/Ω].

3.4.4 DC operating point output

The DC operating point output facility gives information on the state of a device at its operation point.

Quantity	**Equation**	**Description**
LEVEL	500	Model level
RS	R_S	Series resistance
RD	R_D	Small signal diode resistance: dV_{AK1}/dI_D
C1	C_1	Total capacitance: $dQ_D/dV_{AK1} + dQ_T/dV_{AK1}$

Remark: The conductance G_{min} is connected parallel to the resistor R_D; The operating-point output is influenced by the value of G_{min}.

3.5 Equivalent circuit and equations

A full description of D-level-500 for diode is given below. The DC/transient and AC equivalent circuits are shown in Figures 5 and 6 respectively.

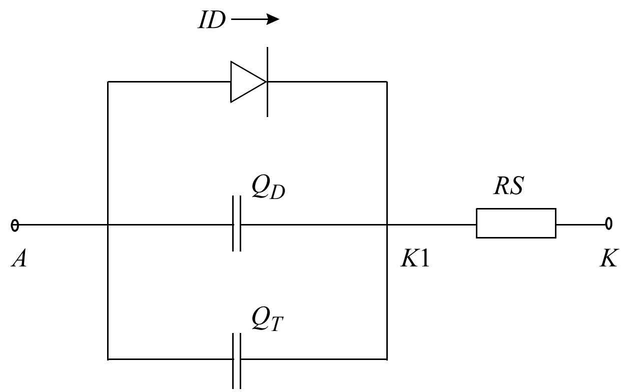

Figure 5: DC/Transient equivalent circuit for diode

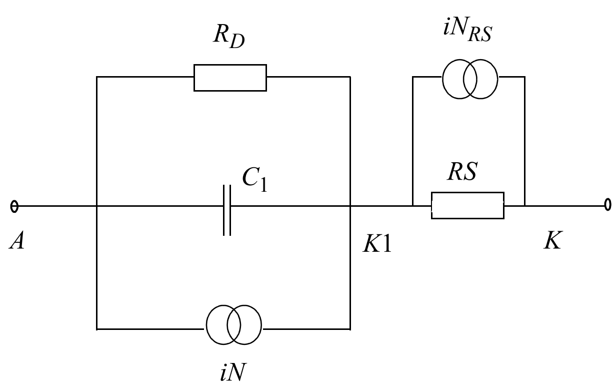

Figure 6: AC equivalent circuit for diode, including noise sources

Temperature effects

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

- Conversions to Kelvins

$$T_K = TEMP + 273.15 + DTA \tag{3.1}$$

$$T_{RK} = TREF + 273.15 \tag{3.2}$$

- Thermal Voltages

$$\begin{aligned} k &= 1.3806226 \cdot 10^{-23}\,\mathrm{JK}^{-1} \\ q &= 1.6021918 \cdot 10^{-19}\,\mathrm{C} \\ V_T &= \left(\frac{k}{q}\right) \cdot T_K \end{aligned} \tag{3.3}$$

$$V_{TR} = \left(\frac{k}{q}\right) \cdot T_{RK} \tag{3.4}$$

- Depletion Capacitances

$$F = \left(\frac{T_K}{T_{RK}}\right)^3 \cdot \exp\left[VG \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right] \tag{3.5}$$

$$VD_T = \left[\left(\frac{VD}{V_{TR}}\right) - \ln(F)\right] \cdot V_T \tag{3.6}$$

$$CJ_T = CJ \cdot \left(\frac{VD}{VD_T}\right)^P \tag{3.7}$$

- Transit Times

$$TAU_T = TAU\left(\frac{T_K}{T_{RK}}\right)^{1.8} \tag{3.8}$$

- Saturation Current

$$IS_T = IS \cdot \left(\frac{T_K}{T_{RK}}\right)^{1.8} \cdot \exp\left[\frac{VG}{N} \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right] \tag{3.9}$$

- Shockley-Read-Hall generation and trap assisted tunneling

$$T_{up} = \left(\frac{T_K}{T_{RK}}\right)^{3/2} \cdot \exp\left[\frac{VG + VLC}{2} \cdot \left(\frac{1}{V_{TR}} - \frac{1}{V_T}\right)\right] \tag{3.10}$$

$$CSRH_T = CSRH \cdot T_{up} \tag{3.11}$$

$$CTAT_T = CTAT \cdot T_{up} \tag{3.12}$$

$$ETAT_T = 70.8 \cdot T_K^{3/2} \tag{3.13}$$

- Band to band tunneling

$$CBBT_T = CBBT \text{ (temperature independent)} \tag{3.14}$$

$$F0 = 1.9 \cdot 10^7 \cdot \left(1.04 - \frac{4.21 \cdot 10^{-4} \cdot T_K^2}{636 + T_K}\right) \tag{3.15}$$

- Avalanche multiplication[1]

$$dT = TEMP + DTA - 25°C \tag{3.16}$$

$$Bn = 1.23 \cdot 10^{6} \tag{3.17}$$

$$Bn_T = Bn \cdot (1 + 7.2 \cdot 10^{-4} \cdot dT - 1.6 \cdot 10^{-6} \cdot dT^2) \tag{3.18}$$

- Breakdown

$$VBR_T = VBR \cdot \left(\frac{T_K}{T_{RK}}\right)^{0.1} \tag{3.19}$$

$$EMVBR_T = EMVBR \cdot \left(\frac{VD_T + VBR_T}{VD + VBR}\right)^{(1-P)} \tag{3.20}$$

- Resistance

$$RS_T = RS \cdot \left(\frac{T_K}{T_{RK}}\right)^{PTRS} \tag{3.21}$$

Model Constants and Parameter Related Constants

$$K = 0.01$$
$$KET = 0.1$$
$$ETM = 3$$

1. 25 °C is the reference temperature at which *Bn* has been determined

- Maximum electric field and depletion layer width at zero bias:

$$E_0 = \frac{EMVBR_T}{\left(1 + \frac{VBR_T}{VD_T}\right)^{1-P}} \tag{3.22}$$

$$W_0 = \frac{VD_T}{E_0 \cdot (1-P)} \tag{3.23}$$

Diode Currents

- First the maximum reverse junction voltage is defined.

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

$$V_j = \begin{cases} -0.99 \cdot VBR_T, & V_{AK1} < -0.99\,VBR_T \\ V_{AK1}, & V_{AK1} \geq -0.99\,VBR_T \end{cases} \tag{3.24}$$

- Ideal Forward Current

$$Id_f = IS_T\left\{\exp\left(\frac{V_j}{N \cdot V_T}\right) - 1\right\} \tag{3.25}$$

- Maximum Electric Field and Depletion Layer Width

$$VD_j = \frac{\sqrt{\left\{\left(1 - \frac{V_j}{VD_T}\right)^2 + \left(\frac{V_j}{VD_T}\right) \cdot K\right\}} + \left(1 - \frac{V_j}{VD_T}\right)}{2} \tag{3.26}$$

$$E_m = E_0 \cdot VD_j^{(1-P)} \tag{3.27}$$

$$W_d = W_0 \cdot VD_j^P \qquad (3.28)$$

- Shockley-Read-Hall Generation

$$I_{srh} = CSRH_T \cdot (W_d - W_0) \qquad (3.29)$$

- Trap Assisted Tunneling

$$ET_0 = \frac{\frac{E_0}{ETAT_T} + ETM - \sqrt{\left(\frac{E_0}{ETAT_T} - ETM\right)^2 + KET}}{2} \qquad (3.30)$$

$$ET = \frac{\frac{E_m}{ETAT_T} + ETM - \sqrt{\left(\frac{E_m}{ETAT_T} - ETM\right)^2 + KET}}{2} \qquad (3.31)$$

$$I_{tat} = CTAT_T \cdot W_d \cdot \left\{\frac{\exp(ET^2) - \exp(ET_0^2)}{\frac{E_m}{ETAT_T}}\right\} \qquad (3.32)$$

- Non-ideal Forward Current including Tunneling

$$Is_{lf} = CSRH_T \cdot \left\{6.28 + 38.58 \cdot \left(\frac{E_m}{ETAT_T}\right) \cdot \exp(ET^2)\right\} \cdot \frac{V_T}{E_m} \qquad (3.33)$$

$$I_{lf} = Is_{lf} \cdot \frac{\exp\left(\frac{V_j}{N \cdot V_T}\right) - 1}{4 \cdot \exp\left(\frac{V_j}{2 \cdot N \cdot V_T}\right) + \exp\left(\frac{VLC}{2 \cdot N \cdot V_T}\right)} \cdot \exp\left(\frac{VLC}{2 \cdot N \cdot V_T}\right) \tag{3.34}$$

- Band to Band Tunneling

$$I_{bbt} = \frac{-CBBT_T \cdot V_j}{\left(\frac{F0}{E_m}\right)^{1.5} \cdot \exp\left(\frac{F0}{E_m}\right)} \tag{3.35}$$

- Avalanche Multiplication

$$\mu = 0.3295 \cdot \left(\frac{E_m}{EMVBR_T}\right)^2 \cdot \exp\left(\frac{Bn_T}{EMVBR_T} - \frac{Bn_T}{E_m}\right) \tag{3.36}$$

- Total Diode Current

$$I_d = \frac{(Id_f + I_{lf} - I_{srh}) \cdot \frac{1 + \exp(-2 \cdot \mu)}{2} - (I_{bbt} + I_{tat}) \cdot \exp(-\mu)}{1 - 2 \cdot \mu \cdot \{1 + \exp(-2 \cdot \mu)\}} \tag{3.37}$$

- Extrapolation of the Reverse Current

$$I_{dBR} = I_d \qquad at\ V_j = -0.99\,VBR_T \tag{3.38}$$

$$G_{dBR} = \frac{dI_d}{dV_j} \qquad at\ V_j = -0.99\,VBR_T \tag{3.39}$$

$$ID = \begin{cases} I_d & V_{AK1} \geq -0.99\,VBR_T \\ I_{dBR} \cdot \exp\left[\left(\dfrac{V_{AK1} + 0.99\,VBR_T}{I_{dBR}}\right) G_{dBR}\right] & V_{AK1} < -0.99\,VBR_T \end{cases} \tag{3.40}$$

Transient model

Transient behaviour is modeled using the DC equations.

- Diffusion charge

$$Q_D = TAU_T \cdot Id_f \tag{3.41}$$

- Depletion charge

$$FC = 1 - \left(\frac{1+P}{3}\right)^{\left(\frac{1}{P}\right)} \tag{3.42}$$

$$Q_{AT} = CJ_T \cdot \left(\frac{VD_T}{1-P}\right) \tag{3.43}$$

$$V_L = FC \cdot VD_T \tag{3.44}$$

$$C_L = CJ_T \cdot (1 - FC)^{-P} \tag{3.45}$$

$$Q_L = Q_{AT} \cdot \{1 - (1 - FC)^{(1-P)}\} \tag{3.46}$$

Then if $V_{AK1} < V_L$

$$Q_T = Q_{AT} \cdot \left[1 - \left\{1 - \left(\frac{V_{AK1}}{VD_T}\right)\right\}^{(1-P)}\right] \tag{3.47}$$

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

$$Q_T = Q_L + C_L \cdot (V_{AK1} - V_L) \cdot \left\{1 + \frac{P \cdot (V_{AK1} - V_L)}{2 \cdot VD_T(1 - FC)}\right\} \tag{3.48}$$

AC Linearized model

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

$$R_D = \frac{1}{dID/dV_{AK1}} \tag{3.49}$$

Where (dID/dV_{AK1}) is the first derivative of the total diode current with respect to the internal voltage V_{AK1}.
The capacitances are defined as:

$$C_T = CJ_T\left\{1 - \left(\frac{V_{AK1}}{VD_T}\right)\right\}^{-P} \qquad for\ V_{AK1} < V_L \tag{3.50}$$

$$C_T = C_L \cdot \left\{1 + \frac{P \cdot (V_{AK1} - V_L)}{VD_T \cdot (1 - FC)}\right\} \qquad for\ V_{AK1} \geq V_L \tag{3.51}$$

$$C_1 = C_T + TAU_T \cdot \left(\frac{Id_f + IS_T}{N \cdot V_T}\right) \tag{3.52}$$

Noise model

For noise analysis, noise sources are added to the small signal model as shown in Figure 6. In these equations f represents the operation frequency of the transistor and Δf is the bandwidth. When Δf is taken as 1 Hz, a noise density is obtained.

- Thermal noise

$$\overline{iN_{RS}^2} = \frac{4 \cdot k \cdot T_K \cdot \Delta f}{RS_T} \tag{3.53}$$

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

  The current noise is only modelled for the ideal forward current Id_f

$$\overline{iN^2} = 2 \cdot q \cdot |Id_f| \cdot \Delta f + KF \cdot MULT \cdot \left|\frac{Id_f}{MULT}\right|^{AF} \cdot \frac{\Delta f}{f} \tag{3.54}$$