3 Diode Model - Level 500

3.1 Introduction

The D-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** users it is available as a built-in model.

3.2 Order in which terminals are specified

D_n (A, K) <parameters>

n : occurrence indicator

<parameters>: list of model parameters

A, K are anode (+) and cathode (-) terminals respectively

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

3.5 Pstar specific values

The default values and clipping values as used by **Pstar** 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	-

3.5.1 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 [36]. By default the devices start in the default state.

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

3.5.2 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].

3.5.3 DC operating point output

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

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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}.

3.6 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 figs. 5 and 6 respectively.

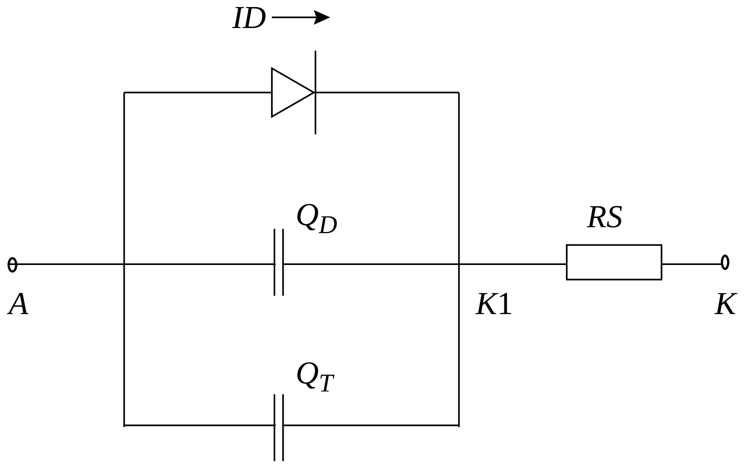

Figure 5: DC/Transient equivalent circuit for diode

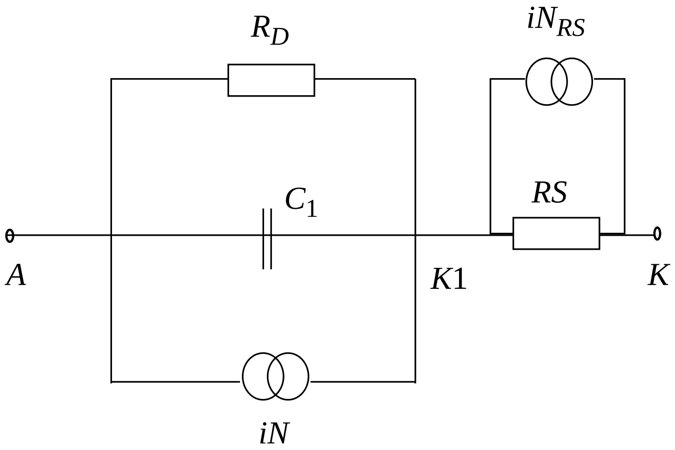

Figure 6: AC equivalent circuit for diode, including noise sources

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

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

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[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

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

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

$$W_d = W_0 \cdot VD_j^P \tag{3.28}$$

- Shockley-Read-Hall Generation

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

- Trap Assisted Tunneling

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

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

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

- Non-ideal Forward Current including Tunneling

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

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

- 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:

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

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

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

Noise model

For noise analysis, noise sources are added to the small signal model as shown in fig. 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

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