1 Bipolar P-N-P Transistor Level 500

1.1 Introduction

The Lteral bipolar transistor model, level 500, provides an extensive description of a lateral integrated circuit junction-isolated PNP transistor. It is meant to be used for DC, transient and AC analyses at all current levels, i.e. including high and low injection.

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

1.2 Physics

1.2.1 Survey of modeled effects

- Temperature effects
- Charge storage effects
- Excess phase shift for current and storage charges
- Substrate effects and parasitic pnp (for the TPS device only)
- High-injection effects
- Built-in electric field in base region
- Bias-dependent Early effect
- Low-level non-ideal base currents
- Hard and quasi-saturation
- Weak avalanche
- Current crowding (DC, AC and transient) and conductivity modulation for base resistance
- Hot carrier effects in the collector epilayer
- Explicit modeling of inactive regions
- Split base-collector depletion capacitance

1.3 Symbols, parameters and constants

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

Position in list	Parameter name	Units	Description
1	*LEVEL*	-	Model level, must be set to 500
2	*IS*	A	Collector-emitter saturation current
3	*BF*		Ideal forward common-emitter current gain
4	*IBF*	A	Saturation current of non-ideal forward base current
5	*VLF*	V	Cross-over voltage of non-ideal forward base current
6	*IK*	A	High injection knee current
7	*XIFV*	-	Vertical fraction of forward current
8	*EAFL*	V	Early voltage of the lateral forward current component at zero collector-base bias
9	*EAFV*	V	Early voltage of the vertical forward current component at zero collector-base bias
10	*BR*	-	Ideal reverse common-emitter current gain
11	*IBR*	A	Saturation current of non-ideal reverse base current
12	*VLR*	V	Cross-over voltage of non-ideal reverse base current
13	*XIRV*	-	Vertical fraction of reverse current
14	*EARL*	V	Early voltage of the lateral reverse current component at zero emitter-base bias
15	*EARV*	V	Early voltage of the vertical reverse current component at zero emitter-base bias
16	*XES*	–	Ratio between saturation current of e-b-s transistor and e-b-c transistor
17	*XHES*	–	Fraction of substrate current of e-b-s transistor subject to high injection
18	*XCS*	–	Ratio between the saturation current of c-b-s transistor and c-b-e transistor
19	*XHCS*	–	Fraction of substrate current of c-b-s transistor subject to high injection
20	*ISS*	A	Saturation current of substrate-base diode
21	*RCEX*	Ω	External part of the collector resistance

Position in list	Parameter name	Units	Description
22	*RCIN*	Ω	Internal part of the collector resistance
23	*RBCC*	Ω	Constant part of the base resistance RBC
24	*RBCV*	Ω	Variable part of the base resistance RBC
25	*RBEC*	Ω	Constant part of the base resistance RBE
26	*RBEV*	Ω	Variable part of the base resistance RBE
27	*REEX*	Ω	External part of the emitter resistance
28	*REIN*	Ω	Internal part of the emitter resistance
29	*RSB*	Ω	Substrate-base leakage resistance
30	*TLAT*	s	Low injection (forward and reverse) transit time of charge stored in the epilayer between emitter and collector
31	*TFVR*	s	Low injection forward transit time due to charge stored in the epilayer under the emitter
32	*TFN*	s	Low injection forward transit time due to charge stored in the emitter and the buried layer under the emitter
33	*CJE*	F	Zero-bias emitter-base depletion capacitance
34	*VDE*	V	Emitter-base diffusion voltage
35	*PE*	–	Emitter-base grading coefficient
36	*TRVR*	s	Low injection reverse transit time due to charge stored in the epilayer under the collector
37	*TRN*	s	Low injection reverse transit time due to charge stored in the collector and the buried layer under the collector
38	*CJC*	F	Zero-bias collector-base depletion capacitance
39	*VDC*	V	Collector-base diffusion voltage
40	*PC*	-	Collector-base grading coefficient
41	*CJS*	F	Zero-bias substrate-base depletion capactitance
42	*VDS*	V	Substrate-base diffusion voltage
43	*PS*	-	Substrate-base grading coefficient
44	*TREF*	°C	Reference temperature of the parameter set
45	*DTA*	°C	Difference between the device temperature and the ambient analysis temperature
46	*VGEB*	V	Bandgap voltage of the emitter-base depletion region
47	*VGCB*	V	Bandgap voltage of the collector-base depletion region
48	*VGSB*	V	Bandgap voltage of the substrate-base depletion region

Position in list	Parameter name	Units	Description
49	*VGB*	V	Bandgap voltage of the base between emitter and collector
50	*VGE*	V	Bandgap voltage of the emitter
51	*VGJE*	V	Bandgap voltage recombination emitter-base junction
52	*AE*	-	Temperature coefficient of *BF*
53	*SPB*	-	Temperature coefficient of the epitaxial base hole mobility
54	*SNB*	-	Temperature coefficient of the epitaxial base electron mobility
55	*SNBN*	-	Temperature coefficient of buried layer electron mobility
56	*SPE*	-	Temperature coefficient of emitter hole mobility
57	*SPC*	-	Temperature coefficient of collector hole mobility
58	*SX*	-	Temperature coefficient of combined minority carrier mobilities in emitter and buried layer
59	*KF*	-	Flickernoise coefficient
60	*AF*	-	Flickernoise exponent
61	*EXPHI*	rad	Excess phase shift

The additional parameters for the thermal model TPLT-level-500 are:

Position in list	Parameter name	Units	Description
62	*RTH*	^{o}C/W	Thermal resistance
63	*CTH*	J/^{o}C	Thermal capacitance
64	*ATH*	-	Temperature coefficient of the thermal resistance

The additional parameter MULT for all level-500 models is listed in the table below.

Position in list	Parameter name	Units	Description
65	*MULT*	-	Multiplication factor

Parameter ***MULT***

This parameter may be used to put several transistors in parallel. To scale the geometry of a transistor use of the process-block is preferable over using this feature.

The following parameters are multiplied by *MULT*:

IS, IBF, IK, IBR, ISS, CJE, CJC, CJS, CTH

Divided by *MULT* are:

RCEX, RCIN, RBCC, RBCV, RBEC, RBEV, REEX, REIN, RSB, RTH

Default and clipping values

The default values and clipping values for the TPL-level-500 are listed below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
1	*LEVEL*	-	500	-	-
2	*IS*	A	1.80×10^{-16}	0.0	-
3	*BF*		131.00	1.0×10^{-4}	-
4	*IBF*	A	2.60×10^{-14}	0.0	-
5	*VLF*	V	0.54	-	-
6	*IK*	A	1.10×10^{-4}	0.0	-
7	*XIFV*	-	0.43	0.0	1.0
8	*EAFL*	V	20.50	0.01	-
9	*EAFV*	V	75.00	0.01	-
10	*BR*	-	25.00	1.0×10^{-4}	-
11	*IBR*	A	1.20×10^{-13}	0.0	-
12	*VLR*	V	0.48	-	-
13	*XIRV*	-	0.43	0.0	1.0
14	*EARL*	V	13.10	0.01	-
15	*EARV*	V	104.00	0.01	-
16	*XES*	–	2.70×10^{-3}	0.0	-
17	*XHES*	–	0.70	0.0	1.0
18	*XCS*	–	3.00	0.0	-
19	*XHCS*	–	1.00	0.0	1.0
20	*ISS*	A	4.00×10^{-13}	0.0	-
21	*RCEX*	Ω	5.00	1.0×10^{-6}	-
22	*RCIN*	Ω	47.00	1.0×10^{-6}	-
23	*RBCC*	Ω	10.00	1.0×10^{-6}	-
24	*RBCV*	Ω	10.00	0.0	-
25	*RBEC*	Ω	10.00	1.0×10^{-6}	-

Position in list	Parameter name	Units	Default	Clip low	Clip high
26	*RBEV*	Ω	50.00	0.0	-
27	*REEX*	Ω	27.00	1.0×10^{-6}	-
28	*REIN*	Ω	66.00	1.0×10^{-6}	-
29	*RSB*	Ω	1.00×10^{15}	1.0×10^{-6}	-
30	*TLAT*	s	2.40×10^{-9}	0.0	-
31	*TFVR*	s	3.00×10^{-8}	0.0	-
32	*TFN*	s	2.00×10^{-10}	0.0	-
33	*CJE*	F	6.10×10^{-14}	0.0	-
34	*VDE*	V	0.52	0.05	-
35	*PE*	–	0.30	0.01	0.99
36	*TRVR*	s	1.00×10^{-9}	0.0	-
37	*TRN*	s	3.00×10^{-9}	0.0	-
38	*CJC*	F	3.90×10^{-13}	0.0	-
39	*VDC*	V	0.57	0.05	-
40	*PC*	-	0.36	0.01	0.99
41	*CJS*	F	1.30×10^{-12}	0.0	-
42	*VDS*	V	0.52	0.05	-
43	*PS*	-	0.35	0.01	0.99
44	*TREF*	°C	25.00	-273.15	-
45	*DTA*	°C	0.00	-	-
46	*VGEB*	V	1.206	0.1	-
47	*VGCB*	V	1.206	0.1	-
48	*VGSB*	V	1.206	0.1	-
49	*VGB*	V	1.206	0.1	-
50	*VGE*	V	1.206	0.1	-
51	*VGJE*	V	1.123	0.1	-
52	*AE*	-	4.48	-	-
53	*SPB*	-	2.853	-	-

Position in list	Parameter name	Units	Default	Clip low	Clip high
54	*SNB*	-	2.60	-	-
55	*SNBN*	-	0.30	-	-
56	*SPE*	-	0.73	-	-
57	*SPC*	-	0.73	-	-
58	*SX*	-	1.00	-	-
59	*KF*	-	0.00	0.0	-
60	*AF*	-	1.00	0.01	-
61	*EXPHI*	rad	0.00	0.0	-

The default values and clipping values for the TPLT-level-500 are:

Position in list	Parameter name	Units	Default	Clip low	Clip high
62	*RTH*	^{o}C/W	300.00	0.00	-
63	*CTH*	J/^{o}C	3.00×10^{-9}	0.00	-
64	*ATH*	-	0.00	-	-

The additional parameter MULT for all level-500 models is listed in the table below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
65	*MULT*	-	1.00	0.00	-

1.4 Equivalent circuit and model equations

This section contains a full description of the TPL-level-500 PNP transistor. The equivalent circuits are shown in Figures 1 and 2.

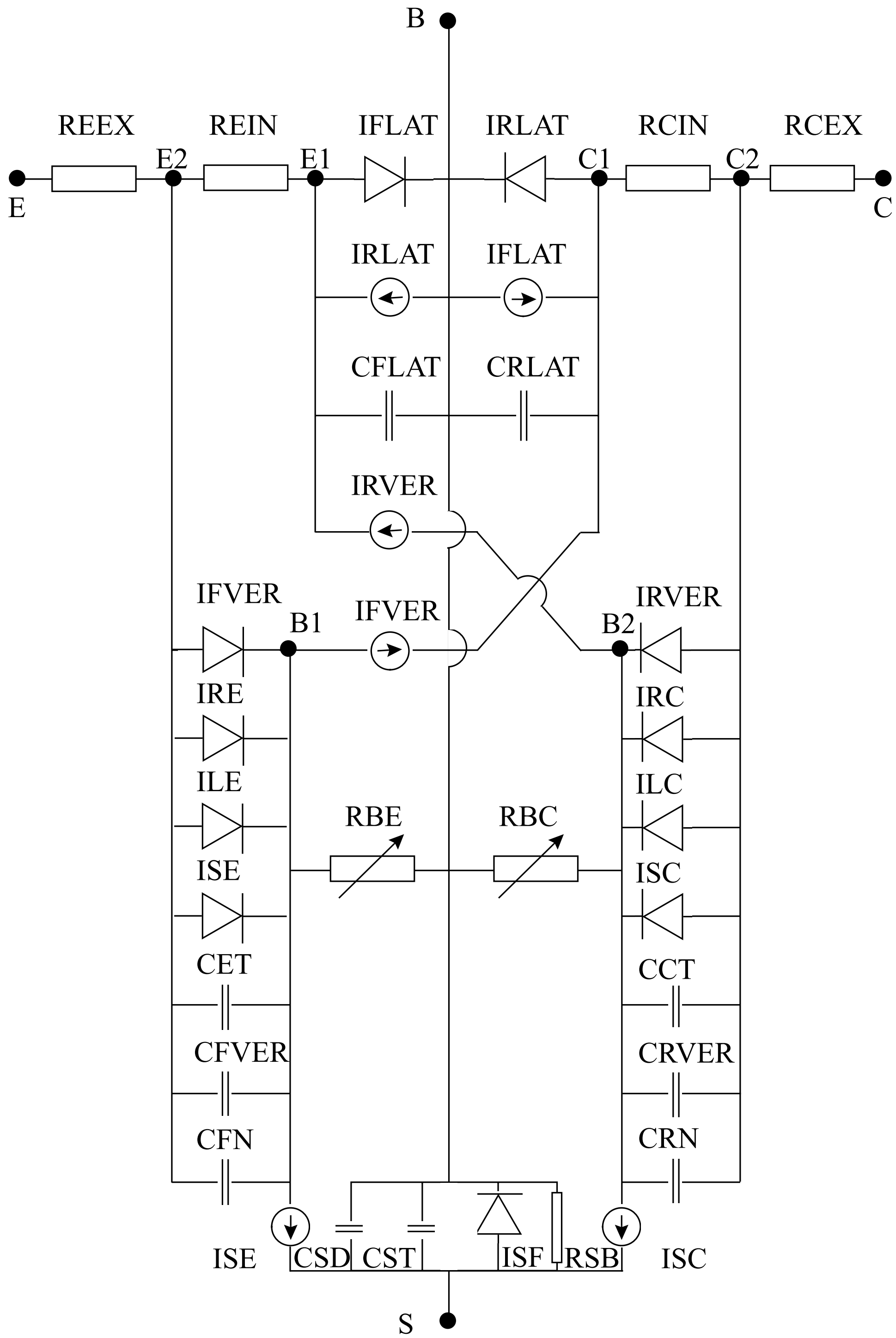


Figure 1: Large signal equivalent circuit

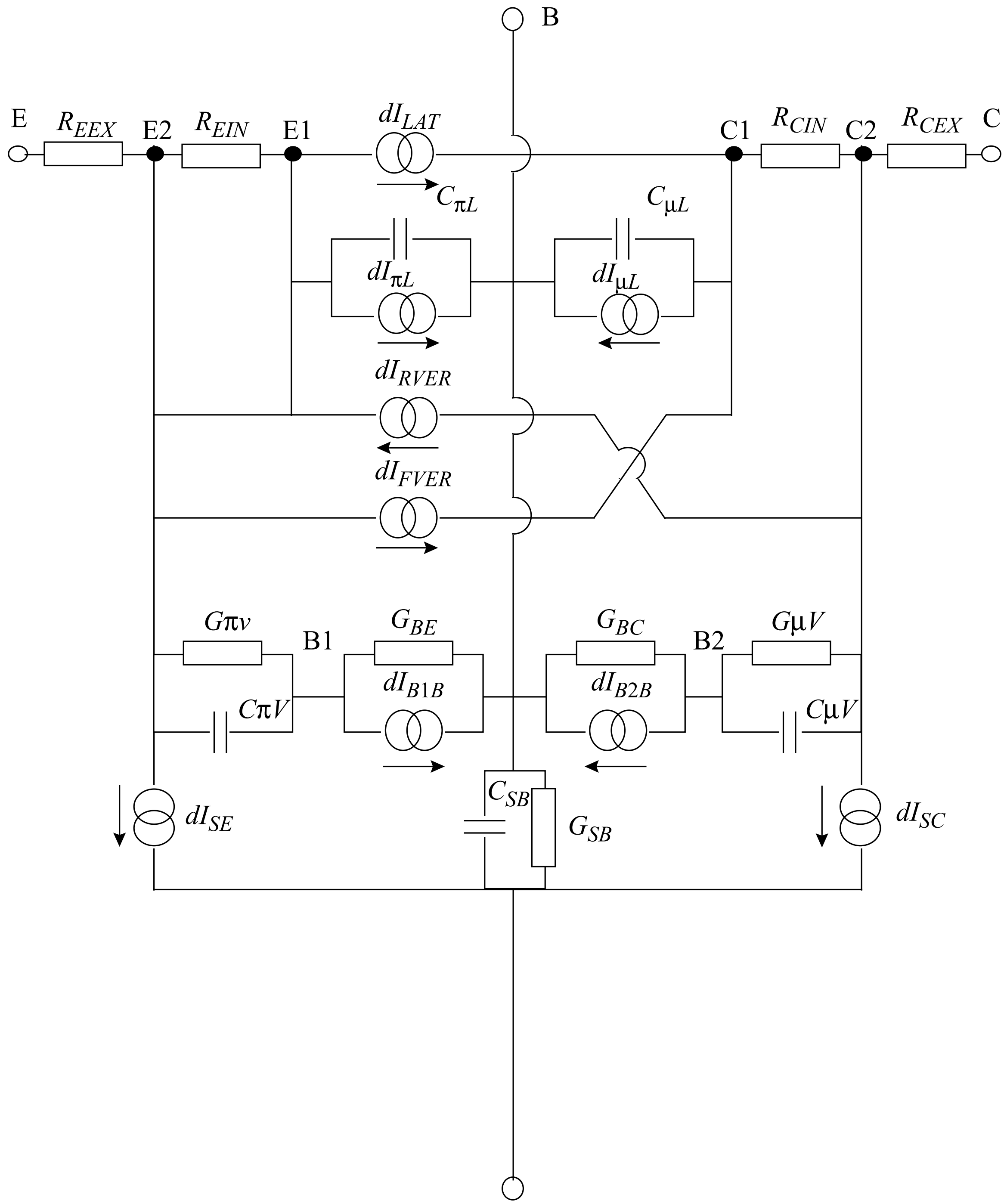


Figure 2: AC equivalent circuit

Model constants

$TEMP = 273.15 + TNOM + DTA$

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

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

$k/q = 0.86171 \cdot 10^{-4} \mathrm{J/K}$

$\delta = 0.01$

$T_{sd} = 1.0 \cdot 10^{-6} \mathrm{s}$ *(fixed transit time for* Q_{sd}*)*

$VD = 0.7 \cdot \mathrm{V}$ *(the base diffusion voltage)*

The default reference temperature *TREF* for parameter determination is 25°C.

Temperature dependence of the parameters

$$T_K = TREF + 273.15 \tag{1.1}$$

$$T_N = \frac{TEMP}{TREF + 273.15} \tag{1.2}$$

$$T_I = \frac{1}{TREF + 273.15} - \frac{1}{TEMP} \tag{1.3}$$

Series resistances:

$$RCIN_T = RCIN \cdot T_N^{SPC} \tag{1.4}$$

$$RBCC_T = RBCC \cdot T_N^{SNBN} \tag{1.5}$$

$$RBCV_T = RBCV \cdot T_N^{SNB} \tag{1.6}$$

$$RBEC_T = RBEC \cdot T_N^{SNBN} \tag{1.7}$$

$$RBEV_T = RBEV \cdot T_N^{SNB} \tag{1.8}$$

$$REIN_T = REIN \cdot T_N^{SPE} \tag{1.9}$$

REEX, *RCEX* and *RSB* are assumed temperature independent.

- Depletion capacitances:

$$VDx_T = -3k\frac{TEMP}{q} \cdot \ln(T_N) + VDx \cdot T_N + (1 - T_N) \cdot V_{gap} \tag{1.10}$$

$$CJx_T = CJx \cdot \left(\frac{VDx}{VDx_T}\right)^{Px} \tag{1.11}$$

for the emitter-base junction: $\begin{cases} V_{gap} = VGEB \\ x = E \end{cases}$

with:for the collector-base junction: $\begin{cases} V_{gap} = VGCB \\ x = C \end{cases}$

for the substrate-base junction: $\begin{cases} V_{gap} = VGSB \\ x = S \end{cases}$

The internal diffusion voltage *VD*:

$$VD_T = -3k\frac{TEMP}{q} \cdot \ln(T_N) + VD \cdot T_N + (1 - T_N) \cdot VGB \tag{1.12}$$

- The Early voltages:

$$EAFL_T = EAFL \cdot \sqrt{VD_T/(VD)} \tag{1.13}$$

The parameters *EARL*, *EAFV* and *EARV* are subject to the same scaling rule.

$$IS_T = IS \cdot T_N^{(4.0 - SPB)} \cdot \exp(q \cdot VGB \cdot T_I/k) \tag{1.14}$$

$$BF_T = BF \cdot T_N^{(AE - SPB)} \cdot \exp\{q \cdot (VGB - VGE) \cdot T_I/k\} \tag{1.15}$$

$$IBF_T = IBF \cdot (T_N)^2 \cdot \exp\{q \cdot (VGJE/2) \cdot T_I/k\} \tag{1.16}$$

$$IK_T = IK \cdot (T_N)^{(1-SPB)} \tag{1.17}$$

$$BR_T = BR \cdot \frac{BF_T}{BF} \tag{1.18}$$

$$IBR_T = IBR \cdot \frac{IBF_T}{IBF} \tag{1.19}$$

$$ISS_T = ISS \cdot (T_N)^2 \cdot \exp(q \cdot VGSB \cdot T_I/k) \tag{1.20}$$

The transit times:

$$TLAT_T = TLAT \cdot T_N^{(SPB-1.0)} \tag{1.21}$$

$$TFVR_T = TFVR \cdot \frac{TLAT_T}{TLAT} \tag{1.22}$$

$$TFN_T = TFN \cdot T_N^{(SX-1.0)} \tag{1.23}$$

$$TRVR_T = TRVR \cdot \frac{TLAT_T}{TLAT} \tag{1.24}$$

$$TRN_T = TRN \cdot \frac{TFN_T}{TFN} \tag{1.25}$$

All other model parameters are assumed to be temperature independent.

Temperature parameters: *VGEB, VGCB, VGSB, VGB, VGE, VGJE, AE, SPB, SNB, SNBN, SPE, SPC, SX*.

Early factors

The Early factors for the components of the main current I_p are derived from the variation of the depletion widths in the base relative to the base width itself.

- Early factor of the lateral current components

$$F_{LAT} = hyp_1\left\{1 - \left(\frac{\sqrt[4]{\left(1 - \frac{V_{E1B}}{VD_T}\right)^2 + \delta}}{1 + \frac{EARL}{2VD_T}} + \frac{\sqrt[4]{\left(1 - \frac{V_{C1B}}{VD_T}\right)^2 + \delta}}{1 + \frac{EAFL}{2VD_T}}\right), \delta_E\right\} \tag{1.26}$$

- Early factor of the forward vertical current component

$$F_{FVER} = hyp_1\left\{1 - \left(\frac{\sqrt[4]{\left(1 - \frac{V_{E2B1}}{VD_T}\right)^2 + \delta}}{1 + \frac{EARV}{2VD_T}} + \frac{\sqrt[4]{\left(1 - \frac{V_{C1B}}{VD_T}\right)^2 + \delta}}{1 + \frac{EAFV}{2VD_T}}\right), \delta_E\right\} \tag{1.27}$$

- Early factor of the reverse vertical current component

$$F_{RVER} = hyp_1\left\{1 - \left(\frac{\sqrt[4]{\left(1 - \frac{V_{E1B}}{VD_T}\right)^2 + \delta}}{1 + \frac{EARV}{2VD_T}} + \frac{\sqrt[4]{\left(1 - \frac{V_{C2B2}}{VD_T}\right)^2 + \delta}}{1 + \frac{EAFV}{2VD_T}}\right), \delta_E\right\} \tag{1.28}$$

$\delta_E = 10^{-3}$; for the definition of the hyp_1 function, see *Appendix A Hyp functions*.
Model parameters : *EAFL* , *EAFV* , *EARL* , *EARV* .

Ideal diodes

$$V_T = \frac{k \cdot TEMP}{q} \tag{1.29}$$

The ideal diode equations are as follows

$$I_{F1} = IS_T \cdot [\exp(V_{E1B}/V_T) - 1] \tag{1.30}$$

$$I_{F2} = IS_T \cdot [\exp(V_{E2B1}/V_T) - 1] \tag{1.31}$$

$$I_{R1} = IS_T \cdot [\exp(V_{C1B}/V_T) - 1] \tag{1.32}$$

$$I_{R2} = IS_T \cdot [\exp(V_{C2B2}/V_T) - 1] \tag{1.33}$$

Model parameter : *IS*.

The main current I_P

$$I_P = I_{FLAT} + I_{FVER} - I_{RLAT} - I_{RVER} \tag{1.34}$$

- Forward currents I_{FLAT} and I_{FVER}

The main forward current is separated into lateral and vertical components originating from the emitter-base junction sidewall and bottom respectively. These formulations include Early and high injection effects and because the two currents depend on different internal emitter-base junction voltages, emitter current crowding is also modelled. The lateral forward current component I_{FLAT}:

$$I_{FLAT} = \left\{ \frac{4 \cdot (1 - XIFV) \cdot I_{F1}}{3 + \sqrt{1 + 16 \cdot \frac{I_{F1}}{IK}}} \right\} / F_{LAT} \tag{1.35}$$

The vertical forward current component I_{FVER}

$$I_{FVER} = \left\{ \frac{4 \cdot XIFV \cdot I_{F2}}{3 + \sqrt{1 + 16 \cdot \frac{I_{F2}}{IK}}} \right\} / F_{FVER} \tag{1.36}$$

Model parameters : *XIFV* , *IK* .

- Reverse currents I_{RLAT} and I_{RVER}

The main reverse current is separated into lateral and vertical components originating from the collector-base junction sidewall and bottom respectively. These formulations include Early and high injection effects and because the two currents depend on different internal collector-base junction voltages, collector current crowding is also modelled.

The lateral reverse current component I_{RLAT}

$$I_{RLAT} = \left\{ \frac{4 \cdot (1 - XIRV) \cdot I_{R1}}{3 + \sqrt{1 + 16 \cdot \frac{I_{R1}}{IK}}} \right\} / F_{LAT} \tag{1.37}$$

The vertical reverse current component I_{RVER}

$$I_{RVER} = \left\{ \frac{4 \cdot XIRV \cdot I_{R2}}{3 + \sqrt{1 + 16 \cdot \frac{I_{R2}}{IK}}} \right\} / F_{RVER} \tag{1.38}$$

Model parameters : *XIRV* .

The Base current

- Forward components

The total forward base current is composed of an ideal and a non-ideal component. Both components depend on the bottom part of the emitter-base junction.

Ideal component :

$$I_{RE} = \frac{I_{F2}}{BF_T} \tag{1.39}$$

Non-ideal component:

$$I_{LE} = \frac{IBF_T \cdot \{\exp(V_{E2B1}/V_T) - 1\}}{\exp(V_{E2B1}/2 \cdot V_T) + \exp(VLF/2 \cdot V_T)} \tag{1.40}$$

Model parameters : BF , IBF , VLF .

- Reverse components

The total reverse base current is composed of an ideal and a non-ideal component. Both components depend on the bottom part of the collector-base junction.

Ideal component:

$$I_{RC} = \frac{I_{R2}}{BR_T} \tag{1.41}$$

Non-ideal component:

$$I_{LC} = \frac{IBR_T \cdot \{\exp(V_{C2B2}/V_T) - 1\}}{\exp(V_{C2B2}/2 \cdot V_T) + \exp(VLR/2 \cdot V_T)} \tag{1.42}$$

Model parameters : BR , IBR , VLR .

The substrate current

- Forward component

The forward substrate component depends on the bottom part of the emitter-base junction and consists of an ideal component and a component subject to high injection effects. The parameter *XHES* determines the fraction subject to high injection.

$$I_{SE} = (1 - XHES) \cdot XES \cdot I_{F2} + \frac{4 \cdot XHES \cdot XES \cdot I_{F2}}{3 + \sqrt{1 + 16 \cdot \frac{I_{F2}}{IK}}} \tag{1.43}$$

Model parameters : *XES* , *XHES* .

Reverse component
The reverse substrate component depends on the bottom part of the collector-base junction and consists of an ideal component and a component subject to high injection effects. The parameter *XHCS* determines the fraction subject to high injection.

$$I_{SC} = (1 - XHCS) \cdot XCS \cdot I_{R2} + \frac{4 \cdot XHCS \cdot XCS \cdot I_{R2}}{3 + \sqrt{1 + 16 \cdot \frac{I_{R2}}{IK}}} \tag{1.44}$$

Model parameters : *XCS* , *XHCS* .

Additional substrate and base current

An ideal diode models the substrate-base junction. The reverse leakage current of this junction can be used to model the zero-crossover phenomena sometimes observed in the base current at low bias conditions and high temperatures.

$$I_{SF} = ISS_T \cdot [\exp(V_{SB}/V_T) - 1] \tag{1.45}$$

Model parameters : *ISS* .

Depletion charges

The Poon-Gummel formulation is used in the modelling of the depletion charges.

- Emitter-base depletion charge

$$Q_{TE} = \frac{-CJE_T}{1-PE} \cdot \left\{ \frac{VDE_T - V_{E2B1}}{\left(\left(1 - \frac{V_{E2B1}}{VDE_T}\right)^2 + \delta\right)^{\frac{PE}{2}}} \right\} \tag{1.46}$$

Model parameters : CJE , VDE , PE .

- Collector-base depletion charge

$$Q_{TC} = \frac{-CJC_T}{1-PC} \cdot \left\{ \frac{VDC_T - V_{C2B2}}{\left(\left(1 - \frac{V_{C2B2}}{VDC_T}\right)^2 + \delta\right)^{\frac{PC}{2}}} \right\} \tag{1.47}$$

Model parameters : CJC , VDC , PC .

- Substrate-base depletion charge

$$Q_{TS} = \frac{-CJS_T}{1-PS} \cdot \left\{ \frac{VDS_T - V_{SB}}{\left(\left(1 - \frac{V_{SB}}{VDS_T}\right)^2 + \delta\right)^{\frac{PS}{2}}} \right\} \tag{1.48}$$

Model parameters : CJS , VDS , PS .

Charges

- Forward stored charges

The storage of charge in the forward active case is divided into three main components. The first component represents charge storage in the epilayer between emitter and collector. Charge storage in the epilayer under the emitter is another component and the storage of charge in the neutral regions forms the third component. The neutral charge formulation is obtained simply from the charge control principle. The epilayer charge storage formulations, however, are obtained by relating the charge storage to the injected minority concentration, p', in the epilayer. In the epilayer between emitter and collector p' is assumed to have a linear profile for all injection levels.

Charge stored in epitaxial base region between emitter and collector:

$$Q_{FLAT} = TLAT_T \cdot IK \cdot \left(\sqrt{1 + 16 \cdot \frac{I_{F1}}{IK}} - 1 \right) \cdot \frac{F_{LAT}}{8} \tag{1.49}$$

Charge stored in epitaxial base region under emitter:

$$Q_{FVER} = TFVR_T \cdot IK \cdot \left(\sqrt{1 + 16 \cdot \frac{I_{F2}}{IK}} - 1 \right) / 8 \tag{1.50}$$

Charge stored in emitter and buried layer under emitter:

$$Q_{FN} = TFN_T \cdot I_{F2} \tag{1.51}$$

Model parameters : $TLAT$, $TFVR$, TFN .

- Reverse stored charges

The storage of charge in the reverse active case is divided into three main components. The first component represents charge storage in the epilayer between emitter and collector. Charge storage in the epilayer under the collector is another component and the storage of charge in the neutral regions forms the third component. Charge formulations are obtained in a similar manner to the forward case.

Charge stored in epitaxial base region between emitter and collector:

$$Q_{RLAT} = TLAT_T \cdot IK \cdot \left(\sqrt{1 + 16 \cdot \frac{I_{R1}}{IK}} - 1\right) \cdot \frac{FLAT}{8} \tag{1.52}$$

Charge stored in epitaxial base region under collector:

$$Q_{RVER} = TRVR_T \cdot IK \cdot \left(\sqrt{1 + 16 \cdot \frac{I_{R2}}{IK}} - 1\right) / 8 \tag{1.53}$$

Charge stored in collector and buried layer under collector:

$$Q_{RN} = TRN_T \cdot I_{R2} \tag{1.54}$$

Model parameters : *TRVR* , *TRN* .

- Substrate-base stored charge

Charge stored in substrate and base due to the substrate-base junction. This charge storage *only* occurs when the substrate-base junction is forward biased (note that *TSD* is a constant):

$$Q_{SD} = TSD \cdot I_{SF} \tag{1.55}$$

Series resistances

emitter	$REEX$	=	constant
	$REIN_T$	=	constant
collector:	$RCEX$	=	constant
	$RCIN_T$	=	constant

The conductivity modulation of the base resistances is derived from the fact that the voltage drop across the epitaxial layer is inversely proportional to the electron concentration under the emitter and collector.

Base resistance under the emitter:

$$RBE_T = RBEC_T + \frac{2 \cdot RBEV_T}{1 + \sqrt{1 + 16 \cdot \dfrac{I_{F2}}{IK}}} \tag{1.56}$$

Base resistance under the collector:

$$RBC_T = RBCC_T + \frac{2 \cdot RBCV_T}{1 + \sqrt{1 + 16 \cdot \dfrac{I_{R2}}{IK}}} \tag{1.57}$$

The resistance *RSB* models ohmic leakage across the substrate-base junction.

Model parameters : *REEX, REIN, RCEX, RCIN, RBEC, RBEV, RBCC, RBCV, RSB*.

Excess phase shift

Excess phase shift is implemented in the following way.
In case the parameter *EXPHI* does not equal zero, calculations are done with a current I_{XLAT} instead of I_{FLAT} and I_{XVER} instead of I_{FVER}. The two currents are connected by means of the differential equation:

$$3\omega_0^2 \cdot I_{FLAT} = \left(\frac{d^2 I_{XFLAT}}{dt^2}\right) + 3\omega_0 \cdot \left(\frac{dI_{XFLAT}}{dt}\right) + 3\omega_0^2 \cdot I_{XFLAT} \tag{1.58}$$

$$3\omega_0^2 \cdot I_{FVER} = \left(\frac{d^2 I_{XVER}}{dt^2}\right) + 3\omega_0 \cdot \left(\frac{dI_{XVER}}{dt}\right) + 3\omega_0^2 \cdot I_{XVER} \tag{1.59}$$

Where

$$\omega_0 = \frac{1}{EXPHI \cdot TLAT_T} \tag{1.60}$$

Noise model

For noise analysis current sources are added to the small signal equivalent circuit. 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:

- Emitter Resistor

$$\overline{iN^2_{REEX}} = \frac{4 \cdot k \cdot T_K}{REEX} \cdot \Delta f \tag{1.61}$$

$$\overline{iN^2_{REIN}} = \frac{4 \cdot k \cdot T_K}{REIN_T} \cdot \Delta f \tag{1.62}$$

- Collector Resistor

$$\overline{iN^2_{RCIN}} = \frac{4 \cdot k \cdot T_K}{RCIN_T} \cdot \Delta f \tag{1.63}$$

$$\overline{iN^2_{RCEX}} = \frac{4 \cdot k \cdot T_K}{RCEX} \cdot \Delta f \tag{1.64}$$

Collector Resistor Noise:

$$\overline{iN^2_{RC}} = \overline{iN^2_{RCIN}} + \overline{iN^2_{RCEX}} \tag{1.65}$$

- Base Resistor

$$\overline{iN^2_{RBE}} = \frac{4 \cdot k \cdot T_K}{RBE_T} \cdot \Delta f \tag{1.66}$$

$$\overline{iN^2_{RBC}} = \frac{4 \cdot k \cdot T_K}{RBC_T} \cdot \Delta f \tag{1.67}$$

$$\overline{iN^2_{RSB}} = \frac{4 \cdot k \cdot T_K}{RSB} \cdot \Delta f \tag{1.68}$$

Base Resistor Noise:

$$\overline{iN^2_{RB}} = \overline{iN^2_{RBE}} + \overline{iN^2_{RBC}} + \overline{iN^2_{RSB}} \tag{1.69}$$

Lateral collector current shot noise:

$$\overline{iN^2_{CLAT}} = 2 \cdot q \cdot \left|I_{FLAT} - I_{RLAT}\right| \cdot \Delta f \tag{1.70}$$

Vertical collector current shot noise:

$$\overline{iN^2_{CVER}} = 2 \cdot q \cdot \left|I_{FVER} - I_{RVER}\right| \cdot \Delta f \tag{1.71}$$

Forward base current shot noise and 1/*f* noise:

$$\overline{iN^2_{B}} = 2 \cdot q \cdot \left|I_{RE} + I_{LE}\right| \cdot \Delta f + \frac{KF \cdot MULT^{1-AF} \cdot \left|I_{RE} + I_{LE}\right|^{AF}}{f} \cdot \Delta f \tag{1.72}$$

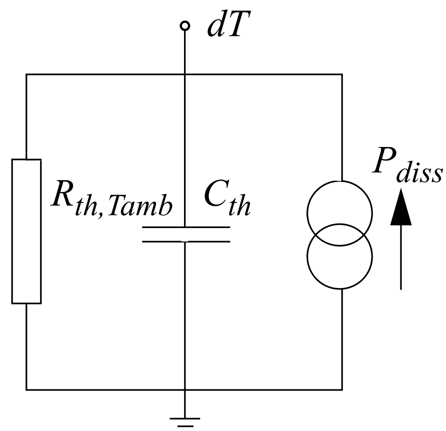
1.4.1 Numerical Adaptation

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 *SB*, *BC*1 and *BE*1. The value of the conductance is 10^{-12} [1/Ω].

1.6 Self-heating

1.6.1 Equivalent circuit

Self-heating is part of the model. It is defined in the usual way by adding a self-heating network (see Figure 3), containing a current source describing the dissipated power, and both a thermal resistance R_{TH} and a thermal capacitance C_{TH}.



Material	A_{th}
Si	1.3
Ge	1.25
GaAs	1.25
AlAs	1.37
InAs	1.1
InP	1.4
GaP	1.4
SiO_2	0.7

Figure 3: On the left, the self-heating network, where the node voltage V_{dT} is used in the temperature scaling relations. Note that for increased flexibility the node dT is available to the user. On the right are parameters values that can be used for A_{th}.

The resistance and capacitance are both connected between ground and the temperature node *dT*. The value of the voltage V_{dT} at the temperature node gives the increase in local temperature. For example, if the value of V_{dT} is 0.5V, the increase of the temperature is 0.5 degrees Celsius.

1.6.2 Model equations

The total dissipated power for the electrical model is a sum of the dissipated power of each branch of the equivalent circuit, and is given by:

For devices without substrate node:

$$P_{diss} = V_{E2E}{}^2/REEX + V_{E1E2}{}^2/REIN + V_{C2C}{}^2/RCEX + V_{C1C2}{}^2/RCIN + V_{B2B}{}^2/RBC + V_{B1B}{}^2/RBE + V_{SB}{}^2/RSB + (I_{RLAT} - I_{FLAT}) \cdot V_{C1E1} + I_{RVER} \cdot V_{C2E1} + I_{FVER} \cdot V_{E2C1} + (I_{RC} + I_{LC}) \cdot V_{C2B2} + (I_{RE} + I_{LE}) \cdot V_{E2B1} + I_{SC} \cdot V_{C2S} + I_{SE} \cdot V_{E2S} + I_{SF} \cdot V_{Sl} \quad (1.73)$$

Note that the effect of the parameter *DTA* and dynamic self-heating as discussed here are independent [1]. To use a more complicated self-heating network, one can increase *RTH* to very large values, make *CTH* zero, and add the wanted self-heating networking externally to the node *dT*.

For the value of A_{th} we recommend using values from literature that describes the temperature scaling of the thermal conductivity. For the most important materials, the values are given in Figure 3, which is largely based on Ref. [2], see also [3].

Please note that taking $C_{th} = 0$ in the self-heating model is *incorrect* for AC simulations (and hence also for transient simulations). The reason is that $C_{th} = 0$ means that self-heating is infinitely fast. In reality, however, self heating is much slower than the relevant time scales in most application. Therefore, for simulations, a non-zero thermal capacitance should always be used, even when the thermal capacitance has not been extracted. Since in practice the thermal time delay is of the order of $1\mu s$, a reasonable estimate for the thermal capacitance can be given by $C_{th} = 1\mu s / R_{th}$.

1.6.3 Usage

Below, an example (*Pstar*) is given to illustrate the working of self-heating.

❑ Example

Title: example self-heating 500;

```
circuit;
 e_be (0, b) 1;
 e_ce (0, c) 3.3;
 e_se (0, s) 3.3;
 tplt_1 (c, b, 0, s, dt) level=500,Rth=100,cth=1e-9;

end;
dc;
print: vn(dt), pdiss.tplt_1;
end;
run;

result:

DC   Analysis.
VN(DT)                =        1.053E+00
Pdiss.TPLT_1          =       10.533E-03
```

The voltage on node *dT* is 1.053+00 V, which means that the local temperature is increased by 1.053 ^{o}C.

1.7 DC Operating point output

The DC operating point output facility gives information on the state of a device at its operation point. Figure 1 shows the DC large signal equivalent circuit of the TPL500 model. The small signal equivalent circuit is given in Figure 2.
REEX, *REIN*, *RCIN* and *RCEX* are constant resistors.

$$dILAT = g_{fL} \cdot dV_{E1B} - g_{rL} \cdot dV_{C1B} \tag{1.74}$$

$$dIFVER = g_{11V} \cdot dV_{E2B1} + g_{12V} \cdot dV_{C1B} \tag{1.75}$$

$$dIRVER = g_{21V} \cdot dV_{E1B} + g_{22V} \cdot dV_{C2B2} \tag{1.76}$$

$$dI_{B1B} = G_{IBE} \cdot dV_{E2B1} \tag{1.77}$$

$$dI_{B2B} = G_{IBC} \cdot dV_{C2B2} \tag{1.78}$$

$$dI_{\pi L} = j\omega \cdot C_{I\pi L} \cdot dV_{C1B} \tag{1.79}$$

$$dI_{\mu L} = j\omega \cdot C_{I\mu L} \cdot dV_{E1B} \tag{1.80}$$

$$dISE = G_{ISE} \cdot dV_{E2B1} \tag{1.81}$$

$$dISC = G_{ISC} \cdot dV_{C2B2} \tag{1.82}$$

3 Note

The operating-point output will not be influenced by the value of G_{min}. I_{B1B} and I_{B2B} represent the current through the nonlinear resistors *RBE* and *RBC* respectively.

Quantity	**Equation**	**Description**
LEVEL	*500*	Model level
REEX	*REEX*	External emitter resistance
REIN	*REIN*	Internal emitter resistance
RCEX	*RCEX*	External collector resistance
RCIN	*RCIN*	Internal collector resistance
GFL	g_{fL}	Forward conductance, lateral path.: $\partial I_{FLAT} / \partial V_{E1B1}$
GRL	g_{rL}	Reverse conductance, lateral path.: $\partial I_{RLAT} / \partial V_{C1B}$
G11	g_{11}	Forward conductance, vertical path.: $\partial I_{FVER} / \partial V_{E2B1}$
G12	g_{12}	Collector Early-effect on I_{FVER}: $\partial I_{FVER} / \partial V_{C1B}$
G21	g_{21}	Emitter Early-effect on I_{RVER}: $\partial I_{RVER} / \partial V_{E1B}$
G22	g_{22}	Reverse conductance, vertical path.: $\partial I_{RVER} / \partial V_{C2B2}$
GPIV	$G_{\pi V}$	Conductance e-b junction: $\partial (I_{RE} + I_{LE}) / \partial V_{E2B1}$
GMUV	$G_{\mu V}$	Conductance c-b junction: $\partial (I_{RC} + I_{LC}) / \partial V_{C2B2}$
GBE	G_{BE}	Emitter-side: base conductance B1-B $\partial I_{B1B} / \partial V_{B1B}$
GIBE	G_{IBE}	Emitter Early-effect on I_{B1B}: $\partial I_{B1B} / \partial V_{E2B1}$
GBC	G_{BC}	Collector-side: base conductance B2-B: $\partial I_{B2B} / \partial V_{B2B}$
GIBC	G_{IBC}	Collector Early-effect on I_{B2B}: $\partial I_{B2B} / \partial V_{C2B2}$
CPIL	$C_{\pi L}$	Forward diffusion cap., lateral path: $\partial Q_{FLAT} / \partial V_{E1B}$
CIPIL	$C_{I\pi L}$	Collector Early-effect on Q_{FLAT}: $\partial Q_{FLAT} / \partial V_{C1B}$
CPIV	$C_{\pi V}$	Forward total capacitance, vertical path: $\partial (Q_{TE} + Q_{FVER} + Q_{FN}) / \partial V_{E2B1}$
CMUL	$C_{\mu L}$	Reverse diffusion capacitance, lateral path: $\partial Q_{RLAT} / \partial V_{C1B}$
CIMUL	$C_{I\mu L}$	Emitter Early-effect on Q_{RLAT}: $\partial Q_{RLAT} / \partial V_{E1B}$

Quantity	Equation	Description
CMUV	$C_{\mu V}$	Reverse total capacitance, vertical path: $\partial(Q_{tc} + Q_{rver} + Q_{rn}) / \partial V_{C2B2}$
GISE	G_{ISE}	Transconductance (parasitic PNP) e-b-s- transistor: $\partial I_{SE} / \partial V_{E2B1}$
GISC	G_{ISC}	Transconductance (parasitic PNP) c-b-s- transistor: $\partial I_{SC} / \partial V_{C2B2}$
GSB	G_{SB}	Conductance s-b junction: $\partial I_{SF} / \partial V_{SB} + 1/R_{SB}$
CSB	C_{SB}	Total capacitance s-b junction: $\partial Q_{TS} / \partial V_{SB} + \partial Q_{SD} / \partial V_{SB}$

1.8 Simulator specific items

1.8.1 Pstar syntax

p channel substrate model: tpl_n (c, b, e, s) level=500, <parameters>
p channel substrate self-heating model:
tplt_n (c, b, e, s, dt) level=500, <parameters>

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

c, b, e, s and dt are collector, base, emitter, substrate and self-heating terminals respectively.

⚠ Care

When assignment by position is used, the order of the parameters must be equal to the order specified in the model definition. Readability is improved if assignment by name is used.

1.8.2 Spectre syntax

p channel substrate model: model modelname bjt500 type=pnp[1] <modpar>
componentname c b e s modelname <inpar>
p channel substrate self-heating model:
model modelname bjt500t type=pnp[1] <modpar>
componentname c b e s dt modelname <inpar>

modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters[2]
<inpar>	:	list of instance parameters[2]

c, b, e, s and dt are collector, base, emitter, substrate and self-heating terminals respectively.

1.Either pnp or pnpl are interpreted as lateral pnp.
2.For more details of these Spectre parameters see also Cadence Spectre Circuit Simulator Reference, version 4.4.6 or 5.0.

1.8.3 ADS syntax

p channel substrate model: model modelname bjt500 gender=0 <modpar>
componentname c b e s modelname <instpar>

p channel substrate self-heating model:
model modelname bjt504t gender=0 <modpar>
componentname c b e s dt modelname <instpar>

modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters
<instpar>	:	list of instance parameters

c, b, e, s and dt are collector, base, emitter, substrate and self-heating terminals respectively.

1.8.4 The ON/OFF condition for Pstar

The solution for 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 [4]. By default the devices start in the default state.

n-channel			
	Default	ON	OFF
V_{C1B}	0.01	0.0	0.0
V_{C2B2}	0.01	0.0	0.0
V_{E1B}	0.7	0.7	0.0
V_{E2B1}	0.75	0.75	0.0
V_{B2B}	0.01	-0.1	0.1
V_{B1B}	0.01	0.1	0.1
V_{SB}	-1.0	-1.0	-1.0

n-channel for self-heating			
	Default	ON	OFF
DT	0.0	0.0	0.0

For p-channel devices the numbers remain the same but have a negative value, i.e. 0.01 becomes -0.01.

1.8.5 The ON/OFF condition for Spectre

n-channel					
	Default	OFF	Saturation	Reverse	Forward
V_{C1B}	0.01	0.0	0.7.	0.7	0.0
V_{C2B2}	0.01	0.0	0.75	0.75	0.0
V_{E1B}	0.7	0.0	0.7	0.0	0.7
V_{E2B1}	0.75	0.0	0.75	0.0	0.75
V_{B2B}	0.01	-0.1	0.0	0.1	-0.1
V_{B1B}	0.01	0.1	0.0	-0.1	0.1
V_{SB}	-1.0	-1.0	-1.0	-1.0	-1.0

n-channel					
	Default	OFF	Saturation	Reverse	Forward
DT	0.0	0.0	0.0	0.0	0.0

For p-channel devices the numbers remain the same but have a negative value, i.e. 0.01 becomes -0.01.

1.8.6 The ON/OFF condition for ADS

n-channel	
	Default
V_{C1B}	0.0
V_{C2B2}	0.0
V_{E1B}	0.0
V_{E2B1}	0.0
V_{B2B}	0.0
V_{B1B}	0.0
V_{SB}	0.0

n-channel for self-heating	
	Default
DT	0.0

For p-channel devices the numbers remain the same but have a negative value, i.e. 0.01 becomes -0.01.

1.9 References

[1] For the most recent model descriptions, source code, and documentation, see the web-site http://www.semiconductors.philips.com/Philips Models.

[2] S.M. Sze, *Physics of Semiconductor Devices*. Wiley, New York, 2 ed., 1981.

[3] V. Palankovski, R. Schultheis, and S. Selberherr, *Simulation of power heterojunction bipolar transistor on gallium arsenide*, *IEEE Trans. Elec. Dev.*, vol 48, pp.1264-1269, 2001. Note: the paper uses $\alpha = 1.65$ for Si, but $\alpha = 1.3$ gives a better fit; also κ_{300} for GaAs is closer to 40 than to the published value of 46 (Palankovski, personal communication).

[4] **Pstar** User Manual.

B Spectre Specific Information

Imax, Imelt, Jmelt parameters

Introduction

Imax, Imelt and Jmelt are Spectre-specific parameters used to help convergence and to prevent numerical problems. We refer in this text only to the use of Imax model parameter in Spectre with SiMKit devices since the other two parameters, Imelt and Jmelt, are not part of the SiMKit code. For information on Imelt and Jmelt refer to Cadence documentation.

Imax model parameter

Imax is a model parameter present in the following SiMKit models:
– juncap and juncap2
– psp and pspnqs (since they contain juncap models)

In Mextram 504 (bjt504) and Modella (bjt500) SiMKit models, Imax is an internal parameter and its value is set through the adapter via the Spectre-specific parameter Imax.

In models that contain junctions, the junction current can be expressed as:

$$I = I_s \exp\left(\frac{V}{N \cdot \phi_{TD}} - 1\right) \quad (18.134)$$

The exponential formula is used until the junction current reaches a maximum (explosion) current Imax.

$$I_{max} = I_s \exp\left(\frac{V_{\exp l}}{N \cdot \phi_{TD}} - 1\right) \quad (18.135)$$

The corresponding voltage for which this happens is called Vexpl (explosion voltage). The voltage explosion expression can be derived from (1):

$$V_{\exp l} = N \cdot \phi_{TD} \log\left(\frac{I_{max}}{I_s}\right) + 1 \quad (18.136)$$

For $V > V_{\exp l}$ the following linear expression is used for the junction current:

$$I = I_{max} + (V - V_{expl})\frac{I_s}{N \cdot \phi_{TD}}\exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}}\right) \tag{18.137}$$

The default value of the Imax model parameter for SiMKit is 1000A. The default value of Imax for Mextram 504 and Modella is 1A. Imax should be set to a value which is large enough so it does not affect the extraction procedure.

Region parameter

Region is an Spectre-specific model parameter used as a convergence aid and gives an estimated DC operating region. The possible values of region depend on the model:

– For Bipolar models:
  – subth: Cut-off or sub-threshold mode
  – fwd: Forward
  – rev: Reverse
  – sat: Saturation.
  – off[1]
  –
– For MOS models:
  – subth: Cut-off or sub-threshold mode;
  – triode: Triode or linear region;
  – sat: Saturation
  – off[1]

For PSP and PSPNQS all regions are allowed, as the PSP(NQS) models both have a MOS part and a juncap (diode). Not all regions are valid for each part, but when e.g. region=forward is set, the initial guesses for the MOS will be set to zero. The same holds for setting a region that is not valid for the JUNCAP.

– For diode models:
  – fwd: Forward
  – rev: Reverse
  – brk: Breakdown
  – off[1]

1.Off is not an electrical region, it just states that the user does not know in what state the device is operating

Model parameters for device reference temperature in Spectre

This text describes the use of the tnom, tref and tr model parameters in Spectre with SiMKit devices to set the device reference temperature.

A Simkit device in Spectre has three model parameter aliases for the model reference temperature, tnom, tref and tr. These three parameters can only be used in a model definition, not as instance parameters.

There is no difference in setting tnom, tref or tr. All three parameters have exactly the same effect. The following three lines are therefore completely equivalent:

```
model nmos11020 mos11020 type=n tnom=30
model nmos11020 mos11020 type=n tref=30
model nmos11020 mos11020 type=n tr=30
```

All three lines set the reference temperature for the mos11020 device to 30 C.

Specifying combinations of tnom, tref and tr in the model definition has no use, only the value of the last parameter in the model definition will be used. E.g.:

```
model nmos11020 mos11020 type=n tnom=30 tref=34
```

will result in the reference temperature for the mos11020 device being set to 34 C, tnom=30 will be overridden by tref=34 which comes after it.

When there is no reference temperature set in the model definition (so no tnom, tref or tr is set), the reference temperature of the model will be set to the value of tnom in the options statement in the Spectre input file. So setting:

```
options1 options tnom=23 gmin=1e-15 reltol=1e-12 \
    vabstol=1e-12 iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the mos11020 device to 23 C.

When no tnom is specified in the options statement and no reference temperature is set in the model definition, the default reference temperature is set to 27 C.
So the lines:

```
options1 options gmin=1e-15 reltol=1e-12 vabstol=1e-12 \
    iabstol=1e-16
 model nmos11020 mos11020 type=n
```

will set the reference temperature of the mos11020 device to 27 C.

The default reference temperature set in the SiMKit device itself is in the Spectre simulator never used. It will always be overwritten by either the default "options tnom", an explicitly set option tnom or by a tnom, tref or tr parameter in the model definition.