12 Bipolar Transistor Level 504

12.1 Introduction

The 504 model provides a detailed description of a vertical integrated circuit and discrete bipolar transistor. It is meant to be used for DC, transient and AC analysis at all current levels, i.e. high and low injection, quasi and hard saturation. This new level 504 version of the Mextram model gives better results for the description of first and higher-order derivatives of the device characteristics than Mextram level 503. This can be especially seen in the output conductance, the cut-off frequency and the low frequency third order distortion. Special attention was paid to the modelling of SiGe transistors. Furthermore we include self-heating in the description.

12.2 Order in which terminals are specified

For the TN device: TN_n (C, B, E) <parameters>
For the TNS device: TNS_n (C, B, E, S) <parameters>

For the TNT device: TNT_n (C, B, E, DT) <parameters>
For the TNST device: TNST_n (C, B, E, S, DT) <parameters>

For the TP device: TP_n (C, B, E) <parameters>
For the TPS device: TPS_n (C, B, E, S) <parameters>

For the TPT device: TPT_n (C, B, E, DT) <parameters>
For the TPST device: TPST_n (C, B, E, S, DT) <parameters>

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

C, B, E, S and DT are collector, base, emitter, substrate and thermal terminals respectively

12.3 Survey of modeled effects

- Bias-dependent Early effect
- Low-level non-ideal base currents
- High injection effects
- Ohmic resistance of the epilayer
- Velocity saturation effects on the resistance of the epilayer
- Hard and quasi-saturation (including Kirk effect)
- Weak avalanche (optionally snap-back behaviour)
- Charge storage effects
- Split base-collector and base-emitter depletion capacitance
- Substrate effects and parasitic PNP
- Explicit modelling of inactive regions
- Current crowding and conductivity modulation of the base resistance
- First order approximation of distributed high frequency effects in the intrinsic base (high-frequency current crowding and excess phase-shift)
- Recombination in the base (meant for SiGe transisitors)
- Early effect in the case of a graded bandgap (SiGe)
- Temperature scaling
- Self-heating
- Thermal noise, shot noise and 1/f noise

12.4 Parameters

The parameters for TN and TP-level-504 are listed in the table below.

Position in list	Parameter name	Units	Description
1	*LEVEL*	-	Model level, must be set to 504
2	*MULT*	-	Multiplication factor
3	*TREF*	°C	Reference temperature
4	*DTA*	°C	Difference of the device temperature to the ambient temperature $(T_{DEVICE} = T_{AMBIENT} + DTA)$
5	*EXMOD*	-	Flag for extended modeling of the reverse current gain
6	*EXPHI*	-	Flag for the distributed high frequency effects in transient
7	*EXAVL*	-	Flag for extended modeling of avalanche currents
8	*IS*	A	Collector-emitter saturation current
9	*IK*	A	Collector-emitter high injection knee current
10	*VER*	V	Reverse Early voltage
11	*VEF*	V	Forward Early voltage
12	*BF*	-	Ideal forward current gain
13	*IBF*	A	Saturation current of the non-ideal forward base current
14	*MLF*	-	Non-ideality factor of the non-ideal forward base current
15	*XIBI*	-	Part of ideal base current that belongs to the sidewall
16	*BRI*	-	Ideal reverse current gain
17	*IBR*	A	Saturation current of the non-ideal reverse base current
18	*VLR*	V	Cross-over voltage of the non-ideal reverse base current
19	*XEXT*	-	Part of I_{EX}, Q_{EX}, Q_{TEX} and I_{SUB} that depends on the base-collector voltage V_{BC1} instead of V_{B1C1}
20	*WAVL*	m	Epilayer thickness used in weak-avalanche model
21	*VAVL*	V	Voltage determining curvature of avalanche current

Position in list	**Parameter name**	**Units**	**Description**
22	*SFH*	-	Current spreading factor of avalanche model (When *EXAVL*=1)
23	*RE*	Ω	Emitter resistance
24	*RBC*	Ω	Constant part of the base resistance
25	*RBV*	Ω	Variable part of the base resistance at zero bias
26	*RCC*	Ω	Constant part of the collector resistance
27	*RCV*	Ω	Resistance of the unmodulated epilayer
28	*SCRCV*	Ω	Space charge resistance of the epilayer
29	*IHC*	A	Critical current for velocity saturation in the epilayer
30	*AXI*	-	Smoothness parameter for the onset of quasi-saturation
31	*CJE*	F	Zero bias emitter-base depletion capacitance
32	*VDE*	V	Emitter-base diffusion voltage
33	*PE*	-	Emitter-base grading coefficient
34	*XCJE*	-	Fraction of the emitter-base depletion capacitance that belongs to the sidewall
35	*CBEO*	-	Emitter-base overlap capacitance
36	*CJC*	F	Zero bias collector-base depletion capacitance
37	*VDC*	V	Collector-base diffusion voltage
38	*PC*	-	Collector-base grading coefficient
39	*XP*	-	Constant part of of *CJC*
40	*MC*	-	Collector current modulation coefficient
41	*XCJC*	-	Fraction of the collector-base depletion capacitance under the emitter area
42	*CBCO*	-	Collector-base overlap capacitance
43	*MTAU*	-	Non-ideality factor of the emitter stored charge
44	*TAUE*	s	Minimum transit time of stored emitter charge
45	*TAUB*	s	Transit time of stored base charge

Position in list	**Parameter name**	**Units**	**Description**
46	*TEPI*	s	Transit time of stored epilayer charge
47	*TAUR*	s	Transit time of reverse extrinsic stored base charge
48	*DEG*	eV	Bandgap difference over the base
49	*XREC*	-	Pre-factor of the recombination part of I_{B1}
50	*AQBO*	-	Temperature coefficient of the zero bias base charge
51	*AE*	-	Temperature coefficient of the resistivity of the emitter
52	*AB*	-	Temperature coefficient of the resistivity of the base
53	*AEPI*	-	Temperature coefficient of the resistivity of the epilayer
54	*AEX*	-	Temperature coefficient of the resistivity of the extrinsic base
55	*AC*	-	Temperature coefficient of the restivity of the buried layer
56	*DVGBF*	V	Band-gap voltage difference of forward current gain
57	*DVGBR*	V	Band-gap voltage difference of reverse current gain
58	*VGB*	V	Band-gap voltage of the base
59	*VGC*	V	Band-gap voltage of the collector
60	*VGJ*	V	Band-gap voltage recombination emitter-base junction
61	*DVGTE*	V	Band-gap voltage difference of emitter stored charge
62	*AF*	-	Flickernoise exponent
63	*KF*	-	Flickernoise coefficient ideal base current
64	*KFN*	-	Flickernoise coefficient non-ideal base current

The additional parameters for the TNS and TPS-level-504 are listed in the table below.

Position in list	**Parameter name**	**Units**	**Description**
65	*ISS*	A	Base-substrate saturation current
66	*IKS*	A	Base-substrate high injection knee current
67	*CJS*	F	Zero bias collector-substrate depletion capacitance
68	*VDS*	V	Collector-substrate diffusion voltage
69	*PS*	-	Collector-substrate grading coefficient
70	*VGS*	V	Band-gap voltage of the substrate
71	*AS*	-	For a closed buried layer: *AS*=*AC* For an open buried layer: *AS*=*AEPI*

The additional parameters for the thermal models TNT, TNST, TPT and TPST-level-504 are listed in the table below.

Position in list	**Parameter name**	**Units**	**Description**
72	*RTH*	°C/W	Thermal resistance
73	*CTH*	J/°C	Thermal capacitance

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*:

$IS \quad IK \quad IBF \quad IBR \quad IHC \quad ISS \quad IKS \quad CJE \quad CJC \quad CJS \quad CTH \quad CBCO \quad CBEO$

Divided by *MULT* are:

$RE \quad RBC \quad RBV \quad RCC \quad RCV \quad SCRCV \quad RTH$

The flicker-noise coefficients are scaled as:

$$KF \rightarrow KF \cdot MULT^{(1-AF)}$$

$$KFN \rightarrow KFN \cdot MULT^{1-[2(MLF-1)+AF(2-MLF)]}$$

Default and clipping values

The default values and clipping values for the TN and TP-level-504 are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	504	-	-
2	*MULT*	-	1.00	0.0	-
3	*TREF*	°C	25.00	-273.15	-
4	*DTA*	°C	0.00	-	-
5	*EXMOD*	-	1.00	0.00	1.00
6	*EXPHI*	-	1.00	0.00	1.00
7	*EXAVL*	-	0.00	0.00	1.00
8	*IS*	A	22.00×10^{-18}	0.00	-
9	*IK*	A	0.10	1.0×10^{-12}	-
10	*VER*	V	2.50	0.01	-
11	*VEF*	V	44.00	0.01	-
12	*BF*	-	215.00	1.0×10^{-4}	-
13	*IBF*	A	2.70×10^{-15}	0.00	-
14	*MLF*	-	2.00	0.10	-
15	*XIBI*	-	0.00	0.00	1.00
16	*BRI*	-	7.00	1.00×10^{-4}	-
17	*IBR*	A	1.00×10^{-15}	0.00	-
18	*VLR*	V	0.20	-	-
19	*XEXT*	-	0.63	0.00	1.00
20	*WAVL*	m	1.10×10^{-6}	1.00×10^{-9}	-
21	*VAVL*	V	3.00	0.01	-
22	*SFH*	-	0.30	0.00	-
23	*RE*	Ω	5.00	1.00×10^{-6}	-

No.	Parameter	Units	Default	Clip low	Clip high
24	*RBC*	Ω	23.00	1.00×10^{-6}	-
25	*RBV*	Ω	18.00	1.00×10^{-6}	-
26	*RCC*	Ω	12.00	1.00×10^{-6}	-
27	*RCV*	Ω	150.00	1.00×10^{-6}	-
28	*SCRCV*	Ω	1250.00	1.00×10^{-6}	-
29	*IHC*	A	4.00×10^{-3}	1.00×10^{-12}	-
30	*AXI*	–	0.30	0.02	-
31	*CJE*	F	73.00×10^{-15}	0.00	-
32	*VDE*	V	0.95	0.05	-
33	*PE*	–	0.40	0.01	0.99
34	*XCJE*	–	0.40	0.00	1.00
35	*CBEO*	-	0.00	0.00	-
36	*CJC*	F	78.00×10^{-15}	0.00	-
37	*VDC*	V	0.68	0.05	-
38	*PC*	-	0.5	0.01	0.99
39	*XP*	-	0.35	0.00	0.99
40	*MC*	-	0.5	0.00	1.00
41	*XCJC*	-	32.00×10^{-3}	0.00	1.00
42	*CBCO*	-	0.00	0.00	-
43	*MTAU*	-	1.00	0.10	-
44	*TAUE*	s	2.00×10^{-12}	0.00	-
45	*TAUB*	s	4.20×10^{-12}	0.00	-
46	*TEPI*	s	41.00×10^{-12}	0.00	-
47	*TAUR*	s	520.00×10^{-12}	0.00	-
48	*DEG*	eV	0.00	-	-

No.	Parameter	Units	Default	Clip low	Clip high
49	$XREC$	-	0.00	0.00	-
50	$AQBO$	-	0.30	-	-
51	AE	-	0.00	-	-
52	AB	-	1.00	-	-
53	$AEPI$	-	2.50	-	-
54	AEX	-	0.62	-	-
55	AC	-	2.00	-	-
56	$DVGBF$	V	50.00×10^{-3}	-	-
57	$DVGBR$	V	45.00×10^{-3}	-	-
58	VGB	V	1.17	0.10	-
59	VGC	V	1.18	0.10	-
60	VGJ	V	1.15	0.10	-
61	$DVGTE$	V	0.05	-	-
62	AF	-	2.00	0.01	-
63	KF	-	20.00×10^{-12}	0.00	-
64	KFN	-	20.00×10^{-12}	0.00	-

The default values and clipping values for the TNS and TPS-level-504 are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
65	*ISS*	A	48.00×10^{-18}	0.00	-
66	*IKS*	A	250.00×10^{-6}	1.0×10^{-12}	-
67	*CJS*	F	315.00×10^{-15}	0.00	-
68	*VDS*	V	0.62	0.05	-
69	*PS*	-	0.34	0.01	0.99
70	*VGS*	V	1.20	0.10	-
71	*AS*	-	1.58	-	-

The default values and clipping values for the TNT, TNST, TPT and TPST-level-504 are listed below.

No.	Parameter	Units	Default	Clip low	Clip high
72	*RTH*	°C/W	300.00	0.00	-
73	*CTH*	J/°C	3.00×10^{-9}	0.00	-

12.5 Pstar specific items

12.5.1 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 non-linear elements. A simplified DCAPPROX mechanism for devices using ON / OFF keywords is mentioned in [46]. By default the devices start in the default state.

TN-level 504			
	Default	ON	OFF
V_{BC1}	-1.0	0.0	-1.0
V_{B1C1}	-1.0	0.0	-1.0
V_{B2C1}	-1.0	0.0	-1.0
V_{B2C2}	-1.0	0.0	-1.0
V_{B1E1}	0.65	0.75	-0.3
V_{B2E1}	0.65	0.75	-0.3
V_{B1B2}	1.0×10^{-6}	1.0×10^{-6}	0.0

TNS-level 504			
	Default	ON	OFF
V_{BC1}	-1.0	0.0	-1.0
V_{B1C1}	-1.0	0.0	-1.0
V_{B2C1}	-1.0	0.0	-1.0
V_{B2C2}	-1.0	0.0	-1.0
V_{B1E1}	0.65	0.75	-0.3
V_{B2E1}	0.65	0.75	-0.3
V_{B1B2}	1.0×10^{-6}	1.0×10^{-6}	0.0
V_{SC1}	-5.0	-5.0	-5.0

TNT-level 504			
	Default	ON	OFF
DT	0.0	0.0	0.0

TNST- level 504			
	Default	ON	OFF
DT	0.0	0.0	0.0

For the TP, TPS, TPT and TPST-level 504 the numbers are inverse.

12.5.2 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 $B1C1$ and $B2E1$. The value of the conductance is 10^{-13} $[1/\Omega]$.

12.5.3 DC operating point output

The operating point information is a list of quantities that describe the internal state of the transistor. When a circuit simulator is able to provide these, it might help the designer understand the behaviour of the transistor and the circuit. The full list of operating point information consist of three parts. First we have all the branch biases, the currents and the charges. Then we have, as usual, the elements that can be used if a full small-signal equivalent circuit is needed. These are all the derivatives of the charges and currents. At last, and possibly the most informative, we have given approximations to the small-signal model which together form a hybrid-π model with similar behaviours as the full Mextram model. In addition the cut-off frequency is included. Note that G_{min} is not included in the expressions of the operating point information.

Since we have 5 internal nodes we need 5 voltage differences to describe the bias at each internal node, given the external biases. We take those that are the most informative for the internal state of the transistor:

The small signal equivalent circuit contains the following conductances. In the terminology we use the notation A_x, A_y, and A_z to denote derivatives of the quantity A to some voltage difference. We use x for base-emitter biases, y is for derivatives w.r.t. V_{B2C2} and z is used for all other base-collector biases. The subindex π is used for base-emitter base currents, μ is used for base-collector base currents, rbv for derivatives of I_{B1B2} and rcv for derivatives of I_{C1C2}. The small signal equivalent circuit is shown in figure 33. The current sources are defined as:

$$\begin{aligned}
dI_n &= g_x \cdot dV_{B2E1} + g_y \cdot dV_{B2C2} + g_z \cdot dV_{B2C1} \\
dI_{C1C2} &= grcv_y \cdot dV_{B2C2} + grcv_z \cdot dV_{B2C1} \\
dI_{BE} &= j\omega \cdot (Cbe_y \cdot dV_{B2C2} + Cbe_z \cdot dV_{B2C1}) \\
dI_{BC} &= g_{\mu x} \cdot dV_{B2E1} + g_{\mu z} \cdot dV_{B2C1} + j\omega \cdot (Cbc_x \cdot dV_{B2E1} + Cbc_z \cdot dV_{B2C1}) \\
dI_{B1B2} &= grbv_x \cdot dV_{B2E1} + grbv_y \cdot dV_{B2C2} + grbv_z \cdot dV_{B2C1} + j\omega \cdot C_{B1B_{2x}} \cdot dV_{B2E1} \\
dSI_{BE} &= j\omega \cdot SC_{TE} \cdot dV_{B2E1}
\end{aligned}$$

For the TNS device:

$$dI_{SUB} = g_{PNP} \cdot dV_{B1C1} + Xg_{PNP} \cdot dV_{BC1}$$

Quantity	**Equation**	**Description**
LEVEL	504	Model level
VB2E1	V_{B2E1}	Internal base-emitter bias
VB2C2	V_{B2C2}	Internal base-collector bias
VB2C1	V_{B2C1}	Internal base-collector bias including epilayer
VB1C1	V_{B1C1}	External base-collector bias without contact resistances
VE1E	V_{E1E}	Bias over emitter resistance
IN	I_N	Main current
IC1C2	I_{C1C2}	Epilayer current
IB1B2	I_{B1B2}	Pinched-base current
IB1	I_{B1}	Ideal forward base current
SIB1	I_{B1}^S	Ideal side-wall base current
IB2	I_{B2}	Non-ideal forward base current
IB3	I_{B3}	Non-ideal reverse base current
IAVL	I_{avl}	Avalanche current
IEX	I_{EX}	Extrinsic reverse base current
XIEX	XI_{EX}	Extrinsic reverse base current
For the TNS device:		
ISUB	I_{sub}	Substrate current
XISUB	XI_{sub}	Substrate current
ISF	I_{Sf}	Substrate failure current
IRE	I_{RE}	Current through emitter resistance
IRBC	I_{RBC}	Current through constant base resistance

Quantity	**Equation**	**Description**
IRCC	I_{RCC}	Current through constant collector resistance
GX	g_x	Forward transconductance $\partial I_N / \partial V_{B2E1}$
QE	Q_E	Emitter charge or emitter neutral charge
QTE	Q_{tE}	Base-emitter depletion charge
SQTE	Q_{tE}^S	Sidewall base-emitter depletion charge
QBE	Q_{BE}	Base-emitter diffusion charge
QBC	Q_{BC}	Base-collector diffusion charge
QTC	Q_{tC}	Base-collector depletion charge
QEPI	Q_{epi}	Epilayer diffusion charge
QB1B2	Q_{B1B2}	AC current crowding charge
QTEX	Q_{tex}	Extrinsic base-collector depletion charge
XQTEX	XQ_{tex}	Extrinsic base-collector depletion charge
QEX	Q_{ex}	Extrinsic base-collector diffusion charge
XQEX	XQ_{ex}	Extrinsic base-collector diffusion charge
For the TNS device:		
QTS	Q_{tS}	Collector-substrate depletion charge
GY	g_y	Reverse transconductance $\partial I_N / \partial V_{B2C2}$
GZ	g_z	Reverse transconductance $\partial I_N / \partial V_{B2C1}$
SGPI	g_π^S	Conductance sidewall b-e junction: $\partial I_{BI}^S / \partial V_{B1E1}$
GPIX	$g_{\pi X}$	Conductance floor b-e junction: $\partial I_{B1} / \partial V_{B2E1} + \partial I_{B2} / \partial V_{B2E1}$
GPIY	$g_{\pi Y}$	Early effect on recombination base current: $\partial I_{B1} / \partial V_{B2C2}$

Quantity	Equation	Description
GPIZ	$g_{\pi Z}$	Early effect on recombination base current: $\partial I_{B1} / \partial V_{B2C1}$
GMUX	$g_{\mu X}$	Early effect on avalanche current limiting: $-\partial I_{AVL} / \partial V_{B2E1}$
GMUY	$g_{\mu Y}$	Conductance of avalanche current: $-\partial I_{AVL} / \partial V_{B2C2}$
GMUZ	$g_{\mu Z}$	Conductance of avalanche current: $-\partial I_{AVL} / \partial V_{B2C1}$
GMUEX	$g_{\mu EX}$	Conductance extrinsic b-c junction: $\partial (I_{EX} + I_{B3}) / \partial V_{B1C1}$
XGMUEX	$Xg_{\mu EX}$	Conductance extrinsic b-c junction: $\partial XI_{EX} / \partial V_{BC1}$
GRCVY	$grcv_y$	Conductance of the epilayer current: $\partial I_{C1C2} / \partial V_{B2C2}$
GRCVZ	$grcv_z$	Conductance of the epilayer current: $\partial I_{C1C2} / \partial V_{B2C1}$
RBV	rbv	Variable part of the base resistance $1 / (\partial I_{B1B2} / \partial V_{B1B2})$
GRBVX	$grbv_X$	Early-effect on base resistance: $\partial I_{B1B2} / \partial V_{B2E1}$
GRBVY	$grbv_Y$	Early-effect on base resistance: $\partial I_{B1B2} / \partial V_{B2C2}$
GRBVZ	$grbv_Z$	Early-effect on base resistance: $\partial I_{B1B2} / \partial V_{B2C1}$
RE	RE_T	Emitter resistance
RBC	RBC_T	Constant base resistance
RCC	RCC_T	Constant collector resistance
For the TNS device:		
GS	g_S	Conductance parasitic PNP transistor: $\partial I_{SUB} / \partial V_{B1C1}$
XGS	Xg_S	Conductance parasitic PNP transistor: $\partial XI_{SUB} / \partial V_{BC1}$
GSUB	g_{SF}	Conductance substrate failure current: $\partial I_{SF} / \partial V_{SC1}$
SCBE	Cbe^S	Capacitance sidewall b-e junction: $\partial Q_{TE}^S / \partial V_{B1E1}$
CBEX	Cbe_X	Capacitance floor b-e junction: $\partial Q_{TE} / \partial V_{B2E1} + \partial Q_{BE} / \partial V_{B2E1} + \partial Q_E / \partial V_{B2E1}$

CBEY	Cbe_Y	Early effect on b-e diffusion charge: $\partial Q_{BE}/\partial V_{B2C2}$
CBEZ	Cbe_Z	Early effect on b-e diffusion charge: $\partial Q_{BE}/\partial V_{B2C1}$
CBCX	Cbc_X	Early effect on b-c diffusion charge: $\partial Q_{BC}/\partial V_{B2E1}$
CBCY	Cbc_Y	Capacitance floor b-c junction: $\partial Q_{TC}/\partial V_{B2C2} + \partial Q_{BC}/\partial V_{B2C2} + \partial Q_{EPI}/\partial V_{B2C2}$
CBCZ	Cbc_Z	Capacitance floor b-c junction: $\partial Q_{TC}/\partial V_{B2C1} + \partial Q_{BC}/\partial V_{B2C1} + \partial Q_{EPI}/\partial V_{B2C1}$
CBCEX	Cbc_{EX}	Capacitance extrinsic b-c junction: $\partial Q_{TEX}/\partial V_{B1C1} + \partial Q_{EX}/\partial V_{B1C1}$
XCBCEX	$XCbc_{EX}$	Capacitance extrinsic b-c junction: $\partial XQ_{TEX}/\partial V_{BC1} + \partial XQ_{EX}/\partial V_{BC1}$
CB1B2	C_{B1B2}	Capacitance AC current crowding: $\partial Q_{B1B2}/\partial V_{B1B2}$
CB1B2X	C_{B1B2X}	Capacitance AC current crowding (only used in transient analysis: $\approx \partial Q_{B1B2}/\partial V_{B2E1}$
CB1B2Y	C_{B1B2Y}	Capacitance AC current crowding (only used in transient analysis: $\approx \partial Q_{B1B2}/\partial V_{B2C2}$
CB1B2Z	C_{B1B2Z}	Capacitance AC current crowding (only used in transient analysis: $\approx \partial Q_{B1B2}/\partial V_{B2C1}$

For the TNS device:

CTS	C_{TS}	Capacitance s-c junction: $\partial Q_{TS}/\partial V_{SC1}$

Remark: The operating-point output will not be influenced by the value of G_{min}.

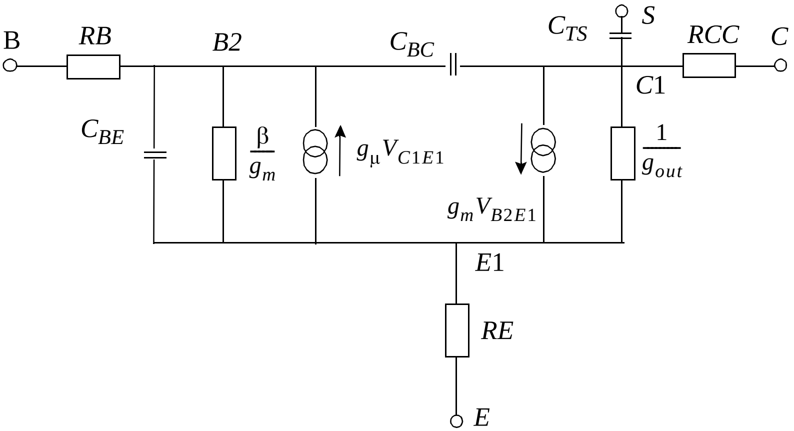

Figure 30: Small-signal equivalent circuit describing the approximate behaviour of the Mextram model. The actual forward Early voltage can be found as $V_{eaf} = I_C/g_{out} - V_{CE}$ *which can be different from the parameter value* V_{EF} *especially when* $dE_g \neq 0$ *.*

The full small-signal circuit is in practice not very useful, since it is difficult to do hand-calculations with it. We therefore include the elements of an approximate small-signal model, shown in figure 30. This model contains the following elements:

Quantity	**Equation**	**Description**
GM	G_M	Transconductance
BETA	$BETA$	Current amplification
GOUT	G_{OUT}	Output conductance
GMU	G_μ	Feedback transconductance
RE	RE	Emitter resistance
RB	RB	Base resistance
RCC	RCC	Constant collector resistance
CBE	C_{BE}	Base-emitter capacitance
CBC	C_{BC}	Base-collector capacitance
For the TNS device:		
CTS	C_{TS}	Collector-substrate capacitance

We make a few assumptions by making this approximation. It is meant to work in forward mode. To keep the model simple, the base-emitter and base-collector capacitance are a sum of various contributions that are in the full model between different nodes. The elements that have not be defined before can be calculated from the small signal parameters of the full model. As help variables we use:

$$\frac{dy}{dx} = \frac{g_X - g_{\mu X}}{grcv_y + g_{\mu Y} - g_Y} \tag{12.1}$$

$$\frac{dy}{dz} = \frac{g_Z - grcv_Z - g_{\mu Z}}{grcv_y + g_{\mu Y} - g_Y} \tag{12.2}$$

$$g_\pi = g_\pi^S + g_{\pi X} + g_{\mu X} + g_{\pi Z} + g_{\mu Z} + (g_{\pi Y} + g_{\mu Y}) \cdot \left[\frac{dy}{dx} + \frac{dy}{dz}\right] \tag{12.3}$$

$$g_m = \frac{grcv_y \cdot (g_x - g_{\mu X} + g_z - g_{\mu Z}) - (grcv_z) \cdot (g_Y - g_{\mu Y})}{grcv_y + g_{\mu Y} - g_Y} \tag{12.4}$$

$$\beta = g_m / g_\pi \tag{12.5}$$

$$g_{out} = \frac{(g_Y - g_{\mu Y}) \cdot grcv_z - (g_Z - g_{\mu Z}) \cdot grcv_Y}{grcv_y + g_{\mu Y} - g_Y} \tag{12.6}$$

$$g_\mu = g_{\pi Z} + g_{\mu Z} + (g_{\pi Y} + g_{\mu Y}) \cdot \frac{dy}{dz} + g_{\mu EX} + Xg_{\mu EX} \tag{12.7}$$

$$RB = RBC_T + rbv \tag{12.8}$$

$$C_{BE} = C_{BE,x} + C_{BE}^S + C_{BC,x} + (C_{BE,y} + C_{BC,y}) \cdot \frac{dy}{dx} + C_{BEO} \tag{12.9}$$

$$C_{BC} = (C_{BE,y} + C_{BC,y}) \cdot \frac{dy}{dz} + C_{BE,z} + C_{BCex} + XC_{BCex} + C_{BCO} \tag{12.10}$$

$$\gamma_X = (g_{\pi X} + g_{\mu X} - grbv_X) \cdot rbv \tag{12.11}$$

$$\gamma_Y = (g_{\pi Y} + g_{\mu Y} - grbv_Y) \cdot rbv \tag{12.12}$$

$$\gamma_Z = (g_{\pi Z} + g_{\mu Z} - grbv_Z) \cdot rbv \tag{12.13}$$

$$g_{BFX} = g_{\pi X} + g_\pi^S \cdot (1 + \gamma_X) \tag{12.14}$$

$$g_{BFY} = g_{\pi Y} + g_\pi^S \cdot \gamma_Y \tag{12.15}$$

$$g_{BFZ} = g_{\pi Z} + g_\pi^S \cdot \gamma_Z \tag{12.16}$$

$$\alpha = \frac{1 + \left[grcv_Y \cdot \frac{dy}{dx}\right] \cdot RCC_T + \left[g_X + g_{BFX} + (g_Y + g_{BFY}) \cdot \frac{dy}{dx}\right] \cdot RE_T}{1 - \left[grcv_Z + grcv_Y \cdot \frac{dy}{dz}\right] \cdot RCC_T - \left[g_Z + g_{BFZ} + (g_Y + g_{BFY}) \cdot \frac{dy}{dz}\right] \cdot RE_T} \tag{12.17}$$

$$r_X = \left[grcv_Y \cdot \frac{dy}{dx} + \alpha \cdot \left(grcv_Z + grcv_Y \cdot \frac{dy}{dz}\right)\right]^{-1} \tag{12.18}$$

$$r_Z = \alpha \cdot r_X \tag{12.19}$$

$$r_Y = \frac{1 - grcv_Z \cdot r_Z}{grcv_Y} \tag{12.20}$$

$$r_{B1B2} = \gamma_X \cdot r_X + \gamma_Y \cdot r_Y + \gamma_Z \cdot r_Z \tag{12.21}$$

$$r_{EX} = r_Z + r_{B1B2} \tag{12.22}$$

$$Xr_{EX} = r_{EX} + RBC_T \cdot [(g_{BFX} + g_{\mu X}) \cdot r_X + (g_{BFY} + g_{\mu Y}) \cdot r_Y + (g_{BFZ} + g_{\mu Z}) \cdot r_Z] \tag{12.23}$$

$$TAU_T = Cbe^S \cdot (r_X + r_{B1B2}) + (Cbe_X + Cbc_X) \cdot r_X + (Cbe_Y + Cbc_Y) \cdot r_Y + \tag{12.24}$$
$$(Cbe_Z + Cbc_Z) \cdot r_Z + Cbc_{EX} \cdot r_{EX} + XCbc_{EX} \cdot Xr_{EX} +$$
$$(CBEO + CBCO) \cdot (Xr_{EX} - RCC_T)$$

Apart from the cut-off frequency we also have some other quantities to describe the internal state of the model and they are presented as OP output.

Quantity	**Equation**	**Description**
FT	f_T	Good approximation for cut-off frequency: $1/(2\pi \cdot TAU_T)$
IQS	I_{qs}	Current at onset of quasi-saturation
XIWEPI	x_i/W_{epi}	Thickness of injection layer
VB2C2STAR	V^*_{B2C2}	Physical value of internal base-collector bias

For self-heating we have the following quantities, presented as OP output:

Quantity	**Equation**	**Description**
PDISS	P_{diss}	Dissipation
TK	T_K	Actual temperature

12.6 Equivalent circuit and equations

A full description of TN / TNS-level-504 for vertical integrated circuit NPN transistor is given below. The equivalent circuits for the TN-level-504 model are shown in figs. 31 and 33 respectively. The equivalent circuits for the TNS-level-504 model are shown in figs. 32 and 33 respectively.

✓ Note

The elements in the figure indicate their position and NOT their functional dependence!

Embedding of PNP transistors

Although NPN transistors are the most used bipolar transistors it is also necessary to be able to describe PNP-transistors. The equations in this chapter are only for NPN transistors. It is however easy to map a PNP-device with its bias conditions onto an NPN model. to do this we need three steps:

The model uses the following internal voltages:

$V_{B2C1}, V_{B2C2}, V_{B2E1}, V_{B1E1}, V_{B1B2}, V_{B1C1}, V_{BC1}, V_{SC1}$

For a PNPthe sign of these voltages must be changed ($V \rightarrow -V$). The value of V_{dT} does *not* change sign.

- Calculate the currents, charges and noise densities with the equations for the NPN transistor. Note that the parameters are still like those for an NPN. For instance all currents like I_s must be taken positive.

- Change the sign of all resulting currents ($I \rightarrow -I$).

$I_N, I_{B1B2}, I_{C1C2}, I_{avl}, I_{B1}, I^S_{B1}, I_{B2}, I_{B3}, I_{ex}, XI_{ex}, I_{sub}, XI_{sub}, I_{sf}$

and charges ($Q \rightarrow -Q$)

$Q_E, Q_{TE}, Q_{TC}, Q_{BE}, Q_{BC}, Q_{epi}, Q_{B1B2}, Q_{ex}, XQ_{ex}, Q_{tex}, XQ_{tex}, Q_{ts}, Q_{BEO}, Q_{BCO}$

The noise current densities do not change sign. The power dissipation term P_{diss} and the thermal charge $C_{th} \cdot V_{dT}$ do not change sign. The following derivatives do need an extra sign:

$\frac{\partial P_{diss}}{\partial V_{B2E1}}$, etc.

all other derivatives $\frac{\partial I}{\partial V}$ and $\frac{\partial Q}{\partial V}$ do not need and extra sign.

Furthermore, note that the constants A_n and B_n for the avalanche model are different for NPN's and for PNP's.

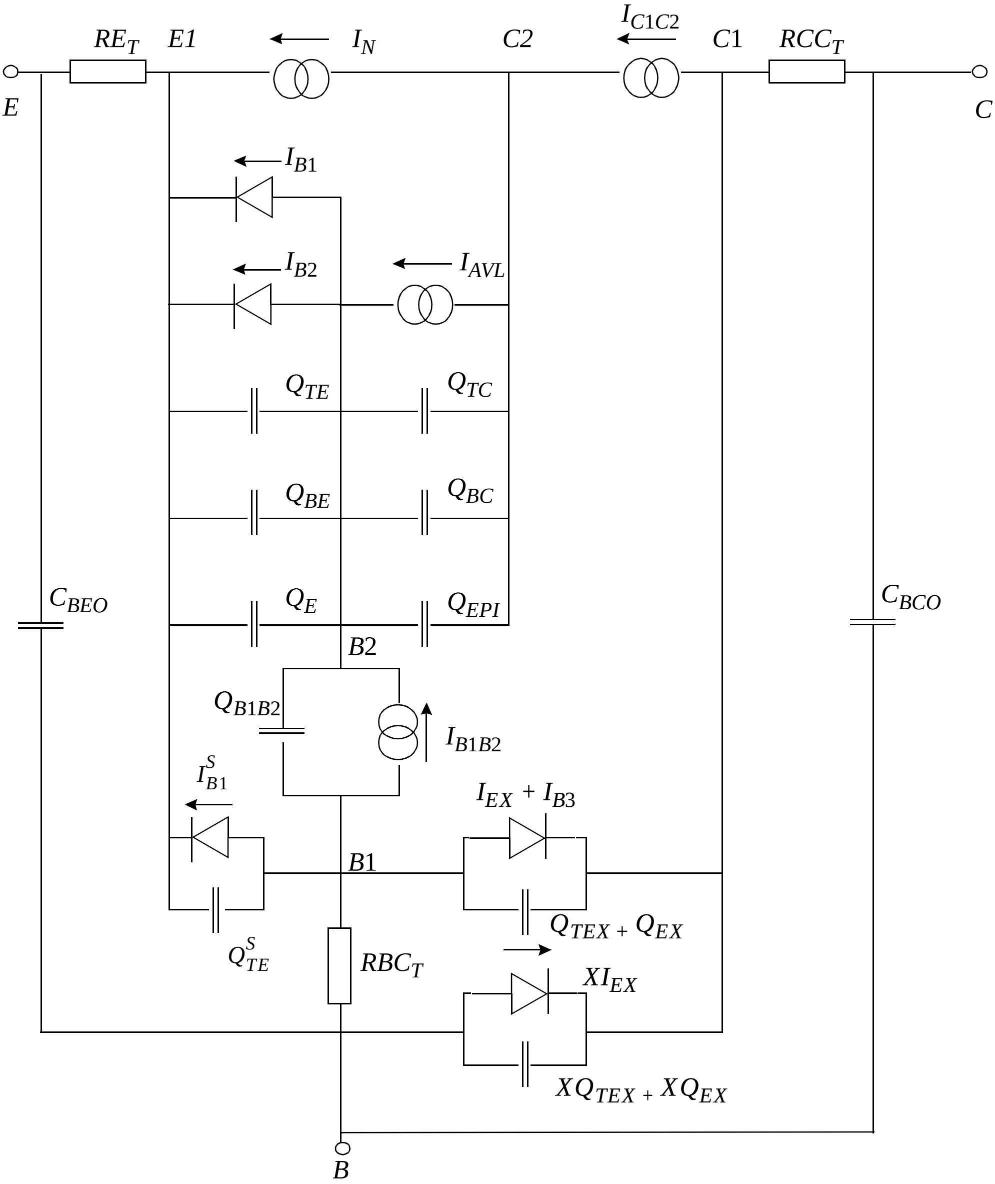

Figure 31: Equivalent circuit for vertical NPN transistor without substrate and self-heating

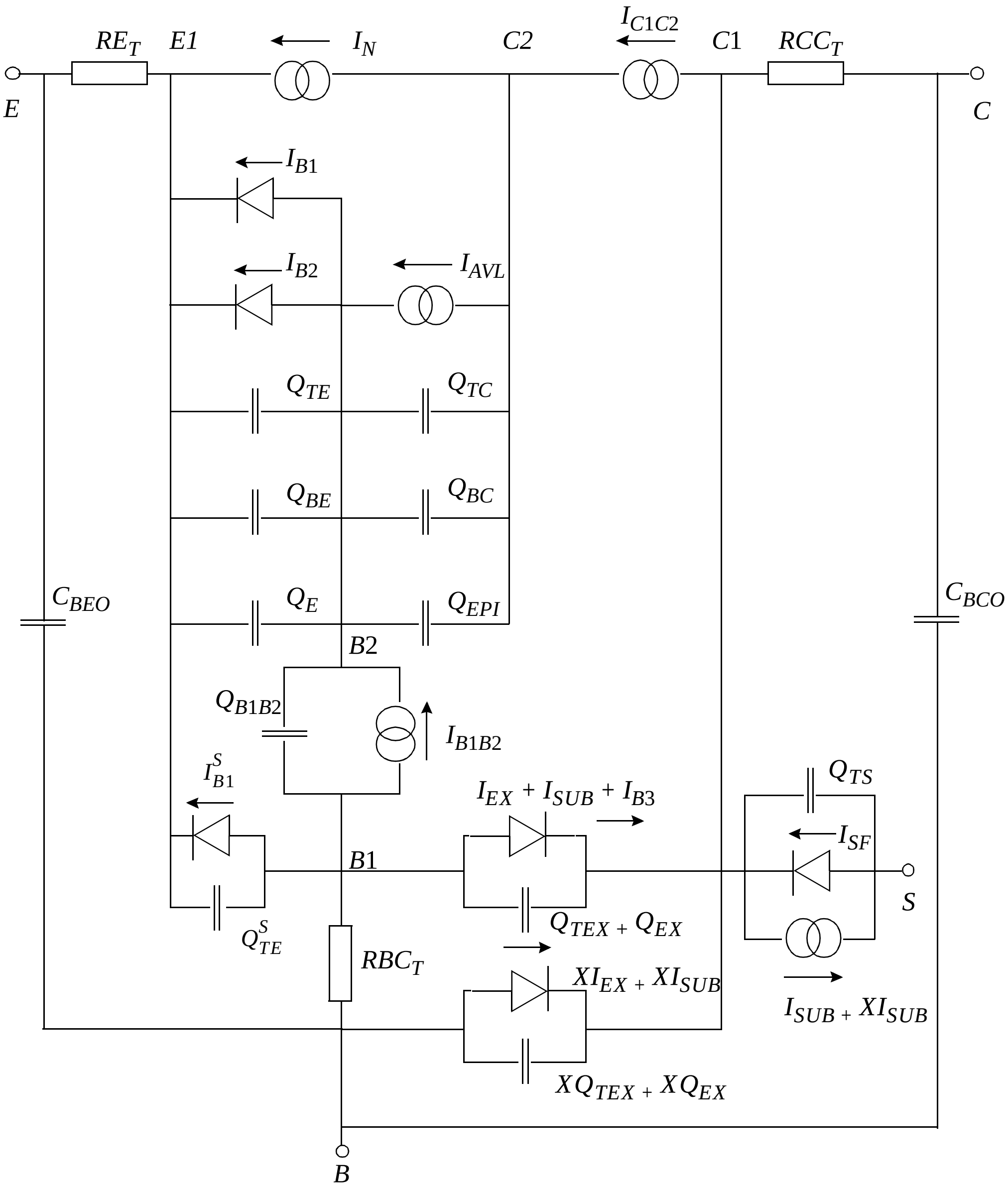

Figure 32: Equivalent circuit for vertical NPN transistor with substrate but without self-heating

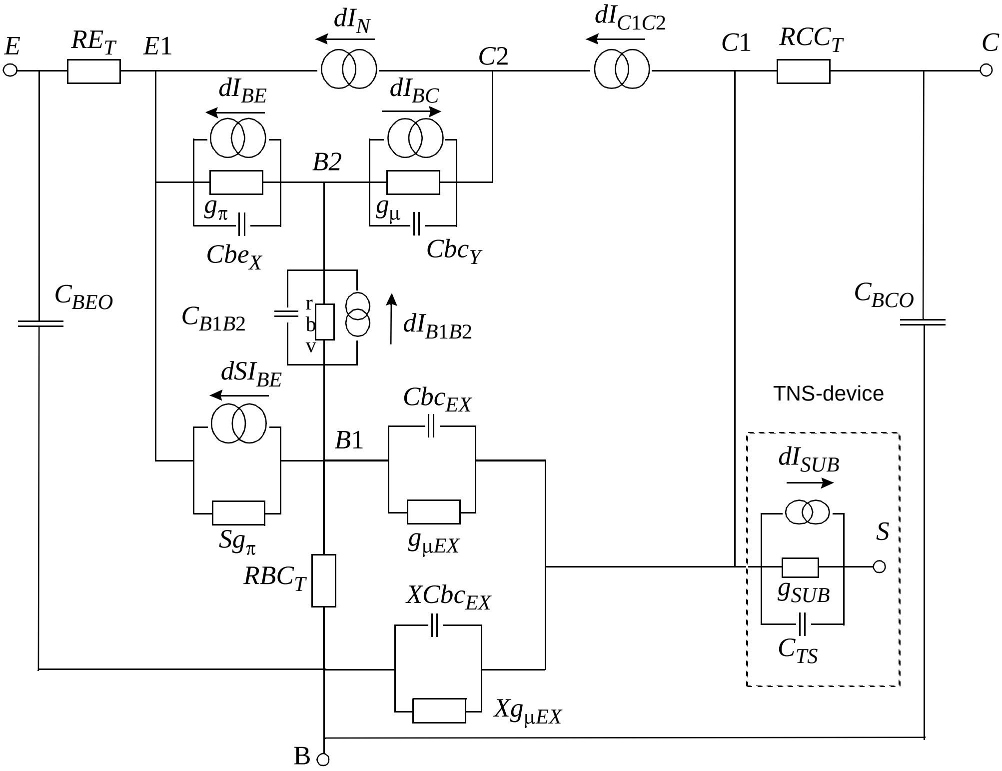

Figure 33: Small signal equivalent for vertical TN/TNS NPN transistor

Model constants

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

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

$$\left(\frac{k}{q}\right) = 0.86171 \cdot 10^{-4}\mathrm{V}/\mathrm{K}$$

$$G_{MIN} = 1.0 \cdot 10^{-13}\mathrm{A}/\mathrm{V}$$

$$V_{d,\,low} = 0.05\ \mathrm{V}$$

$$a_{je} = 3.0$$

$$a_{jc} = 2.0$$

$$a_{js} = 2.0$$

Constants A and B for impact ionization depend on transistor type:

for NPN:

$$A_n = 7.03 \cdot 10^{7}\mathrm{m}^{-1}$$

$$B_n = 1.23 \cdot 10^{8}\mathrm{V} \cdot \mathrm{m}^{-1}$$

for PNP:

$$A_n = 1.58 \cdot 10^{8}\mathrm{m}^{-1}$$

$$B_n = 2.04 \cdot 10^{8}\mathrm{V} \cdot \mathrm{m}^{-1}$$

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

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 Kelvin

✓ Note

Note the addition of the voltage V_{dT} of the thermal node (See “Self-heating” on page 334.).

$$T_K = TEMP + DTA + 273.15 + V_{dT} \tag{12.25}$$

$$T_{RK} = TREF + 273.15 \tag{12.26}$$

$$t_N = \frac{T_K}{T_{RK}} \tag{12.27}$$

- Thermal Voltage

$$V_T = \left(\frac{k}{q}\right) \cdot T_K \tag{12.28}$$

$$V_{TR} = \left(\frac{k}{q}\right) \cdot T_{RK} \tag{12.29}$$

$$\frac{1}{V_{\Delta T}} = \frac{1}{V_T} - \frac{1}{V_{TR}} \tag{12.30}$$

- Resistances

The various parameters A describe the mobility of the corresponding regions: $\mu \sim t_N^{-A}$. The temperature dependence of the zero-bias charge goes as $Q_{B0T} / Q_{B0} = t_N^{AQB0}$.

$$RE_T = RE \cdot t_N^{AE} \tag{12.31}$$

$$RBV_T = RBV \cdot t_N^{(AB - AQB0)} \tag{12.32}$$

$$RBC_T = RBC \cdot t_N^{AEX} \tag{12.33}$$

$$RCC_T = RCC \cdot t_N^{AC} \tag{12.34}$$

$$RCV_T = RCV \cdot t_N^{AEPI} \tag{12.35}$$

- Depletion capacitance

The junction diffusion voltages VDE, VDC, and VDS with respect to temperature are:

$$UDE_T = -3 \cdot V_T \cdot \ln(t_N) + VDE \cdot t_N + (1 - t_N) \cdot VGB \tag{12.36}$$

$$VDE_T = UDE_T + V_T \cdot \ln\{1 + \exp[(V_{d,\,low} - UDE_T)/V_T]\} \tag{12.37}$$

$$CJE_T = CJE \cdot \left(\frac{VDE}{VDE_T}\right)^{PE} \tag{12.38}$$

where VDE is the junction diffusion voltage and PE is the grading coefficient;

$$UDC_T = -3 \cdot V_T \cdot \ln(t_N) + VDC \cdot t_N + (1 - t_N) \cdot VGC \tag{12.39}$$

$$VDC_T = UDC_T + V_T \cdot \ln\{1 + \exp[(V_{d,\,low} - UDC_T)/V_T]\} \tag{12.40}$$

where VDC is the junction diffusion voltage.

The collector depletion capacitance is divided in a variable and constant part. The constant part is temperature independent.

$$CJC_T = CJC \cdot \left[(1 - XP) \cdot \left(\frac{VDC}{VDC_T}\right)^{PC} + XP\right] \tag{12.41}$$

$$XP_T = XP \cdot \left[(1 - XP) \cdot \left(\frac{VDC}{VDC_T}\right)^{PC} + XP\right]^{-1} \tag{12.42}$$

Where PC is the grading coefficient.

For the TNS device:

$$UDS_T = -3 \cdot V_T \cdot \ln(t_N) + VDS \cdot t_N + (1 - t_N) \cdot VGS \tag{12.43}$$

$$VDS_T = UDS_T + V_T \cdot \ln\{1 + \exp[(V_{d,\,low} - UDS_T)/V_T]\} \tag{12.44}$$

$$CJS_T = CJS \cdot \left(\frac{VDS}{VDS_T}\right)^{PS} \tag{12.45}$$

Where VDS is the junction diffusion voltage and PS is the grading coefficient.

- Current gain

$$BF_T = BF \cdot t_N^{(AE - AB - AQB0)} \cdot \exp[-DVGBF/V_{\Delta T}] \tag{12.46}$$

$$BRI_T = BRI \cdot \exp[-DVGBR/V_{\Delta T}] \tag{12.47}$$

- Currents and Voltages

$$IS_T = IS \cdot t_N^{(4 - AB - AQB0)} \cdot \exp[-VGB/V_{\Delta T}] \tag{12.48}$$

$$IK_T = IK \cdot t_N^{(1 - AB)} \tag{12.49}$$

$$IBF_T = IBF \cdot t_N^{(6 - 2MLF)} \cdot \exp[-VGJ/(MLF \cdot V_{\Delta T})] \tag{12.50}$$

$$IBR_T = IBR \cdot t_N^2 \cdot \exp[-VGC/(2 \cdot V_{\Delta T})] \tag{12.51}$$

$$VEF_T = VEF \cdot t_N^{AQB0}\left[(1-XP) \cdot \left(\frac{VDC}{VDC_T}\right)^{PC} + XP\right]^{-1} \tag{12.52}$$

$$VER_T = VER \cdot t_N^{AQB0}\left(\frac{VDE}{VDE_T}\right)^{-PE} \tag{12.53}$$

For the TNS device:

The temperature dependence of *ISS* and *IKS* is given by *AS* and *VGS*.
AS equals *AC* for a closed buried layer (BN) and *AS* equals *AEPI* for an open buried layer.

$$ISS_T = ISS \cdot t_N^{(4-AS)} \cdot \exp[-VGS/V_{\Delta T}] \tag{12.54}$$

$$IKS_T = IKS \cdot t_N^{(1-AS)} \cdot \frac{IS_T}{IS} \cdot \frac{ISS}{ISS_T} \tag{12.55}$$

When either $IS = 0$ or $ISS_T = 0$ then $IKS_T = IKS \cdot t_N^{(1-AS)}$

- Transit times

$$TAUE_T = TAUE \cdot t_N^{(AB-2)} \cdot \exp[-DVGTE/V_{\Delta T}] \tag{12.56}$$

$$TAUB_T = TAUB \cdot t_N^{(AQB0+AB-1)} \tag{12.57}$$

$$TEPI_T = TEPI \cdot t_N^{(AEPI-1)} \tag{12.58}$$

$$TAUR_T = TAUR \cdot \frac{TAUB_T + TEPI_T}{TAUB + TEPI} \tag{12.59}$$

- Avalanche constant

Note that this temperature rule is independent of $TREF$ since we take B_n as a material constant.

$$B_{nT} = B_n[1 + 7.2 \cdot 10^{-4}(T_K - 300) - 1.6 \cdot 10^{-6}(T_K - 300)^2] \qquad (12.60)$$

- Heterojunction features

$$DEG_T = DEG \cdot t_N^{AQB0} \qquad (12.61)$$

Description of currents

- Ideal forward current and reverse current.

$$I_F = IS_T \cdot \exp\left(\frac{V_{B2E1}}{V_T}\right) \qquad (12.62)$$

$$I_R = IS_T \cdot \exp\left(\frac{V^*_{B2C2}}{V_T}\right) \qquad (12.63)$$

The value of V^*_{B2C2} is not always the same as the node voltage V_{B2C2}. The expression for $\exp(V^*_{B2C2} / V_T)$ is given in Eqs. 12.114 and 12.116.

- The main current I_N

The Moll-Ross or integral charge-control relation is used to take high injection in the base into account. To avoid dividing by zero at punch-through in Eq. 12.67 the depletion charge term q_0 is modified.

✓ Note

For SiGe transistors q_0^I might differ from q_0^Q, defined in Eq. 12.95, See “Heterojunction features” on page 330.

$$q_0^I = 1 + \frac{V_{TE}}{VER_T} + \frac{V_{TC}}{VEF_T} \tag{12.64}$$

$$q_1^I = \frac{q_0^I + \sqrt{(q_0^I)^2 + 0.01}}{2} \tag{12.65}$$

$$q_B^I = q_1^I\left(1 + \frac{1}{2}n_0 + \frac{1}{2}n_B\right) \tag{12.66}$$

$$I_N = \frac{I_F - I_R}{q_B^I} \tag{12.67}$$

✓ Note

The expressions for V_{TE} , V_{TC} , n_0 and n_B are given by Eqs. 12.122, 12.138, 12.153 and 12.156 respectively.

- Forward base currents.

The total ideal base current is separated into a bulk and sidewall component. The bulk component depends on voltage V_{B2E1} and the sidewall component on voltage V_{B1E1}. The separation is given by parameter *XIBI*.

✓ Note

I_{B1} becomes more complicated when $XREC \neq 0$. See “Heterojunction features” on page 330.

Bulk component:

$$I_{B1} = (1 - XIBI) \cdot \frac{IS_T}{BF_T} \cdot \left\{\exp\left(\frac{V_{B2E1}}{V_T}\right) - 1\right\} \tag{12.68}$$

Sidewall component:

$$I_{B1}^S = XIBI \cdot \frac{IS_T}{BF_T} \cdot \left\{\exp\left(\frac{V_{B1E1}}{V_T}\right) - 1\right\} \tag{12.69}$$

The non-ideal base current is given by:

$$I_{B2} = IBF_T \cdot \left\{ \exp\left(\frac{V_{B2E1}}{MLF \cdot V_T}\right) - 1 \right\} + G_{MIN} \cdot V_{B2E1} \tag{12.70}$$

- Reverse base currents.

In TN / TNS-level 504, the non-ideal reverse current is:

$$I_{B3} = IBR_T \cdot \left\{ \frac{\exp\left(\frac{V_{B1C1}}{V_T}\right) - 1}{\exp\left(\frac{V_{B1C1}}{2 \cdot V_T}\right) + \exp\left(\frac{VLR_T}{2 \cdot V_T}\right)} \right\} + G_{MIN} \cdot V_{B1C1} \tag{12.71}$$

For the TNS device:

The substrate current (holes injected from base to substrate or reversely, the main current of the parasitic PNP), including high injection is given by:

$$I_{SUB} = \frac{2 \cdot ISS_T \cdot \left\{ \exp\left(\frac{V_{B1C1}}{V_T}\right) - 1 \right\}}{1 + \sqrt{1 + 4 \cdot \frac{IS_T}{IKS_T} \cdot \left\{ \exp\left(\frac{V_{B1C1}}{V_T}\right) \right\}}} \tag{12.72}$$

The current with substrate bias in forward is only included as a signal to the designer

$$I_{SF} = ISS_T \cdot \left\{ \exp\left(\frac{V_{SC1}}{V_T}\right) - 1 \right\} \tag{12.73}$$

The extrinsic base current (electrons injected from collector to extrinsic base, similar to I_{B1}) is given by:

$$g_1 = \frac{4 \cdot IS_T \cdot \exp\left(\frac{V_{B1C1}}{V_T}\right)}{IK_T} \tag{12.74}$$

$$n_{BEX} = \frac{g_1}{1 + \sqrt{1 + g_1}} \tag{12.75}$$

$$I_{EX} = \frac{1}{BRI_T} \cdot \left\{ \frac{1}{2} \cdot IK_T \cdot n_{BEX} - IS_T \right\} \tag{12.76}$$

- Weak avalanche current

In reverse mode $I_{C1C2} \leq 0$ or hard saturation $V_{B2C1} \geq VDC_T$ the avalanche current is zero.

$$I_{AVL} = 0 \tag{12.77}$$

In forward mode we have the following gradient of the electric field for zero bias:

$$dEdx_0 = \frac{2VAVL}{WAVL^2} \tag{12.78}$$

The depletion layer thickness becomes:

$$X_D = \sqrt{\frac{2}{dEdx_0}} \cdot \sqrt{\frac{VDC_T - V_{B2C1}}{1 - I_{CAP}/IHC}} \tag{12.79}$$

The current I_{CAP} will be given in Eq. 12.135.

The generation of avalanche current increases at high current levels. This is only taken into account when flag $EXAVL = 1$.

When $EXAVL = 0$, then the effective thickness of the epilayer is:

$$W_{eff} = WAVL \tag{12.80}$$

When $EXAVL = 1$, then:

$$W_{eff} = WAVL \cdot \left(1 - \frac{X_i}{2 \cdot W_{EPI}}\right)^2 \tag{12.81}$$

For either value of $EXAVL$ the thickness over which the electric field is important is:

$$W_D = \frac{x_D \cdot W_{eff}}{\sqrt{x_D^2 + W_{eff}^2}} \tag{12.82}$$

The average electric field and the field at the base-collector junction are:

$$E_{AV} = \frac{VDC_T - V_{B2C1}}{W_D} \tag{12.83}$$

$$E_0 = E_{AV} + \frac{1}{2} \cdot W_D \cdot dEdx_0 \cdot \left(1 - \frac{I_{CAP}}{IHC}\right) \tag{12.84}$$

When $EXAVL = 0$, then the maximum of the electric field is:

$$E_M = E_0 \tag{12.85}$$

When $EXAVL = 1$, then

$$SH_W = 1 + 2 \cdot SFH \cdot \left(1 + \frac{2X_i}{W_{EPI}}\right) \tag{12.86}$$

$$E_{fi} = \frac{1 + SFH}{1 + 2SFH} \tag{12.87}$$

$$E_W = E_{AV} - \frac{1}{2} \cdot W_D \cdot dEdx_0 \cdot \left(E_{fi} - \frac{I_{C1C2}}{IHC \cdot SH_W}\right) \tag{12.88}$$

$$E_M = \frac{1}{2} \cdot (E_W + E_0 + \sqrt{(E_W - E_0)^2 + 0.1 \cdot E_{AV}^2 \cdot I_{CAP}/IHC}) \tag{12.89}$$

The injection thickness X_i/W_{EPI} is given in Eq. 12.111.

For either value of $EXAVL$ the intersection point λ_D and the generation factor G_{EM} are:

$$\lambda_D = \frac{E_M \cdot W_D}{2 \cdot (E_M - E_{AV})} \tag{12.90}$$

$$G_{EM} = \frac{A_n}{B_{nT}} \cdot E_M \cdot \lambda_D \cdot \left\{ \exp\left(\frac{-B_{nT}}{E_M}\right) - \exp\left[\frac{-B_{nT}}{E_M} \cdot \left(1 + \frac{W_{eff}}{\lambda_D}\right)\right] \right\} \tag{12.91}$$

When $E_M \approx E_{AV}$ the expression for λ_D will diverge. Hence for $(1 - E_{AV}/E_M) < 10^{-7}$ we need to take the appropriate analytical limit and get:

$$G_{EM} = A_n \cdot W_{eff} \cdot \exp\left(\frac{-B_{nT}}{E_M}\right) \tag{12.92}$$

The generation factor may not exceed 1 and may not exceed

$$G_{MAX} = \frac{V_T}{I_{C1C2} \cdot (RBC_T + RB2)} + \frac{q_B^I}{BF_T} + \frac{RE_T}{RBC_T + RB2} \tag{12.93}$$

The variable base resistance $RB2$ is given in Eq. 12.98. The base charge term q_B^I is given by Eq. 12.66. The current I_{C1C2} is given by Eq. 12.104. The avalanche current then is:

$$I_{AVL} = I_{C1C2} \cdot \frac{G_{EM} \cdot G_{MAX}}{G_{EM} \cdot (1 + G_{MAX}) + G_{MAX}} \tag{12.94}$$

- Series resistances:

emitter: RE_T = constant
base: RBC_T = constant
collector: RCC_T = constant

- Variable base resistance
  The variable part of the base resistance is modulated by the base charges and takes into account the base current crowding:

$$q_0^Q = 1 + \frac{V_{TE}}{VER_T} + \frac{V_{TC}}{VEF_T} \tag{12.95}$$

$$q_1^Q = \frac{q_0^Q + \sqrt{(q_0^Q)^2 + 0.01}}{2} \tag{12.96}$$

$$q_B^Q = q_1^Q\left(1 + \frac{1}{2}n_0 + \frac{1}{2}n_B\right) \tag{12.97}$$

$$RB2 = \frac{3 \cdot RBV_T}{q_B^Q} \tag{12.98}$$

$$I_{B1B2} = \frac{2 \cdot V_T}{RB2} \cdot \left\{\exp\left(\frac{V_{B1B2}}{V_T}\right) - 1\right\} + \frac{V_{B1B2}}{RB2} \tag{12.99}$$

✓ Note

Note the correspondance and differences between RB2 and I_N from Eq. 12.67

- Variable collector resistance.

This model of the epilayer resistance takes into account:

  - The decrease in resistance due to carriers injected from the base if only the internal base-collector junction is forward biased (quasi-saturation) and if both the internal and external base-collector junction are forward biased (hard saturation and reverse mode of operation).
  - Ohmic current flow at low current densities.
  - Space charge limited current flow at high current densities (Kirk effect; only in forward mode).

The current through the epilayer is given by:

$$K_0 = \sqrt{1 + 4 \cdot \exp[(V_{B2C2} - VDC_T)/V_T]} \tag{12.100}$$

$$K_W = \sqrt{1 + 4 \cdot \exp[(V_{B2C1} - VDC_T)/V_T]} \tag{12.101}$$

$$p_W = \frac{2 \cdot \exp[(V_{B2C1} - VDC_T)/V_T]}{1 + K_W} \tag{12.102}$$

For numerical reasons: when $p_W < e^{-40}$ then $p_W \rightarrow 0$

$$E_C = V_T \cdot \left[K_0 - K_W - \ln\left(\frac{K_0 + 1}{K_W + 1}\right)\right] \tag{12.103}$$

$$I_{C1C2} = \frac{E_C + V_{C1C2}}{RCV_T} \tag{12.104}$$

In reverse mode the node voltage difference V_{B2C2} is the quantity that we use in further calculations. In forward mode the relation between the voltage difference V_{B2C2} and the current I_{C1C2} is not smooth enough. We will instead calculate V^*_{B2C2} that is to be used in subsequent calculations. It has smoother properties than V_{B2C2} itself. In forward mode the node voltage V_{C2} is only used for Eqs. 12.100 and 12.104. For the rest of the quantities in the epilayer model a distinction must be made between forward and reverse mode.

Forward mode ($I_{C1C2} > 0$) The voltage and current at which quasi-saturation or Kirk effect start are:

$$V_{qs}^{th} = VDC_T + 2 \cdot V_T \cdot \ln\left(\frac{I_{C1C2} \cdot RCV_T}{2 \cdot V_T} + 1\right) - V_{B2C1} \tag{12.105}$$

$$V_{qs} = \frac{1}{2}\left\{V_{qs}^{th} + \sqrt{(V_{qs}^{th})^2 + 4 \cdot (0.1 VDC_T)^2}\right\} \tag{12.106}$$

$$I_{qs} = \frac{V_{qs}}{SCRCV} \cdot \frac{V_{qs} + IHC \cdot SCRCV}{V_{qs} + IHC \cdot RCV_T} \tag{12.107}$$

$$\alpha = \frac{1 + AXI \cdot \ln\{1 + \exp[(I_{C1C2}/I_{qs} - 1)/AXI]\}}{1 + AXI \cdot \ln\{1 + \exp[-1/AXI]\}} \tag{12.108}$$

We need to solve:

$$\alpha \cdot I_{qs} = \frac{V_{qs}}{SCRCV \cdot y_i^2} \cdot \frac{V_{qs} + SCRCV \cdot IHC \cdot y_i}{V_{qs} + RCV_T \cdot IHC}$$

which leads to

$$v = \frac{V_{qs}}{IHC \cdot SCRCV} \tag{12.109}$$

$$y_i = \frac{1 + \sqrt{1 + 4 \cdot \alpha \cdot v \cdot (1+v)}}{2 \cdot \alpha \cdot (1+v)} \tag{12.110}$$

The injection thickness is given by:

$$\frac{x_i}{W_{epi}} = 1 - \frac{y_i}{1 + p_W \cdot y_i} \tag{12.111}$$

The hole density p_0^* at the base-collector junction is

$$g = \frac{I_{C1C2} \cdot RCV_T}{2 \cdot V_T} \cdot \frac{x_i}{W_{epi}} \tag{12.112}$$

$$p_0^* = \frac{g-1}{2} + \sqrt{\left(\frac{g-1}{2}\right)^2 + 2g + p_W \cdot (p_W + g + 1)} \tag{12.113}$$

For numerical reasons: when $p_0^* < e^{-40}$ then $p_0^* \rightarrow 0$

$$e^{V_{B2C2}^*/V_T} = p_0^* \cdot (p_0^* + 1) \exp(VDC_T/V_T) \tag{12.114}$$

Reverse mode $(I_{C1C2} \leq 0)$ The hole density at the base-collector junction is:

$$p_0^* = \frac{2 \exp\{(V_{B2C2} - VDC_T)/V_T\}}{1 + K_0} \tag{12.115}$$

$$\exp(V^*_{B2C2}/V_T) = \exp(V_{B2C2}/V_T) \tag{12.116}$$

The injection thickness is:

$$\frac{x_i}{W_{epi}} = \frac{E_c}{E_c + V_{B2C2} - V_{B2C1}} \tag{12.117}$$

Numerical problems might arise for $I_{C1C2} \approx 0$. When $|V_{C1C2}| < 10^{-5} V_T$ or $|E_c| < e^{-40} V_T(K_0 + K_W)$ approximate

$$p_{av} = \frac{p_0{}^* + p_W}{2} \tag{12.118}$$

$$\frac{x_i}{W_{epi}} = \frac{p_{av}}{p_{av} + 1} \tag{12.119}$$

Description of charges

- Emitter depletion charges

The total base-emitter depletion capacitance is separated into a bulk and sidewall component. The bulk component is located between node $E1$ and node $B2$ and the sidewall component between nodes $B1$ and $E1$ (see Fig. 32).

The bulk component is:

$$V_{FE} = VDE_T \cdot (1 - a_{jE}^{-1/PE}) \tag{12.120}$$

$$V_{jE} = V_{B2E1} - 0.1VDE_T \cdot \ln\{1 + \exp[(V_{B2E1} - V_{FE})/0.1VDE_T]\} \tag{12.121}$$

$$V_{TE} = \frac{VDE_T}{1 - PE} \cdot [1 - (1 - V_{jE}/VDE_T)^{1-PE}] + a_{jE} \cdot (V_{B2E1} - V_{jE}) \tag{12.122}$$

$$Q_{TE} = (1 - XCJE) \cdot CJE_T \cdot V_{TE} \tag{12.123}$$

The sidewall component is

$$V_{jE}^{S} = V_{B1E1} - 0.1VDE_T \cdot \ln\{1 + \exp[(V_{B1E1} - V_{FE})/0.1VDE_T]\} \tag{12.124}$$

$$Q_{TE}^{s} = XCJE \cdot CJE_T \cdot \left(\frac{VDE_T}{1-PE} \cdot [1 - (1 - V_{jE}^{S}/VDE_T)^{1-PE}] + a_{jE} \cdot (V_{B1E1} - V_{jE}^{S})\right) \tag{12.125}$$

- Intrinsic collector depletion charge

In forward mode $(I_{C1C2} > 0)$ then

$$B_1 = \frac{1}{2}SCRCV \cdot (I_{C1C2} - IHC) \tag{12.126}$$

$$B_2 = SCRCV \cdot RCV_T \cdot IHC \cdot I_{C1C2} \tag{12.127}$$

$$V_{xi=0} = B_1 + \sqrt{B_1^2 + B_2} \tag{12.128}$$

In reverse mode $(I_{C1C2}) \le 0$ then

$$V_{xi=0} = V_{C1C2} \tag{12.129}$$

The junction voltage for the capacitance is given by

$$V_{junc} = V_{B2C1} + V_{xi=0} \tag{12.130}$$

$$V_{ch} = \begin{cases} 0.1VDC_T & I_{C1C2} \le 0 \\ VDC_T \cdot \left(0.1 + 2 \cdot \dfrac{I_{C1C2}}{I_{C1C2} + I_{qs}}\right) & I_{C1C2} > 0 \end{cases} \tag{12.131}$$

$$b_{jc} = \frac{a_{jc} - XP_T}{1 - XP_T} \tag{12.132}$$

$$V_{FC} = VDC_T \cdot (1 - b_{jc}^{-1/PC}) \tag{12.133}$$

$$V_{jc} = V_{junc} - V_{ch} \cdot \ln\{1 + \exp[(V_{junc} - V_{FC})/V_{ch}]\} \tag{12.134}$$

$$I_{CAP} = \begin{cases} \dfrac{IHC \cdot I_{C1C2}}{IHC + I_{C1C2}} & I_{C1C2} > 0 \\ I_{C1C2} & I_{C1C2} \le 0 \end{cases} \tag{12.135}$$

$$f_I = \left(1 - \frac{I_{CAP}}{IHC}\right)^{MC} \tag{12.136}$$

$$V_{CV} = \frac{VDC_T}{1 - PC} \cdot [1 - f_I \cdot (1 - V_{jC}/VDC_T)^{1 - PC}] + f_I \cdot b_{jC} \cdot (V_{junc} - V_{jC}) \tag{12.137}$$

$$V_{TC} = (1 - XP_T) \cdot V_{CV} + XP_T \cdot V_{B2C1} \tag{12.138}$$

$$Q_{TC} = XCJC \cdot CJC_T \cdot V_{TC} \tag{12.139}$$

- Extrinsic collector depletion charges Q_{TEX} and XQ_{TEX}.
  The extrinsic collector depletion charge is partitioned between nodes $B1$ and $C1$ and nodes B and $C1$ respectively, independent of flag $EXMOD$.

$$V_{jC_{EX}} = V_{B1C1} - 0.1VDC_T \cdot \ln\{1 + \exp[(V_{B1C1} - V_{FC})/0.1VDC_T]\} \tag{12.140}$$

$$VTEX_V = \frac{VDC_T}{1 - PC} \cdot [1 - (1 - V_{jC_{EX}}/VDC_T)^{1 - PC}] + b_{jC} \cdot (V_{B1C1} - V_{jC_{EX}}) \tag{12.141}$$

$$Q_{TEX} = CJC_T \cdot [(1 - XP_T) \cdot VTEX_V + XP_T \cdot V_{B1C1}] \cdot (1 - XCJC) \cdot (1 - XEXT) \tag{12.142}$$

$$XV_{jC_{EX}} = V_{BC1} - 0.1VDC_T \cdot \ln\{1 + \exp[(V_{BC1} - V_{FC})/0.1VDC_T]\} \tag{12.143}$$

$$XVTEX_V = \frac{VDC_T}{1-PC} \cdot [1-(1-XV_{jC_{EX}}/VDC_T)^{1-PC}] + b_{jC} \cdot (V_{BC1} - XV_{jC_{EX}}) \tag{12.144}$$

$$XQ_{TEX} = CJC_T \cdot [(1-XP_T) \cdot XVTEX_V + XP_T \cdot V_{BC1}] \cdot (1-XCJC) \cdot XEXT \tag{12.145}$$

For the TNS device:
Depletion charge Q_{TS}.

$$V_{FS} = VDS_T \cdot (1 - a_{js}^{-1/PS}) \tag{12.146}$$

$$V_{jS} = V_{SC1} - 0.1VDS_T \cdot \ln\{1 + \exp[(V_{SC1} - V_{FS})/0.1VDS_T]\} \tag{12.147}$$

$$Q_{TS} = CJS_T \cdot \left\{ \frac{VDS_T}{1-PS} \cdot [1-(1-V_{jS}/VDS_T)^{1-PS}] + a_{js} \cdot (V_{SC1} - V_{jS}) \right\} \tag{12.148}$$

- Stored emitter charge Q_E

$$Q_{E0} = TAUE_T \cdot IK_T \cdot \left(\frac{IS_T}{IK_T}\right)^{1/MTAU} \tag{12.149}$$

$$Q_E = Q_{E0} \cdot (e^{V_{B2E1}/MTAU \cdot V_T} - 1) \tag{12.150}$$

- Stored base charges

$$Q_{B0} = TAUB_T \cdot IK_T \tag{12.151}$$

$$f_1 = \frac{4 \cdot IS_T}{IK_T} \cdot \exp\left(\frac{V_{B2E1}}{V_T}\right) \tag{12.152}$$

$$n_0 = \frac{f_1}{1 + \sqrt{1 + f_1}} \tag{12.153}$$

$$Q_{BE} = \frac{1}{2} \cdot Q_{B0} \cdot n_0 \cdot q_1^Q \tag{12.154}$$

$$f_2 = \frac{4 \cdot IS_T}{IK_T} \cdot \exp\left(\frac{V^*_{B2C2}}{V_T}\right) \tag{12.155}$$

$$n_B = \frac{f_2}{1 + \sqrt{1 + f_2}} \tag{12.156}$$

$$Q_{BC} = \frac{1}{2} \cdot Q_{B0} \cdot n_B \cdot q_1^Q \tag{12.157}$$

The expression for $\exp\left(\frac{V^*_{B2C2}}{V_T}\right)$ is given in Eqs. 12.114 and 12.116.

- Stored epilayer charge

$$Q_{EPI0} = \frac{4 \cdot TEPI_T \cdot V_T}{RCV_T} \tag{12.158}$$

$$Q_{EPI} = \frac{1}{2} \cdot Q_{EPI0} \cdot \frac{x_i}{W_{EPI}} \cdot (p_0^* + p_W + 2) \tag{12.159}$$

- Stored extrinsic charges

$$g_2 = 4 \cdot \exp\left(\frac{V_{B1C1} - VDC_T}{V_T}\right) \tag{12.160}$$

$$p_{WEX} = \frac{g_2}{1 + \sqrt{1 + g_2}} \tag{12.161}$$

$$Q_{EX} = \frac{TAUR_T}{TAUB_T + TEPI_T} \cdot \left(\frac{1}{2} \cdot Q_{B0} \cdot n_{Bex} + \frac{1}{2} \cdot Q_{EPI0} \cdot p_{Wex}\right) \tag{12.162}$$

The electron density n_{Bex} is given in Eq. 12.75.

- Overlap charges

The overlap capacitances C_{BEO} and C_{BCO} are constant.

Extended modeling of the reverse current gain *EXMOD=1*

- Currents

The reverse currents I_{EX} and I_{SUB} are redefined

$$I_{EX} \rightarrow (1 - XEXT) \cdot I_{EX} \tag{12.163}$$

For the TNS device:

$$I_{SUB} \rightarrow (1 - XEXT) \cdot I_{SUB} \tag{12.164}$$

The part $XEXT$ of the reverse currents in the extrinsic transistor are connected to the external base node;

$$Xg_1 = \frac{4 \cdot IS_T \cdot \exp\left(\frac{V_{BC1}}{V_T}\right)}{IK_T} \tag{12.165}$$

$$Xn_{BEX} = \frac{Xg_1}{1 + \sqrt{1 + Xg_1}} \tag{12.166}$$

$$XIM_{EX} = \frac{XEXT}{BRI_T} \cdot \left(\frac{1}{2} \cdot IK_T \cdot Xn_{BEX} - IS_T\right) \tag{12.167}$$

For the TNS device:

$$XIM_{SUB} = XEXT \cdot \frac{2 \cdot ISS_T \cdot \left\{\exp\left(\frac{V_{BC1}}{V_T}\right) - 1\right\}}{1 + \sqrt{1 + 4 \cdot \frac{IS_T}{IKS_T} \cdot \left\{\exp\left(\frac{V_{BC1}}{V_T}\right)\right\}}} \tag{12.168}$$

To improve the convergency behaviour the diode-like currents in the branch B-C1 are limited by a resistance of value RCC_T:

For the TN device:

$$V_{EX} = V_T \cdot \left\{ 2 - \ln\left(\frac{XEXT \cdot (IS_T / BRI_T) \cdot RCC_T}{V_T} \right) \right\} \tag{12.169}$$

For the TNS device:

$$V_{EX} = V_T \cdot \left\{ 2 - \ln\left(\frac{XEXT \cdot (IS_T / BRI_T + ISS_T) \cdot RCC_T}{V_T} \right) \right\} \tag{12.170}$$

$$VB_{EX} = \frac{1}{2} \cdot [(V_{BC1} - V_{EX}) + \sqrt{(V_{BC1} - V_{EX})^2 + 0.0121}] \tag{12.171}$$

For the TN-device:

$$F_{EX} = \frac{VB_{EX}}{XIM_{EX} \cdot RCC_T + VB_{EX} + XEXT \cdot IS_T \cdot RCC_T / BRI_T} \tag{12.172}$$

For the TNS-device:

$$F_{EX} = \frac{VB_{EX}}{XEXT \cdot (IS_T / BRI_T + ISS_T) \cdot RCC_T + (XIM_{EX} + XIM_{SUB}) \cdot RCC_T + VB_{EX}} \tag{12.173}$$

$$XI_{SUB} = F_{EX} \cdot XIM_{SUB} \tag{12.174}$$

$$XI_{EX} = F_{EX} \cdot XIM_{EX} \tag{12.175}$$

- Charges

The charge Q_{EX} is redefined:

$$Q_{EX} \rightarrow (1 - XEXT) \cdot Q_{EX} \tag{12.176}$$

$$Xg_2 = 4 \cdot \exp\left\{\left(\frac{V_{BC1} - VDC_T}{V_T}\right)\right\} \tag{12.177}$$

$$Xp_{WEX} = \frac{Xg_2}{1 + \sqrt{1 + Xg_2}} \tag{12.178}$$

$$XQ_{EX} = F_{EX} \cdot XEXT \cdot \frac{TAUR_T}{TAUB_T + TEPI_T} \cdot \left(\frac{1}{2} \cdot Q_{B0} \cdot Xn_{BEX} + \frac{1}{2} \cdot Q_{EPI0} \cdot Xp_{WEX}\right) \tag{12.179}$$

Distributed high frequency effects in the intrinsic base

Distributed high frequency effects are modeled, in first order approximation, both in lateral direction (current crowding) and in vertical direction (excess phase shift). The distributed effects are an optional part of the Mextram model and can be switched on/off by a flag (on: $EXPHI = 1$ and off: $EXPHI = 0$). The high frequency current crowding is modeled by;

$$Q_{B1B2} = \frac{1}{5} \cdot V_{B1B2} \cdot \left(\frac{\partial Q_{TE}}{\partial V_{B2E1}} + \frac{1}{2} \cdot Q_{B0} \cdot q_1^Q \cdot \frac{\partial n_0}{\partial V_{B2E1}} + \frac{\partial Q_E}{\partial V_{B2E1}} \right) \tag{12.180}$$

For simplicity reasons only the forward depletion and diffusion charges are taken into account. (Note that the second term is the derivative of $Q_{BE} = \frac{1}{2} \cdot Q_{B0} \cdot q_1^Q \cdot n_0$, but with the derivative of q_1^Q neglected).

In vertical direction (excess phase shift) base-charge-partitioning is used. For simplicity reasons it is only implemented for the forward base charge (Q_{BE}) and for high level injection. Now Q_{BE} (Eq. 12.154) and Q_{BC} (Eq. 12.157) are redefined according to;

$$Q_{BC} \rightarrow \frac{1}{3} \cdot Q_{BE} + Q_{BC} \tag{12.181}$$

$$Q_{BE} \rightarrow \frac{2}{3} \cdot Q_{BE} \tag{12.182}$$

Heterojunction features

The most important difference between SiGe and pure Si transistors is the functional difference between hole charges and Gummel number. When the Ge concentration has a non-zero slope $dE_g \neq 0$ we redefine the q_0^I describing the Early effect for the currents (the q_0^Q remains unchanged).

$$q_0^I \rightarrow \frac{\exp\left(\left[\frac{V_{TE}}{VER_T} + 1\right] \cdot \frac{DEG_T}{V_T}\right) - \exp\left(\frac{-V_{TC}}{VEF_T} \cdot \frac{DEG_T}{V_T}\right)}{\exp\left(\frac{DEG_T}{V_T}\right) - 1} \tag{12.183}$$

Another feature that might be needed for SiGe transistors is recombination in the base. This changes the forward ideal base current (when $XREC \neq 0$).

$$\begin{aligned} I_{B1} \rightarrow \frac{IS_T}{BF_T} \cdot (1 - XIBI) \cdot \Bigg[& (1 - XREC) \cdot \left\{ \exp\left(\frac{V_{B2E1}}{V_T}\right) - 1 \right\} \\ & + XREC \cdot \left(\exp\left(\frac{V_{B2E1}}{V_T}\right) + \exp\left(\frac{V^*_{B2C2}}{V_T}\right) - 2 \right) \cdot \left(1 + \frac{V_{TC}}{VEF_T}\right) \Bigg] \end{aligned} \tag{12.184}$$

The last term also describes Auger recombination in high injection.

Noise model

For noise analysis noise 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

Emitter Resistor Noise

$$\overline{iN_{RE}^2} = \frac{4 \cdot k \cdot T_K}{RE_T} \cdot \Delta f \tag{12.185}$$

- Base Resistor

$$\overline{iN_{RBC}^2} = \frac{4 \cdot k \cdot T_K}{RBC_T} \cdot \Delta f \tag{12.186}$$

For the variable part of the base resistance a different formula is used, taking into account the effect of current crowding on noise behaviour:

$$\overline{iN_{RBV}^2} = \frac{4 \cdot k \cdot T_K}{RB2} \cdot \frac{4\exp\left(\frac{V_{B1B2}}{V_T}\right) + 5}{3} \cdot \Delta f \tag{12.187}$$

Base Resistor Noise

$$\overline{iN_{RB}^2} = \overline{iN_{RBV}^2} + \overline{iN_{RBC}^2} \tag{12.188}$$

- Collector Resistor

$$\overline{iN_{RCC}^2} = \frac{4 \cdot k \cdot T_K}{RCC_T} \cdot \Delta f \tag{12.189}$$

For the variable part of the collector resistance we take base-widening into account:

$$\overline{iN_{RCV}^2} = \frac{4 \cdot k \cdot T_K}{RCV_T} \cdot \left(1 + \frac{Q_{EPI}}{Q_{EPI0}}\right) \cdot \Delta f \tag{12.190}$$

Collector Resistor Noise

$$\overline{iN_{RC}^2} = \overline{iN_{RCV}^2} + \overline{iN_{RCC}^2} \tag{12.191}$$

- Collector current

Collector current shot noise

$$\overline{iN_C^2} = 2 \cdot q \cdot \frac{I_f + I_r}{q_B^I} \cdot \Delta f \tag{12.192}$$

- Base Current

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

$$\overline{iN_B^2} = \begin{aligned} &\left\{2q[|I_{B1}| + |I_{B2}|] + \frac{KF}{f}(1 - XIBI) \cdot \left(\frac{|I_{B1}|}{1 - XIBI}\right)^{AF}\right. \\ &\left. + \frac{KFN}{f} \cdot |I_{B2}|^{2 \cdot (MLF - 1) + AF \cdot (2 - MLF)}\right\} \cdot \Delta f \end{aligned} \tag{12.193}$$

Emitter-base sidewall current shot noise and $1/f$ noise:

$$\overline{iN_{BS}^2} = \left\{2 \cdot q \cdot |I_{B1}^S| + \frac{KF}{f} \cdot XIBI \cdot \left(\frac{|I_{B1}^S|}{XIBI}\right)^{AF}\right\} \cdot \Delta f \tag{12.194}$$

Reverse base current shot noise and $1/f$ noise:

$$\overline{iN_{B3}^2} = \left\{2 \cdot q \cdot |I_{B3}| + \frac{KF}{f} \cdot (|I_{B3}|)^{AF}\right\} \cdot \Delta f \tag{12.195}$$

Base Current Shot Noise

$$\overline{iN_{RB}^2} = \overline{iN_B^2} + \overline{iN_{BS}^2} + \overline{iN_{B3}^2} \tag{12.196}$$

- Extrinsic Current

Extrinsic current shot noise and $1/f$ noise
When $EXMOD = 0$ we have:

$$\overline{iN_{IEX}^2} = \left\{2 \cdot q \cdot |I_{EX}| + \frac{KF}{f} \cdot (|I_{EX}|)^{AF}\right\} \cdot \Delta f \tag{12.197}$$

If $EXMOD = 1$ we have:

$$\overline{iN_{IEX}^2} = \left\{2 \cdot q \cdot |I_{EX}| + \frac{KF}{f} \cdot (1 - XEXT) \cdot \left(\frac{|I_{EX}|}{1 - XEXT}\right)^{AF}\right\} \cdot \Delta f \tag{12.198}$$

$$\overline{iN_{XIEX}^2} = \left\{2 \cdot q \cdot |XI_{EX}| + \frac{KF}{f} \cdot XEXT \cdot \left(\frac{|XI_{EX}|}{XEXT}\right)^{AF}\right\} \cdot \Delta f \tag{12.199}$$

Extrinsic Current Shot Noise

$$\overline{iN_{EX}^2} = \overline{iN_{IEX}^2} + \overline{iN_{XIEX}^2} \tag{12.200}$$

For the TNS-device:

- Substrate current
  (between nodes B1 and S, resp. B and S)

$$\overline{iN_{I_{SUB}}^2} = 2q \cdot |I_{SUB}| \cdot \Delta f \tag{12.201}$$

$$\overline{iN_{XI_{SUB}}^2} = 2q \cdot |XI_{SUB}| \cdot \Delta f \tag{12.202}$$

Substrate current shot noise

$$\overline{iN_{sub}^2} = \overline{iN_{I_{SUB}}^2} + \overline{iN_{XI_{SUB}}^2}$$

Self-heating

For self-heating an extra network is introduced, see figure 34. It contains the self-heating resistance RTH and capacitance CTH, 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. The dissipation for the TNT / TPT devices is given by:

$$\begin{aligned} P_{diss} = {} & I_N \cdot (V_{B2E1} - V^*_{B2C2}) + I_{C1C2} \cdot (V^*_{B2C2} - V_{B2C1}) - I_{avl} \cdot V^*_{B2C2} + \\ & V^2_{EE1} / RE_T + V^2_{CC1} / RCC_T + V^2_{BB1} / RBC_T + \\ & I_{B1B2} \cdot V_{B1B2} + (I_{B1} + I_{B2}) \cdot V_{B2E1} + I^S_{B1} \cdot V_{B1E1 +} \\ & (I_{EX} + I_{B3}) \cdot V_{B1C1} + XI_{EX} \cdot V_{BC1} + \end{aligned} \tag{12.203}$$

The dissipation for the TNST / TPST devices is given by:

$$\begin{aligned} P_{diss} = {} & I_N \cdot (V_{B2E1} - V^*_{B2C2}) + I_{C1C2} \cdot (V^*_{B2C2} - V_{B2C1}) - I_{avl} \cdot V^*_{B2C2} + \\ & V^2_{EE1} / RE_T + V^2_{CC1} / RCC_T + V^2_{BB1} / RBC_T + \\ & I_{B1B2} \cdot V_{B1B2} + (I_{B1} + I_{B2}) \cdot V_{B2E1} + I^S_{B1} \cdot V_{B1E1 +} \\ & (I_{EX} + I_{B3} + I_{SUB}) \cdot V_{B1C1} + (XI_{EX} + XI_{SUB}) \cdot V_{BC1} \\ & (XI_{SUB} + I_{SUB} - I_{sf}) \cdot V_{C1S} \end{aligned} \tag{12.204}$$

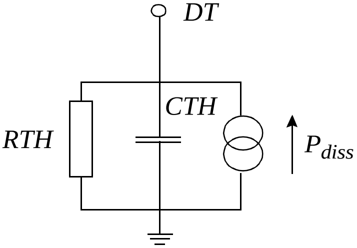

Figure 34: The self-heating network. Note that for increased flexibility the node DT is available to the user.