11 Bipolar P-N-P Transistors TP/TPS Level 503

11.1 Introduction

The TP / TPS-level-503 model provides a detailed description of a vertical integrated circuit PNP 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. In comparison with TP / TPS-level-502 the description of the collector region is improved. The base-collector depletion charge and the reverse current I_R now depend on the same internal base-collector voltage V_{C2B2}. The modeling of the epilayer resistance is rewritten and takes into account current spreading. All this results in a more accurate modeling of the collector transit time. Other parts of the models are rewritten to obtain better convergency behaviour. For **Pstar** users they are available as built-in model.

The models TP-level-503 and TPS-level-503 are almost identical. In case of a difference between the models, it will be mentioned explicitly that the information given is only relevant for the model TP-level-503 or TPS-level-503.

11.2 Order in which terminals are specified

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

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

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

11.3 Survey of modeled effects

- Temperature effects
- Charge storage effects
- 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
- Hot carrier effects in the collector epilayer
- Explicit modeling of inactive regions
- Split base-collector depletion capacitance
- Current crowding and conductivity modulation for base resistance
- First order approximation of distributed high frequency effects in the intrinsic base (high frequency current crowding and excess phase shift).

11.4 Parameters

The parameters for the TPS-level-503 are listed below.

Position in list TN	TNS	Parameter name	Units	Description
1	1	*LEVEL*	-	Model level, must be set to 503
2	2	*MULT*	-	Multiplication factor
3	3	*TREF*	°C	Reference temperature
4	4	*DTA*	K	Difference of the device temperature to the ambient temperature $(T_{DEVICE} = T_{AMBIENT} + DTA)$
5	5	*EXMOD*	-	Flag for extended modeling of the reverse current gain (default is .false. =0 and .true. =1)
6	6	*EXPHI*	-	Flag for distributed high frequency effects in transient (default is .false. =0 and .true. =1)
7	7	*EXAVL*	-	Flag for extended modeling of avalanche currents (default is .false =0 and .true. =1)
8	8	*IS*	A	Collector-emitter saturation current
9	9	*BF*	-	Ideal forward current gain
10	10	*XIBI*	-	Fraction of ideal base current that belongs to the sidewall
11	11	*IBF*	A	Saturation current of the non-ideal forward base current
12	12	*VLF*	V	Cross-over voltage of the non-ideal forward base current
13	13	*IK*	A	High-injection knee current
14	14	*BRI*	-	Ideal reverse current gain
15	15	*IBR*	A	Saturation current of the non-ideal reverse base current
16	16	*VLR*	V	Cross-over voltage of the non-ideal reverse base current
17	17	*XEXT*	-	Part of I_{EX}, Q_{EX}, Q_{TEX} and I_{SUB} that depends on the base-collector voltage V_{BC1}
18	18	*QBO*	C	Base charge at zero bias

Position in list		Parameter name	Units	Description
TN	**TNS**			
19	19	*ETA*	-	Factor of the built-in field of the base (= η)
20	20	*AVL*	-	Weak avalanche parameter
21	21	*EFI*	-	Electric field intercept (with *EXAVL*=1).
22	22	*IHC*	A	Critical current for hot carriers
23	23	*RCC*	Ω	Constant part of the collector resistance
24	24	*RCV*	Ω	Resistance of the unmodulated epilayer
25	25	*SCRCV*	Ω	Space charge resistance of the epilayer
26	26	*SFH*	-	Current spreading factor epilayer
27	27	*RBC*	Ω	Constant part of the base resistance
28	28	*RBV*	Ω	Variable part of the base resistance at zero bias
29	29	*RE*	Ω	Emitter series resistance
30	30	*TAUNE*	s	Minimum delay time of neutral and emitter charge
31	31	*MTAU*	-	Non-ideality factor of the neutral and emitter charge
32	32	*CJE*	F	Zero bias collector-base depletion capacitance
33	33	*VDE*	V	Emitter-base diffusion voltage
34	34	*PE*	-	Emitter-base grading coefficient
35	35	*XCJE*	-	fraction of the emitter-base depletion capacitance that belongs to the sidewall
36	36	*CJC*	F	Zero bias collector-base depletion capacitance
37	37	*VDC*	V	Collector-base diffusion voltage
38	38	*PC*	-	Collector-base grading coefficient variable part
39	39	*XP*	-	Constant part of of *CJC*
40	40	*MC*	-	Collector current modulation coefficient
41	41	*XCJC*	-	fraction of the collector-base depletion capacitance under the emitter area
42	42	*VGE*	V	Band-gap voltage of the emitter
43	43	*VGB*	V	Band-gap voltage of the base
44	44	*VGC*	V	Band-gap voltage of the collector
45	45	*VGJ*	V	Band-gap voltage recombination emitter-base junction

Position in list		**Parameter name**	**Units**	**Description**
TN	**TNS**			
46	46	*VI*	V	Ionization voltage base dope
47	47	*NA*	cm^{-3}	Maximum base dope concentration
48	48	*ER*	-	Temperature coefficient of *VLF* and *VLR*
49	49	*AB*	-	Temperature coefficient resistivity base
50	50	*AEPI*	-	Temperature coefficient resistivity of the epilayer
51	51	*AEX*	-	Temperature coefficient resistivity of the extrinsic base
52	52	*AC*	-	Temperature coefficient restivity of the buried layer
53	53	*KF*	-	Flickernoise coefficient ideal base current
54	54	*KFN*	-	Flickernoise coefficient non-ideal base current
55	55	*AF*	-	Flickernoise exponent
*	56	*ISS*	A	base-substrate saturation current
*	57	*IKS*	A	Knee current of the substrate
*	58	*CJS*	F	Zero bias collector-substrate depletion capacitance
*	59	*VDS*	V	Collector-substrate diffusion voltage
*	60	*PS*	-	Collector-substrate grading coefficient
*	61	*VGS*	V	Band-gap voltage of the substrate
*	62	*AS*	-	For a closed buried layer: *AS*=*AC* For an open buried layer: *AS*=*AEPI*

✓ Note

The parameters marked by * are not valid for the TP-level-503 model.

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*:

The TP device: *IS IK IBF IBR QBO IHC CJE CJC*

The TPS device: *IS IK IBF IBR ISS IKS QBO IHC CJE CJC CJS*

Divided by *MULT* are:

RCC SCRCV RCV RBC RBV RE

11.5 Pstar specific values

The default values and clipping values as used by **Pstar** for the TP/TPS-level-503 are listed below (The parameters marked by * are not valid for the TP-level-503 model).

No.	Parameter	Units	Default	Clip low	Clip high
1	*LEVEL*	-	503	-	-
2	*MULT*	-	1.00	0.0	-
3	*TREF*	°C	25.00	-273.15	-
4	*DTA*	K	0.00	-	-
5	*EXMOD*	-	1.00	0.0	1.0
6	*EXPHI*	-	0.00	0.0	1.0
7	*EXAVL*	-	0.00	0.0	1.0
8	*IS*	A	5.00×10^{-17}	0.0	-
9	*BF*	-	140.00	1.0×10^{-4}	-
10	*XIBI*	-	0.00	0.0	1.0
11	*IBF*	A	2.00×10^{-14}	0.0	-
12	*VLF*	V	0.50	-	-
13	*IK*	A	15.00×10^{-3}	1.0×10^{-12}	-
14	*BRI*	-	16.00	1.0×10^{-4}	-
15	*IBR*	A	8.00×10^{-15}	0.0	-
16	*VLR*	V	0.50	-	-
17	*XEXT*	-	0.50	0.0	1.0
18	*QBO*	C	1.20×10^{-12}	1.0×10^{-18}	-
19	*ETA*	-	4.00	0.0	-
20	*AVL*	-	50.00	0.1	-
21	*EFI*	-	0.70	0.0	-
22	*IHC*	A	3.00×10^{-3}	1.0×10^{-12}	-
23	*RCC*	Ω	25.00	1.0×10^{-6}	-
24	*RCV*	Ω	750.00	1.0×10^{-6}	-

No.	Parameter	Units	Default	Clip low	Clip high
25	*SCRCV*	Ω	1000.00	1.0×10^{-6}	-
26	*SFH*	-	0.60	0.0	-
27	*RBC*	Ω	50.00	1.0×10^{-6}	-
28	*RBV*	Ω	100.00	1.0×10^{-6}	-
29	*RE*	Ω	2.00	1.0×10^{-6}	-
30	*TAUNE*	s	3.00×10^{-10}	0.0	-
31	*MTAU*	-	1.18	1.0	2.0
32	*CJE*	F	2.50×10^{-13}	1.0×10^{-21}	-
33	*VDE*	V	0.90	0.05	-
34	*PE*	-	0.33	0.01	0.99
35	*XCJE*	-	0.50	0.0	1.0
36	*CJC*	F	1.30×10^{-13}	1.0×10^{-21}	-
37	*VDC*	V	0.60	0.05	-
38	*PC*	-	0.40	0.01	0.99
39	*XP*	-	0.20	0.0	1.0
40	*MC*	-	0.50	0.0	1.0
41	*XCJC*	-	0.10	0.0	0.999
42	*VGE*	V	1.01	0.1	-
43	*VGB*	V	1.18	0.1	-
44	*VGC*	V	1.205	0.1	-
45	*VGJ*	V	1.10	0.1	-
46	*VI*	V	0.04	0.0	-
47	*NA*	cm^{-3}	3.00×10^{17}	1.0×10^{2}	-
48	*ER*	-	2.00×10^{-3}	-	-
49	*AB*	-	1.35	-	-
50	*AEPI*	-	2.15	-	-
51	*AEX*	-	1.00	-	-
52	*AC*	-	0.40	-	-
53	*KF*	-	2.00×10^{-16}	0.0	-

No.	Parameter	Units	Default	Clip low	Clip high
54	*KFN*	-	2.00×10^{-16}	0.0	-
55	*AF*	-	1.00	0.01	-
56*	*ISS*	A	6.00×10^{-16}	0.0	-
57*	*IKS*	A	5.00×10^{-6}	1.0×10^{-12}	-
58*	*CJS*	F	1.00×10^{-12}	0.0	-
59*	*VDS*	V	0.50	0.05	-
60*	*PS*	-	0.33	0.01	0.99
61*	*VGS*	V	1.15	0.1	-
62*	*AS*	-	2.15	-	-

11.5.1 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 [36]. By default the devices start in the default state.

TP level 503			
	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

TPS level 503			
	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

11.5.2 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} $[1/\Omega]$.

11.5.3 DC operating point output

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

$$
\begin{aligned}
dI_n &= g_x \cdot dV_{E1B2} + g_y \cdot dV_{C2B2} + g_z \cdot dV_{C1B2} \\
dI_{C2C1} &= grcv_y \cdot dV_{C2B2} + grcv_z \cdot dV_{C1B2} \\
dI_{EB} &= j\omega \cdot (Cbe_y \cdot dV_{C2B2} + Cbe_z \cdot dV_{C1B2}) \\
dI_{CB} &= g_{\mu x} \cdot dV_{E1B2} + g_{\mu z} \cdot dV_{C1B2} + j\omega \cdot (Cbc_x \cdot dV_{E1B2} + Cbc_z \cdot dV_{C1B2}) \\
dI_{B2B1} &= grbv_x \cdot dV_{E1B2} + grbv_y \cdot dV_{C2B2} + grbv_z \cdot dV_{C1B2} + j\omega \cdot C_{B_{2x}B_1} \cdot dV_{E1B2} \\
dSI_{EB} &= j\omega \cdot SC_{TE} \cdot dV_{E1B2}
\end{aligned}
$$

For the TPS device:

$$dI_{SUB} = g_{NPN} \cdot dV_{C1B1} + Xg_{NPN} \cdot dV_{C1B}$$

Quantity	Equation	Description
LEVEL	503	Model level
RE	*RE*	Emitter resistance
RCC	*RCC*	Constant part of the collector resistance
RBC	*RBC*	Constant part of the base resistance
RBV	*RBV*	Variable part of the base resistance
GPI	g_π	Conductance floor b-e junction: $\partial I_{B1}/\partial V_{E1B2} + \partial I_{B2}/\partial V_{E1B2}$
SGPI	Sg_π	Conductance sidewall e-b junction: $\partial I_{B1}{}^S/\partial V_{E1B1}$

For the TP device:

GMUEX	$g_{\mu EX}$	Conductance floor extrinsic c-b junction: $\partial(I_{EX} + I_{B3})/\partial V_{C1B1}$
XGMUEX	$Xg_{\mu EX}$	Conductance sidewall extrinsic c-b junction: $\partial XI_{EX}/\partial V_{C1B}$

For the TPS device:		
GMUEX	$g_{\mu EX}$	$\partial(I_{EX} + I_{B3} + I_{SUB}) / \partial V_{C1B1}$
XGMUEX	$Xg_{\mu EX}$	$\partial(XI_{EX} + XI_{SUB}) / \partial V_{C1B}$

CBEX	Cbe_X	Capacitance floor e-b junction: $\partial Q_{TE} / \partial V_{E1B2} + \partial Q_{BE} / \partial V_{E1B2} + \partial Q_N / \partial V_{E1B2}$
CBCY	Cbc_Y	Capacitance intrinsic c-b junction: $\partial Q_{TC} / \partial V_{C2B2} + \partial Q_{CB} / \partial V_{C2B2} + \partial Q_{EPI} / \partial V_{C2B2}$
CBCEX	Cbc_{EX}	Capacitance floor extrinsic c-b junction: $\partial Q_{TEX} / \partial V_{C1B1} + \partial Q_{EX} / \partial V_{C1B1}$
XCBCEX	$XCbc_{EX}$	Capacitance sidewall extrinsic c-b junction: $\partial XQ_{TEX} / \partial V_{C1B1} + \partial XQ_{EX} / \partial V_{C1B}$
CB1B2	C_{B2B1}	Capacitance AC current crowding: $\partial Q_{B2B1} / \partial V_{B2B1}$
GX	g_x	Forward transconductance: $\partial I_N / \partial V_{E1B2}$
GY	g_y	Reverse transconductance: $\partial I_N / \partial V_{C2B2}$
GZ	g_z	Collector Early-effect on I_N : $\partial I_N / \partial V_{C1B2}$
GRCVX	$grcv_x$	Obsolete! $\partial I_{C1C2} / \partial V_{E1B2}$
GRCVY	$grcv_y$	Conductance with respect to external voltage: $\partial I_{C2C1} / \partial V_{C2B2}$
GRCVZ	$grcv_z$	Conductance with respect to external voltage: $\partial I_{C2C1} / \partial V_{C1B2}$
CBEY	Cbe_Y	Internal collector Early-effect on Q_{BE} : $\partial Q_{BE} / \partial V_{C2B2}$ (includes repartitioning for EXPHI)
CBEZ	Cbe_Z	External collector Early-effect on Q_{BE} : $\partial Q_{BE} / \partial V_{C1B2}$ (includes repartitioning for EXPHI)
GMU	g_μ	Dependence avalanche multiplication on internal c-b junction: $-\partial I_{AVL} / \partial V_{C2B2}$
GMUX	$g_{\mu X}$	Dependence avalanche multiplication on internal e-b junction: $-\partial I_{AVL} / \partial V_{E1B2}$

GMUZ	$g_{\mu Z}$	Dependence avalanche multiplication on external c-b junction: $-\partial I_{AVL}/\partial V_{C1B2}$
CBCX	Cbc_X	Emitter Early-effect on Q_{BC}: $\partial Q_{CB}/\partial V_{E1B2}$
CBCZ	Cbc_Z	Collector Early-effect on Q_{TC}, Q_{BC} and Q_{EPI}: $\partial Q_{TC}/\partial V_{C1B2} + \partial V_{CB}/\partial V_{C1B2} + \partial Q_{EPI}/\partial V_{C1B2}$
GRBVX	$grbv_X$	Emitter Early-effect on I_{B2B1}: $\partial I_{B2B1}/\partial V_{E1B2}$
GRBVY	$grbv_Y$	Internal collector Early-effect on I_{B2B1}: $\partial I_{B2B1}/\partial V_{C2B2}$
GRBVZ	$grbv_Z$	External Early-effect on I_{B2B1}: $\partial I_{B2B1}/\partial V_{C1B2}$
CB2B1X	C_{B2B1X}	Dependence of Q_{B2B1} on internal e-b junction voltage: $\partial Q_{B2B1}/\partial V_{E1B2}$
SCTE	SC_{TE}	Dependence of Q^S_{TE} on internal e-b junction voltage: $\partial Q^S_{TE}/\partial V_{E1B2}$

For the TPS device:

Quantity	**Equation**	
GSUB	g_{sub}	Conductance c-s junction: $\partial I_{SF}/\partial V_{C1S}$
CTS	C_{TS}	Capacitance c-s junction: $\partial Q_{TS}/\partial V_{C1S}$
GNPN	g_{NPN}	Transconductance floor extrinsic NPN transistor: $\partial I_{SUB}/\partial V_{C1B1}$
XGNPN	Xg_{NPN}	Transconductance sidewall extrinsic NPN transistor: $\partial XI_{SUB}/\partial V_{C1B}$

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

11.6 Equivalent circuit and equations

A full description of TP / TPS-level-503 for vertical integrated circuit NPN transistor is given below. The equivalent circuits for the TP-level-503 model are shown in Figs. 27 and fig. 29 respectively. The equivalent circuits for the TPS-level-503 model are shown in figs. 28 and 29 respectively.

✓ Note

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

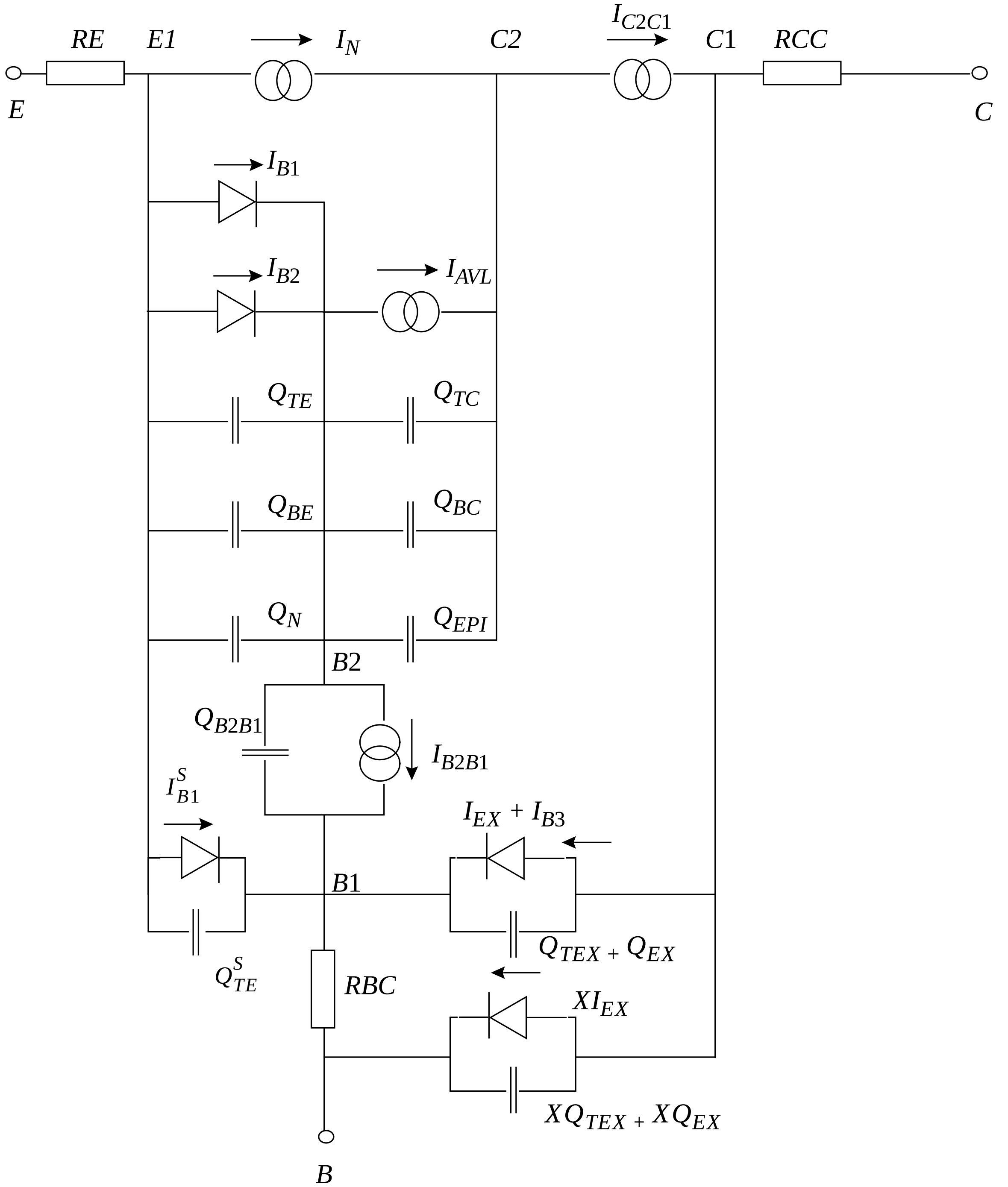

Figure 27: Equivalent circuit for TP PNP transistor

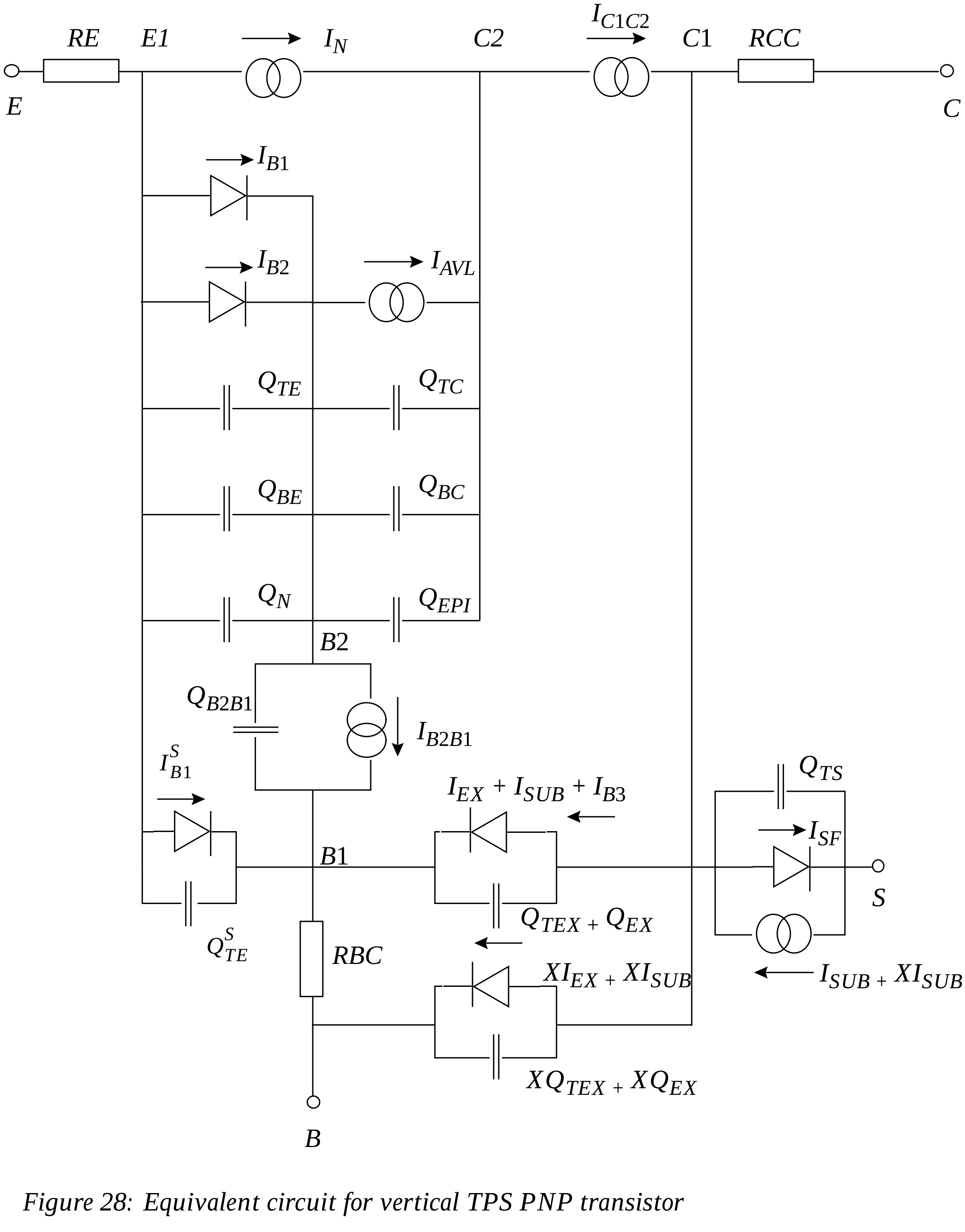

Figure 28: Equivalent circuit for vertical TPS PNP transistor

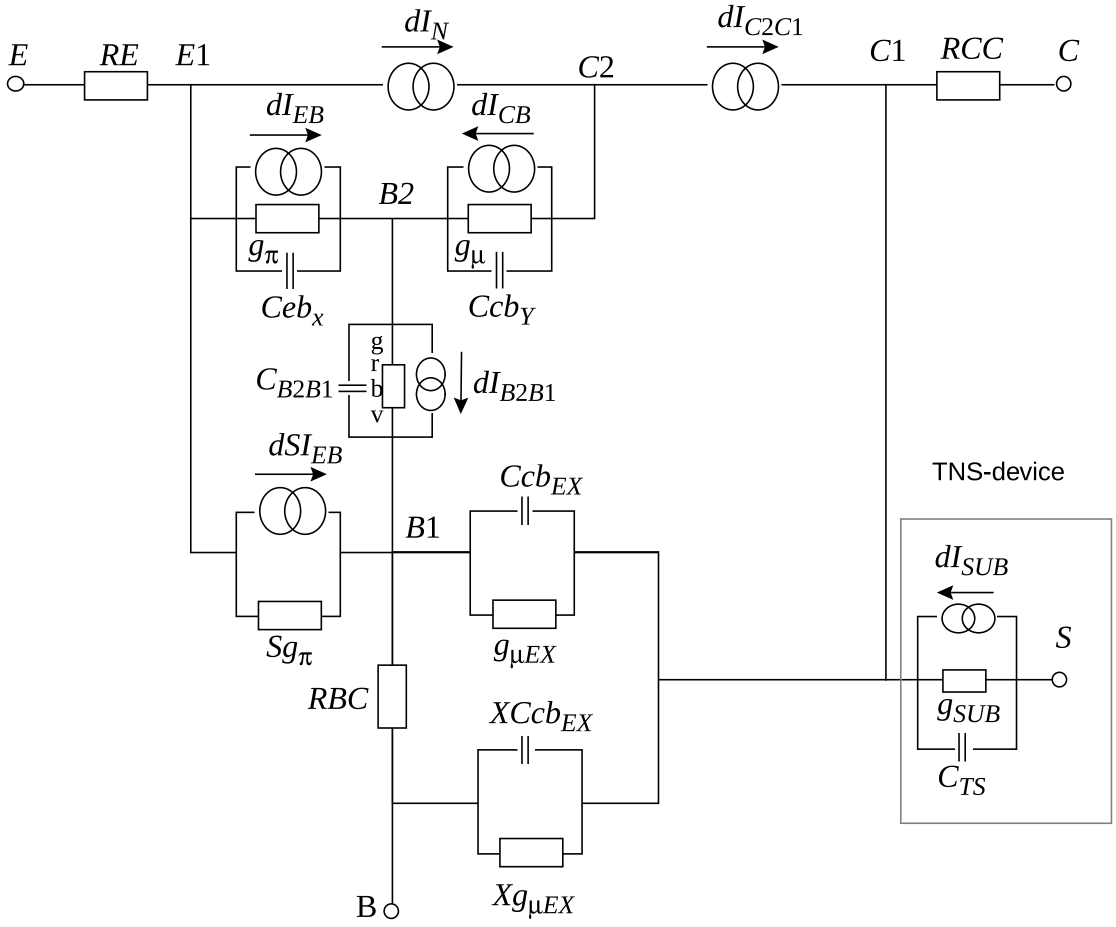

Figure 29: Small signal equivalent circuit for vertical TP/TPS PNP transistor

Model constants

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

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

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

$$\varepsilon = 1.036 \cdot 10^{-12}\mathrm{C/V \cdot cm}$$

$$V_{lim} = 8. \cdot 10^{6}\mathrm{cm/sec}$$

$$G_{MIN} = 1. \cdot 10^{-13}\mathrm{A/V}$$

$$K = .01$$

$$CK = .1$$

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

for PNP:

$$A_p = 1.58 \cdot 10^{6}\mathrm{cm}^{-1}$$

$$B_p = 2.04 \cdot 10^{6} V \cdot \mathrm{cm}^{-1}$$

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

$$T_K = TEMP + DTA + 273.15 \qquad (11.1)$$

$$T_{RK} = TREF + 273.15 \qquad (11.2)$$

$$T_N = \frac{T_K}{T_{RK}} \qquad (11.3)$$

$$T_I = \frac{1}{T_{RK}} - \frac{1}{T_K} \tag{11.4}$$

- Thermal Voltage

$$V_T = \left(\frac{k}{q}\right) \cdot T_K \tag{11.5}$$

- Resistances

$$RBC_T = RBC \cdot T_N{}^{AEX} \tag{11.6}$$

$$RBV_T = RBV \cdot T_N{}^{AB} \tag{11.7}$$

$$RCC_T = RCC \cdot T_N{}^{AC} \tag{11.8}$$

$$RCV_T = RCV \cdot T_N{}^{AEPI} \tag{11.9}$$

- Depletion capacitance

The junction diffusion voltage and junction capacitance with respect to temperature is:

$$VDE_T = -3 \cdot \left(\frac{k}{q}\right) \cdot T_K \cdot \ln(T_N) + VDE \cdot T_N + (1 - T_N) \cdot VGB \tag{11.10}$$

$$CJE_T = CJE \cdot \left(\frac{VDE}{VDE_T}\right)^{PE} \tag{11.11}$$

Where *VDE* is the junction diffusion voltage and *PE* is the grading coefficient.

$$VDC_T = -3 \cdot \left(\frac{k}{q}\right) \cdot T_K \cdot \ln(T_N) + VDC \cdot T_N + (1 - T_N) \cdot VGC \tag{11.12}$$

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.

$$CJC_T = CJC \cdot \left[(1 - XP) \cdot \left(\frac{VDC}{VDC_T}\right)^{PC} + XP\right] \tag{11.13}$$

$$XP_T = XP \cdot \frac{CJC}{CJC_T} \tag{11.14}$$

Where *PC* is the grading coefficient.

For the TPS-device:

$$VDS_T = -3 \cdot \left(\frac{k}{q}\right) \cdot T_K \cdot \ln(T_N) + VDS \cdot T_N + (1 - T_N) \cdot VGS \tag{11.15}$$

$$CJS_T = CJS \cdot \left(\frac{VDS}{VDS_T}\right)^{PS} \tag{11.16}$$

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

- Base charge

$$\begin{aligned} QE_T &= (1 - XCJE) \cdot \frac{CJE_T \cdot VDE_T}{1 - PE} \\ QB0_T &= g_{i_T} \cdot Q_{imp} - QE_T - XCJC \cdot CJC_T \cdot VDC_T\left(\frac{1 - XP_T}{1 - PC} + XP_T\right) \end{aligned} \tag{11.17}$$

with:

$$g_{i_T} = \frac{-R_T + \sqrt{R_T^2 + 8 \cdot R_T}}{4} \qquad (for\ R_T \to \infty : g_{i_T} = 1)$$

$$R_T = (T_K)^{1.5} \cdot \frac{4.82 \cdot 10^{15}}{NA} \cdot \exp\left[-\left(\frac{q}{k}\right) \cdot \frac{VI}{T_K}\right]$$

$$Q_{imp} = \frac{1}{g_i} \cdot \left\{QB0 + QE + XCJC \cdot CJC \cdot VDC\left(\frac{1-XP}{1-PC} + XP\right)\right\}$$

$$QE = (1 - XCJE) \cdot \frac{CJE \cdot VDE}{1 - PE}$$

$$g_i = \frac{-R + \sqrt{R^2 + 8 \cdot R}}{4} \qquad (for\ R \to \infty : g_i = 1)$$

$$R = (T_{RK})^{1.5} \cdot \frac{4.82 \cdot 10^{15}}{NA} \cdot \exp\left[-\left(\frac{q}{k}\right) \cdot \frac{VI}{T_{RK}}\right]$$

Q_{imp} has to be calculated with all parameter values at the reference temperature.

- Current gain

$$BF_T = BF \cdot T_N^{(0.03 - 1.5 \cdot AB)} \cdot \exp\left[\left(\frac{q}{k}\right) \cdot (VGB - VGE) \cdot T_I\right] \tag{11.18}$$

The parameter *BRI* is assumed to be temperature independent.

- Currents and Voltages

$$IS_T = IS \cdot T_N^{(3.8 - 1.5 \cdot AB)} \cdot \exp\left[\left(\frac{q}{k}\right) \cdot VGB \cdot T_I\right] \tag{11.19}$$

$$IBF_T = IBF \cdot T_N^2 \cdot \exp\left[\left(\frac{q}{k}\right) \cdot \left(\frac{VGJ}{2}\right) \cdot T_I\right] \tag{11.20}$$

$$VLF_T = VLF - ER \cdot (T_K - T_{RK}) \tag{11.21}$$

$$IK_T = IK \cdot T_N^{(1 - AB)} \tag{11.22}$$

$$IBR_T = IBR \cdot T_N^2 \cdot \exp\left[\left(\frac{q}{k}\right) \cdot \left(\frac{VGC}{2}\right) \cdot T_I\right] \tag{11.23}$$

$$VLR_T = VLR - ER \cdot (T_K - T_{RK}) \tag{11.24}$$

For the TPS-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.

$$ISS_T = ISS \cdot T_N^{(3.5 + AS)} \cdot \exp\left[\left(\frac{q}{k}\right) \cdot VGS \cdot T_I\right] \tag{11.25}$$

$$IKS_T = IKS \cdot T_N^{(1 - AS)} \tag{11.26}$$

- Transit times

$$MTAU_T = \frac{MTAU}{MTAU - T_N \cdot (MTAU - 1)} \tag{11.27}$$

$$TAUNE_T = TAUNE \cdot T_N^{(1 + AB)} \cdot \left\{\frac{T_{RK}^{1/MTAU}}{T_K^{1/MTAU_T}}\right\}^3 \cdot \exp\left[\left(\frac{q}{k}\right) \cdot \left\{VGJ \cdot T_I + VGB \cdot \left(\frac{1}{MTAU_T \cdot T_K} - \frac{1}{MTAU_T \cdot T_{RK}}\right)\right\}\right] \tag{11.28}$$

- Avalanche parameter

$$\begin{aligned} \Delta T_1 &= TREF - 25 \\ \Delta T_2 &= TEMP + DTA - 25 \\ AVL_T &= AVL \cdot \frac{1 + 7.2 \cdot 10^{-4} \cdot \Delta T_2 - 1.6 \cdot 10^{-6} \cdot (\Delta T_2)^2}{1 + 7.2 \cdot 10^{-4} \cdot \Delta T_1 - 1.6 \cdot 10^{-6} \cdot (\Delta T_1)^2} \cdot \frac{CJC}{CJC_T} \end{aligned} \tag{11.29}$$

Temperature related parameters

For the TP device:	*VGE, VGB, VGJ, VGC, AB, AEX, AC, AEPI, VI, NA* and *ER*.
For the TPS device:	*VGE, VGB, VGJ, VGS, VGC, AB, AEX, AC, AEPI, AS, VI, NA* and *ER*.

Parameter dependent constants

$$ah0 = 2 \cdot \left[\frac{1 - \exp(-\eta)}{\eta}\right] \tag{11.30}$$

$$ahb = ah0 \tag{11.31}$$

$$alb = \exp(-\eta) \tag{11.32}$$

$$bh0 = \frac{1}{ah0} \tag{11.33}$$

$$bhb = bh0 \tag{11.34}$$

$$bl0 = \frac{\eta - (1 - alb)}{(1 - alb)^2} \tag{11.35}$$

$$blb = \frac{1 - (\eta + 1) \cdot alb}{(1 - alb)^2} \tag{11.36}$$

Model parameter: *ETA* (η)

Description of currents

- Ideal forward current and reverse current.

$$I_F = IS_T \cdot \exp\left(\frac{V_{E1B2}}{V_T}\right) \tag{11.37}$$

$$I_R = IS_T \cdot \exp\left(\frac{V_{C2B2}}{V_T}\right) \tag{11.38}$$

Model parameter: *IS*

- The main current I_N

The Moll-Ross formulation is used to take into account high injection in the base. To avoid dividing by zero the depletion charge term is modified.

$$q_0 = 1 + \frac{Q_{TE} + Q_{TC}}{QB0_T}$$
$$q_1 = \frac{q_0 + \sqrt{q_0^2 + K}}{2} \tag{11.39}$$

$$q_2 = \frac{Q_{BE} + Q_{BC}}{QB0_T} \tag{11.40}$$

$$I_N = \frac{I_F - I_R}{q_1 + q_2} \tag{11.41}$$

Model parameter: *QB0*

✓ Note

The depletion charges Q_{TE} , Q_{TC} , Q_{BE} and Q_{BC} are given by Eqs. 11.83, 11.87, 11.96 and 11.99 respectively.

- Forward base currents.

The total ideal base current is separated into a bulk and sidewall component. The bulk component depends on voltage V_{E1B2} and the sidewall component on voltage V_{E1B1}. The separation is given by parameter *XIBI*.

Bulk component:

$$I_{B1} = (1 - XIBI) \cdot \frac{IS_T}{BF_T} \cdot \left\{\exp\left(\frac{V_{E1B2}}{V_T}\right) - 1\right\} \tag{11.42}$$

Sidewall component:

$$I_{B1}^S = XIBI \cdot \frac{IS_T}{BF_T} \cdot \left\{\exp\left(\frac{V_{E1B1}}{V_T}\right) - 1\right\} \tag{11.43}$$

The non-ideal base current is given by:

$$I_{B2} = IBF_T \cdot \left\{ \frac{\exp\left(\frac{V_{E1B2}}{V_T}\right) - 1}{\exp\left(\frac{V_{E1B2}}{2 \cdot V_T}\right) + \exp\left(\frac{VLF_T}{2 \cdot V_T}\right)} \right\} + G_{MIN} \cdot V_{E1B2} \qquad (11.44)$$

Model parameters: *IS*, *BF*, *XIBI*, *IBF* and *VLF*

- Reverse base currents.

In TP/TPS-level-503 the non-ideal reverse current is part of the basic Mextram model.

$$I_{B3} = IBR_T \cdot \left\{ \frac{\exp\left(\frac{V_{C1B1}}{V_T}\right) - 1}{\exp\left(\frac{V_{C1B1}}{2 \cdot V_T}\right) + \exp\left(\frac{VLR_T}{2 \cdot V_T}\right)} \right\} + G_{MIN} \cdot V_{C1B1} \qquad (11.45)$$

For the TPS-device:

The substrate current (holes injected from base to substrate), including high injection is given by:

$$I_{SUB} = \frac{2 \cdot ISS_T \cdot \left\{ \exp\left(\frac{V_{C1B1}}{V_T}\right) - 1 \right\}}{1 + \sqrt{1 + 4 \cdot \frac{IS_T}{IKS_T} \cdot \left\{ \exp\left(\frac{V_{C1B1}}{V_T}\right) - 1 \right\}}} \qquad (11.46)$$

Note that the knee of the substrate current is projected on the emitter current, therefore in the square root: $4 \cdot IS_T / IKS_T$

$$I_{SF} = ISS_T \cdot \left\{ \exp\left(\frac{V_{C1S}}{V_T}\right) - 1 \right\} \qquad (11.47)$$

The extrinsic base current (electrons injected from collector to extrinsic base) is given by:

$$g_1 = \frac{4 \cdot IS_T \cdot (aho)^2 \cdot \exp\left(\frac{V_{C1B1}}{V_T}\right)}{IK_T \cdot (alb)^2}$$

$$n_{BEX} = alb \cdot \frac{g_1}{2 \cdot [1 + \sqrt{1 + g_1}]} \tag{11.48}$$

$$g_{EX} = \frac{1}{BRI}$$

$$I_{EX} = g_{EX} \cdot \left\{\frac{alb + n_{BEX}}{ahb + n_{BEX}} \cdot \frac{IK_T}{ahb} \cdot n_{BEX} - IS_T\right\}$$

Model parameters:
For the TP-device: *IBR*, *VLR*, *BRI*, *IS*, *ETA*, *IK*
For the TPS-device: *IBR*, *VLR*, *ISS IKS*, *BRI*, *IS*, *ETA*, *IK*

- Weak avalanche current

if $I_N \leq 0$ or $I_{CAP} \leq 0$ then $I_{AVL} = 0$
The current I_{CAP} is defined by equation 11.85 or 11.86 respectively.

At low current level the internal junction voltage is;

$$V_J = -V_{C1B2} - I_{CAP} \cdot RCV_T \tag{11.49}$$

If $V_j > -0.9 \cdot VDC_T$ then

$$WD_{EPI} = \frac{AVL_T}{B_p \cdot XP_T} \tag{11.50}$$

$$F_C^{-1} = (1 - XP_T) \cdot \frac{\left(1 - \frac{I_{CAP}}{IHC}\right)^{MC}}{\left(1 + \frac{V_J}{VDC_T}\right)^{PC}} + XP_T \tag{11.51}$$

$$W_D = F_C \cdot \frac{AVL_T}{B_p} \tag{11.52}$$

$$dEWD = F_C \cdot VDC_T \cdot \frac{B_p}{AVL_T} \tag{11.53}$$

$$E_0 = \frac{V_J + VDC_T}{W_D} + dEWD \cdot \left(1 - \frac{I_{CAP}}{IHC}\right) + \frac{I_{CAP} \cdot RCV_T}{WD_{EPI}} \tag{11.54}$$

$$E_1 = \frac{V_J + VDC_T}{W_D} + \frac{I_{CAP} \cdot RCV_T}{WD_{EPI}} \tag{11.55}$$

If $EXAVL = 0$ then $E_M = E_0$

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

$$\frac{X_I}{W_{EPI}} = \frac{E_C}{I_{C2C1} \cdot RCV_T} \tag{11.56}$$

$$SH_W = 1 + 2 \cdot SFH \cdot \left(1 + 2 \cdot \frac{X_I}{W_{EPI}}\right) \tag{11.57}$$

$$\begin{aligned} E_2 &= \frac{-V_{C1B2} + VDC_T}{W_D \cdot \left(1 - \frac{X_I}{2 \cdot W_{EPI}}\right)^2} - dEWD \cdot \left(1 - \frac{X_I}{W_{EPI}}\right) \cdot \left(EFI - \frac{I_N}{IHC \cdot SH_W}\right) \\ E_M &= E_0 + \frac{E_2 - E_0 + \sqrt{(E_2 - E_0)^2 + CK \cdot I_{CAP}/I_{HC} \cdot E_1^2}}{2} \end{aligned} \tag{11.58}$$

E_C and I_{C2C1} are given by equations 11.67, 11.80 or 11.81 respectively.

The intersection point X_D and the avalanche current become;

$$X_D = \frac{E_M \cdot W_D}{2 \cdot (E_M - E_1)} \tag{11.59}$$

$$G_{EM} = \frac{A_p}{B_p} \cdot E_M \cdot X_D \cdot \left\{ \exp\left(\frac{-B_p}{E_M}\right) - \exp\left(\frac{-B_p}{E_M} \cdot \left(1 + \frac{W_D}{X_D}\right)\right) \right\} \tag{11.60}$$

$$G_{MAX} = \frac{V_T}{I_N \cdot (RBC_T + RB2)} + \frac{q_1 + q_2}{BF_T} + \frac{RE}{RBC_T + RB2} \tag{11.61}$$

$$I_{AVL} = I_N \cdot \frac{G_{EM} \cdot G_{MAX}}{G_{EM} \cdot (1 + G_{MAX}) + G_{MAX}} \tag{11.62}$$

If $V_j \leq -0.9 \cdot VDC_T$ then $I_{AVL}=0$

Model parameters: *AVL* , *EFI*, *XP*, *MC*, *PC*, *VDC*, *RCV*, *IHC*, *SFH*

✓ Note

The variable intrinsic base resistance $RB2$ and the base charge terms q_1 and q_2 are given by equations 11.63, 11.39 and 11.40 respectively.

- Series resistances:

emitter:	*RE*	=	constant
collector:	*RCC*	=	constant
base:	*RBC*	=	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:

$$RB2 = \frac{3 \cdot RBV_T}{q_1 + q_2} \tag{11.63}$$

$$I_{B1B2} = \frac{2 \cdot V_T}{RB2} \cdot \left\{ \exp\left(\frac{V_{B2B1}}{V_T}\right) - 1 \right\} + \frac{V_{B2B1}}{RB2} \tag{11.64}$$

The base charge terms q_1 and q_2 are given by equations 11.39 and 11.40 respectively.

Model parameter: *RBV*

- 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 (reverse mode of operation).
- Ohmic current flow at low current densities.
- Space charge limited current flow at high current densities.
- Current spreading in the epilayer.

The epilayer current is computed by solving a cubic equation.

$$K_0 = \sqrt{1 + 4 \cdot \exp[(V_{C2B2} - VDC_T)/V_T]} \tag{11.65}$$

$$K_W = \sqrt{1 + 4 \cdot \exp[(V_{C1B2} - VDC_T)/V_T]} \tag{11.66}$$

$$E_C = V_T \cdot \left[K_0 - K_W - \ln\left(\frac{K_0 + 1}{K_W + 1}\right) \right] \tag{11.67}$$

If V_{C2B2} - $V_{C1B2} > 0$ (forward mode) then

$$S_F = \frac{2 \cdot SFH}{1 + SFH} \tag{11.68}$$

$$V = \frac{V_{C2B2} - V_{C1B2}}{IHC \cdot RCV_T} \tag{11.69}$$

$$E = \frac{E_C}{IHC \cdot RCV_T} \tag{11.70}$$

$$R = \frac{RCV_T}{SCRCV} \tag{11.71}$$

$$A_2 = -2 \cdot E - \frac{V + R \cdot V^2 + E}{1 + V} \tag{11.72}$$

$$A_1 = \frac{E^2 \cdot (3 + V) + 2 \cdot E \cdot V - S_F \cdot E \cdot R \cdot V^2}{1 + V} \tag{11.73}$$

$$A_0 = -\frac{E^2 \cdot (E + V)}{1 + V} \tag{11.74}$$

$$q = A_1/3 - A_2^2/9 \tag{11.75}$$

$$r = (A_1 \cdot A_2 - 3 \cdot A_0)/6 - A_2^3/27 \tag{11.76}$$

$$s = \sqrt{q^3 + r^2} \tag{11.77}$$

$$s_1 = (r + s)^{1/3} \tag{11.78}$$

$$s_2 = (r - s)^{1/3} \tag{11.79}$$

$$I_{C2C1} = IHC \cdot (s_1 + s_2 - A_2/3) \tag{11.80}$$

The argument of the square root of equation 11.77 may become negative. Then s, s_1 and s_2 are complex. The magnitude of the imaginary part of s_1 and s_2 are equal and differ in sign.

If V_{C2B2} - $V_{C1B2} \leq 0$ (reverse mode) then

$$I_{C2C1} = \frac{E_C + V_{C2B2} - V_{C1B2}}{RCV_T} \tag{11.81}$$

Model Parameters: *IHC, RCV, SCRCV, SFH, VDC*

Description of charges

- Emitter depletion charge Q_{TE}

The total base-emitter depletion charge depends on V_{E1B2} :

$$Q_{TE}^{tot} = \frac{CJE_T \cdot VDE_T \cdot (1+K)}{1-PE+K} \cdot \left[1 - \frac{(1+K)^{\left(\frac{PE}{2}\right)} \cdot \left(1 - \frac{V_{E1B2}}{VDE_T}\right)}{\left\{\left(1 - \frac{V_{E1B2}}{VDE_T}\right)^2 + K\right\}^{\left(\frac{PE}{2}\right)}}\right] \tag{11.82}$$

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. 27).

$$Q_{TE} = (1 - XCJE) \cdot Q_{TE}^{tot} \tag{11.83}$$

$$Q_{TE}^{s} = XCJE \cdot Q_{TE}^{tot} \tag{11.84}$$

Model parameters : *CJE* , *VDE* , *PE* , *XCJE*

- Intrinsic collector depletion charge Q_{TC_1}

If V_{C2B2} - $V_{C1B2} > 0$ then

$$I_{CAP} = \frac{IHC \cdot (V_{C2B2} - V_{C1B2})}{V_{C2B2} - V_{C1B2} + IHC \cdot RCV_T}$$
$$CKI = CK + \frac{I_{CAP}}{IHC} \tag{11.85}$$

If V_{C2B2} - $V_{C1B2} \leq 0$ then

$$I_{CAP} = \frac{V_{C2B2} - V_{C1B2}}{RCV_T}$$
$$CKI = CK \tag{11.86}$$

The base-collector depletion charge is divided into a constant part (parameter *XP*) and a variable part. The constant part represents the finite thickness of the epilayer. The depletion charge is a function of the internal and external base-collector junction voltage.

$$VC_1 = \frac{(1 + CK)^{\left(\frac{PC}{2}\right)} \cdot \left(1 - \frac{V_{C2B2}}{VDC_T}\right)}{\left\{\left(1 - \frac{V_{C2B2}}{VDC_T}\right)^2 + CKI\right\}^{\left(\frac{PC}{2}\right)}} \cdot \left(1 - \frac{I_{CAP}}{IHC}\right)^{MC} \tag{11.87}$$
$$VC_V = \frac{VDC_T \cdot (1 - XP_T) \cdot (1 + CK)}{1 - PC + CK} \cdot (1 - VC_1)$$
$$Q_{TC_1} = XCJC \cdot CJC_T \cdot \{VC_V - XP_T \cdot (I_{CAP} \cdot RCV_T - V_{C2B2})\}$$

Parameters: *XCJC, CJC, VDC, PC, XP* , *MC* , *RCV, IHC*

- Collector transit time in quasi-saturation $\Delta\, Q_{SAT}$

The current through the epilayer (equation 11.80) without injection (E_C=0) is;

$$V_{C2C1} = V_{C2B2} - V_{C1B2}$$
$$I_{(EC = 0)} = \frac{IHC \cdot SCRCV \cdot V_{C2C1} + V^2_{C2C1}}{SCRCV \cdot (IHC \cdot RCV_T + V_{C2C1})}$$

To force the same current I_{C2C1} through the epilayer without injection, we need an epilayer voltage of $V_{(EC=0)}$;

$$B_1 = 0.5 \cdot SCRCV \cdot (I_{C2C1} - IHC)$$
$$B_2 = SCRCV \cdot IHC \cdot RCV_T \cdot I_{C2C1}$$
$$V_{(EC=0)} = B_1 + \sqrt{B_1 \cdot B_1 + B_2}$$

The differential resistance $R_{(EC=0)} = \partial V_{(EC=0)} / \partial I_{C2C1}$ is given by;

$$R_{(EC=0)} = \frac{SCRCV \cdot (V_{(EC=0)} + IHC \cdot RCV_T)^2}{V^2_{(EC=0)} + 2 \cdot V_{(EC=0)} \cdot IHC \cdot RCV_T + SCRCV \cdot IHC^2 \cdot RCV_T}$$

The collector transit time in quasi-saturation now becomes;

$$\Delta Q_{SAT} = R_{(EC=0)} \cdot \frac{\partial Q_{TC_1}}{\partial V_{C2B2}} \cdot (I_{C2C1} - I_{(EC=0)}) \qquad (11.88)$$

The total collector depletion and transit time charge is

if $I_{C2C1} > 0$ then

$$Q_{TC} = Q_{TC_1} + \Delta Q_{SAT} \qquad (11.89)$$

if $I_{C2C1} \le 0$ then

$$Q_{TC} = Q_{TC_1} \qquad (11.90)$$

- Extrinsic collector depletion charges Q_{TEX} and XQ_{TEX}.

  The extrinsic collector depletion charge is partitioned between nodes *B*1 and *C*1 and nodes *B* and *C*1 respectively independent of flag *EXMOD*.

$$VTEX_1 = \frac{(1+CK)^{\left(\frac{PC}{2}\right)} \cdot \left(1 - \frac{V_{C1B1}}{VDC_T}\right)}{\left\{\left(1 - \frac{V_{C1B1}}{VDC_T}\right)^2 + CK\right\}^{\left(\frac{PC}{2}\right)}} \tag{11.91}$$

$$VTEX_V = \frac{VDC_T \cdot (1 - XP_T) \cdot (1 + CK)}{1 - PC + CK} \cdot (1 - VTEX_1)$$

$$Q_{TEX} = (1 - XEXT) \cdot (1 - XCJC) \cdot CJC_T \cdot (VTEX_V + XP_T \cdot V_{C1B1})$$

To the external base node is connected;

$$XVTEX_1 = \frac{(1+CK)^{\left(\frac{PC}{2}\right)} \cdot \left(1 - \frac{V_{C1B}}{VDC_T}\right)}{\left\{\left(1 - \frac{V_{C1B}}{VDC_T}\right)^2 + CK\right\}^{\left(\frac{PC}{2}\right)}} \tag{11.92}$$

$$XVTEX_V = \frac{VDC_T \cdot (1 - XP_T) \cdot (1 + CK)}{1 - PC + CK} \cdot (1 - XVTEX_1)$$

$$XQ_{TEX} = XEXT \cdot (1 - XCJC) \cdot CJC_T \cdot (XVTEX_V + XP_T \cdot V_{C1B})$$

Model parameters: *XCJC*, *CJC*, *VDC*, *PC*, *XP* , *XEXT*

For the TPS-device:

- Depletion charge Q_{TS}.

$$Q_{TS} = \frac{CJS_T \cdot VDS_T \cdot (1+K)}{1 - PS + K} \cdot \left[1 - \frac{(1+K)^{\left(\frac{PS}{2}\right)} \cdot \left(1 - \frac{V_{C1S}}{VDS_T}\right)}{\left\{\left(1 - \frac{V_{C1S}}{VDS_T}\right)^2 + K\right\}^{\left(\frac{PS}{2}\right)}}\right] \tag{11.93}$$

Model parameters: *CJS*, *VDS* and *PS*

- Stored base charges Q_{BE} and Q_{BC}

$$Q_B = q_1 \cdot QB0_T \tag{11.94}$$

$$f_1 = \frac{4 \cdot IS_T \cdot (aho)^2}{IK_T} \cdot \exp\left(\frac{V_{E1B2}}{V_T}\right)$$
$$n_0 = \frac{f_1}{2 \cdot (1 + \sqrt{1 + f_1})} \tag{11.95}$$

$$Q_{BE} = Q_B \cdot n_0 \cdot \left[\frac{\frac{1}{2} + \left(\frac{aho}{4}\right) + n_0}{\left[\left(\frac{1}{2} + \frac{aho}{4}\right)\right] \cdot \left(\frac{bho}{blo}\right) + n_0}\right] \cdot bho \tag{11.96}$$

$$f_2 = 4 \cdot IS_T \cdot (aho)^2 \cdot \exp\left(\frac{V_{C2B2}}{V_T}\right) / \{IK_T \cdot (alb)^2\} \tag{11.97}$$

$$n_B = alb \cdot \frac{f_2}{2 \cdot (1 + \sqrt{1 + f_2})} \tag{11.98}$$

$$Q_{BC} = Q_B \cdot n_B \cdot \left\{\frac{alb \cdot blb + n_B}{alb \cdot bhb + n_B}\right\} \cdot bhb \tag{11.99}$$

Model parameters: *QB0, IK, ETA, IS*

- Neutral and emitter charge

$$Q_{N0} = TAUNE_T \cdot IK_T \cdot \left(\frac{IS_T}{IK_T}\right)^{\left(\frac{1}{MTAU_T}\right)} \cdot \sqrt{MTAU_T \cdot (2 - MTAU_T)} \cdot \left\{\frac{MTAU_T - 1}{2 \cdot (2 - MTAU_T)}\right\}^{\left(1 - \frac{1}{MTAU_T}\right)} \tag{11.100}$$

$$Q_N = Q_{N0} \cdot \left\{\exp\left(\frac{V_{E1B2}}{V_T \cdot MTAU_T}\right) - 1\right\} \tag{11.101}$$

Model parameters: *TAUNE, MTAU, IS*

- Stored epilayer charge

$|V_{C1B2} - V_{C2B2}| > 1 \cdot 10^{-8}$ then

$$Q_{EPI} = IS_T \cdot QB0_T \cdot \frac{\exp\left(\frac{V_{C2B2}}{V_T}\right) - \exp\left(\frac{V_{C1B2}}{V_T}\right)}{I_{C2C1}} \qquad (11.102)$$

The current I_{C2C1} is given by equation 11.80 or 11.81 respectively.

if $|V_{C1B2} - V_{C2B2}| \le 1 \cdot 10^{-8}$ then

$$p_0 = \frac{2 \cdot \{\exp(V_{C2B2} - VDC_T) / V_T\}}{(1 + K_0)} \qquad (11.103)$$

$$p_w = \frac{2 \cdot \{\exp(V_{C1B2} - VDC_T) / V_T\}}{(1 + K_W)} \qquad (11.104)$$

$$Q_{EPI} = RCV_T \cdot IS_T \cdot QB0_T \cdot \exp\left(\frac{VDC_T}{V_T}\right) \cdot \frac{p_0 + p_w}{2 \cdot V_T} \qquad (11.105)$$

Model parameters: *QB0, RCV, VDC, IS*

- Extrinsic charges

$$g_2 = 4 \cdot \exp\left(\frac{V_{C1B1} - VDC_T}{V_T}\right) \qquad (11.106)$$

$$p_{WEX} = \frac{g_2}{2 \cdot (1 + \sqrt{1 + g_2})} \qquad (11.107)$$

$$g_3 = \frac{RCV_T \cdot IS_T \cdot \exp\left(\frac{VDC_T}{V_T}\right)}{V_T} \quad (11.108)$$

$$g_4 = \frac{alb \cdot blb + n_{BEX}}{alb \cdot bhb + n_{BEX}} \cdot bhb \quad (11.109)$$

$$Q_{EX} = QB0_T \cdot \left(\frac{1 - XCJC}{XCJC}\right) \cdot (g_3 \cdot p_{WEX} + g_4 \cdot n_{BEX}) \quad (11.110)$$

Model parameters: *QB0*, *RCV*, *VDC*, *IS*, *XCJC*

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

- Currents

The base current I_{EX} is redefined

$$I_{EX} = (1 - XEXT) \cdot I_{EX} \quad (11.111)$$

For the TPS-device:

The base current I_{SUB} is redefined:

$$I_{SUB} = (1 - XEXT) \cdot I_{SUB} \quad (11.112)$$

A part $XEXT$ of the base current of the extrinsic transistor is connected to the base terminal;

For the TPS-device:

$$XIM_{SUB} = XEXT \cdot \frac{2 \cdot ISS_T \cdot \left\{\exp\left(\frac{V_{C1B}}{V_T}\right) - 1\right\}}{1 + \sqrt{1 + 4 \cdot \frac{IS_T}{IKS_T}\left\{\exp\left(\frac{V_{C1B}}{V_T}\right) - 1\right\}}} \quad (11.113)$$

$$Xg_1 = \frac{4 \cdot IS_T \cdot (aho)^2 \cdot \exp\left(\frac{V_{C1B}}{V_T}\right)}{IK_T \cdot (alb)^2} \quad (11.114)$$

$$Xn_{BEX} = alb \cdot \frac{Xg_1}{2 \cdot [1 + \sqrt{1 + Xg_1}]} \tag{11.115}$$

$$XIM_{EX} = XEXT \cdot g_{EX} \cdot \left(\frac{alb + Xn_{BEX}}{ahb + Xn_{BEX}} \cdot \frac{IK_T}{ahb} \cdot Xn_{BEX} - IS_T\right) \tag{11.116}$$

To improve convergency behaviour the conductivity of branch c1-b is limited to $1 / RCC_T$.

For the TP-device:

$$V_{EX} = V_T \cdot \left\{ \ln\left(\frac{V_T}{XEXT \cdot (IS_T \cdot g_{EX}) \cdot RCC_T}\right) + 2 \right\} \tag{11.117}$$

For the TPS-device:

$$V_{EX} = V_T \cdot \left\{ \ln\left(\frac{V_T}{XEXT \cdot (IS_T \cdot g_{EX} + ISS_T) \cdot RCC_T}\right) + 2 \right\} \tag{11.118}$$

$$VB_{EX} = \frac{-(V_{EX} - V_{C1B}) + \sqrt{(V_{EX} - V_{C1B})^2 + K}}{2} \tag{11.119}$$

For the TP-device:

$$F_{EX} = \frac{VB_{EX}}{RCC_T \cdot XIM_{EX} + VB_{EX}} \tag{11.120}$$

For the TPS-device:

$$F_{EX} = \frac{VB_{EX}}{RCC_T \cdot (XIM_{EX} + XIM_{SUB}) + VB_{EX}} \tag{11.121}$$

$$XI_{SUB} = F_{EX} \cdot XIM_{SUB} \tag{11.122}$$

$$XI_{EX} = F_{EX} \cdot XIM_{EX} \tag{11.123}$$

- Charges

The charge Q_{EX} is redefined:

$$Q_{EX} = (1 - XEXT) \cdot Q_{EX} \tag{11.124}$$

$$Xg_2 = 4 \cdot \exp\left\{\left(\frac{V_{C1B} - VDC_T}{V_T}\right)\right\} \tag{11.125}$$

$$Xp_{WEX} = \frac{Xg_2}{2 \cdot [1 + \sqrt{1 + Xg_2}]} \tag{11.126}$$

$$Xg_4 = \frac{alb \cdot blb + Xn_{BEX}}{alb \cdot bhb + Xn_{BEX}} \cdot bhb \tag{11.127}$$

$$XQ_{EX} = F_{EX} \cdot XEXT \cdot QB0_T \cdot \frac{1 - XCJC}{XCJC} \cdot \{(g_3 \cdot Xp_{WEX}) + (Xg_4 \cdot Xn_{BEX})\} \tag{11.128}$$

Model parameter: *XEXT*

✓ Note

The depletion charges *QTEX* and *XQTEX* are distributed always over the internal and external base node independent of *EXMOD*.

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 part of the Mextram model and can be switched on / off with the flag EXPHI. The high frequency current crowding is modeled by;

$$C_B = \frac{1}{5} \cdot \left(\frac{\partial Q_{TE}}{\partial V_{E1B2}} + \frac{\partial Q_{BE}}{\partial V_{E1B2}} + \frac{\partial Q_N}{\partial V_{E1B2}}\right) \tag{11.129}$$

$$Q_{B2B1} = C_B \cdot V_{B2B1} \tag{11.130}$$

For simplicity reasons only the forward depletion and diffusion charges are taken into account. The partial derivative of Q_{B2B1} with respect to V_{E1B2} has to be neglected in AC analysis. In transient analysis (if *EXPHI*=1) the convergency behaviour may be improved by approximating this derivative with;

$$\frac{\partial Q_{B2B1}}{\partial V_{E1B2}} = \left(\frac{\partial Q_{BE}}{\partial V_{E1B2}} + \frac{\partial Q_N}{\partial V_{E1B2}}\right) \cdot \left(\frac{V_{B2B1}}{5 \cdot V_T}\right) \tag{11.131}$$

In vertical direction (excess phase shift) base-charge-partitioning is used. For simplicity reasons it is only implemented for the forward base charge (*QBE*) and for low level injection. Now *QBE* (Eq. 11.96) and *QBC* (Eq. 11.99) are redefined according to;

$$QBE' = (1 - q_C) \cdot QBE \tag{11.132}$$

$$QBC' = q_C \cdot QBE + QBC \tag{11.133}$$

$$q_C = \frac{2 + \eta - (2 - \eta) \cdot \exp(\eta)}{2 - \eta - (1 - \eta) \cdot \exp(\eta) - \exp(-\eta)} \tag{11.134}$$

For $\eta = 0$ the partitioning factor q_C is $1/3$.

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:

$$\overline{iN^2_{RE}} = \frac{4 \cdot k \cdot T_K}{RE} \cdot \Delta f \tag{11.135}$$

$$\overline{iN^2_{RBC}} = \frac{4 \cdot k \cdot T_K}{RBC_T} \cdot \Delta f \tag{11.136}$$

$$\overline{iN^2_{RCC}} = \frac{4 \cdot k \cdot T_K}{RCC_T} \cdot \Delta f \tag{11.137}$$

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

$$\overline{iN_{RBV}^2} = \frac{5.26 \cdot k \cdot T_K}{RB2} \cdot \left\{1 + 2 \cdot \exp\left(\frac{V_{B2B1}}{V_T}\right)\right\}^{\left(\frac{3}{4}\right)} \cdot \Delta f \tag{11.138}$$

Collector current shot noise:

$$\overline{iN_C^2} = 2 \cdot q \cdot |I_N| \cdot \Delta f \tag{11.139}$$

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

$$\overline{iN_B^2} = \left(2q[|I_{B1}| + |I_{B2}|] + \frac{MULT}{f}\left[KFN\left(\frac{|I_{B2}|}{MULT}\right)^2 + KF\left(\frac{|I_{B1}|}{MULT}\right)^{AF}\right]\right) \cdot \Delta f \tag{11.140}$$

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

$$\overline{iN_{BS}^2} = \left\{2 \cdot q \cdot |I_{B1}^S| + \frac{MULT}{f} \cdot KF \cdot \left(\frac{|I_{B1}^S|}{MULT}\right)^{AF}\right\} \cdot \Delta f \tag{11.141}$$

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

$$\overline{iN_{B3}^2} = \left[2 \cdot q \cdot |I_{B3}| + \frac{MULT}{f} \cdot KF \cdot \left(\frac{|I_{B3}|}{MULT}\right)^{AF}\right] \cdot \Delta f \tag{11.142}$$

Extrinsic current shot noise and $1/f$ noise:

$$\overline{iN_{IEX}^2} = \left[2 \cdot q \cdot |I_{EX}| + \frac{KF}{f} \cdot \left(\frac{|I_{EX}|}{MULT}\right)^{AF} \cdot MULT\right] \cdot \Delta f \tag{11.143}$$

If $EXMOD$ = TRUE we also have:

$$\overline{iN_{XIEX}^2} = \left[2 \cdot q \cdot |XI_{EX}| + \frac{KF}{f} \cdot \left(\frac{|XI_{EX}|}{MULT}\right)^{AF} \cdot MULT\right] \cdot \Delta f \tag{11.144}$$