Bipolar transistor

General form

```
Q<name> < collector node> <base node> <emitter node>
+ [substrate node] <model name> [area value]
```

Examples

```
Q1 14 2 13 PNPNOM
Q13 15 3  0 1 NPNSTRONG 1.5
Q7 VC 5 12 [SUB] LATPNP
```

Model form

```
.MODEL <model name> NPN [model parameters]
.MODEL <model name> PNP [model parameters]
.MODEL <model name> LPNP [model parameters]
```

Arguments and options

`[substrate node]`

is optional, and if not specified, the default is the ground.

Because the simulator allows alphanumeric names for nodes, and because there is no easy way to distinguish these from the model names, the name (not a number) used for the substrate node needs to be enclosed with square brackets [ ]. Otherwise, nodes would be interpreted as model names. See the third example.

`[area value]`

is the relative device area and has a default value of 1.

Comments

The simulator supports the following two models for a bipolar transistor:

Level 1: Gummel-Poon model

Level 2: Mextram model

Mextram is an extended model that can describe various features of the modern down-scaled transistor, such as avalanche, collector epilayer current, and overlap capacitances. The Mextram model supported by this simulator is level 504. For more information about Mextram 504, you can visit *http://www.semiconductors.philips.com/Philips_Models/bipolar/mextram/*.

Note: Simulations might take more time for circuit involving the Mextram model in comparison to Gummel-Poon due to the complex nature of the equations. The convergence issues might also be more.

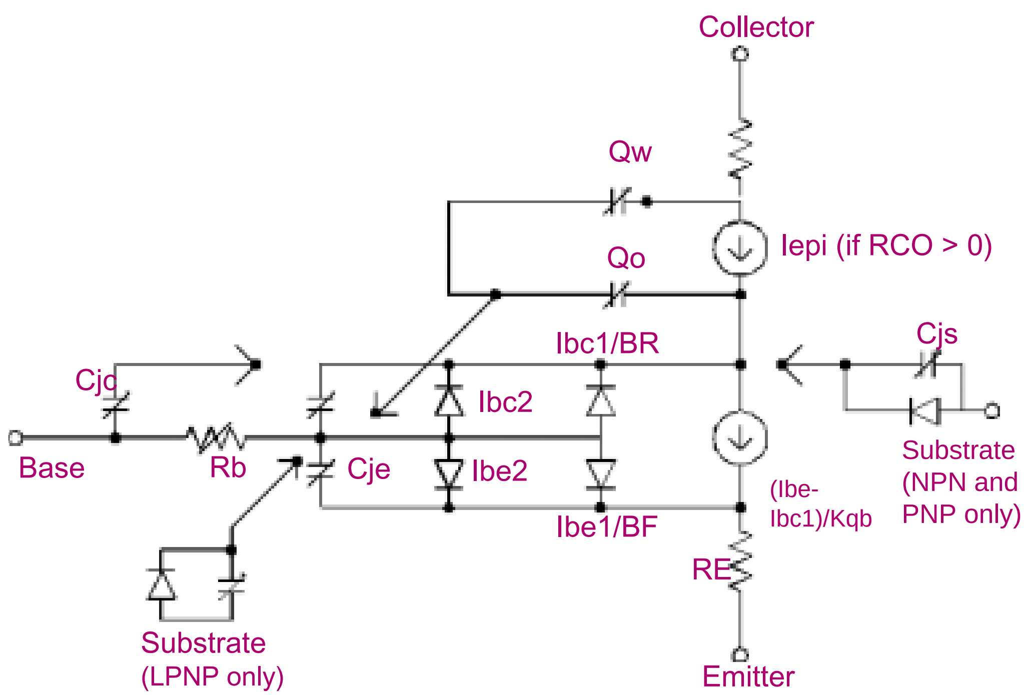
Following is a list of effects that are better modelled by Mextram:

- Temperature
- Charge storage
- Substrate
- Parasitic PNP
- Low-level, non-ideal base currents
- Hard- and quasi-saturation
- Weak avalanche
- Hot carrier effects in the collector epilayer
- Explicit modelling of inactive regions
- Split base-collector depletion capacitance
- Current crowding and conductivity modulation for base resistance
- Distributed high frequency effects in the intrinsic base (high frequency current crowding and excess phase shift)
- High-injection
- Built-in electric field in base region
- Bias-dependent Early effect

Note: The self heating effect of Mextram model level 504 is not supported in release 10.5. As a result, the self heating effect equations and parameters are not implemented in this simulation

Description The bipolar transistor is modeled as an intrinsic transistor using ohmic resistances in series with the collector (RC/area), with the base (value varies with current, see Bipolar transistor equations on page 276), and with the emitter (RE/area).

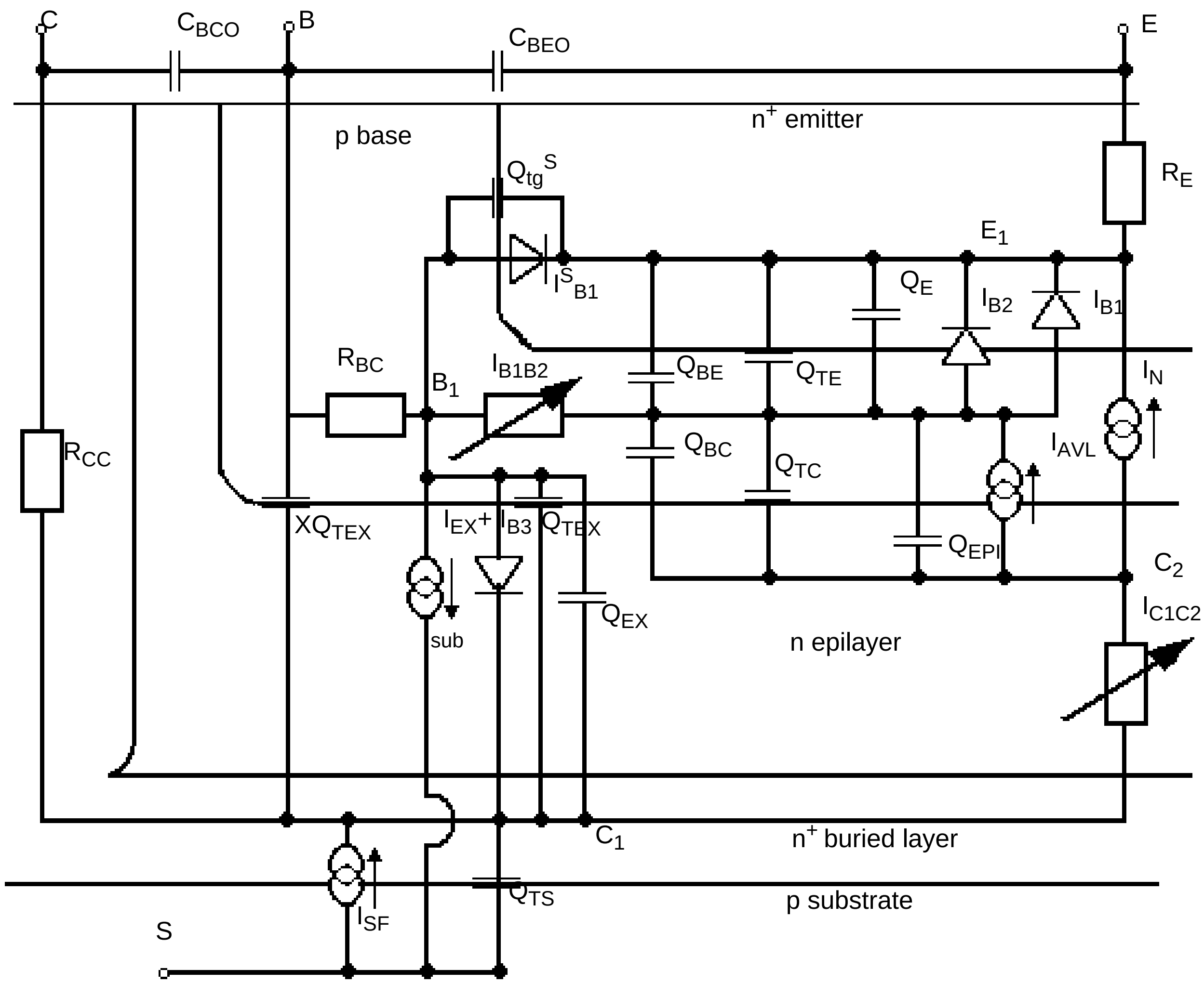
Model Level 1



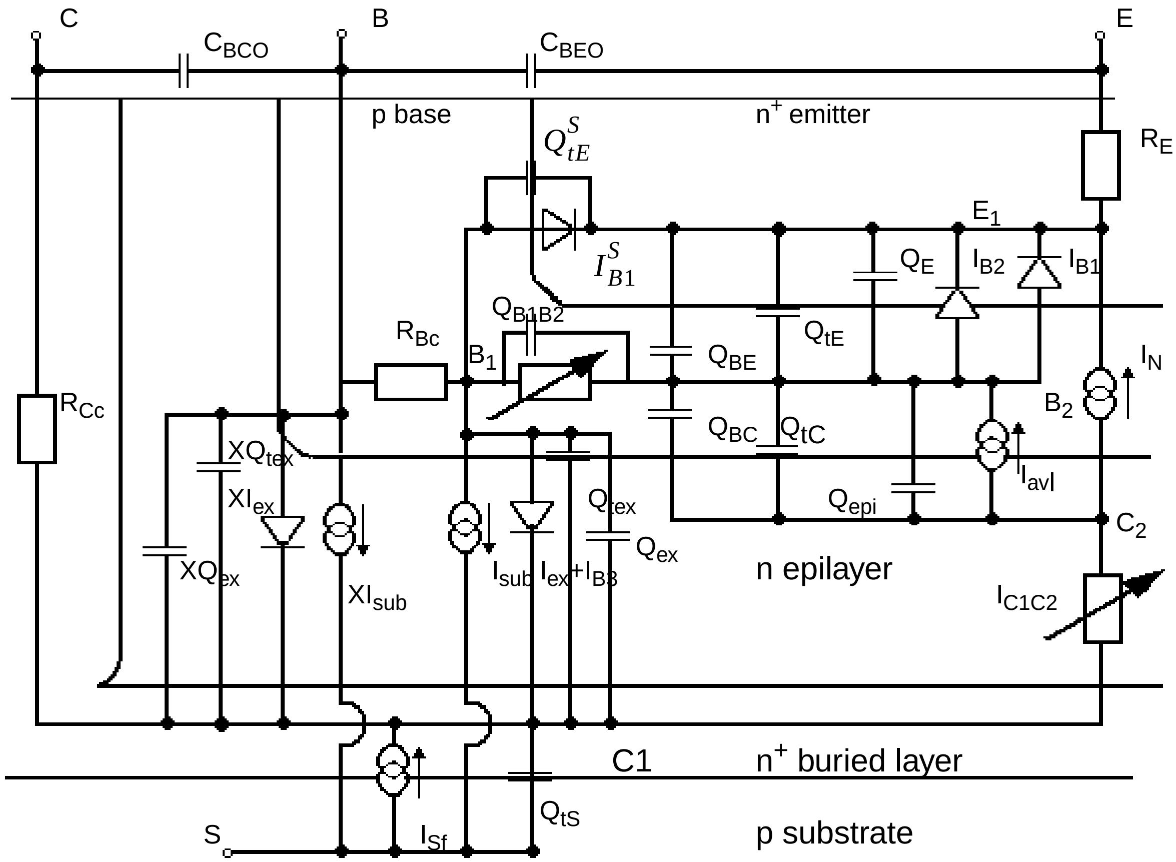
Note: Positive current is current flowing into a terminal.

Model Level 2

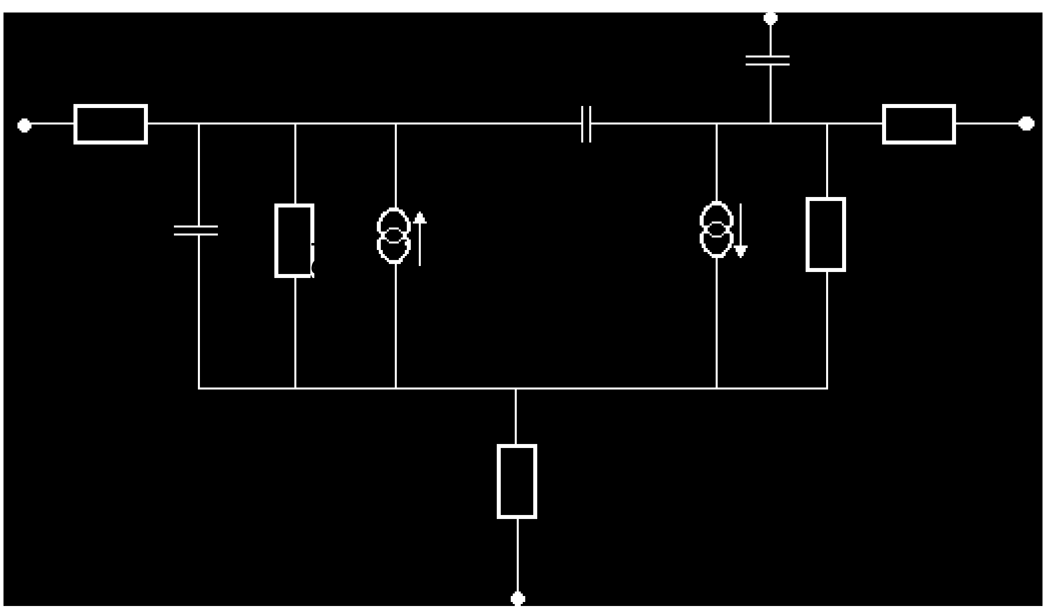
The equivalent circuit for model level 2 shows the intrinsic part of the transistor and the base, emitter, and the collector or epilayer resistance.



You can use two flags, EXMOD and EXPHI, to introduce additional elements to the schematic of a transistor in model level 2.



The small signal equivalent circuit is shown by the following figure.



The small signal model uses the following small-signal parameters:

Note: The conductances are derivatives with respect to three different biases, namely, base-emitter denoted by the subscript x, internal base-collector denoted by the subscript y, and base-collector denoted by the subscript z.

The transconductance, g_m, is given by the following equation:

$$g_m = \frac{g_{\mathrm{Rcv,y}}(g_x - g_{\mu,x} + g_z - g_{\mu,z}) - (g_{\mathrm{Rcv,x}} + g_{\mathrm{Rcv,z}})(g_y - g_{\mu,y})}{g_{\mathrm{Rcv,y}} + g_{\mu,y} - g_y}$$

The base conductance, g_π, is given by the following equation:

$$g_\pi = gS_\pi + g_{\pi,x} + g_{\mu,x} + g_{\pi,z} + g_{\mu,z} + (g_{\pi,y} + g_{\mu,y})\left[\frac{dy}{dx} + \frac{dy}{dz}\right]$$

The current amplification, β, is given by the following equation:

$$\beta = g_m / g_\pi$$

The output conductance, g_{out}, is given by the following equation:

$$g_{out} = \frac{(g_y - g_{\mu,y})g_{\mathrm{Rcv,z}} - (g_z - g_{\mu,z})g_{\mathrm{Rcv,y}}}{g_{\mathrm{Rcv,y}} + g_{\mu,y} - g_y}$$

The feedback transconductance, g_μ, is given by the following equation:

$$g_\mu = g_{\pi,z} + g_{\mu,z} + (g_{\pi,y} + g_{\mu,y}) \cdot \frac{dy}{dz} + g_{\mu ex} + Xg_{\mu ex}$$

The base-emitter capacitance, C_{BE}, is given by the following equation:

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

The base-collector capacitance, C_{BC}, is given by the following equation:

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

In addition to the listed parameters, the cut-off frequency f_T is another important design parameter. The cut-off frequency is a compound small-signal quantity and can be represented in terms of the total transit time, as given by the following equation:

$$f_T = 1/(2\pi\tau_T)$$

The total transit time, τ_T, is given by the following equation:

$$\tau_T = C_{BE}{}^{S} \cdot (r_x + r_{b1b2}) + (C_{\mathrm{BE,x}} + C_{\mathrm{BC,x}}) \cdot r_x$$

$$(C_{\mathrm{BE,y}} + C_{\mathrm{BC,y}}) \cdot r_y + (C_{\mathrm{BE,z}} + C_{\mathrm{BC,z}}) \cdot r_z + C_{\mathrm{BCex}} r_{ex}$$

$$XC_{\mathrm{BCex}} Xr_{ex} + (C_{BEO} + C_{BCO})(Xr_{ex} - R_{Cc})$$

For model parameters with alternate names, such as VAF and VA (the alternate name is shown by using parentheses), either name can be used.

For model types NPN and PNP, the isolation junction capacitance is connected between the intrinsic-collector and substrate nodes. This is the same as in SPICE2, or SPICE3, and works well for vertical IC transistor structures. For lateral IC transistor structures there is a third model, LPNP, where the isolation junction capacitance is connected between the intrinsic-base and substrate nodes.

Capture parts

The following table lists the set of bipolar transistor breakout parts designed for customizing model parameters for simulation. These are useful for setting up Monte Carlo and worst-case analyses with device and/or lot tolerances specified for individual model parameters.

Part name	Model type	Property	Property description
QBREAKL	LPNP	AREA MODEL	area scaling factor LNP model name
QBREAKN QBREAKN3 QBREAKN4	NPN	AREA MODEL	area scaling factor NPN model name
QBREAKP QBREAKP3 QBREAKP4	PNP	AREA MODEL	area scaling factor PNP model name

Setting operating temperature

Operating temperature can be set to be different from the global circuit temperature by defining one of the model parameters: T_ABS, T_REL_GLOBAL, or T_REL_LOCAL. Additionally, model parameters can be assigned unique measurement temperatures using the T_MEASURED model parameter. See Bipolar transistor model parameters on page 268 for more information.

Bipolar transistor model parameters

Model level 1

Model parameters[1]	Description	Units	Default
AF	flicker noise exponent		1.0
BF	ideal maximum forward beta		100.0
BR	ideal maximum reverse beta		1.0
CJC	base-collector zero-bias p-n capacitance	farad	0.0
CJE	base-emitter zero-bias p-n capacitance	farad	0.0
CJS (CCS)	substrate zero-bias p-n capacitance	farad	0.0
CN	quasi-saturation temperature coefficient for hole mobility		2.42 NPN 2.20 PNP
D	quasi-saturation temperature coefficient for scattering-limited hole carrier velocity		0.87 NPN 0.52 PNP
EG	bandgap voltage (barrier height)	eV	1.11
FC	forward-bias depletion capacitor coefficient		0.5
GAMMA	epitaxial region doping factor		1E-11
IKF (IK)	corner for forward-beta high-current roll-off	amp	infinite
IKR	corner for reverse-beta high-current roll-off	amp	infinite
IRB	current at which Rb falls halfway to	amp	infinite
IS	transport saturation current	amp	1E-16
ISC (C4) †	base-collector leakage saturation current	amp	0.0
ISE (C2) †	base-emitter leakage saturation current	amp	0.0
ISS	substrate p-n saturation current	amp	0.0
ITF	transit time dependency on Ic	amp	0.0
KF	flicker noise coefficient		0.0

Model parameters[1]	Description	Units	Default
MJC (MC)	base-collector p-n grading factor		0.33
MJE (ME)	base-emitter p-n grading factor		0.33
MJS (MS)	substrate p-n grading factor		0.0
NC	base-collector leakage emission coefficient		2.0
NE	base-emitter leakage emission coefficient		1.5
NF	forward current emission coefficient		1.0
NK	high-current roll-off coefficient		0.5
NR	reverse current emission coefficient		1.0
NS	substrate p-n emission coefficient		1.0
PTF	excess phase @ 1/(2π·TF)Hz	degree	0.0
QCO	epitaxial region charge factor	coulomb	0.0
QUASIMOD	quasi-saturation model flag for temperature dependence if QUASIMOD = 0, then no GAMMA, RCO, VO temperature dependence if QUASIMOD = 1, then include GAMMA, RCO, VO temperature dependence		0
RB	zero-bias (maximum) base resistance	ohm	0.0
RBM	minimum base resistance	ohm	RB
RC	collector ohmic resistance	ohm	0.0
RCO ‡	epitaxial region resistance	ohm	0.0
RE	emitter ohmic resistance	ohm	0.0
TF	ideal forward transit time	sec	0.0
TR	ideal reverse transit time	sec	0.0
TRB1	RB temperature coefficient (linear)	$^{\circ}C^{-1}$	0.0
TRB2	RB temperature coefficient (quadratic)	$^{\circ}C^{-2}$	0.0
TRC1	RC temperature coefficient (linear)	$^{\circ}C^{-1}$	0.0
TRC2	RC temperature coefficient (quadratic)	$^{\circ}C^{-2}$	0.0

Model parameters[1]	Description	Units	Default
TRE1	RE temperature coefficient (linear)	$°C^{-1}$	0.0
TRE2	RE temperature coefficient (quadratic)	$°C^{-2}$	0.0
TRM1	RBM temperature coefficient (linear)	$°C^{-1}$	0.0
TRM2	RBM temperature coefficient (quadratic)	$°C^{-2}$	0.0
T_ABS	absolute temperature	°C	
T_MEASURED	measured temperature	°C	
T_REL_GLOBAL	relative to current temperature	°C	
T_REL_LOCAL	relative to AKO model temperature	°C	
VAF (VA)	forward Early voltage	volt	infinite
VAR (VB)	reverse Early voltage	volt	infinite
VG	quasi-saturation extrapolated bandgap voltage at 0° K	V	1.206
VJC (PC)	base-collector built-in potential	volt	0.75
VJE (PE)	base-emitter built-in potential	volt	0.75
VJS (PS)	substrate p-n built-in potential	volt	0.75
VO	carrier mobility knee voltage	volt	10.0
VTF	transit time dependency on Vbc	volt	infinite
XCJC	fraction of CJC connected internally to Rb		1.0
XCJC2	fraction of CJC connected internally to Rb		1.0
XCJS	fraction of CJS connected internally to Rc		
XTB	forward and reverse beta temperature coefficient		0.0
XTF	transit time bias dependence coefficient		0.0
XTI (PT)	IS temperature effect exponent		3.0

1. For information on T_MEASURED, T_ABS, T_REL_GLOBAL, and T_REL_LOCAL, see .MODEL (model definition) on page 55.

† The parameters ISE (C2) and ISC (C4) can be set to be greater than one. In this case, they are interpreted as multipliers of IS instead of absolute currents: that is, if ISE is greater than one, then it is replaced by ISE·IS. Likewise for ISC.

‡ If the model parameter RCO is specified, then quasi-saturation effects are included.

Distribution of the CJC capacitance

The distribution of the CJC capacitance is specified by XCJC and XCJC2. The model parameter XCJC2 is used like XCJC. The differences between the two parameters are as follows.

Branch	XCJC	XCJC2
intrinsic base to intrinsic collector	XCJC*CJC	XCJC2*CJC
extrinsic base to **intrinsic** collector	(1.0 – XCJC)*CJC	not applicable
extrinsic base to **extrinsic** collector	not applicable	(1.0 – XCJC2)*CJC

When XCJC2 is specified in the range $0 <$ XCJC2 < 1.0, XCJC is ignored. Also, the extrinsic base to extrinsic collector capacitance (Cbx2) and the gain-bandwidth product (Ft2) are included in the operating point information (in the output listing generated during a Bias Point Detail analysis, .OP (bias point) on page 66). For backward compatibility, the parameter XCJC and the associated calculation of Cbx and Ft remain unchanged. Cbx and Ft appears in the output listing only when XCJC is specified.

The use of XCJC2 produces more accurate results because Cbx2 (the fraction of CJC associated with the intrinsic collector node) now equals the ratio of the device's emitter area-to-base area. This results in a better correlation between the measured data and the gain bandwidth product (Ft2) calculated by PSpice.

XCJS, which is valid in the range $0 \leq$ XCJS ≤ 1.0, specifies a portion of the CJS capacitance to be between the external substrate and external collector nodes instead of between the external substrate and internal collector nodes. When XJCS is 1, CJS is applied totally between the external substrate and internal collector nodes. When XCJS is 0, CJS is applied totally between the external substrate and external collector codes.

Model level 2

Model Parameters	Description	Units	Default Value
Level 2: general parameters			
EXAVL	flag for the extended modelling of avalanche currents		0
EXMOD	flag for the extended modelling of the external regions		0

Model Parameters	Description	Units	Default Value
EXPHI	flag for the extended modelling of distributed HF effects in transients		0
MULT	number of parallel transistors modelled together		1.0
Level 2: intrinsic and extrinsic charge and current split parameters			
XCJC	sidewall fraction collector-base depletion capacitance that is under the emitter	farad	32E-03
XCJE	sidewall fraction of the emitter-base depletion capacitance	farad	0.4
XEXT	fraction of external charges between B and C1	coulomb	0.63
XIBI	sidewall fraction of the ideal base current	amp	0.0
Level 2: current parameters			
BF	current gain of ideal forward base current		215.0
BRI (BR)	current gain of ideal reverse base current		7.0
IBF	saturation current of the non-ideal forward base current		2.7E-15
IBR	saturation current of the non-ideal reverse base current	amp	1.0E-15
IK (IKF)	intrinsic transistor high-injection knee current	amp	0.1
IKS	parasitic PNP transistor high-knee current	amp	250.0E-6
IS	intrinsic transistor saturation current	amp	22.0E-18
ISS	parasitic PNP transistor saturation current	amp	48.0E-18
MLF	non-ideality factor of the non-ideal forward base current		2.0
SFH	Voltage describing the curvature of the avalanche current	volt	0.3

Model Parameters	Description	Units	Default Value
VAVL	Voltage for the curvature of the avalanche current	volt	3.0
VEF (VAF)	forward early voltage of the intrinsic transistor	volt	44.0
VER (VAR)	reverse early voltage of the intrinsic transistor	volt	2.5
VLR	non-ideal base current cross-over voltage	volt	0.2
WAVL	effective width of epilayer for avalanche current	m	1.1E-6
Level 2: resistance parameters (variable and constant)			
AXI	smoothing parameters for the epilayer model		0.3
IHC	epilayer critical current for hot-carriers	amp	4.0E-3
RBC	external base constant resistance	ohm	23.0
RBV	pinched base low current resistance (under the emitter)	ohm	18.0
RCC (RC)	external collector constant resistance	ohm	12
RCV	epilayer low current resistance	ohm	150.0
RE	external emitter constant resistance	ohm	5.0
SCRCV	epilayer space charge resistance	ohm	1250.0
Level 2: depletion capacitance parameters			
CBCO	base-collector overlap capacitance	farad	0.0
CBEO	base-emitter overlap capacitance	farad	0.0
CJC	collector-base junction depletion capacitance at zero bias	farad	78.0E-15
CJE	emitter-base junction depletion capacitance at zero bias	farad	73.0E-15
CJS	collector-substrate junction depletion capacitance at zero bias	farad	315.0E-15

Model Parameters	Description	Units	Default Value
MC (MJC)	collector depletion charge current modulation factor		0.5
PC (VJC)	collector-base depletion capacitance grading coefficient		0.5
PE (VJE)	emitter-base depletion capacitance grading coefficient		0.4
PS (VJS)	collector-substrate depletion capacitance grading coefficient		0.34
VDC	built-in diffusion voltage collector-base	volt	0.68
VDE	built-in diffusion voltage emitter-base	volt	0.95
VDS	built-in diffusion voltage emitter-substrate	volt	0.62
XP (XC)	constant fraction of collector-base depletion capacitance	farad	0.35
Level 2: transit time parameters (diffusion charges)			
TAUB	base transmit time	sec	4.2E-12
TAUE	emitter charge transmit time	sec	2.0E-12
TEPI	collector epilayer transmit time	sec	41.0E-12
TAUR	reverse transmit time	sec	520.0E-12
MTAU	emitter charge non-ideality factor		1.0
Level 2: noise parameters			
AF	flickernoise exponent		2.0
KF	ideal base current flickernoise coefficient		2.0E-11
KFN	non-ideal base current flickernoise coefficient		2.0E-11
Level 2: temperature parameters			
AB	temperature coefficient of RB (pinched base low current resistance)	$^{\circ}C^{-1}$	1.0
AC	temperature coefficient of RCC (external collector constant resistance)	$^{\circ}C^{-1}$	2.0

Model Parameters	Description	Units	Default Value
AE	temperature coefficient of RE (external emitter constance resistance)	$^{\circ}C^{-1}$	0.0
AEPI	temperature coefficient of RCV (epilayer low current resistance)	$^{\circ}C^{-1}$	2.5
AEX	temperature coefficient of RBC (external base constant resistance)	$^{\circ}C^{-1}$	0.62
AQBO	zero bias base charge temperature coefficient	$^{\circ}C^{-1}$	0.3
AS	temperature coefficient of the mobility related to the substrate currents	$^{\circ}C^{-1}$	1.58
DVGBF	band-gap voltage difference for forward current gain	volt	0.05
DVGBR	band-gap voltage difference for reverse current gain	volt	0.045
DVGTE	band-gap voltage difference for emitter charge	volt	0.05
DTA	difference between device and ambient temperature	$^{\circ}C$	0.0
TREF	reference temperature	$^{\circ}C$	25.0
	if a value is defined for .temp, it will override the value specified in the TREF parameter		
VGB	base band-gap voltage	volt	1.17
VGC	collector band-gap voltage	volt	1.18
VGJ	base-emitter junction recombination band-gap voltage	volt	1.15
VGS	substrate band-gap voltage	volt	1.20
Level 2: SiGe parameters			
DEG	base band-gap difference		0.0
XREC	base recombination prefactor		0.0

Bipolar transistor equations

Model level 1

The equations in this section describe an NPN transistor. For the PNP and LPNP devices, reverse the signs of all voltages and currents.

The following variables are used:

Vbe	= intrinsic base-intrinsic emitter voltage
Vbc	= intrinsic base-intrinsic collector voltage
Vbs	= intrinsic base-substrate voltage
Vbw	= intrinsic base-extrinsic collector voltage (quasi-saturation only)
Vbx	= extrinsic base-intrinsic collector voltage
Vce	= intrinsic collector-intrinsic emitter voltage
Vjs	= (NPN) intrinsic collector-substrate voltage = (PNP) intrinsic substrate-collector voltage = (LPNP) intrinsic base-substrate voltage
Vt	= $k \cdot T/q$ (thermal voltage)
k	= Boltzmann's constant
q	= electron charge
T	= analysis temperature (˚K)
Tnom	= nominal temperature (set using the TNOM option)

Other variables are listed in Bipolar transistor model parameters on page 268.

Note: Positive current is current flowing into a terminal.

Bipolar transistor equations for DC current

Ib = base current = $area \cdot (\text{Ibe1}/\text{BF} + \text{Ibe2} + \text{Ibc1}/\text{BR} + \text{Ibc2})$

Ic = collector current = $area \cdot (\text{Ibe1}/\text{Kqb} - \text{Ibc1}/\text{Kqb} - \text{Ibc1}/\text{BR} - \text{Ibc2})$

Ibe1 = forward diffusion current = $\text{IS} \cdot (e^{\text{Vbe}/(\text{NF} \cdot \text{Vt})} - 1)$

Ibe2 = non-ideal base-emitter current = $\text{ISE} \cdot (e^{\text{Vbe}/(\text{NE} \cdot \text{Vt})} - 1)$

Bipolar transistor equations for DC current

Ibc1 = reverse diffusion current = $IS \cdot (e^{Vbc/(NR \cdot Vt)} - 1)$

Ibc2 = non-ideal base-collector current = $ISC \cdot (e^{Vbc/(NC \cdot Vt)} - 1)$

Kqb = base charge factor = $Kq1 \cdot (1 + (1 + 4 \cdot Kq2)^{NK})/2$

$Kq1 = 1/(1 - Vbc/VAF - Vbe/VAR)$

$Kq2 = Ibe1/IKF + Ibc1/IKR$

Is = substrate current = $area \cdot ISS \cdot (e^{Vjs/(NS \cdot Vt)} - 1)$

Rb = actual base parasitic resistance

Case 1

for: IRB = infinite (default value)

then: $Rb = (RBM + (RB - RBM)/Kqb)/area$

Case 2

For: IRB > 0

then:

$$Rb = \left(RBM + 3 \cdot (RB - RBM) \cdot \frac{\tan(x) - x}{x \cdot (\tan(x))^2}\right)/area$$

where:

$$x = \frac{(1 + (144/\pi^2) \cdot Ib/(area \cdot \mathbf{IRB}))^{1/2} - 1}{(24/\pi^2) \cdot (Ib/(area \cdot \mathbf{IRB}))^{1/2}}$$

Bipolar transistor equations for capacitance

All capacitances, except Cbx, are between terminals of the intrinsic transistor which is inside of the collector, base, and emitter parasitic resistances. Cbx is between the intrinsic collector and the extrinsic base.

base-emitter capacitance
Cbe = base-emitter capacitance = $Ctbe + area \cdot Cjbe$
Ctbe = transit time capacitance = $tf \cdot Gbe$

tf = effective TF = $TF \cdot (1+XTF \cdot (Ibe1/(Ibe1+area \cdot ITF))^2 \cdot e^{Vbc/(1.44 \cdot VTF)})$

Gbe = DC base-emitter conductance = $(d\text{Ibe})/(d\text{Vb})$

Ibe = Ibe1 + Ibe2

$Cjbe = CJE \cdot (1-Vbe/VJE)^{-MJE}$	*IF*	$Vbe \le FC \cdot VJE$
$Cjbe = CJE \cdot (1-FC)^{-(1+MJE)} \cdot (1-FC \cdot (1+MJE) + MJE \cdot Vbe/VJE)$	*IF*	$Vbe > FC \cdot VJE$

base-collector capacitance

Cbc = base-collector capacitance = Ctbc + $area \cdot XCJC \cdot Cjbc$

Ctbc = transit time capacitance = $TR \cdot Gbc$

Gbc = DC base-collector conductance = $(d\text{Ibc})/(d\text{Vbc})$

$Cjbc = CJC \cdot (1-Vbc/VJC)^{-MJC}$	*IF*	$Vbc < FC \cdot VJC$
$Cjbc = CJC \cdot (1-FC)^{-(1+MJC)} \cdot (1\ FC \cdot (1+MJC)+MJC \cdot Vbc/VJC)$	*IF*	$Vbc > FC \cdot VJC$

extrinsic-base to intrinsic-collector capacitance

Cbx = extrinsic-base to intrinsic-collector capacitance = $area \cdot (1-XCJC) \cdot Cjbx$

$Cjbx = CJC \cdot (1-Vbx/VJC)^{-MJC}$	*IF*	$Vbx \le FC \cdot VJC$
$Cjbx = CJC \cdot (1-FC)^{-(1+MJC)} \cdot (1-FC \cdot (1+MJC)+MJC \cdot Vbx/VJC)$	*IF*	$Vbx > FC \cdot VJC$

substrate junction capacitance

Cjs = substrate junction capacitance = $area \cdot Cjjs$

$Cjjs = CJS \cdot (1-Vjs/VJS)^{-MJS}$(assumes FC = 0)	*IF*	$Vjs \le 0$
$Cjjs = CJS \cdot (1+MJS \cdot Vjs/VJS)$	*IF*	$Vjs > 0$

Bipolar transistor equations for quasi-saturation effect

Quasi-saturation is an operating region where the internal base-collector metallurgical junction is forward biased, while the external base-collector terminal remains reverse biased.

This effect is modeled by extending the intrinsic Gummel-Poon model, adding a new internal node, a controlled current source, Iepi, and two controlled capacitances, represented by the charges Qo and Qw. These additions are only included if the model parameter RCO is specified. See reference [3] of Model level 2 on page 280 for the derivation of this extension.

$$\text{Iepi} = \mathit{area}\cdot(\text{VO}\cdot(\text{Vt}\cdot(\text{K(Vbc)}-\text{K(Vbn)}-\ln((1+\text{K(Vbc)})/(1+\text{K(Vbn)})))+\text{Vbc}-\text{Vbn}))/\text{RCO}\cdot(|\text{Vbc}-\text{Vbn}|+\text{VO})$$

$$\text{Qo} = \mathit{area}\cdot\text{QCO}\cdot(\text{K(Vbc)}-1-\text{GAMMA}/2)$$

$$\text{Qw} = \mathit{area}\cdot\text{QCO}\cdot(\text{K(Vbn)}-1-\text{GAMMA}/2)$$

where

$$\text{K(v)} = (1+\text{GAMMA}\cdot e^{(\text{v/Vt})})^{1/2}$$

Bipolar transistor equations for temperature effect

$$\text{IS(T)} = \text{IS}\cdot e^{(\text{T/Tnom}-1)\cdot\text{EG}/(\text{N}\cdot\text{Vt})}\cdot(\text{T/Tnom})^{\text{XTI/N}}$$

where N = 1

$$\text{ISE(T)} = (\text{ISE}/(\text{T/Tnom})^{\text{XTB}})\cdot e^{(\text{T/Tnom}-1)\cdot\text{EG}/(\text{NE}\cdot\text{Vt})}\cdot(\text{T/Tnom})^{\text{XTI/NE}}$$

$$\text{ISC(T)} = (\text{ISC}/(\text{T/Tnom})^{\text{XTB}})\cdot e^{(\text{T/Tnom}-1)\cdot\text{EG}/(\text{NC}\cdot\text{Vt})}\cdot(\text{T/Tnom})^{\text{XTI/NC}}$$

$$\text{ISS(T)} = (\text{ISS}/(\text{T/Tnom})^{\text{XTB}})\cdot e^{(\text{T/Tnom}-1)\cdot\text{EG}/(\text{NS}\cdot\text{Vt})}\cdot(\text{T/Tnom})^{\text{XTI/NS}}$$

$$\text{BF(T)} = \text{BF}\cdot(\text{T/Tnom})^{\text{XTB}}$$

$$\text{BR(T)} = \text{BR}\cdot(\text{T/Tnom})^{\text{XTB}}$$

$$\text{RE(T)} = \text{RE}\cdot(1+\text{TRE1}\cdot(\text{T}-\text{Tnom})+\text{TRE2}\cdot(\text{T}-\text{Tnom})^2)$$

$$\text{RB(T)} = \text{RB}\cdot(1+\text{TRB1}\cdot(\text{T}-\text{Tnom})+\text{TRB2}\cdot(\text{T}-\text{Tnom})^2)$$

$$\text{RBM(T)} = \text{RBM}\cdot(1+\text{TRM1}\cdot(\text{T}-\text{Tnom})+\text{TRM2}\cdot(\text{T}-\text{Tnom})^2)$$

$$\text{RC(T)} = \text{RC}\cdot(1+\text{TRC1}\cdot(\text{T}-\text{Tnom})+\text{TRC2}\cdot(\text{T}-\text{Tnom})^2)$$

$$\text{VJE(T)} = \text{VJE}\cdot\text{T/Tnom} - 3\cdot\text{Vt}\cdot\ln(\text{T/Tnom}) - \text{Eg(Tnom)}\cdot\text{T/Tnom} + \text{Eg(T)}$$

$$\text{VJC(T)} = \text{VJC}\cdot\text{T/Tnom} - 3\cdot\text{Vt}\cdot\ln(\text{T/Tnom}) - \text{Eg(Tnom)}\cdot\text{T/Tnom} + \text{Eg(T)}$$

$$\text{VJS(T)} = \text{VJS}\cdot\text{T/Tnom} - 3\cdot\text{Vt}\cdot\ln(\text{T/Tnom}) - \text{Eg(Tnom)}\cdot\text{T/Tnom} + \text{Eg(T)}$$

where Eg(T) = silicon bandgap energy = $1.16 - .000702\cdot T^2/(T+1108)$

$$\text{CJE(T)} = \text{CJE}\cdot(1+\text{MJE}\cdot(.0004\cdot(\text{T}-\text{Tnom})+(1-\text{VJE(T)}/\text{VJE})))$$

$$\text{CJC(T)} = \text{CJC}\cdot(1+\text{MJC}\cdot(.0004\cdot(\text{T}-\text{Tnom})+(1-\text{VJC(T)}/\text{VJC})))$$

$$\text{CJS(T)} = \text{CJS}\cdot(1+\text{MJS}\cdot(.0004\cdot(\text{T}-\text{Tnom})+(1-\text{VJS(T)}/\text{VJS})))$$

Note: The development of the temperature dependencies for the quasi-saturation model parameters GAMMA, RCO, and VO are described in Model level 2 on page 280, (reference [3]). These temperature dependencies are only used when the model parameter QUASIMOD = 1.0.

$$\mathrm{GAMMA}(T) = \mathrm{GAMMA}(Tnom)\cdot(T/Tnom)^{3}\cdot\exp(-qVG/k\cdot(1/T - 1/Tnom))$$

$$\mathrm{RCO}(T) = \mathrm{RCO}(Tnom)\cdot(T/Tnom)^{CN}$$

$$\mathrm{VO}(T) = \mathrm{VO}(Tnom)\cdot(T/Tnom)^{CN - D}$$

Bipolar transistor equations for noise

Noise is calculated assuming a 1.0-hertz bandwidth, using the following spectral power densities (per unit bandwidth):

	parasitic resistances thermal noise
RC	$Ic^2 = 4\cdot k\cdot T/(RC/area)$
RB	$Ib^2 = 4\cdot k\cdot T/RB$
RE	$Ie^2 = 4\cdot k\cdot T/(RE/area)$
	base and collector currents shot and flicker noise
IB	$Ib^2 = 2\cdot q\cdot Ib + KF\cdot Ib^{AF}/FREQUENCY$
IC	$Ic^2 = 2\cdot q\cdot Ic$

Model level 2

The equations in this section describe a NPN transistor and use the following variables:

I_{c1c2} =epilayer current
I_{b1b2} =pinched-base current
I_{b1} =ideal forward base current
I_{b2} =non-ideal forward base current
I_{sb1} =ideal side-wall base current

I_{sub}	=substrate current
V_{b2e1}	=internal base-emitter bias
V_{b2c2}	=internal base-collector bias
V_{b2c1}	=internal base-collector bias including epilayer
V_{b1c1}	=external base-collector bias without contact resistances
V_{e1e}	=bias over emitter resistance
V_t	$= k \cdot T / q$ (thermal voltage)
k	=Boltzmann's constant
q	=electron charge

Main current

The Early effect current due to the variation in the width of the base is given by the following equations.

Forward current

$$= Is \cdot e^{(Vb2e1)/(V}$$

Reverse current

$$= Is \cdot e^{(Vb2c2)/(V}$$

Main current

$$In = \frac{If - Ir}{Qb}$$

The base currents are given by the following equations.

Ideal forward base current

$$1 = \frac{Is}{Bf} \cdot (e^{(Vb2e1)/(Vt)} -$$

Non-ideal forward base current

$$2 = Ibf \cdot (e^{(Vb2e1)/(Mlf \cdot Vt)} -$$

Ideal reverse base current

$$= \frac{Is}{Bri} \cdot \frac{2 \cdot (e^{(Vb1c1)/(Vt)} - 1)}{1 + \sqrt{1 + (Is \cdot e^{(Vb1c1)/(Vt)})/(}}$$

Non-ideal reverse base current

$$= I_{br} \cdot \frac{e^{(Vb1c1)/(Vt)} - 1}{e^{(Vb1c1)/(2 \cdot Vt)} + e^{(Vlr)/(2 \cdot}}$$

In addition to main and base current, this model has an avalanche current, given by the following equation.

$$Iavl = Ic1c2 \times G \cdot (Vb1c1, Ic1c2)$$

where G is the generation factor.

The substrate current, Isub models the parasitic PNP main current in reverse bias.

$$Isub = \frac{2 \cdot Iss \cdot (e^{(Vb1c1)/(Vt)} - 1)}{1 + \sqrt{1 + (Is \cdot e^{(Vb1c1)/(Vt)})/(Ikb)}}$$

The base resistance is modeled as an extrinsic part, RBC, and a variable intrinsic part, RBV. The current through the base resistance is a function of the applied voltage and is given by the following equation.

$$b2 = \frac{Qb}{3 \cdot Rbv} \cdot [2 \cdot Vt \cdot (e^{(Vb1b2)/(Vt)} - 1) + Vb1$$

Depletion capacitance

The depletion capacitance at the emitter-base junction is given by the following equation

$$.Cje_T = (Cje)\left(\frac{Vde}{Vde_T}\right)^{PE}$$

The depletion capacitance at the collector -substrate junction is given by the following equation:

$$Cjs_T = Cjs\left(\frac{Vds}{Vds_T}\right)^{PS}$$

The depletion capacitance at the collector-base junction capacitance is given by the following equation:

$$Cjc_T = C_{jc}\left[(1 - Xp)\left(\frac{Vdc}{Vdc_T}\right)^{PC} + Xp\right]$$

Diffusion charges

Equations for diffusion charges depend upon the current transit time. In low current, the base and the emitter contributions are modelled by the following equations.

Base contribution

$$Qbe = Q1Tb \cdot If \cdot \frac{2}{1 + \sqrt{1 + 4 \cdot (If)/(Ik)}}$$

Emitter contribution

$$Qe = Te \cdot Is \cdot e^{(Vb2e1)/(Mt \cdot Vt)}$$

The high current contributions are due to a finite voltage drop in the collector epilayer and base widening given by the following equations.

$$Qbc = q1 \cdot Tb \cdot Ir \cdot \frac{2}{1 + \sqrt{1 + 4 \cdot (Ir)/(Ik)}}$$

$$Qepi = Tepi \cdot \left(\frac{Xi}{Wepi}\right)^2 \cdot Iepi$$

Excess phase shift

The excess phase shift is an optional effect in Mextram and is modelled only if EXPHI is 1. Both the collector and emitter contributes to the phase shift.

The phase shift is given by the following equations:

$$Qbe = q \cdot Aem\int_0^{Wb} n(X)(1 - x/(Wb))dx$$

$$Qbc = q \cdot Aem\int_0^{Wb} n(X)(x/(Wb))dx$$

Where,

$$n(X) = n(0) \cdot (\sinh[\lambda(1 - x/(Wb))])/(\sinh\lambda)$$

and

$$\lambda = (j\omega Wb^2)/(Dn)$$

The current to the emitter and the collector are given by:

$$I(0) = Idc + j\omega\frac{2}{3}Qtot = \left(Idc + \frac{d\left(\frac{2}{3}Qtot\right)}{dt}\right)$$

$$I(Wb) = Idc - j\omega\frac{1}{3}Qtot = \left(Idc - \frac{d\left(\frac{1}{3}Qtot\right)}{dt}\right)$$

The AC current crowding or the extra effect in the lateral direction is modelled by the following equation:

$$Qb1b2 = \frac{1}{5} \cdot Vb1b2 \cdot (Cte + Cbe + Ce)$$

Noise model equations

The two types of noise, thermal noise due to parasitic resistance and flicker noise due to base and collector currents, are modelled by the following equations.

Parasitic resistances thermal noise

$$Ic = 4 \cdot k \cdot T/((Rc)/(MULT))$$

$$Ib = 4 \cdot k \cdot T/(Rb)$$

$$Ie = 4 \cdot k \cdot T/((Re)/(MULT))$$

Base and collector currents shot and flicker noise

$$Ib = 2 \cdot q \cdot Ib + Kf \cdot (Ib)/(FREQUENCY)$$

$$Ic = 2 \cdot q \cdot Ic$$

Bipolar transistor equations for temperature effect

$$Ist = Is(Tn)^{4 - Ab - Abq0} e^{(-Vgb)/V\Delta t}$$

$$Ibft = Ibf(Tn)^{6 - 2Mlf} e^{(-Vgf)/((Mlf)(V\Delta t))}$$

$$Ibrt = Ibr(Tn)^{2} e^{(-VGC)/(2V\Delta T)}$$

$$Isst = Iss(Tn)^{4 - AS} e^{(-VGS)/(V\Delta T)}$$

For power gains, the model uses bandgap difference between emitter and base $(dVG\beta F)$ or base and collector $(dVG\beta R)$.

$$\beta ft = \beta f(Tn)^{Ae - Ab - Aqb0} e^{(-dVG\beta F)/(V\Delta T)}$$

$$\beta rit = \beta rIe^{(-dVG\beta R)/(V\Delta T)}$$

Resistances are not constant over temperature. As a result, the resistances have parameters linked to the temperature dependence.

$$Ret = Re(Tn)^{Ae}$$

$$Rbvt = Rbv(Tn)^{Ab - Aqb0}$$

$$Rbct = Rbc(Tn)^{Aex}$$

$$Rcct = Rcc(Tn)^{Ac}$$

$$Rcvt = Rcv(Tn)^{Aepi}$$

$$Vdt = (-3Vt)\ln Tn + (Vd)(Tn) + (1 - Tn)Vg$$

The following equation gives the scaling factor of capacitances after temperature scaling of the diffusion voltages is done.

$$Cjt = Cj\left(\frac{Vd}{Vdt}\right)^{\rho}$$

where ρ is the grading coefficient.

Quasi saturation/high injection effect equations

Quasi saturation or high injection effect can occur due ohmic resistance or space-charge limited resistance in the epilayer region. If the resistance is due to space-charge, the effect is also known as Kirk effect.

The quasi saturation voltage drop is given by the following equation:

$$Vqs = Vdc - Vb2c1 = -\int_0^{Wepi} E(X)dx$$

The current is given by the following equation:

$$Iqs = (Vqs)/(Rcv)$$

For higher currents, the equation is given by:

$$Iqs = (Vqs)/(SCRcv)$$

Current crowding equations

Following is the general DC current crowding equation:

$$I(x) = \frac{2 \cdot Vt \cdot Lem}{\rho \cdot Hem} Z\tan[Z(1 - x/(Hem))]$$

where,

L_{em}	=emitter length
H_{em}	=emitter width
ρ	=pinch resistance
Z	=integration constant

For the boundary condition, I(x=Hem)=0, the equation is:

$$Ib = \frac{2 \cdot Vt \cdot Lem}{\rho \cdot Hem} Z \tan Z$$

The voltage is given by the following equation:

$$e^{V/(Vt)} = \frac{Z}{\tan Z \cos^2[Z(1 - x/(Hem))]}$$

In the low current limit Z is small and the equation is:

$$\frac{Vb1b2}{Ib} = \frac{\rho Hem}{3Lem} = Rbv$$

In the high current limit $Z \rightarrow \pi/2$ and the equation is:

$$\left(e^{(Vb1b2)/(Vt)} = \frac{Z \tan Z}{\sin Z}\right) \rightarrow \left(Z \tan Z = Ib \frac{\rho Hem}{2VtLem}\right)$$

The current is given by:

$$Ib = \frac{2Vt}{3Rbv} e^{(Vb1b2)/(Vt)}$$

By interpolating between the high and low current limits, we can derive the following equation:

$$Ib = \frac{1}{3Rbv}[2Vt(e^{(Vb1b2)/(Vt)} - 1) + Vb1b2]$$

The resistance seen by the current is given by the following equations:

$$Rb2 = \frac{3Rbv}{qb}$$

$$Ib1b2 = \frac{1}{Rb2}[2Vt(e^{(Vb1b2)/(Vt)} - 1) + Vb1b2]$$

Bipolar transit time equations

The transit time for the base for closely related knee current is given by the following equation:

$$TAUb = TAUb \cdot tn^{Aqb0 + Ab - 1}$$

Similarly, the transit time for the epilayer is given by the following equation:

$$TAUepit = TAUepi \cdot tn^{Aepi - 1}$$

The reverse transmit time is given by the following equation:

$$TAUrt = TAUr \cdot \frac{TAUbt + TAUepit}{TAUb + TAUepi}$$

The emitter charge is given by the following equation:

$$Qe = TAUe \cdot \sqrt{IsIk} \cdot e^{(Vb2e1)/(2Vt)}$$

Therefore, the emitter transit time is given by the following equation:

$$TAUet = TAUe \cdot tn^{Ab - 2} \cdot \exp[(-dVgtaue)/(V\Delta t)]$$

References

For more information on bipolar transistor models, refer to:

[1] Ian Getreu, *Modeling the Bipolar Transistor*, Tektronix, Inc. part# 062-2841-00.

For a generally detailed discussion of the U.C. Berkeley SPICE models, including the bipolar transistor, refer to:

[2] P. Antognetti and G. Massobrio, *Semiconductor Device Modeling with SPICE*, McGraw-Hill, 1988.

For a description of the extension for the quasi-saturation effect, refer to:

[3] G. M. Kull, L. W. Nagel, S. W. Lee, P. Lloyd, E. J. Prendergast, and H. K. Dirks, “A Unified Circuit Model for Bipolar Transistors Including Quasi-Saturation Effects,” *IEEE Transactions on Electron Devices*, ED-32, 1103-1113 (1985).

For more information on the Mextram model, refer to:

[3]J.C.J. Paasschens, W.J. Kloosterman, and R. v.d. Toorn, *Model derivation of Mextram 504 - The physics behind the model*, Koinklijke Philips Electronics N.V. 2002

For a comparison of Mextram and the Gummel-Poon model, refer to:

[4]J.C.J. Paasschens and R. v.d. Toorn, *Introduction to and Usage of the Bipolar Transistor Model Mextram*, Koninklijke Philips Electronics N.V. 2002