Vorstellung des Bipolar-Transistormodells SQ3 von Siemens und Vergleich von SQ3 mit SGP und VBIC95

Für das Foundary-Geschäft ist in Zukunft der Übergang zu einem leistungsfähigen, international etablierten und in jedem Designsystem verfügbaren Bipolar-Transistormodell erforderlich.

- ✶ Überblick über das bei Siemens verwendete Inhouse-BJT-Modell SQ3.
- ✶ Vergleich der grundlegenden Modellierungsideen von SQ3, SGP und VBIC95.
- ✶ Überlegungen, unter welchen Bedingungen ein Übergang auf ein international standardisiertes Bipolarmodell möglich und sinnvoll ist.

Anforderungen an ein neues Device Modell um internationale Akzeptanz zu finden.

- Wesentliche Verbesserung der Modellierungsgenauigkeit gegenüber etablierten Modellen.
- Verfügbarkeit in allen gängigen Simulatoren.
- Numerische Stabilität des Modells auch bei der Simulation großer Schaltungsblöcke.
- Akzeptable Simulations-geschwindigkeit.
- Skalierbarkeit und “Worst-case”-Tauglichkeit des Modells.
- Intuitives Modellverständnis.
- Unaufwendige Gewinnung von Parametersätzen mit bereits produktiv eingesetzten Extraktionsverfahren.
- Direkte Abbildung der Devicephysik auf verständliche Gleichungen.
- Verfügbarkeit einer kontinuierlichen Wartung, Pflege und Dokumentation sowie technischer Unterstützung durch ein unabhängiges Institut oder eine anerkannte Universität.
- Weiterentwicklungsperspektiven für das Modell im Hinblick auf kommende Technologiefortschritte.

Requirements for a new, international accepted device model

- ✶ Significant improvement of simulation accuracy compared to established simulation models
- ✶ Availability in all common used circuit simulation programs.
- ✶ Numerical stability (everywhere).
- ✶ Short simulation time.
- ✶ Scalable model.
- ✶ Intuitive model understanding for experienced model users.
- ✶ "Worst-case" capability.
- ✶ Downward compatibility of extraction procedure for model parameter extraction.
- ✶ Physically based model equations.
- ✶ Central and commonly accepted model maintenance by an independent Institute an approved University.
- ✶ Perspectives for continuous model advancement.
- ✶ Good (technical) model documentation.

Anforderungen an einen neuen Bipolar - Modellstandard für Sub-µ BiCMOS-Prozesse

✶ Mindestanforderungen

⇒ Modellierung des/der parasitären Transistoren und Effekte.

⇒ Modellierung der verteilten Natur des Basis-Emitter Komplexes (Verteiltes RC-Netzwerk).

⇒ Temperaturmodellierung der DC- und AC-Parameter im Bereich $-40°C \le T \le 150°C$.

⇒ Korrekte Modellierung der Transitfrequenz

- in abhängig von der Kollektorspannung $f_T=f_T(U_{BC})$
- im Hochstrombereich bis zu Kollektorströmen $I_C = 3*I_C(@f_{Tmax})$

⇒ Rauschmodell vergleichbar Spice.

✶ Wichtige Zusatzanforderungen

⇒ Modellierung der spannungsabhaengigkeit der Earlyspannung.

⇒ Modellierung der Avalanchmultiplikation und der Durchbrüche.

⇒ Korrekte Modellierung der Quasisaettigung.

⇒ Verbessertes Kapazitätsmodell welches die Sperrschichtkapazität in Flußpolung besser modelliert und zusätzlich die modellierung von konstanten Sitzkapazitäten ermöglicht.

⇒ Skalierbarkeit des Modells für Transistor-Längenflöten.

Anforderungen an einen neuen Bipolar - Modellstandard für Sub-µ BiCMOS-Prozesse

- ✶ Wünschenswerte Verbesserungen:
  - ⇒ Bessere Modellierung des Transistor-Reversebetriebs.
  - ⇒ Modellierung der Selbsterwärmung des Transistors.
  - ⇒ Aufteilung der Basis-Kollektor und der Kollektor-Substratkapazität in Rand und Bodenanteil.
  - ⇒ Modellierung von Junction-Leckströmen und deren Temperaturabhaengigkeit bei Sperrpolung des PN-Übergangs im Bereich von -40°C ≤ T ≤ 200°C.
  - ⇒ Verbessertes Substratmodell unter Berücksichtigung des dielektrischen Kapazitätsbelags des Substrats.
  - ⇒ Eignung des Modells für statistische Analysen und für „Worst-Case“ Untersuchungen.
  - ⇒ Erweiterung des “Exess-Phase” Modells auf Transientenanalysen und exakte implementierung einer Allpaßfunktion die zu einer Zeit- bzw. Phasenverschiebung des Transportstromes führt.

Comparison of Siemens SQ3 and VBIC 95 Bipolar Transistor Models

In 1995 the new bipolar transistor model VBIC95 was introduced to become a new world wide standard for modeling and characterization.

VBIC is in many aspects compatible with the current aging SGP standard and so circuit designers and modeling engineers can carry on there understanding of BJT-Models.

Siemens HL would like to support in the future a world wide standard model if

- ➲ model accuracy and performance,
- ➲ availability and support in the most important simulators,
- ➲ numerical stability and efficiency,

is comparable to our Inhouse-BJT-model SQ3.

Subcircuit-Models vs. Complet-Device Modells

	Advantages	Disadvantages
Subcircuit Model	Great Modeling	➢ One transistor consists of a lot of circuit elements ➢ More nodes than necesarry
One-Transistor Model	➢ No redundance ➢ Easer Parameter handling ➢ Higher simulation efficience ➢	Not flexible in the use of other devices

Subcircuit Model of NPN

Q1: active npn transistor

Q2: parasitic substrate pnp

Compact BJT Model:

Siemens SQ3 or

SGP (Standard Berkeley)

$RE = R_{ei} + R_{ex0}$

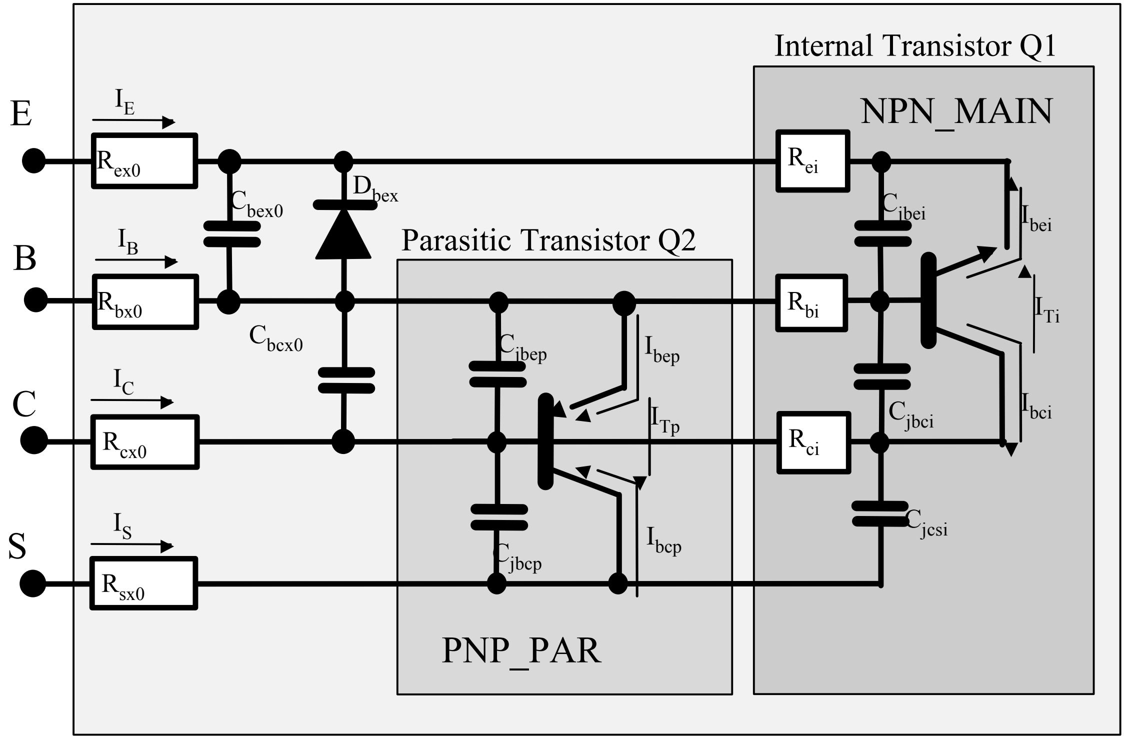
$RB = R_{bi}(Q1) + R_{bx0}$

$RC = R_{ci}(I_c) + R_{cx0}$

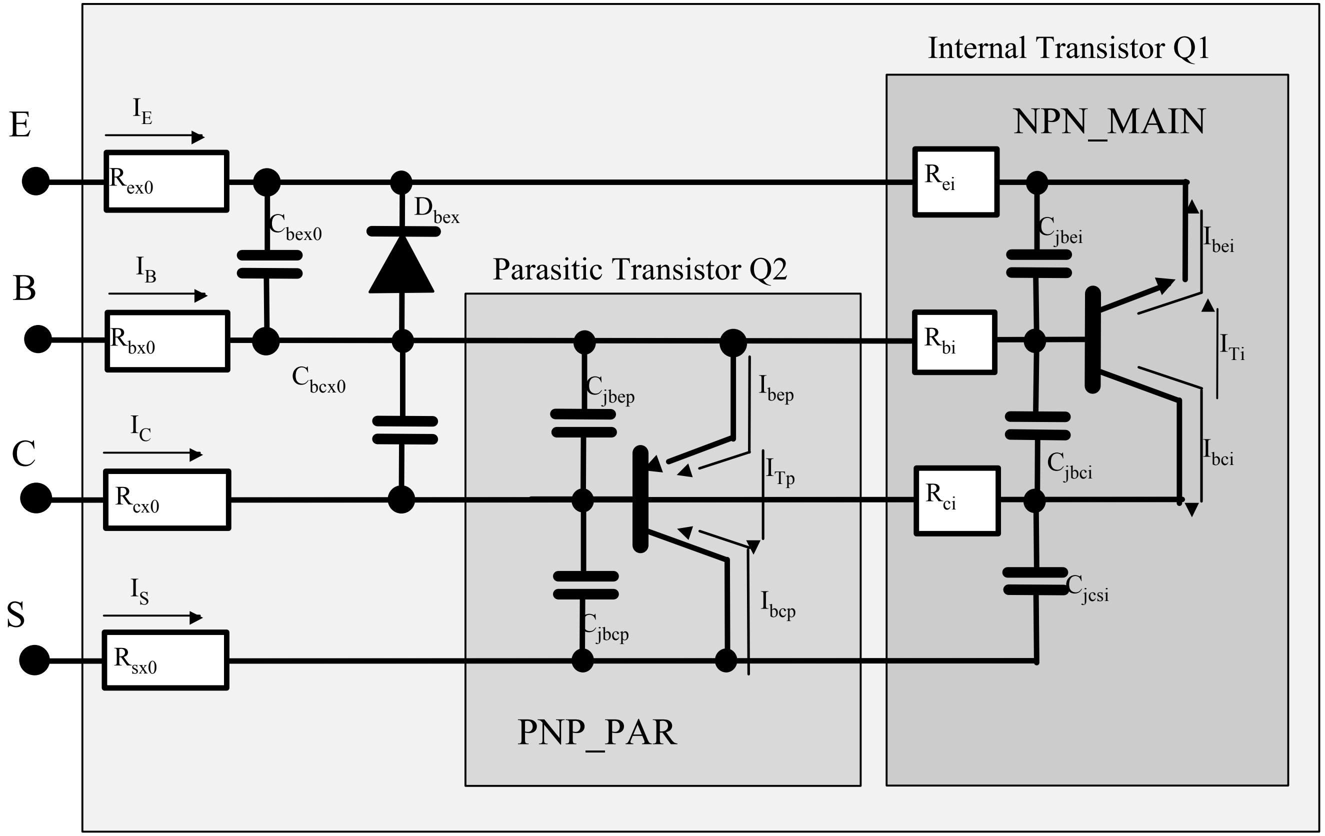
$CJE = C_{jbei}(Q1) + C_{jD}(D_{bex}) + C_{bex0}$

$CJC = C_{jbci}(Q1) + C_{jbep}(Q2) + C_{bcx0}$

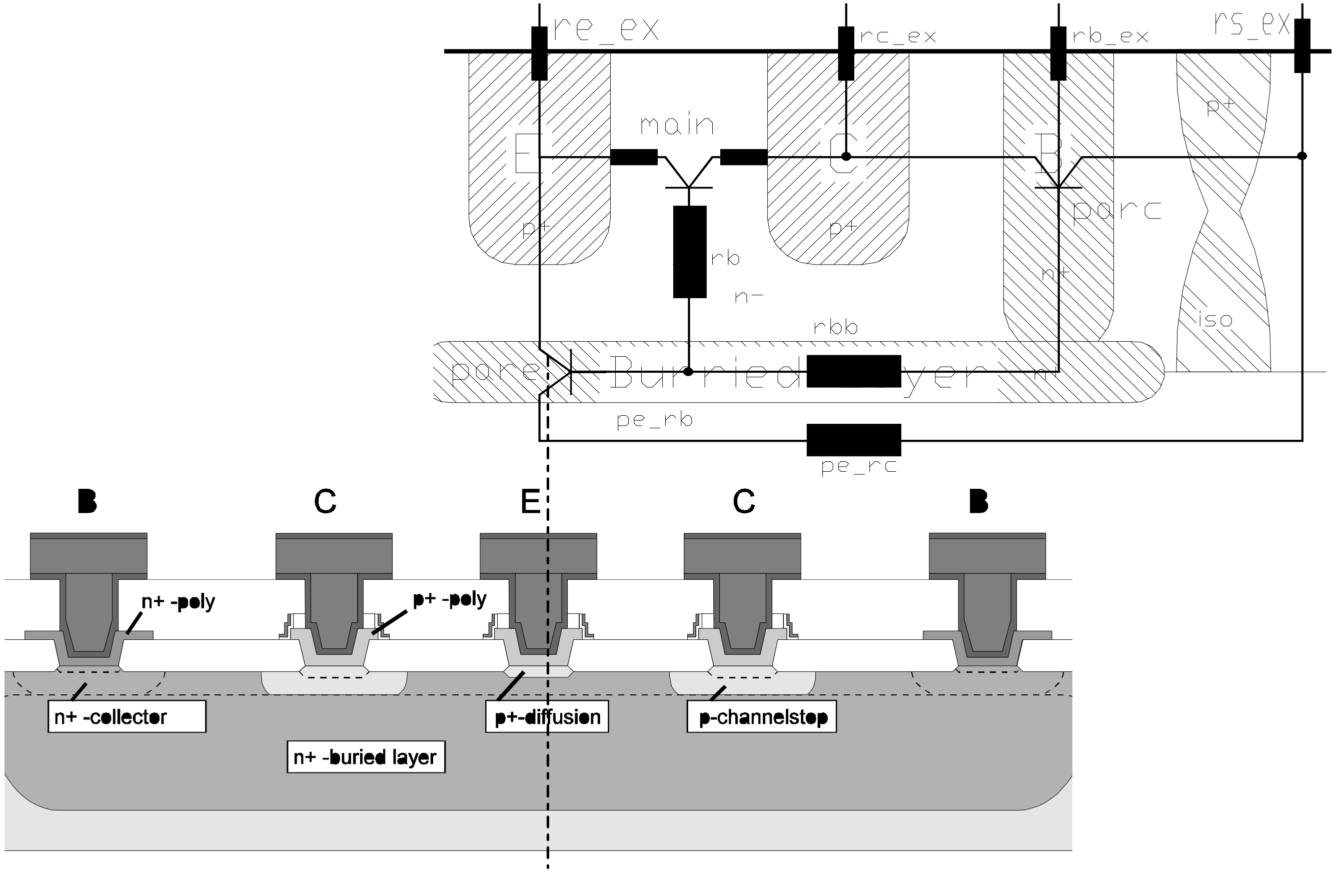
$CJS = C_{jcsi}(Q1) + C_{jbcp}(Q2)$

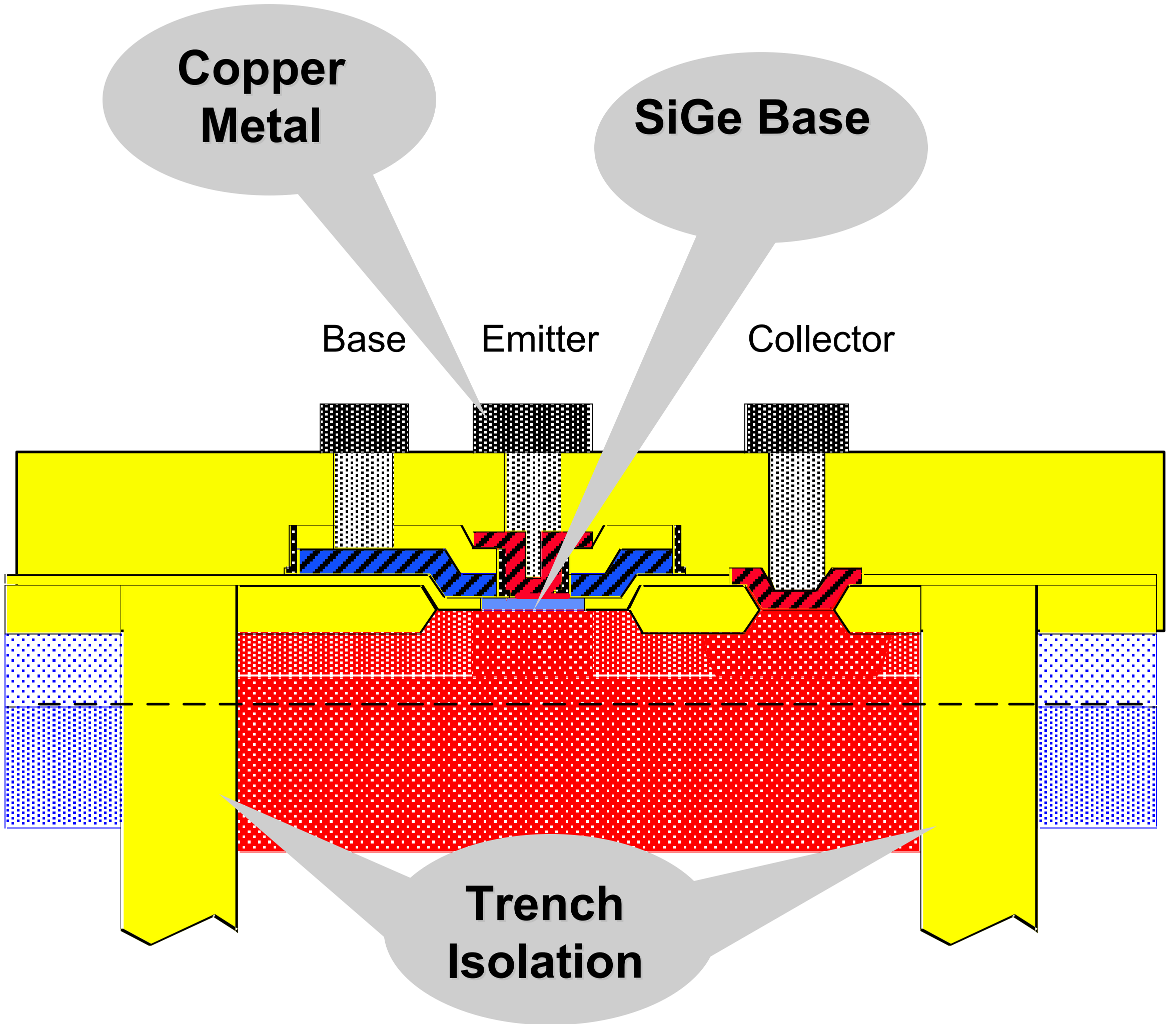


Siemens NPN-Subcircuit Model



3-Transistor Subcircuit Model of Lateral PNP




Copper Metal
SiGe Base
Base
Emitter
Collector
Trench Isolation

Forward and Reverse Transport Current Models

- SGP: $$I_T = \frac{I_{tf} - I_{tr}}{q_b} = \frac{IS}{q_b} \cdot \left[\left(e^{\frac{V_{be}}{NF \cdot V_T}} - 1 \right) - \left(e^{\frac{V_{bc}}{NR \cdot V_T}} - 1 \right) \right]$$

- SQ3: $$I_T = \frac{I_{tf} - I_{tr}}{q_b} = \frac{IS}{q_b} \cdot \left[\left(e^{\frac{V_{be}}{V_T}} - 1 \right) - \left(e^{\frac{V_{bc}}{V_T}} - 1 \right) \right]$$

- VBIC: $$I_{Ti} = \frac{I_{tfi} - I_{tri}}{q_{bi}} = \frac{IS}{q_b} \cdot \left[\left(e^{\frac{V_{bei}}{NF \cdot V_T}} - 1 \right) - \left(e^{\frac{V_{bci}}{NR \cdot V_T}} - 1 \right) \right]$$

$$I_{Tp} = \frac{I_{tfp} - I_{trp}}{q_{bp}} = \frac{ISP}{q_{bp}} \cdot \left[\left(WSP \cdot e^{\frac{V_{bep}}{NFP \cdot V_T}} + (1 - WSP) \cdot e^{\frac{V_{bci}}{NFP \cdot V_T}} - 1 \right) - \underbrace{\left(e^{\frac{V_{bcp}}{NFP \cdot V_T}} - 1 \right)}_{I_{trp}} \right]$$

Normalized Base Charge Models

- SGP: $$q_b = \frac{q_1}{2} \cdot \left(1 + \sqrt{1 + 4 \cdot q_2}\right)$$
- SQ3: $$q_b = \frac{q_1}{2} \cdot \left(1 + \sqrt{1 + 4 \cdot q_2}\right)$$
- VBIC95 uses the original Gummel-Poon Equation:

$$q_{bi} = \frac{1}{2} \cdot \left(q_{1i} + \sqrt{q_{1i}^2 + 4 \cdot q_{2i}}\right)$$

$$q_{bp} = \frac{1}{2} \cdot \left(1.0 + \sqrt{1.0 + 4 \cdot q_{2p}}\right)$$

Early-Effect of the parasitic transistor is neglected

Normalized Base Charge Models

	Early-Effect Model	High Injection Model
✶ SGP:	$q_1 = \dfrac{1}{\left(1 - \dfrac{V_{be}}{VAR} - \dfrac{V_{bc}}{VAF}\right)}$	$q_2 = \dfrac{I_{tf}}{IKF} + \dfrac{I_{tr}}{IKR}$
✶ SQ3:	$q_1 = \dfrac{1}{\left(1 - \dfrac{V_{be}}{vbr} - \dfrac{V_{bc}}{vbf}\right)}$	$q_2 = \dfrac{I_{tf}}{jbf} + \dfrac{I_{tr}}{jbr}$
✶ VBIC95:	$q_{1i} = 1.0 + \dfrac{fqjbei}{VER} + \dfrac{fqjbci}{VEF}$ *fqjbei* and *fqjbci* are the normalized depletion charges functions at the internal base-emitter and the internal base-collector junction	$q_{2i} = \dfrac{I_{tf}}{IKF} + \dfrac{I_{tr}}{IKR}$ $q_{2p} = \dfrac{I_{tfp}}{IKP}$

Base-Emitter Junction Current Models

- SGP:

$$I_{be} = \frac{IS}{BF} \cdot \left(e^{\frac{V_{be}}{NF \cdot V_T}} - 1 \right) + ISE \cdot \left(e^{\frac{V_{be}}{NE \cdot V_T}} - 1 \right)$$

- SQ3:

$$I_{be} = ibe \cdot \left(e^{\frac{V_{be}}{nbf \cdot V_T}} - 1 \right) + jle \cdot \left(e^{\frac{V_{be}}{nle \cdot V_T}} - 1 \right)$$

- VBIC95:

$$I_{bei} = IBEI \cdot \left(e^{\frac{V_{bei}}{NEI \cdot V_T}} - 1 \right) + IBEN \cdot \left(e^{\frac{V_{bei}}{NEN \cdot V_T}} - 1 \right)$$

$$I_{bex} = IBEI \cdot \left(e^{\frac{V_{bex}}{NEI \cdot V_T}} - 1 \right) + IBEN \cdot \left(e^{\frac{V_{bex}}{NEN \cdot V_T}} - 1 \right)$$

$$I_{be} = WBE \cdot I_{bei} + (1 - WBE) \cdot I_{bex}$$

In VBIC95 the total emitter-base junction current is the sum of the internal PN-diode current I_{bei} and the sidewall diode current component I_{bex}.

Base-Collector Junction Current Models

- SGP: $$I_{bc} = \frac{IS}{BR} \cdot \left(e^{\frac{V_{bc}}{NR \cdot V_T}} - 1 \right) + ISC \cdot \left(e^{\frac{V_{bc}}{NC \cdot V_T}} - 1 \right)$$

- SQ3: $$I_{bc} = ibc \cdot \left(e^{\frac{V_{bc}}{nbr \cdot V_T}} - 1 \right) + jlc \cdot \left(e^{\frac{V_{bc}}{nlc \cdot V_T}} - 1 \right)$$

- VBIC95: $$I_{bci} = IBCI \cdot \left(e^{\frac{V_{bci}}{NCI \cdot V_T}} - 1 \right) + IBCN \cdot \left(e^{\frac{V_{bci}}{NCN \cdot V_T}} - 1 \right)$$

$$I_{bep} = IBEIP \cdot \left(e^{\frac{V_{bep}}{NCI \cdot V_T}} - 1 \right) + IBENP \cdot \left(e^{\frac{V_{bep}}{NCN \cdot V_T}} - 1 \right)$$

$$I_{bc} = I_{bci} + I_{bep} - I_{gc}$$

In VBIC95 the total base-collector junction current is the sum of the internal base-collector diode current I_{bci} and the base-emitter diode current component I_{bep} of the parasitic transistor. I_{gc} is an additional weak avalanche current significant at high base-collector bias.

Weak avalanche multiplication model

The model Parameter AVC2 can be modeled as temperature dependent in VBIC95

- SGP: ----------
- SQ3: ----------
- VBIC: $I_{gc} = AVC1 \cdot (I_{Ti} - I_{bci}) \cdot V_{lbc}(V_{bci}) \cdot exp\left\{\left[- AVC2(T) \cdot V_{lbc}(V_{bci})\right]^{(MC-1)}\right\}$

$$\text{where}: \quad V_{lbc}(V_{bci}) = 0.5 \cdot \left(\sqrt{(PC - V_{bci})^2 + 0.01} + PC - V_{bci}\right)$$

PC is the Built-in voltage parameter of the base-collector junction.

- MEXTRAM: A more physical based but rather complicate set of equations. The MEXTRAM avalanche model is a more sophisticate extension of the VBIC-avalanche Model.

Collector Resistance and Quasi-Saturation model

- SGP: Constant resistor RC
- SQ3: Constant resistor RC
- VBIC:

$$I_{rci} = \frac{V_{rci} + V_{cor}}{RCI \cdot \sqrt{1 + \left[\dfrac{(V_{rci} + V_{cor})}{VO + \dfrac{0.5}{HRCF} \cdot \sqrt{V_{rci}^2 + 0.01}} \right]^2}}$$

$$V_{cor} = V_T \cdot \left[\sqrt{1 + GAMM \cdot e^{\frac{V_{bci}}{V_T}}} - \sqrt{1 + GAMM \cdot e^{\frac{V_{bcx}}{V_T}}} - \log\left(\frac{1 + \sqrt{1 + GAMM \cdot e^{\frac{V_{bci}}{V_T}}}}{1 + \sqrt{1 + GAMM \cdot e^{\frac{V_{bcx}}{V_T}}}} \right) \right].$$

The saturation velocity voltage *VO* and the high current RC correction factor *HRCF* are limited to values greater than zero to avoid numerical problems

Base Resistance Models

- SGP:

$$\text{If IRB} > 0: \quad r_{bb} = RBM + 3 \cdot (RB - RBM) \cdot \frac{\tan(z) - z}{z \cdot \tan^2(z)}$$

$$\text{If IRB} \leq 0: \quad r_{bb} = RBM + \frac{RB - RBM}{q_b}$$

- SQ3:

$$\text{If jrb} > 0: \quad r_{bb} = rbm + 3 \cdot rbi \cdot \frac{\tan(z) - z}{z \cdot \tan^2(z)}$$

$$\text{If jrb} \leq 0: \quad r_{bb} = rbm + \frac{rbi}{q_b}$$

- VBIC:

$$r_{bbi} = RBX + \frac{RBI}{q_{bi}} \qquad r_{bbp} = \frac{RBP}{q_{bp}}$$

- Mextram:

$$r_{bibx} = \frac{3 \cdot RBV}{q_b \cdot \left[1 + s\,(V_{rbi})\right]} \quad \text{where}: \quad s\,(V_{rbi}) = 2 \cdot \frac{V_T}{V_{rbi}} \cdot \left(e^{\frac{V_{rbi}}{V_T}} - 1\right)$$

Depletion Charge Models

★ SGP and SQ3:

$$q_j = \begin{cases} = CJ \cdot fqjr & \text{if : } V_x < fc \cdot VJ \\ = CJ \cdot fqjf & \text{if : } V_x \geq fc \cdot VJ \end{cases}$$

Charge normalization uses the following definition :

$$\lim_{V_x \mapsto 0} fqjr(V_x) = 0$$

$$fqjr = \frac{VJ}{1-MJ} \cdot \left[1 - \left(1 - \frac{V_x}{VJ} \right)^{(1-MJ)} \right]$$

$$fqjf = VJ \cdot \frac{1-(1-FC)^{(1-MJ)}}{1-MJ} + (V_x - FC \cdot VJ) \cdot \frac{\left[1 - FC + \frac{MJ}{2 \cdot VJ} \cdot (V_x - FC \cdot VJ) \right]}{(1-FC)^{(1+MJ)}}$$

★ VBIC:

$$q_j(V_x) = CJ \cdot fqj$$

$$fqj = \left\{ \frac{P}{1-M} \cdot \left[\left(1 - \frac{V_{l0}}{P} \right)^{(1-M)} - \left(1 - \frac{V_l(V_x)}{P} \right)^{(1-M)} \right] + \frac{V_x - V_l(V_x) + V_{l0}}{(1-FC)^{-M}} \right\}$$

In VBIC95 the applied internal junction Voltage V_x is converted to an effective junction voltage $V_l(V_x)$!

Depletion Charge Model of VBIC95

- In VBIC95 limitation of the internally applied junction capacitance voltage V_x by introduction of a smoothing function $V_l(V_x)$ to avoid the pole position.

$$V_l(V_x) = 0.5 \cdot \left(V_X + FC \cdot P - \sqrt{(V_x - FC \cdot P)^2 + AJ} \right)$$

$$V_{l0} = \lim_{V_x \to 0} V_l = 0.5 \cdot \left(FC.P - \sqrt{FC^2 P^2 + AJ} \right)$$

The value of AJ models the transition region. The transition region increases with increasing AJ.

- For $V_x >> P$ and $V_x << P$ V_l reaches the following limits:

$$V_x >> +FC \cdot P \Rightarrow \lim_{V_x \to +\infty} V_l(V_x) = 0.5 \cdot FC \cdot P$$

$$V_x << -FC \cdot P \Rightarrow \lim_{V_x \to -\infty} V_l(V_x) \approx V_x$$

Junction Capacitance and Depletion Charge

- SGP and SQ3: If $V_x < fc \cdot VJ$: $\quad C_j = CJ \cdot \dfrac{1}{\left(1 - \dfrac{V_x}{VJ}\right)^{MJ}}$

  If $V_x \geq fc \cdot VJ$: $\quad C_j = CJ \cdot \dfrac{\left(1 - FC \cdot (1 + MJ) + \dfrac{MJ \cdot V_x}{VJ}\right)}{(1 - FC)^{(MJ+1)}}$

- VBIC: $C_j(V_x) = \dfrac{dq_{jx}}{dV_l} \cdot \dfrac{\P V_l}{\P V_x} = \dfrac{CJ}{4 \cdot (1 - FC)^M} + CJ \cdot \left(\dfrac{1}{\left(1 - \dfrac{V_l}{P}\right)^M} - \dfrac{1}{(1 - FC)^{-M}} \right) \cdot \dfrac{\P V_l}{\P V_x}$

VBIC95 uses a C_∞-continuous depletion capacitance model with a bias-dependent built-in voltage $V_l(V_x)$.

Diffusion charges

- SGP and SQ3:

$$q_{Dbe} = \frac{I_{tf}\tau_{ff}}{q_b}, \qquad \Rightarrow C_{Dbe}(V_{be}) = \frac{\partial q_{Dbe}}{\partial V_{be}} = \frac{\partial}{\partial V_{be}}\left(\frac{I_{tf}\tau_{ff}}{q_b}\right)$$

$$q_{Dbc} = I_{tr} \cdot TR; \qquad \Rightarrow C_{Dbc}(V_{bc}) = \frac{\partial q_{Dbc}}{\partial V_{bc}} = TR \cdot \frac{\partial}{\partial V_{bc}}(I_{tr})$$

- VBIC95 :

$$q_{Dbei} = \frac{I_{tfi}\tau_{ff}}{q_{bi}}, \qquad \Rightarrow C_{Dbei}(V_{bei}) = \frac{\partial q_{Dbei}}{\partial V_{bei}} = \frac{\partial}{\partial V_{bei}}\left(\frac{I_{tfi}\tau_{ff}}{q_{bi}}\right)$$

$$q_{Dbci} = I_{tri} \cdot TR; \qquad \Rightarrow C_{Dbci}(V_{bci}) = \frac{\partial q_{Dbci}}{\partial V_{bci}} = TR \cdot \frac{\partial}{\partial V_{bci}}(I_{tri})$$

$$q_{Dbep} = I_{tfp} \cdot TR; \qquad \Rightarrow C_{Dbep}(V_{bep}) = \frac{\partial q_{Dbep}}{\partial V_{bep}} = TR \cdot \frac{\partial}{\partial V_{bep}}(I_{tfp})$$

Quasi-Saturation Charge (VBIC95 only)

- ✶ In quasi-saturation by the effects of base-push out, current-spreading and carrier velocity saturation additional charge is stored in the Epi-layer.

  ➔ Leads to a strong decrease of the transistor cutoff-frequency

These additional charge storage elements are modeled inVBIC95 by:

$$q_{sati} = QCO \cdot \sqrt{1 + GAMM \cdot e^{\frac{V_{bci}}{V_T}}}$$

$$q_{satx} = QCO \cdot \sqrt{1 + GAMM \cdot e^{\frac{V_{bcx}}{V_T}}}$$

Quasi-saturation charge model parameters are QCO and GAMM

Transit Time Models:

- SGP :

$$t_{ff} = TF \cdot \left(1 + XTF \cdot \left(\frac{I_{tf}}{ITF + I_{tf}} \right)^2 e^{\frac{V_{bc}}{1.44 \cdot VTF}} \right)$$

- VBIC95 :

If $I_{tfi} \leq 0$:

$$t_{ff} = TF \cdot \left(1 + q_{1i} \cdot QTF \right)$$

If $I_{tfi} > 0$:

$$t_{ff} = TF \cdot \left(1 + q_{1i} \cdot QTF \right) \cdot \left(1 + XTF \cdot \left(\frac{I_{tfi}}{ITF + I_{tfi}} \right)^2 \cdot e^{\frac{V_{bci}}{1.44 \cdot VTF}} \right)$$

Transit Time Models:

★ SQ3:

$$t_{ff} = TF \cdot \frac{1}{\left(1 - \frac{V_{bc}}{vta}\right)^{mta}} \cdot \frac{1 + \left(\frac{I_T - I_{bc}}{itk \cdot \left(1 - \frac{V_{bc}}{vtk}\right)^{mtk}}\right)^{ktk}}{1 + \left(\frac{I_T - I_{bc}}{itg \cdot \left(1 - \frac{V_{bc}}{vtg}\right)^{mtg}}\right)^{ktk}}$$

Linearization at :

$V_{bc} \geq FCTF \cdot VTA(T_{dev})$

$V_{bc} \geq FCTFI \cdot VTK(T_{dev})$

$V_{bc} \geq FCTFI \cdot VTG(T_{dev})$

to avoid singularities.

Numerical implementation:

$$t_{ff} = TF \cdot f_{vta} \cdot \frac{1 + \left(f_{vtk} \cdot \frac{(I_T - I_{bc})}{itk}\right)^{ktk}}{1 + \left(f_{vtg} \cdot \frac{(I_T - I_{bc})}{itg}\right)^{ktk}}$$

Transit Time Model of SQ3:

Case A : $V_{bc} \geq FCT_X \cdot VT_X(T_{dev})$:

$$f_{vtx} = \frac{\left(1 - FCT_X \cdot (1 + MT_X) + MT_X \frac{V_{BC}}{VT_X}\right)}{(1 - FCT_X)^{(MT_X + 1)}}$$

Case B : $-FCV_X < V_{bc} < FCT_X \cdot VT_X(T_{dev})$:

$$f_{vtx} = \frac{1}{\left(1 - \frac{V_{BC}}{VT_x}\right)^{MT_x}}$$

$$t_{ff} = TF \cdot f_{vta} \cdot \frac{1 + \left(f_{vtk} \cdot \frac{(I_T - I_{bc})}{itk}\right)^{ktk}}{1 + \left(f_{vtg} \cdot \frac{(I_T - I_{bc})}{itg}\right)^{ktk}}$$

Case C : $V_{bc} < -FCV_X$:

$$f_{vtx} = \left[1 + \frac{FCV_X}{VT_x} + 0.1 \cdot \left(1 - e^{\frac{V_{BC} + FCV_X}{0.1 \cdot VT_X}}\right)\right]^{-MT_x}$$

Excess Phase Models

Basic modeling idea

$$I_{tfx} = I_{tf} \cdot \Phi(s)$$

with the complex frequency variable $s=jw$.

Basic approach for the excess phase-shift function:

$$\Phi(s) = 3w_0^2 \frac{1}{s^2 + 3w_0 s + w_0^2}$$

Φ(s) is an all pass filter with not effects the signal magnitude but leads to a signal phase shift θ

$$q = \arctan \frac{3\frac{w}{w_0}}{3 - \left(\frac{w}{w_0}\right)^2}$$

✶ SGP and SQ3:

A first order approximation for $\omega < \omega_0$ is made:

$$q \approx \frac{w}{w_0}$$

$$w_0 = \frac{1}{TF\left(2p\frac{PTF}{360}\right)}$$

✶ For this approximation the phase shift is:

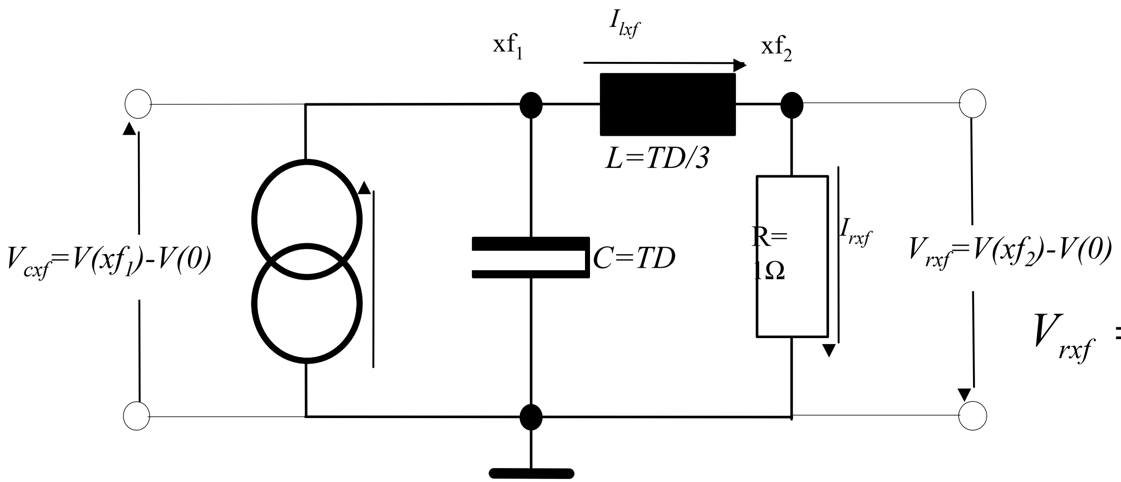
$$q = 2p\, f \cdot TF \cdot \left(2p\frac{PTF}{360}\right)$$

Excess Phase Models

✶ VBIC95:

VBIC95 solves the equation $\Phi(s) = 3w_0^2 \dfrac{1}{s^2 + 3w_0 s + w_0^2}$.

by adding the following "Excess Phase Network" and the definition $w_0 = \dfrac{1}{TD}$:



$$V_{rxf} = \frac{1}{LC \cdot \left(s^2 + \frac{s}{L} + \frac{1}{LC} \right)}$$

Temperature scaling rules

Basic definitions:

Device to nominal temperature ratio:

$$rT = \frac{T_{dev}}{TNOM + 273.15}$$

T_{dev} is the actual device temperature in [°K]

Thermal voltage:

$$V_T = \frac{k_B T_{dev}}{e} = 8.6173857e^{-5} \cdot T_{dev}$$

Temperature offset:

$$\Delta T = T_{dev} - TNOM - 273.15$$

Transport saturation currents:

✶ SGP:

$$IS(T_{dev}) = IS(TNOM) \cdot rT^{XTI} \cdot \exp\left[(rT - 1) \cdot \frac{EG}{V_T} \right]$$

✶ SQ3:

$$IS(T_{dev}) = IS(TNOM) \cdot rT^{pt} \cdot \exp\left[(rT - 1) \cdot \frac{eg}{V_T} \right]$$

✶ VBIC95:

$$IS(T_{dev}) = IS(TNOM) \cdot rT^{XIS} \cdot \exp\left[(rT - 1) \cdot \frac{EA}{VT} \right]^{\frac{1}{NF}}$$

$$ISP(T_{dev}) = ISP(TNOM) \cdot rT^{XIS} \cdot \exp\left[(rT - 1) \cdot \frac{EA}{VT} \right]^{\frac{1}{NFP}}$$

$$NF(T_{dev}) = NF(TNOM) \cdot \left[1 + TNF \cdot \Delta T \right] \cdot$$

Temperature scaling rules

Base-emitter diode saturation currents:

- SGP:

$$BF(T_{dev}) = BF(TNOM) \cdot rT^{XTB}$$

$$ISE(T_{dev}) = ISE(TNOM) \cdot rT^{\left(\frac{XTI}{NE} - XTB\right)} \cdot \exp\left[(rT - 1) \cdot \frac{EG}{NE \cdot V_T} \right]$$

- SQ3:

$$ibe(T_{dev}) = ibe(TNOM) \cdot [1 + tcibe \cdot \Delta T] \cdot rT^{\left(\frac{pt}{nbf} - tb\right)} \cdot \exp\left[(rT - 1) \cdot \frac{eg}{nbf \cdot V_T} \right]$$

$$jle(T_{dev}) = jle(TNOM) \cdot [1 + tcjle \cdot \Delta T] \cdot rT^{\left(\frac{pt}{nle} - tb\right)} \cdot \exp\left[(rT - 1) \cdot \frac{eg}{nle \cdot V_T} \right]$$

$$nbf(T_{dev}) = nbf(TNOM) \cdot [1 + tcnbf \cdot \Delta T]$$

Temperature scaling rules

Base-emitter diode saturation currents:

✶ VBIC95:

- VBIC95 uses separate temperature exponents and activation energy parameters for the ideal and the non-ideal saturation current.
- Every junction has a different, junction-specific activation energy.

$$IBEI(T_{dev}) = IBEI(TNOM) \cdot rT^{XII} \cdot \exp\left[\left(rT - 1 \right) \cdot \frac{EAIE}{V_T} \right]^{\frac{1}{NEI}}$$

$$IBEN(T_{dev}) = IBEN(TNOM) \cdot rT^{XIN} \cdot \exp\left[\left(rT - 1 \right) \cdot \frac{EANE}{V_T} \right]^{\frac{1}{NEN}}$$

The temperature behavior of series resistance

Series resistors:

✶ SGP:

RE, RB, RBM, RC: $$RE = RE(TNOM)\cdot\left[1+TRE1\cdot\Delta T+TRE2\cdot\Delta T^{2}\right]$$

✶ SQ3:

re, rbi, rbm, rc: $$re = re(TNOM)\cdot\left[1+tce1\cdot\Delta T+tce2\cdot\Delta T^{2}\right]$$

✶ VBIC95:

RE, RBI, RBX, RCI, RCX, RBP, RS:

$$RE = RE(TNOM)\cdot rT^{XRE}$$

Temperature scaling rules of capacitance parameter

Zero bias junction capacitance:

- SGP: $$CJ(T_{dev}) = CJ(TNOM) \cdot \left[\frac{VJ(TNOM)}{V(T_{dev})} \right]^{MJ}$$

- SQ3: If $tccj = 0$ AND $tcvj = 0$ then:

$$cj(T_{dev}) = cj(TNOM) \cdot \left[\frac{vj(TNOM)}{V(T_{dev})} \right]^{mj}$$

If $tccj \neq 0$ OR $tcvj \neq 0$ then:

$$cj(T_{dev}) = cj(TNOM) \cdot \left[1 + tccj \cdot \Delta T \right]$$

- VBIC95: $$P(T_{dev}) = P(TNOM) \cdot \left[\frac{P(TNOM)}{P(T_{dev})} \right]^{M}$$

Temperature scaling rules of capacitance parameters

Built-In Voltage:

- SGP:

$$vj(T_{dev}) = vj(TNOM)\cdot rT - 3\cdot V_T \cdot \ln(rT) + (1-rT)\cdot EG + 7.02e-4\cdot\left[\frac{rT\cdot TNOM^2}{1108+TNOM} - \frac{T_{dev}^2}{1108+T_{dev}}\right]$$

- SQ3:

If $tccj = 0$ AND $tcvj = 0$ then: SGP-Equation:

If $tccj \neq 0$ OR $tcvj \neq 0$ then: $vj(T_{dev}) = vj(TNOM)\cdot\left[1 + tcvj\cdot\Delta T\right]$

- VBIC95:

$$P(T_{dev}) = P_2 + 2\cdot V_T\cdot\ln\left[0.5 + \sqrt{0.25 + \exp\left(-\frac{P_2}{V_T}\right)}\right]$$

where $P_2 = 4\cdot V_T\cdot\sinh\left(\frac{P(TNOM)}{2\cdot V_T}\right)\cdot rT - 3\cdot V_T\cdot\ln(rT) + (1-rT)\cdot EA$

Temperature scaling rules

Early Voltage:

- SGP: -----------
- SQ3: $vbf(T_{dev}) = vbf(TNOM) \cdot [1 + tcvbf \cdot \Delta T]$
  $vbr(T_{dev}) = vbr(TNOM) \cdot [1 + tcvbr \cdot \Delta T]$
- VBIC95: -----------

High injection knee current:

- SGP: -----------
- SQ3: $jbf(T_{dev}) = jbf(TNOM) \cdot [1 + tcjbf1 \cdot \Delta T + tcjbf2 \cdot \Delta T^2]$
  $jbr(T_{dev}) = jbr(TNOM) \cdot [1 + tcjbr \cdot \Delta T]$
- VBIC95: -----------

Temperature scaling rules

Weak Avalanche current parameters:

- ✶ SGP: -----------
- ✶ SQ3: -----------
- ✶ VBIC95: $AVC2(T_{dev}) = AVC2(TNOM) \cdot [1 + TAVC \cdot \Delta T]$

Quasi-saturation model parameters:

- ✶ SGP: -----------
- ✶ SQ3: -----------
- ✶ VBIC95: $VTO(T_{dev}) = VTO(TNOM) \cdot \left[rT^{XVO} \cdot e^{\frac{EA \cdot (rT-1)}{V_T}} \right]$

$$GAMM(T_{dev}) = GAMM(TNOM) \cdot rT^{XVO}$$

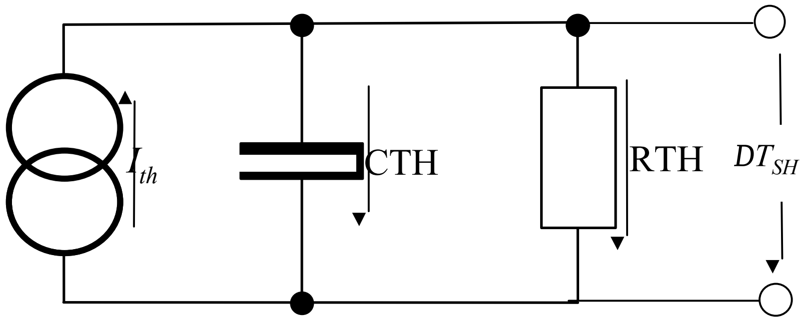
Self Heating Model of VBIC95:

✶ Basic Idea:

- Flow quantity: Total power dissipation $\boldsymbol{I_{th}}$ (through variable).
  I_{th} is calculated by power summation over all network branches:

$$I_{th} = \sum_{ij} I_{ij} \cdot V_{ij}$$

- Branch variable: Temperature difference $\mathrm{D}\mathbf{T_{SH}}$ (across variable).



$$\Delta T_{SH} = RTH \cdot I_{th}$$

$$Q_{cth} = CTH \cdot \Delta T_{SH}$$

Thermal Network of a electronic device
Thermal capacitance of the device structure: CTH
Thermal resistance of the device structure: RTH

The Self-Heating model parameters are RTH and CTH

SGP and SQ3 Noise Models

- Thermal noise sources:

$$\overline{i_r^2} = \frac{4 \cdot k_B \cdot T_{dev}}{r} \cdot \Delta f$$

Thermal noise sources are associated with RE, RBB and RC

- Shot noise source:

$$\overline{i_s^2} = 2 \cdot e \cdot I \cdot \Delta f$$

Shot noise sources are associated with the transport current $I=I_T$ and the total base current $I=I_B$.

- Flicker noise source:

$$\overline{i_s^2} = KF \cdot I^{AF} \cdot \frac{\Delta f}{f}$$

A flicker noise sources is associated with the total base current $I=I_B$.

The Noise model parameters are AF and KF

VBIC95 Noise Model

- Thermal noise sources:

$$\overline{i_r^2} = 4 \cdot k_B \cdot g_{ij} \cdot T_{dev} \cdot \Delta f$$

In VBIC95 the branch conductivities $\mathbf{g_{ij}}$ over the resistor elements are calculated under the actual bias condition by:

$$g_{ij} = \frac{\partial V_{ij}}{\partial V_{ij}}$$

Thermal noise sources are associated with all resistive pathes at RE, RBX, RBI, RBP, RCI,RCX and RS.

- Shot noise source:

$$\overline{i_s^2} = 2 \cdot e \cdot I \cdot \Delta f$$

Shot noise sources are associated with the forward transport currents $I=I_{tfi}$, I_{tfp} and the base currents $I=I_{bei}$ and $I=I_{bep}$.

- Flicker noise source:

$$\overline{i_s^2} = KF \cdot I^{AF} \cdot \frac{\Delta f}{f^{BFN}}$$

Flicker noise sources are associated with internal base currents $I=I_{bei}$ and $I=I_{bep}$.

The Noise model parameters are
AF, KF and BFN

Flicker and shot noise of I_{bex}, I_{bci}, I_{bcp} and I_{tri} are not considered.

Siemens SQ3 vs. Standard Berkeley SGP Model

SQ3

- ✶ Base current definition independent of Transfer current.
- ✶ Parasitic substrate capacitance and resistance.
- ✶ Very powerful transit time model vs. VCE-voltage and collector current.
- ✶ **Substantially** improved temperature scaling of:
  - all DC-Parameters.
  - Junction capacitance parameters.
  - Transit time parameters.

SGP

- ✶ Coupling between Base and Transfer current.
- ✶ No parasitic substrate transistor effects.
- ✶ Poor transit time model.
- ✶ No temperature modeling of
  - resistances,
  - beta
  - high current effects
  - capacitances
  - transit time

Siemens Transistor Model

✶ Main advantages of Siemens SQ3 vs. Standard Berkeley SGP Model :

- Independent modeling of junction- and transport currents as in VBIC95.
- High accuracy in modeling dynamic behavior over the whole
  - ⇒VCE voltage range $0.25 < V \leq VCE_{max}$,
  - ⇒ temperature range from -40°C ≤ TEMP ≤ +150°C,

  because of the availability of a sophisticate transit time model.
- All relevant temperature effects are modeled.

  ➔ Only 1 parameter set covers the whole temperature range.

✶ Main disadvantages of Siemens SQ3 vs VBIC95:

- No Quasi-saturation and avalanche multiplication model available.
- Bad Early-Effect model.
- Piecewise defined depletion charge model.
- Proprietary model.

  ➔ available only in SABER and SPECTRE.

Advantages of the new VBIC95 Bipolar Model

- ✶ Base current definition independent of transfer current.
- ✶ Enhanced Early-effect model.
- ✶ First-order distributed-base model.
- ✶ Quasi-saturation model (Kull-model) for Epi-resistance and charge storage.
- ✶ Weak avalanche multiplication model for BC-junction.
- ✶ Improved “Excess-Phase” model.
- ✶ Parasitic substrate transistor model is completely included in the model.
- ✶ Parasitic overlap capacitances .
- ✶ Worst-case ability.
- ✶ More physical, single piece depletion capacitance model.
- ✶ Upgraded transit time model vs. collector current and VCE-voltage.
- ✶ **Substantially** improved temperature modeling of
  - resistances,
  - saturation currents and beta,
  - high current effects,
  - capacitances.
- ✶ Self heating mode.l
- ✶ Enhanced “Excess-Phase” model.
- ✶ Enhanced noise model.

Desirable improvements in future VBIC Bipolar Model Standards

- ✶ Availability of a three-terminal model for three-sheet devices and subcircuit modeling.
- ✶ Availability of model scaling over emitter geometry by simple scaling rules.
- ✶ Significant enhancement of the transit time model for better diffusion charge description versus collector current and VCE-voltage.
- ✶ Possibility to model temperature mapping of transit time parameters.
- ✶ Temperature mapping of IKF and IKR.
- ✶ Disposability of an enhanced substrate coupling model. The dielectric capacitance of substrate must be considered.
- ✶ Introduction of a constant capacitance term into the junction capacitance equation. This allows better fits to capacitance profiles in retrograde doped wells.
- ✶ Possibility to model VBE, VBC and VCE junction breakdown.
- ✶ Possibility to model leakage- and tunneling currents in pn-junctions.

Desirable improvements in future VBIC Bipolar Model Standards

- ✶ Improvements in the implemented Epi-layer model for a better describe of the bias dependent collector resistance and epi-layer charge.
- ✶ Decoupling of the DC- and AC- quasi-saturation parameters GAMM.
- ✶ Better base resistance description for the parasitic transistor.
- ✶ Inclusion of all possible noise sources into the VBIC model.