The Bipolar Transistor Model Mextram

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Outline

- The Bipolar Transistor Model Mextram
  - Model description
- RF performance
- Scalability and statistical modelling
- The future of Mextram
  - New release in 1999
  - Modelling of SiGe bipolar transistors
- Summary

- Introduction to Mextram
- Equivalent circuit
- Charge modelling
  - Depletion charges, diffusion charges
- Collector current
  - Early effect, high injection
- Base current
  - Forward current gain, reverse current gain
- Avalanche multiplication
- Series resistances
  - Base resistance, collector epilayer resistance
- Miscellaneous

- Mextram has been introduced within Philips in 1985
  - Updates
    - 1987 Mextram 502
    - 1993 Mextram 503
  - Physics based
  - Developed for analog applications
  - Suited for both digital and analog applications
- Mextram/MM9 have been introduced in public domain in 1993
  - **http://www.semiconductors.philips.com/Philips_Models/**

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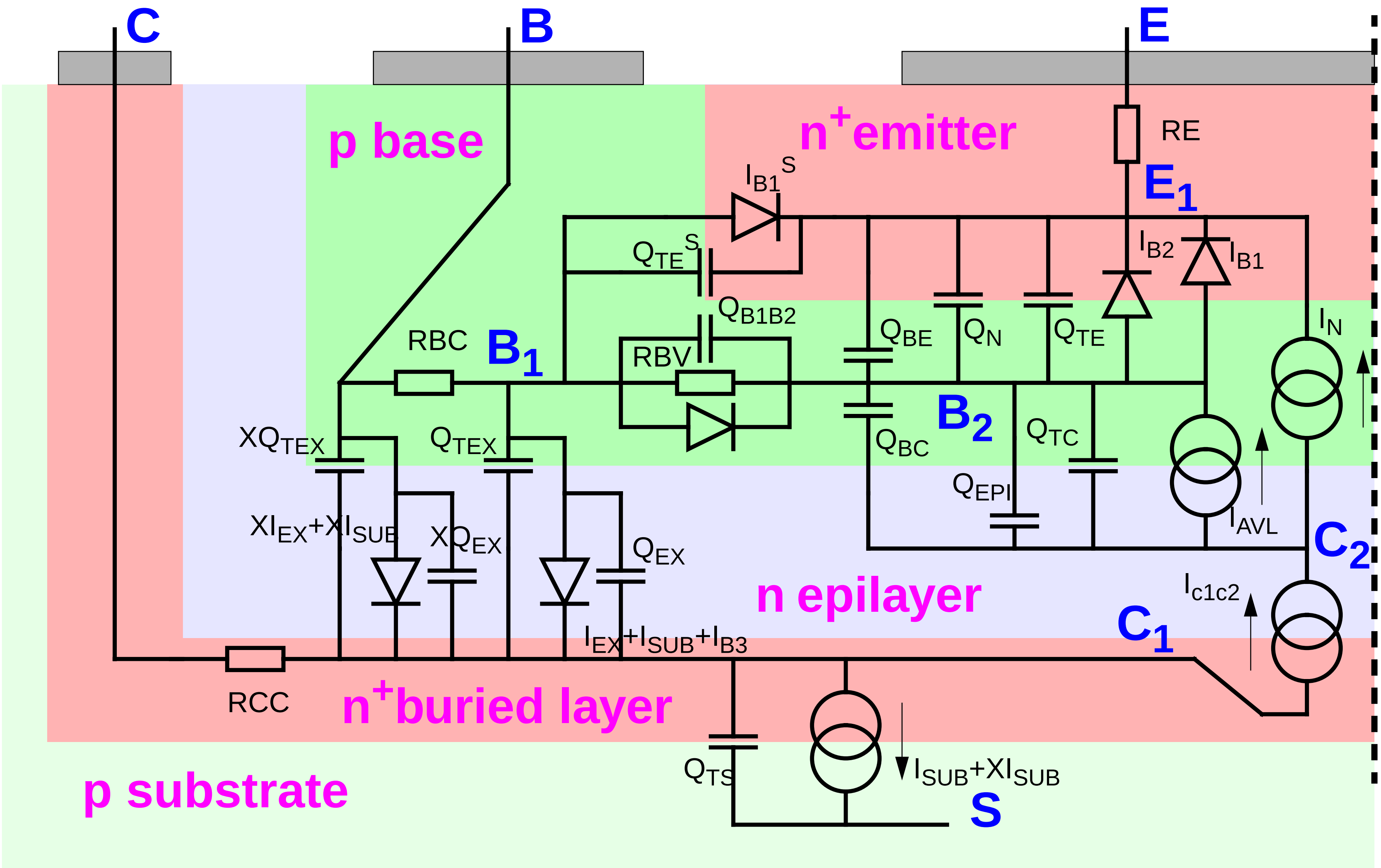
C
B
E
p base
n+emitter
RE
E1
IB1S
QTES
IB2
IB1
QB1B2
RBC
B1
RBV
QBE
QN
QTE
IN
XQTEX
QTEX
B2
QBC
QTC
QEPI
IAVL
C2
XIEX+XISUB
XQEX
QEX
n epilayer
Ic1c2
C1
IEX+ISUB+IB3
RCC
n+buried layer
QTS
ISUB+XISUB
S
p substrate

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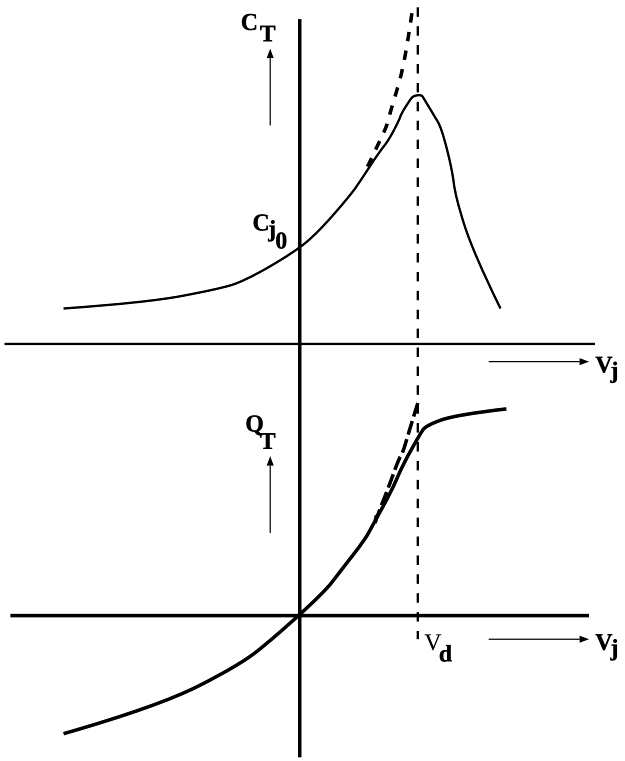
Depletion charges and capacitances

$$C_{DEPL}(V_j) = \frac{Cj_0}{\left(1 - \frac{V_j}{V_d}\right)^p}$$

$$Q_{DEPL}(V_j) = \int_0^{V_j} C_{DEPL}(V_j) \cdot dV$$

$$= \frac{Cj_0 \cdot V_d}{1-p} \cdot \left\{ 1 - \left(1 - \frac{V_j}{V_d}\right)^{1-p} \right\}$$

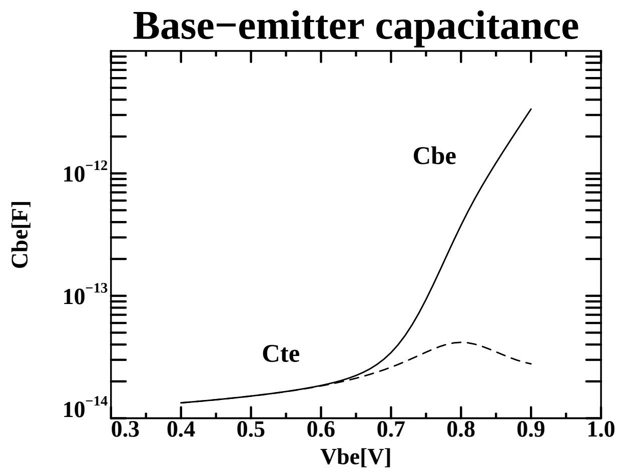


- $Q_{DEPL}(0) = 0$
- singularity at $V_j = V_d$

$$Q_{DEPL}(V_j) = \frac{(1+K)\cdot Cj_0 \cdot V_d}{1-p+K} \cdot \left[1 - \frac{(1+K)^{p/2} \cdot \left(1 - \frac{V_j}{V_d}\right)}{\left\{\left(1 - \frac{V_j}{V_d}\right)^2 + K\right\}^{p/2}} \right]$$

base-emitter junction:

$$Q_{T_e} = Q_{DEPL}(V_{b2e1}, Cj_e, V_{de}, p_e, K = 0.01) \cdot (1 - XCj_e)$$
$$Q^S_{T_e} = Q_{DEPL}(V_{b1e1}, Cj_e, V_{de}, p_e, K = 0.01) \cdot XCj_e$$



substrate-collector junction:

$$Q_{T_s} = Q_{DEPL}(V_{sc1}, Cj_s, V_{ds}, p_s, K = 0.01)$$

extrinsic base-collector junction:

takes into account finite thickness of the epilayer: $XP = \frac{x_{d_0}}{W_{epi}}$

$$Q_{T_{ex}} = (1 - XCj_c) \cdot \left[(1 - XP) \cdot Q_{DEPL}(V_{b1c1}, Cj_c, V_{dc}, p_c, K = 0.1) + XP \cdot Cj_c \cdot V_{b1c1}\right]$$

base-collector capacitance underneath the emitter depends on collector current !

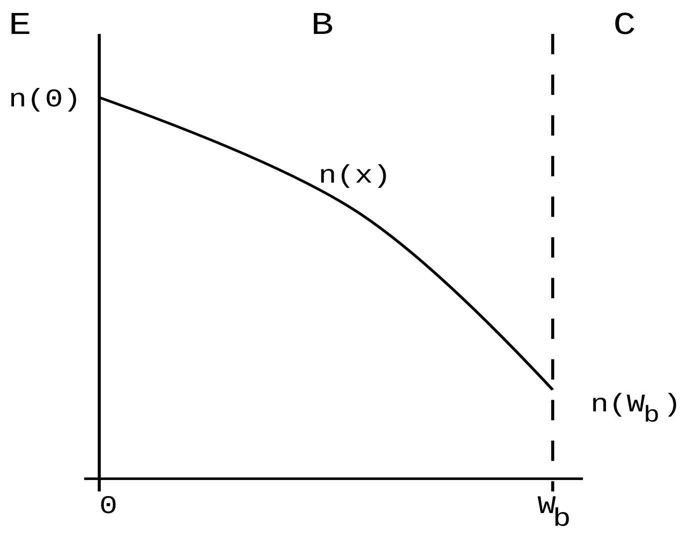
Diffusion charges: Q_{be}, Q_{bc}

Assumptions:

- no recombination in the quasi-neutral base: $J_p = 0$ and $p = n + N_a$
- non-homogeneous base doping: $N(x) = \hat{N}_a \cdot \exp\left(\frac{-\eta \cdot x}{W_b}\right)$

With boundary conditions $n(0)$ and $n(W_b)$ we can derive:

$$
\begin{aligned}
n(x) &= f(x,\eta) \cdot n(0) + r(x,\eta) \cdot n(W_b) \\
Q_{be} &= q \cdot A_{em} \cdot n(0) \cdot \int_0^{W_b} f(x,\eta) \cdot dx \\
Q_{bc} &= q \cdot A_{em} \cdot n(W_b) \cdot \int_0^{W_b} r(x,\eta) \cdot dx
\end{aligned}
$$



with normalized carrier densities: $n_0 = n(0)/\hat{N}_a, \qquad n_b = n(W_b)/\hat{N}_a$

$$n_0 \cdot (1 + n_0) = \frac{n_i^2}{\hat{N}_a^2} \cdot \exp\left(\frac{V_{b2e1}}{V_t}\right)$$

$$n_b \cdot \left(e^{-\eta} + n_b\right) = \frac{n_i^2}{\hat{N}_a^2} \cdot \exp\left(\frac{V_{b2c2}}{V_t}\right)$$

neutral base width $(0 - W_b)$ is modulated by the depletion layers:

$Q_b = Q_{b_0} + Q_{T_e} + Q_{T_c} = Q_{b_0} \cdot (1 + q_1) \qquad q_1$ accounts for Early effect

final result:

$$Q_{be} = Q_{b_0} \cdot (1 + q_1) \cdot F(\eta, n_0) \cdot n_0$$

$$Q_{bc} = Q_{b_0} \cdot (1 + q_1) \cdot R(\eta, n_b) \cdot n_b$$

collector epilayer underneath the emitter and extrinsic collector regions:

$$Q_{epi} = I_s \cdot Q_{b_0} \cdot \frac{\exp\left(\frac{V_{b2c2}}{V_t}\right) - \exp\left(\frac{V_{b2c1}}{V_t}\right)}{I_{epi}}$$

$$Q_{ex} = \frac{1 - XCj_c}{XCj_c} \cdot \left(Q_{bc}(V_{b1c1}) + Q_{epi}(V_{b1c1})\right)$$

emitter charge storage: *parameters:* τ_e, m_τ

$$Q_{n_e} = \tau_e \cdot I_s \cdot \left[\exp\left(\frac{V_{b2e1}}{m_\tau \cdot V_t}\right) - 1\right]$$

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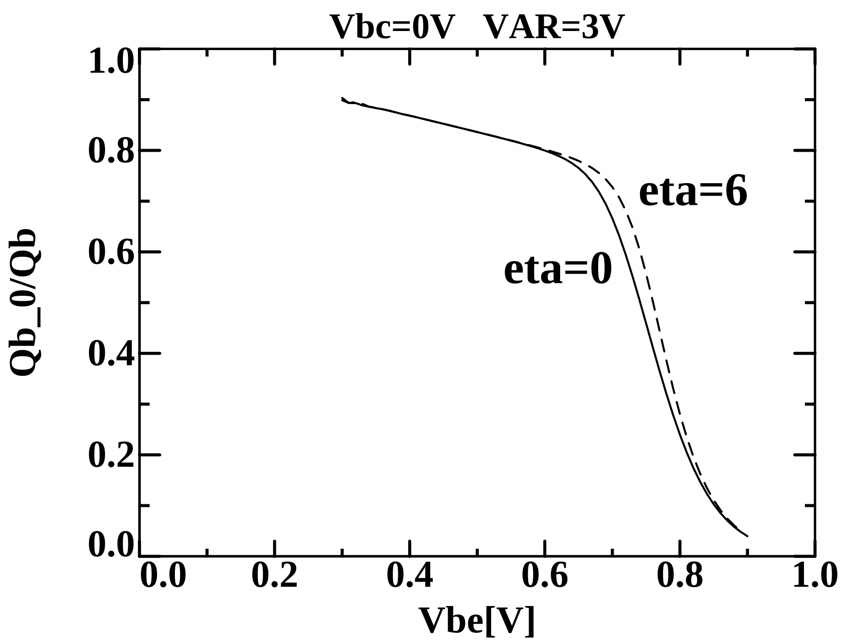
Moll-Ross relation for the main electron current

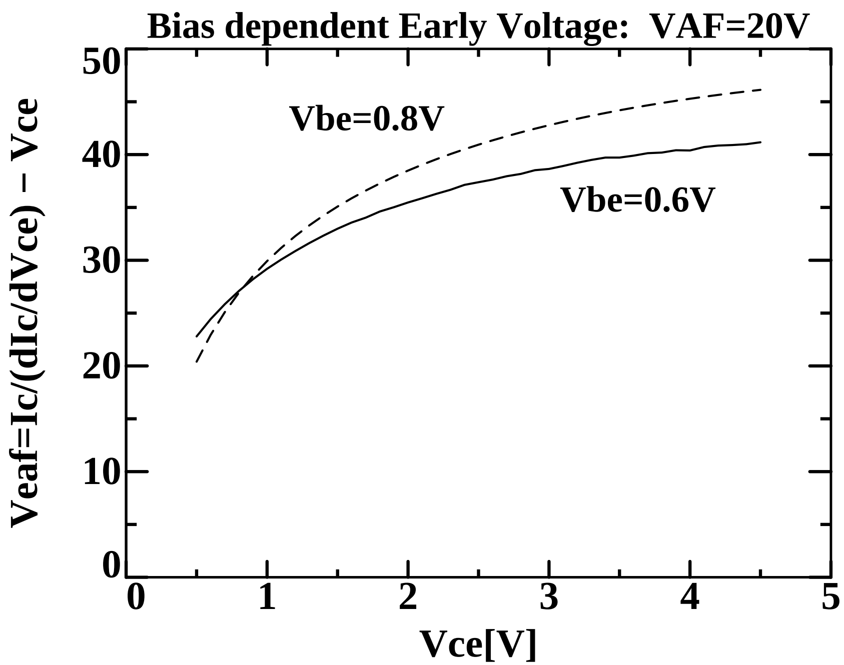
$$
\begin{aligned}
I_n &= I_s \cdot \frac{\exp\left(\frac{V_{b2e1}}{V_t}\right) - \exp\left(\frac{V_{b2c2}}{V_t}\right)}{Q_b / Q_{b_0}} = \frac{I_f - I_r}{q_b} \\
Q_b &= q \cdot A_{em} \cdot \int_e^c p \cdot dx = Q_{b_0} + Q_{T_e} + Q_{T_c} + Q_{be} + Q_{bc} \\
q_b &= \frac{Q_b}{Q_{b_0}} = 1 + \frac{Q_{T_e} + Q_{T_c}}{Q_{b_0}} + \frac{Q_{be} + Q_{bc}}{Q_{b_0}}
\end{aligned}
$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$q_1 \qquad\qquad q_2$$

Early effect — high injection base





Main differences comparing with GP:

- bias dependent Early effect.
- punch-through: $Q_{T_e} + Q_{T_c} = -Q_{b_0}$
- Mextram has only one knee current
- In Mextram high injection is related to the diffusion charges

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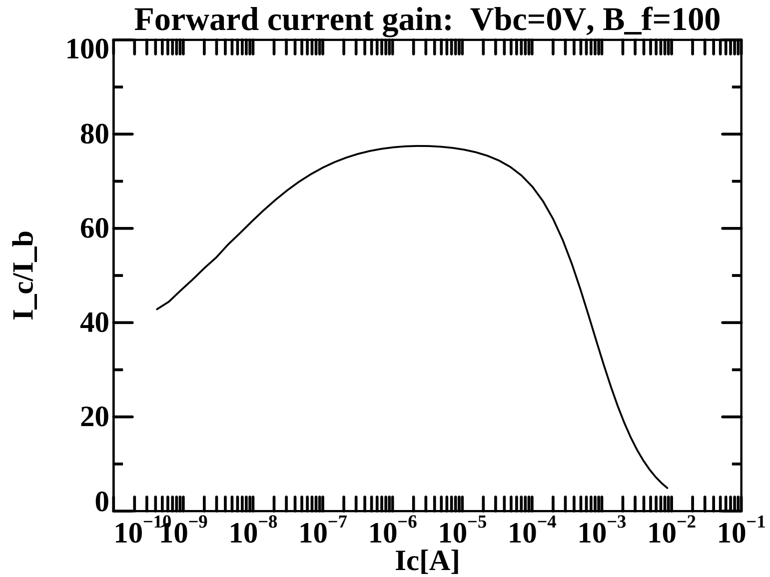
Base current: forward current gain

forward active region: ideal bottom/sidewall component +
non-ideal component based on SRH recombination

$$I_b = I_{b\,f} \cdot \frac{\exp\left(V_{b2e1}/V_t\right) - 1}{\exp\left[V_{b2e1}/\left(2 \cdot V_t\right)\right] + \exp\left[V_{L\,f}/\left(2 \cdot V_t\right)\right]}$$
$$+ \frac{I_s}{B_f} \cdot \left[\exp\left(\frac{V_{b2e1}}{V_t}\right) - 1\right] \cdot \left(1 - X I_{b_i}\right)$$
$$+ \frac{I_s}{B_f} \cdot \left[\exp\left(\frac{V_{b1e1}}{V_t}\right) - 1\right] \cdot X I_{b_i}$$



Parameters: B_f, $X I_{b_i}$, $I_{b\,f}$, $V_{L\,f}$

reverse base current contains three components: $I_b = I_{ex} + I_{b_3} + I_{sub}$

- electrons injected from the collector into the extrinsic base: I_{ex}
- non-ideal component based on SRH recombination: I_{b_3}
- substrate current of the parasitic PNP: I_{sub}

$$I_{ex} = \frac{I_s}{B_{ri}} \cdot \frac{\exp\left(\frac{V_{b1c1}}{V_t}\right) - 1}{1 + q_{ex}}$$

$$I_{b_3} = I_{b_r} \cdot \frac{\exp\left(V_{b1c1}/V_t\right) - 1}{\exp\left[V_{b1c1}/\left(2 \cdot V_t\right)\right] + \exp\left[V_{L_r}/\left(2 \cdot V_t\right)\right]}$$

$$I_{sub} = \frac{2 \cdot I_{S_s} \cdot \left\{\exp\left(\frac{V_{b1c1}}{V_t}\right) - 1\right\}}{1 + \sqrt{1 + 4 \cdot \frac{I_s}{I_{k_s}} \cdot \left\{\exp\left(\frac{V_{b1c1}}{V_t}\right) - 1\right\}}}$$

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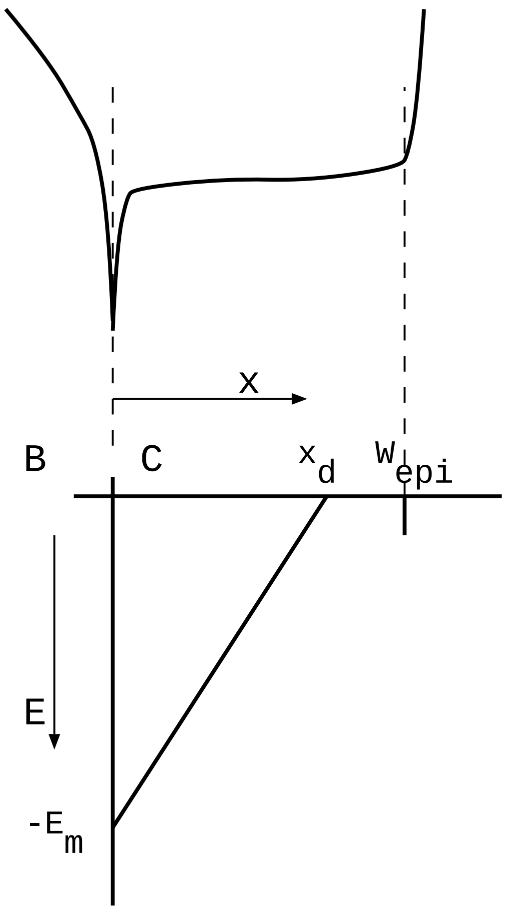
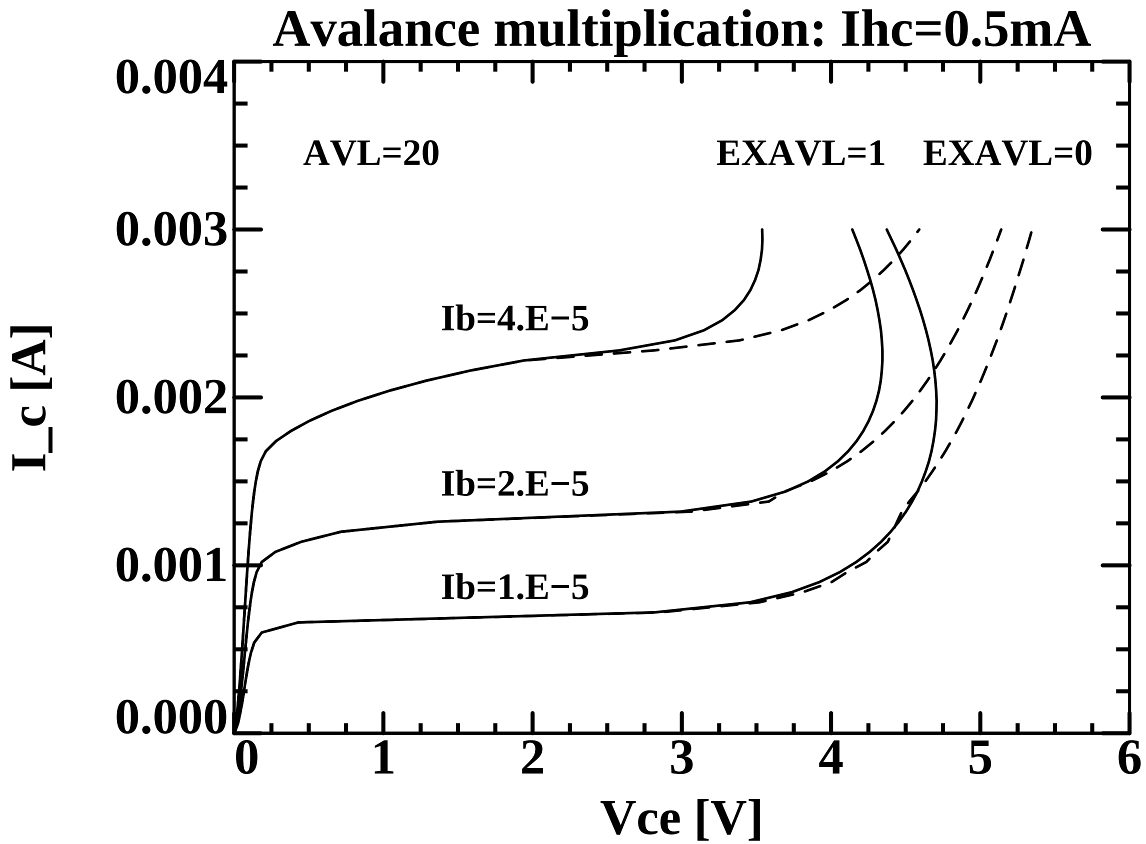
Weak avalanche model means: $I_{avl} < I_c \approx I_n$

$$I_{avl} = I_n \cdot \int_0^{x_d} \alpha_n \cdot \exp\left(\frac{-b_n}{|E(x)|}\right) \cdot dx$$

$$|E(x)| = E_m \cdot \left(1 - \frac{x}{\lambda}\right) \approx E_m \cdot \frac{1}{1 + \frac{x}{\lambda}}$$



x_d, E_m and λ are bias-dependent and can all be related to the depletion layer thickness at zero bias (x_{d_0}).



Parameters: $Avl = b_n \cdot x_{d_0}, (I_{hc}, SFH, XP \;....)$

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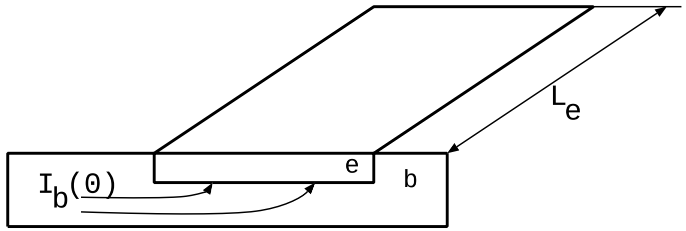
1) R_e, R_{b_c}, R_{c_c} are constant
2) R_{b_v}, R_{c_v} are bias-dependent

Resistance model R_b of the pinched base accounts for

- base charge modulation: $R_b = R_{b_v}/q_b$
- DC current crowding, based on elementary model (Hauser)
  A very good approximation (Groendijk) is;

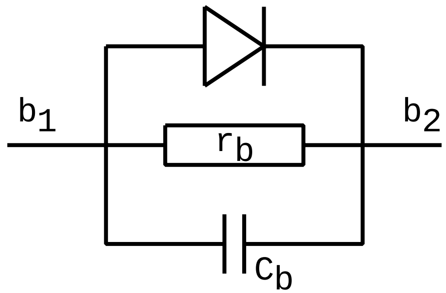
$$I_{b1b2} \;=\; \frac{2 \cdot V_t}{3 \cdot R_b} \cdot \left(\exp\left(\frac{V_{b1b2}}{V_t}\right) - 1\right) + \frac{V_{b1b2}}{3 \cdot R_b}$$



note: with reversal base current (decharging,avalanche) $r_b > R_{b_v}$!!

- AC current crowding

$$C_b \;=\; \frac{1}{5} \cdot \left(\frac{\partial Q_{Te}}{\partial V_{b2e1}} + \frac{\partial Q_{be}}{\partial V_{b2e1}} + \frac{\partial Q_n}{\partial V_{b2e1}}\right)$$



Collector epilayer resistance model

forces the voltage on node $c_2 \longrightarrow I_r,\ Q_{bc},\ Q_{epi},\ Q_{T_c}$

In this way we model base push out and the collector transit time.

Two cases have to be considered:

- ohmic current flow: model of Kull;

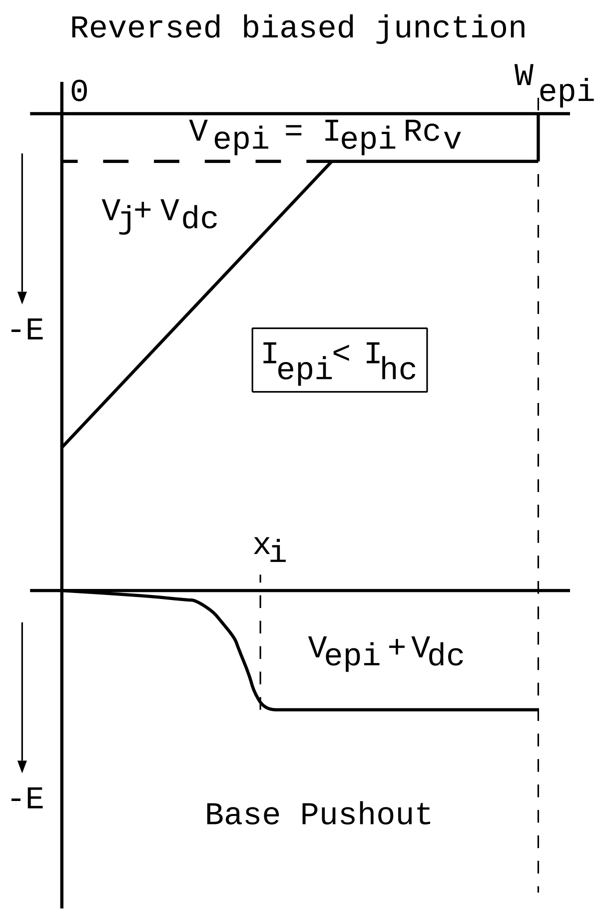
  neutrality $p + N_{epi} \approx n,\ J_p = 0$
- velocity saturated current flow

$$I_{epi} = \frac{E_c + V_{epi}}{R_{c_v}}$$

$$E_c = V_t \cdot \left[K_0 - K_w - \ln\left(\frac{K_0+1}{K_w+1}\right)\right]$$

$$K_0 = \sqrt{1 + 4 \cdot \exp[(V_{b2c2} - Vd_c)/V_t]}$$

$$K_w = \sqrt{1 + 4 \cdot \exp[(V_{b2c1} - Vd_c)/V_t]}$$



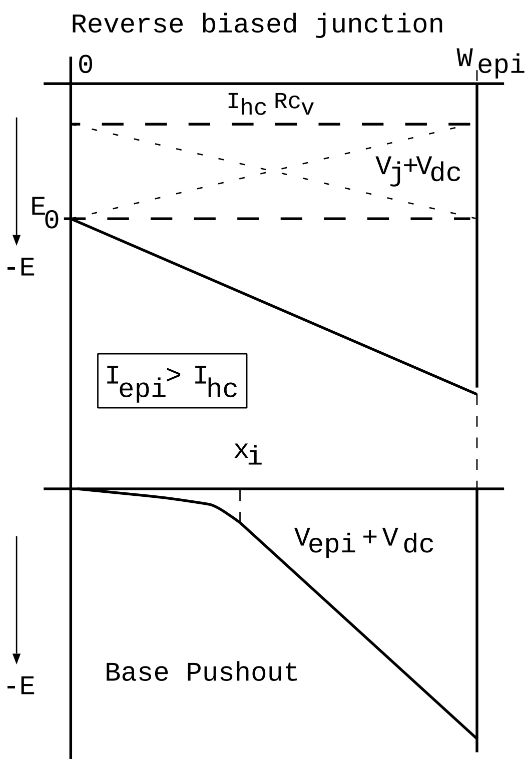
- velocity saturated current flow

$$\frac{dE}{dx} = \frac{q \cdot N_{epi}}{\epsilon} \cdot \left(1 - \frac{I_{epi}}{I_{hc}}\right)$$

$$V_{cb} + Vd_c = -\int_0^{W_{epi}} E(x) \cdot dx$$

$$= -E(0) \cdot W_{epi} + \frac{q \cdot N_{epi} \cdot W_{epi}^2}{2 \cdot \epsilon} \cdot \left(\frac{I_{epi}}{I_{hc}} - 1\right)$$

$$-E(0) \cdot W_{epi} = V_j + V_{dc} + I_{hc} \cdot R_{cv}$$

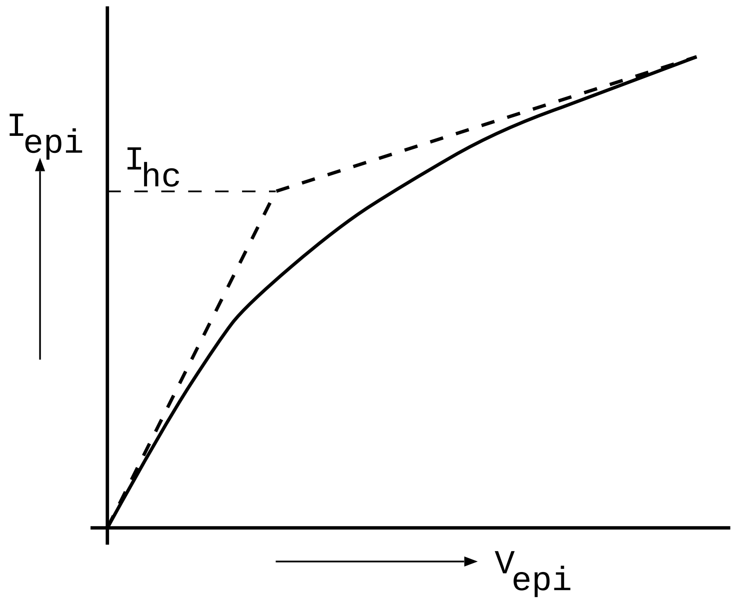


$$\Longrightarrow \quad I_{epi} = I_{hc} + \frac{V_{cb} - V_j - I_{hc} \cdot R_{c_v}}{SCR_{c_v}}$$

$$SCR_{c_v} = \frac{W_{epi}^2}{2 \cdot \epsilon \cdot v_s \cdot A_{eff}}$$

Combine ohmic and saturated current flow and include injection region:

$$I_{hc} \longrightarrow I_{low}$$
$$R_{c_v} \longrightarrow R_{c_v} \cdot (1 - X_i/W_{epi})$$
$$SCR_{c_v} \longrightarrow SCR_{c_v} \cdot (1 - X_i/W_{epi})^2$$



Final epilayer resistance model:

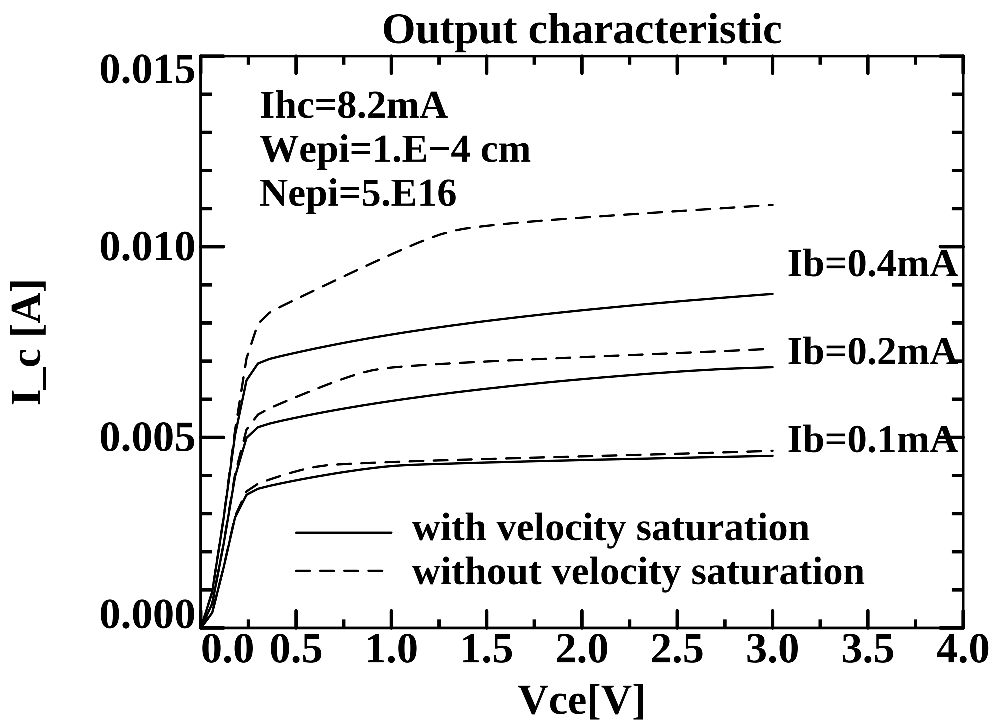
$$X_i/W_{epi} = \frac{E_c}{I_{epi} \cdot R_{c_v}}$$

$$I_{low} = \frac{I_{hc} \cdot V_{epi}}{V_{epi} + I_{hc} \cdot R_{c_v} \cdot (1 - X_i/W_{epi})}$$

$$I_{epi} = I_{low} + \frac{V_{epi} - I_{low} \cdot R_{c_v} \cdot (1 - X_i/W_{epi})}{SCR_{c_v} \cdot (1 - X_i/W_{epi})^2}$$

This leads to a cubic equation for I_{epi}

Influence of velocity saturation on the output characteristic.



Parameters: R_{c_v}, I_{hc}, SCR_{c_v}, V_{dc}

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Noise Sources

1. thermal noise;

   $\overline{i_N^2} = \frac{4 \cdot k \cdot T}{R}$ is valid for R_e, R_{c_c}, R_{b_c} and slightly different for R_{b_v}.

2. shot noise;

   $\overline{i_N^2} = 2 \cdot q \cdot I$ is valid for I_n, I_{b_1}, $I_{b_1}^S$, I_{b_2}, I_{b_3}, I_{ex} and $X I_{ex}$

3. $1/f$ noise of the base current;

   $\overline{i_N^2} = KF \cdot I_b^{AF}$ is valid for I_{b_1}, $I_{b_1}^S$, I_{b_3}, I_{ex}, $X I_{ex}$
   and for the non-ideal forward base current we have $KFN \cdot \left(I_{b_2}\right)^2$

The Mextram model contains extensive temperature scaling rules.
They are applied to the following parameters:

Resistances	R_{b_c}, R_{b_v}, R_{c_v}, R_{c_c}
Capacitances	C_{j_e}, V_{d_e}, C_{j_c}, V_{d_c}, XP, C_{j_s}, V_{d_s}, Q_{b_0}, Q_{n_0}, m_τ
Saturation currents	I_s, I_{s_s}
gain modelling	B_f, I_{bf}, V_{Lf}, B_{ri}, I_{b_r}, V_{L_r}, I_k, I_{k_s}
avalanche	Avl

The parameters in the temperature scaling rules are:

V_{g_e}, V_{g_b}, V_{g_c}, V_{g_s}, V_{g_j}	Bandgap voltages
A_b, A_{epi}, A_{ex}, A_c, A_s	Mobility exponents
V_i, N_a	Q_{b_0}
E_r	V_{Lf}, V_{L_r}

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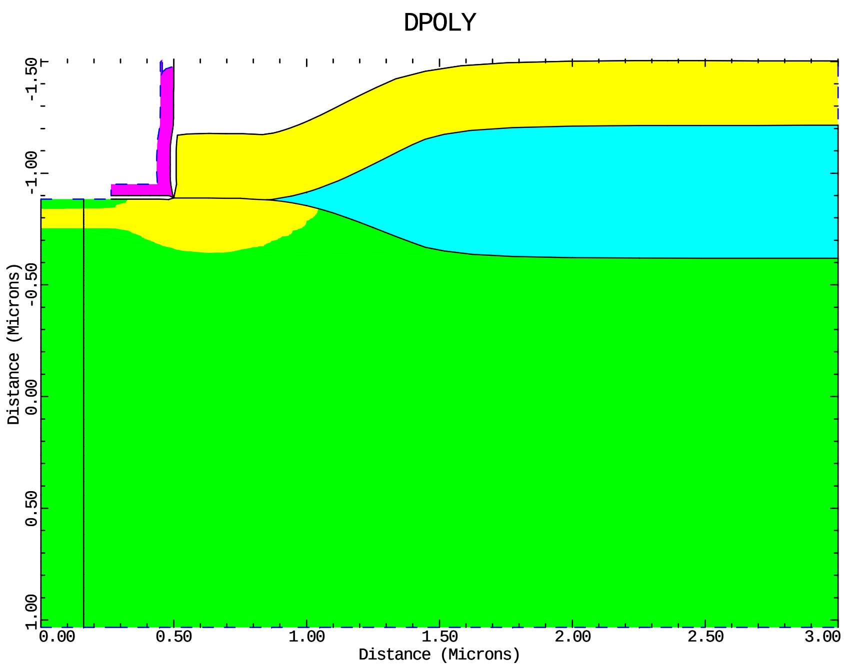
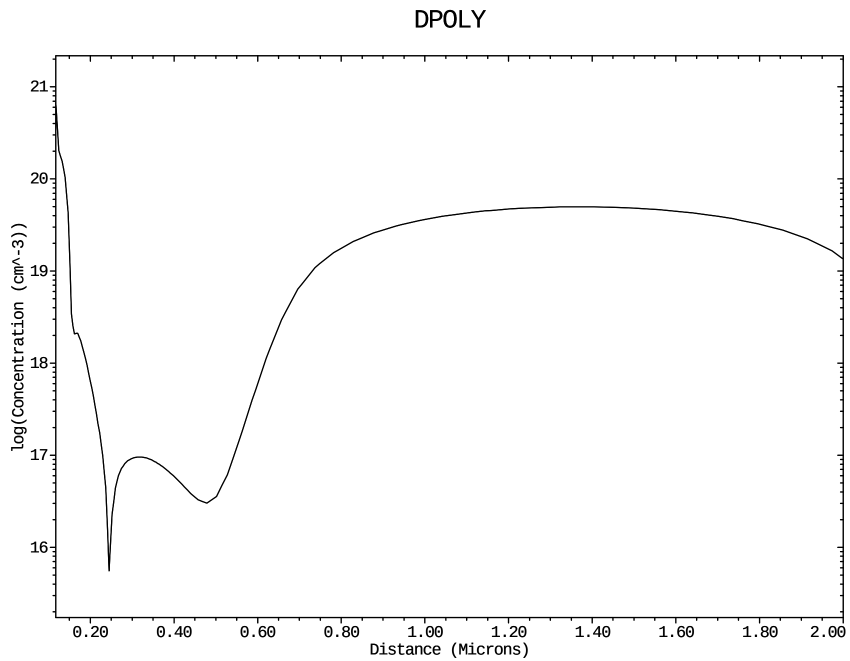
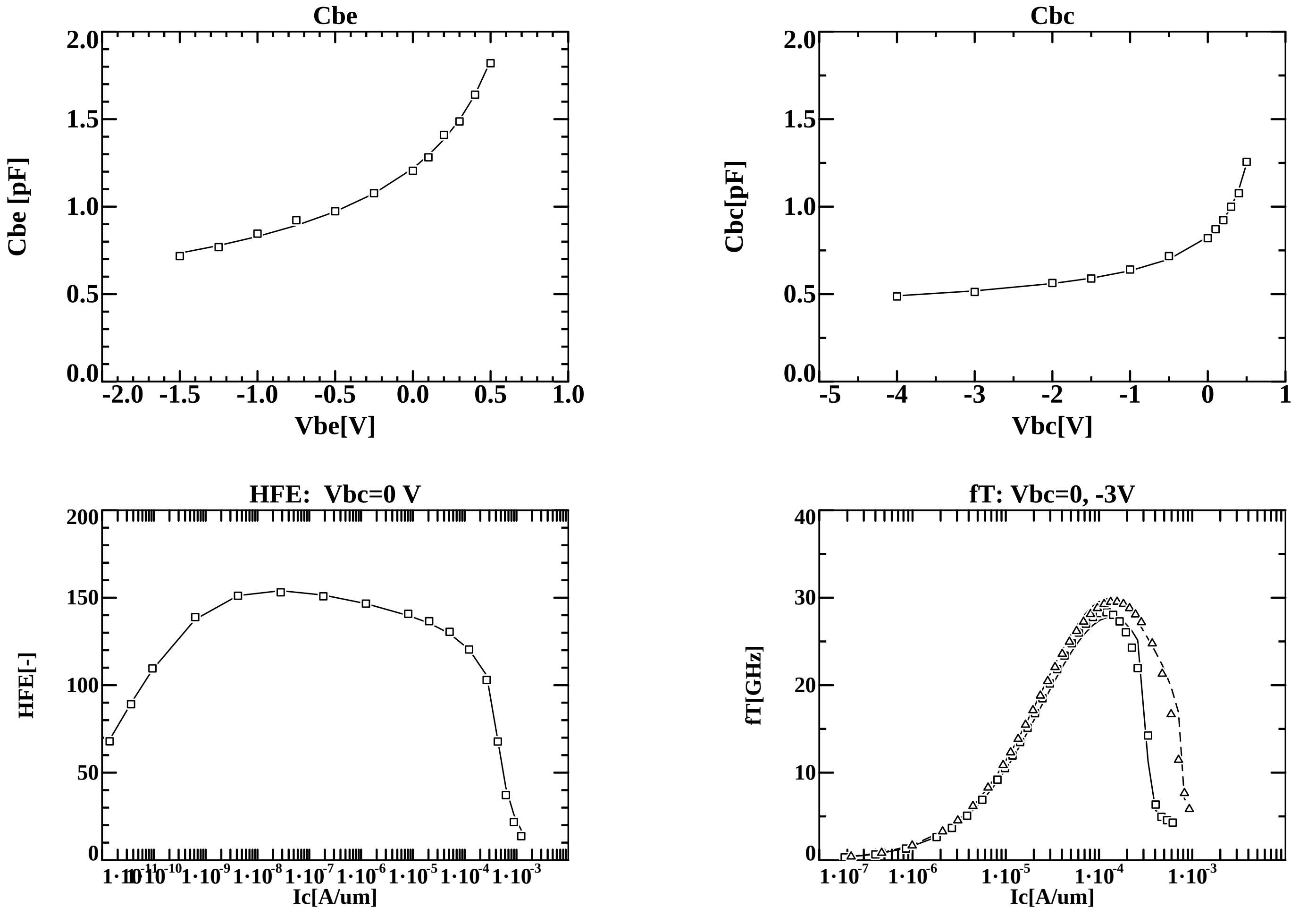


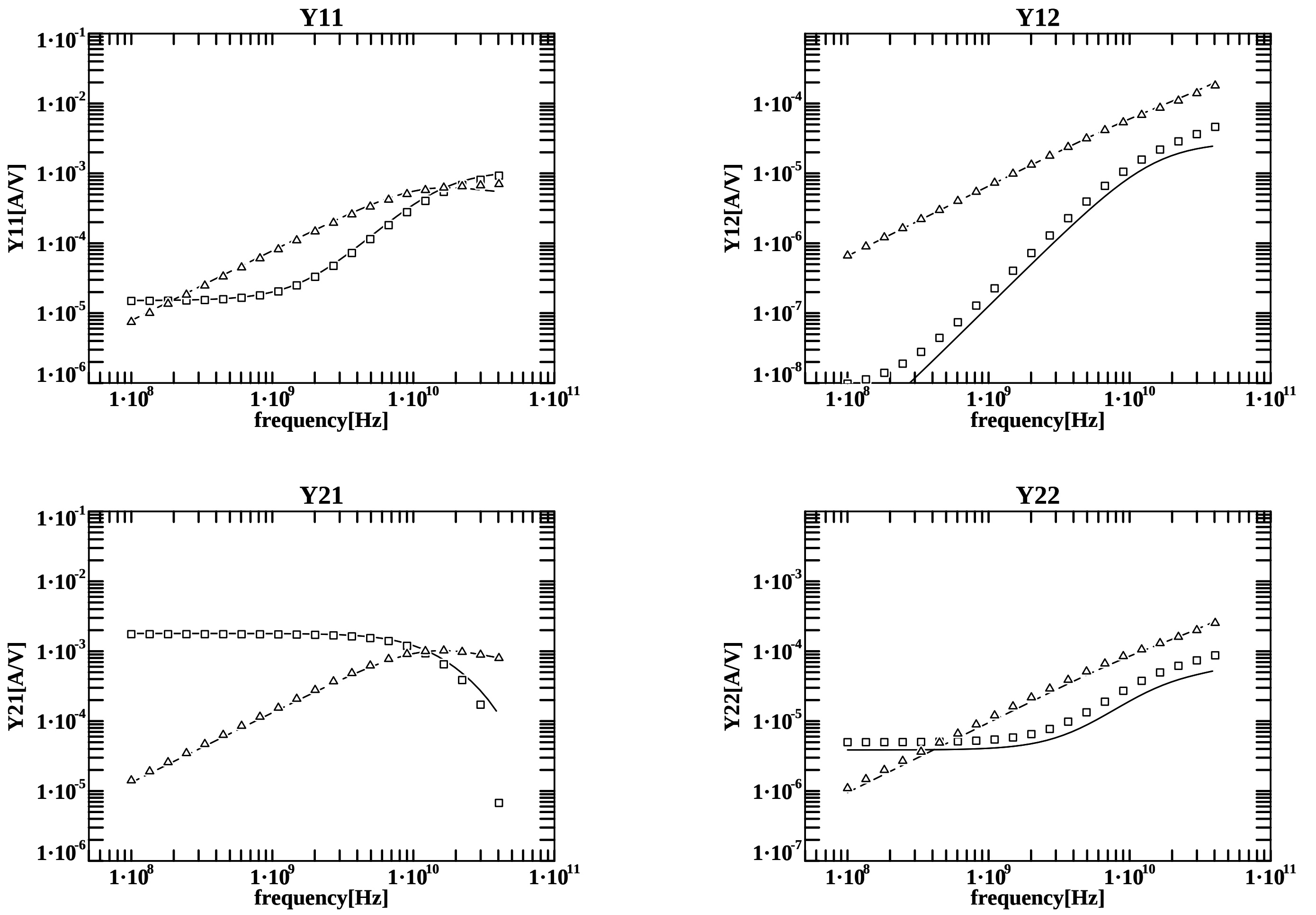


Cross section of the double poly bipolar transistor and the doping profile at the center of the device.

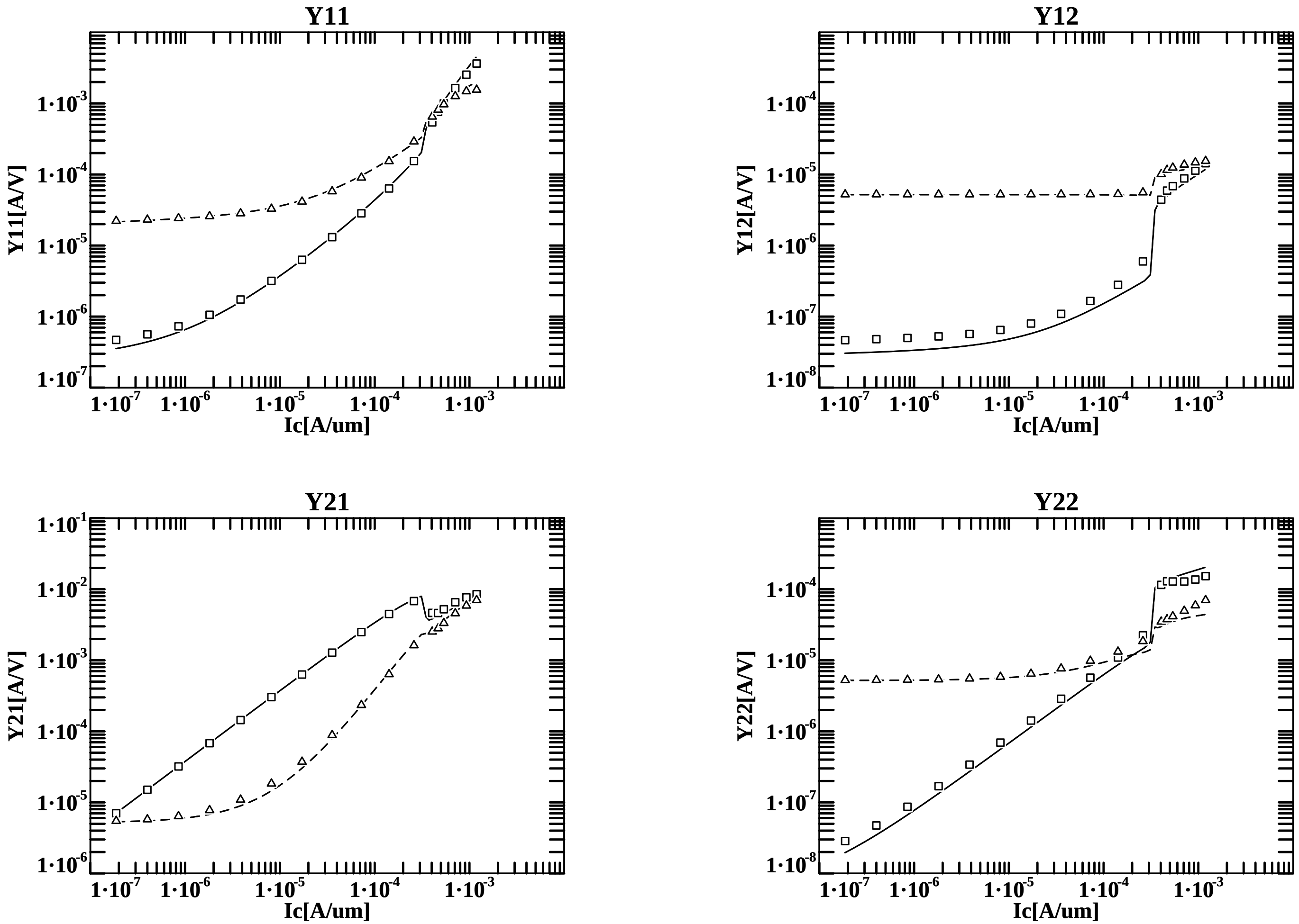
dpoly1: Results parameter extraction Mextram model versus Medici



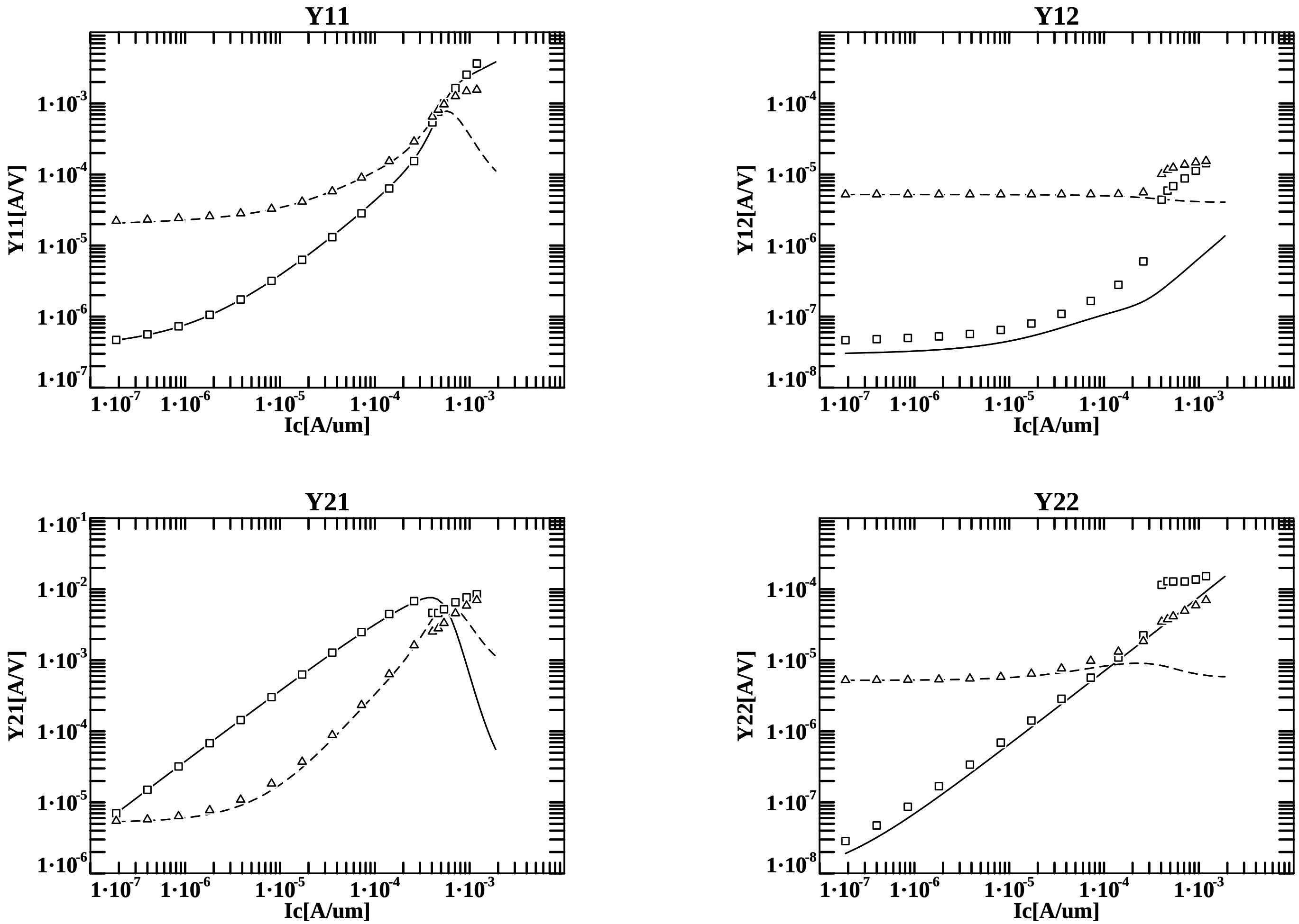
dpoly1: bias: Vbe=0.85 Vce=0.5 Medici Mextram



dpoly1: bias Vbc=0.0V freq: 1.0Ghz Medici Mextram



dpoly1: bias Vbc=0.0V freq: 1.0Ghz Medici SGP



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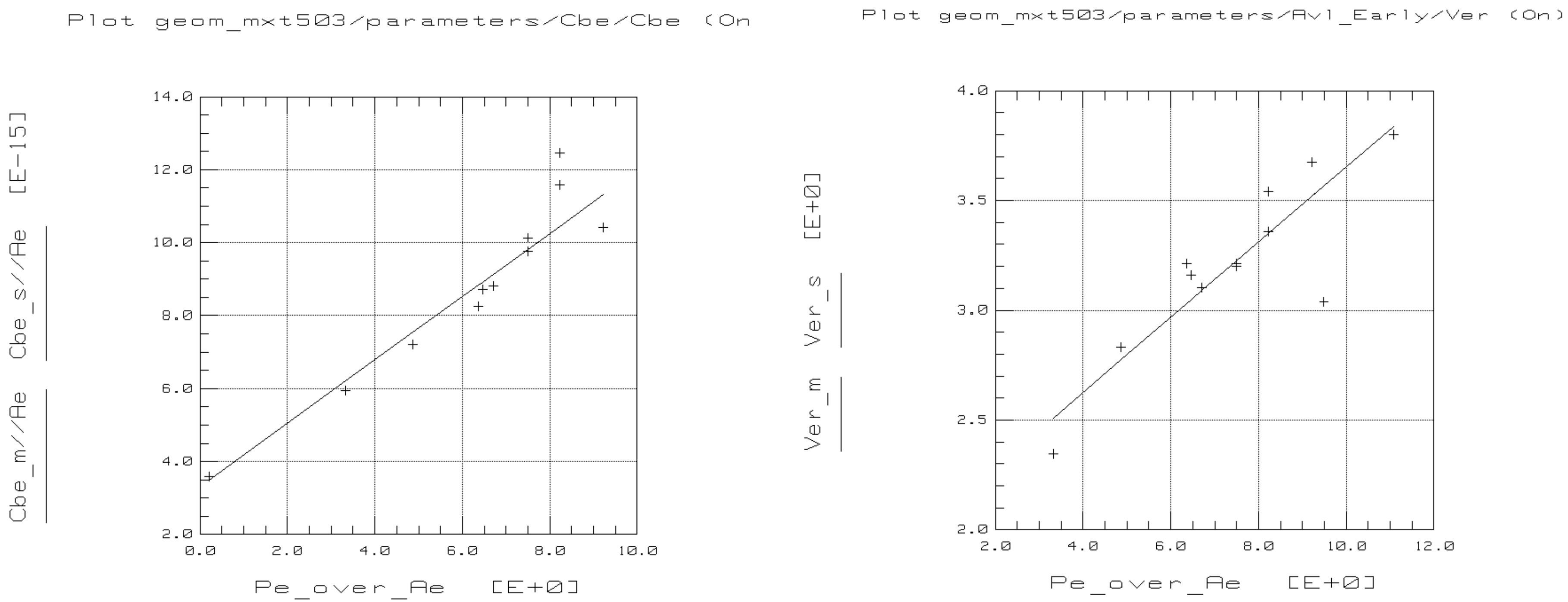
In general we have as a geometrical scaling rule:

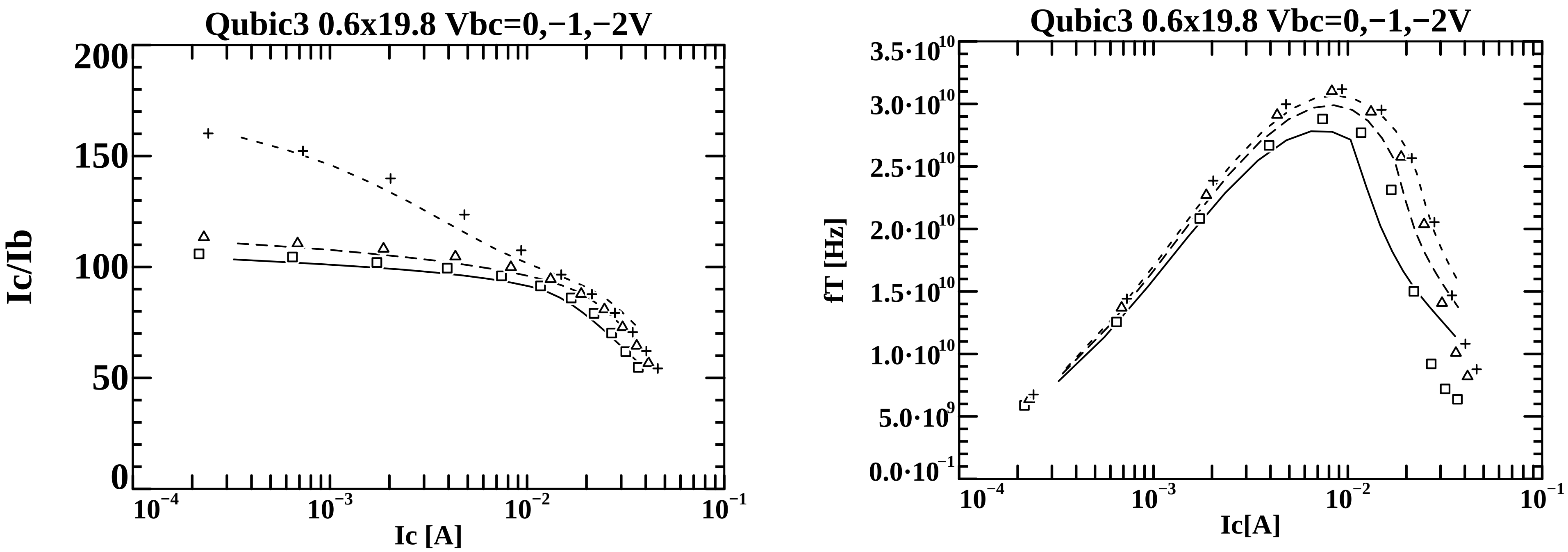
- rectangular geometry $W \times L$
- model parameter $p = p_b \cdot W \cdot L + 2 \cdot p_s \cdot (W + L)$
  No corner contributions.
- p_b and p_s are unity parameters and process-dependent
  They are correlated with PCM data like ρ_{ext}, ρ_{pinch} and BV_{cb0}

Statistical models can use the same scaling rules !

Average values $\overline{p}$ and variances σ_p^2 follow from $\overline{W}$, $\overline{L}$, $\overline{p_b}$, $\overline{p_s}$
and σ_W^2, σ_L^2, $\sigma_{p_b}^2$, $\sigma_{p_s}^2$.



Geometry dependence of the base-emitter capacitance and the reverse Early voltage.



Device characteristic after geometric scaling of a double-poly npn transistor, fabricated in the Philips Semiconductors Qubic-3 process.
Emitter dimension in silicon : 0.6 x 19.8 μm^2.

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- **The future of Mextram**
  - New release in 1999
  - Modelling of SiGe bipolar transistors
- Summary

- From benchmarking of Mextram versus Vbic.
  - more physics based (complicated) model description
  - less number of parameters
  - more correlations between DC and AC
  - more experience needed to perform parameter extraction
  - only one free parameters to model cut off frequency f_T
  - no self heating, because in Philips:
    - feature of the inhouse circuit simulator Pstar
    - available for all device models.
    - not only self heating, also from neighbours is easy possible
  - no substrate series resistance

What can be expected of Mextram 504?

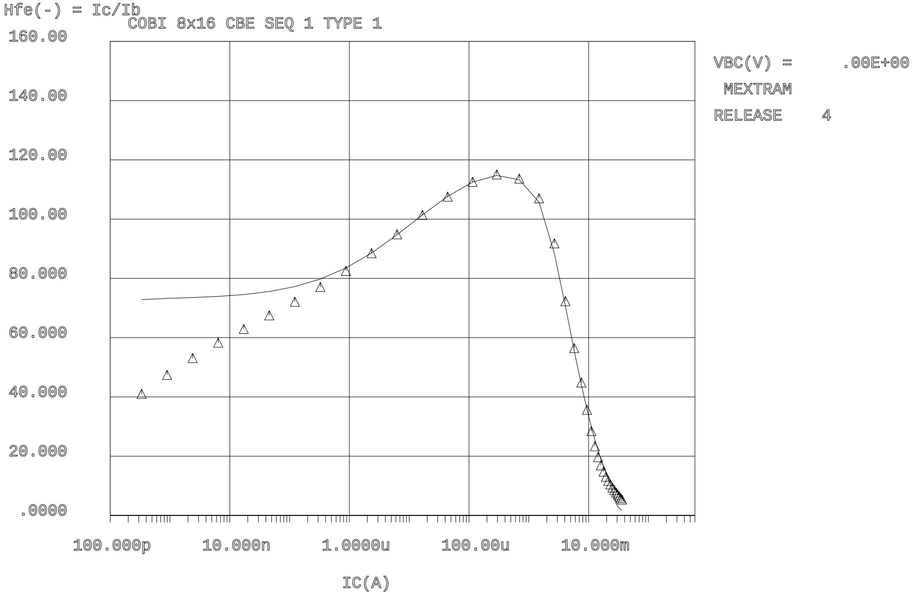
- review of the complete model $\rightarrow$ documentation
- introduction of additional parameters in existing Mextram model formulations
- modelling of SiGe transistors
- until now no new phenomenon like collector breakdown, tunneling/avalanche at BE junction

Achieved until now:

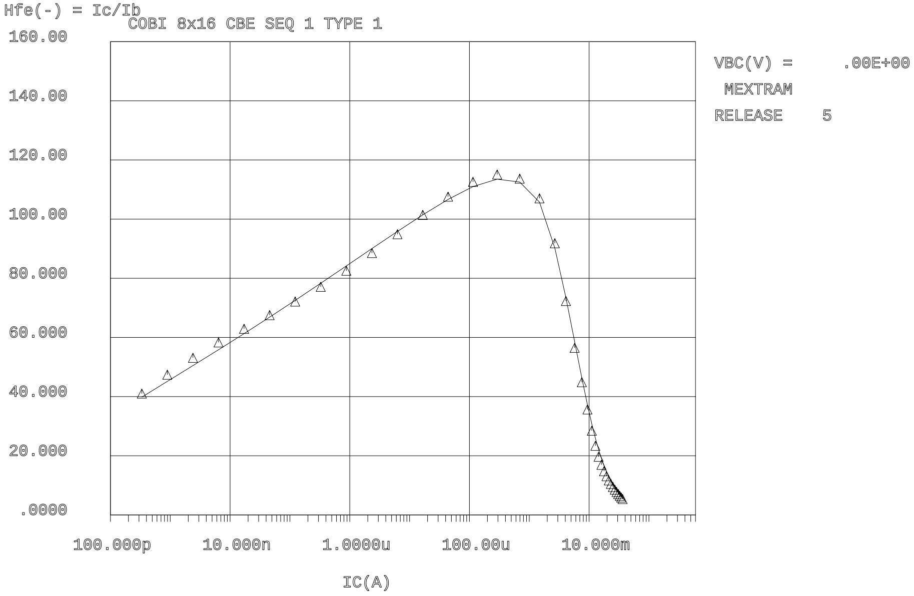
- more flexible non-ideal forward base current, compatible with GP and Mextram 503.2 (one additional parameter).
- modelling of the SiGe transistor (two additional parameters)
- simplified and improved thermal noise model for the bias dependent part of the base resistance Rb_v (DC current crowding)
- improved temperature scaling of neutral base charge Q_{b_0} (Early effect).

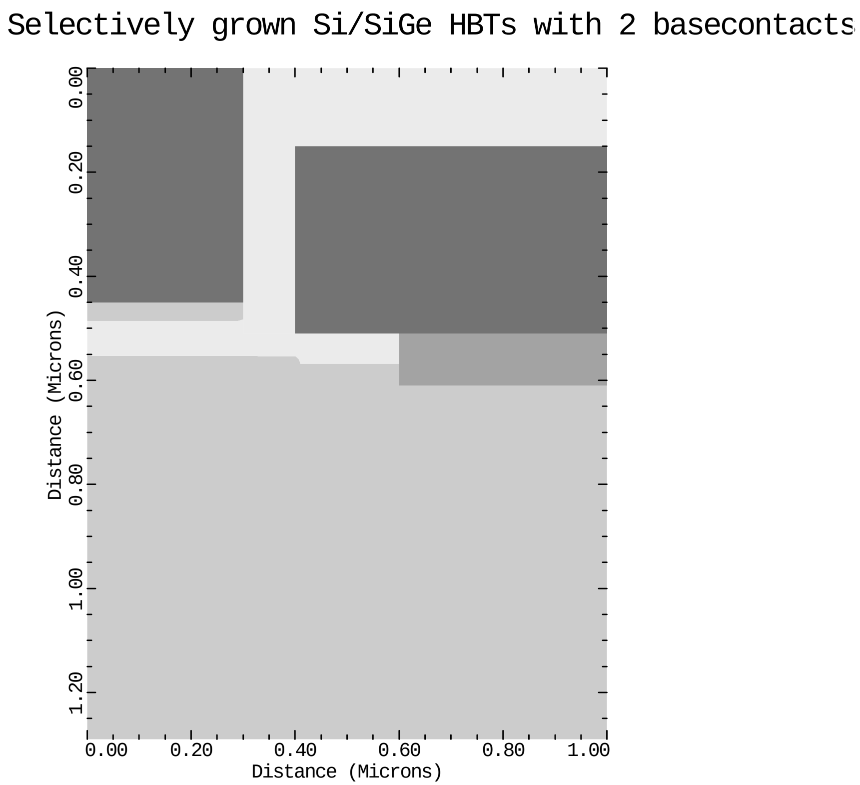
example: COBI process, CBE layout

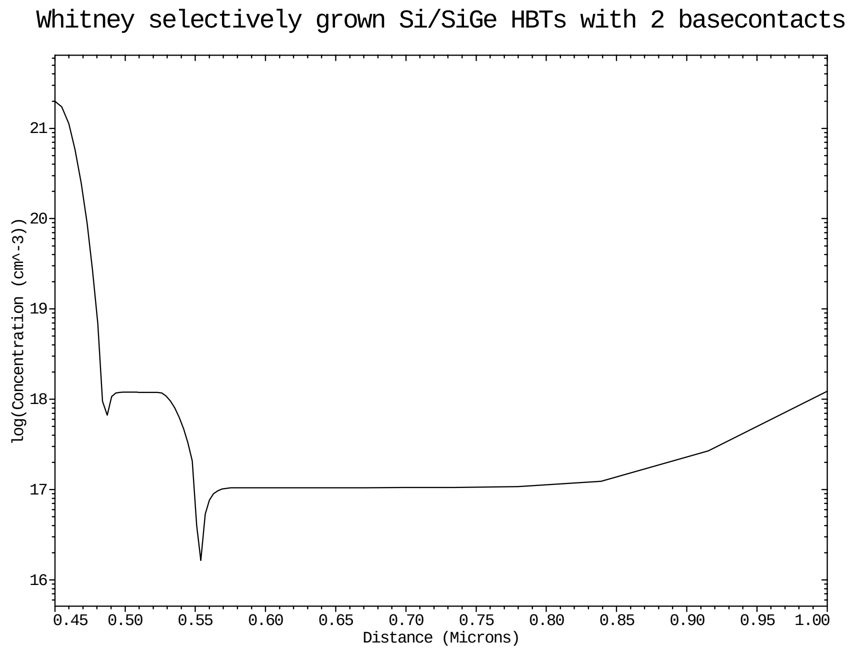
Mextram 503.2



Mextram 504.0

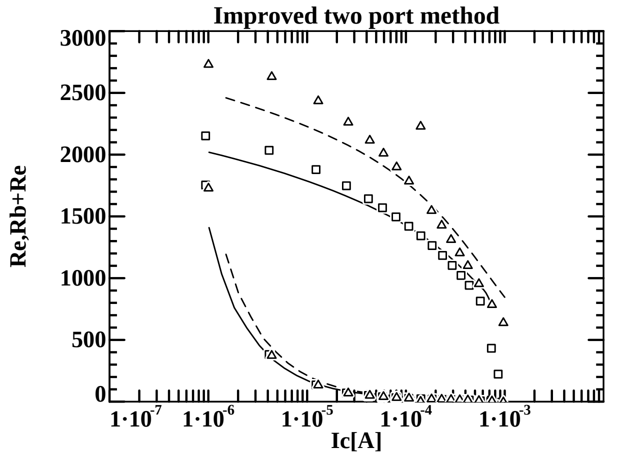


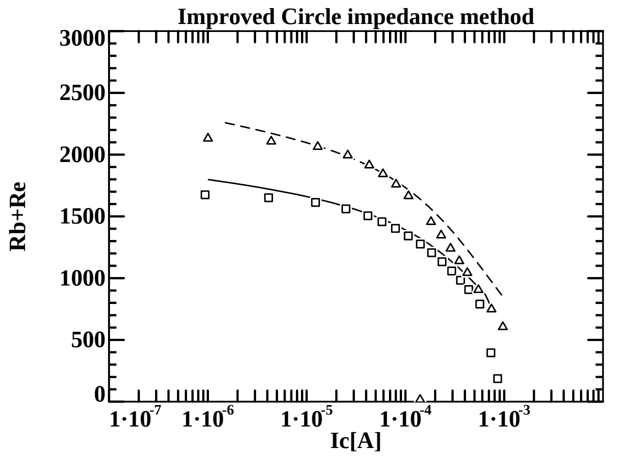


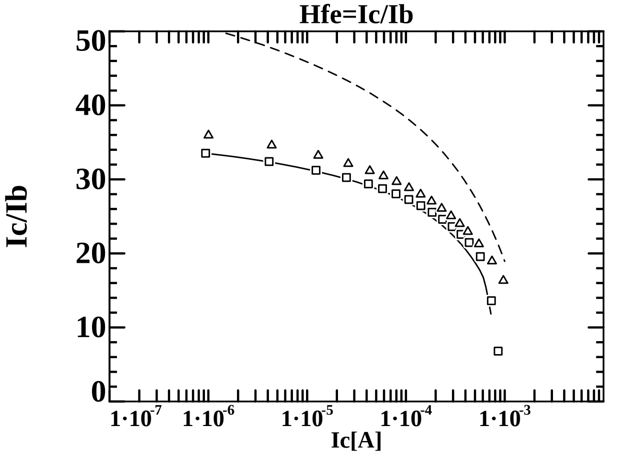


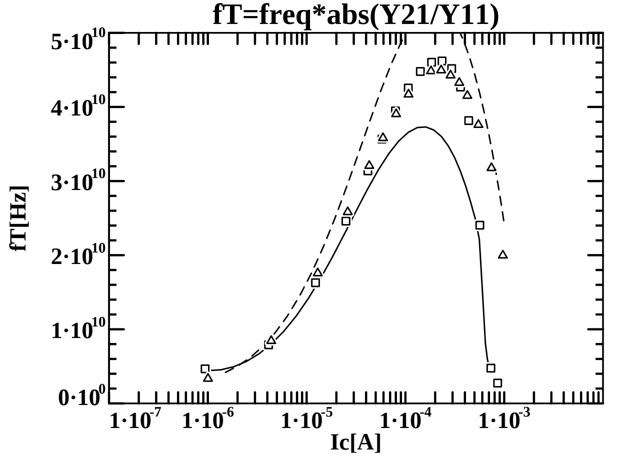
Cross section of the SiGe transistor and the doping profile at the center of the device.

SiGe freq=10.0Ghz, Vbc= 0,-3V XCjc=0.5 Medici









Dependence of collector voltage on current gain and cut-off frequency f_T is different for SiGe transistors.

Moll-Ross relation for the main electron current

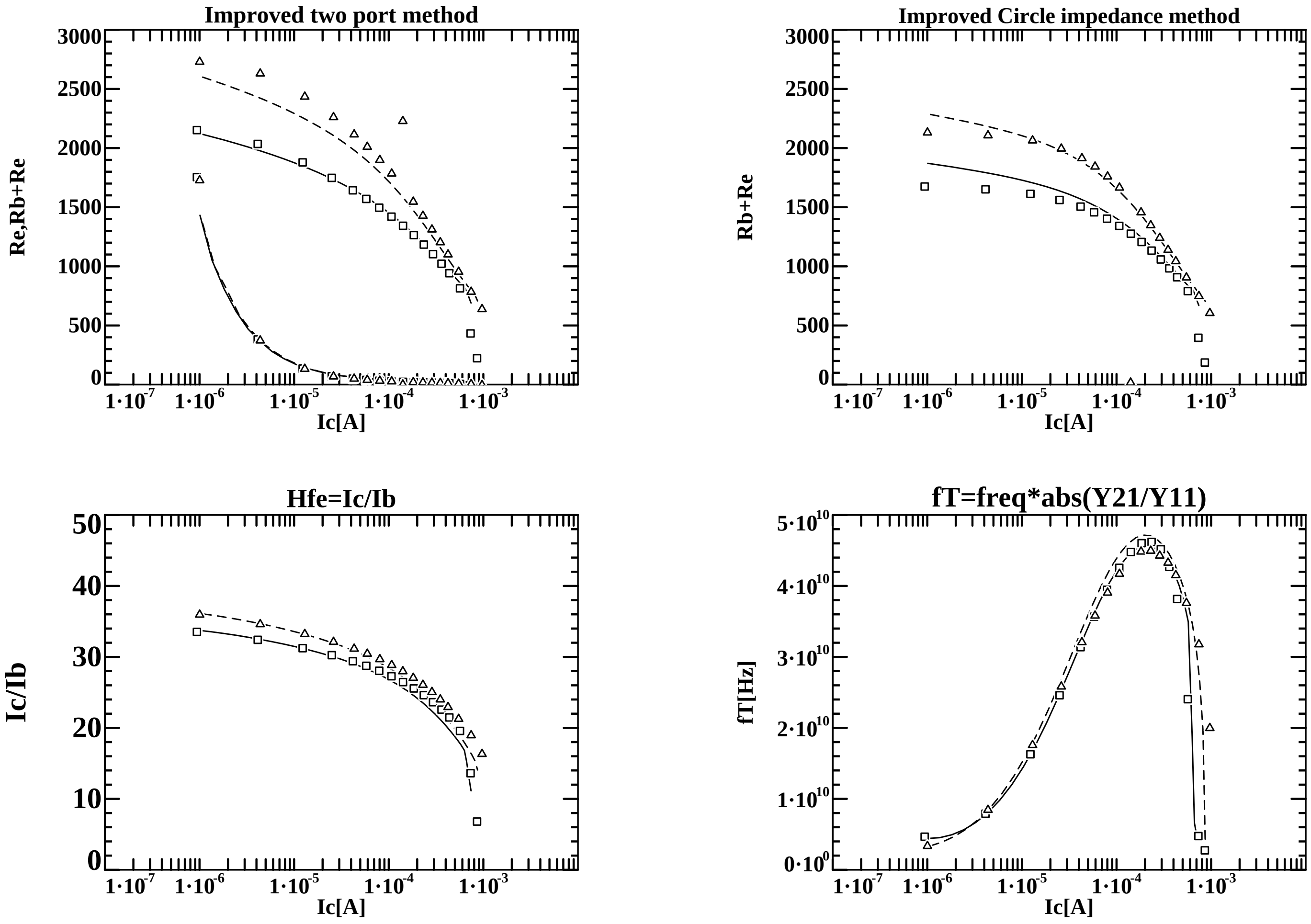
$$I_n = I_s \cdot \left[\exp\left(\frac{V_{b2e1}}{V_t}\right) - \exp\left(\frac{V_{b2c2}}{V_t}\right)\right] \cdot \frac{Q_{b_0}}{Q_{b_0} + Q_{T_e} + Q_{T_c} + Q_{be} + Q_{bc}}$$

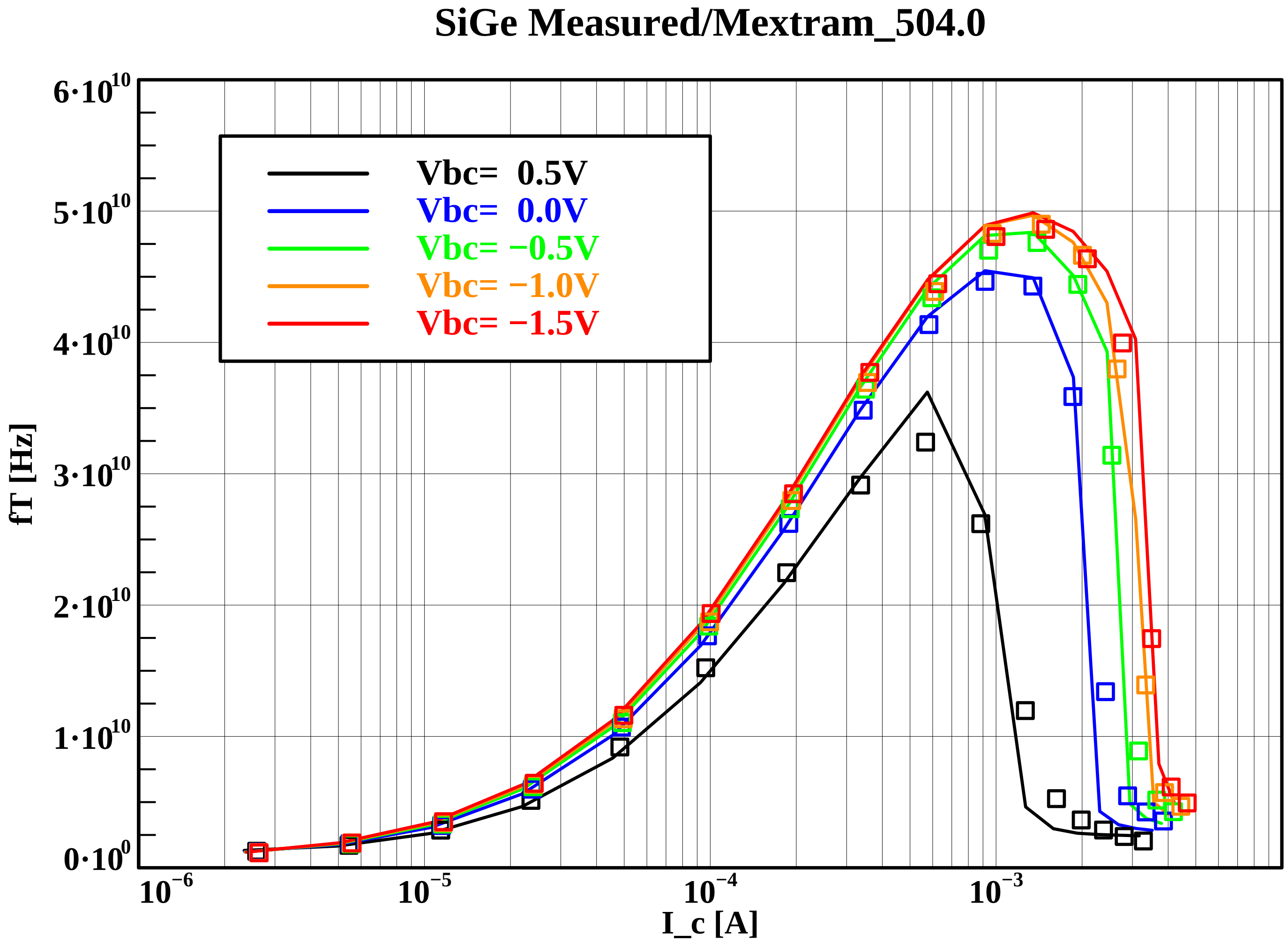
$$I_n = \frac{I_f - I_r}{q_b^i} \qquad q_b^i = 1 + \frac{Q_{be} + Q_{bc}}{Q_{b_0}} + \frac{V_{T_e}}{VER} + \frac{V_{T_c}}{VEF}$$

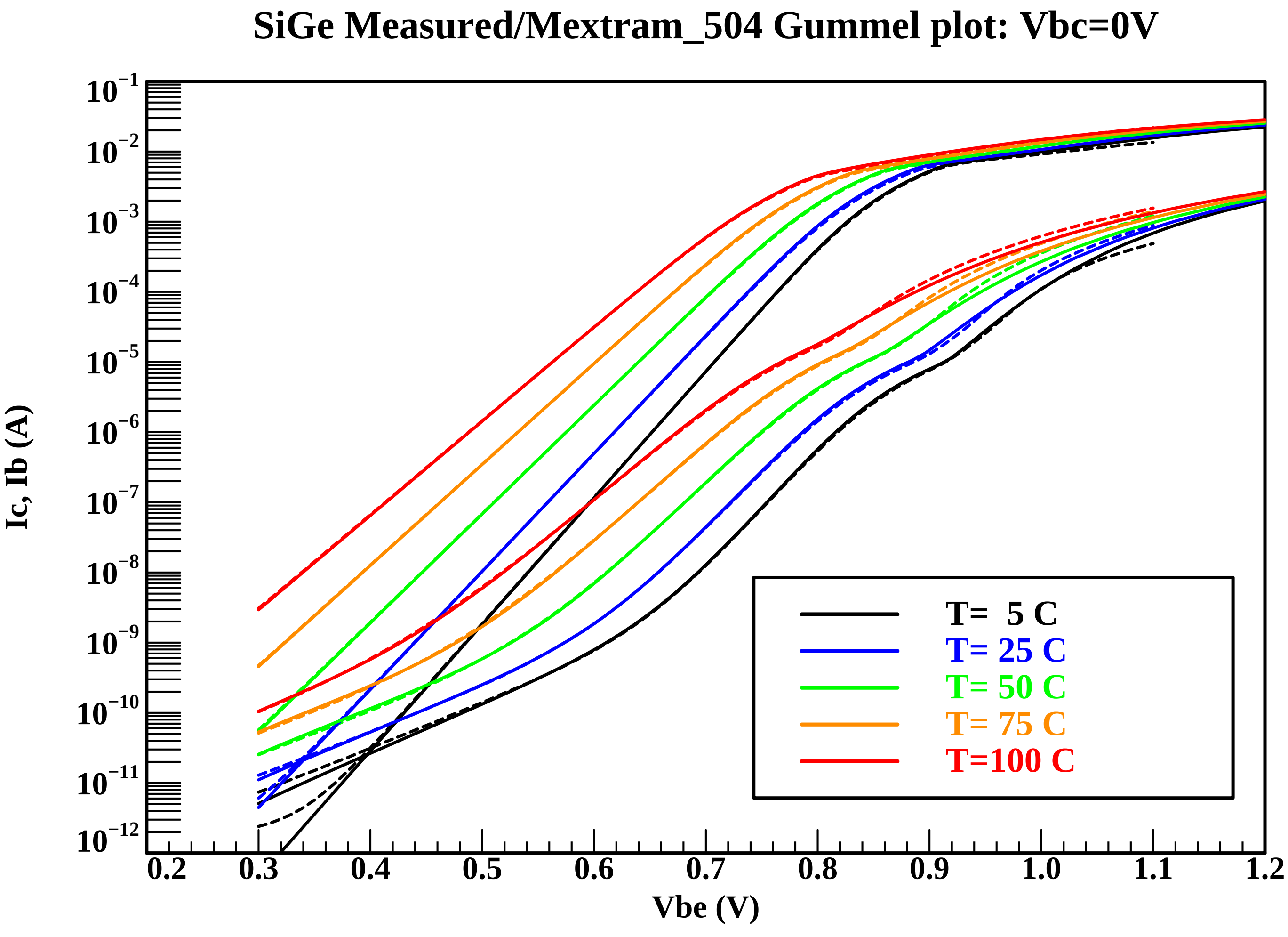
$$R_b = \frac{Rb_v}{q_b^r} \qquad q_b^r = 1 + \frac{Q_{be} + Q_{bc}}{Q_{b_0}} + \frac{Q_{T_e} + Q_{T_c}}{Q_{b_0}}$$

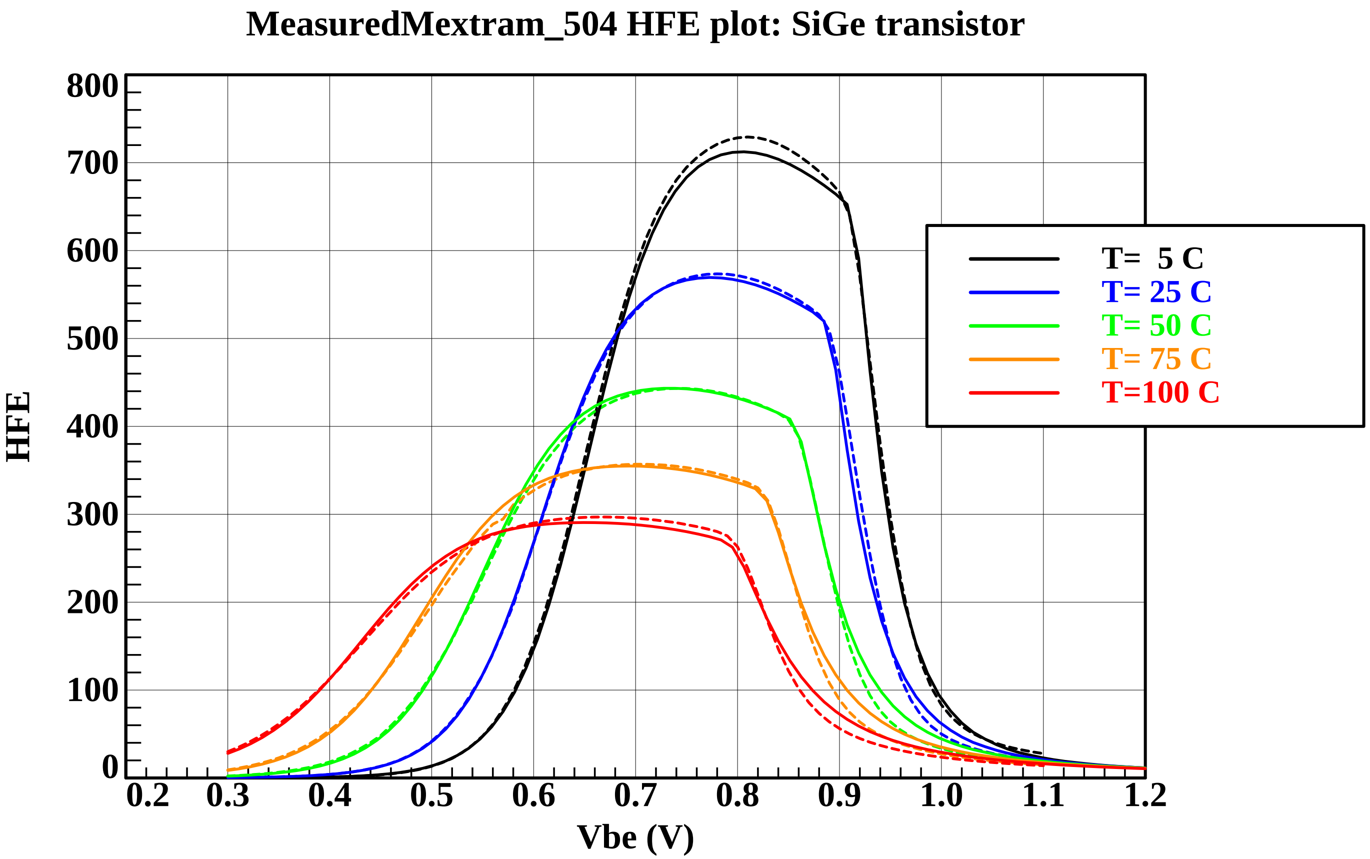
$$VER = \frac{Q_{b_0}}{(1 - XCj_e) \cdot Cj_e} \qquad VEF = \frac{Q_{b_0}}{XCj_c \cdot Cj_c}$$

SiGe freq=10.0Ghz, Vbc= 0,-3V Medici M504




SiGe Measured/Mextram_504.0
Vbc= 0.5V
Vbc= 0.0V
Vbc= −0.5V
Vbc= −1.0V
Vbc= −1.5V
6·10^10
5·10^10
4·10^10
3·10^10
2·10^10
1·10^10
0·10^0
fT [Hz]
10^−6
10^−5
10^−4
10^−3
I_c [A]


SiGe Measured/Mextram_504 Gummel plot: Vbc=0V
Ic, Ib (A)
Vbe (V)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
T= 5 C
T= 25 C
T= 50 C
T= 75 C
T=100 C



MeasuredMextram_504 HFE plot: SiGe transistor
HFE
800
700
600
500
400
300
200
100
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Vbe (V)
T= 5 C
T= 25 C
T= 50 C
T= 75 C
T=100 C

- The Mextram Bipolar Transistor Model
  - Model description
- RF performance
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- **Summary**

- Bias-dependent Early effect modelled by means of depletion charges
- Charge storage in quasi-neutral regions modelled independently from currents
- Influence of built-in electric field
- High-injection effects in the base
- Current- and voltage dependent c-b depletion capacitance
- Quasi-saturation and hot-carriers (Kirk) effect in the collector epilayer
- Bias-dependent current gain
- Avalanche multiplication valid for all collector current levels
- Conductivity modulation of the base
- DC and AC e-b current crowding
- Sidewall contributions to currents and depletion charges
- Explicit modelling of inactive regions: parasitic PNP, split c-b capacitance and substrate effects
- Temperature dependencies of the model parameters
- Physics-based parameters, facilitating geometrical scaling and statistical modelling

- Mextram 504 is able to model SiGe transistors accurately
  - Bias dependency of the collector current.
  - Cut off frequency f_T and small signal Y parameters.
  - Temperature scaling.
- More flexibility in parameter extraction by introducing additional parameters.

Future work:

- Temperature scaling in general and in particular of f_T