MEXTRAM (level 504)
the Philips model for bipolar transistors

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FSA modeling workshop 2002

Contents

- **History**
- **Modelled effects**
  - some basic bipolar characteristics
- **Improved description of output conductance and f_T**
  - How an improved description gives smoother behaviour
- **Some optional features:**
  - The effect of a graded Ge content in the base
  - Neutral base recombination
  - Self-heating
  - Advanced avalanche modelling: snapback
- **Geometric scaling**
- **Status of Mextram 504**

History

- Mextram has been developed by Philips Research

- Physics based, suitable for digital and analog applications

- Introduced in 1985

- Updates

$\longrightarrow$ level 502: 1987

$\longrightarrow$ level 503: 1993

$\longrightarrow$ level 504: 2000

- In public domain since 1995

`http://www.semiconductors.philips.com/Philips_Models`

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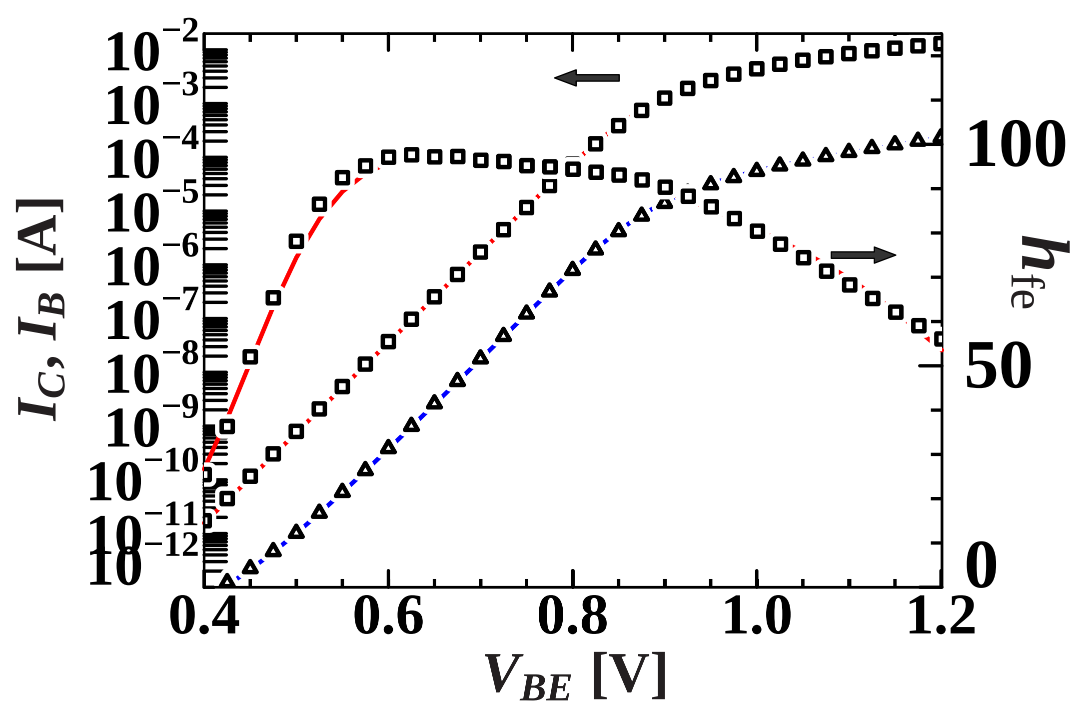
Modelled effects: Gummel plot

Collector current, base current and current gain

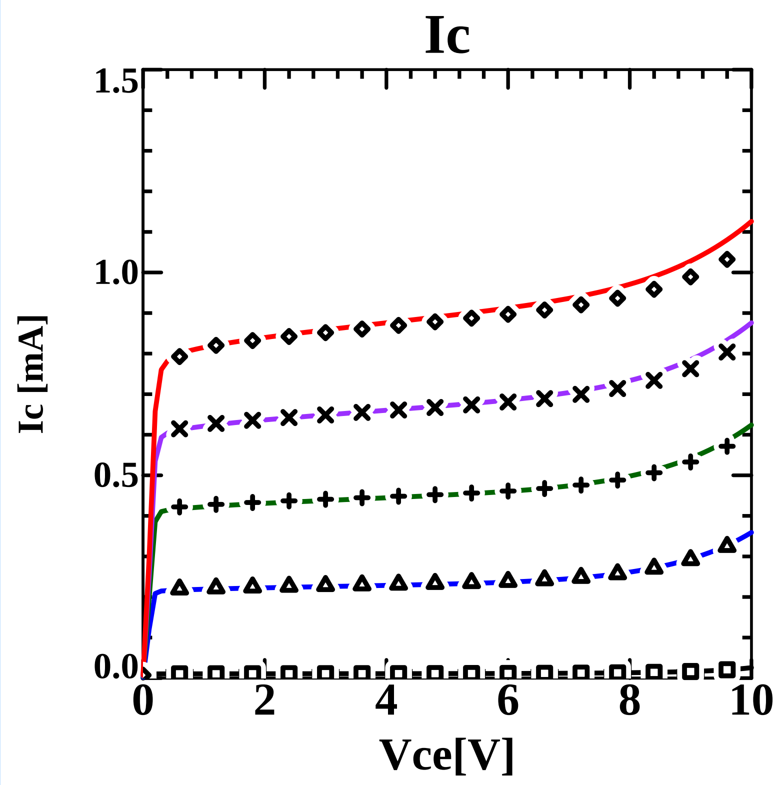


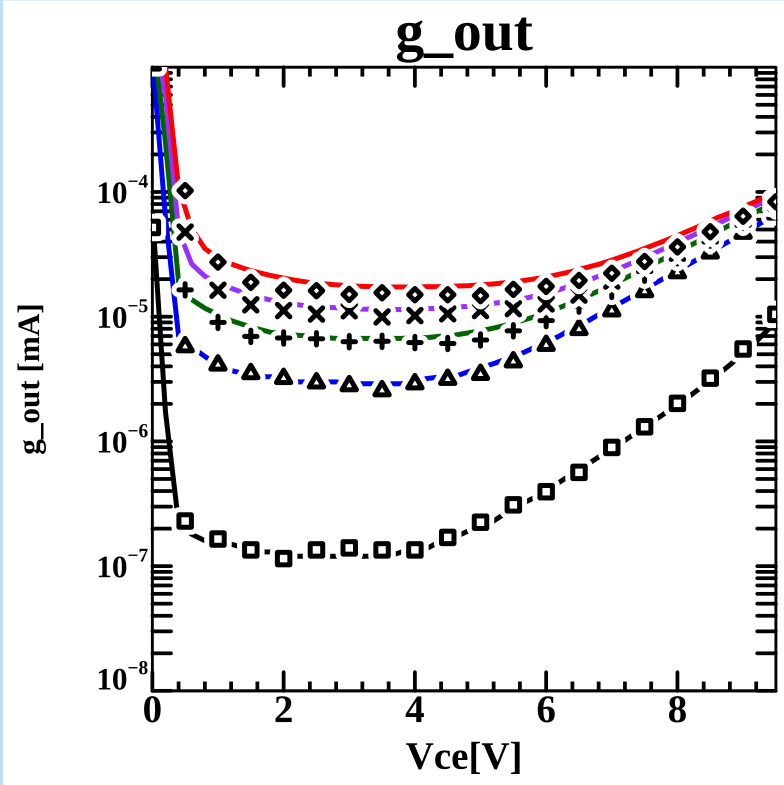
Non-ideal base current ($V_{BE} < 0.55$V)

Bias dependent reverse Early effect (o.a. in h_{fe}: $V_{BE} = 0.5$–0.9V)

High current effects (resistances, knee, Kirk effect) ($V_{BE} > 0.9$V)

Modelled effects: Output characteristic





Bias dependent Early effect (g_{out} not constant)

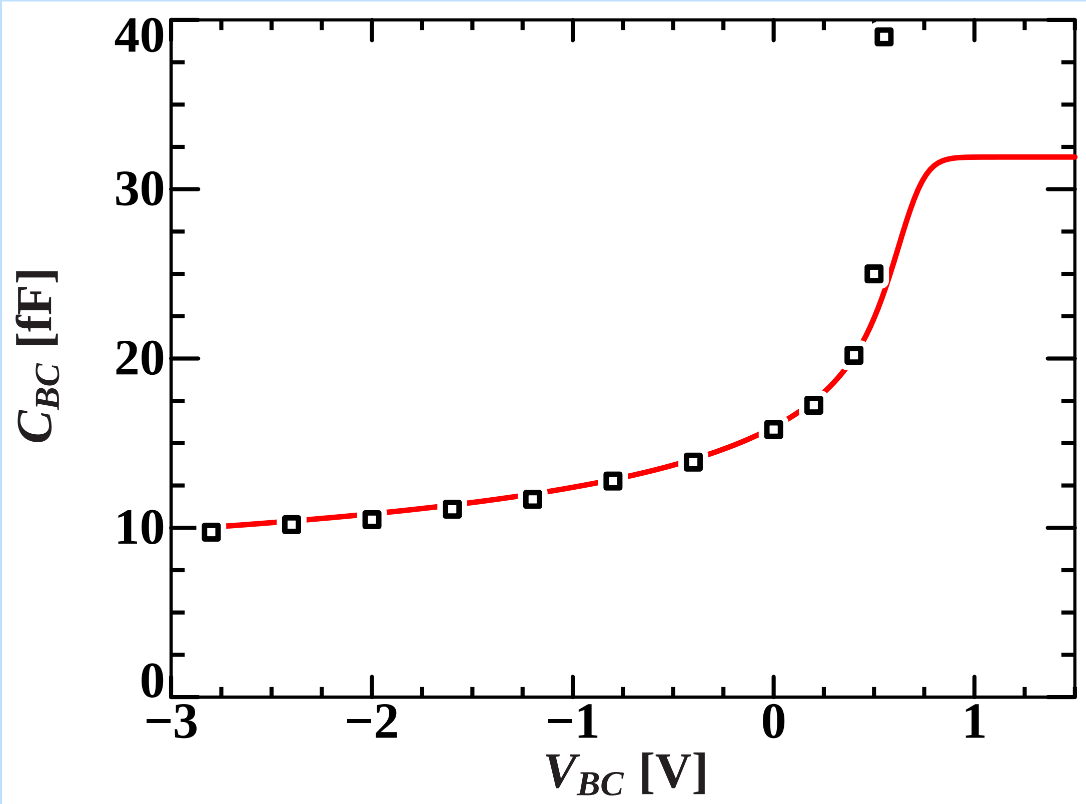
Quasi-saturation/Kirk effect: current reduction at lower voltages/ high current densities

Hard saturation ($V_{CE} < 0.6$V)

Avalanche ($V_{CE} > 4$V)

Depletion capacitances

Depletion capacitances in Mextram:



When diffusion charge becomes important ($V_{BC} > 0.5$V):

depletion capacitance levels off (not important anymore)

Diffusion charges

Spice-Gummel-Poon: as function of current

$$Q_{\mathrm{diff}} = \tau_f I_f$$

Mextram: as function of carrier densities

$$Q_{\mathrm{diff,E}} = \tau_E \; I_s \; e^{V_{BE}/m_\tau V_T}$$

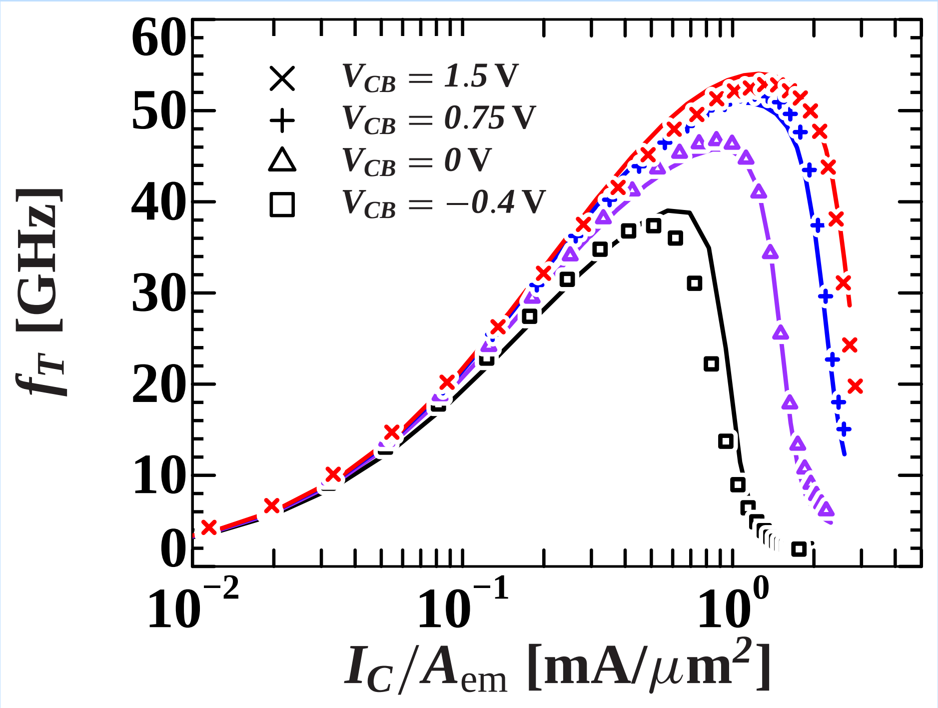
$$Q_{\mathrm{diff,B}} = \frac{1}{2} \, Q_{B0} \qquad (n_0 + n_B) \propto \tau_B$$

$$Q_{\mathrm{diff,epi}} = \frac{1}{2} \, Q_{\mathrm{epi0}} \, \frac{x_i}{W_{\mathrm{epi}}} \quad p_0 \qquad \propto \tau_{epi}$$

n_0, n_B: electron concentration in base

p_0: hole concentration in epilayer

Modelled effects: Cut-off frequency (Research SiGe)



Capacitances (low currents)

Transit times (around top of f_T)

Quasi-saturation/Kirk effect (beyond top f_T)

Reverse transit time (hard saturation, negative V_{CB})

Independence of parameters

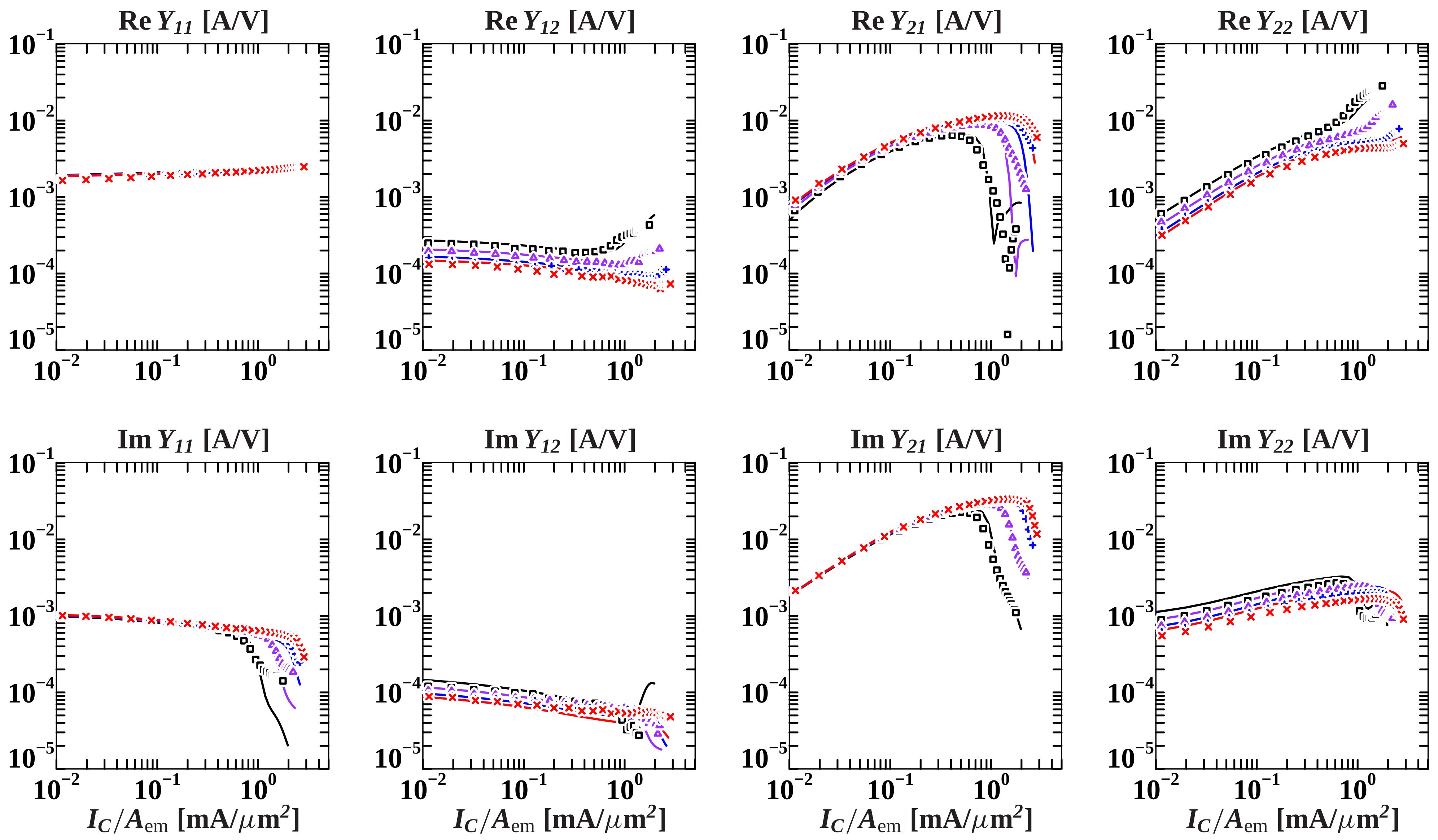
- Capacitance values and transit times do not influence DC behaviour

- Base parameters I_s, I_k, τ_B are separate from epilayer parameters R_{Cv}, SCR_{Cv}, I_{hc}, τ_{epi}

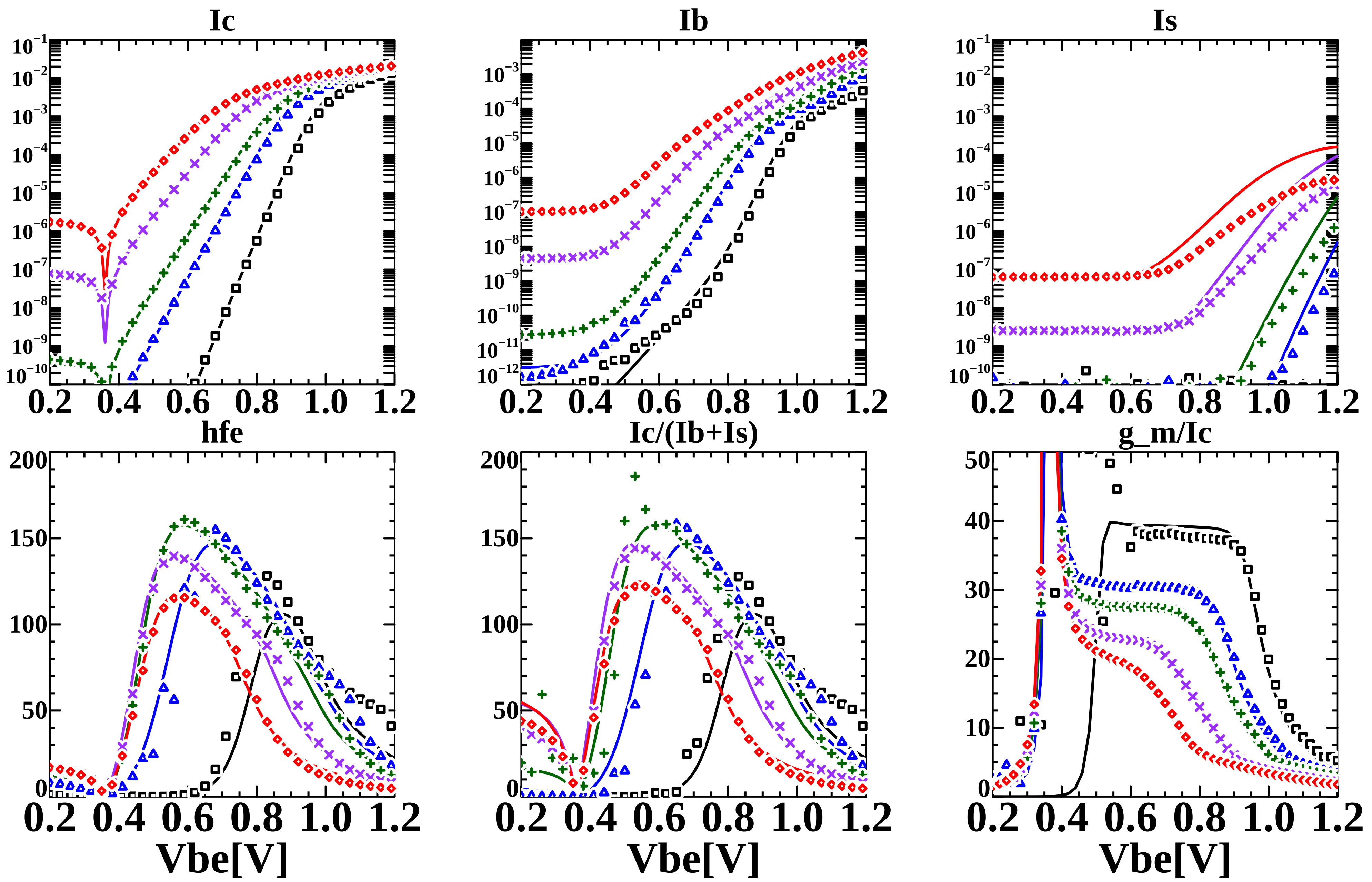
$\Rightarrow$ Ge in base does not influence epilayer parameters

- Independency simplifies parameter extraction

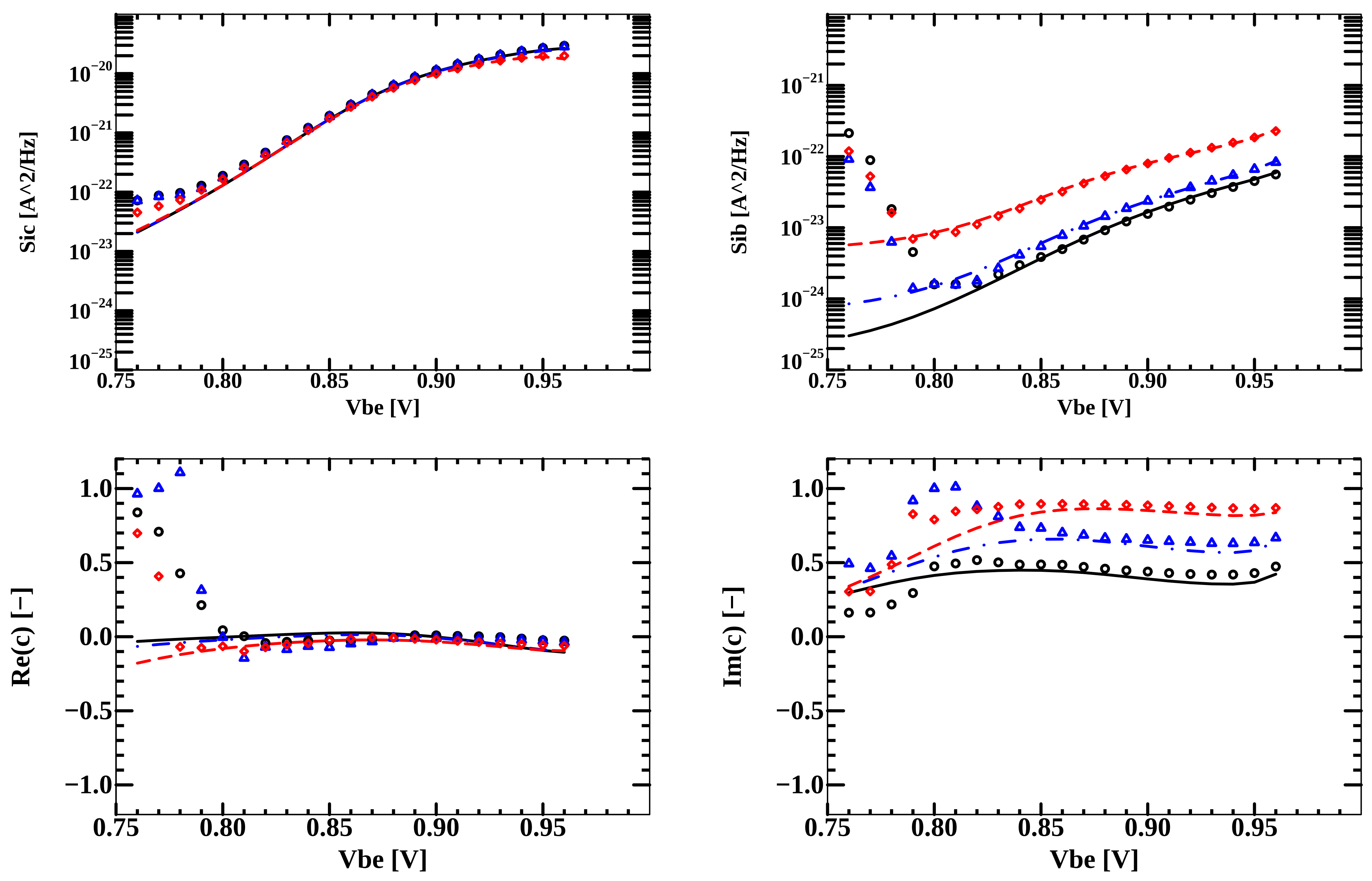
Small-signal parameters $V_{CB} = -0.4, 0, 0.75, 1.5$V (Research SiGe)



Temp. scaling $V_{CB} = -0.36$V, $T = -50, 25, 62.5, 137.5, 200$°C



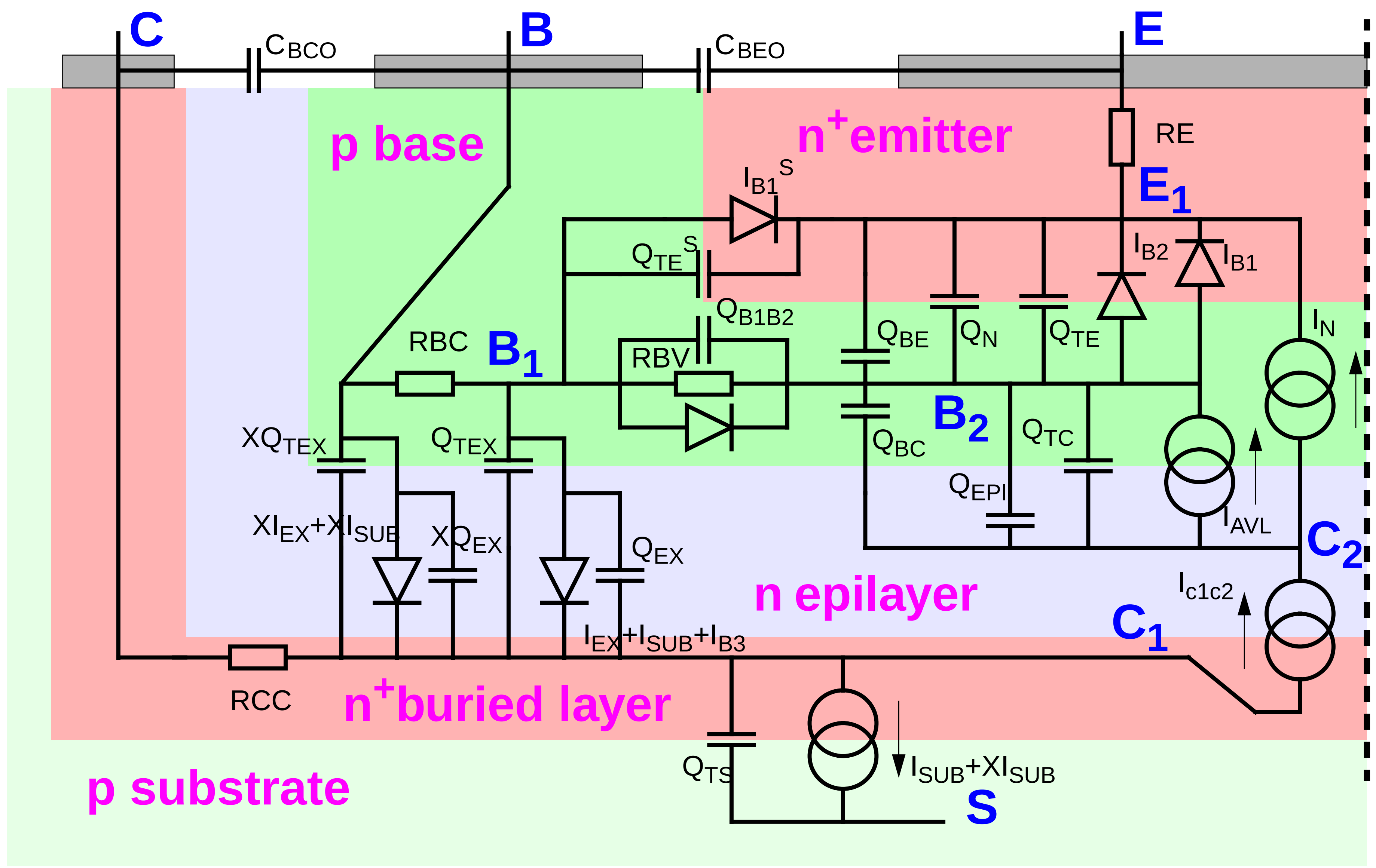
RF noise model ($0.5 \times 20.3\ \mu m^2$, $f = 1, 2, 5.5$ GHz, $V_{CE} = 2$ V)



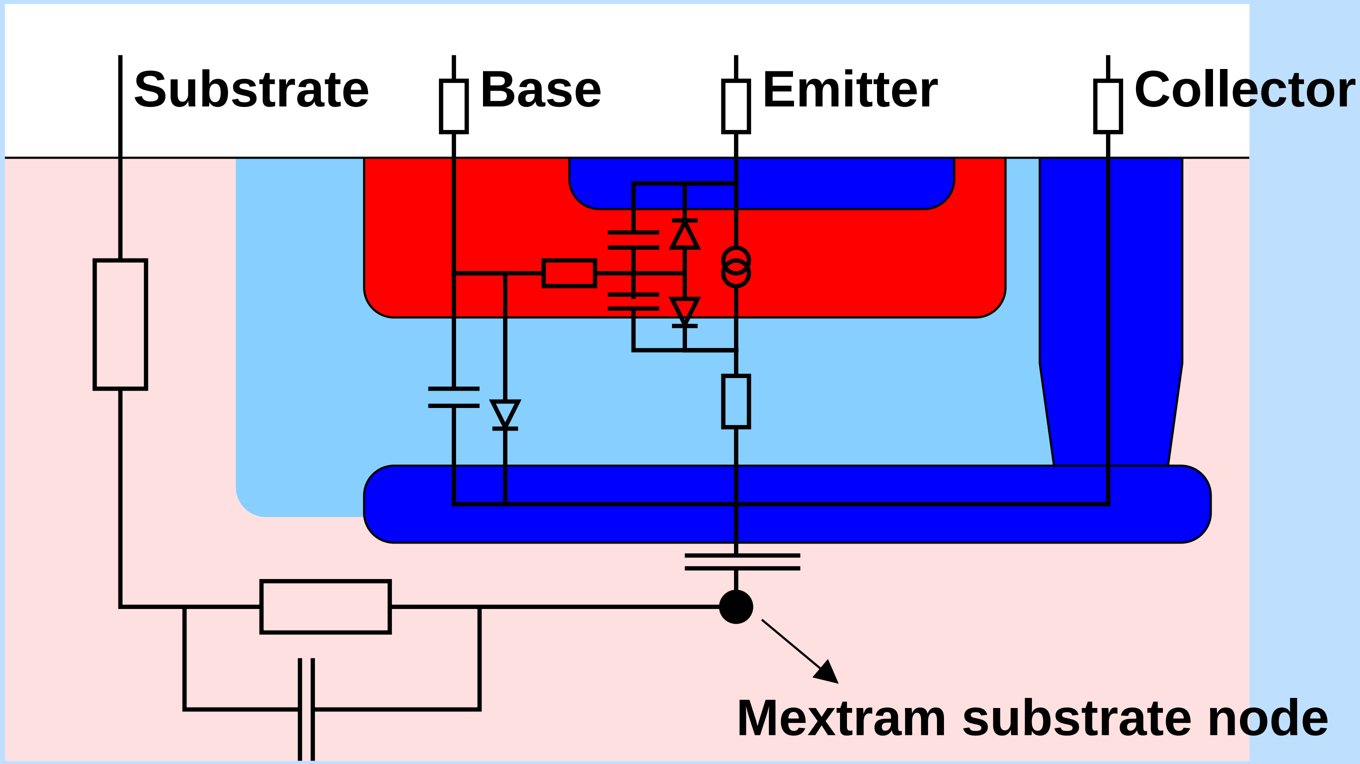
Parameters of Mextram

Forward current modelling	:	25
Reverse current modelling (including PNP)	:	6
Extra parameters used only in charge modelling	:	14
Temperature scaling model	:	14
Self-heating	:	2
Noise model ($1/f$)	:	3
HBT options	:	2
General parameters (level, flags, reference temperature)	:	7
Total	:	73

Equivalent circuit describing the elements of a bipolar transistor



Substrate resistance



Mextram does not contain substrate network:

- On-wafer characterization layout differs from final design
- Never complex enough when really needed

List of modelled effects

Modelled better in Mextram than in Spice-Gummel-Poon

- **Current gain (incl. reverse Early effect)**
- **Early effect (bias dependent) $\rightarrow$ output conductance**
- **Reverse behaviour**
- **Cut-off frequency f_T $\rightarrow$ all high-frequency behaviour**
- **Both low and high-frequency distortion**
- **Large signal modelling $\rightarrow$ e.g. power amplifiers**

List of modelled effects (cont.)

Modelled in Mextram, but not in Spice-Gummel-Poon

- **AC and DC Current crowding in base-resistance**
- **Substrate effects (parasitic transistor)**
- **descriptions for emitter-base sidewall region**
- **descriptions for collector-base extrinsic region**
- **Splitting of capacitances $\longrightarrow$ extra delay times**
- **Overlap capacitances**

List of modelled effects (cont.)

Modelled in Mextram, but not in Spice-Gummel-Poon

- **Specific SiGe effects**
- **Self-heating**
- **Weak avalanche, also at high currents**
- **Quasi-saturation and Kirk effect $\longrightarrow$ better HF behaviour**

These last effects are important when supply voltage is low

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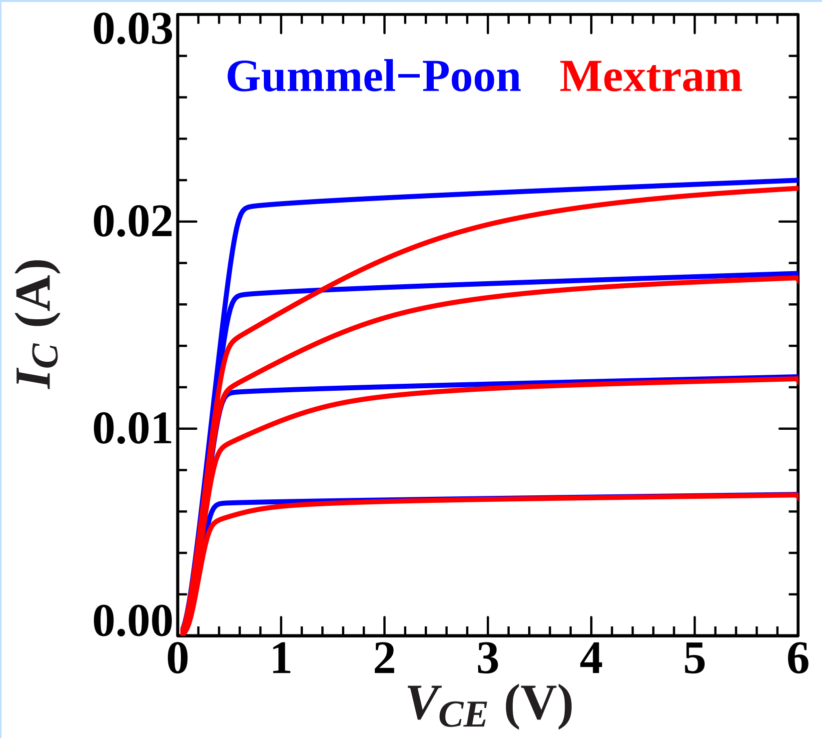
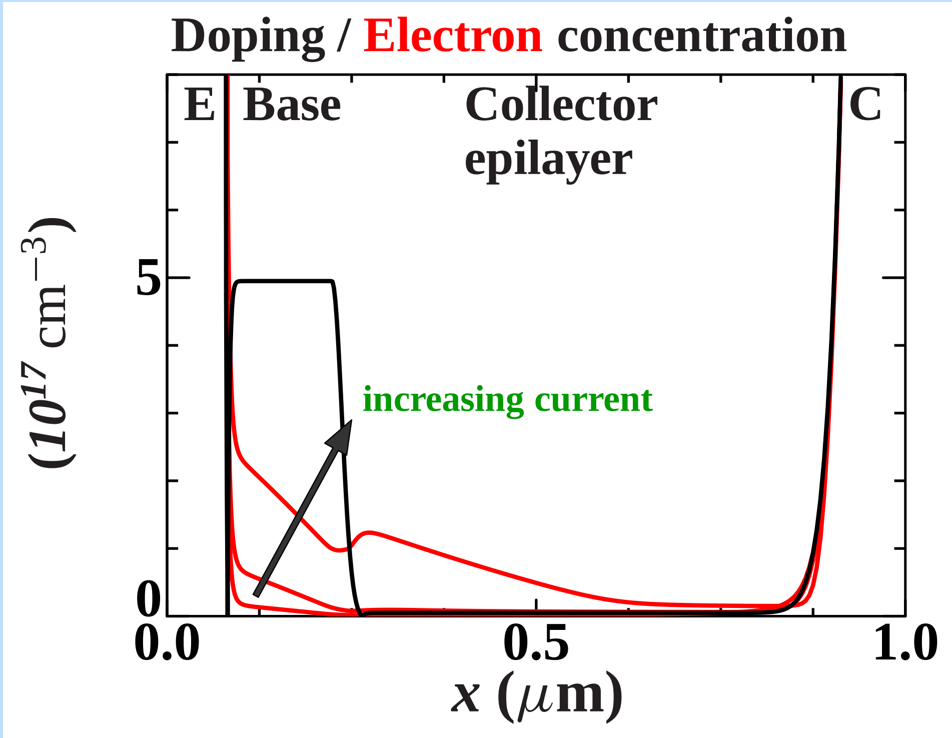
Quasi saturation/Kirk effect





For large enough currents base widening occurs:

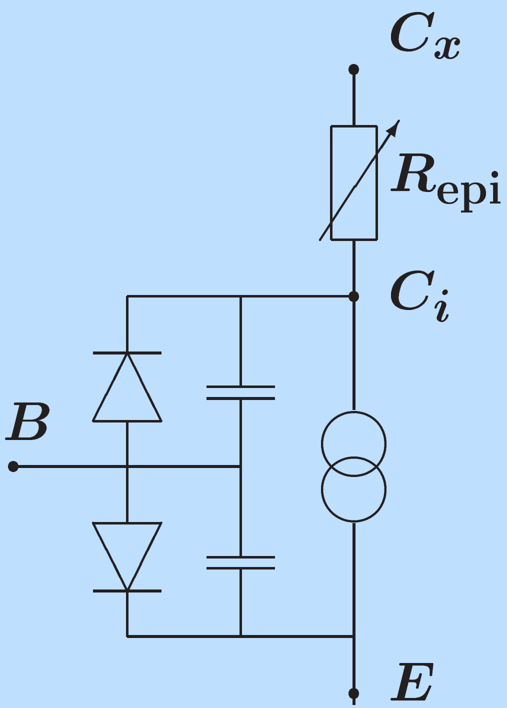
a lot of charge gets injected into the collector epilayer.

Consequence: reduction of current and of cut-off frequency.

Not modelled in Spice-Gummel-Poon model

Modelling quasi-saturation/Kirk effect

The intrinsic part of Mextram looks like



Model for epilayer resistance:

$$I_{\mathrm{epi}}\,(\,V_{BCi}\,,V_{BCx}\,)$$

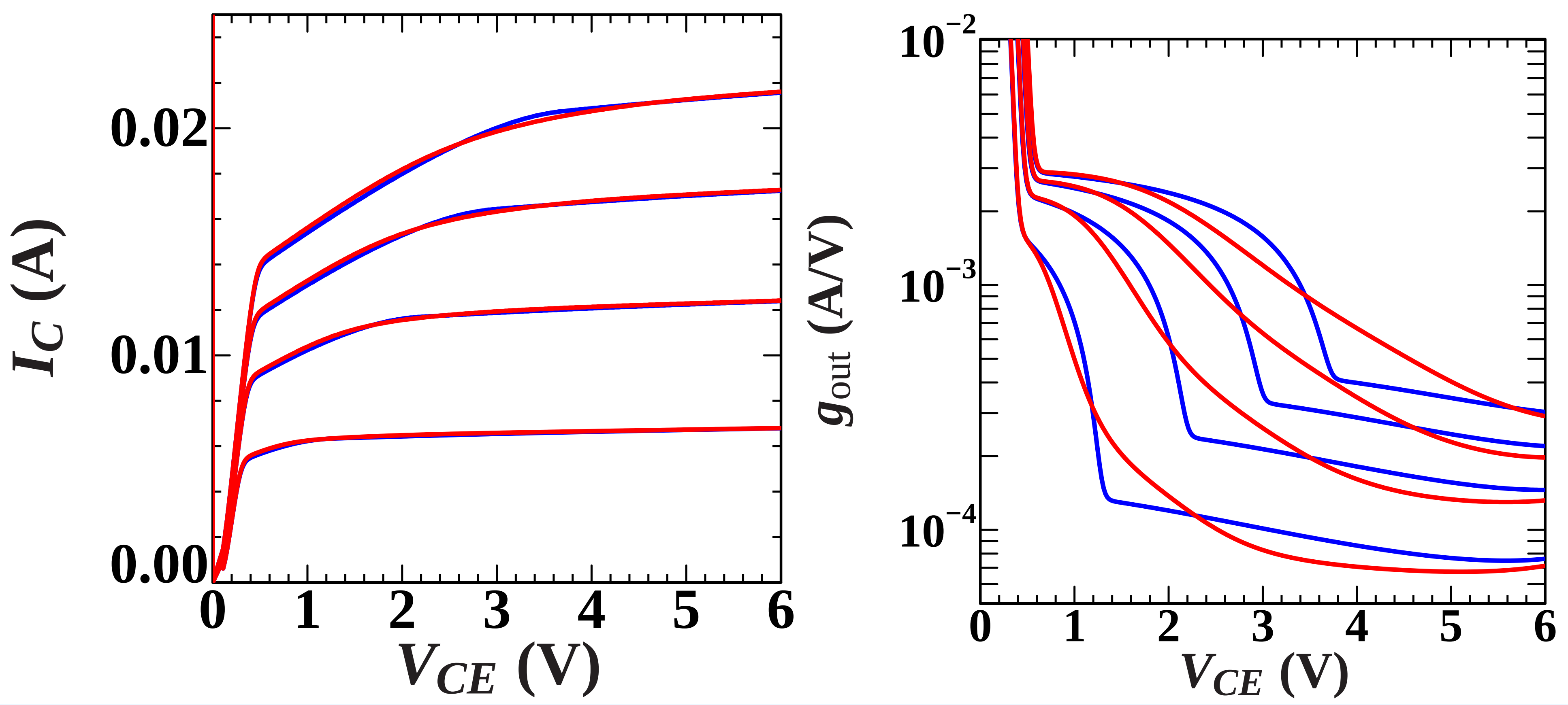
The model contains:

- Ohmic resistance
- Resistance modulation due to excess electrons
- Quasi-saturation (incl. Kirk effect)

504 improvement: model comparison

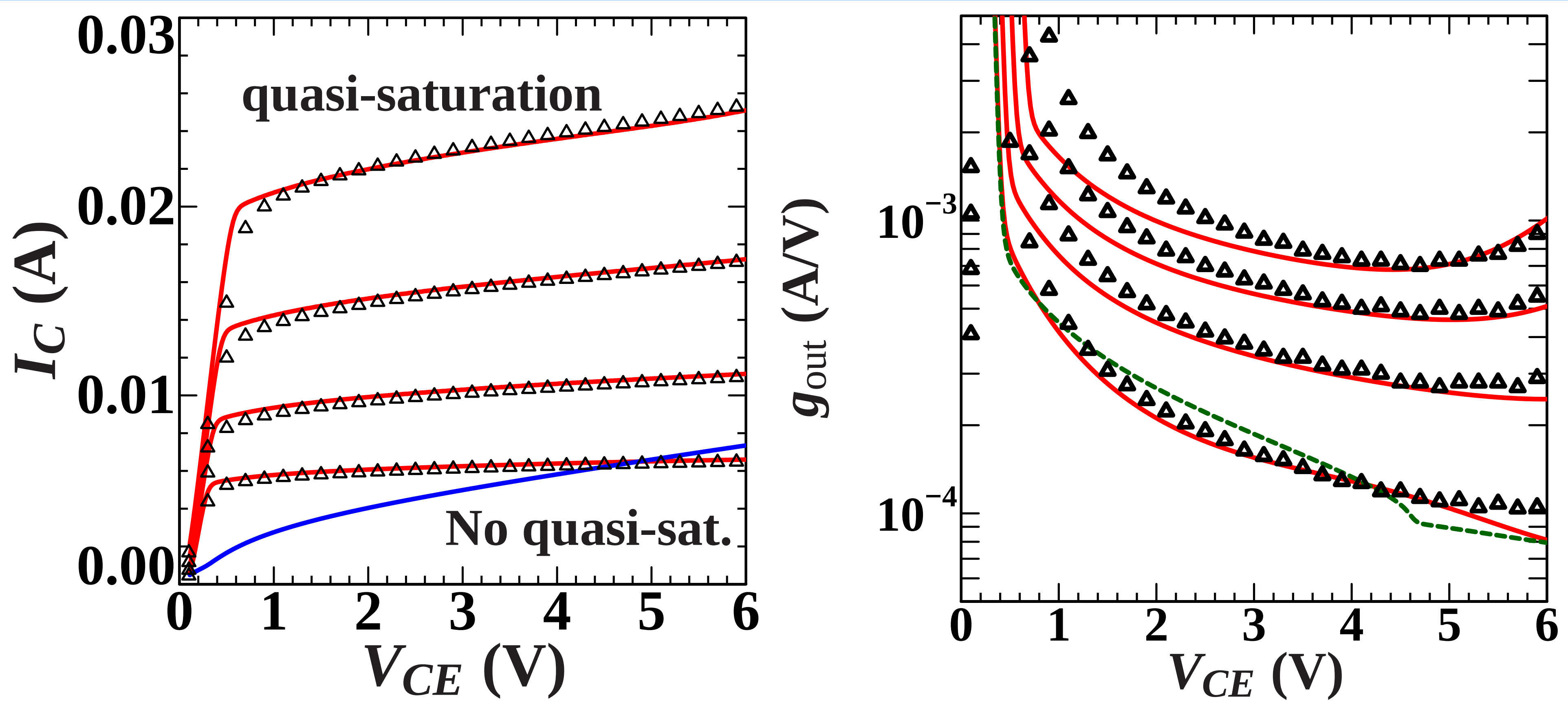
old model: shows kinks in output conductance

Mextram (new model): smoother behaviour



504 improvement: experimental results: (12V BiCMOS process)

Mextram (new model). As one can see: measurements do not show kink at the point where quasi-saturation starts



Blue line: current where quasi-saturation starts

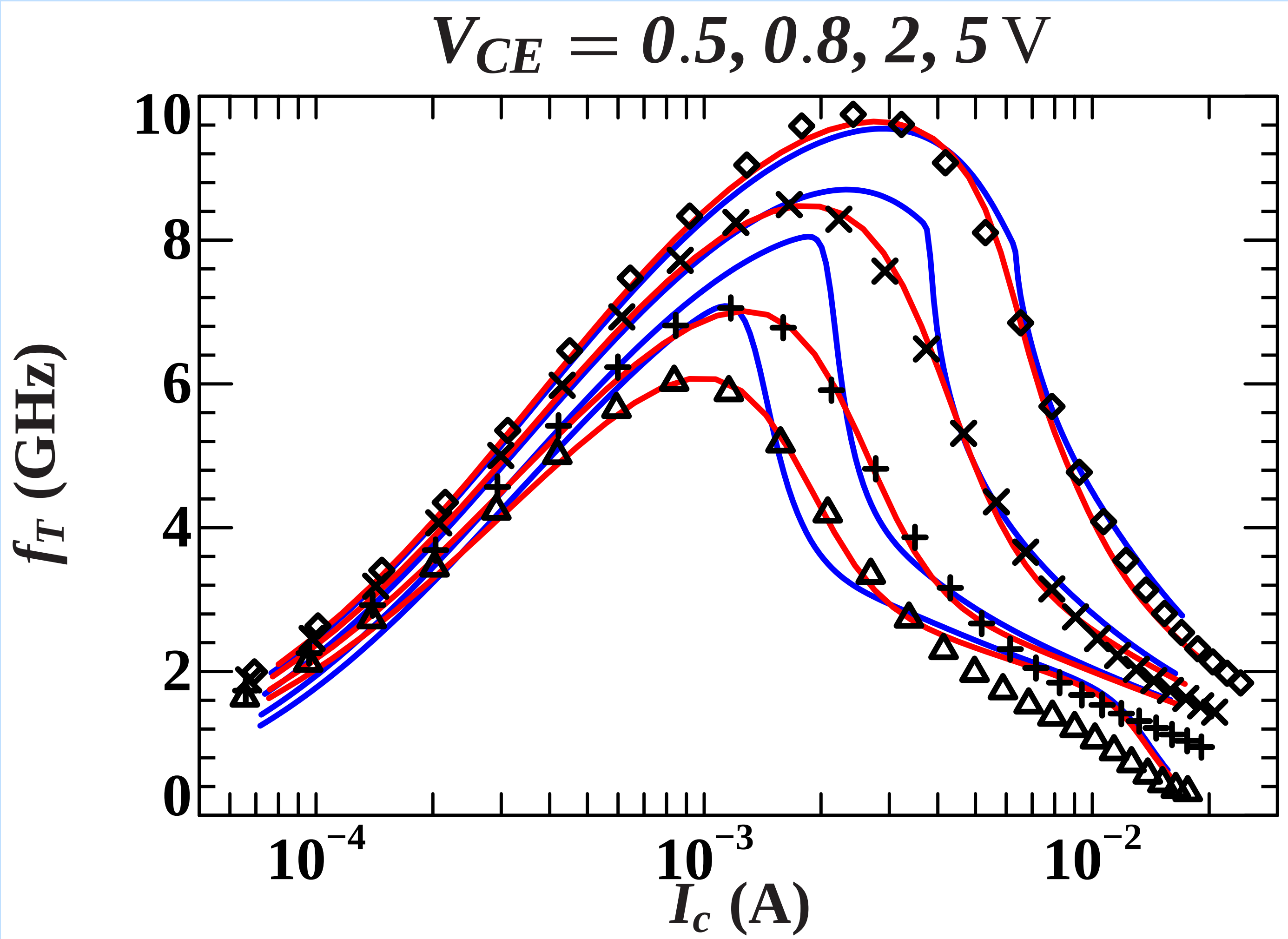
Green line: result from old model

504 improvement: experimental results: (12V BiCMOS process)

old model

Mextram (new model)

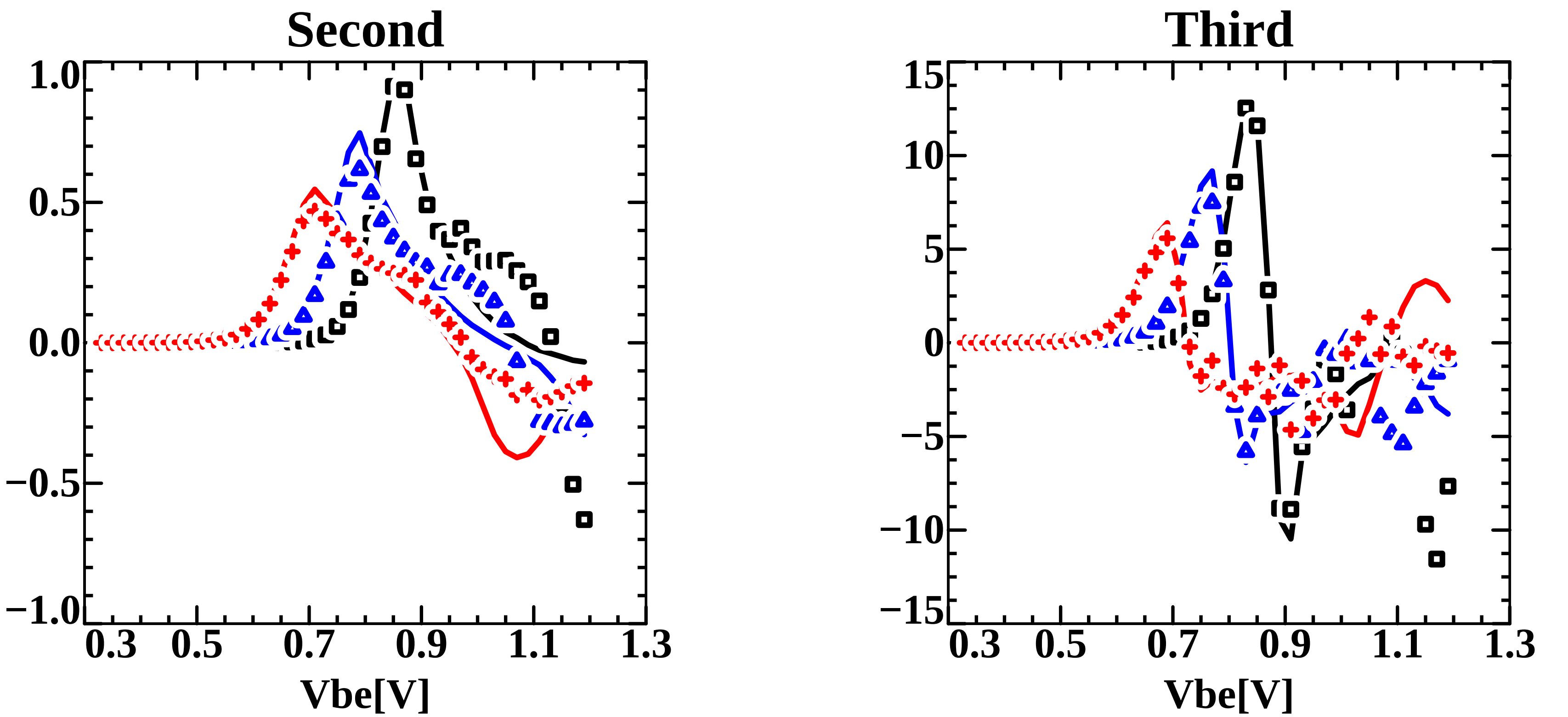
Also for cut-off frequency description improved



504 improvement: experimental results: (12V BiCMOS process)

2nd and 3th derivative of collector current I_C in Gummel plot

Temperature = 25 , 75 , 125 °C



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- SiGe transistor in case of a graded Ge -profile

- Collector-bias dependent base current for SiGe

- Self-heating

- Advanced avalanche modelling at high currents

SiGe transistors

Mextram 504 tested on on various SiGe processes

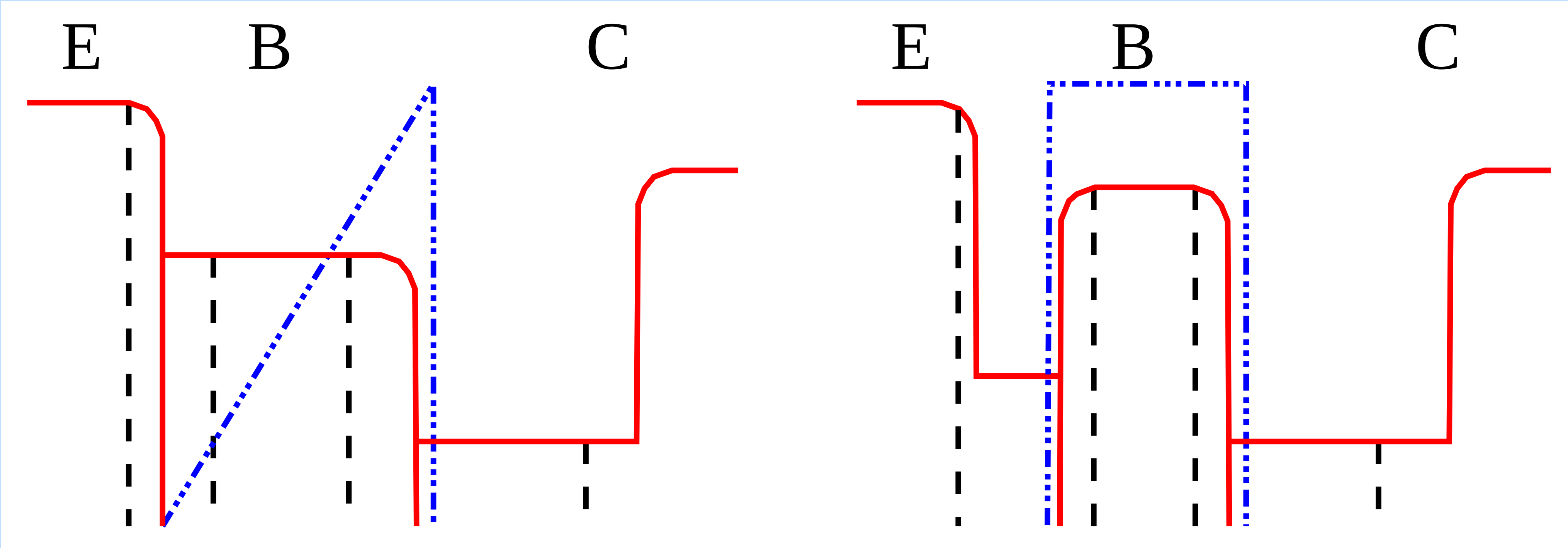
- **Device simulations**
- **Philips (QUBiC4G, various versions from research)**
- **Infineon, ST (data from international model comparison)**
- **Temic/Atmel**

For most processes no special SiGe options needed, however . . .

Graded Ge profile or box-like profile

Doping profile

Ge content



First IBM process and Infineon process have graded Ge-content

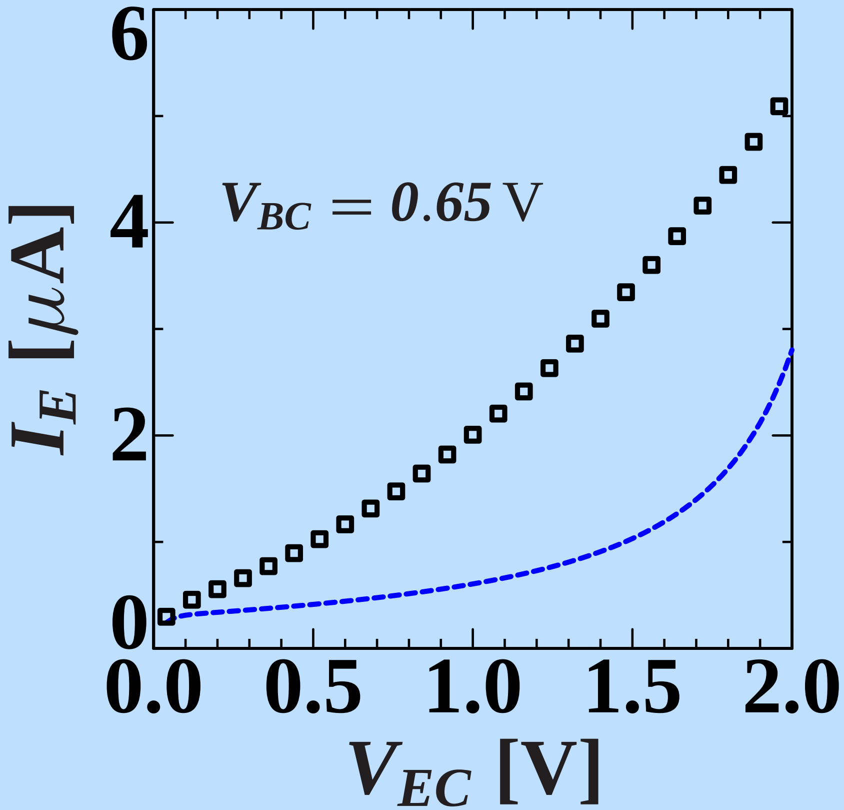
Philips has box-like Ge profile

For both cases an option is available in Mextram

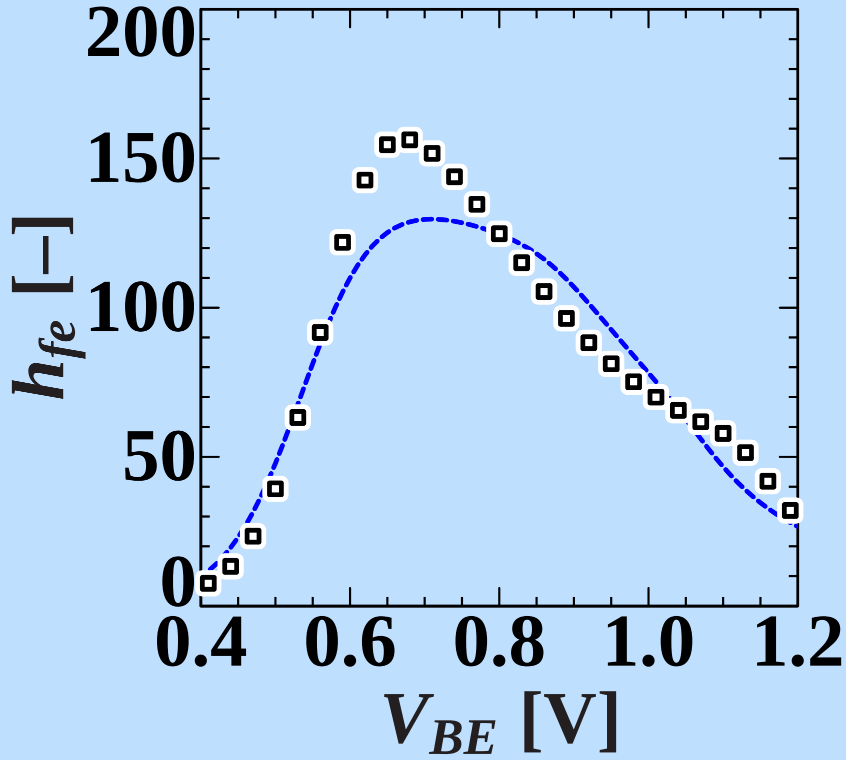
Graded Ge profile: Reverse Early effect (Infineon SiGe)

Reverse Early effect can be seen in two different measurements:

Reverse Early measurement



Forward current gain

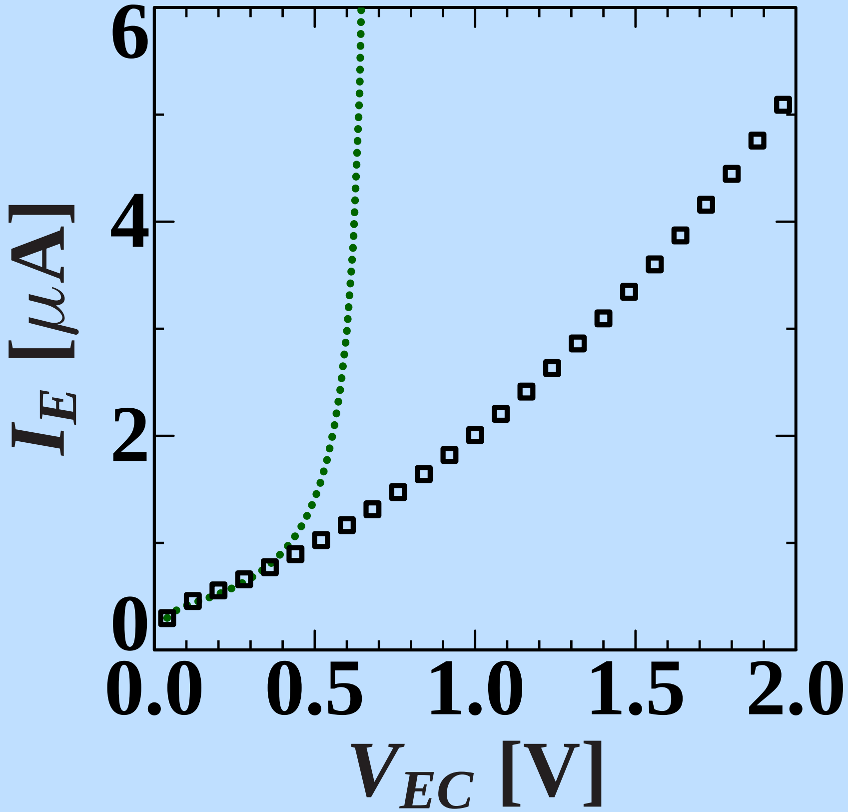


Blue lines are for one parameter set:

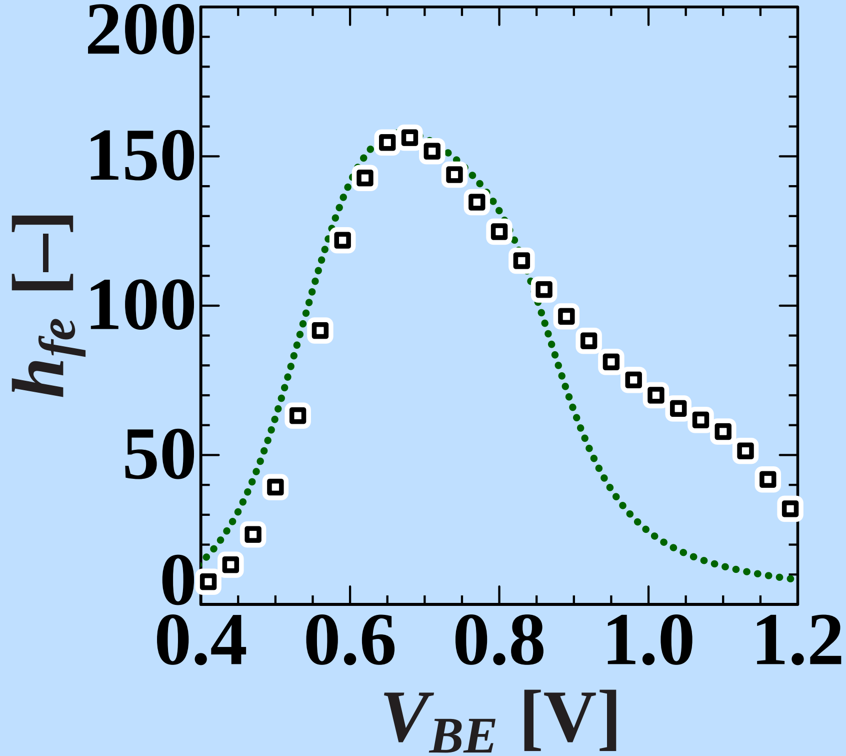
not possible to fit both forward and reverse measurement.

Graded Ge profile: Reverse Early effect

Reverse Early measurement



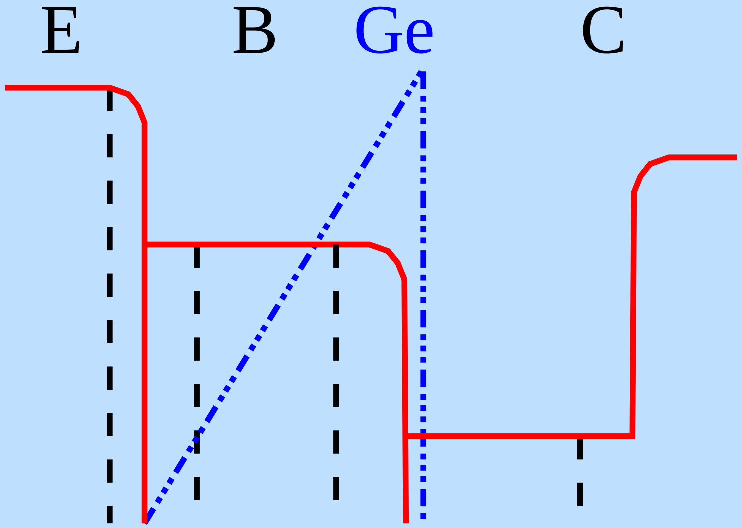
Forward current gain



green lines are for another parameter set:

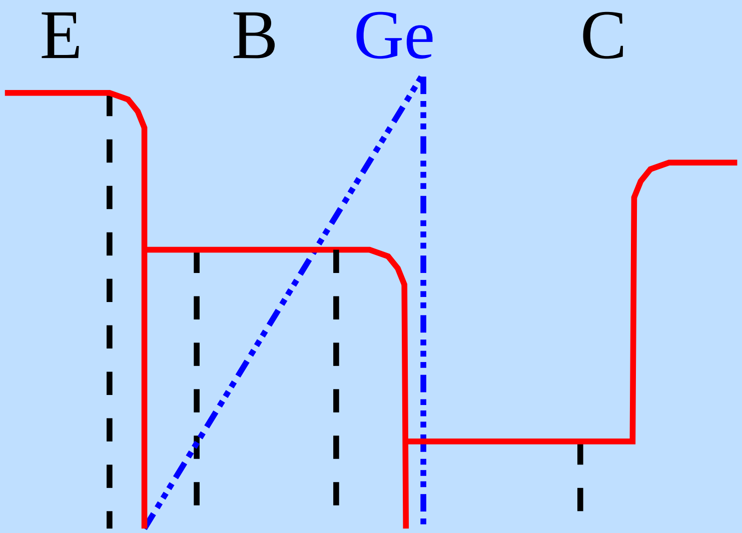
Better result for $V_{EC} < 0.5\,\mathrm{V}$, but not for larger voltages.

Graded Ge profile: model improvement



$$n_i^2 \propto \exp\left(\frac{x}{W_B} \quad \frac{\Delta E_g}{kT}\right)$$

Graded Ge profile: model improvement



$$n_i^2 \propto \exp\left(\frac{x}{W_B}\,\frac{\Delta E_g}{kT}\right)$$

Base charge: $$\frac{Q_B}{Q_{B0}} \simeq 1 + \frac{V_{BE}}{V_{er}} + \frac{V_{BC}}{V_{ef}}$$

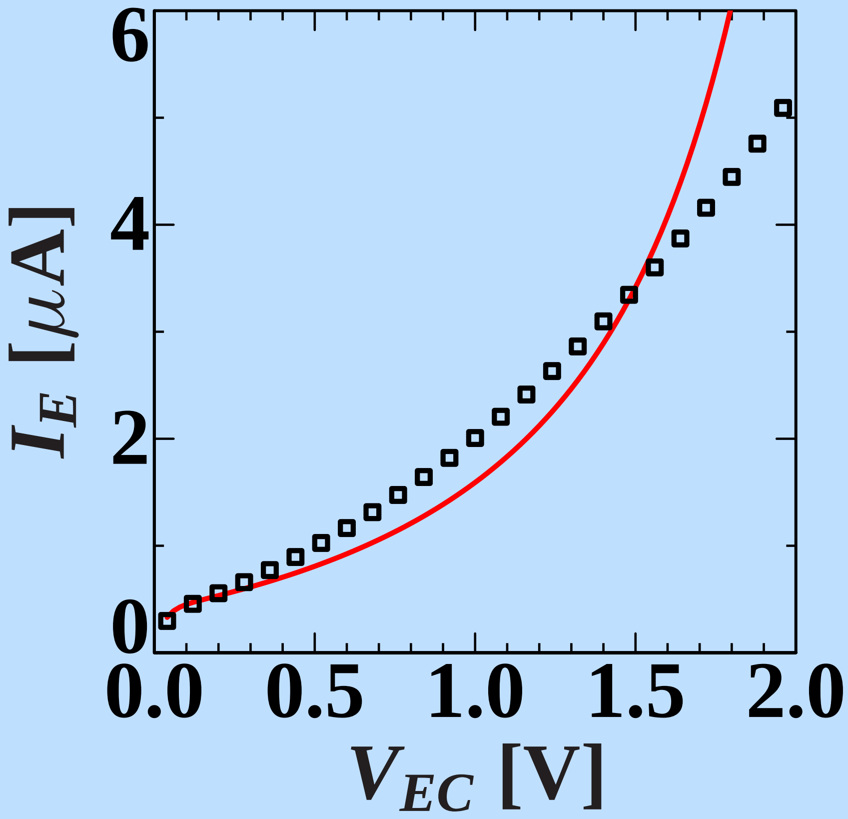
Gummel number:

$$\frac{G_B}{G_{B0}} \simeq \frac{\exp\left(\left[1+\frac{V_{BE}}{V_{er}}\right]\,\frac{\Delta E_g}{kT}\right) - \exp\left(-\frac{V_{BC}}{V_{ef}}\,\frac{\Delta E_g}{kT}\right)}{\exp\left(\frac{\Delta E_g}{kT}\right) - 1}$$

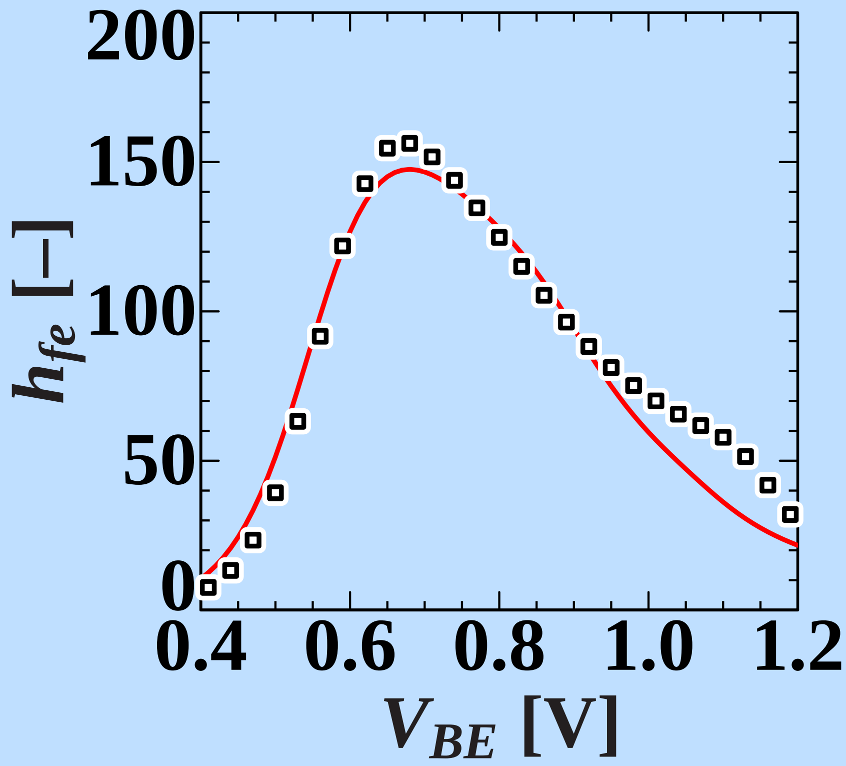
Graded Ge profile: Reverse Early effect

With new Mextram option, now including the Ge grading:

Reverse Early measurement



Forward current gain



Effective reverse Early voltage:

large **small**

Optional features of Mextram

- **SiGe transistor in case of a graded Ge -profile**

- **Collector-bias dependent base current for SiGe**

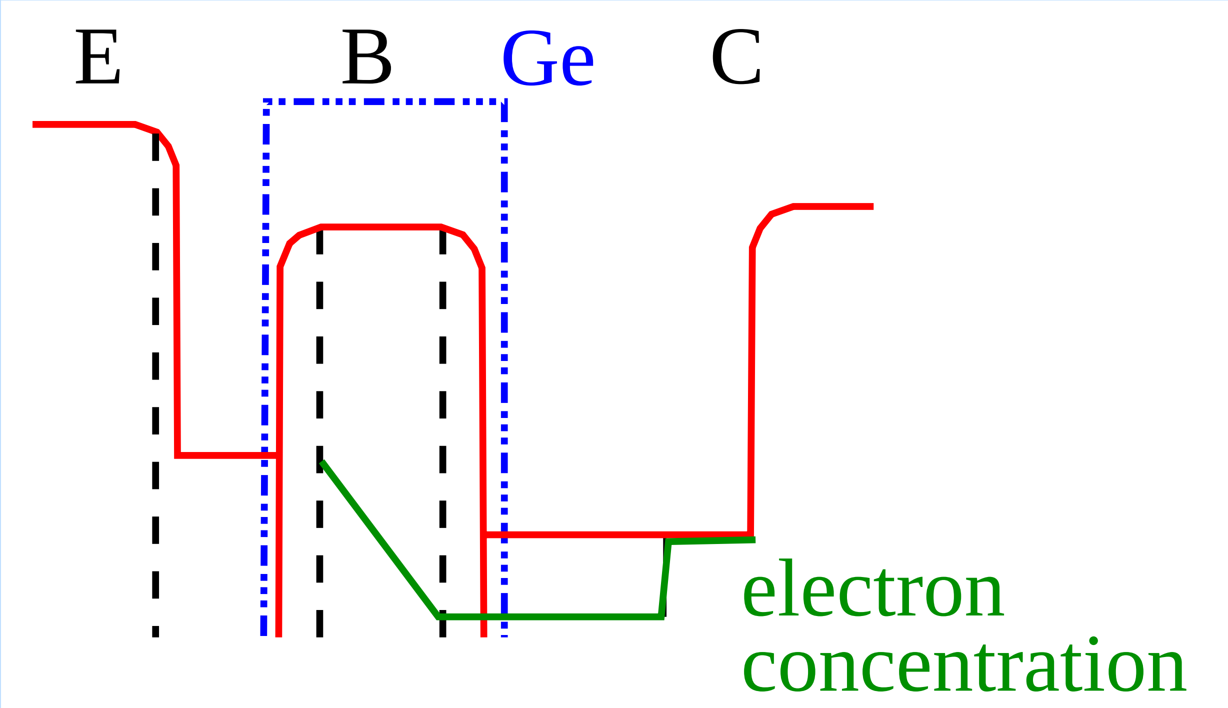
- **Self-heating**

- **Advanced avalanche modelling at high currents**

Modern Ge profile

Doping profile: high base doping, smaller emitter-cap doping

Ge content: square profile

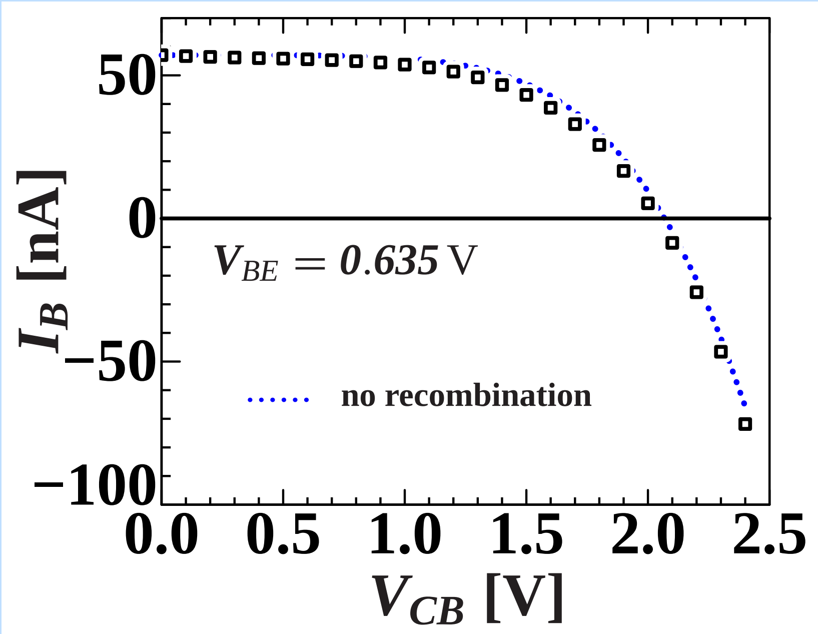


Due to high base doping Neutral Base Recombination (NBR) becomes important.

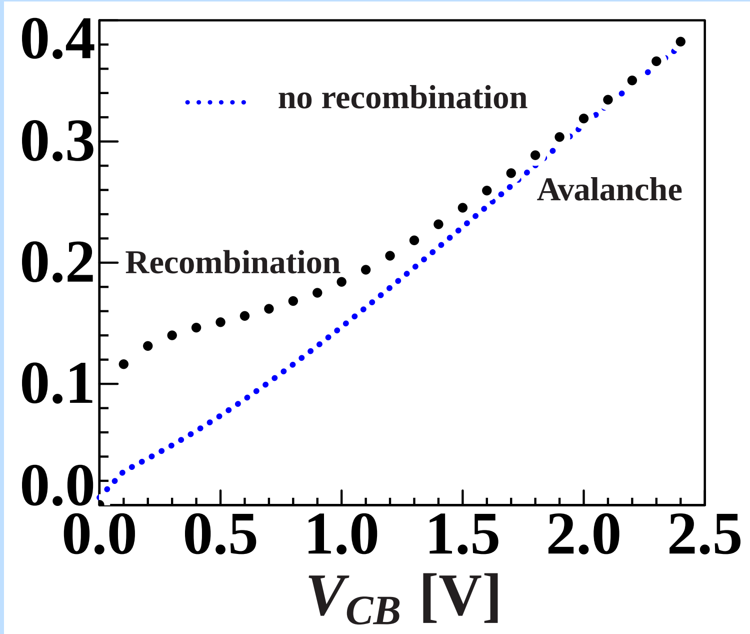
Modern Ge profile: Neutral base recombination (Atmel SiGe)

dotted: without Neutral Base Recombination (NBR)

Base current



$G_{\mathrm{I.I.}}^{1/5}$



Generation of Impact Inionisation : $G_{\mathrm{I.I.}} = (I_B@0\mathrm{V} - I_B)/I_C$

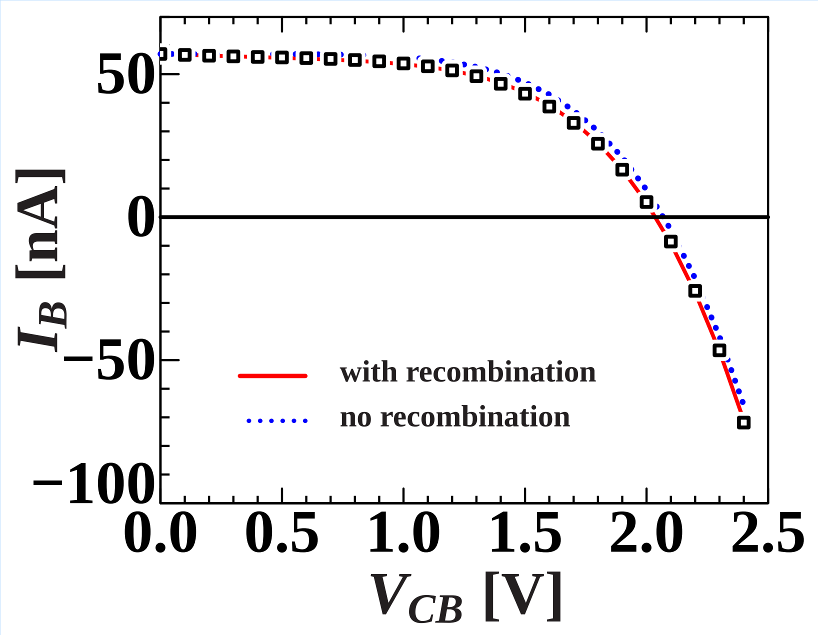
For pure avalanche effect (no NBR): $G_{\mathrm{I.I.}}^{1/5}$ is straight line.

Modern Ge profile: Neutral base recombination

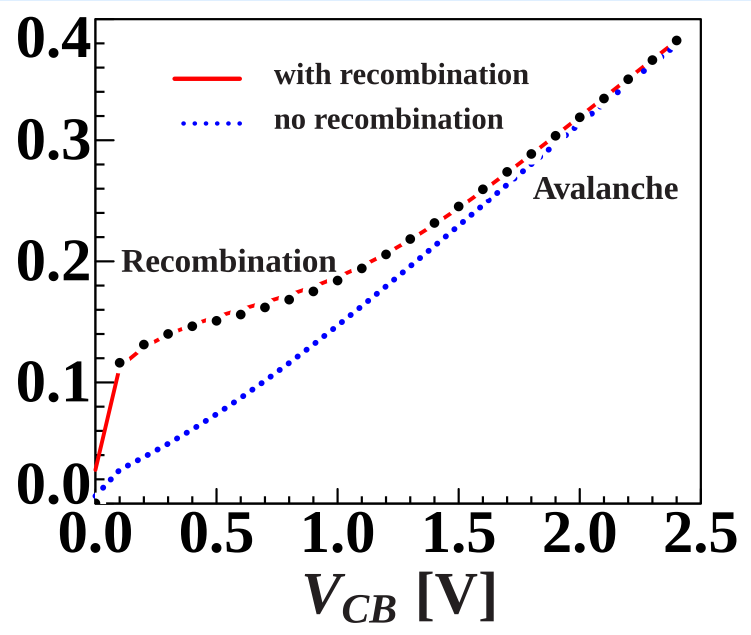
dotted: without Neutral Base Recombination (NBR)

solid: with NBR: new Mextram 504 option, one extra parameter

Base current



$G_{\mathrm{I.I.}}^{1/5}$



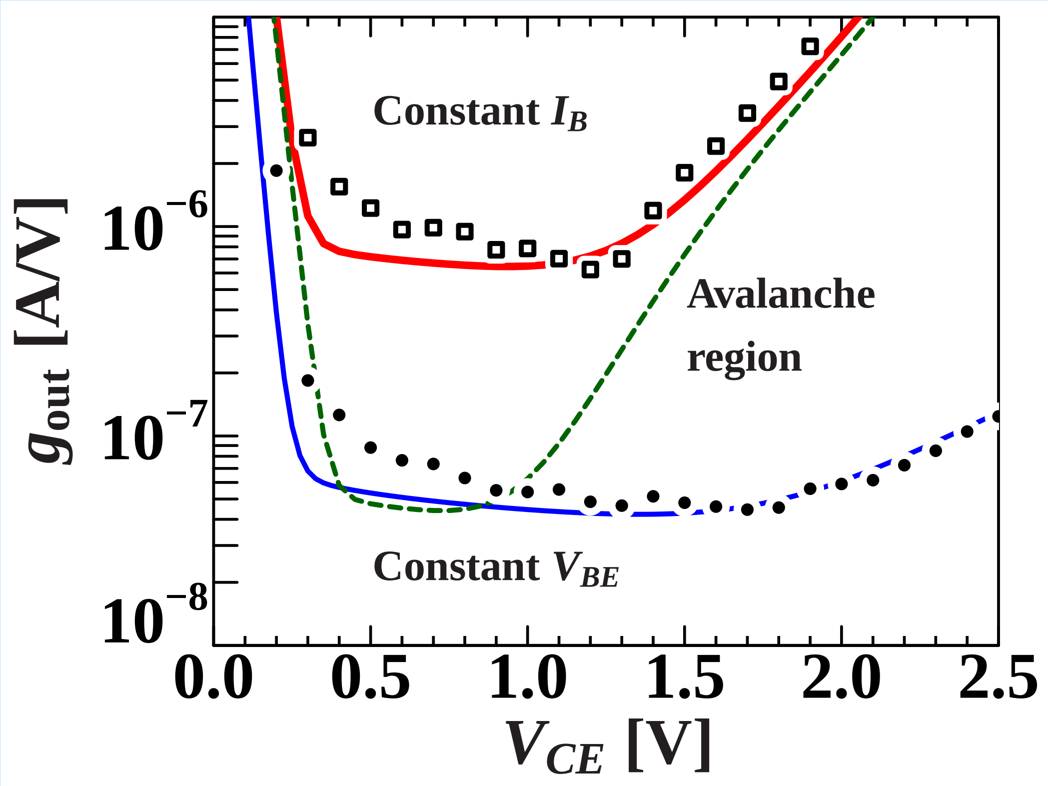
New base current: $$I_B \simeq \frac{I_S}{\beta_f} \exp\left(\frac{V_{BE}}{V_T}\right) \cdot \left(1 - X_{rec}\frac{V_{CB}}{V_{ef}}\right)$$

Modern Ge profile: NBR effect on output conductance

Constant V_{BE} with or without Neutral Base Recombination (NBR)

Constant I_B without NBR (dashed)

Constant I_B with NBR (new model option)



Optional features of Mextram

- SiGe transistor in case of a graded Ge -profile
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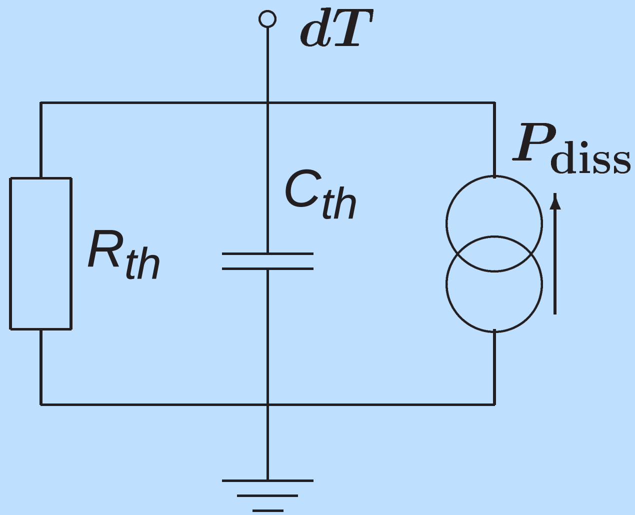
- Self-heating
- Advanced avalanche modelling at high currents

Self-heating:

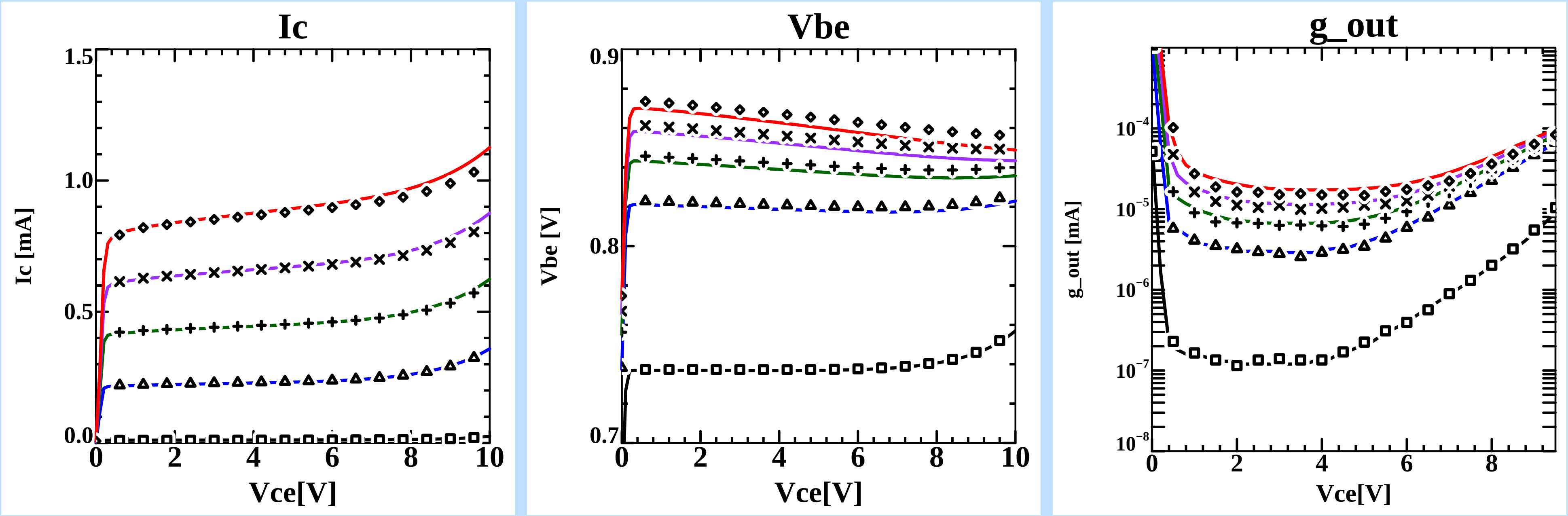
an increase in temperature due to power dissipation

- **Standard extra sub-circuit**



- **Dissipation P_{diss}: sum over the dissipation in every branch**

Selfheating: output characteristic at constant I_B



Mextram 504 is first Philips model with full self-heating

(our simulator allowed a trick to handle self-heating)

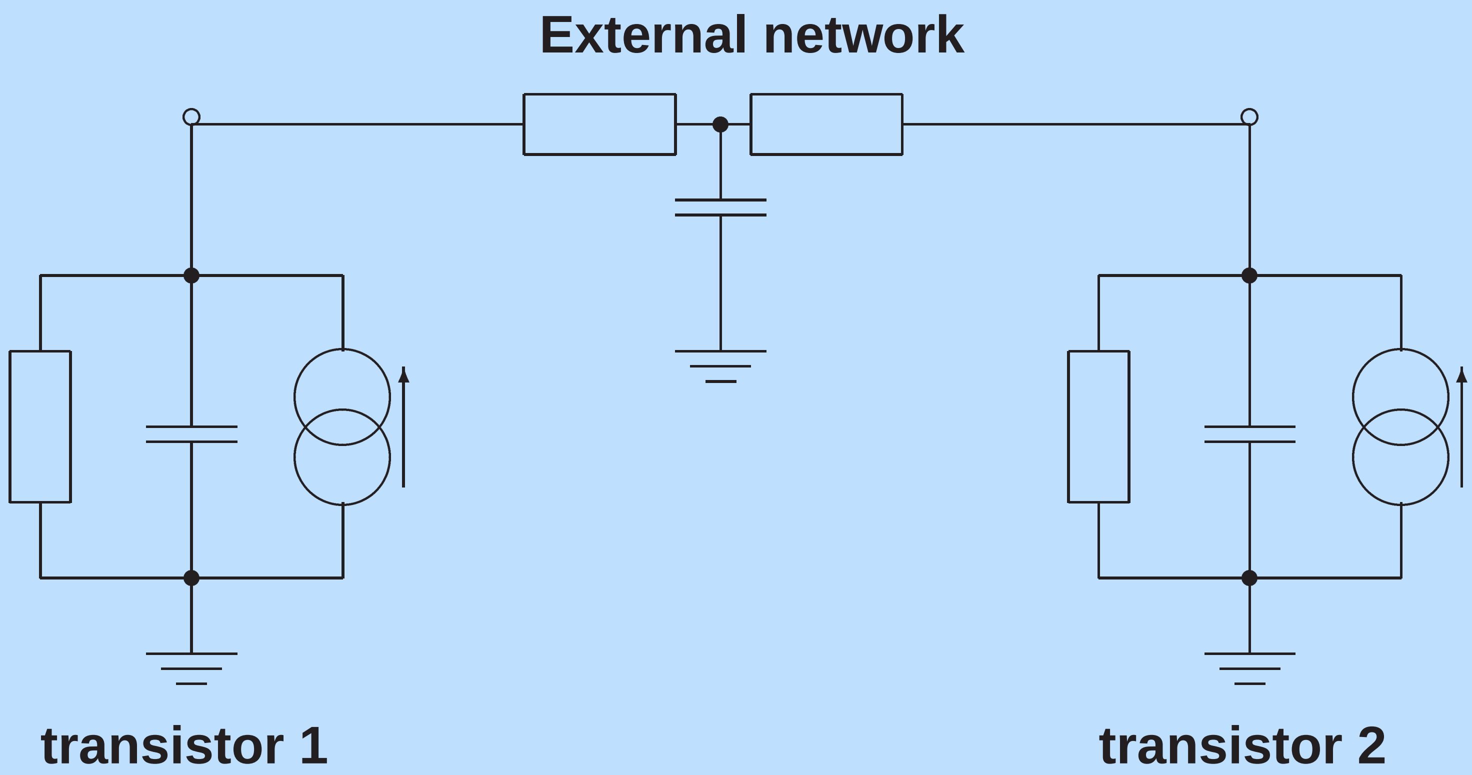
In case of selfheating: V_{BE} decreases always

For pure Si transistors: I_C increases with V_{CE}

For SiGe transistors: I_C decreases with V_{CE}

Selfheating and mutual heating

It is possible to model mutual heating using an external network



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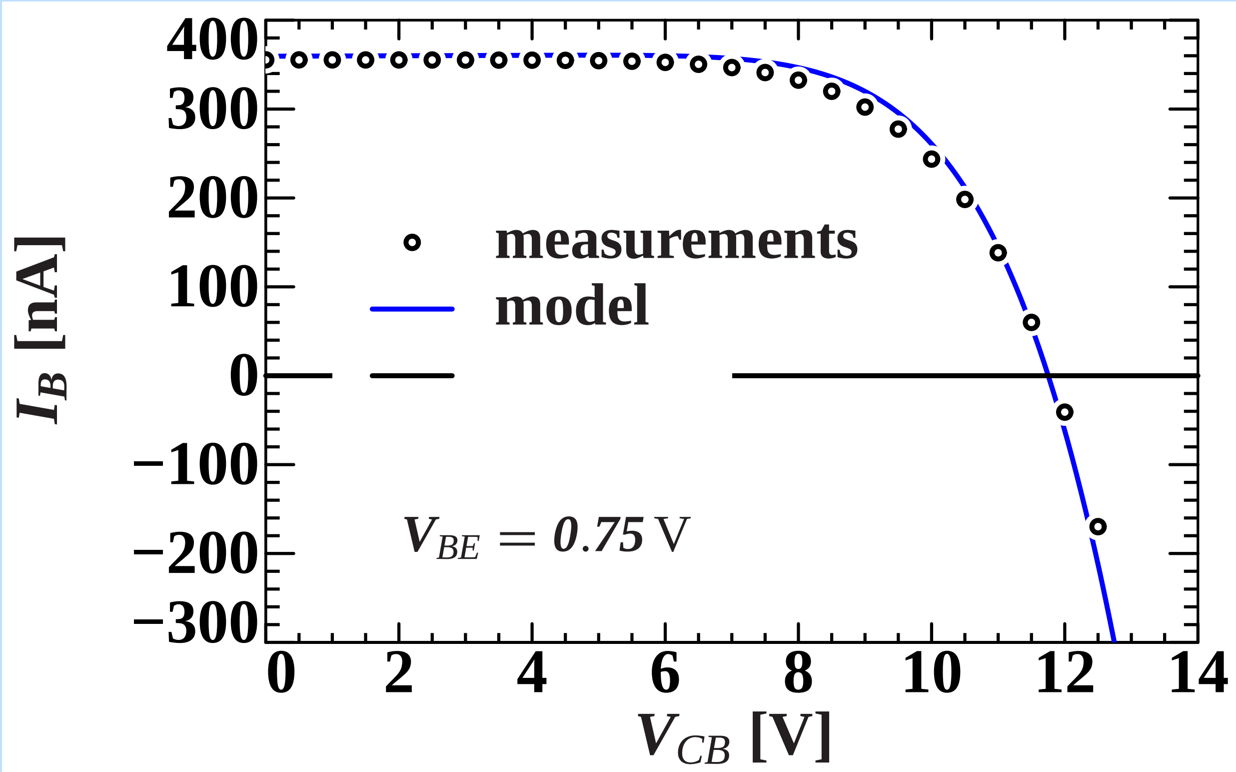
Extended avalanche: low currents

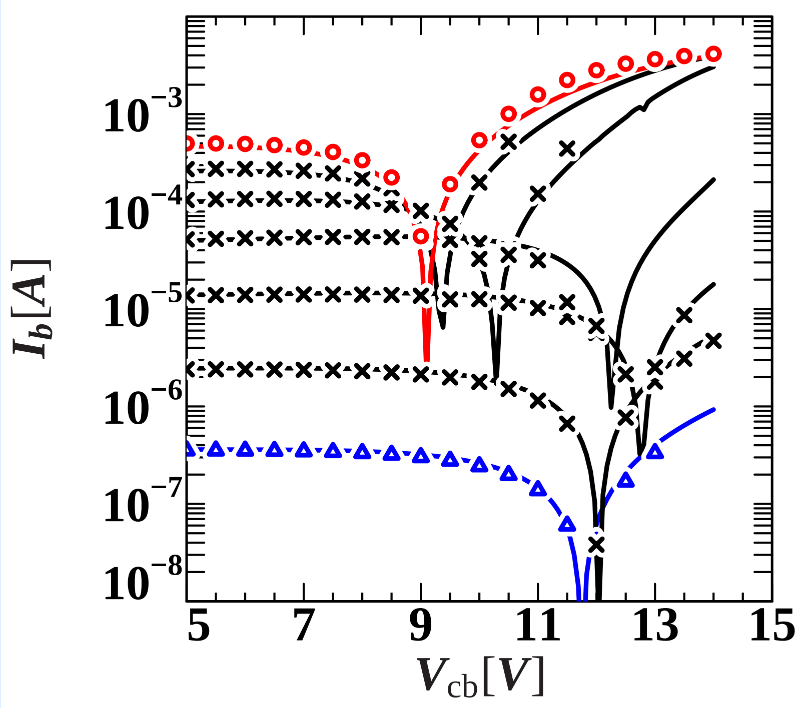


Breakdown voltage $BV_{\rm ceo}$ is where $I_B = 0$ (at constant V_{BE})

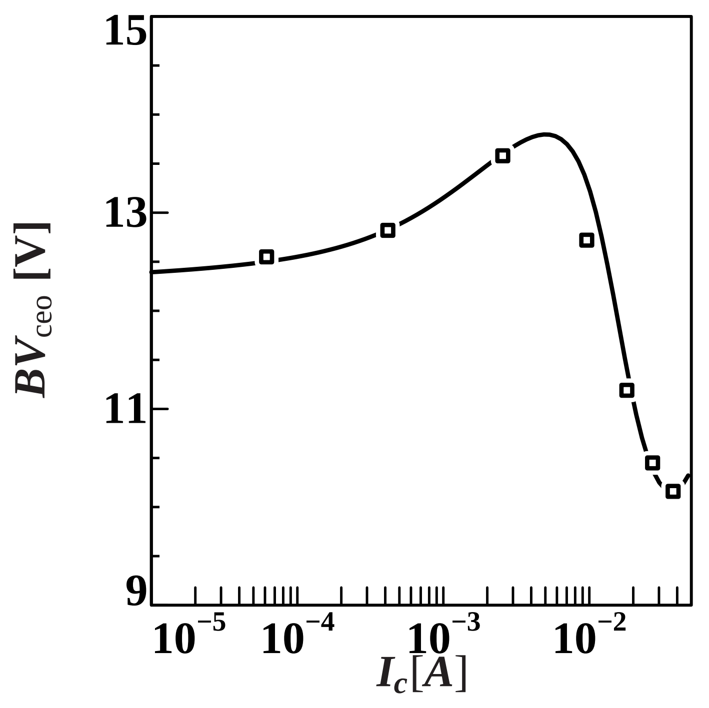
For this process $BV_{\rm ceo} \simeq 12\,\rm V$.

Extended avalanche: breakdown voltage depends on current level

Base current



$BV_{\mathrm{ceo}} = V_{\mathrm{ce}} @ I_B{=}0$



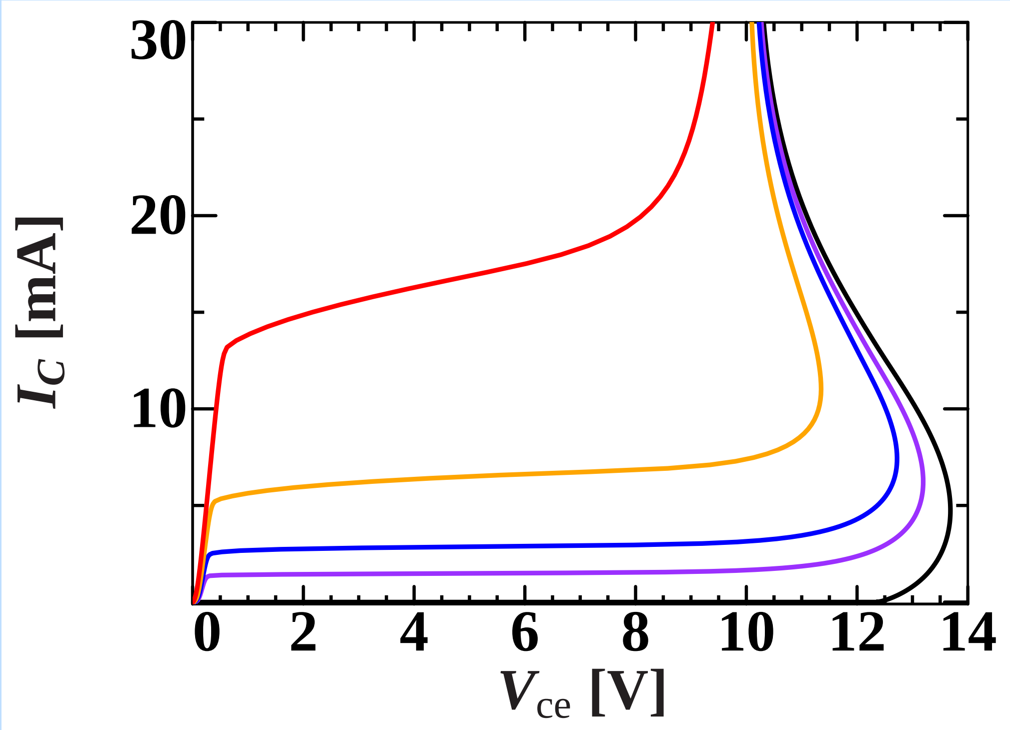
For increasing currents BV_{ceo} normally increases

For high currents BV_{ceo} can decrease again due to Kirk effect

Extended avalanche: snapback

Mextram is the only model capable of describing snapback

output characteristic at constant base current



Snapback is bad for convergence $\longrightarrow$ optional feature

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Geometric scaling

The model parameters for a single transistor are called

electrical parameters

These electrical parameters are a function of geometry

Geometry is given by $W_{\mathrm{em}} \times L_{\mathrm{em}}$ **,** $W_{\mathrm{base}} \times L_{\mathrm{base}}$ **etc.**

Example:

$$I_S = I_S^{bottom}\, W_{\mathrm{em}} L_{\mathrm{em}} + 2\, I_S^{sidewall}\, (W_{\mathrm{em}} + L_{\mathrm{em}})$$

$\Rightarrow I_S^{bottom}$ **and** $I_S^{sidewall}$ **are unity parameters**

Geometric scaling

MOS transistors

Miniset

$\rightarrow$ **Electrical parameters and temperature scaling**

Maxiset

$\rightarrow$ **Geometry scaling parameters**

Bipolar technologies have more geometric variations

Bipolar transistors

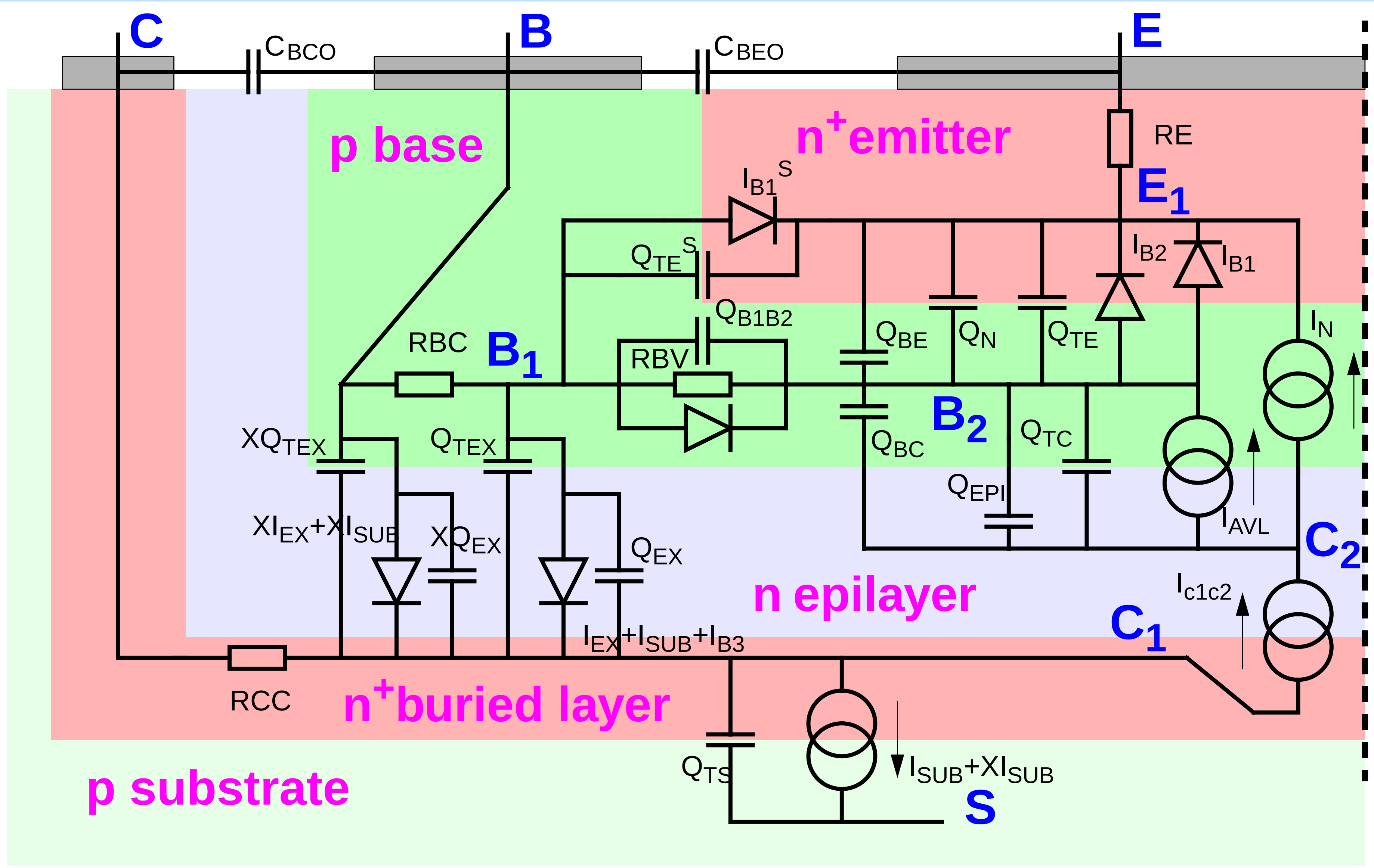
Within Mextram

$\rightarrow$ **Electrical parameters and temperature scaling**

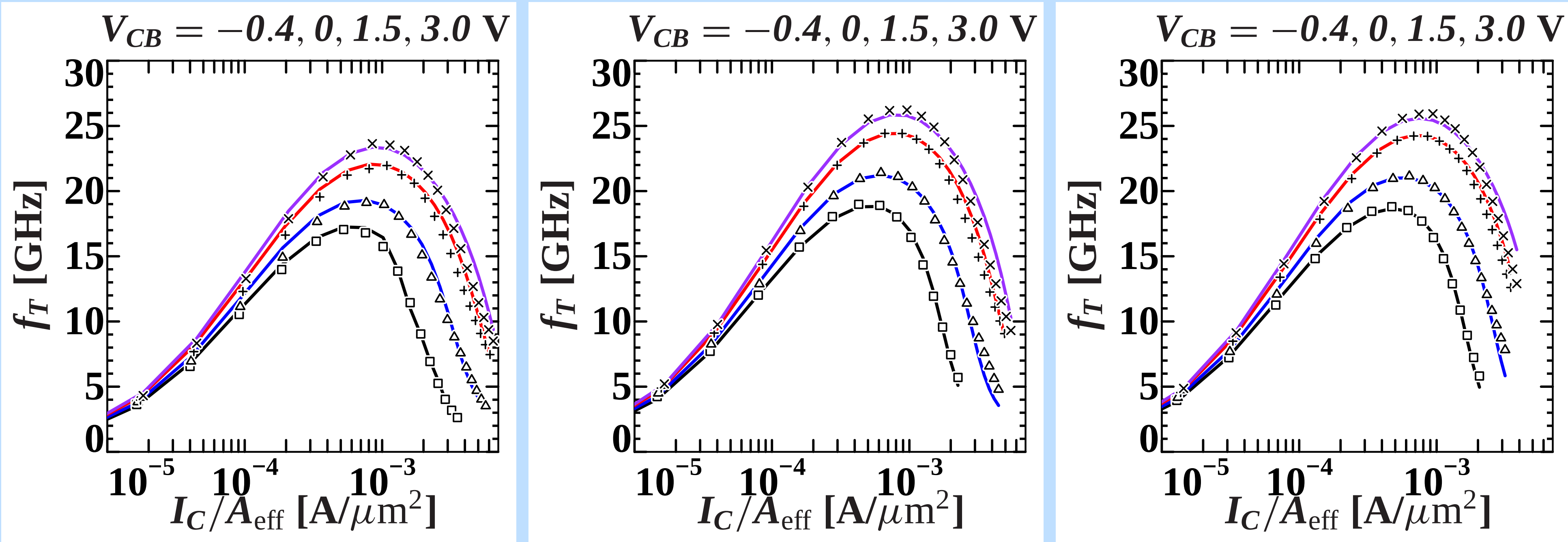
Outside of Mextram

$\rightarrow$ **Geometry scaling**

Equivalent circuit describing the elements of a bipolar transistor



Example: cut-off frequency f_T (0.35μm BiCMOS)



$0.7 \times 1.4\ \mu m^2$ $0.7 \times 5.6\ \mu m^2$ $0.7 \times 20.0\ \mu m^2$

$\rightarrow$ a designer is free to choose any length within layout rules.

Contents

- History
- Modelled effects
  - some basic bipolar characteristics
- Improved description of output conductance and f_T
  - How an improved description gives smoother behaviour
- Some optional features:
  - The effect of a graded Ge content in the base
  - Neutral base recombination
  - Self-heating
  - Advanced avalanche modelling: snapback
- Geometric scaling
- Status of Mextram 504

Status of Mextram 504

Companies using Mextram:

- Philips (of course), TSMC, TI

Companies evaluating Mextram:

- Analog Devices, Samsung, IBM

Mextram is implemented in (as far as we know):

Spectre (Cadence)	(DLL: on our web—4.4.6: Dec. 2001)
HSpice (Synopsys/Avant!)	(2002)
ADS (Agilent)	(March 2002)
Eldo (Mentor Graphics)	(March 2001)
Pstar (In-house)	(4.1, June 2001)

Summary

Mextram is an advanced compact bipolar model:

- **is based on physics**
- **can be used for analogue and digital applications**
- **special attention is paid to (higher-order) derivatives**
- **describes the various regions of the transistor**
- **contains temperature scaling and can be scaled geometrically**

Summary (cont.)

- Mextram gives excellent description of
  - Early effect and output conductance
  - High-current effects
  - High-frequency behaviour
  - Noise behaviour

- Mextram contains features for
  - Non-constant Ge profiles
  - Early effect on the base current
  - Extended avalanche for high currents
  - Self- and mutual heating

- Mextram is implemented in various commercial simulators

More information

Our Web-site [1] contains:

Documentation

→ **Model definition [2]**

→ **Derivation of all equations [3]**

→ **Parameter extraction [4]**

→ **Comparison between Mextram 503 and Vbic 95 [5]**

→ **A number of publications like [6, 7, 8, 9, 10]**

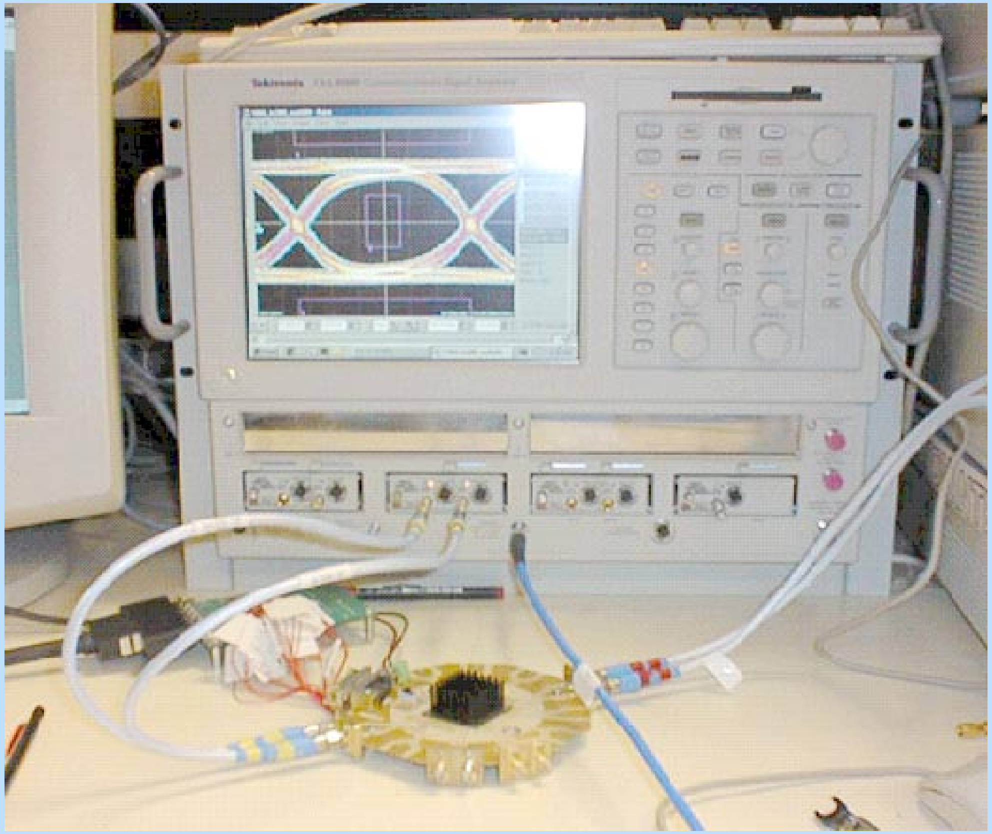
→ **A number of presentations like [11,12,13,14]**

Source code

→ **Full Mextram 504 code including simple solver**

→ **Spectre Model Kit (dynamically linkable library)**

Real example



World's first 20 $\times$ 20 10Gb/s crosspoint switch (optical networking)

Designed using Mextram (first time right)

Based on 1D simulations combined with measured scaling rules

References

1. For the most recent model descriptions, source code, and documentation, see the website http://www.semiconductors.philips.com/Philips_Models.

2. J. C. J. Paasschens and W. J. Kloosterman, “The Mextram bipolar transistor model, level 504,” Unclassified Report NL-UR 2000/811, Philips Nat.Lab., 2000. See Ref. [1].

3. J. C. J. Paasschens, W. J. Kloosterman, and R. van der Toorn, “Model derivation of Mextram 504. The physics behind the model,” Unclassified Report NL-UR 2002/806, Philips Nat.Lab., 2002. See Ref. [1].

4. J. C. J. Paasschens, W. J. Kloosterman, and R. J. Havens, “Parameter extraction for the bipolar transistor model Mextram, level 504,” Unclassified Report NL-UR 2001/801, Philips Nat.Lab., 2001. See Ref. [1].

5. W. J. Kloosterman, “Comparison of Mextram and the Vbic95 bipolar transistor model,” Unclassified Report 034/96, Philips Nat.Lab., 1996. See Ref. [1].

6. J. C. J. Paasschens, W. J. Kloosterman, and R. J. Havens, “Modelling two SiGe HBT specific features for circuit simulation,” in *Proc. of the Bipolar Circuits and Technology Meeting*, pp. 38–41, 2001. Paper 2.2.

7. J. C. J. Paasschens, W. J. Kloosterman, R. J. Havens, and H. C. de Graaff, “Improved compact modeling of ouput conductance and cutoff frequency of bipolar transistors,” *IEEE J. of Solid-State Circuits*, vol. 36, pp. 1390–1398, 2001.

8. J. C. J. Paasschens, W. J. Kloosterman, R. J. Havens, and H. C. de Graaff, "Improved modeling of ouput conductance and cut-off frequency of bipolar transistors," in *Proc. of the Bipolar Circuits and Technology Meeting*, pp. 62–65, 2000. Paper 3.3.

9. W. J. Kloosterman, J. C. J. Paasschens, and R. J. Havens, "A comprehensive bipolar avalanche multiplication compact model for circuit simulation," in *Proc. of the Bipolar Circuits and Technology Meeting*, pp. 172–175, 2000. Paper 10.1.

10. P. Deixler, R. Colclaser, D. Bower, N. Bell, W. D. Boer, D. Szmyd, S. Bardy, W. Wilbanks, P. Barre, M. van Houdt, J. C. J. Paasschens, H. Veenstra, E. van der Heijden, J. J. T. M. Donkers, and J. W. Slotboom, "QUBiC4G: A $f_t/f_{\mathrm{max}}=70/100\,\mathrm{GHz}$ $0.25\,\mu\mathrm{m}$ low power SiGe-BiCMOS production technology with high quality passives for $12.5\,\mathrm{Gb/s}$ optical networking and emerging wireless applications up to $20\,\mathrm{GHz}$," in *Proc. of the Bipolar Circuits and Technology Meeting*, 2002. Accepted for publication.

11. W. J. Kloosterman, "Mextram 503.2," Presentation CMC, Dec 10, 1998. See Refs. 1 and 20.

12. W. J. Kloosterman, "Mextram 503.2, experimental results," Presentation CMC, Sep. 29, 1999. See Refs. 1 and 20.

13. J. C. J. Paasschens, "Mextram 504," Presentation CMC, Dec. 9, 1999. See Refs. 1 and 20.

14. J. C. J. Paasschens, "Mextram 504, experimental results," Presentation CMC, March 27, 2000. See Refs. 1 and 20.