Modeling high-speed SiGe-HBTs with HICUM/L2 v2.31

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12th HICUM Workshop, Newport Beach, CA (USA), 2012

Outline

- Introduction
- HICUM equivalent circuit
- Transfer current
- Mobile charges
- Vertical NQS-effects
- Lateral NQS-effect
- Noise modeling
- Self-heating
- Experimental results

Introduction

- Experimental results ...
  - from DOTFIVE project (3 different process generations of 3 different technology partners)
  - from characterizing other process types (production, high-voltage)

=> observation of a variety of physical effects

- some effects were difficult to describe with physics-based model parameters with existing v2.24

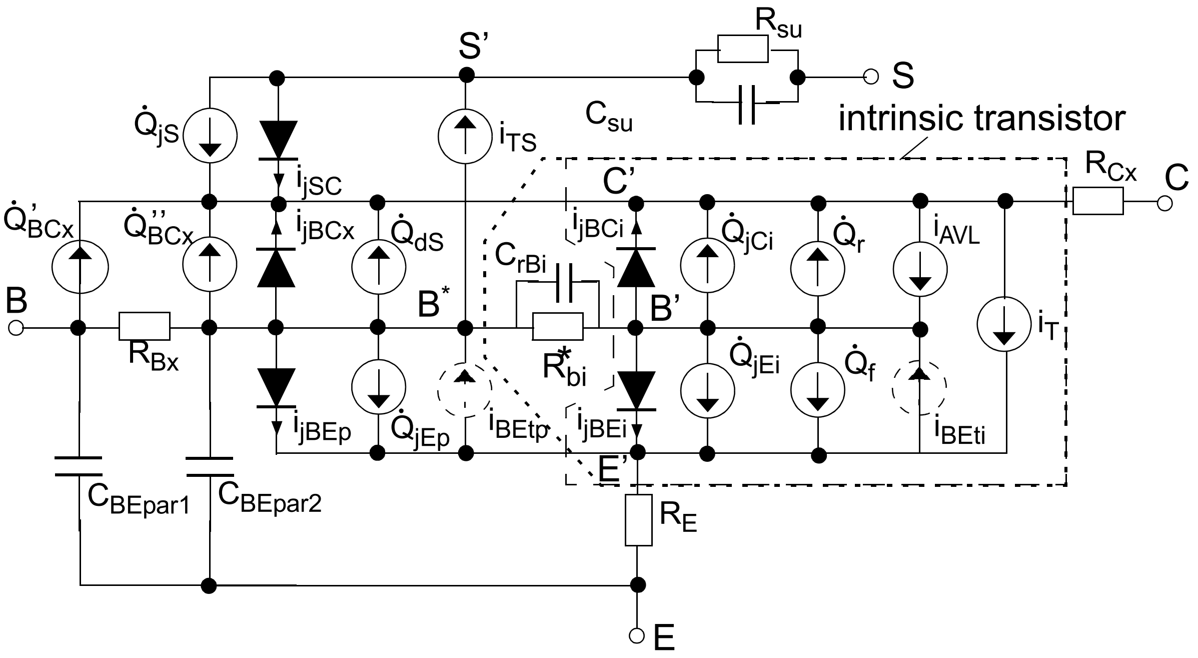
=> motivation for extension to v2.31

- heavy use of BTE, HD, DD device simulation for model development

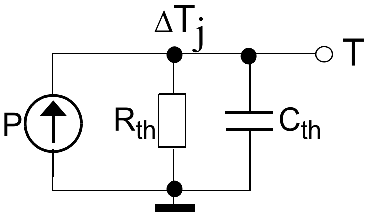
=> final verification always on experimental results

=> this presentation: overview and details on ***v2.31*** extensions

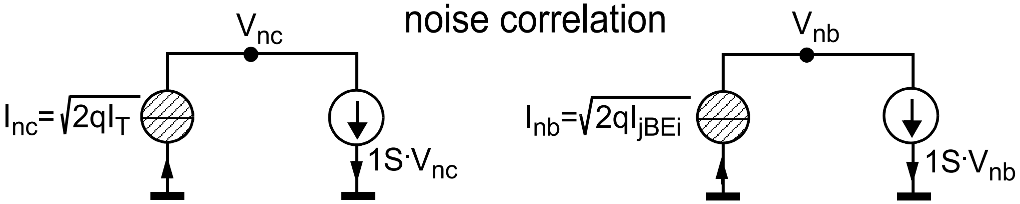
HICUM equivalent circuit



thermal network

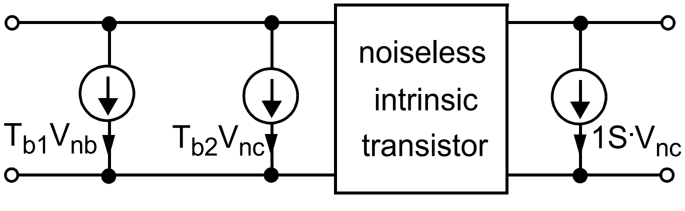


noise correlation

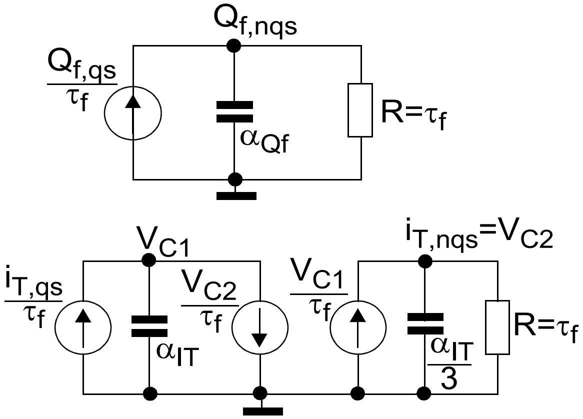


$T_{b1}=1+j\omega\tau_f\sqrt{B_f(2\alpha_{qf}-\alpha_{IT})^2}$

$T_{b2}=j\omega\tau_f\,\alpha_{IT}$



vertical NQS effects



Transfer current

... in HICUM is based on the GICCR

- From 1D drift-diffusion-transport equation: $I_T = c_0 \dfrac{\exp\left(\dfrac{V_{BEi}}{V_T}\right) - \exp\left(\dfrac{V_{BCi}}{V_T}\right)}{\int_0^{l_W} h_j h_v h_g p\,dx}$
- Weight functions h_j and h_v are 1 in the 1D case, c_0 is a bias independent constant.
- Weight function h_g reads $h_g(x) = \dfrac{\overline{\mu_{nr} n_{ir}^2}}{\mu_n(x) n_i^2(x)}$, with "*r*" as reference region
- Reference region in HICUM is the neutral base: $h_k = \dfrac{\int_k \dfrac{\overline{\mu_n(x_B) n_i^2(x_B)}}{\mu_n(x) n_i^2(x)} p(x)dx}{\int_k p(x)dx}$

k represents the various regions in the transistor

Transfer current related charge

- Actual charge in the transistor is divided into zero-bias, depletion and mobile charge component: $Q_p = qA_E\int p(x)dx = Q_{p0} + \Delta Q_j + \Delta Q_m$
- Transfer current expression from GICCR:

$$I_T = \frac{c_{10}}{Q_{pT}}\left[\exp\left(\frac{V_{BEi}}{V_T}\right) - \exp\left(\frac{V_{BCi}}{V_T}\right)\right] = i_{Tf} - i_{Tr}$$

with *weighted* hole charge

$$Q_{pT} = Q_{p0} + \underbrace{h_{jEi}Q_{jEi} + h_{jCi}Q_{jCi}}_{\Delta Q_j} + Q_{fT} + Q_{rT}$$

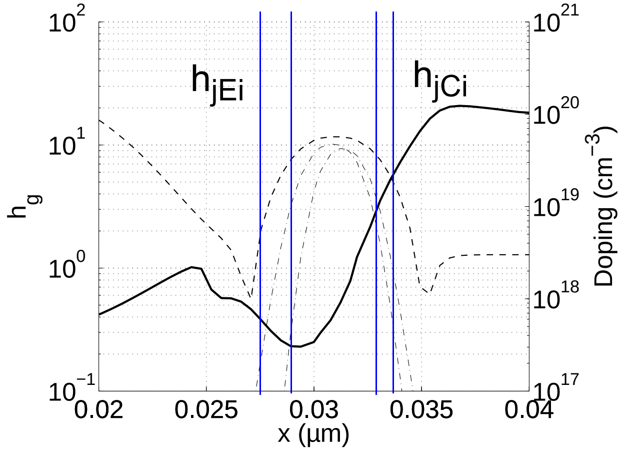
and weighted mobile charge (h_{f0} newly introduced in v2.3)

$$Q_{fT} = \boxed{h_{f0}}\tau_{f0}i_{Tf} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}\Delta Q_{Cf} \quad , \quad Q_{rT} = \tau_r i_{Tr}$$

=> Transfer current is directly related to charges defined from small- and large-signal behavior

GICCR allows taking into account material composition

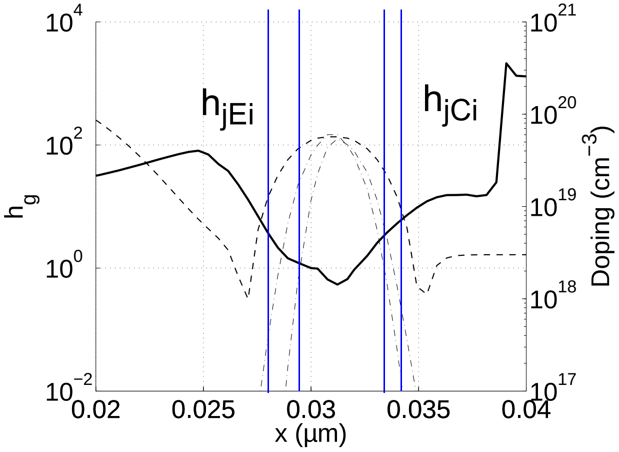
Si BJT

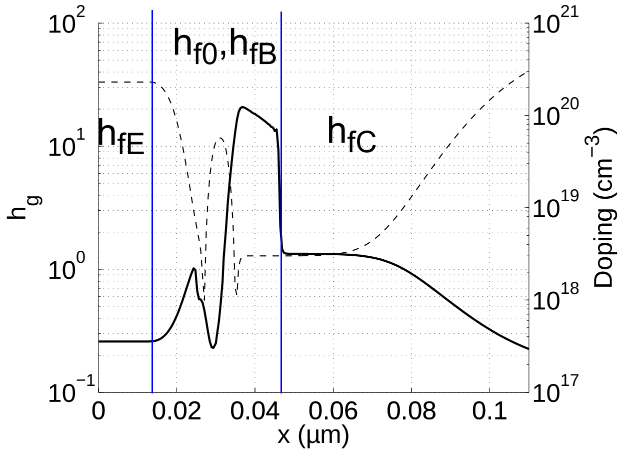


Low-current weight factors

	Si	SiGe
h_{jEi}	0.2	1.0
h_{jCi}	2.7	2.4

SiGe HBT

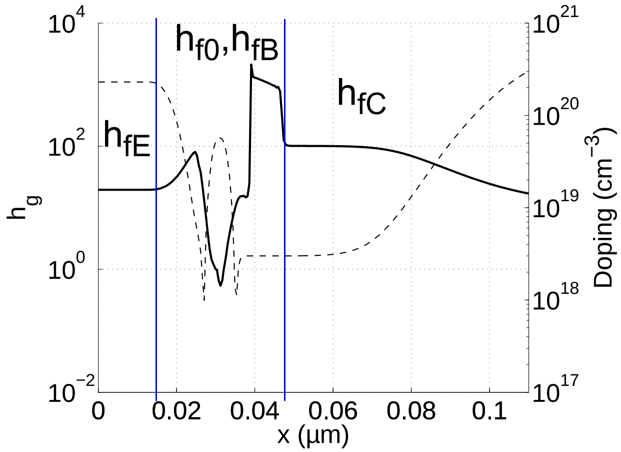




High-current weight factors

	Si	SiGe
h_{fE}	0.7	31.3
h_{fC}	1.9	84.5
h_{f0}	0.98	5
h_{fB}	1.1	1.6

(*base as reference region*)

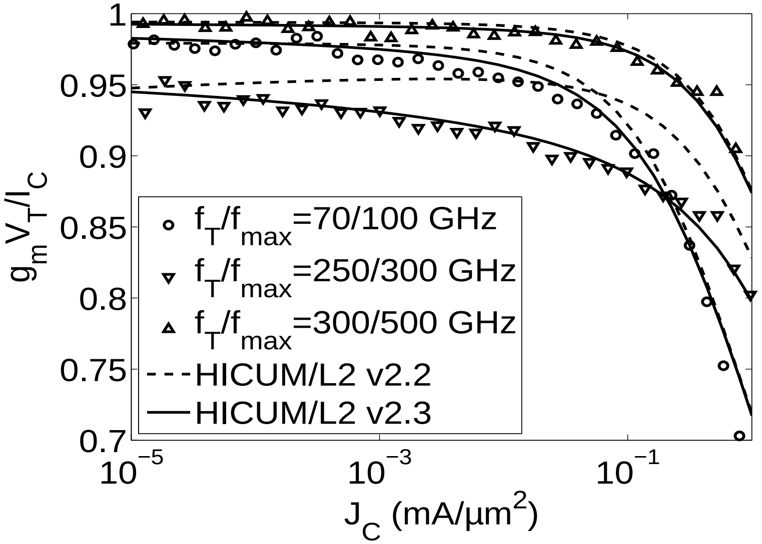


Normalized transconductance

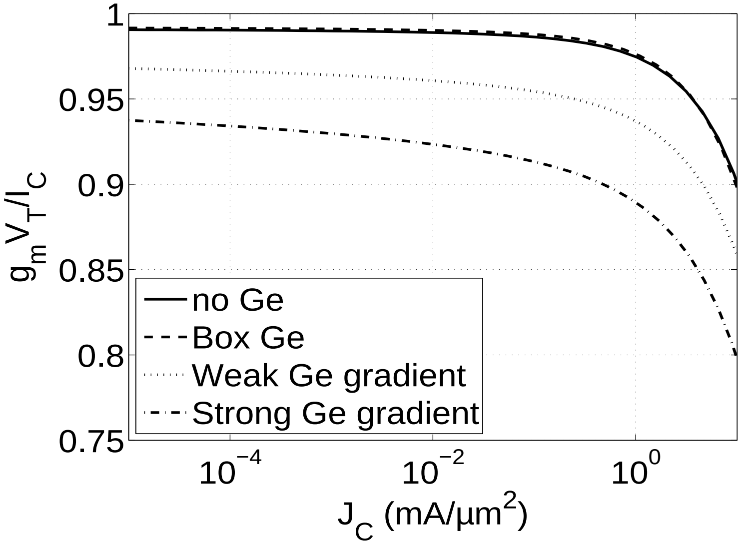
$g_m/(I_C/V_T)$ can be used to identify device non-ideality and to compare technologies

- experimental observation: drop in normalized transconductance already at low to medium injection for some technologies.

experimental data



1D device simulation



- cannot be described with simple (bias independent) reverse Early voltage models
- From 1D device simulation: effect is directly related to Ge grading in BE-SCR

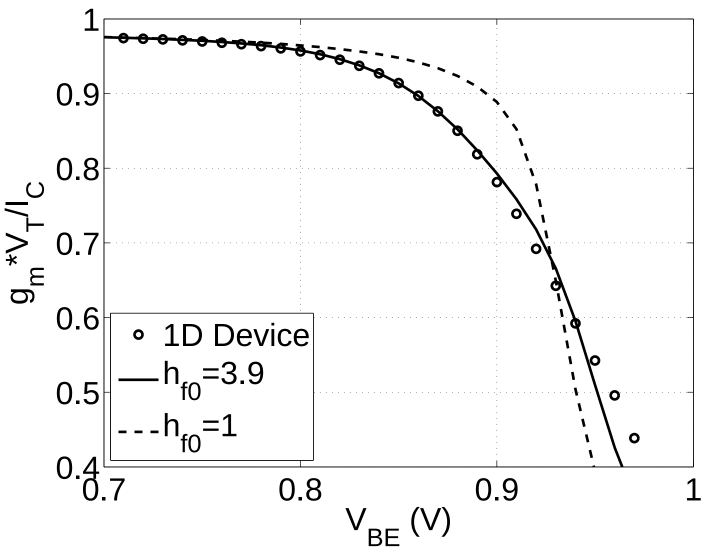
=> explicitly included in v2.30: $h_{jEi} = h_{jEi0}\frac{\exp(u)-1}{u}$, $u = \boxed{a_{hjEi}}(1-(V_{BEi}/V_{DEi})^{z_{Ei}})$

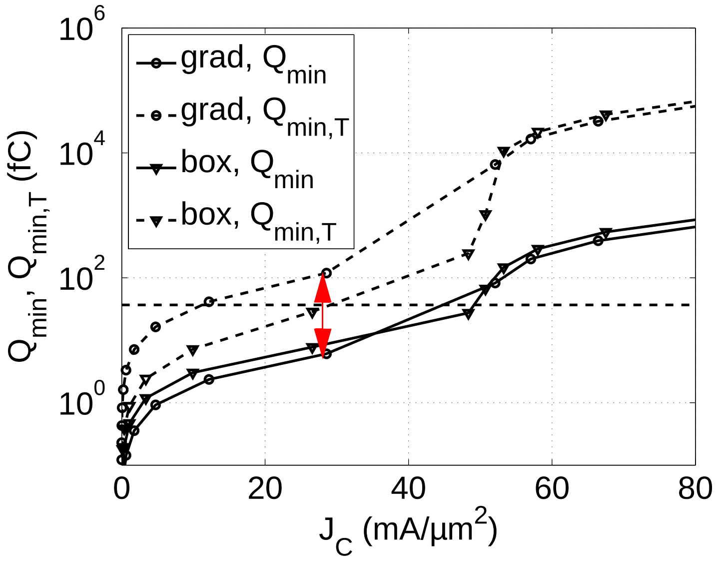
Transconductance at medium injection

Stronger reduction of $g_m/(I_C/V_T)$ could not be described with meaningful Q_{p0} values

- Need to keep physics-based value for Q_{p0} for accurate modeling of internal base (sheet) resistance => extract Q_{p0} from tetrodes rather than from transfer current.
  - For graded Ge, weighted mobile charge is much larger than actual mobile charge (mostly concentrated in neutral base) => need to introduce h_{f0}:

$$Q_{fT} = h_{f0}\tau_{f0}i_{Tf} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}\Delta Q_{Cf}$$





=> strongly improves g_m modeling at medium bias

Temperature dependence of new weight factors

... due to bandgap differences

- h_{jEi} also incl. movement of SCR boundaries

$$h_{jEi0}(T) = h_{jEi0}(T_0)\exp\left(\frac{\Delta V_{gBE}}{V_T}\left(\left(\frac{T}{T_0}\right)^{\zeta_{vgBE}} - 1\right)\right),$$

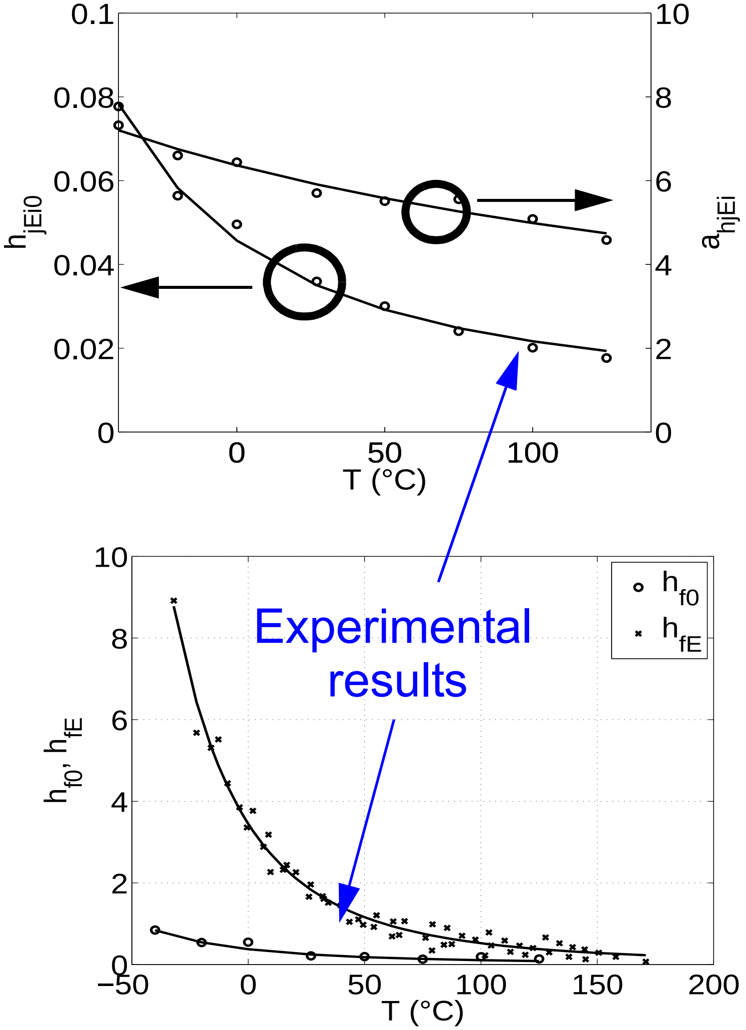
$$a_{hjEi}(T) = a_{hjEi}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{hjEi}}$$

- Medium-current weight factor

$$h_{f0}(T) = h_{f0}(T_0)\exp\left(\frac{\Delta V_{gBE}}{V_T}\left(\frac{T}{T_0} - 1\right)\right)$$

- High-current weight factor

$$h_{f(E,C)}(T) = h_{f(E,C)}(T_0)\exp\left(\frac{V_{gB} - V_{g(E,C)}}{V_T}\left(\frac{T}{T_0} - 1\right)\right)$$

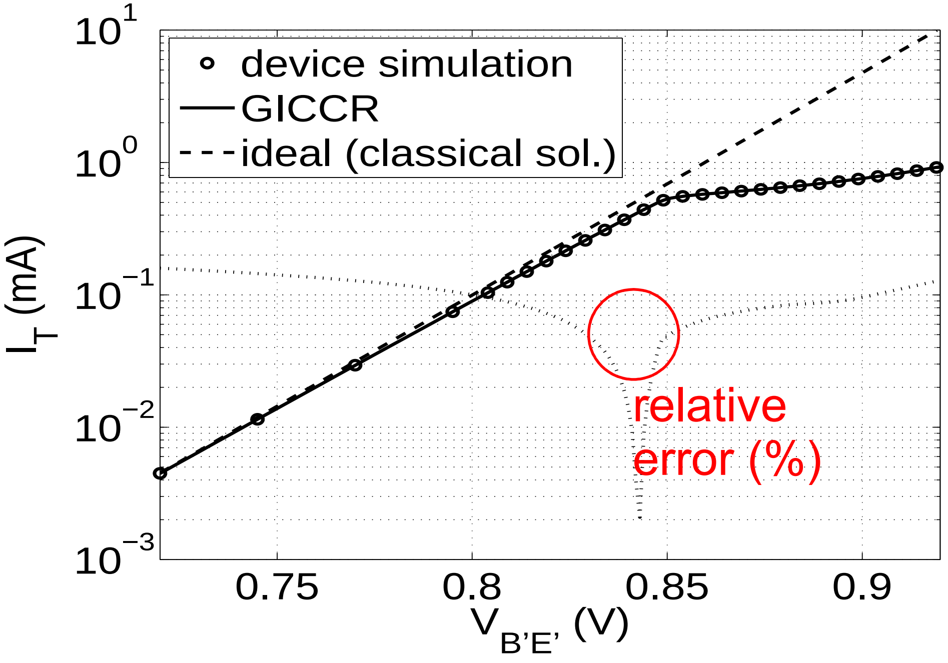


Experimental results

Results

- Physics-based extensions in v2.30 and v2.31
  - Material composition related effects modeled explicitly by physics-based equations
  - Takes into account temperature effects due to different bandgap values

=> Accurate transfer current modeling by GICCR with physics-based charges, weight factors, and parameters



=> New version has been successfully applied to several recent technologies

Mobile charges

- forward active bias mobile charge in HICUM

$$Q_f = \tau_{f0} + \Delta Q_{Ef} + \Delta Q_{fh}$$

  - corresponding transit time

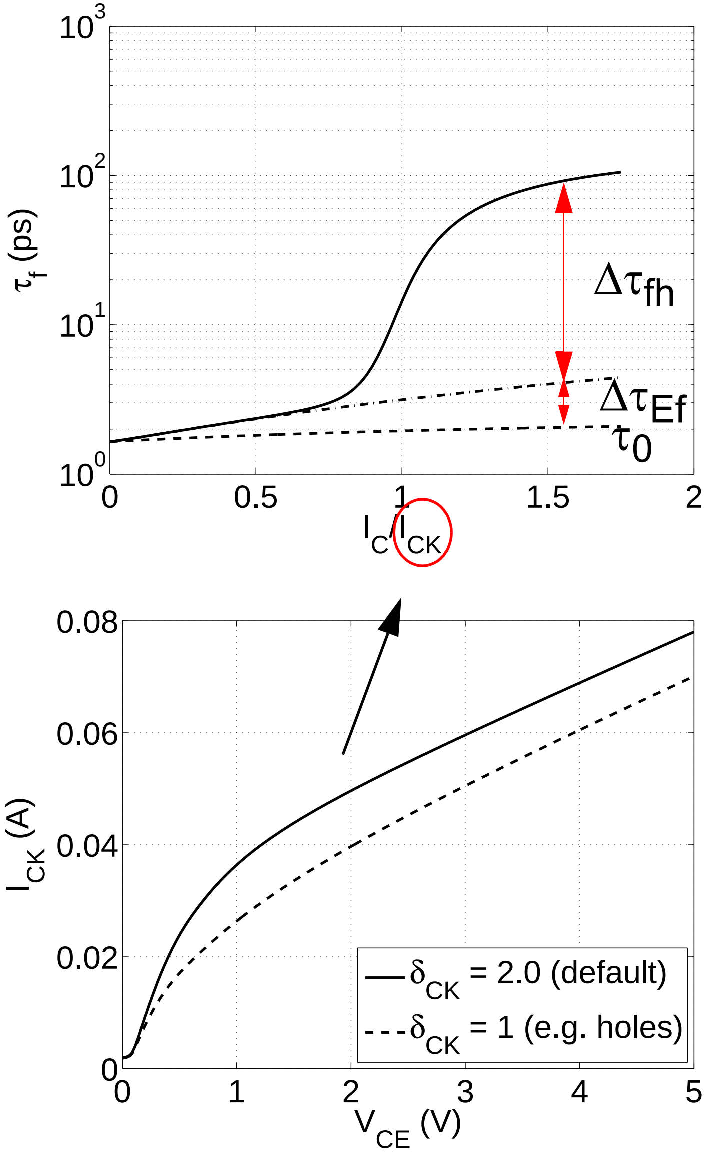
$$\tau_f = \tau_{f0} + \Delta\tau_{Ef} + \Delta\tau_{fh}$$

  - follows: $Q_f = \int_0^{i_{Tf}} \tau_f \, di_T'$

- ccritical current I_{CK}
  - added parameter for better fitting to field dependence of mobility.

$$I_{CK} = \frac{v_{ceff}/r_{Ci0}}{\left(1+\left(\frac{v_{ceff}}{V_{lim}}\right)^{\delta_{CK}}\right)^{1/\delta_{CK}}}\left[1+\frac{x+\sqrt{x^2+a_{ickpt}}}{2}\right]$$

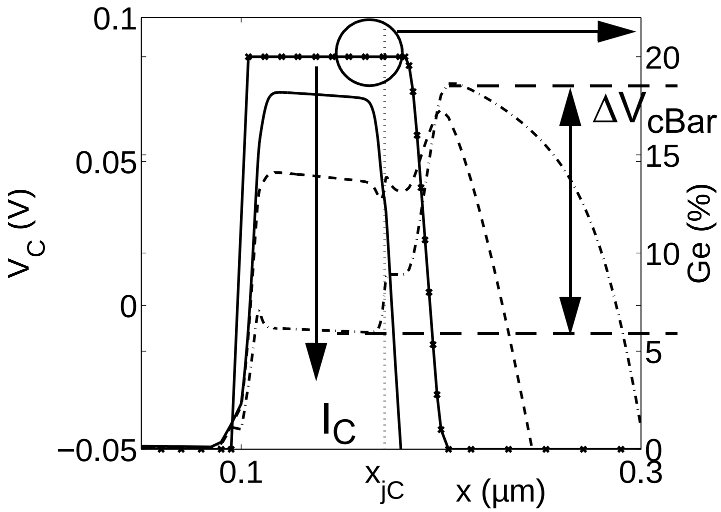
  - default $\delta_{CK}=2$
  - parameter allows better fitter for, e.g., pnp

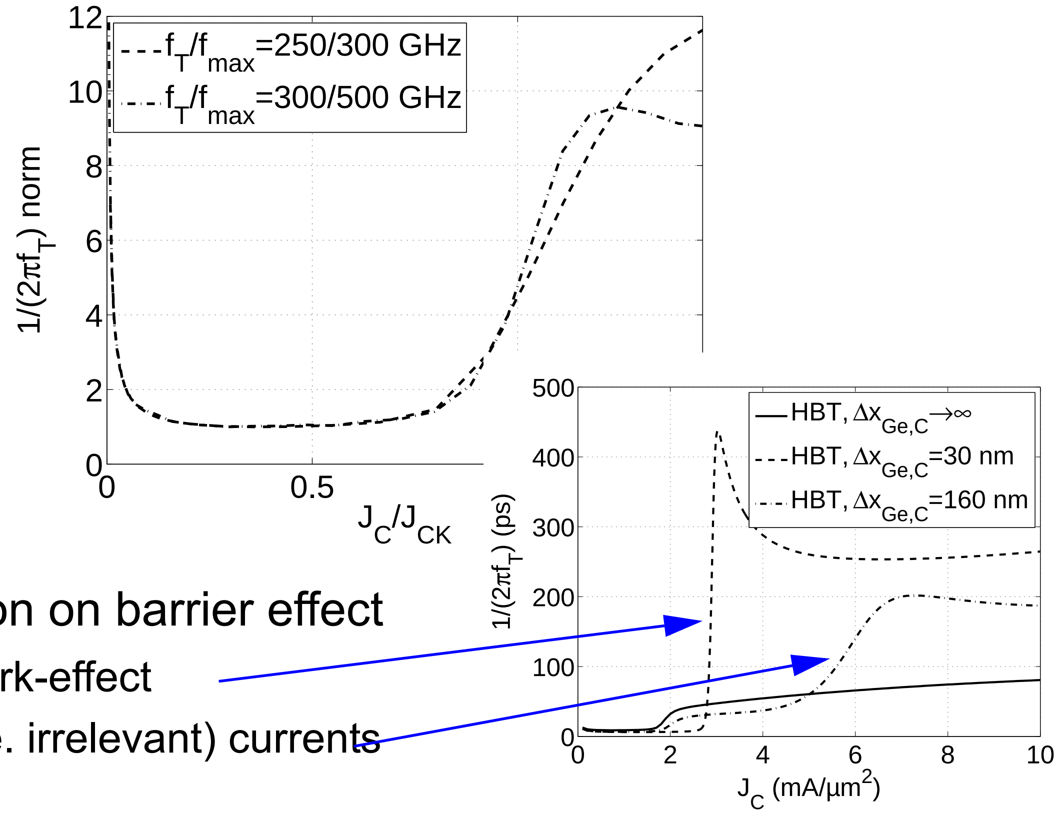


BC barrier effect

- In HICUM v2.30, the collector heterojunction barrier effect is modeled.
  - Barrier effect becomes more pronounced in advanced SiGe HBT generations
  - Formation of barrier in conduction band strongly related to Kirk-effect in well-designed HBT

=> more rapid increase of transit time beyond I_{CK}



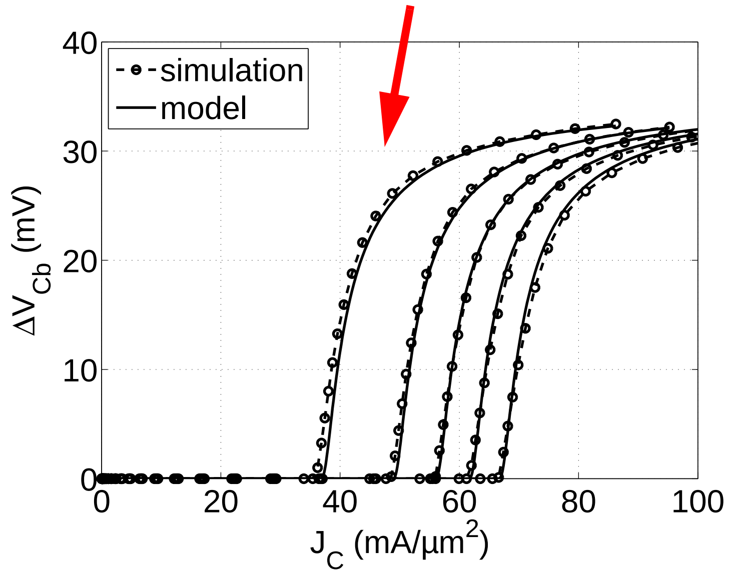


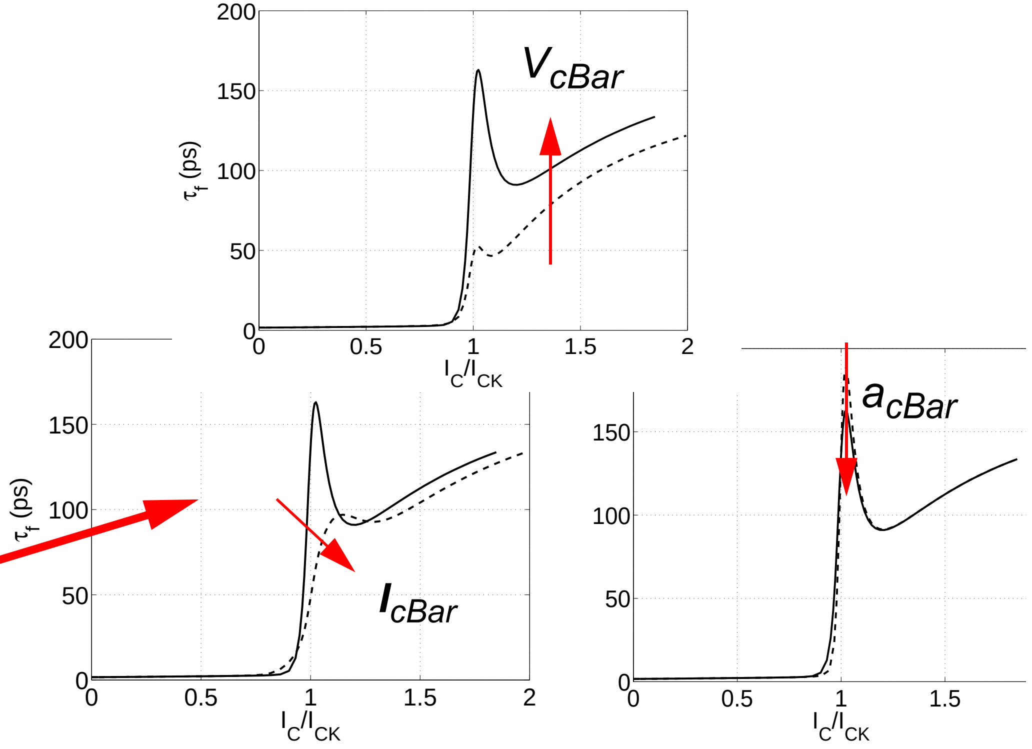
- Influence of heterojunction position on barrier effect
  - Close to BC-junction -> related to Kirk-effect
  - Far in the collector -> at too high (i.e. irrelevant) currents

Modeling the BC barrier effect

- Onset of barrier effect is still given by I_{CK} (for a "well-designed" DHBT)
- barrier voltage (from bias dependent conduction band barrier):

$$\Delta V_{cB} = V_{cBar}\exp\left(-\frac{2}{i_{bar}+\sqrt{i_{bar}^2+a_{cBar}}}\right) \quad \text{with} \quad i_{bar} = \frac{i_{Tf}-I_{CK}}{I_{cBar}}$$





- New parameters: V_{cBar}, I_{cBar}, a_{cBar}

New mobile charge formulation at high injection

- Include barrier related base and collector charge terms explicitly:

$$Q_{f,h} = \Delta Q_{Ef} + \Delta Q_{Bf,b} + \underbrace{\Delta Q_{Bf,c} + \Delta Q_{Cf,c}}_{Q_{fh,c}}$$

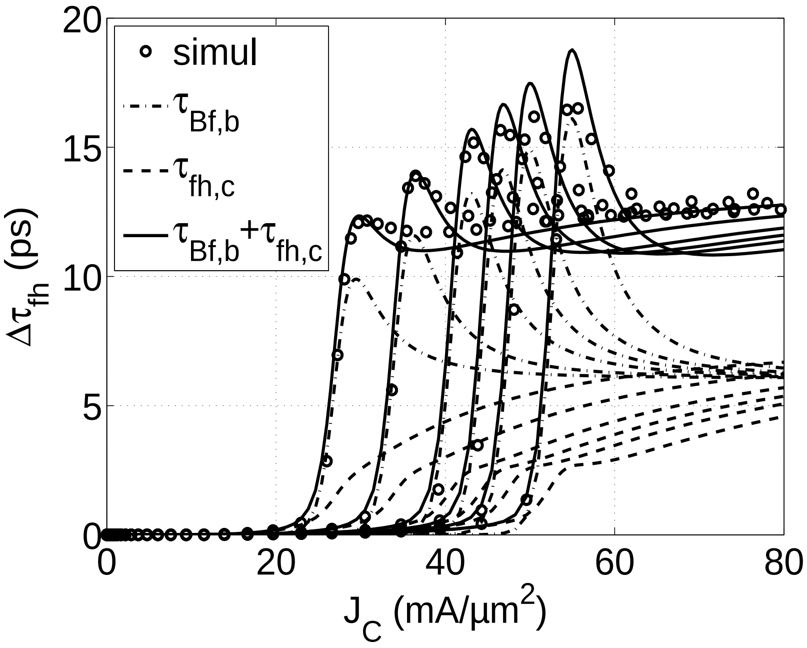
- Barrier related base charge term calculated by a bias dependent barrier voltage.

$$\Delta Q_{Bf,b} = \tau_{Bfvs} i_{Tf}\left[\exp\left(\frac{\Delta V_C}{V_T}\right) - 1\right]$$

with already existing $\tau_{Bfvs} = (1 - f_{\tau hc})\tau_{hCs}$

- Kirk-effect related transit times are "delayed" by the formation of the barrier:

$$\Delta Q_{fh,c} = \tau_{hCs} i_{Tf} w^2 \exp\left(\frac{\Delta V_C - V_{Cbar}}{V_T}\right)$$



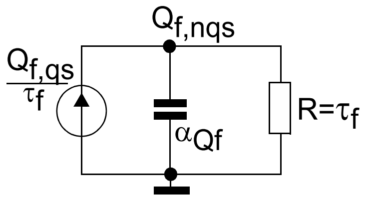
=> very accurate and flexible, and still backwards compatible

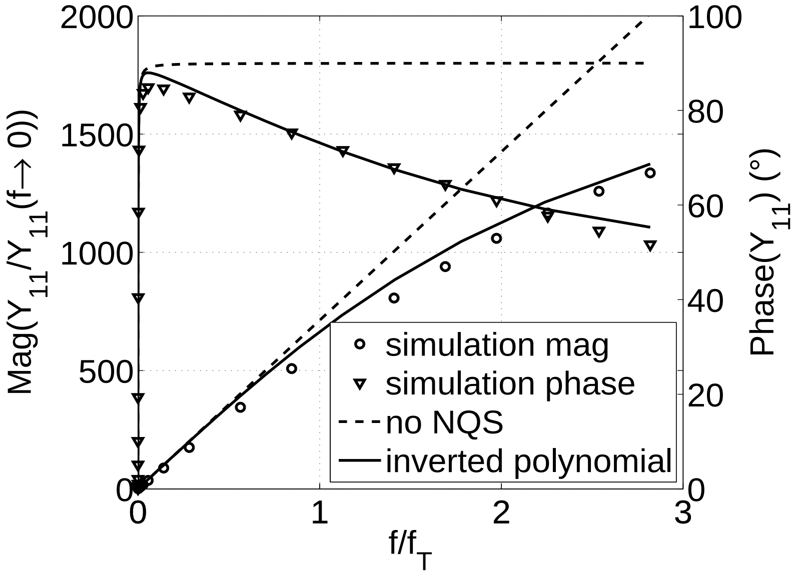
Vertical NQS-effects

HICUM includes mobile charge and transfer current related NQS effects

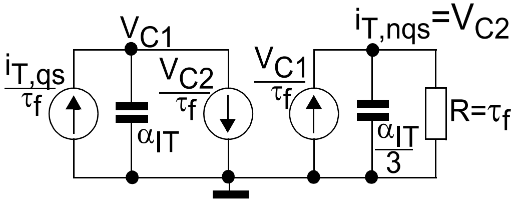
=> modeled using polynomial approximation and separate networks

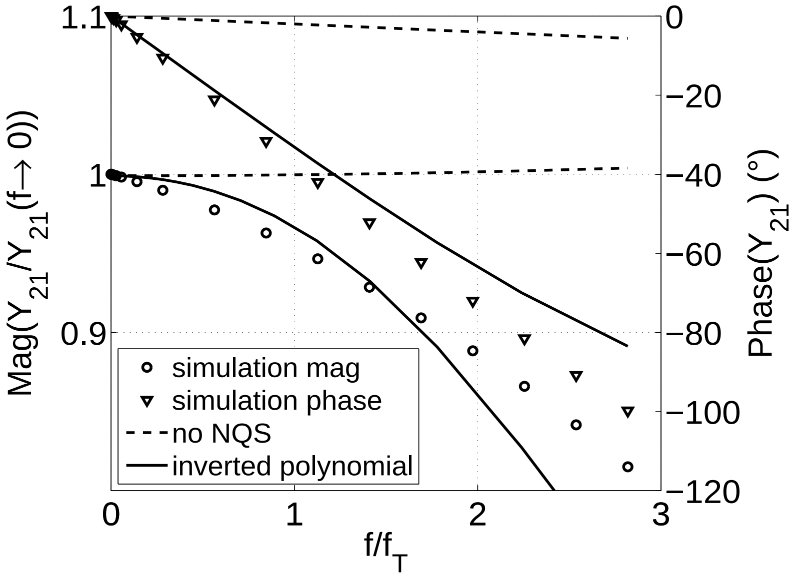
charge delay and input admittance





transfer current delay and transconductance



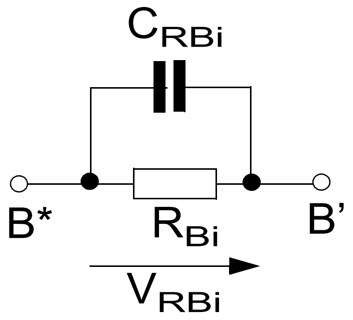


=> Good agreement in small-signal and large-signal simulation

Lateral NQS-effect

... caused by high-frequency emitter current crowding

- theoretical solution only for small-signal case (and negligible DC current crowding) => simple capacitance parallel to R_{Bi}:



$$C_{RBi} = f_{CRBi}(C_{jEi} + C_{jCi} + C_{dEi} + C_{dCi})$$

- Verilog-A only allows adjunct network with charge definition: $Q_{RBi} = C_{RBi}V_{RBi}$ or

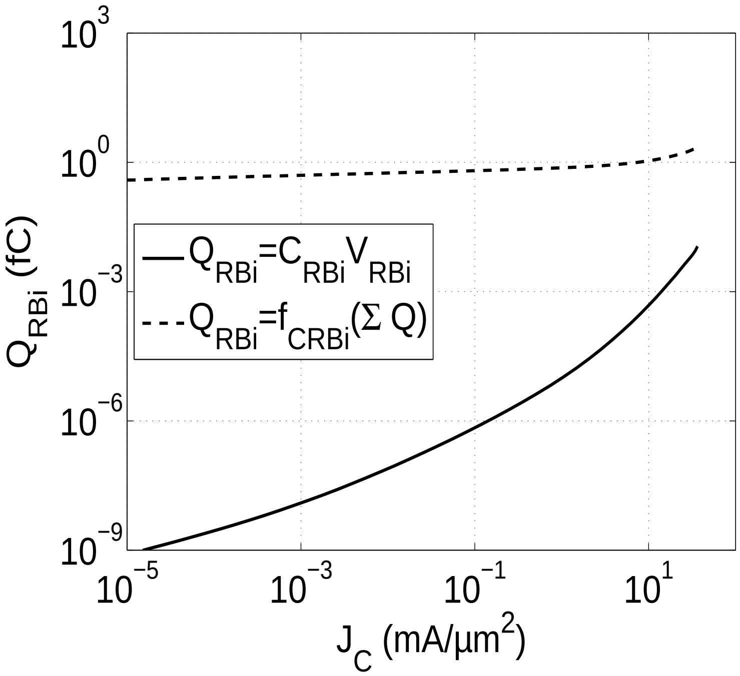
$$Q_{RBi} = f_{CRBi}(Q_{jEi} + Q_{jCi} + Q_{dEi} + Q_{dCi})?$$

  - latter leads to strong overestimation of the charge, current and admittance
  - present solution ***ONLY*** valid for ***small-signal operation*** and *not too high frequencies*

Do NOT use for large-signal operation!!

=> still under investigation

- Feedback from circuit design?



Problems with implementation of lateral NQS-effect

... caused by undesired derivatives

- small-signal form of $Q_{RBi} = C_{RBi}V_{RBi}$ in Verilog-A leads to

$$\frac{dQ_{RBi}}{dt} = \frac{d(C_{RBi}V_{RBi})}{dt} = C_{RBi}\frac{dV_{RBi}}{dt} + \frac{dC_{RBi}}{dV_{RBi}}V_{RBi}\frac{dV_{RBi}}{dt}$$

theoretical solution

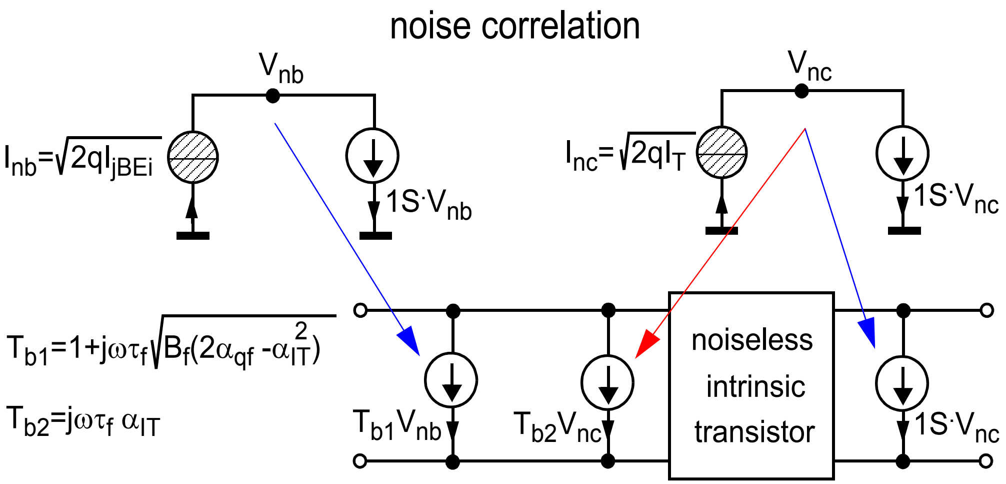
not present in small-signal theory

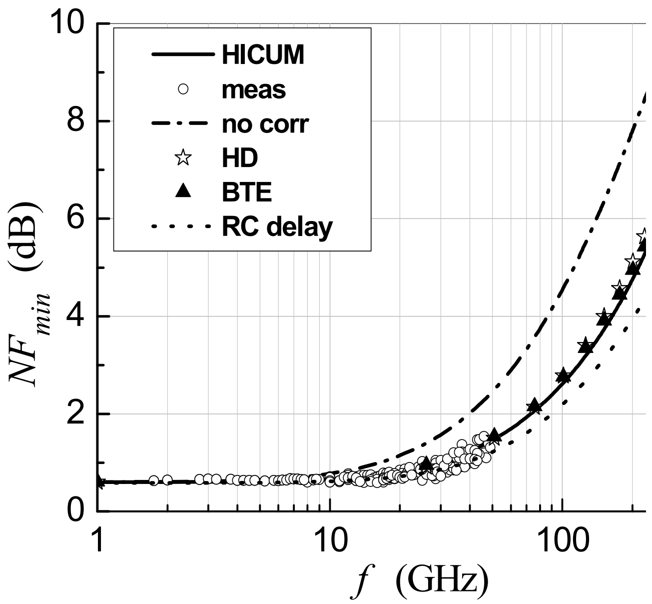
=> undesired derivative from Verlog-A implementation constraints

- Also: undesired derivatives result in large overhead of compiled code since dC_{RBi}/dV_{RBi} internally requires the calculation of the derivatives of ***all nonlinear*** *capacitances* (incl. for C_{dEi} and C_{dCi})
- alternatives are presently under investigation

Noise modeling

- New noise correlation model in v2.31 is valid at all frequencies
  - physically connected to NQS effects => can use same delay time and assoc. parameters



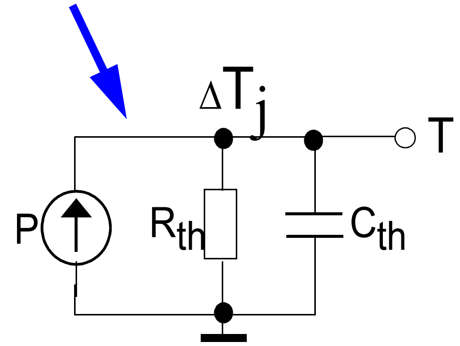


- Additional flicker noise contribution for emitter resistance R_E

$$\overline{I_{rE}^2} = \frac{K_{fre} I_E^{A_{fre}}}{f} + \frac{4kT}{R_E}$$

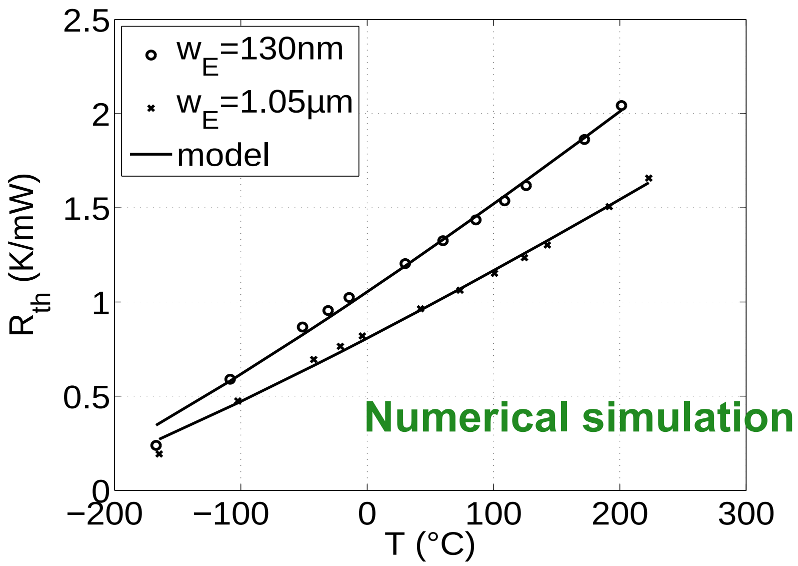
Self-heating

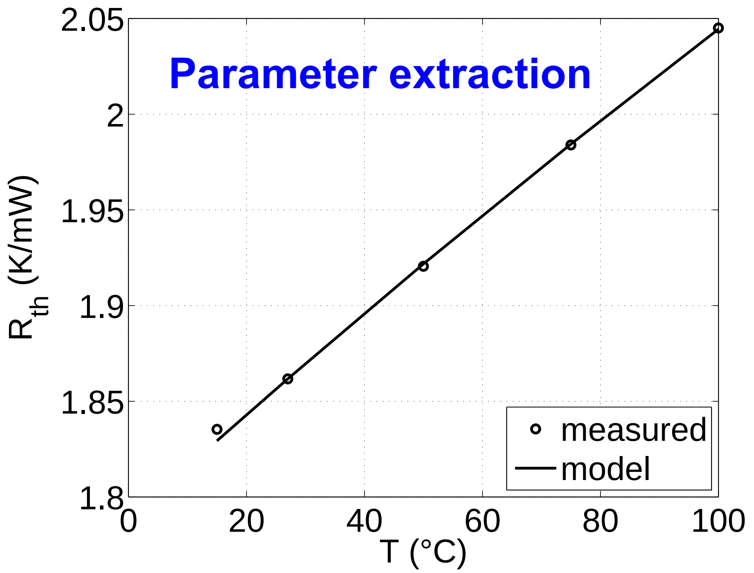
intra-device thermal coupling (self-heating) described by *single-pole network*



- dissipated power: $P = f(I_T, V_{CEi}, I_{BE}, I_{BC}, R_B, R_E, R_{CX}, I_{AVL})$
- Based on observations of experimental data and solution of heat transport equation:

$$R_{th}(T) = R_{th}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{Rth}}$$





- Temperature node also allows modeling of *inter*-device thermal coupling

Summary on V2.31 extensions

list of new model parameters and flags

Parameter	Def.	Description
δ_{CK}	2	Fitting factor for I_{CK}
a_{hjEi}	0	Parameter describing the slope of $h_{jEi}(V_{BE})$
r_{hjEi}	1	Smoothing parameter for $h_{jEi}(V_{BE})$ at high voltage.
ΔV_{gBE}	0	Bandgap difference between base and BE-junction, used for h_{jEi0} and h_{f0}.
ζ_{hjEi}	1	Temperature coefficient for a_{hjEi}.
ζ_{VgBE}	1	Temperature coefficient for h_{jEi0}.
h_{f0}	1	Weight factor for the low current minority charge.
V_{cBar}	0	Barrier voltage, =0 turns the model off.
a_{cBar}	0.01	Smoothing parameter for barrier voltage.
i_{cBar}	0	Normalization parameter, =0 turns the model off.
ζ_{rth}	0	Temperature coefficient for R_{th}
FLCONO	0	High-frequency noise correlation flag
$\mathrm{Kf}_{\mathrm{rE}}$	0	R_E flicker noise coefficient
$\mathrm{Af}_{\mathrm{rE}}$	2	R_E flicker noise exponent factor
TYPE	1	Flag for npn (1) and pnp (-1) transistors

Experimental results

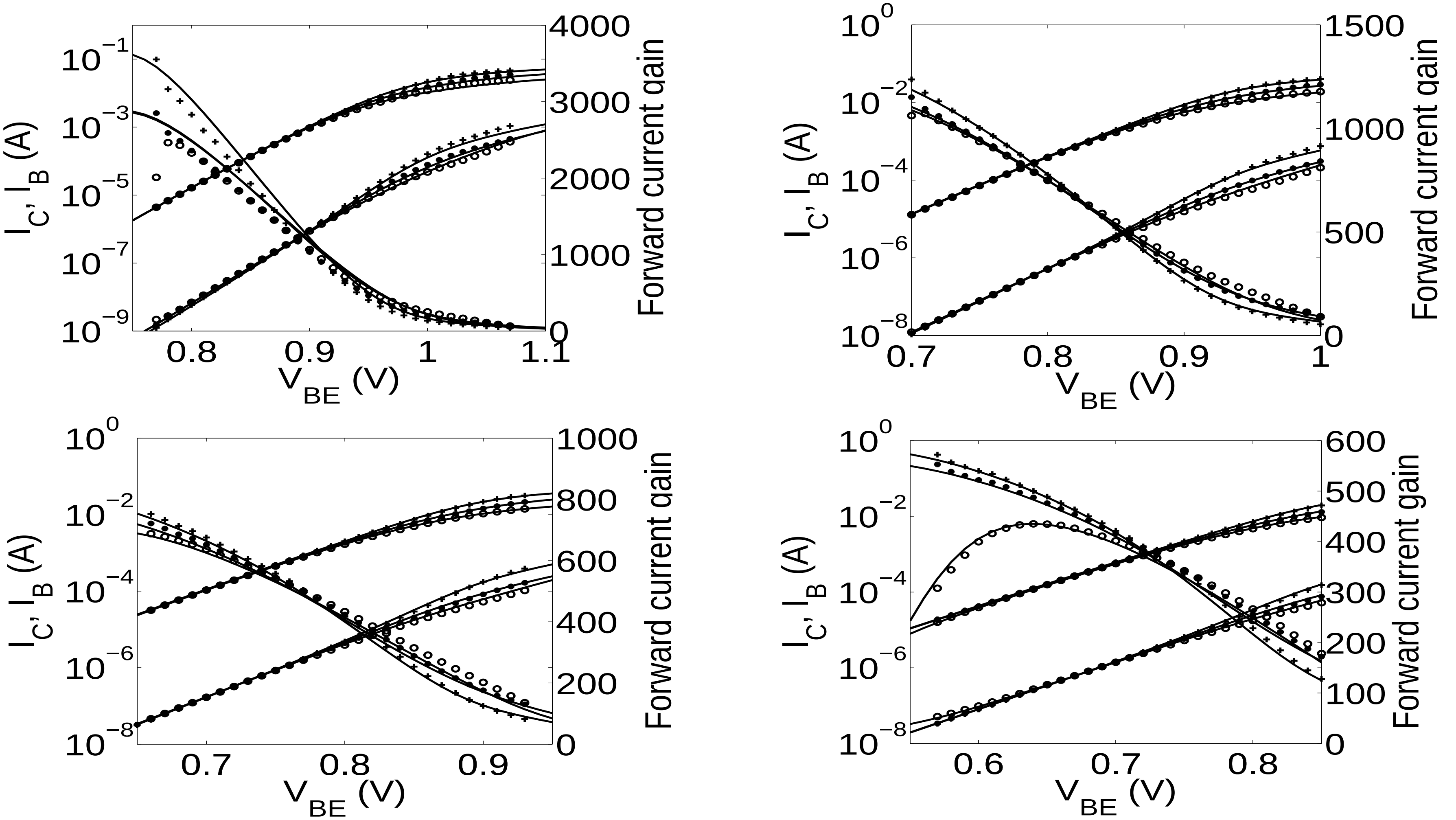
Technologies shown here

- ST B9MW with f_T/f_{max} = 200/300 GHz, A_{E0} = 1x0.13x4.87 μm^2
- IHP SGB25V with f_T/f_{max} = 75/95 GHz, A_{E0} = 1x0.64x12.68 μm^2
- IHP 500GHz with f_T/f_{max} = 300/500 GHz, A_{E0} = 8x0.12x0.96 μm^2

=> Comparison over large bias, temperature, and geometry range

ST B9MW technology

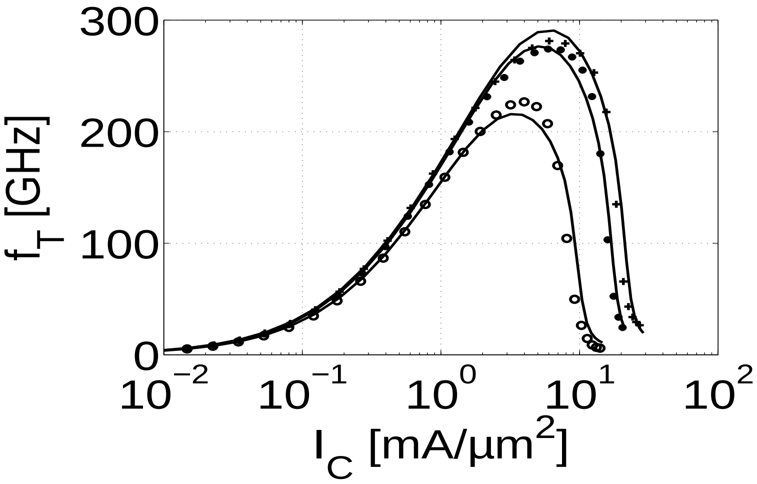
Forward gummel characteristics for [-40, 27, 75, 125]°C.

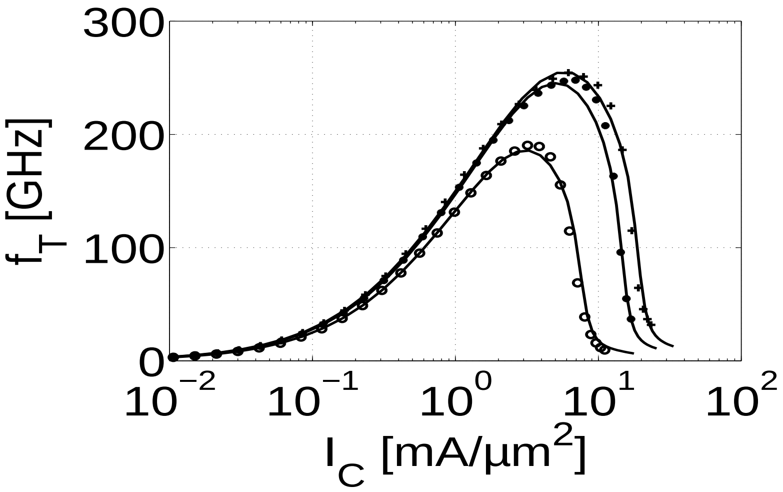


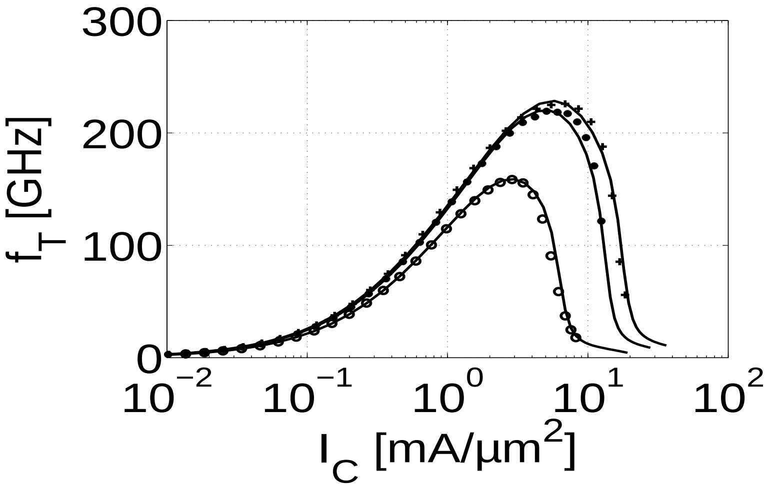
=> very good agreement over wide bias and T range

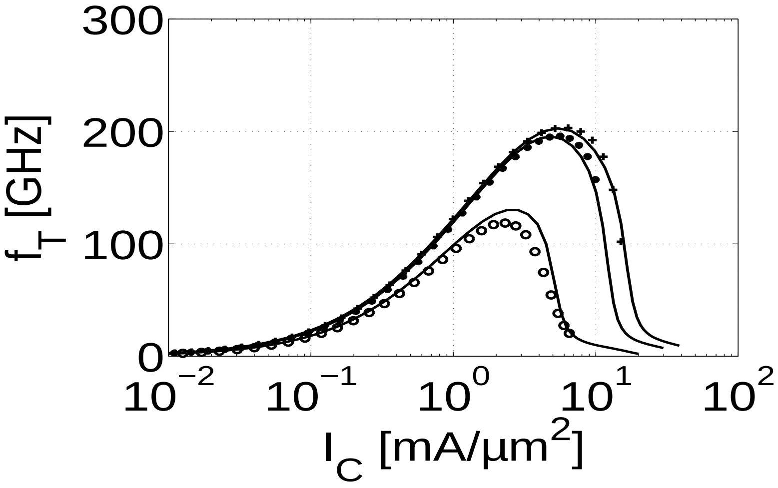
ST technology (cont'd)

transit frequency for [-40, 27, 75, 125]°C.





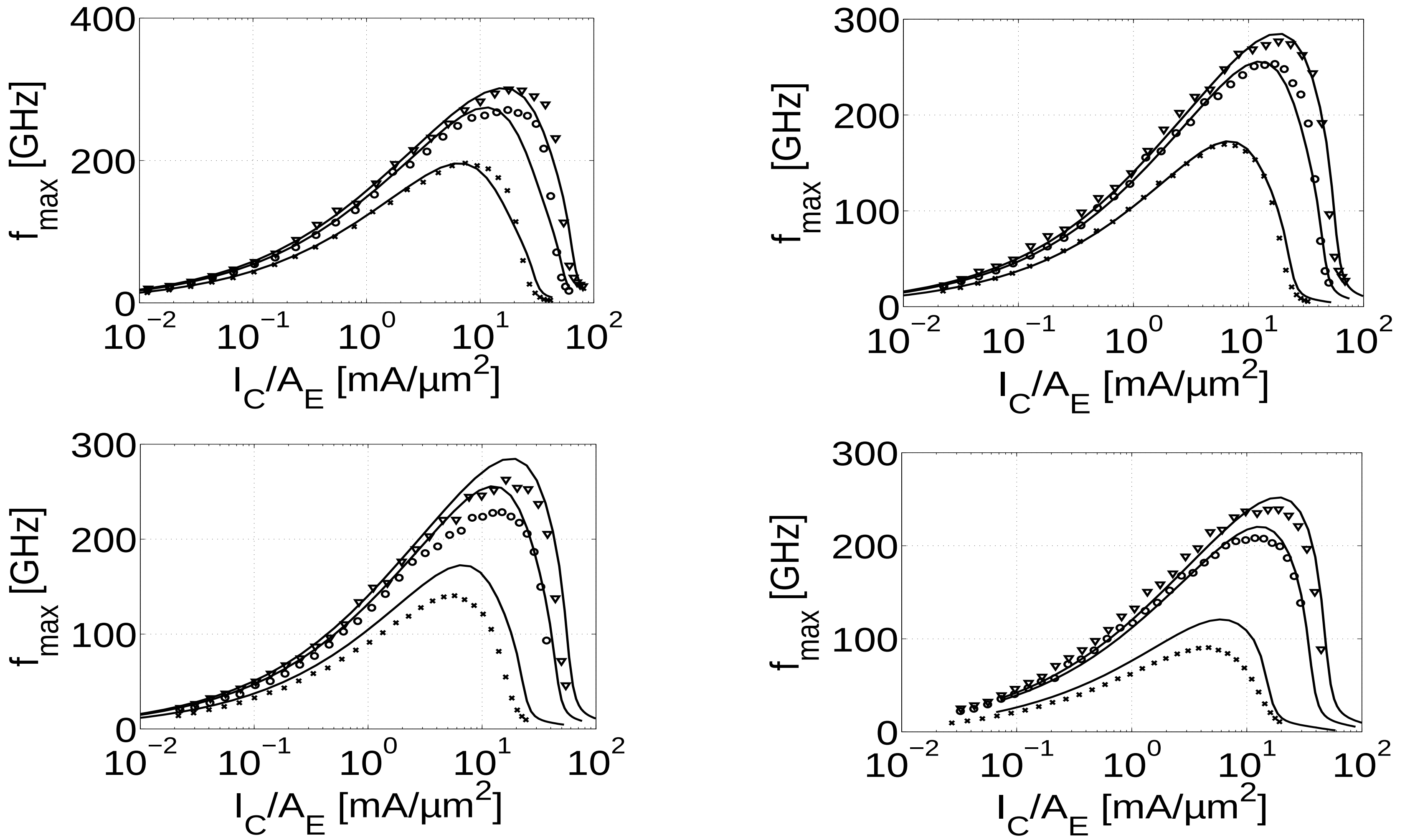




=> very good agreement over wide bias and T range

ST technology (cont’d)

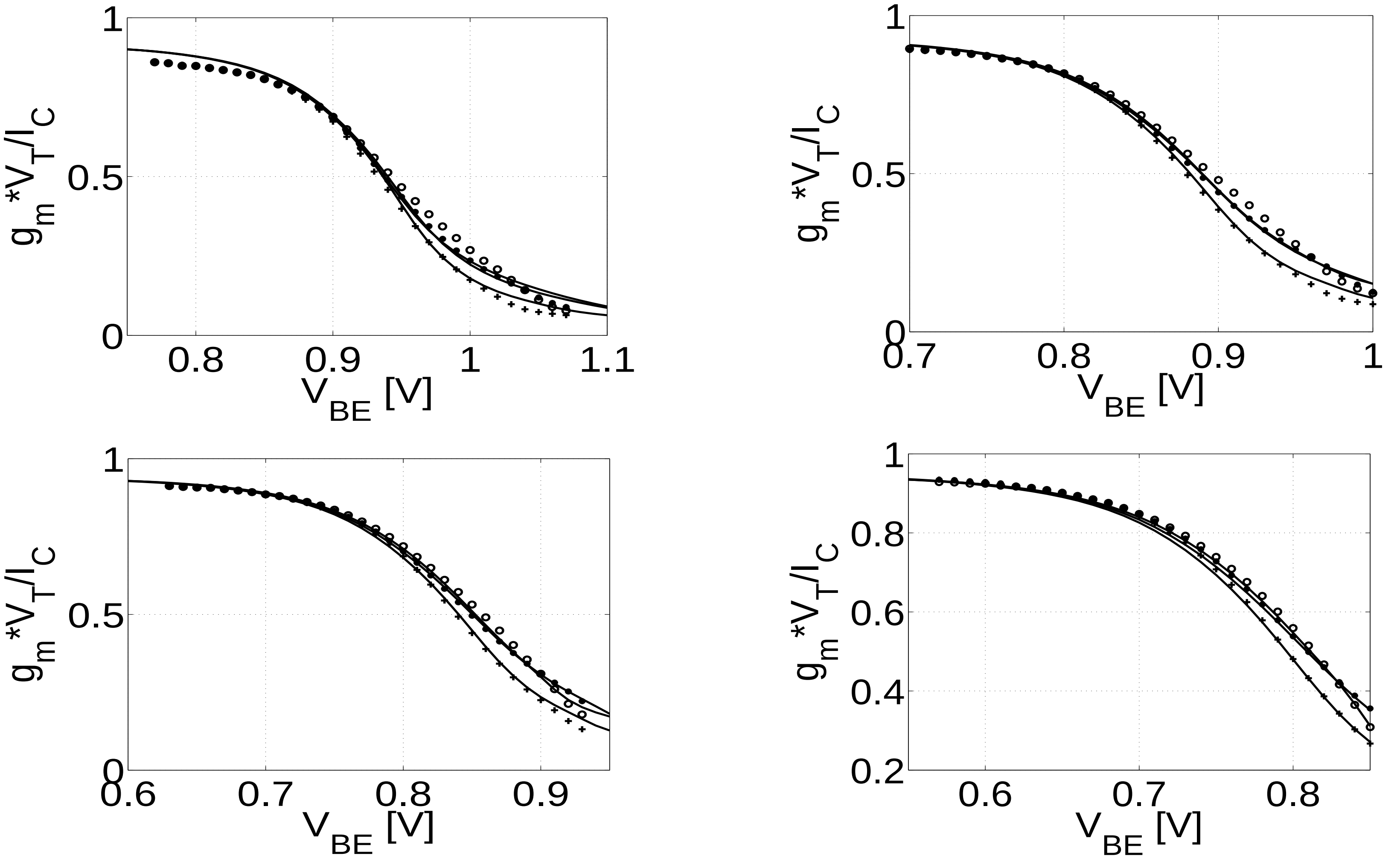
Maximum oscillation frequency for [-40, 27, 75, 125]°C.



=> good agreement over wide bias and T range

ST technology (cont’d)

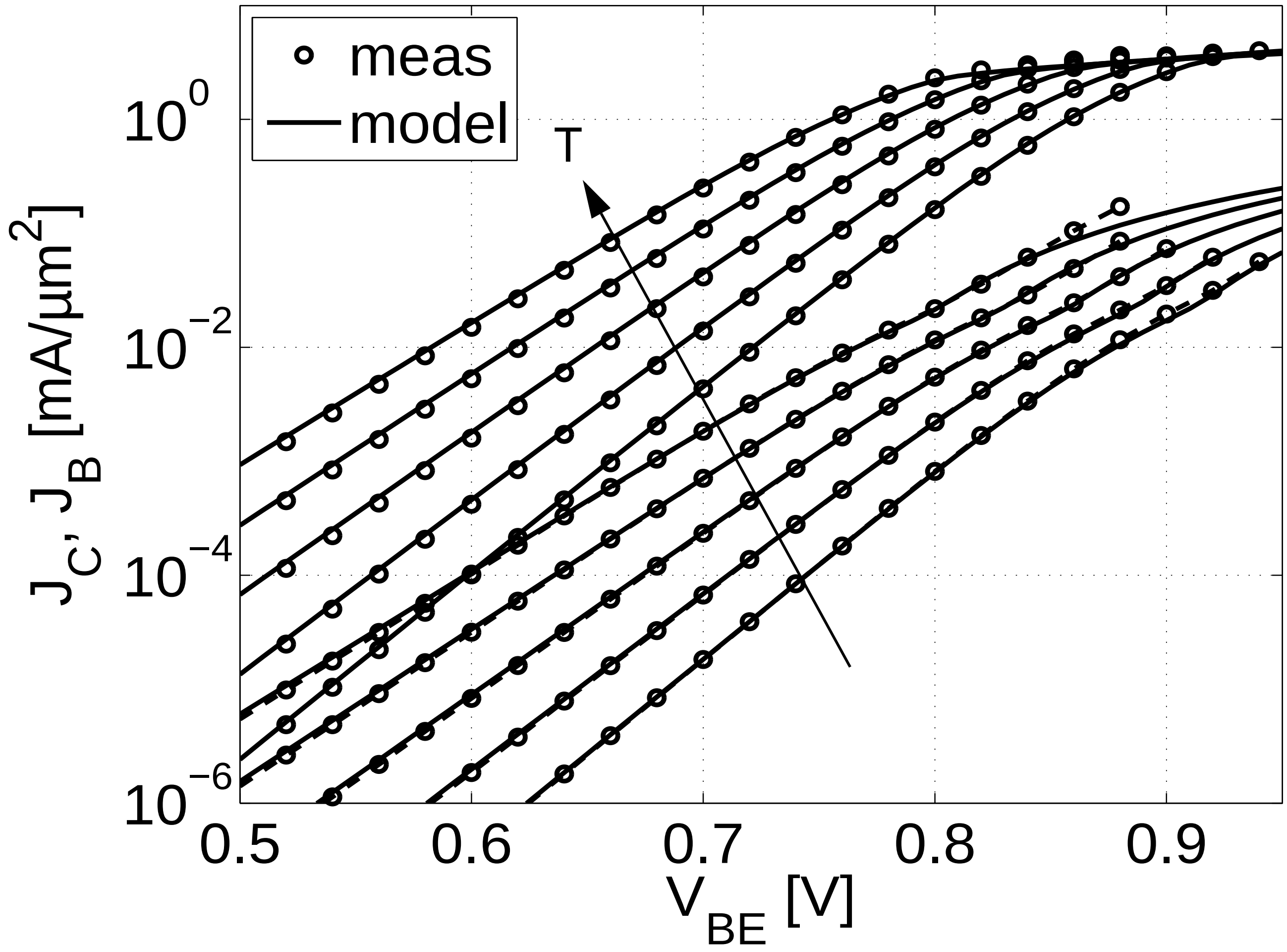
Normalized transconductance for [-40, 27, 75, 125]°C.



=> very good agreement over wide bias and T range

IHP SGB25V technology

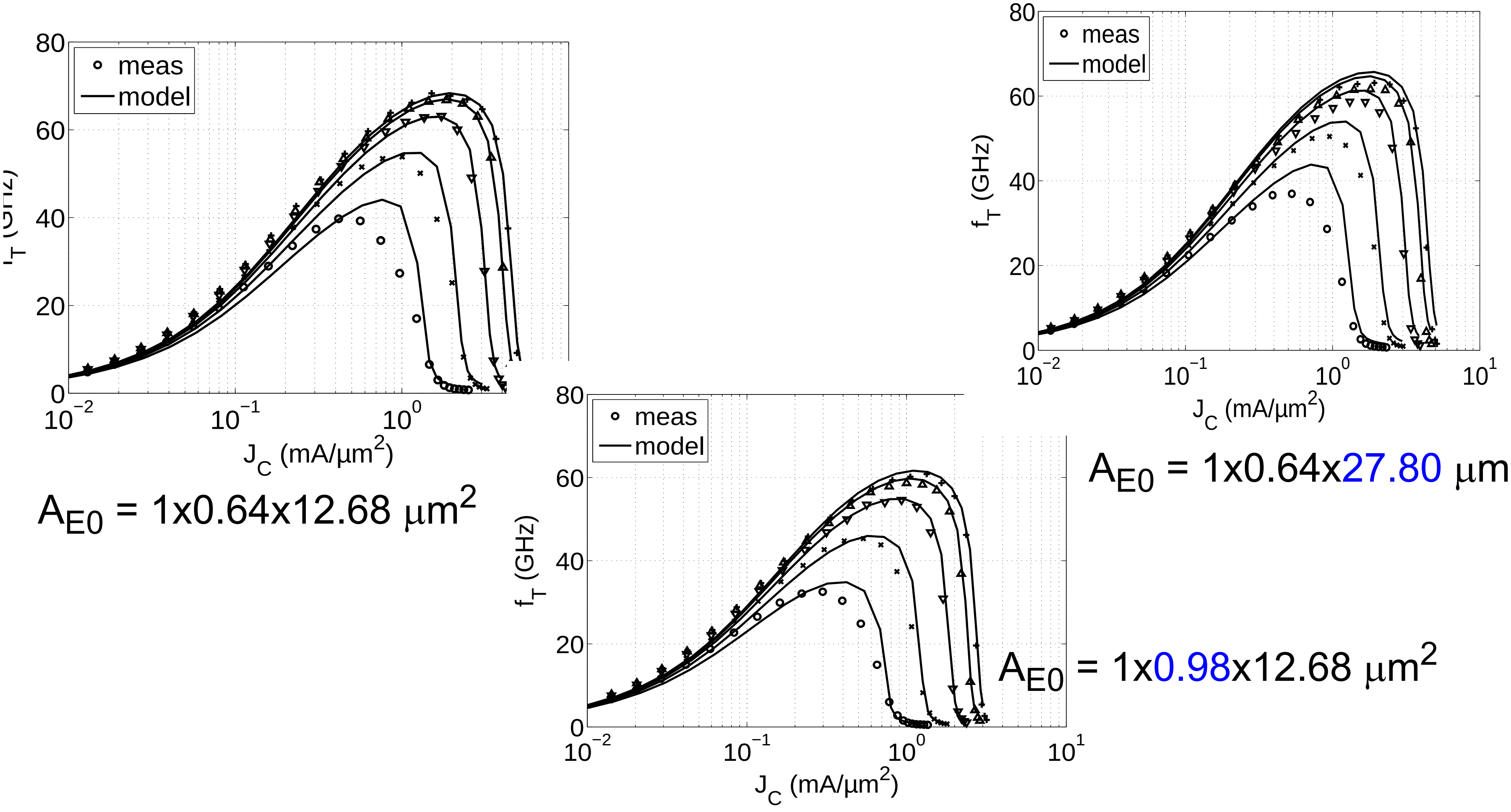
Temperature dependence of forward Gummel characteristics



=> very good agreement over wide bias and T range

IHP SGB25V technology (cont'd)

geometry scaling of transit frequency



A_{E0} = 1x0.64x12.68 µm^2

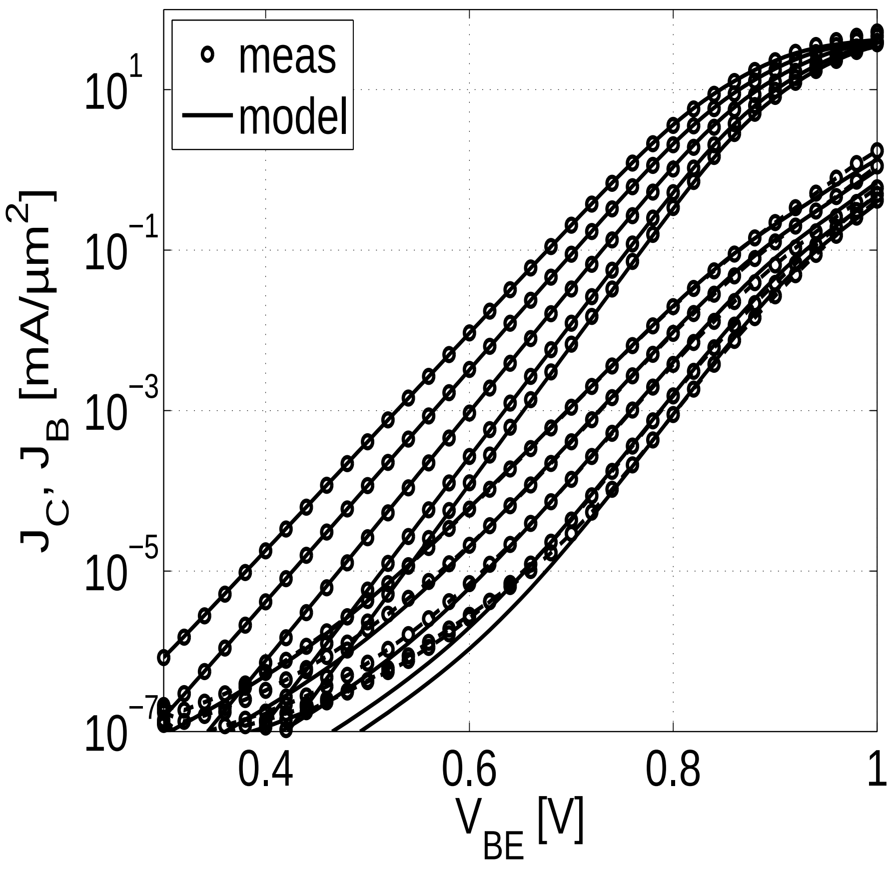
A_{E0} = 1x0.64x27.80 µm^2

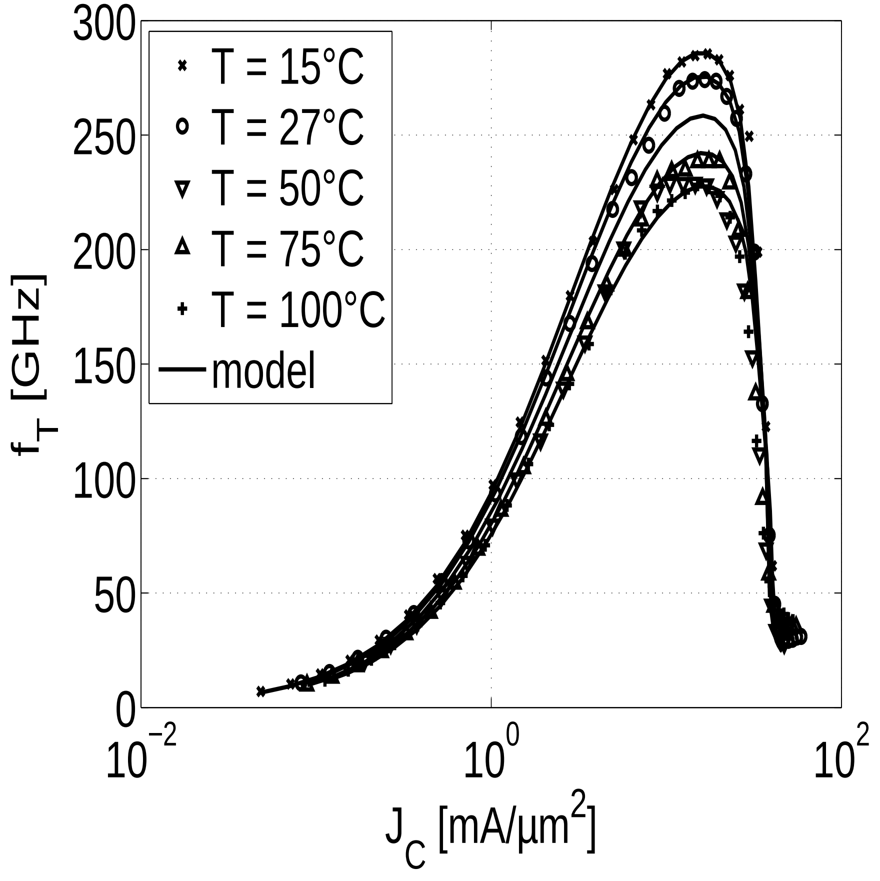
A_{E0} = 1x0.98x12.68 µm^2

=> good agreement over geometry and wide bias range

IHP 500GHz technology

Temperature dependence of forward Gummel characteristics and transit frequency

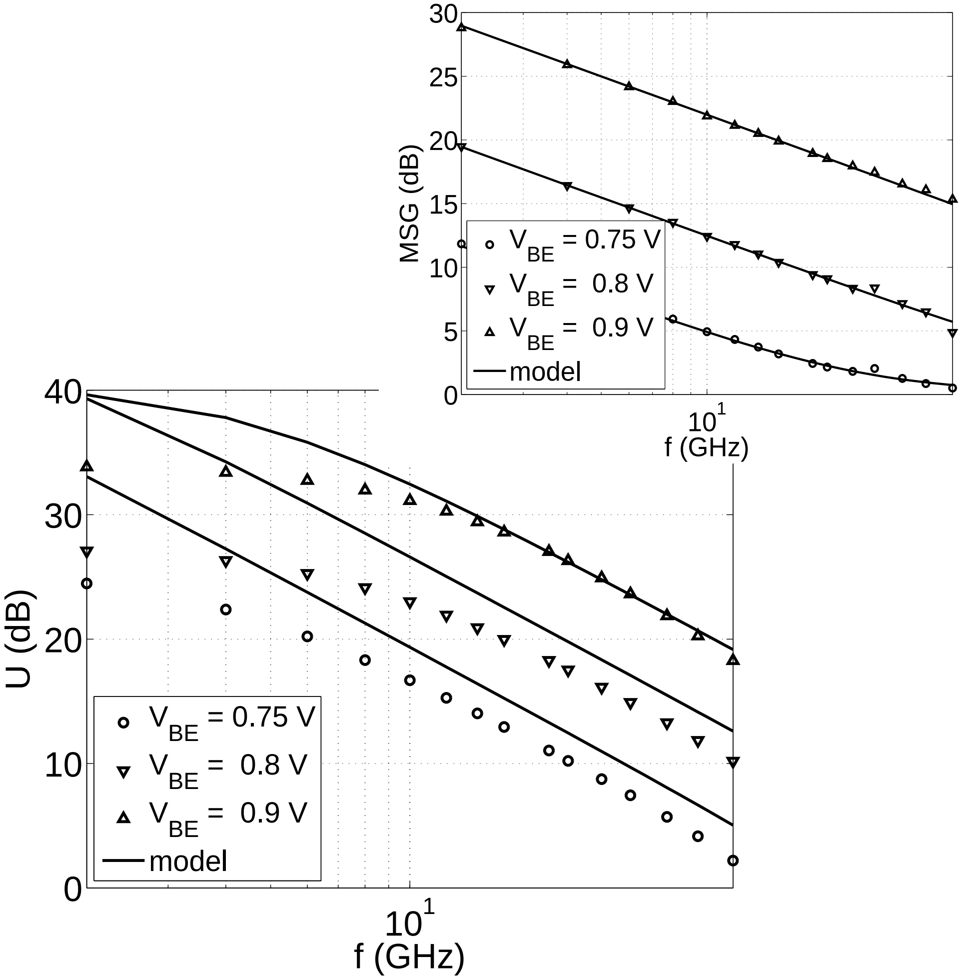




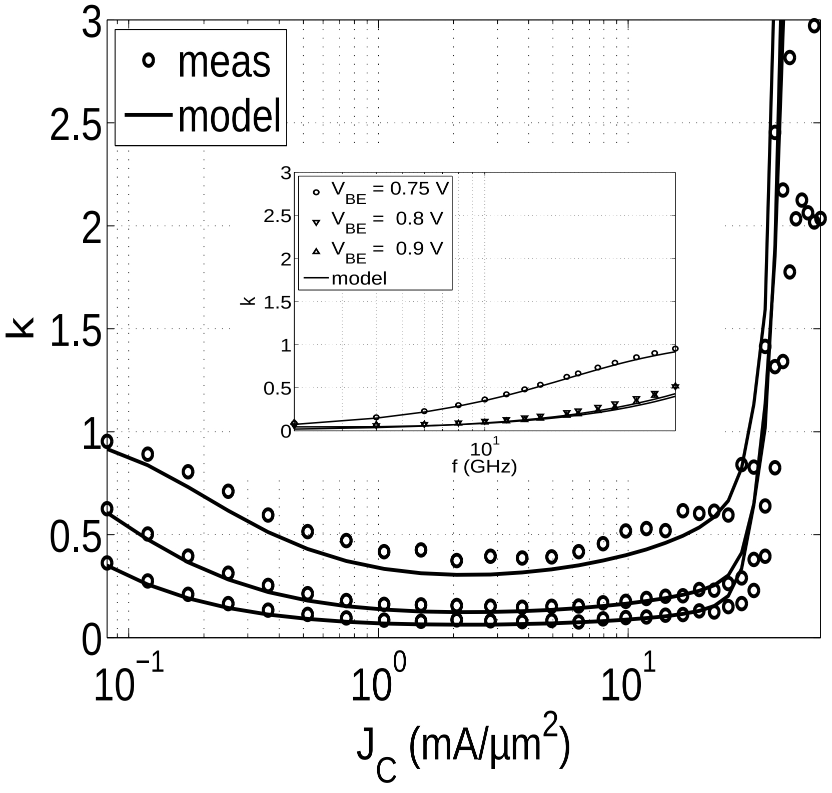
=> very good agreement over wide bias and geometry range

IHP 500GHz technology (cont'd)

power gain



stability factor



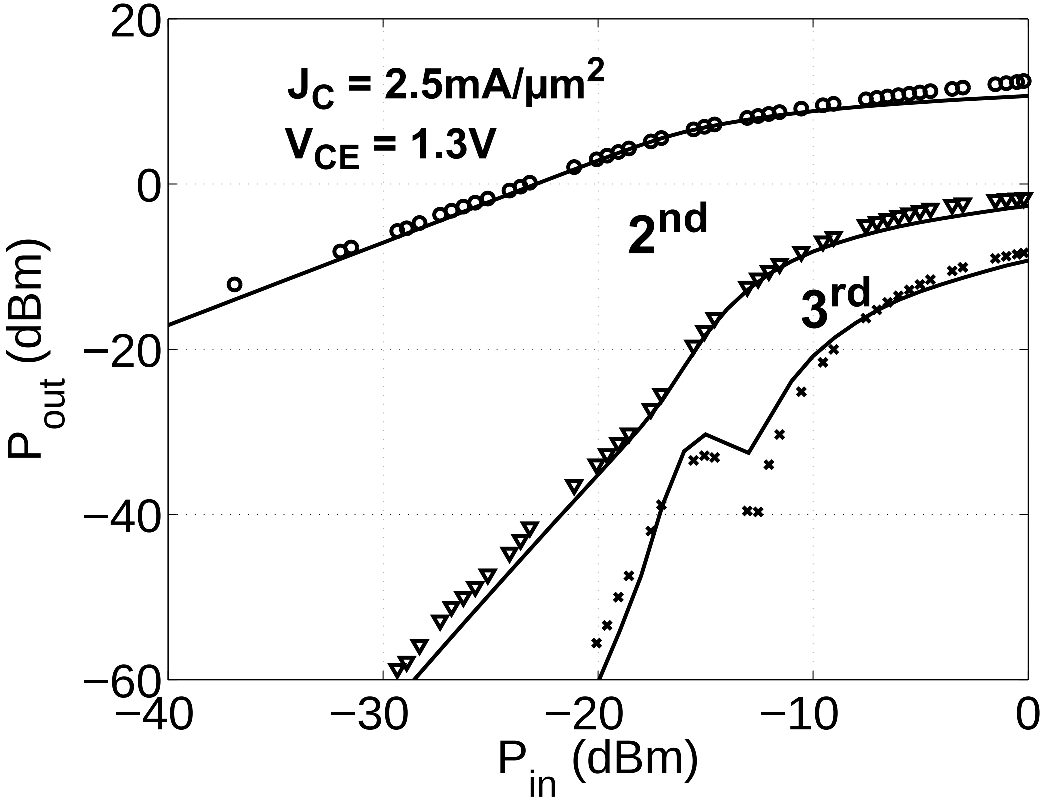
not stable below peak f_T

=> reasonable agreement over frequency and wide bias range

IHP 500GHz technology (cont'd)

Large-signal results for A_{E0} = 0.12 x 10μm^2 (4 in parallel)

harmonic distortion @ f_0 = 8GHz



=> very good agreement for dynamic characteristics

Summary and conclusions

- observation of various physical effects both in advanced technologies (during DOTFIVE project) and other technologies measured in our lab
- HICUM/L2 v2.31 extensions
  - BC barrier effect & improved description of material composition in transfer current and g_m
  - BC barrier effect in mobile charge
  - temperature dependence of new parameters and of thermal resistance
  - HF noise correlation model valid up to very high frequencies
  - miscellaneous: flicker noise addition in RE, optimized NQS effect VA implement., pnp flag
- access to variety of (production) technologies for modle verification is very important => otherwise difficult to make a model widely applicable throughout industry
- need better measurement capability for small- and large-signal model verification
- Goal for InP HBTs: extend HICUM/L2
  - add specific physical effects (as determined to be relevant)
  - enable geometry scaling => circuit optimization and statistical modeling
  - generate scalable HICUM/L0 and distributed HICUM/L4 automatically from L2

=> offer unified and flexible HBT modeling strategy

Acknowledgments

- IHP, Frakfurt/Oder, Germany
- ST Microelectronics, Grenoble, France
- EU CATRENE project RF2THzSiSoC