

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

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Outline

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

Introduction

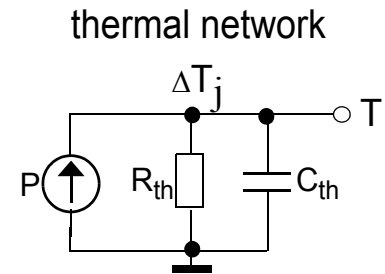
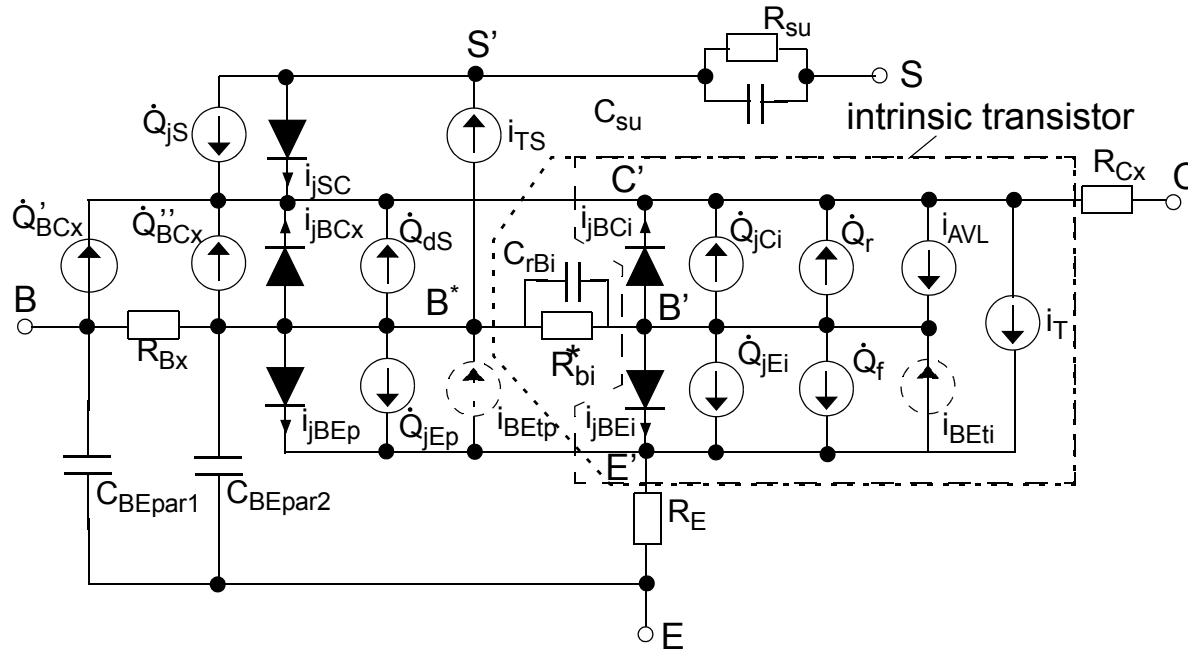
- Experimental results ...
 - from DOTFIVE project (3 different process generations of 3 different technology partners)
 - from characterizing other process types (production, high-voltage)

=> observation of a variety of physical effects
 - some effects were difficult to describe with physics-based model parameters with existing v2.24

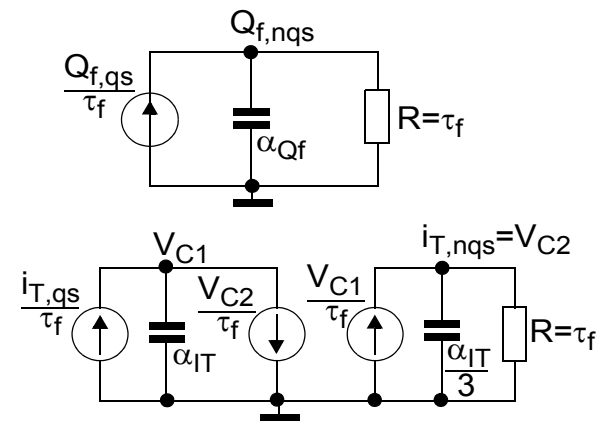
=> motivation for extension to v2.31
 - heavy use of BTE, HD, DD device simulation for model development

=> final verification always on experimental results
- => this presentation: overview and details on **v2.31** extensions

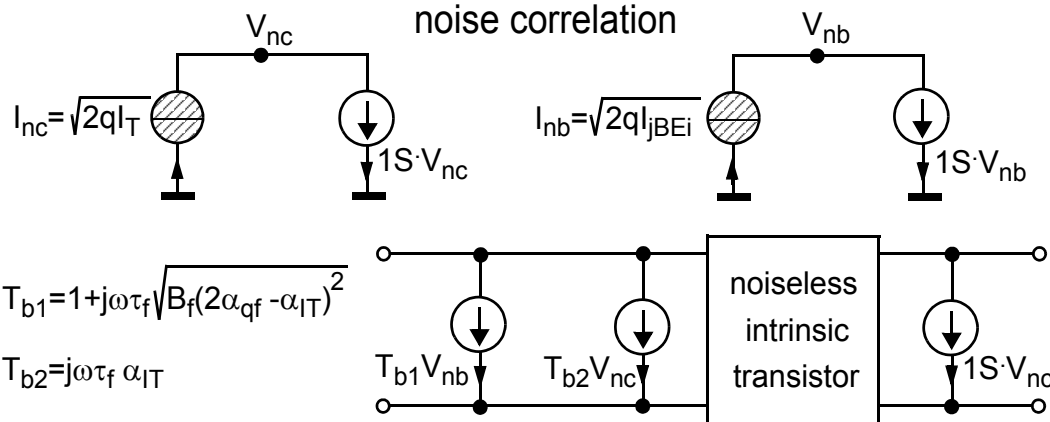
HICUM equivalent circuit



vertical NQS effects



noise correlation



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

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

Transfer current

... in HICUM is based on the GICCR

- From 1D drift-diffusion-transport equation:
$$I_T = c_0 \frac{\exp\left(\frac{V_{BEi}}{V_T}\right) - \exp\left(\frac{V_{BCi}}{V_T}\right)}{\int_0^{l_w} h_j h_v h_g p dx}$$
- 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 $h_g(x) = \frac{\overline{\mu_{nr} n_{ir}^2}}{\mu_n(x) n_i^2(x)}$, with "r" as reference region

- Reference region in HICUM is the neutral base:
$$h_k = \frac{\int_k \frac{\overline{\mu_n(x_B) n_i^2(x_B)}}{\mu_n(x) n_i^2(x)} p(x) dx}{\int_k p(x) dx}$$

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

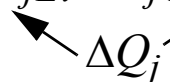
component: $Q_p = qA_E \int p(x) dx = Q_{p0} + \Delta Q_j + \Delta Q_m$

- 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

$$Q_{pT} = Q_{p0} + h_{jEi} Q_{jEi} + h_{jCi} Q_{jCi} + Q_{fT} + Q_{rT}$$



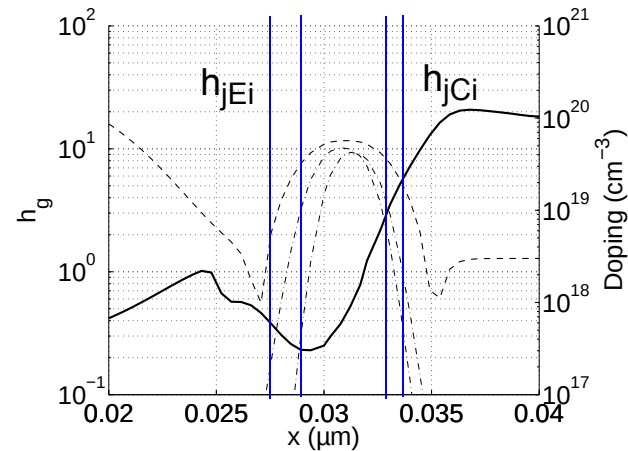
and weighted mobile charge (h_{f0} newly introduced in v2.3)

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

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

GICCR allows taking into account material composition

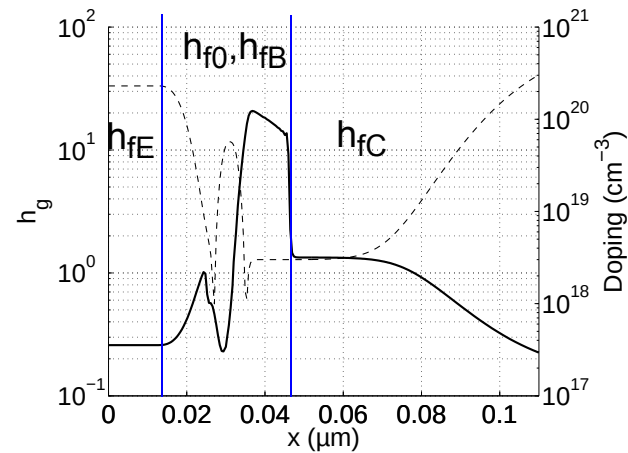
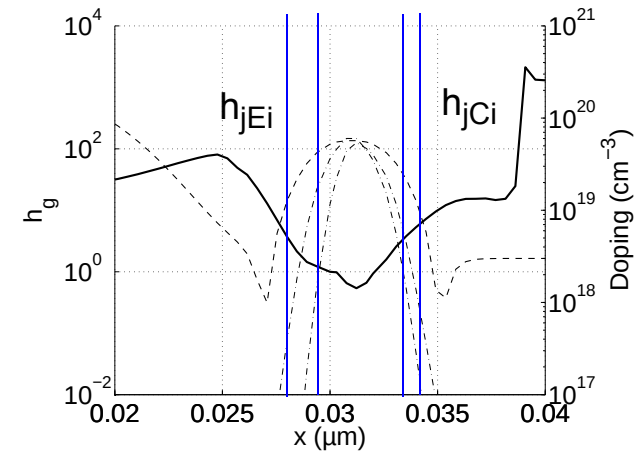
Si BJT



Low-current weight factors

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

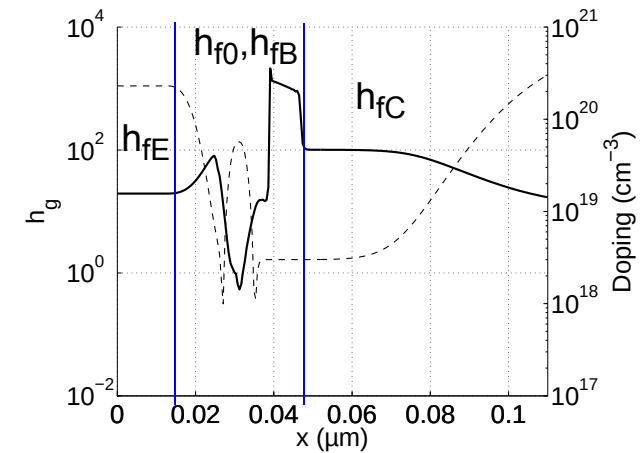
SiGe HBT



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

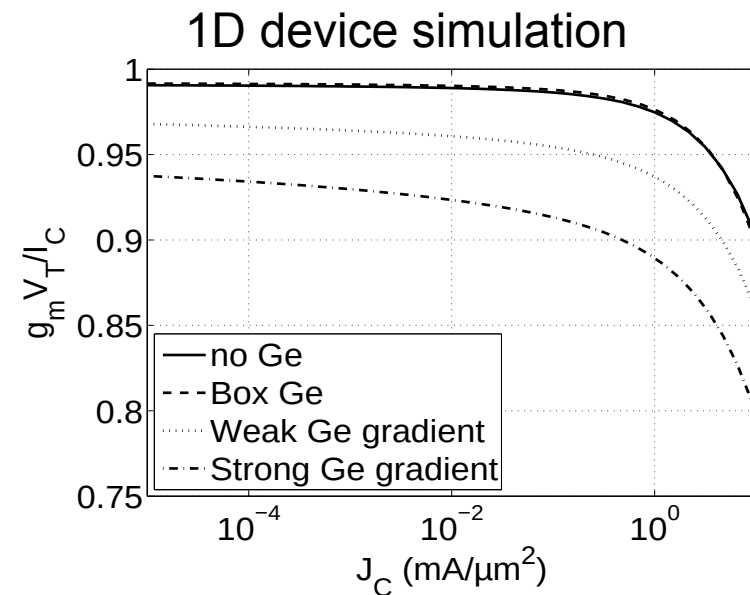
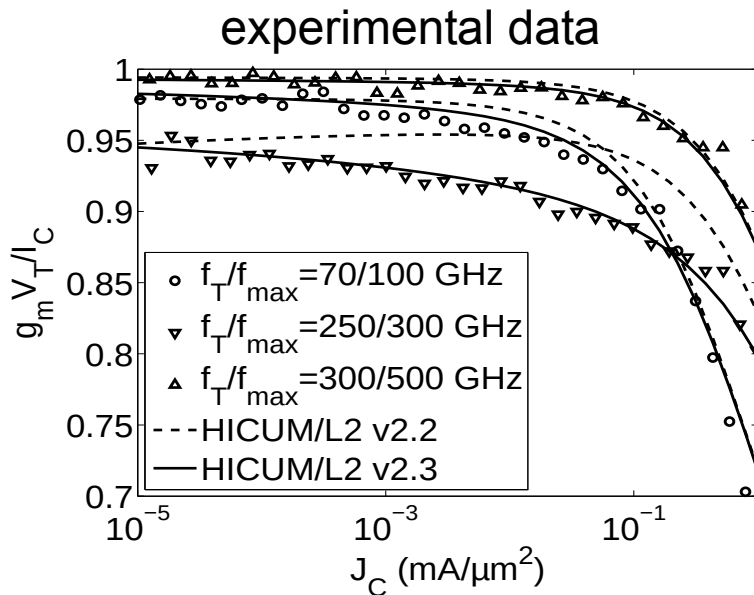
(base as reference region)



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.



- 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

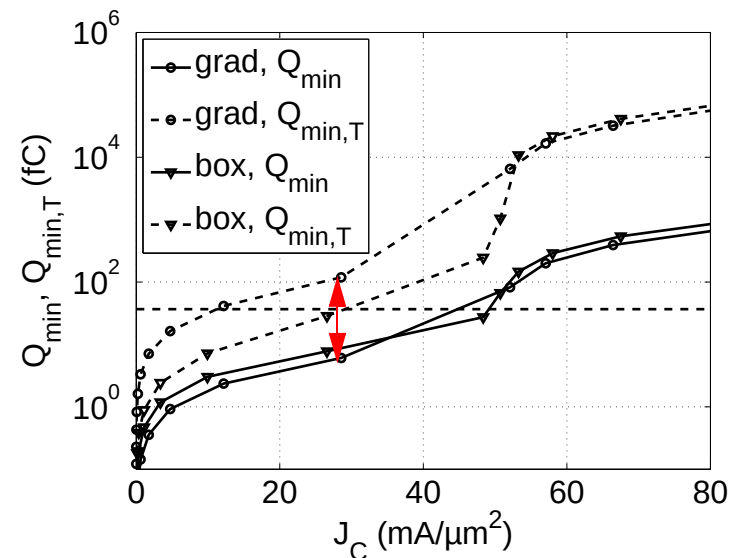
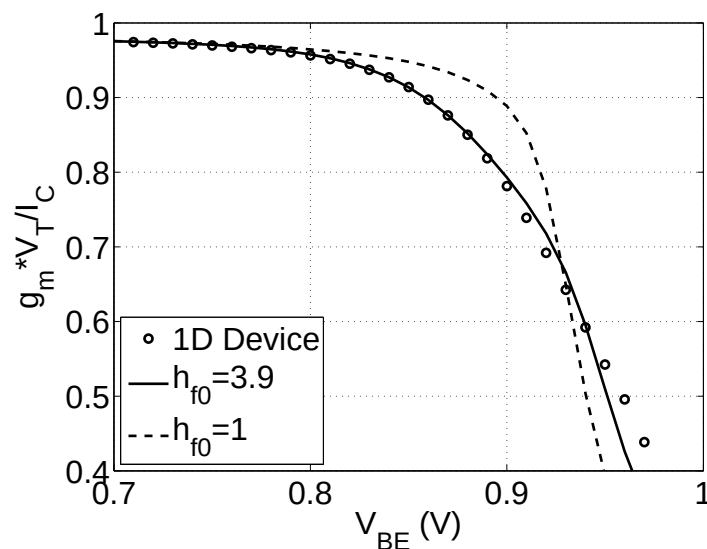
=> explicitly included in v2.30: $h_{jEi} = h_{jEi0} \frac{\exp(u) - 1}{u}$, $u = a_{hjEi} (1 - (V_{BEi}/V_{DEi})^{z_{Ei}})$

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

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

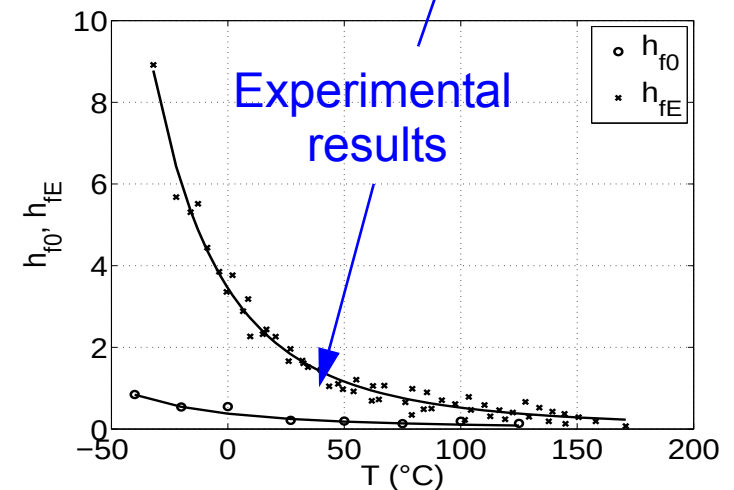
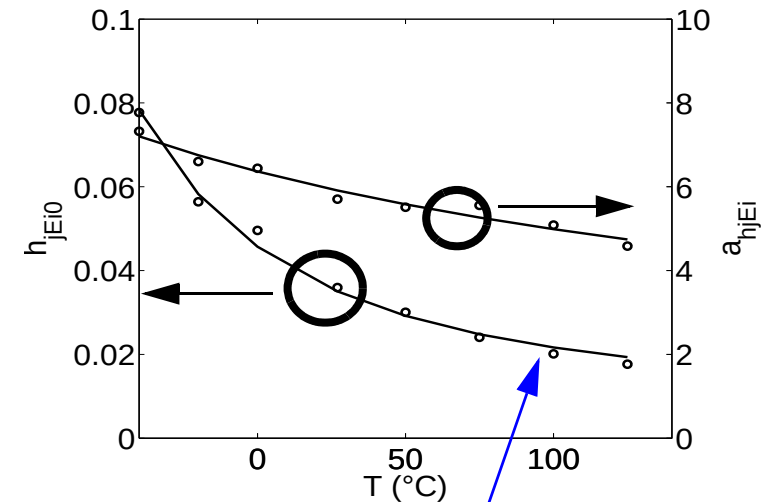
$$a_{hjEi}(T) = a_{hjEi}(T_0) \left(\frac{T}{T_0}\right)^{\zeta_{hjEi}}$$

- 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

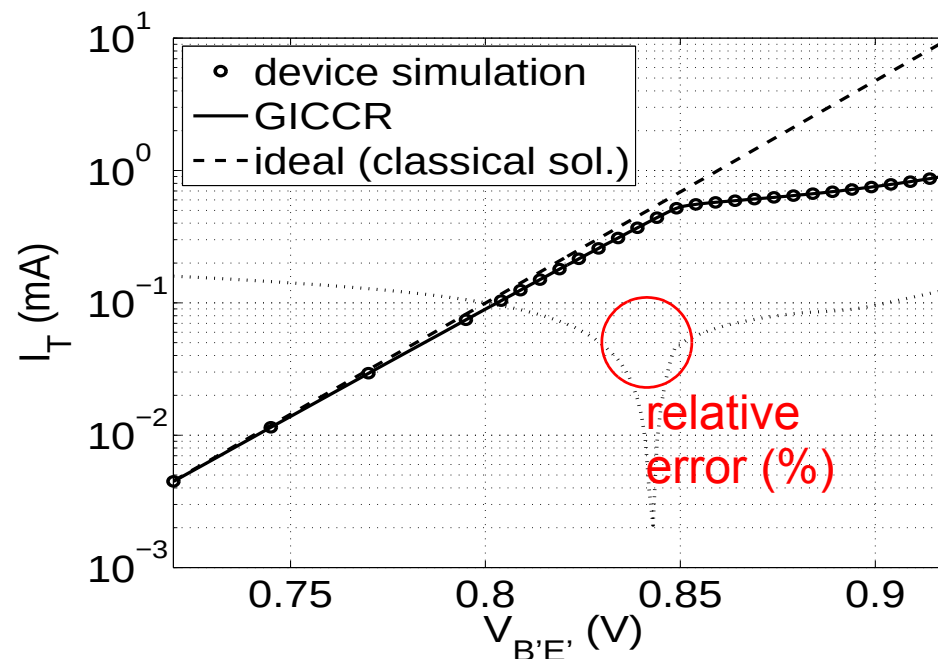
$$h_{f(E,C)}(T) = h_{f(E,C)}(T_0) \exp\left(\frac{V_{gB} - V_{g(E,C)}}{V_T} \left(\frac{T}{T_0} - 1\right)\right)$$



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

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

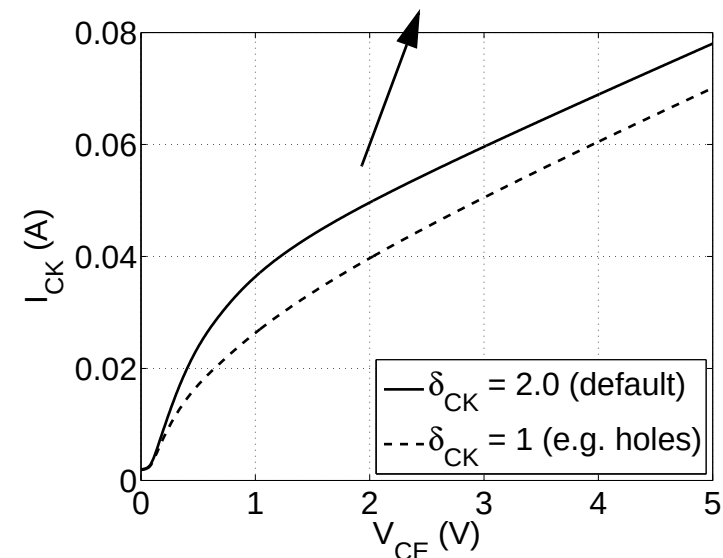
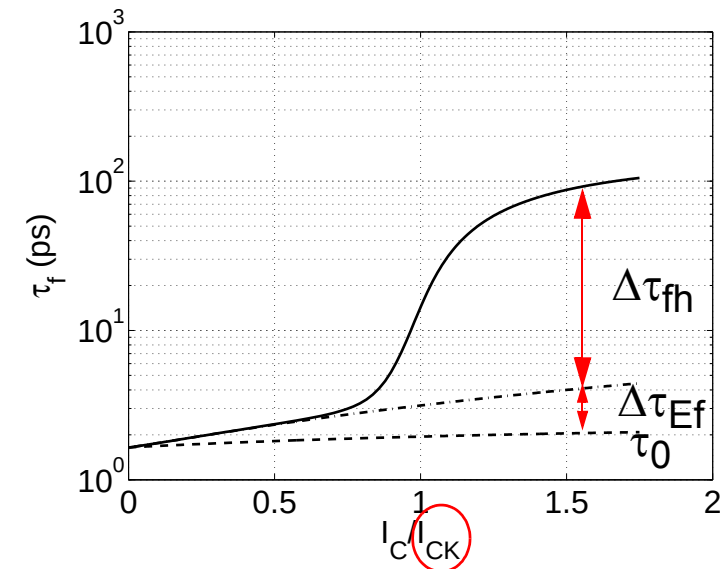
- follows: $Q_f = \int_0^{i_{Tf}} \tau_f di_T'$

- critical current I_{CK}

- added parameter for better fitting to field dependence of mobility.

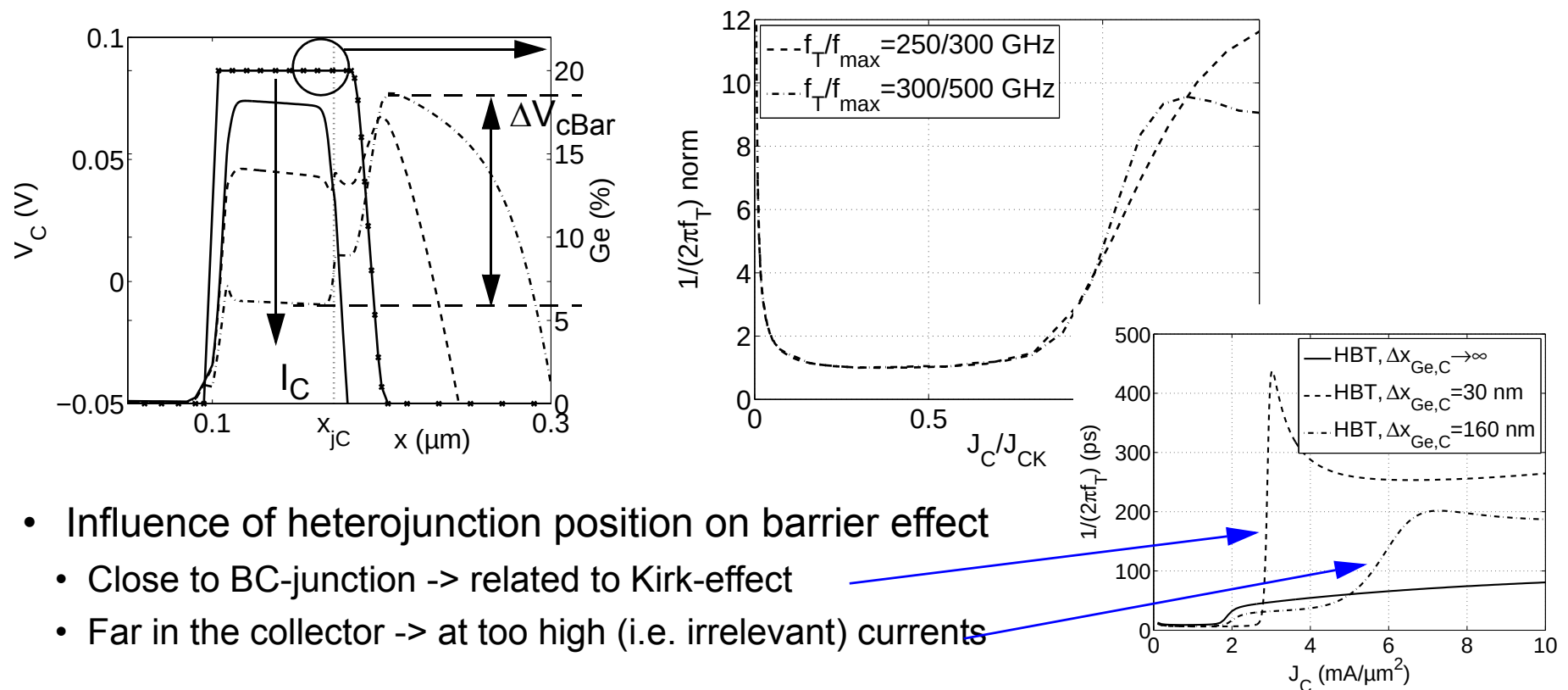
$$I_{CK} = \frac{v_{ceff}/r_{Ci0}}{\left(1 + \left(\frac{v_{ceff}}{V_{lim}}\right)^{\delta_{CK}}\right)^{1/\delta_{CK}}} \left[1 + \frac{x + \sqrt{x^2 + a_{ickpt}}}{2}\right]$$

- default $\delta_{CK}=2$
- parameter allows better fit 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}

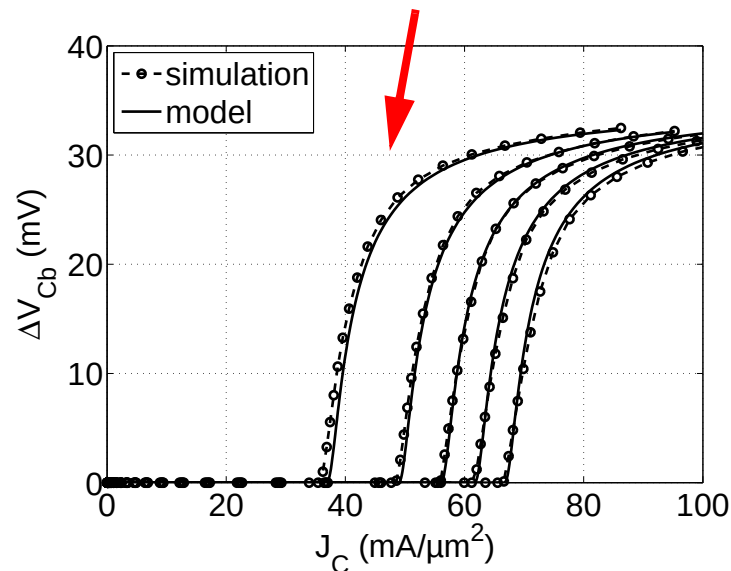


- Influence of heterojunction position on barrier effect
 - Close to BC-junction -> related to Kirk-effect
 - Far in the collector -> at too high (i.e. irrelevant) currents

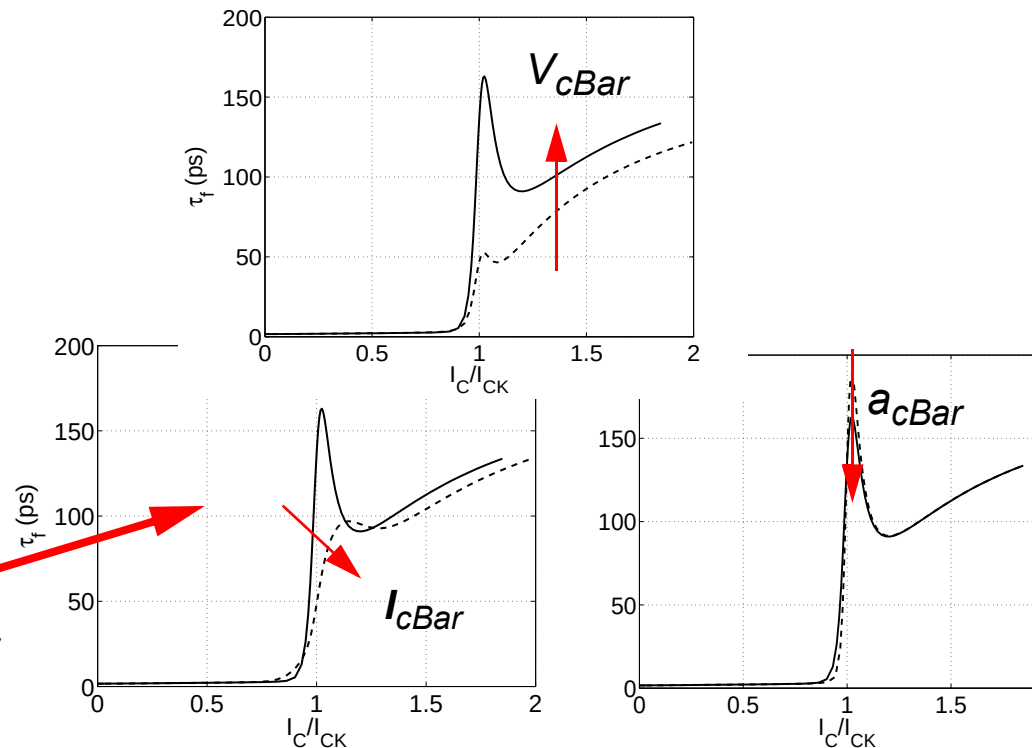
Modeling the BC barrier effect

- 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:

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

$\swarrow \quad \nearrow$
 $Q_{fh,c}$

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

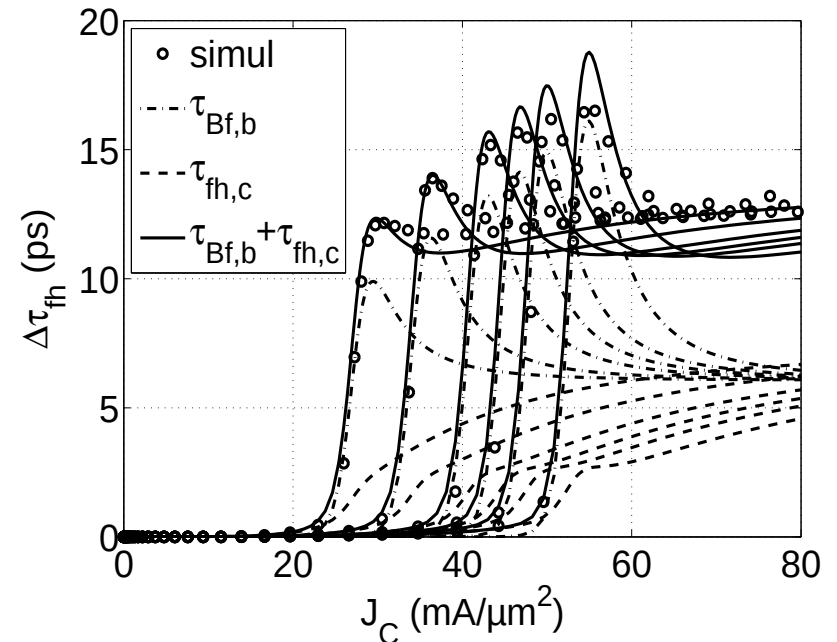
$$\Delta Q_{Bf,b} = \tau_{Bfvs} i_{Tf} \left[\exp\left(\frac{\Delta V_C}{V_T}\right) - 1 \right]$$

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



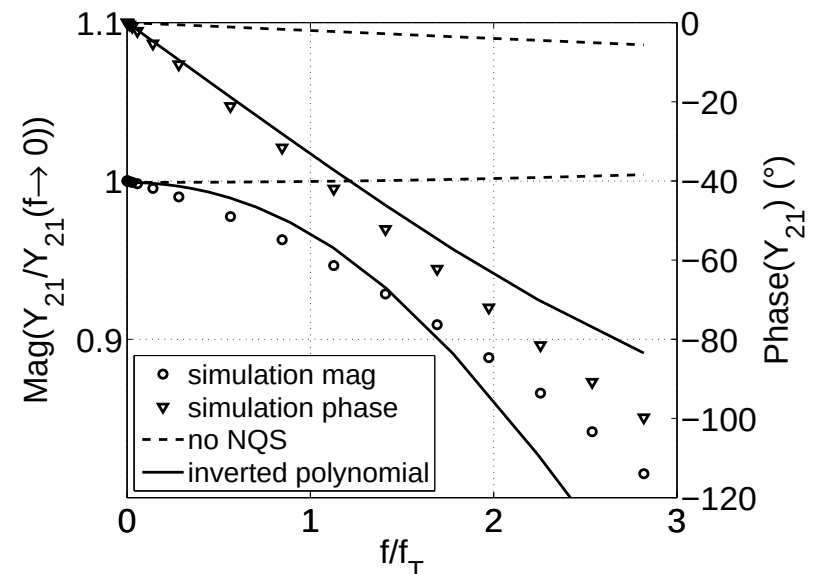
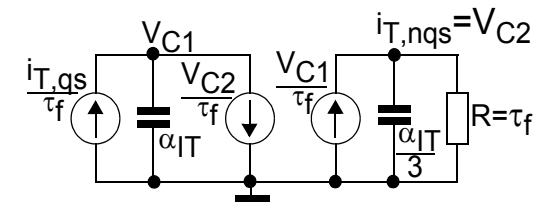
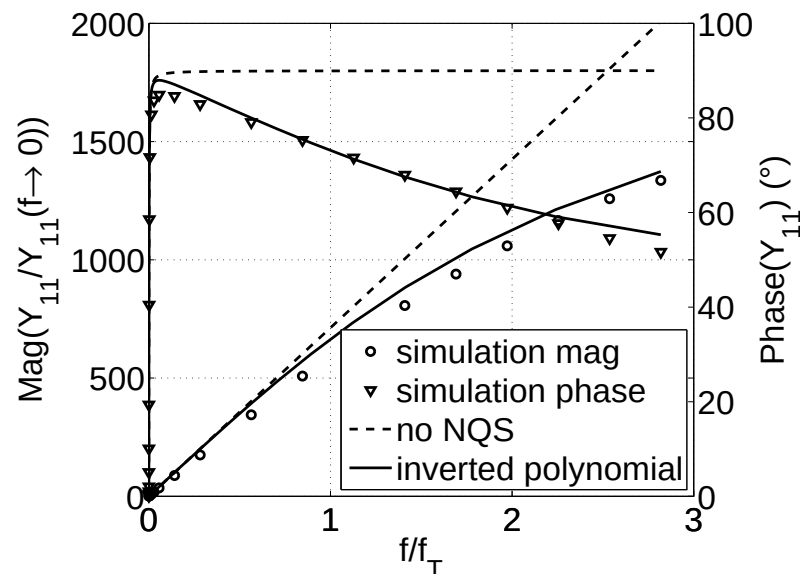
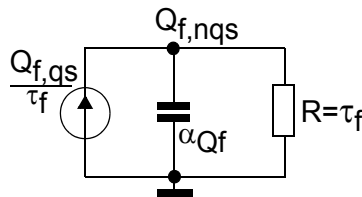
Vertical NQS-effects

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

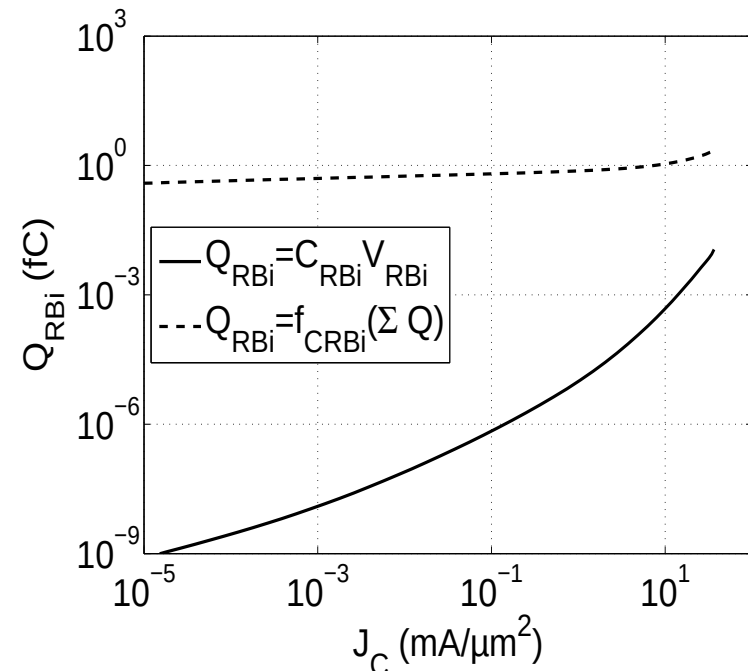
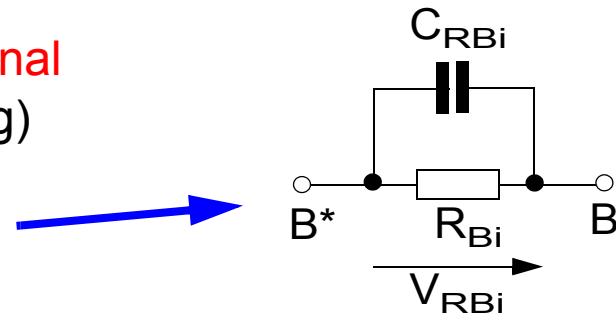
$$Q_{RBi} = f_{CRBi}(Q_{jEi} + Q_{jCi} + Q_{dEi} + Q_{dCi})?$$

- 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

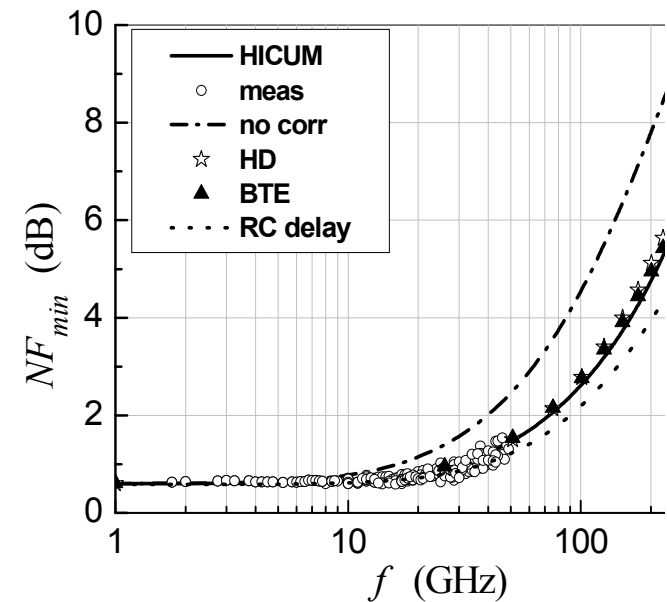
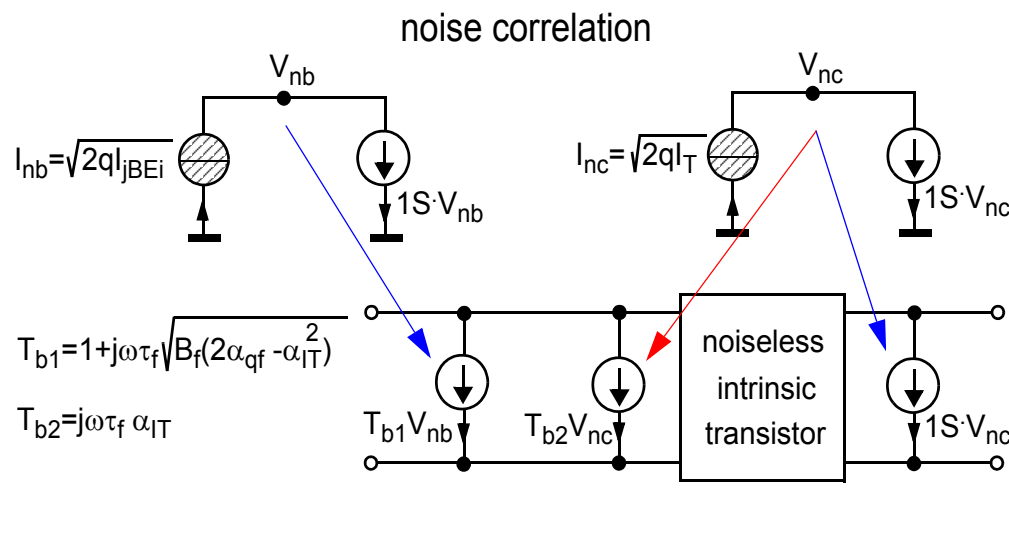
$$\frac{dQ_{RBi}}{dt} = \frac{d(C_{RBi} V_{RBi})}{dt} = \underbrace{C_{RBi} \frac{dV_{RBi}}{dt}}_{\text{theoretical solution}} + \underbrace{\frac{dC_{RBi}}{dV_{RBi}} V_{RBi} \frac{dV_{RBi}}{dt}}_{\text{not present in small-signal theory}}$$

=> undesired derivative from Verilog-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

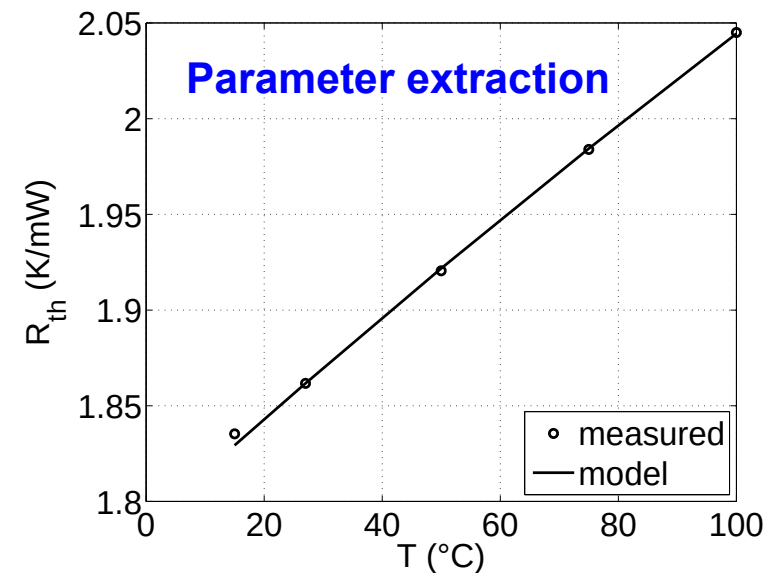
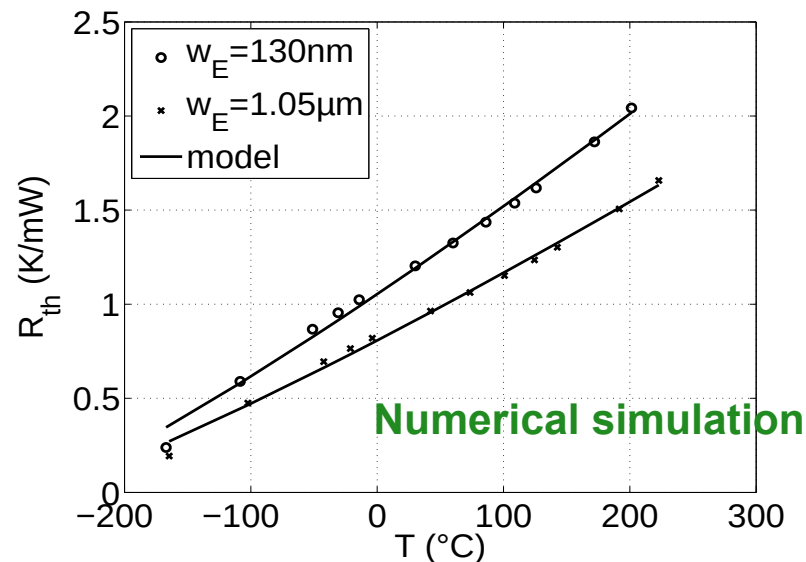
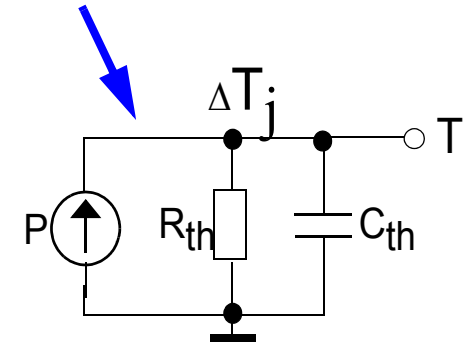
$$\overline{I_{rE}^2} = \frac{K_{fre} I_E^{A_{fre}}}{f} + \frac{4kT}{R_E}$$

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
$K_{f_{rE}}$	0	R_E flicker noise coefficient
$A_{f_{rE}}$	2	R_E flicker noise exponent factor
TYPE	1	Flag for npn (1) and pnp (-1) transistors

Experimental results

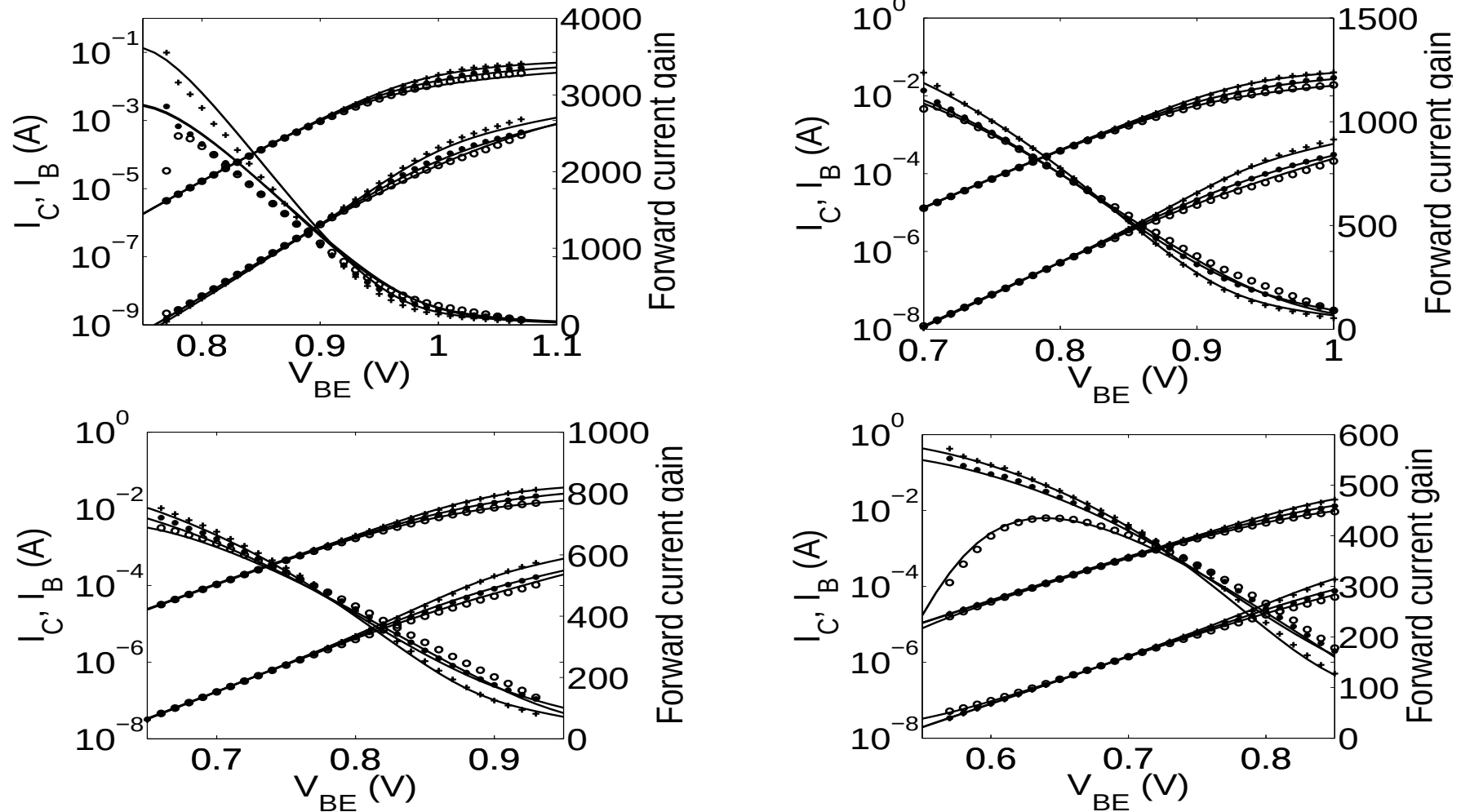
Technologies shown here

- ST B9MW with $f_T/f_{max} = 200/300$ GHz, $A_{E0} = 1 \times 0.13 \times 4.87 \mu\text{m}^2$
- IHP SGB25V with $f_T/f_{max} = 75/95$ GHz, $A_{E0} = 1 \times 0.64 \times 12.68 \mu\text{m}^2$
- IHP 500GHz with $f_T/f_{max} = 300/500$ GHz, $A_{E0} = 8 \times 0.12 \times 0.96 \mu\text{m}^2$

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

ST B9MW technology

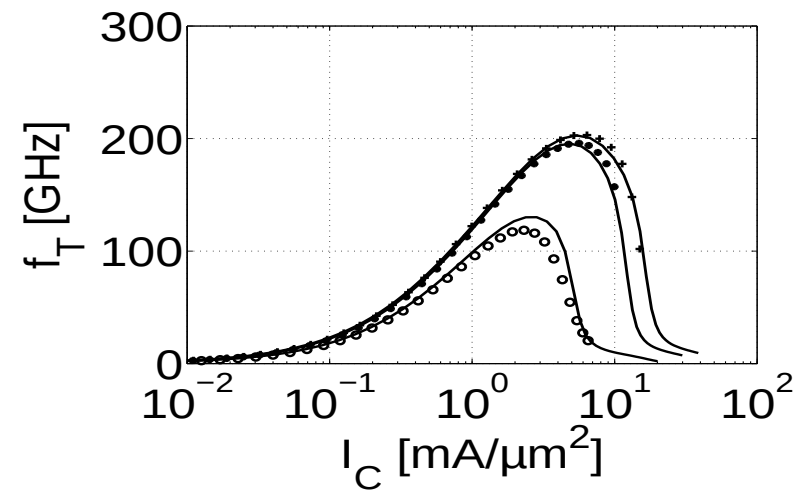
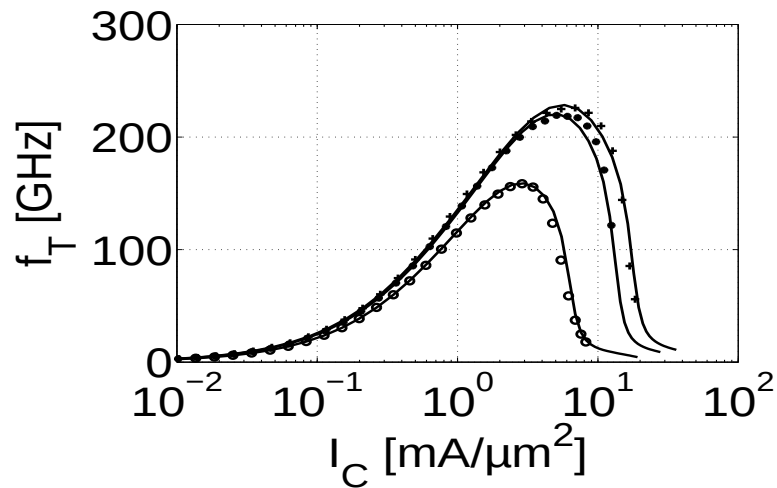
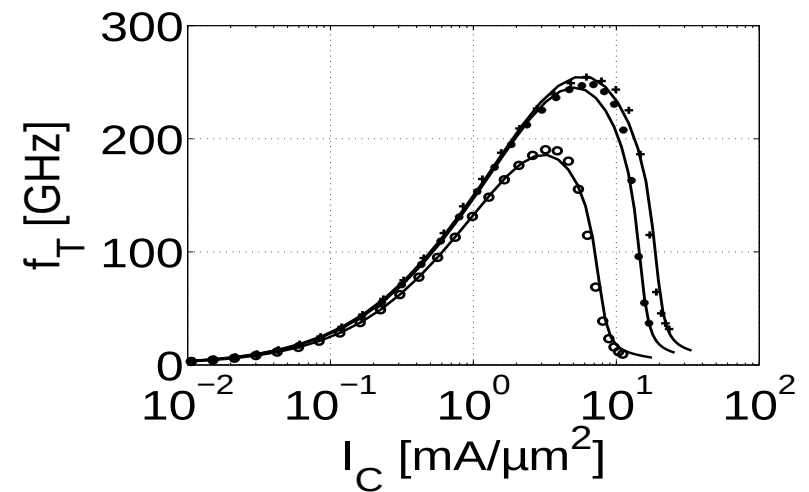
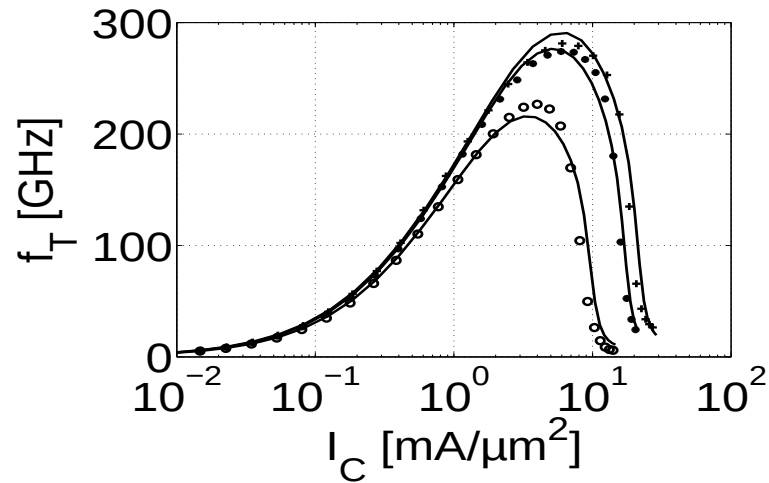
Forward gummel characteristics for $[-40, 27, 75, 125]^{\circ}\text{C}$.



=> very good agreement over wide bias and T range

ST technology (cont'd)

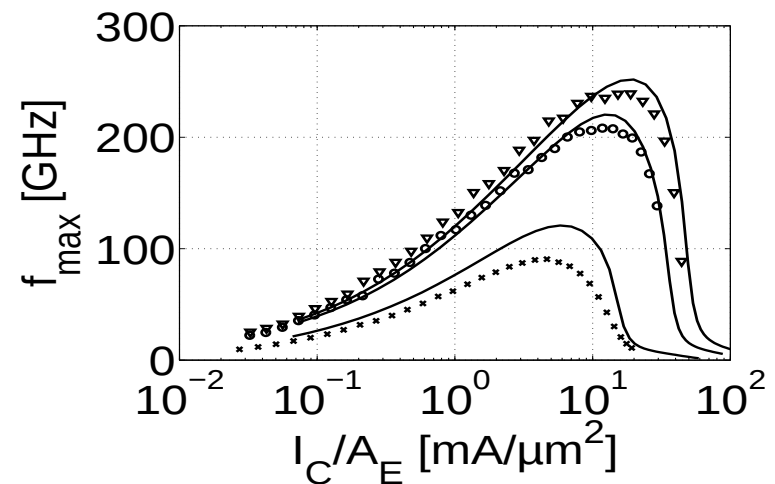
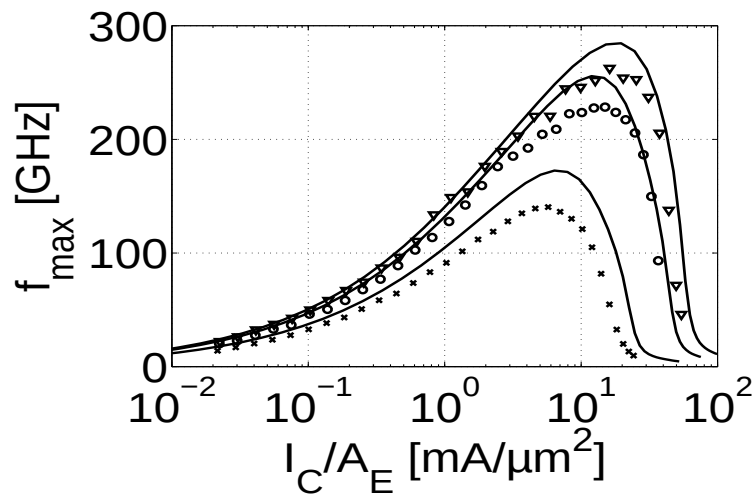
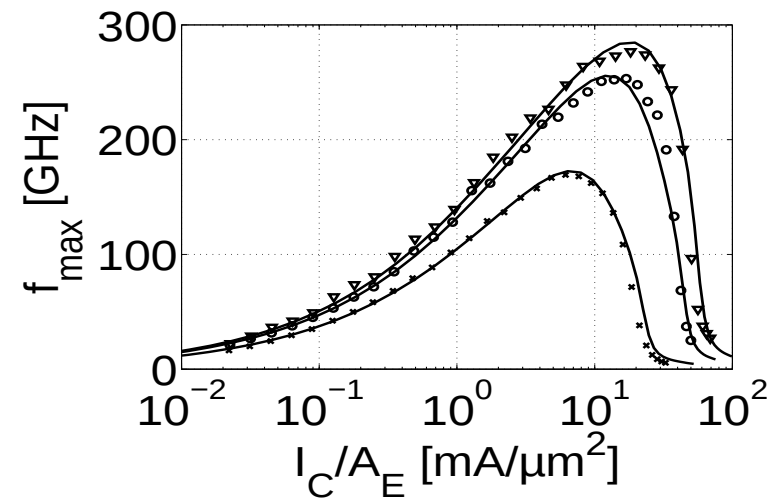
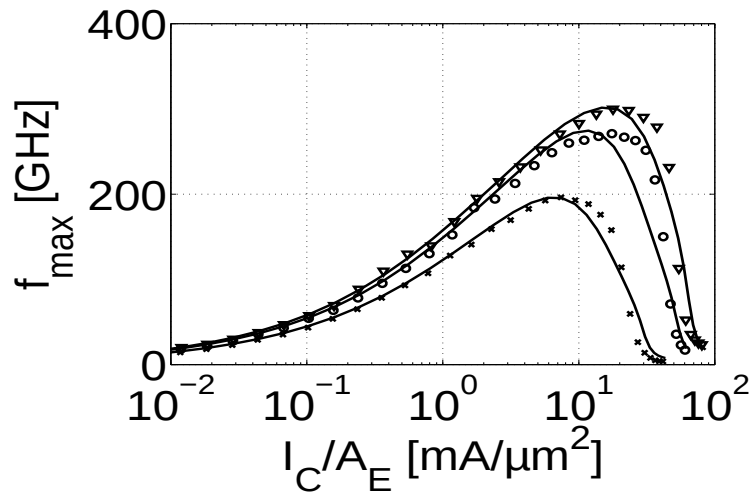
transit frequency for [-40, 27, 75, 125]°C.



=> very good agreement over wide bias and T range

ST technology (cont'd)

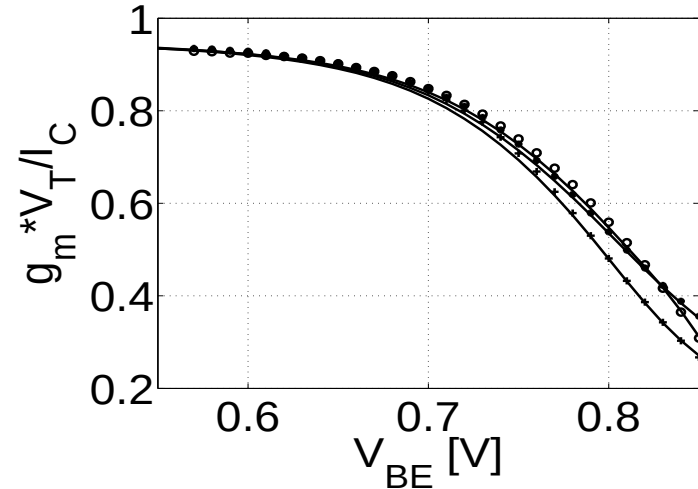
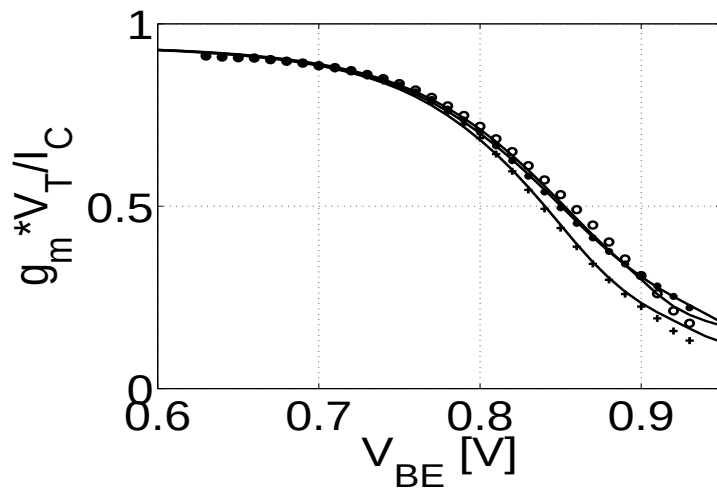
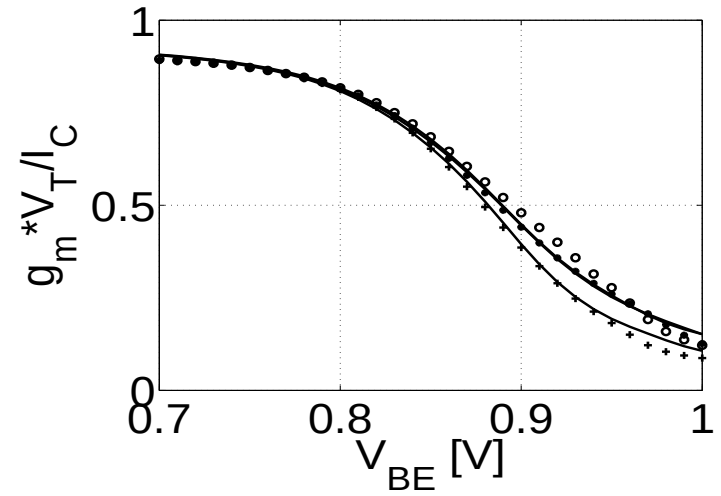
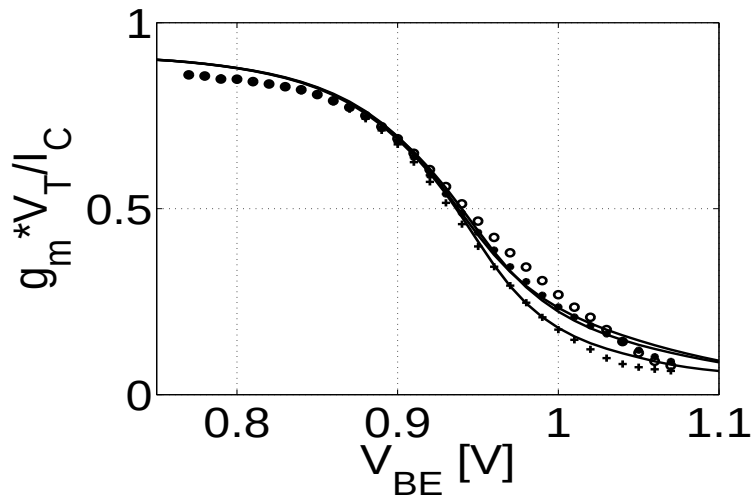
Maximum oscillation frequency for [-40, 27, 75, 125]°C.



=> good agreement over wide bias and T range

ST technology (cont'd)

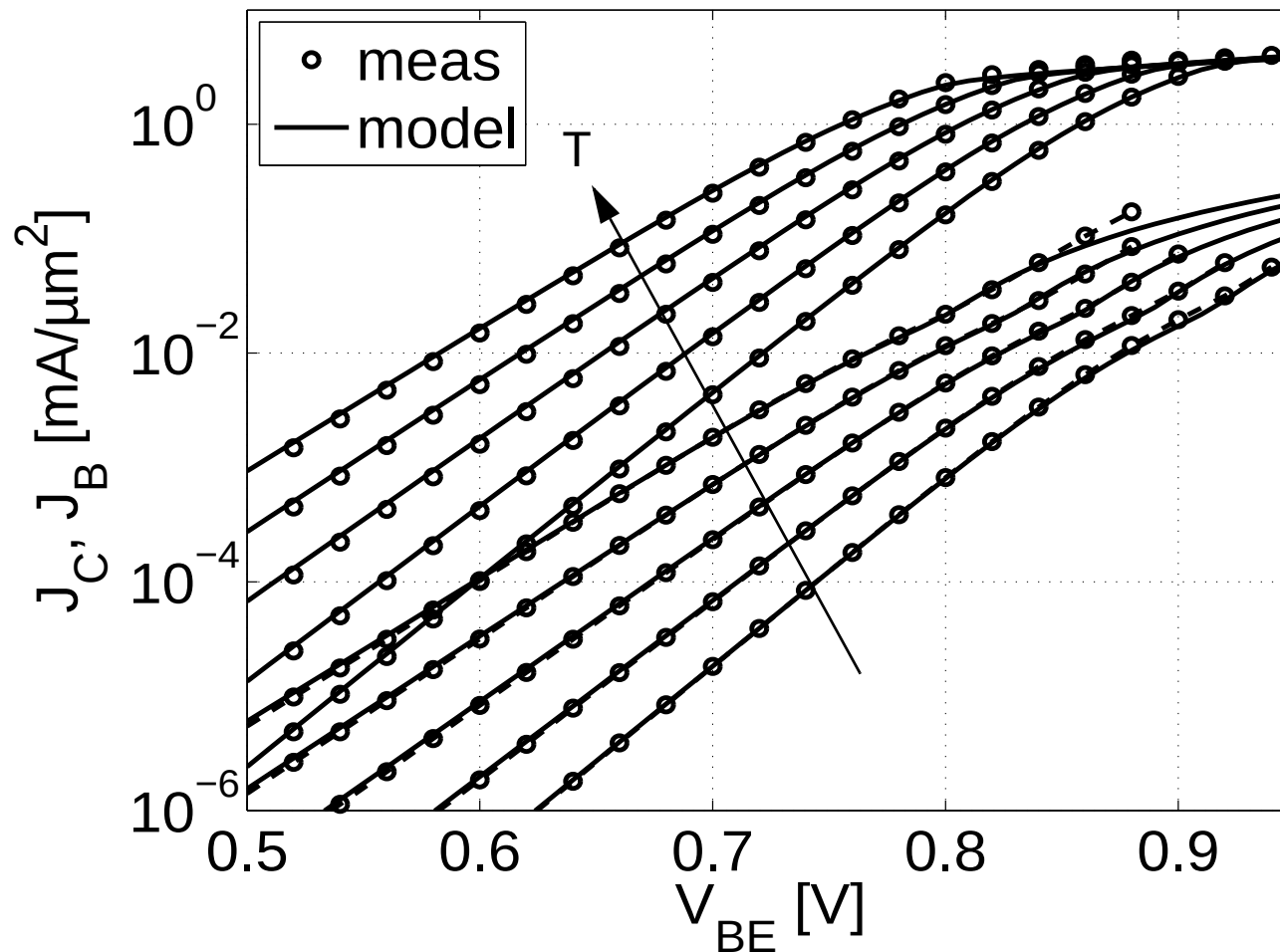
Normalized transconductance for $[-40, 27, 75, 125]^{\circ}\text{C}$.



=> very good agreement over wide bias and T range

IHP SGB25V technology

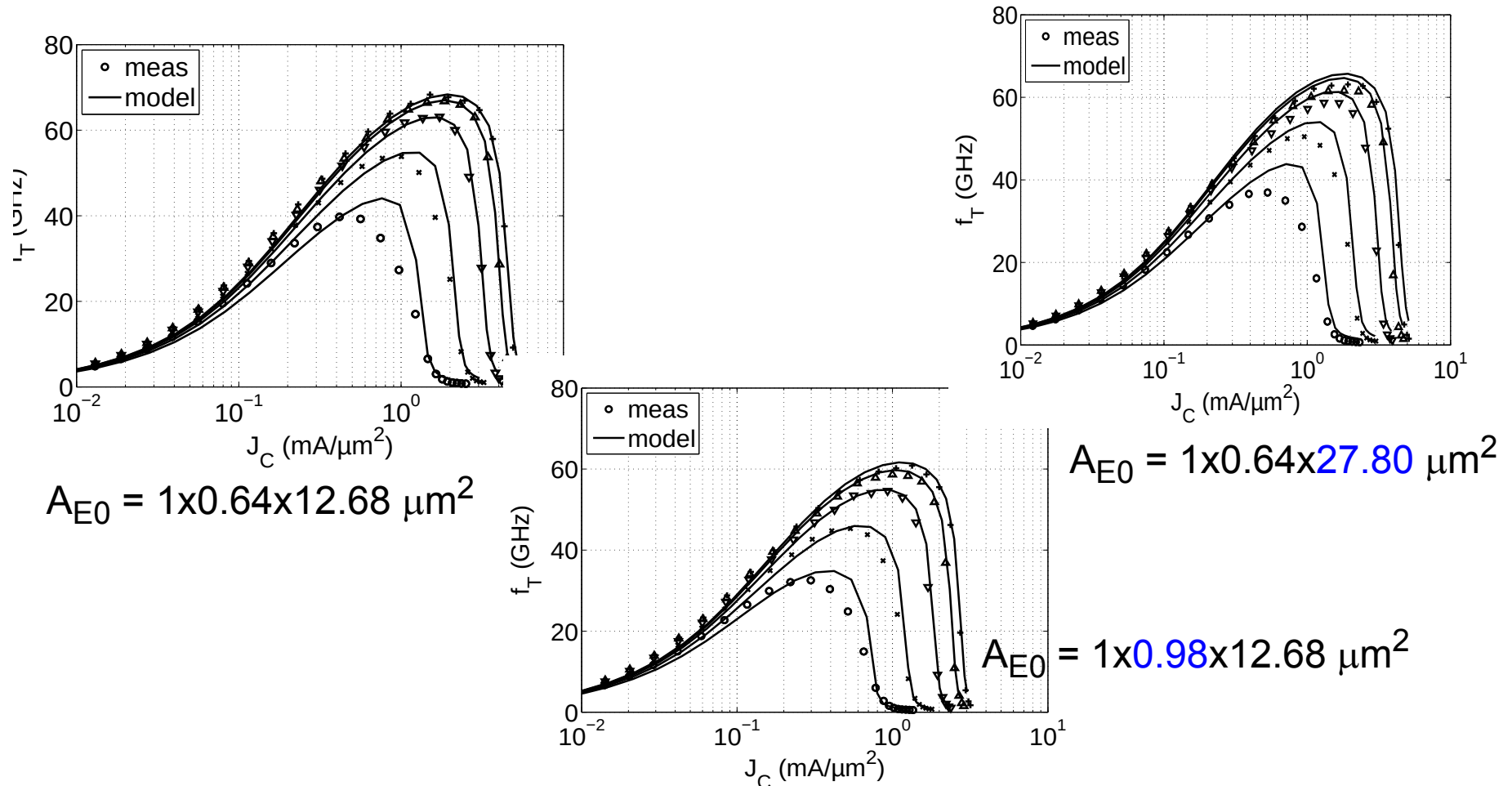
Temperature dependence of forward Gummel characteristics



=> very good agreement over wide bias and T range

IHP SGB25V technology (cont'd)

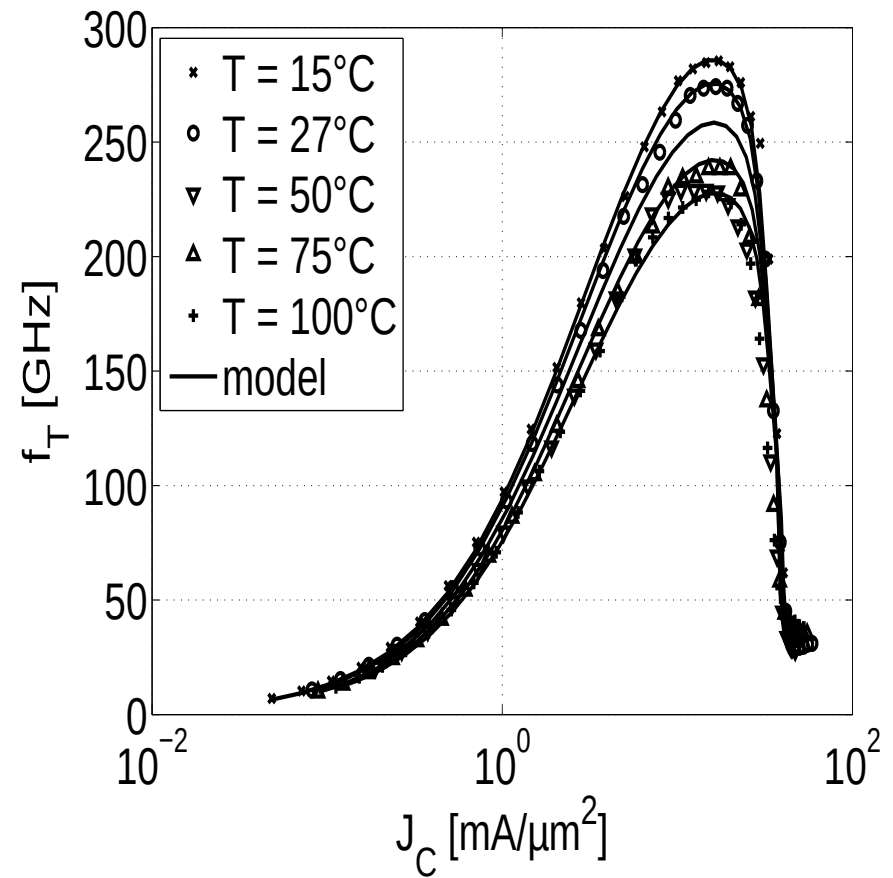
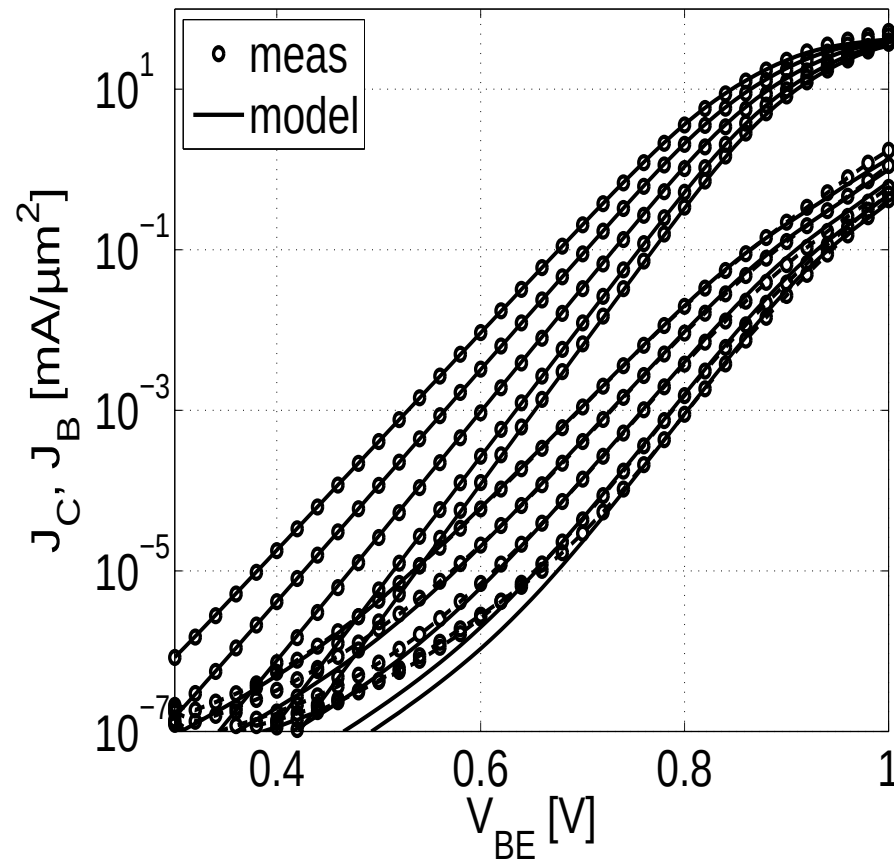
geometry scaling of transit frequency



=> good agreement over geometry and wide bias range

IHP 500GHz technology

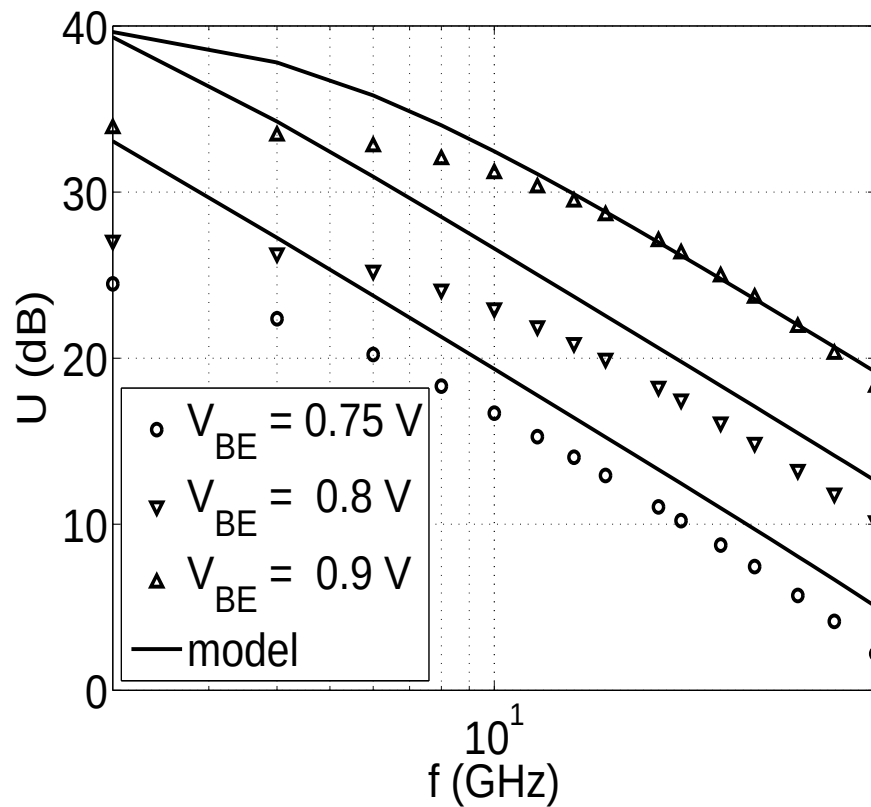
Temperature dependence of forward Gummel characteristics and transit frequency



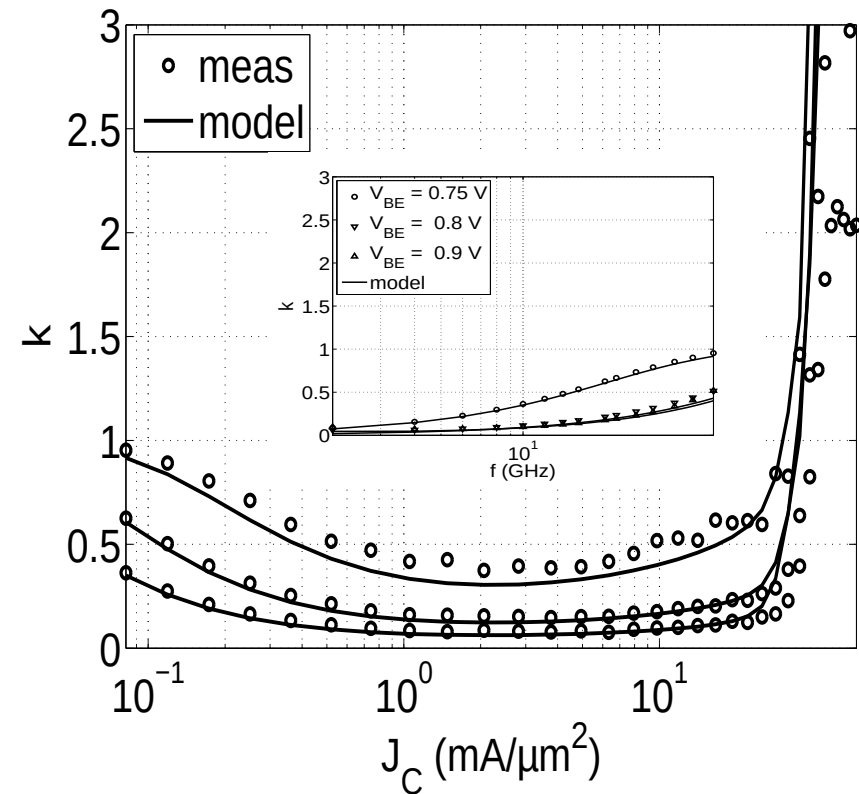
=> very good agreement over wide bias and geometry range

IHP 500GHz technology (cont'd)

power gain



stability factor



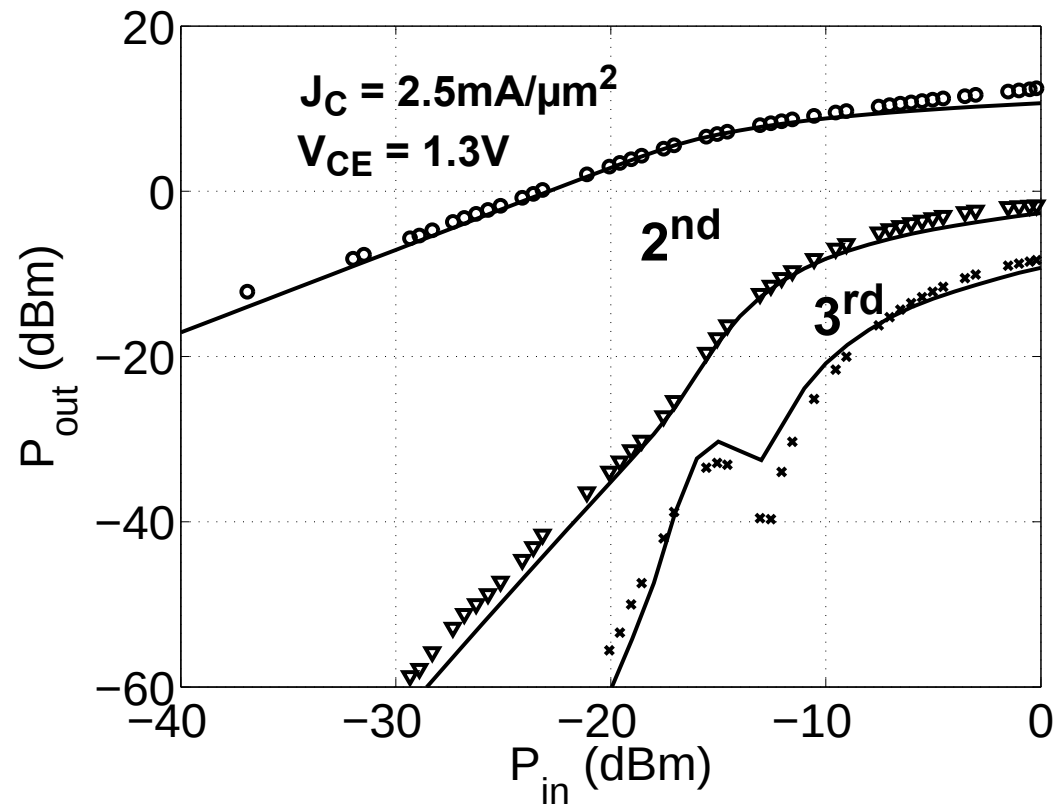
not stable below peak f_T

=> reasonable agreement over frequency and wide bias range

IHP 500GHz technology (cont'd)

Large-signal results for $A_{E0} = 0.12 \times 10 \mu\text{m}^2$ (4 in parallel)

harmonic distortion @ $f_0 = 8\text{GHz}$



=> 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 model 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

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