Extraction of Scalable HiCuM Parameters and Verifikation for Advanced SiGe HBTs

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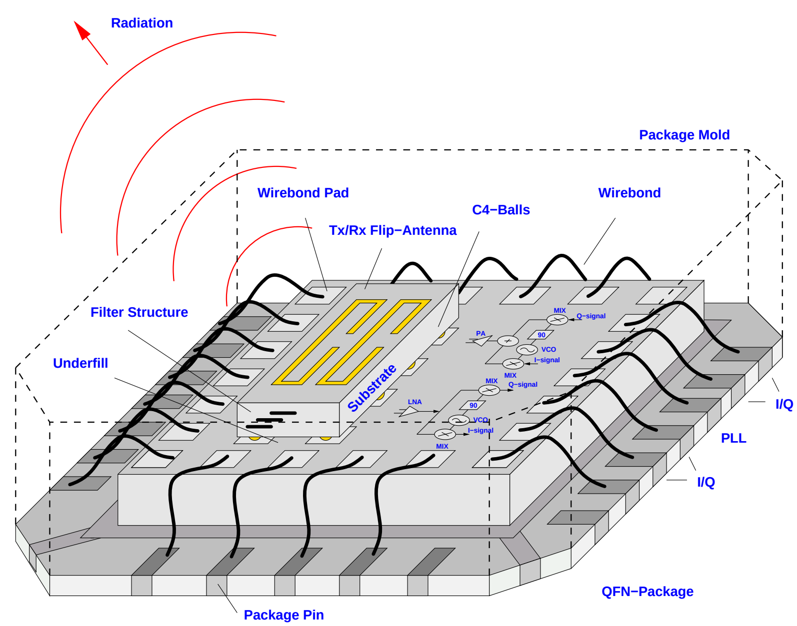
Outline

- **Motivation**
- **Modeling Methodology**
- **Parameter Extraction Procedure**
- **Results**
  - DC
  - Small Signal
  - High-Frequency Noise
  - Distortion
- **Summary**

200 GHz SiGe HBT Technology: Applications in the W-band

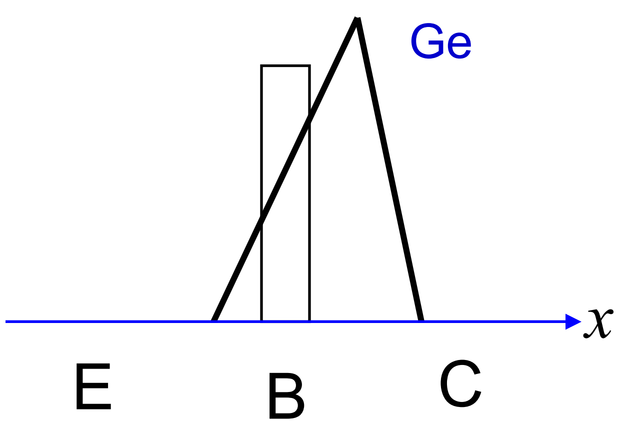
- 60 GHz ISM band
  - Wireless PAN
    - Large Available Bandwidth (57-64 GHz)
    - Potential for high data rates: 200Mb/s to > 1Gb/s
  - Point to Point links
- 77 GHz Automotive Radar Sensors

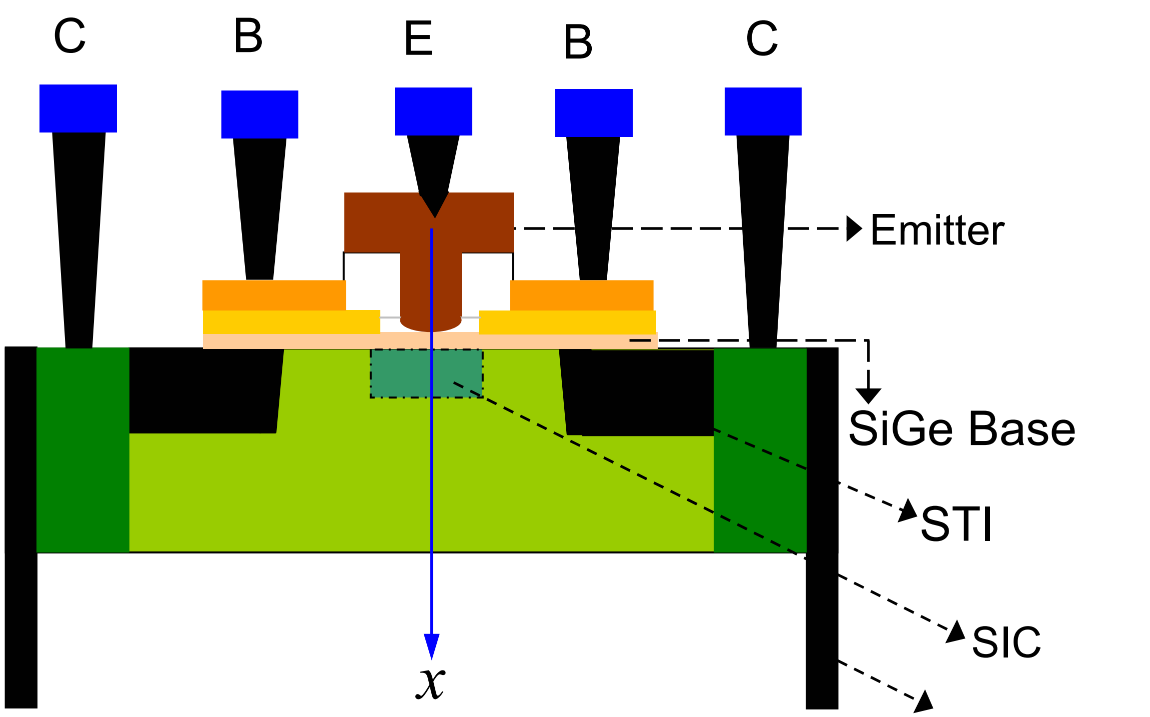
IBM's Vision for a Fully Integrated Packaged Low-cost SiGe MMW Transceiver



Structure of an Advanced SiGe HBT

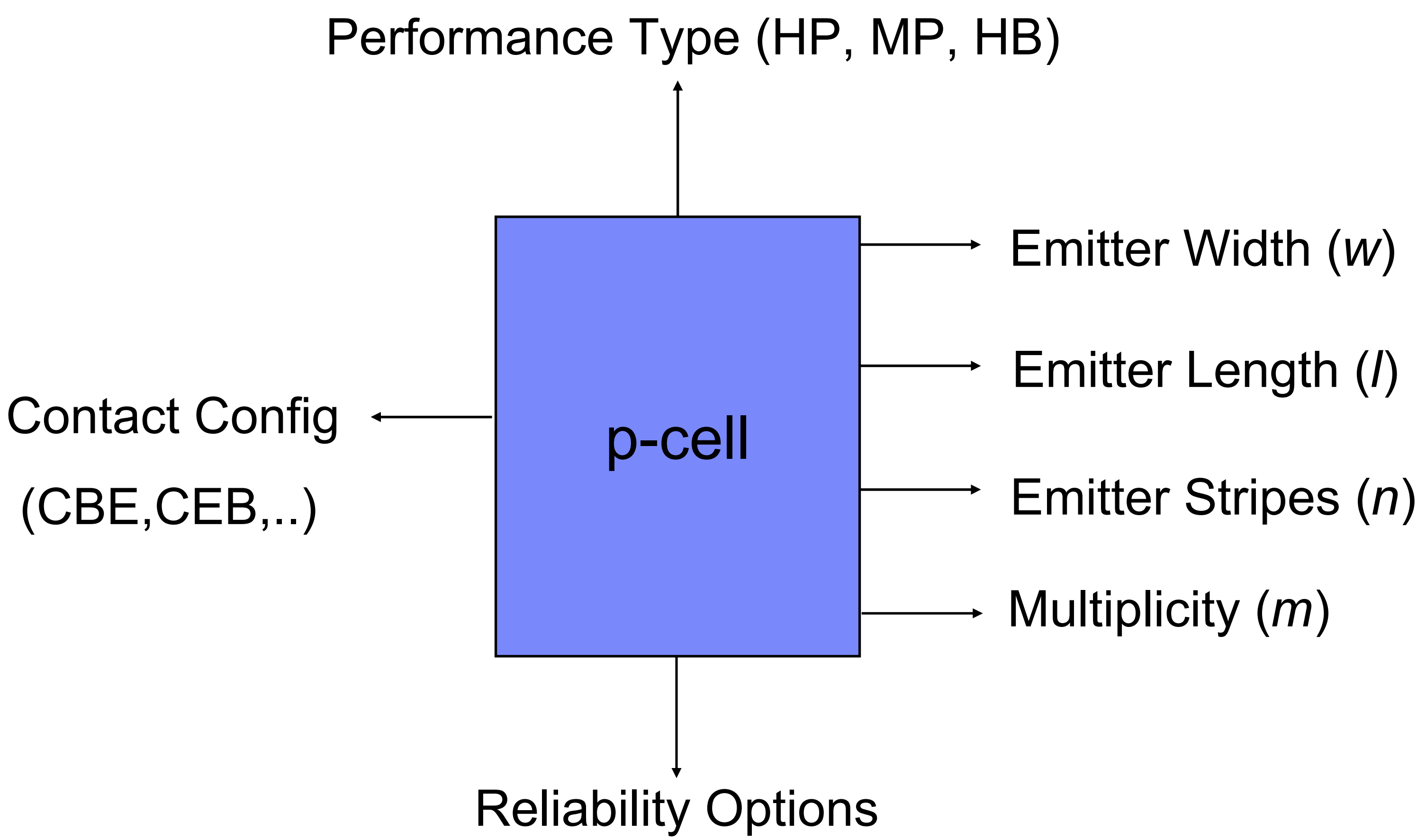
- Ge ramp and base thickness help in Speed
- SIC tailoring for Breakdown



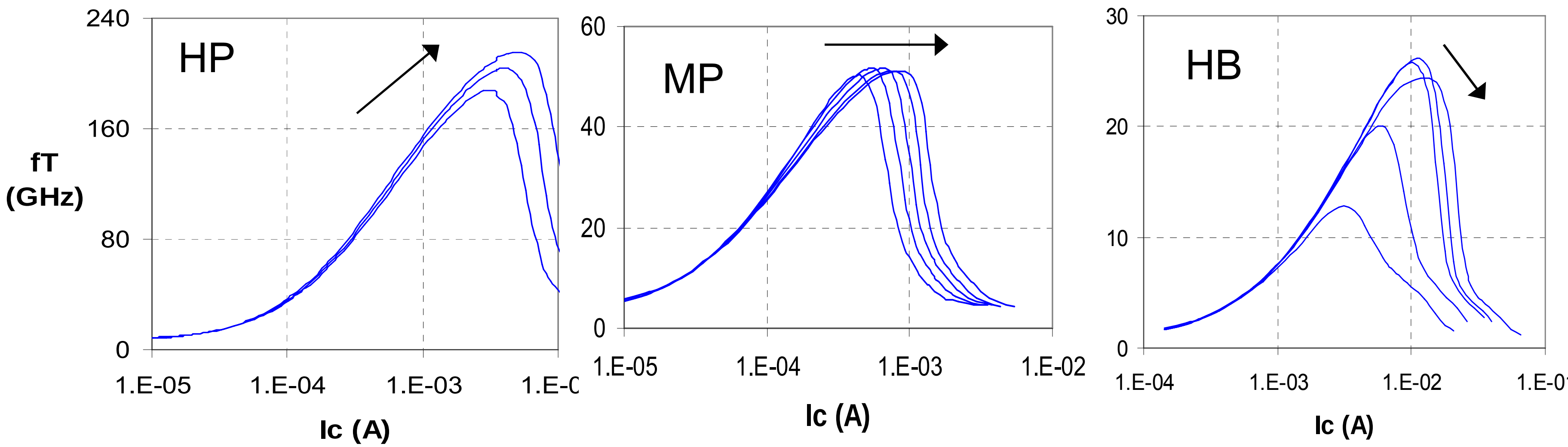


J.S.Rieh, Proc. of IEEE

Expected Scope of Model Scalability

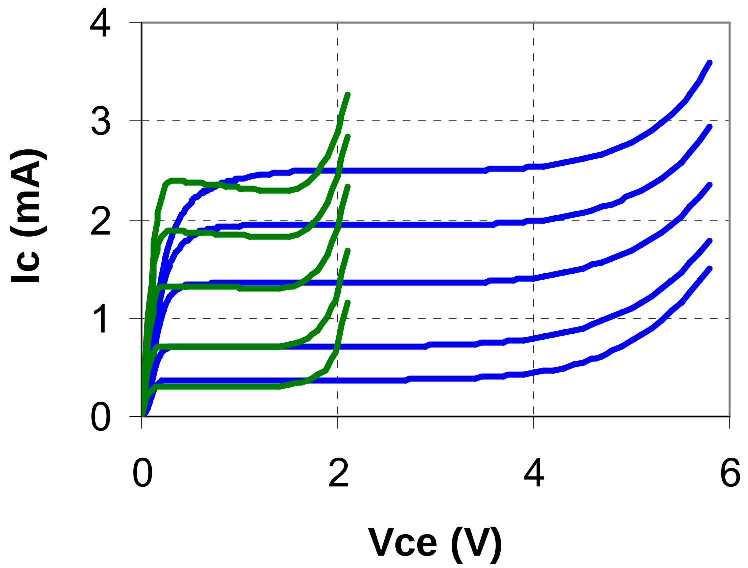


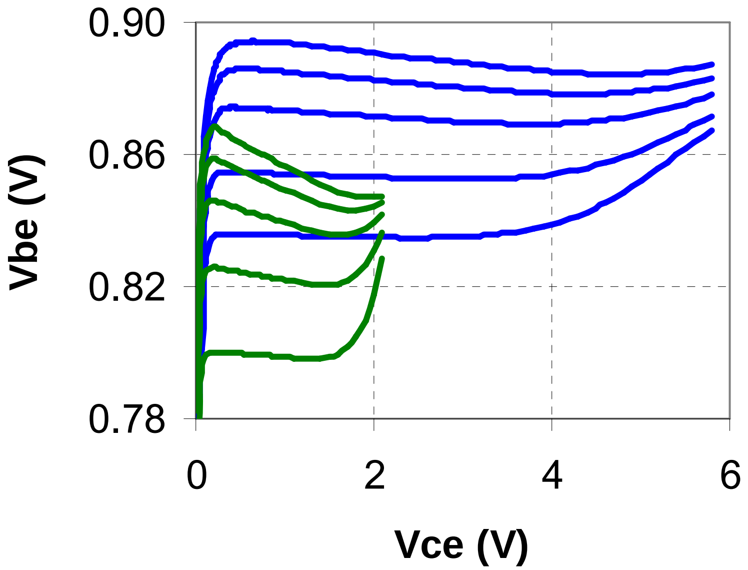
Variation of f_T - Ic with Vcb



- Depending on the collector profile, fT may increase or decrease with Vcb
- Difficult to model this effect by Spice Gummel- Poon

Avalanche and Self-heating Regimes





- The BVCEO spans a wide range in a given technology
- The effect of self-heating becomes severe in advanced HBTs
- Quasi-saturation modeling critical for applications using HB devices (eg. PAs)

HICUM (High-Current Model) Parameters for Extraction

	# of parameters
Terminal Resistances	4
Capacitances (BE, BC, CS C-V)	23
Saturation Currents	22
(Fwd and Inverse, Ideal and non-ideal)	
Low current transit time	3
High current transit time	10
Self-heating	2
Avalanche	2
Substrate Transistor/Substrate Network	7
Noise and NQS	5
Temperature coefficients	14

Methodology

Test Structures:	Transistors of various geometries
	Specialized Test Structures
Measurements:	DC, S-parameters (110GHz)
Model:	Hicum 2.1
Parameter Extraction:	Matlab
Simulations:	Spectre (Cadence)

- Scaling Equations are implemented in Spectre language in the model file

Junction Capacitance Extraction Flow

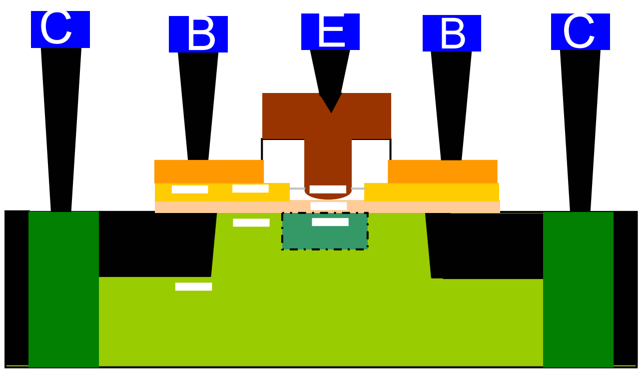
Cold-S: (i) Vbe=0, vary Vcb (ii) Vcb=0, vary Vbe

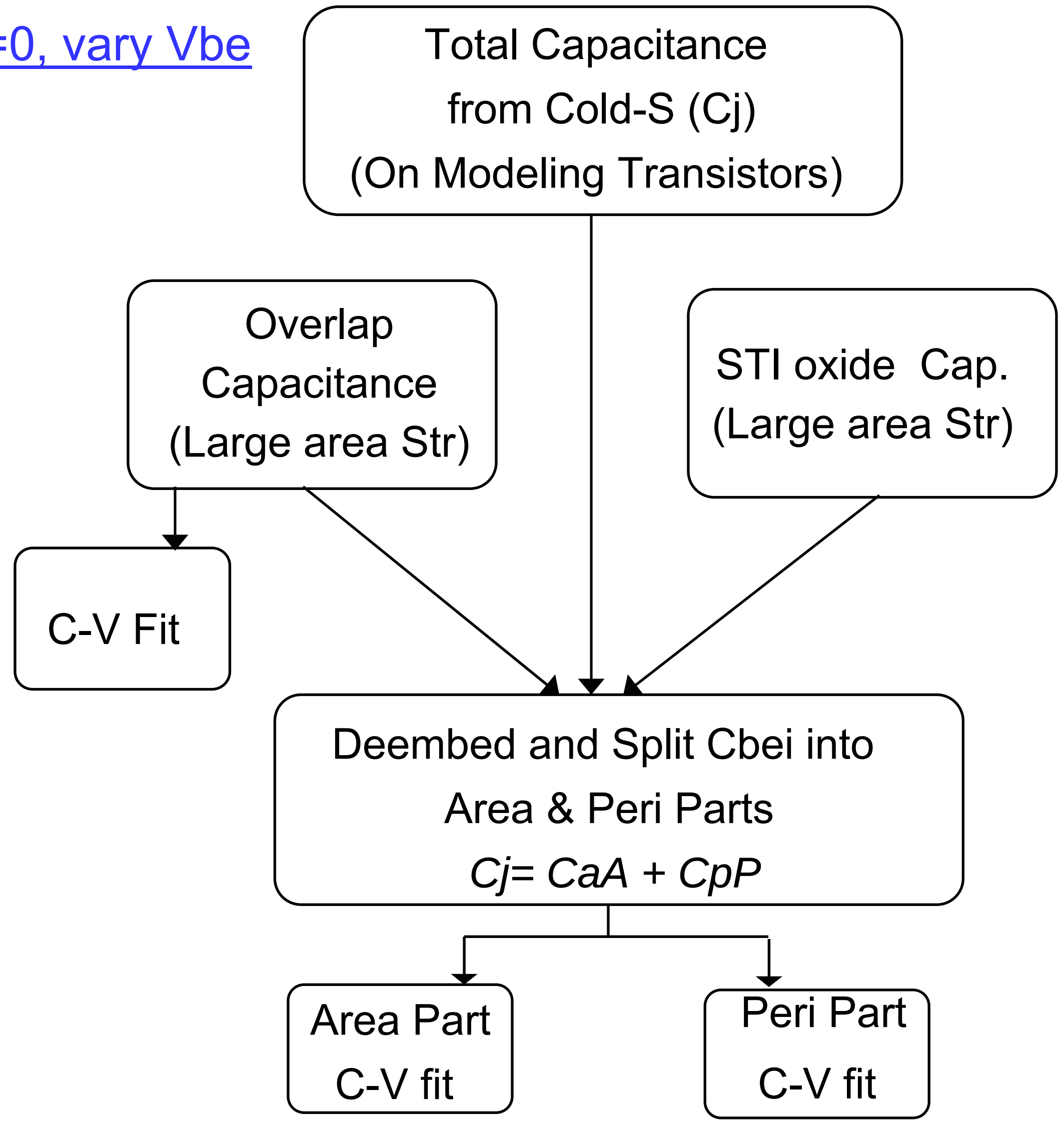
$$Cbe = \frac{imag(Y11) + imag(Y12)}{2\pi f}$$

$$Cbc = -\frac{imag(Y12)}{2\pi f}$$

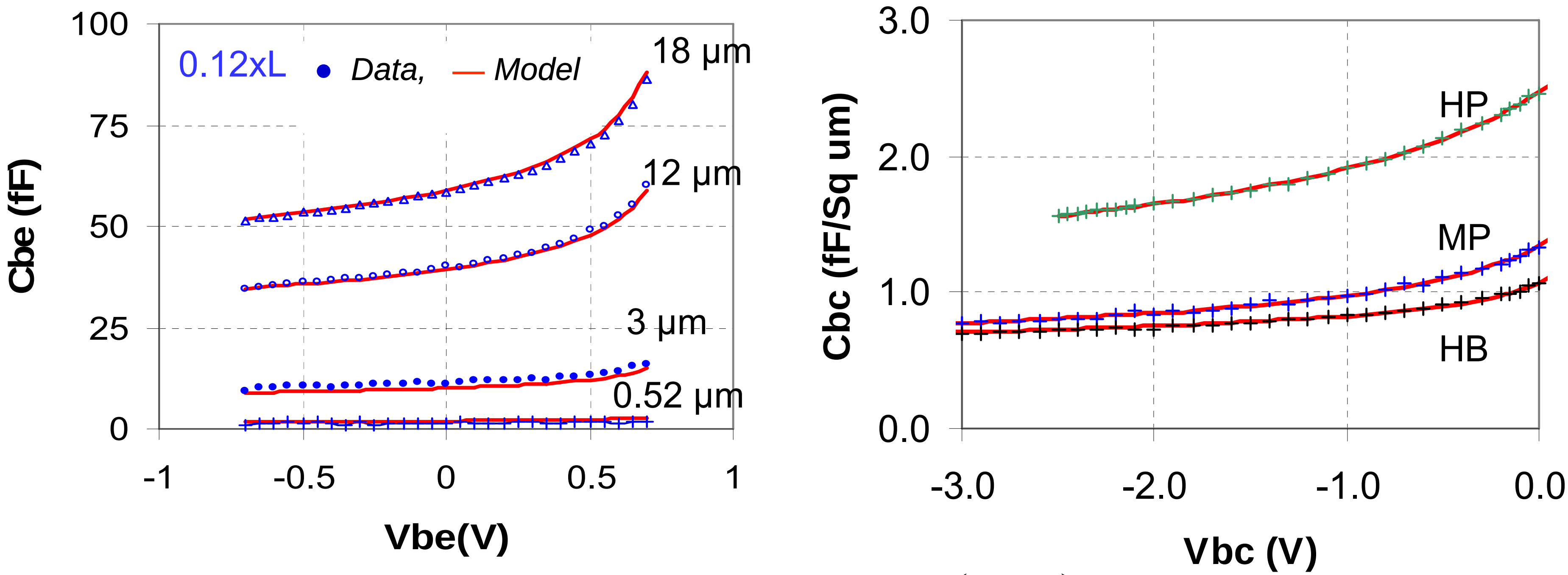
$$Ccs = -\frac{1}{2\pi f . imag\left(\frac{1}{Y12 + Y22}\right)}$$

$$Rsub = real\left(\frac{1}{Y12 + Y22}\right)$$





Scaling of Junction Capacitances



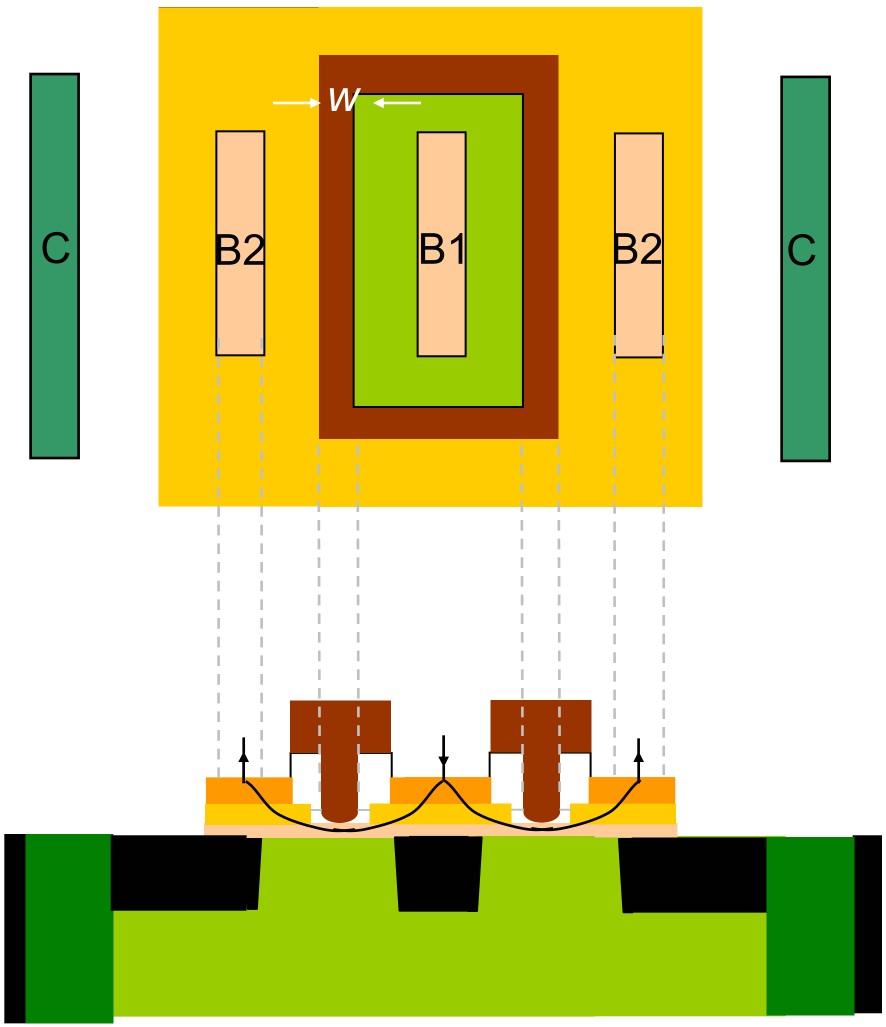
$$C = \frac{C0}{(1 - Vj / Vbi)^{Z}}$$

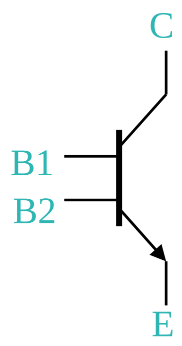
$$Vbi = kT . \ln\left(\frac{n_{n0}}{n_{p0}}\right)$$

$$n_{n0}(HP) > n_{n0}(SP) > n_{n0}(HB)$$

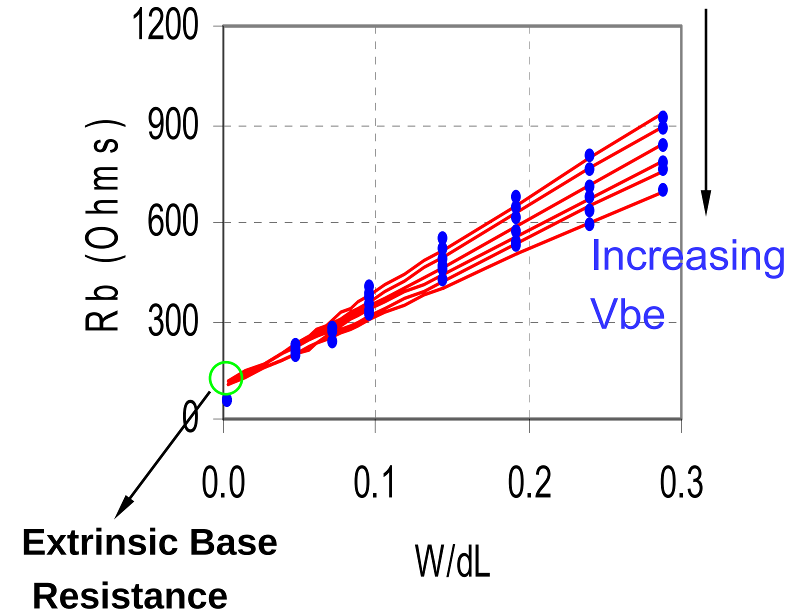
$$Vbi = 0.95V(HP), 0.65V(SP), 0.55V(HB)$$

Base Resistance Test Structures

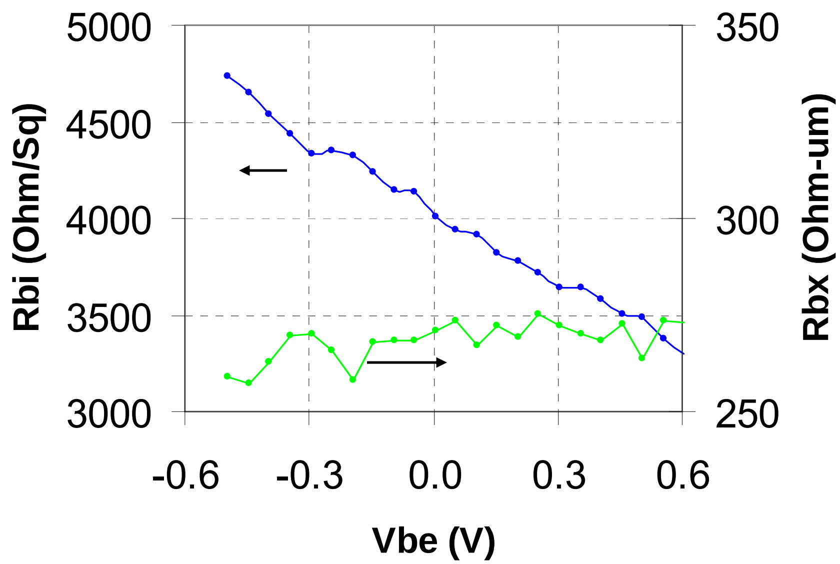


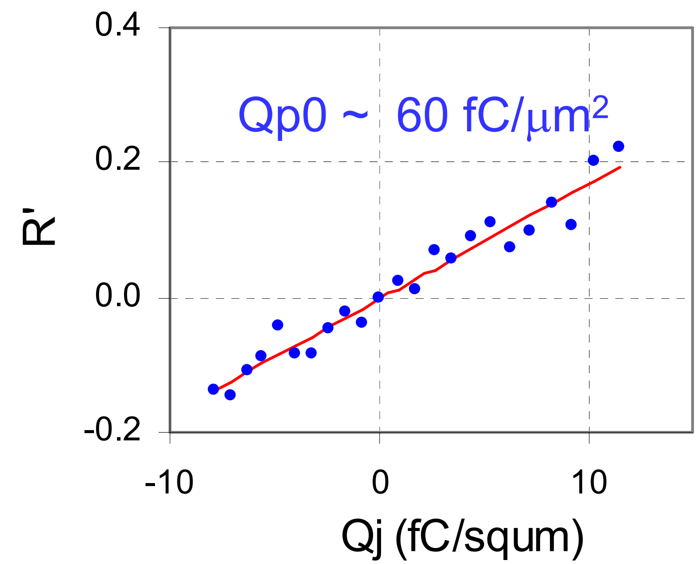


$$R_b = \frac{V_{B1,B2}}{\Delta I} = r_x + \frac{r_{bi}}{2}\frac{W}{\Delta L}$$



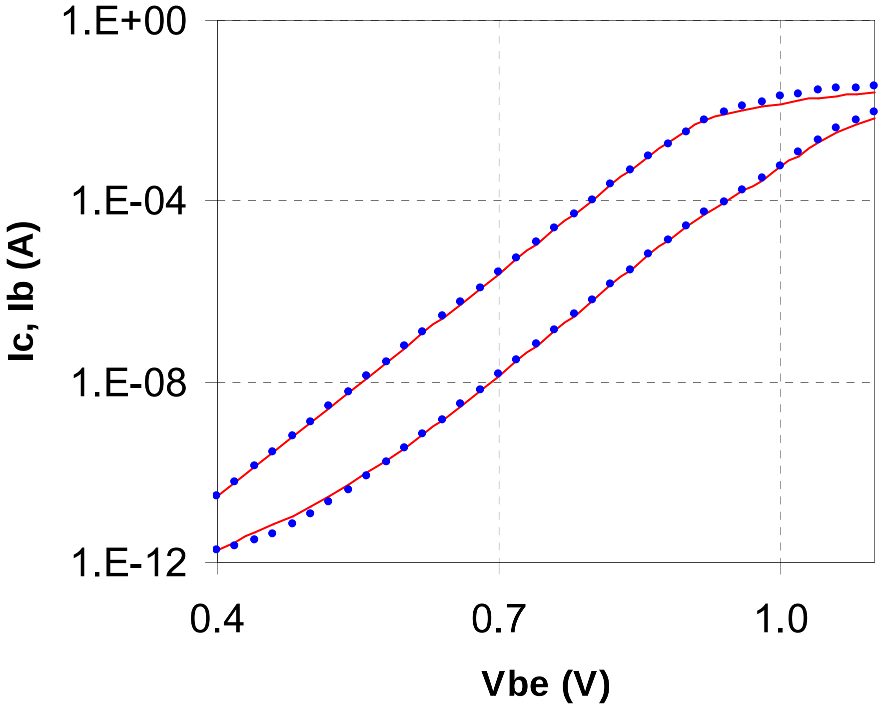
Bias Dependence of Base Resistance and Extraction of Zero-bias Hole Charge in the Base

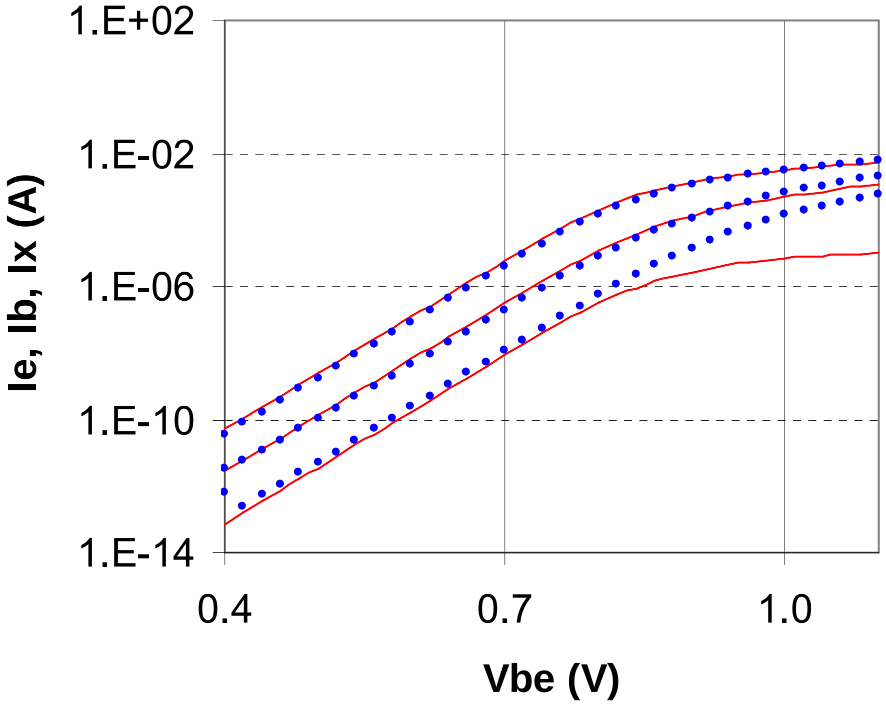




$$\frac{1}{r_{bi}} = q\int_{x1}^{x2} \mu_p p dx \longrightarrow R' \equiv \frac{rbi0}{rbi} - 1 \approx \frac{Qjei + Qjci}{Qp0}$$

Transfer Current: Forward and Reverse Gummels



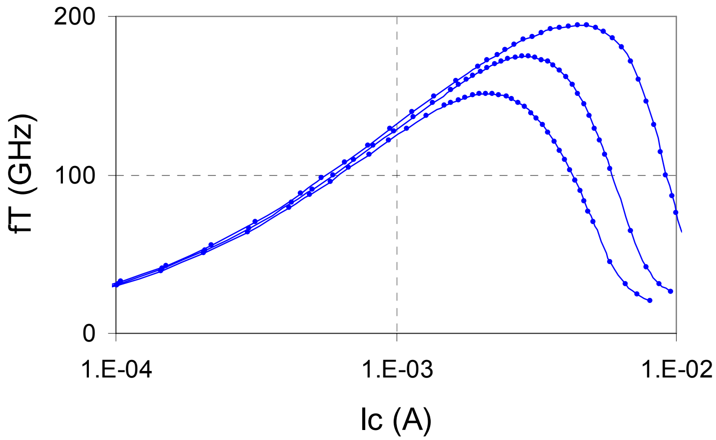


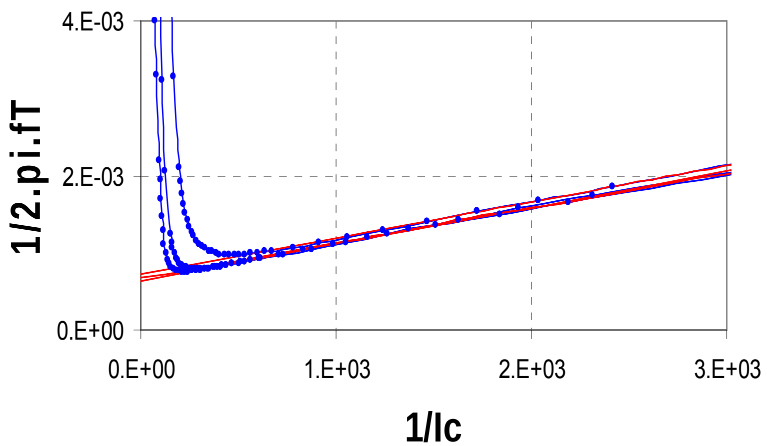
$$i_T = \frac{Is}{Q_{pT}/Q_{p0}}\left[\exp\frac{V_{be}}{Vt} - \exp\frac{V_{bc}}{Vt}\right]$$

$$Q_{pT} = Q_{p0} + h_{jei}Q_{jei} + h_{jci}Q_{jci} + Q_{fT} + Q_{rT}$$

$$Q_{fT} = h_{fe}Q_{fe} + Q_{fb} + h_{fc}Q_{fc}$$

Extraction of Low Current Total Transit Time

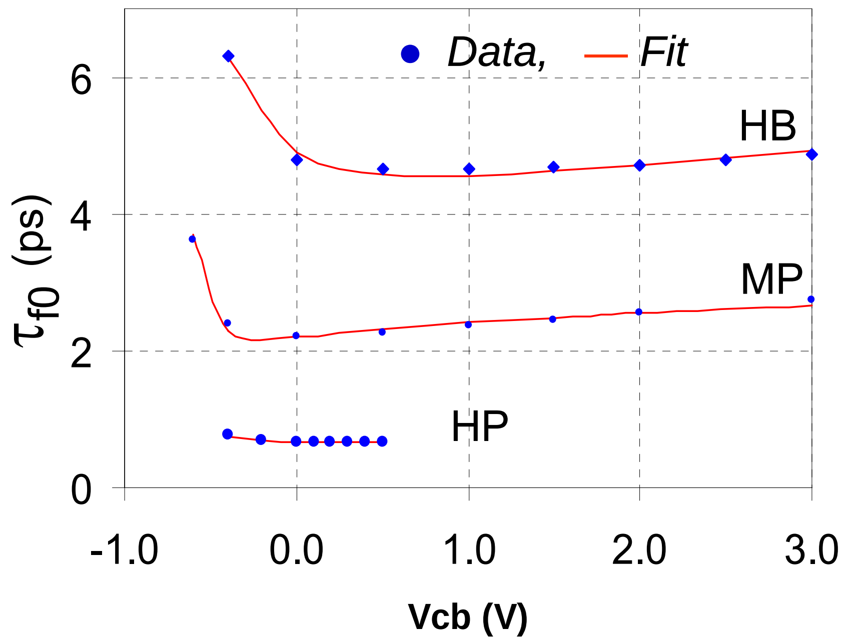




$$\frac{1}{2\pi . f_T} = \tau_f + (C_{je} + C_{jc})\frac{V_T}{Ic} + (rcx + re)C_{jc}$$

$$\tau_f = \tau_{ec} = \tau_{Ef} + \tau_{BE} + \tau_B + \tau_{BC} + \tau_{pC}$$

Extraction of the Low Current Transit Time Components



Collector	τ_0(ps)	$\Delta\tau_{0h}$(ps)	τ_{bfvl}(ps)
HP	0.66	-0.1	0.1
MP	2.2	2.6	2.73
HB	4.9	3.5	6.0

$$\tau_{f0} = \tau_0 + \Delta\tau_{0h}(c-1) + \tau_{bfvl}\left(\frac{1}{c} - 1\right)$$

τ_0 = predominantly neutral base (not f(V))

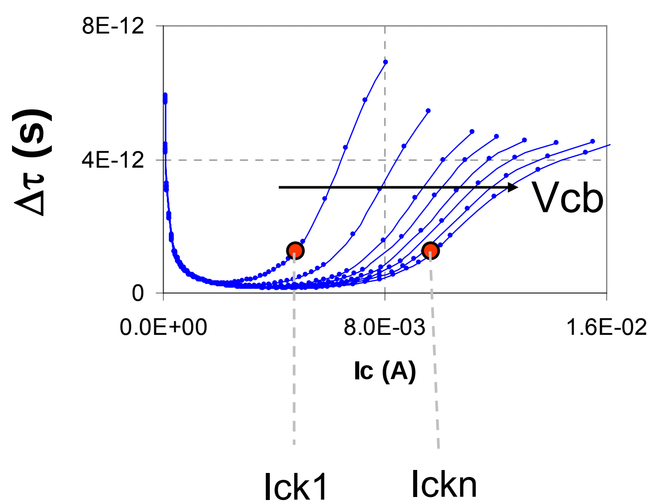
$\Delta\tau_{0h}$ = { BC SCR Component; Early Effect Component }

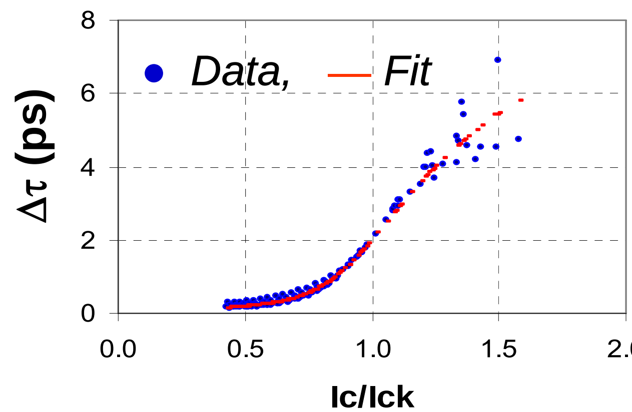
τ_{bfvl} = carrier jam component

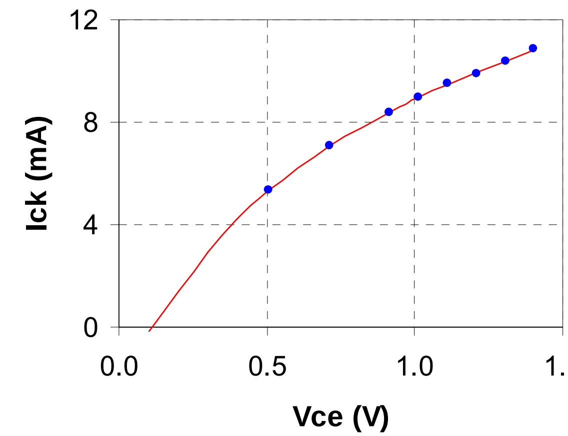
c = cjci0/cjci

Extraction of the High Current Transit Time Parameters

- Ick: critical current for the onset of high-current effects (base push-out)
- High-current part of the transit time: $\Delta\tau = \tau_f - \tau_{f0}$
- Ick is determined graphically

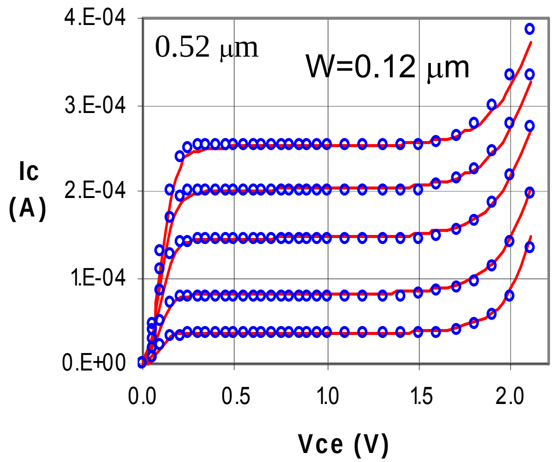


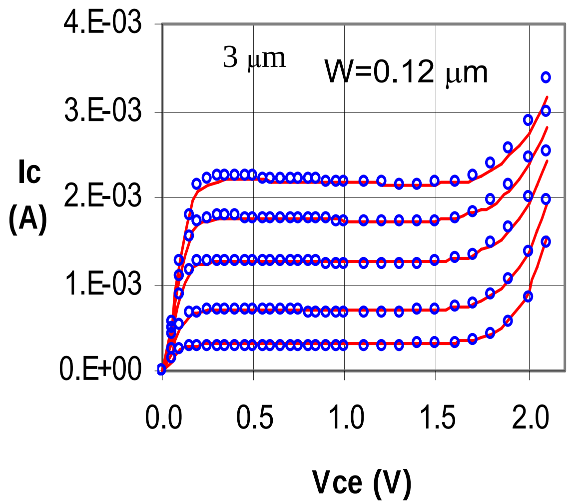


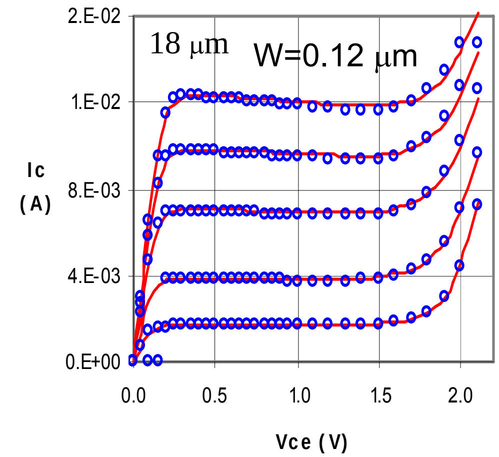


$$Ick = \frac{V_{ce}'}{r_{ci0}} \frac{1}{\sqrt{1+\left(\frac{V_{ce}'}{V_{\lim}}\right)^2}} \left(1+\frac{V_{ce}'-V_{\lim}}{V_{PT}}\right)$$

Geometry Scaling of the Output Curves

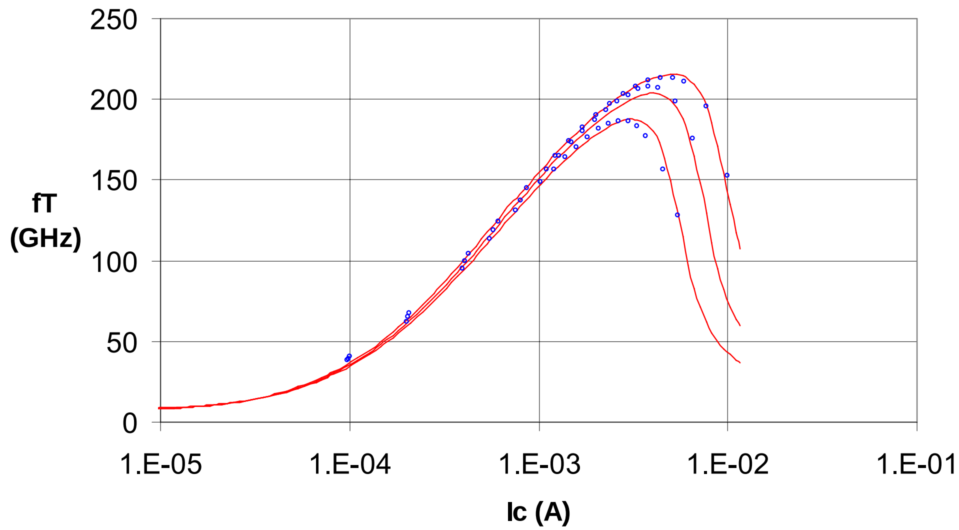


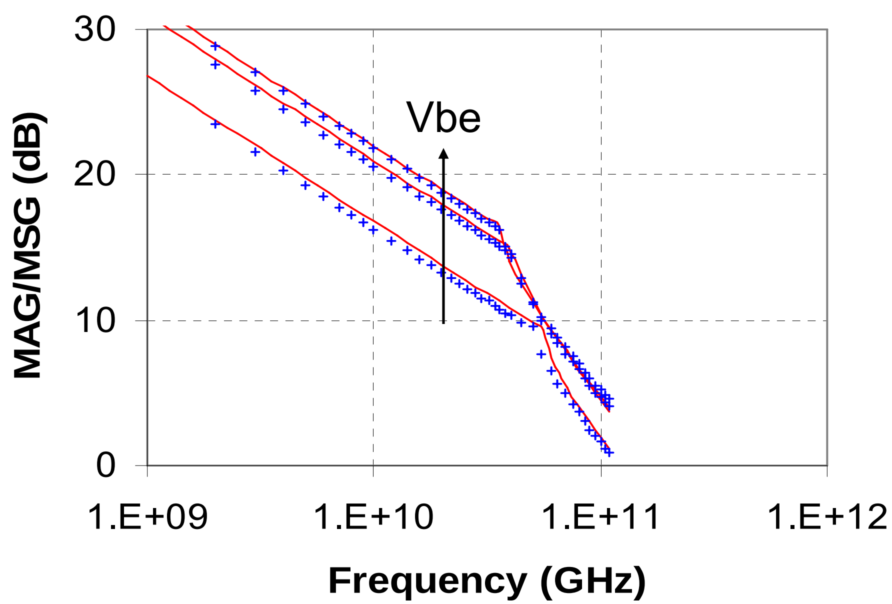




fT-Vcb and MAG/MSG: Model vs Measurement

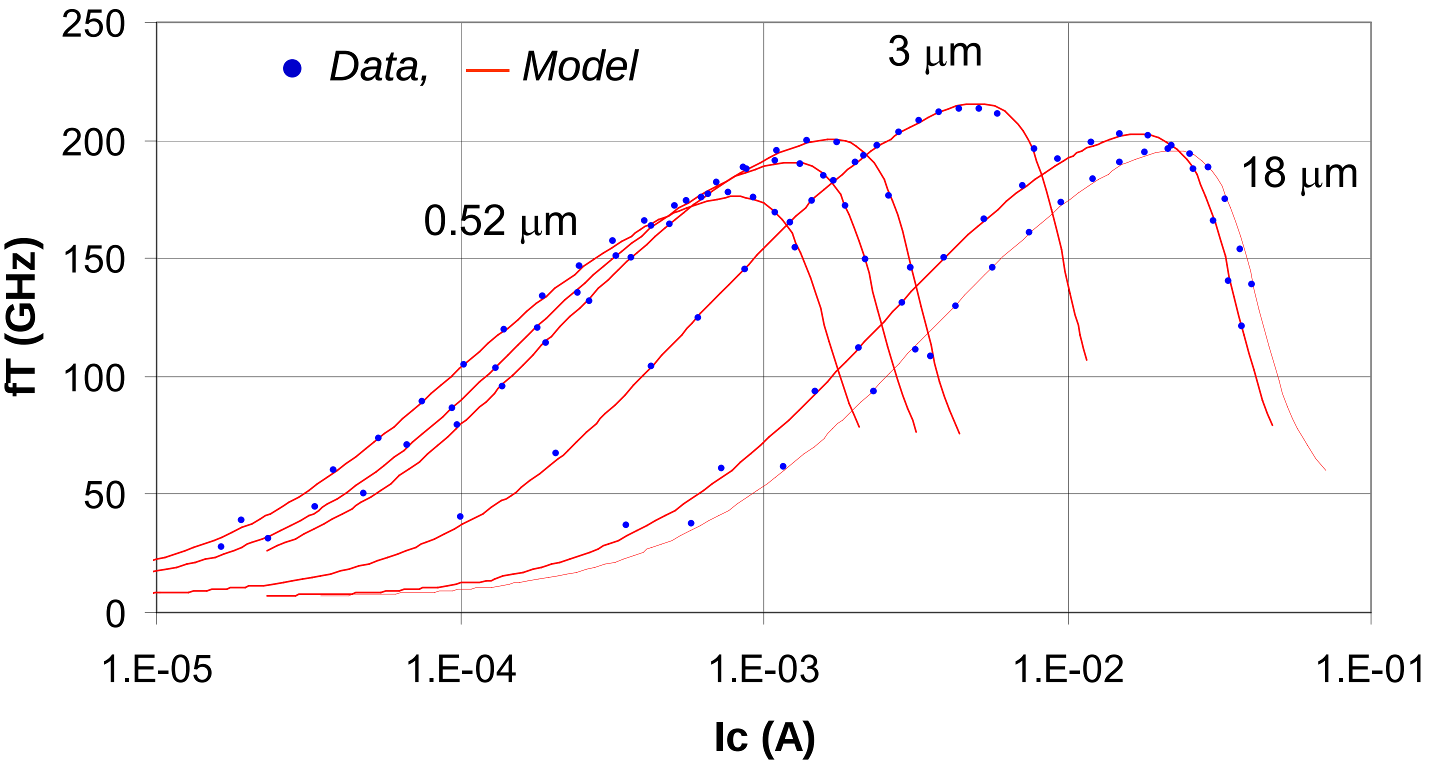
Vcb= -0.4, 0, 0.5





● *Data,* — *Model*

Geometry Scaling of fT-Ic



Noise Parameter Simulations

High Frequency Noise Parameter Simulations

- Simulated by SP (with noise) engine in Spectre

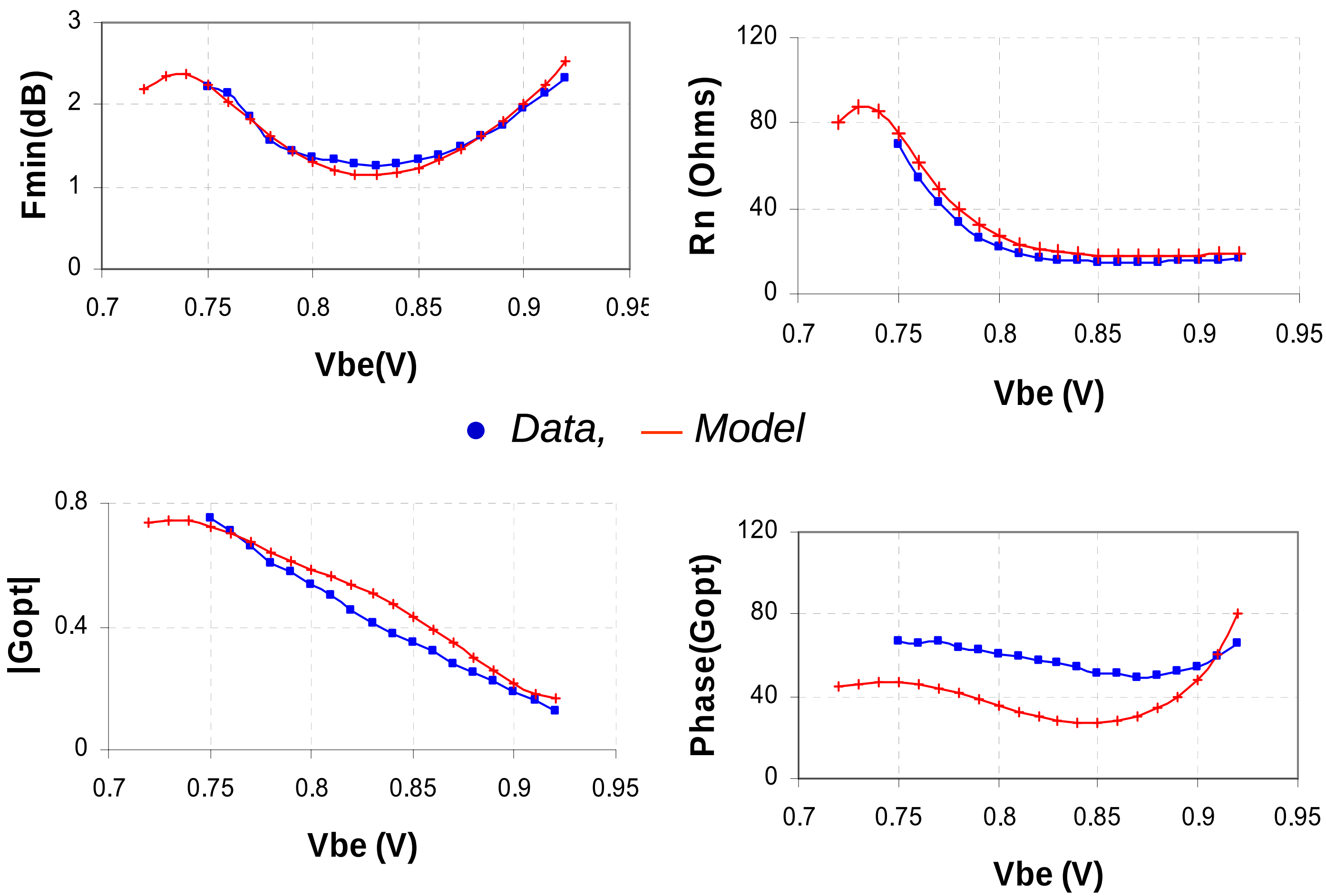
$$F = F_{\min} + \frac{R_n}{G_G}\left|Y_G - Y_{G,opt}\right|^2$$

F_{min} : Minimum Noise Figure

R_n: Noise Resistance

$Y_{G,opt}$: The optimum admittance to get minimum noise ($G_{G,opt}$ + $jB_{G,opt}$)

Noise Parameters: Measurement vs Model (at 18 GHz)

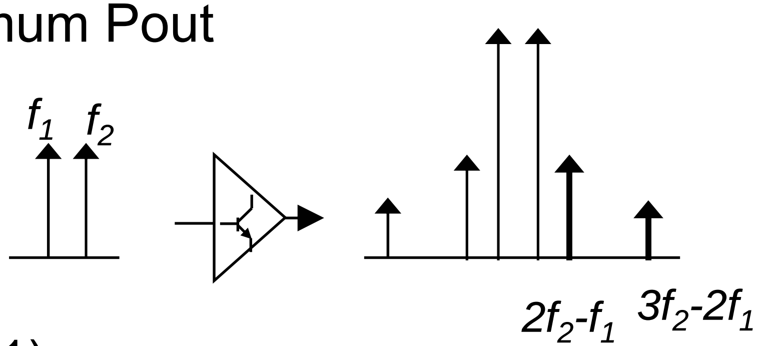


Linearity Measurements and Simulations

- Linearity simulations provide a good check to the accuracy of the model parameter set and model implementation in the simulator

Measurements

- Measurements done on an ATN Load pull system
- Tuned for Maximum PAE/ Maximum Pout
- f1=5 GHz, f2 = 5.001 GHz



Simulations

- Harmonic Balance in RFDE (IC51)
- QPSS in Spectre (IC51)
- Simulated 2-tone distortion behavior

Improved Rbi Implementation for Better Convergence-1

$$r_i = r_{bi0} \frac{q_0}{q_0 + \Delta q_p}$$, where $$\Delta q_p = \Delta q_{jei} + \Delta q_{jci} + q_f$$

$\Delta q_p \le -q_0$, leads to divide-by-zero errors

We addressed this in ADS2005 by limiting Δq_p

$\Delta q_p = q_{jei} + q_{jci} + q_f$ when $\Delta q_p > q_{0\lim}$

$\Delta q_p = q_{0\lim}$, when $\Delta q_p \le q_{0\lim}$

where $q_{0\lim} = -F * q0,\quad 0 < F < 1.$

A value of *F*=0.75 is found to provide a good trade-off between convergence and compatibility with the reference implementation.

Improved Rbi Implementation for Better Convergence-2

Hyperbolic smoothing is applied to the limiting function to eliminate derivative discontinuities at q_{0lim}-

$$\Delta q_{p0} = qjei + qjci + qf$$

$$\Delta q_p = q_{0\lim} + \frac{1}{2}\left[\Delta q_{p0} - q_{0\lim} + \sqrt{(\Delta q_{p0} - q_{0\lim})^2 + \delta^2}\right]$$

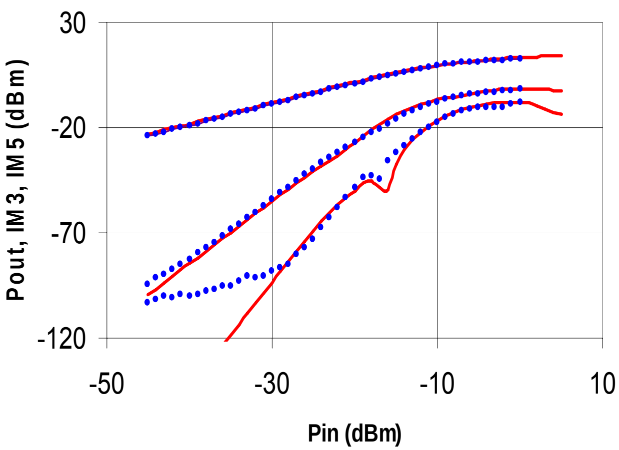
Where δ controls the trade-off between smoothness and accuracy. A good choice for δ is d=1e-3*q_0’ where q_0’ is the parameter describing the temperature-independent part of q_0. Derivative expressions are altered as follows:

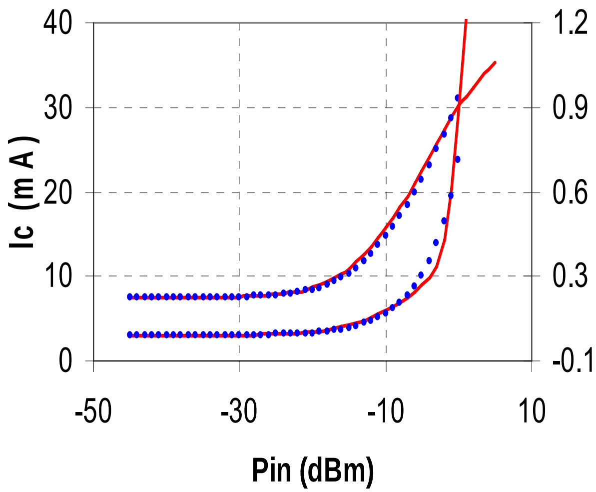
$$\frac{d\Delta q_p}{dV_{bei}} = \frac{d\Delta q_p}{dq_{p0}} \cdot \frac{d\Delta q_{p0}}{dV_{bei}},$$

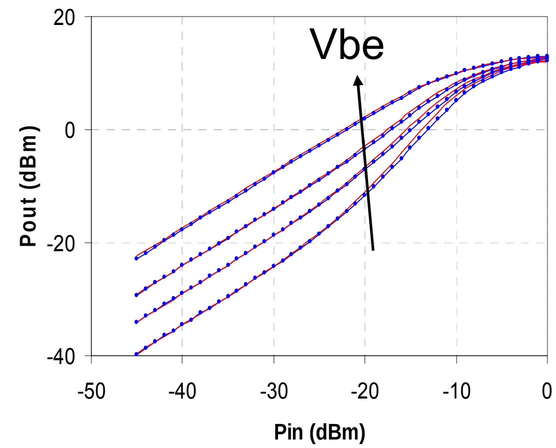
$$\frac{d\Delta q_p}{dT} = \frac{d\Delta q_p}{dq_{0\lim}} \cdot \frac{dq_{0\lim}}{dT} + \frac{d\Delta q_p}{d\Delta q_{p0}} \cdot \frac{d\Delta q_{p0}}{dT}$$

Inter Modulation Distortion: Measurement vs Model

- Biased at Vbe = 0.86 V, Vce= 1.36V, corresponds to 35% of peak fT current
- Self-biasing effect is well captured
- Bias dependence is well modeled







● *Data,* — *Model*

Summary

- Most of the important parameters can be extracted by simple measurements and expressions and fitting routines
- Scaling of these parameters is technology and device layout dependent
- Hicum 2.1 is able to describe the device characteristics satisfactorily