Overview on HICUM/L0 v1.3

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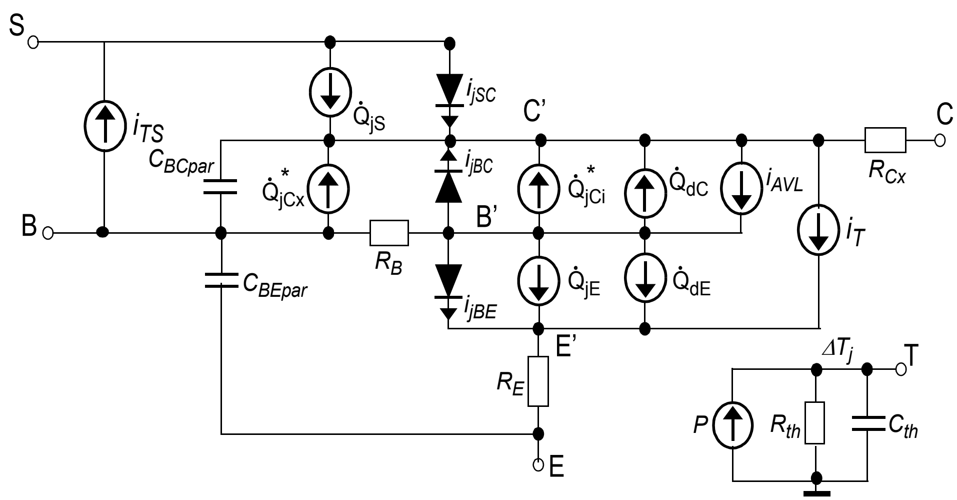
Outline

- Introduction
- Transfer Current
- Temperature dependence
- Experimental results
- Conclusion

Introduction

- Need for simplified models:
  - computationally intensive circuit simulation (large-scale, long transients)
  - single device availability and extraction (e.g., for III/V HBTs)
  - preliminary design phase
  - can mix with sophisticated models (HICUM, MEXTRAM, VBIC) for critical devices

=> HICUM/L0 v1.30



available in 10+ circuit simulators

- **Improvements over SGPM**
  - transfer current: simplified GICCR (incl. quasi-saturation)
  - mobile charge: high-current effects
  - depletion charge: punch-through, forward bias limiting
  - collector avalanche effect
  - improved base resistance(bias, T)
  - self-heating (incl. external T node)
  - substrate transistor integrated

=> parameter extraction: single device or generated from HICUM/L2

About this presentation ...

... overview on recent changes from v1.2 to v1.3

- transfer current
  - improved model formulation for low- and medium-current region
    => bias dependent reverse Early effect via weight factor h_{jEi} as in HICUM/L2 v2.31
  - high-current region (incl. quasi-saturation)
    => closed-form solution for transfer current via Cardano equation
- Temperature dependence
  - reverse Early voltage V_{Er}
  - high injection current I_{Qfh}
  - thermal resistance

Note: HICUM/L0 can be reduced to SGPM for compatibility purposes
(except yet for NQS effect)

- Experimental verification
  - ST B3T process: bias and T dependence

Transfer Current

- formulation at low and medium current densities ($V_{C'E'}$ > 0.2V)

$$I_{Tf} = I_{Tfl} = \frac{I_S}{1 + \frac{v_{jEid}}{V_{Er}} + \frac{v_{jCid}}{V_{Ef}} + \frac{I_{Tf}}{I_{Qf}}} \exp\left(\frac{V_{B'E'}}{m_{Cf} V_T}\right)$$ with $v_{jXid} = Q_{jXi}/C_{jXi0}$ (X = E, C)

- observed drop in normalized transconductance caused by impact of Ge grading in BE SCR on reverse Early voltage $V_{Er} = Q_{P0}/(h_{jEi}C_{jEi0})$ (see HICUM/L2 v2.31)
- proposal by Huszka et al. (implemented in v1.2; cf. HICUM WS 2009)
  - interpret $N_B/(\mu_n n_i^2)$ in GICCR as effective doping concentration
  - apply classical depletion charge calculation
    => same bias dependent formulation for Q_{jEi} and C_{jEi} but different parameters
  - interpret weighted GICCR charge as "DC Charge"
    => use same equation, but define new set of DC depletion charge parameters for v_{jEid}
- Issues
  - weakness in interpretation of parameters to physical device structure
  - no temperature dependence included (DC charge T dependence differs via $h_{jEi}(T)$)

New approach at low to medium current densities

apply HICUM/L2 v2.31 solution for modeling (normalized) transconductance

- bias dependent weight factor h_{jEi} yields bias dependent reverse Early voltage:

$$V_{Er} = V_{Er0} / \left(\frac{\exp(u) - 1}{u} \right) \quad \text{with} \quad u = a_{VEr} \left[1 - \left(1 - \frac{v_j}{V_{DE}} \right)^{z_E} \right]$$ (v_j = smoothed $V_{B'E'}$)

=> now includes material composition explicitly

- new parameters:
  - V_{Er0} => Early voltage at $V_{BE} = 0$
  - a_{VEr} => *new parameter* for bias dependence of V_{Er} ($a_{VEr} = a_{hjEi}$ in L2)
- advantages of new formulation
  - maintain physics-based depletion capacitance parameters (extracted from AC data)
  - new parameters have clear link to device structure and T dependence
- medium current densities: weight factor h_{f0} in L2 v2.31
  => can be included by simply adjusting parameter value for I_{Qf}

High-current region

- complete GICCR can only be solved iteratively (cf. HICUM/L2)
  => HICUM/L0 uses simplification of mobile charge at high injection
- starting point is simplified transfer current expression from L2:

$$I_{Tf} = \frac{I_S}{1 + \frac{v_{jEid}}{V_{Er}} + \frac{v_{jCid}}{V_{Ef}} + \frac{I_{Tf}}{I_{Qf}} + \frac{I_{Tr}}{I_{Qr}} + \Delta q_{fT}} \exp\left(\frac{V_{B'E'}}{m_{Cf}V_T}\right)$$

- simplified normalized mobile charge from HICUM/L2:

$$\Delta q_{fT} = \frac{[(1 - f_{thc}) + h_{fC}f_{thc}]\tau_{hcs}I_{Tf}w^2 + h_{fE}\tau_{Ef0}\left(\frac{I_{Tf}}{I_{CK}}\right)^{g_{\tau E}} \frac{I_{Tf}}{1 + g_{\tau E}}}{Q_{p0h,0}}$$

with $w(I_{Tf})$ as normalized collector injection width

=> further simplifications needed for obtaining closed-form solution

High-current region (cont'd)

- defining
  - depletion component $q_j = 1 + v_{jEid}/V_{Er} + v_{jCid}/V_{Ef}$
  - ideal current components $I_{Tfi} = I_S \exp\left(\frac{V_{B'E'}}{m_{Cf}V_T}\right)$, $I_{Tri} = I_S \exp\left(\frac{V_{B'C'}}{m_{Cr}V_T}\right)$
  - low-current injection component $q_{fl} = I_{Tfi}/I_{Qf} + I_{Tri}/I_{Qr}$

=> $q_{pT} = q_j + \frac{q_{fl}}{q_{pT}} + \frac{\Delta q_{fT}}{q_{pT}}$

- neglecting high-current injection component Δq_{fT} yields quadratic equation

=> solution $q_{pT} \rightarrow q_{pTl} = \frac{q_j}{2} + \sqrt{\left(\frac{q_j}{2}\right)^2 + q_{fl}}$

=> transfer current $I_{Tf} \rightarrow I_{Tfl} = \frac{I_{Tfi}}{q_{pTl}}$ => equivalent to SPICE GP model:

High-current region (cont'd)

- initial L0 v1.1 used Δq_{fT} with $I_{Tf} \rightarrow I_{Tfl}$ as "high-current correction"

  => solution can become inconsistent or yield $g_m \leq 0$ for certain parameter choices

- intermediate fix was implemented at IFX and included in v1.2
  - complicated derivation
  - questionable assumptions => limited applicability?
- setting *$g_{\tau fE} = 1$* and defining the new model parameters

$$I_{Qfh} = \frac{Q_{p0h,0}}{[(1-f_{thc})+h_{fC}f_{thc}]\tau_{hcs}}, \quad t_{fh} = \frac{h_{fE}\tau_{Ef0}}{2[(1-f_{thc})+h_{fC}f_{thc}]\tau_{hcs}}$$

yields *further simplified and more compact* expression

$$\Delta q_{fT} = \left(I_{Tf}w^2 + \frac{t_{fh}}{I_{CK}}I_{Tf}^2\right)/I_{Qfh}$$

High-current region (cont'd)

- define ideal base/collector component $\Delta q_{BCfi} = (I_{Tfi}/I_{Qfh})w^2$ and ideal emitter component $\Delta q_{Efi} = t_{fh}I_{Tfi}^2/(I_{Qfh}I_{CK})$

$$\Rightarrow \quad q_{pT} = q_j + \frac{q_{fl}}{q_{pT}} + \frac{\Delta q_{BCfi}}{q_{pT}} + \frac{\Delta q_{Efi}}{q_{pT}^2}$$

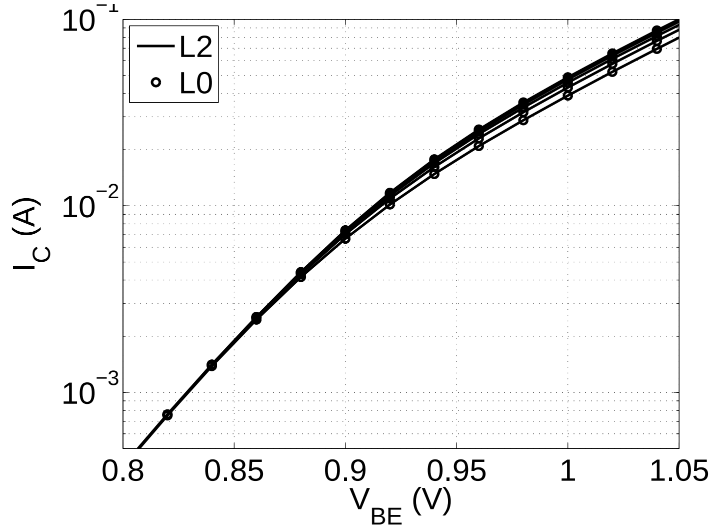
- third-order polynomial $q_{pT}^3 - q_j q_{pT}^2 - (q_{fl} + \Delta q_{BCfi})q_{pT} - \Delta q_{Efi} = 0$

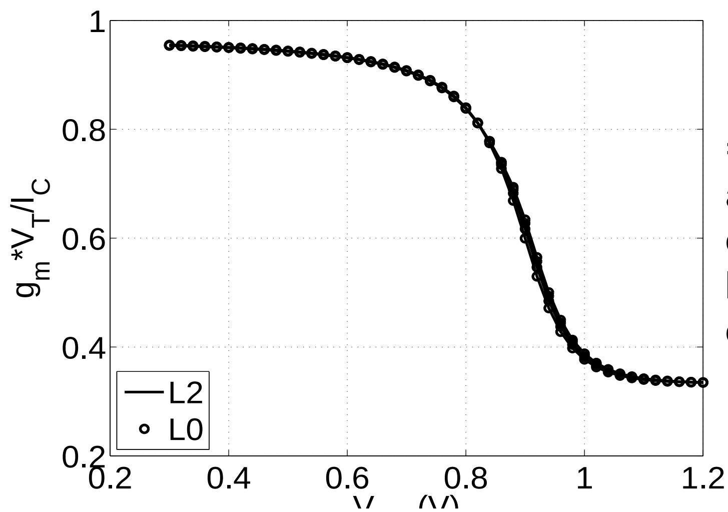
=> can be solved using Cardano's method

- solution procedure
  - q_{pT} is calculated for the asymtotic cases w=0 and w=1 (using still the previous square root solution to reduce numerical complexity)
    => results are used to calculate the final value for w as function of I_{Ck} and $I_{Tfi}/q_{pT,l}$
  - with the actual w => final q_{pT} is calculated from third-order polynomial

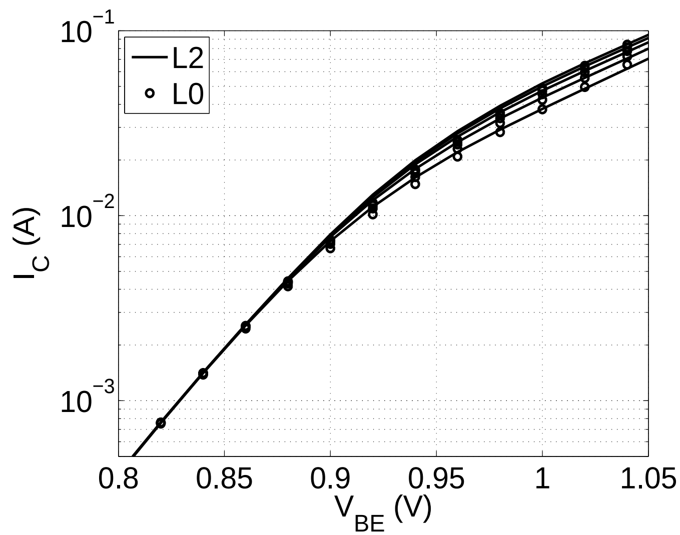
=> new solution method yields closed-form solution and saves computational effort

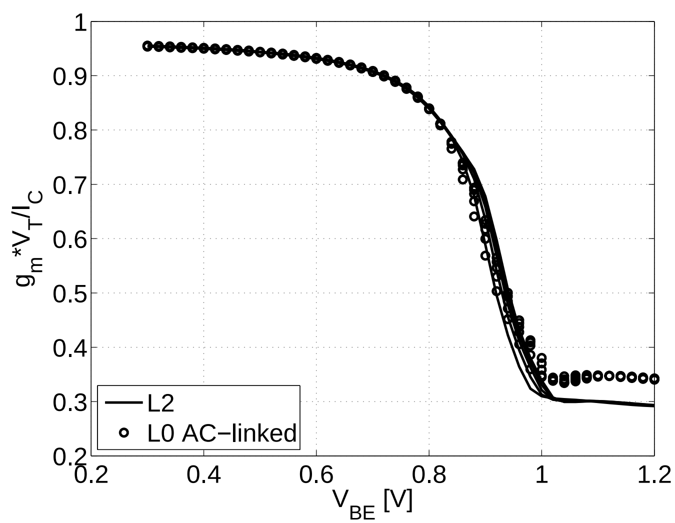
Impact of simplification in Δq_{fT}





$g_{\tau fE}$ =1
=> transfer current and transconductance of L0 with Cardano solution perfectly fit those of L2 (also with $g_{\tau fE}$ =1)





For practical cases $g_{\tau fE}$ may differ from 1

$g_{\tau fE}$ =1.47
=> still acceptable fit (with Cardano solution)

=> good agreement at high current densities for realistic conditions

Cardano's approach for solving cubic equation

- by substituting $x = z - a/3$ => normalized cubic equation $x^3 + ax^2 + bx + c = 0$ can be transformed to reduced one:

$$z^3 + pz + q = 0, \text{ with } p = b - \frac{a^2}{3}, \quad q = \frac{2a^3}{27} - \frac{ab}{3} + c$$

- *Discriminant* $D = \left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3$ => determines nature of solution

- Depending on sign of *D* three possible cases:
  - *D = 0* => $x = 3(q/p) - a/3$
  - D > 0 => $x = \sqrt[3]{q/2 - \sqrt{D}} + \sqrt[3]{-q/2 - \sqrt{D}} - \frac{a}{3}$
  - *D < 0* => $x = k\cos\left(\frac{\Phi}{3}\right) - \frac{a}{3}$ with $k = 2\sqrt{\frac{abs(p)}{3}}$ and $\Phi = \text{acos}\left(-\frac{q}{2} \Big/ \left(\sqrt{-\frac{p^3}{27}}\right)\right)$

=> implemented in Verilog-A code of HICUM/L0 v1.3

Temperature dependence

(see HICUM/L2 presentation for detailed discussions and results)

- reverse Early voltage parameters (according to h_{jEi})

$$V_{Er0}(T) = V_{Er0}(T_0)\exp\left[-\frac{\Delta V_{vgBE}}{V_T}\left(\left(\frac{T}{T_0}\right)^{\zeta_{vgBE}} - 1\right)\right] , \quad a_{VEr}(T) = a_{VEr}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{VEr}}$$

- low-injection charge related onset current (according to h_{f0})

$$I_{Qf}(T) = I_{Qf}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{IQf}}\exp\left[-\frac{\Delta V_{vgBE}}{V_T}\left(\frac{T}{T_0} - 1\right)\right]$$

- high-injection charge related onset current

$$I_{Qfh}(T) = I_{Qfh}(T_0)(1 + \alpha_{IQfh}\Delta T + k_{IQfh}\Delta T^2)$$

Temperature dependence (contd.)

- high-injection related normalized storage time

$$t_{fh}(T) = t_{fh}(T_0)\frac{I_{Qfh}(T)}{I_{Qfh}(T_0)}\exp\left(\frac{V_{gb}-V_{ge}}{V_T}\left(\frac{T}{T_0}-1\right)\right)$$

- thermal resistance

$$r_{th}(T) = r_{th}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{rth}}$$

Note: values at T_0 are model parameters

Summary of changes

- New L0 parameters

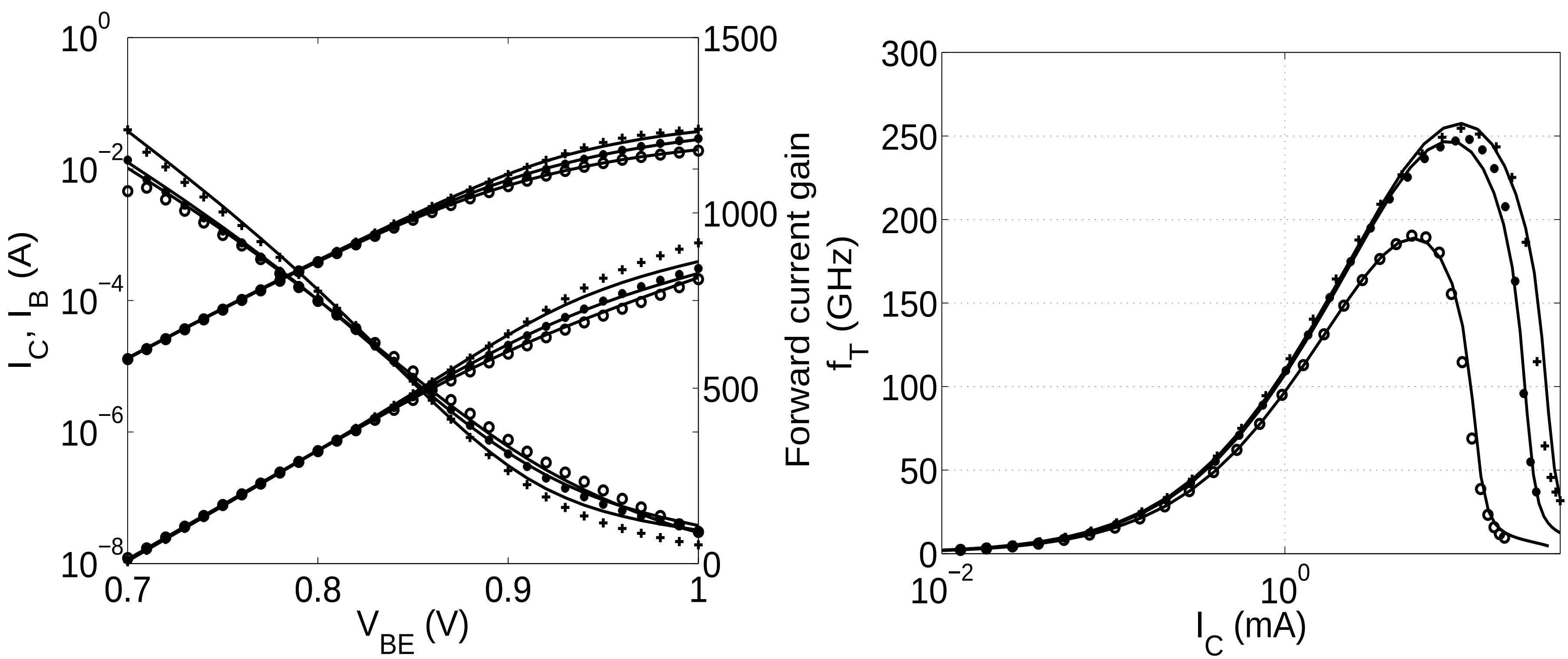
Parameter	Default	Description
a_{VEr}	0	Parameter for bias dependence of V_{Er}
ΔV_{gBE}	0	Bandgap difference between base and BE-junction. Used for temperature dependence of V_{Er} and I_{qf}
ζ_{vgBE}	1	Temperature parameter for V_{Er}
ζ_{VEr}	-1	Temperature parameter for reverse Early voltage *VEr*
α_{iqfh}	0	First-order temperature coefficient for I_{qfh}
k_{iqfh}	0	Second-order temperature coefficient for I_{qfh}
it_mod	0	Switch for different transfer current formulations (*0*:IFX-model (2^{nd} order equation);*1*:Cardano (3^{nd} order equation))
tef_temp	1	Switch for turning $t_{ef0}(T)$ equation on and off (*0*: off ;*1*: on)

- Model Implementation
  - full backward compatibility => *DC-charge* parameters (V_{DEDC}, z_{EDC}, a_{jEDC}) are kept separately from those for the *AC-charge*
  - bias dependence of V_{Er} can be turned off by setting a_{VEr} to zero

Experimental results

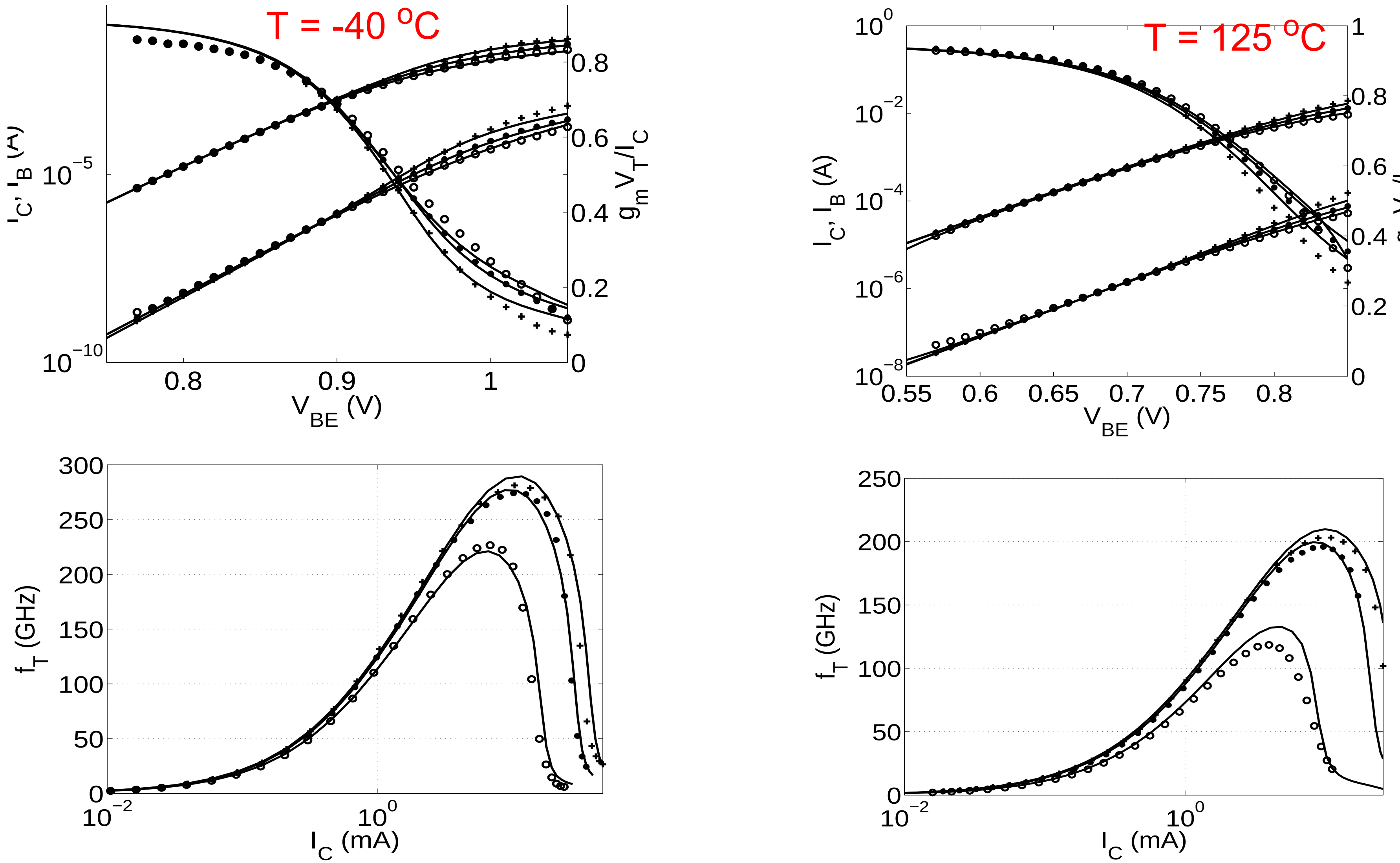
- B3T process from ST
  - Parameters were obtained automatically from (actually extracted) Hicum/L2 parameters

T = 27 °C



=> excellent agreement over wide bias range

B3T results (cont'd)



=> good results also over wide temperature range

InP HBT technology

- III-V HBT compact models
  - DC formulation often still SGPM based, often customized external extensions
  - no geometry scaling
  - typically contain significant empirical fitting instead of physics-based equations
  - are typically not implemented across simulation platforms (e.g. AHBT is avail. in ADS only)

=> more recently: Verilog implementation (at 20...100% speed penalty)

- parameter extraction focused on single device (vs. scalable in silicon)
  => few discrete parameter sets => circuit optimization via device sizing impossible
- efficient statistical modeling impossible (although more needed than for silicon technologies)

=> little incentive for implementation and support by EDA vendors

=> deployment of III-V HBT technology is limited by model capabilities

The silicon industry has demonstrated that a certain cooperation between foundries is beneficial to the business of all

Experimental results for InP HBTs

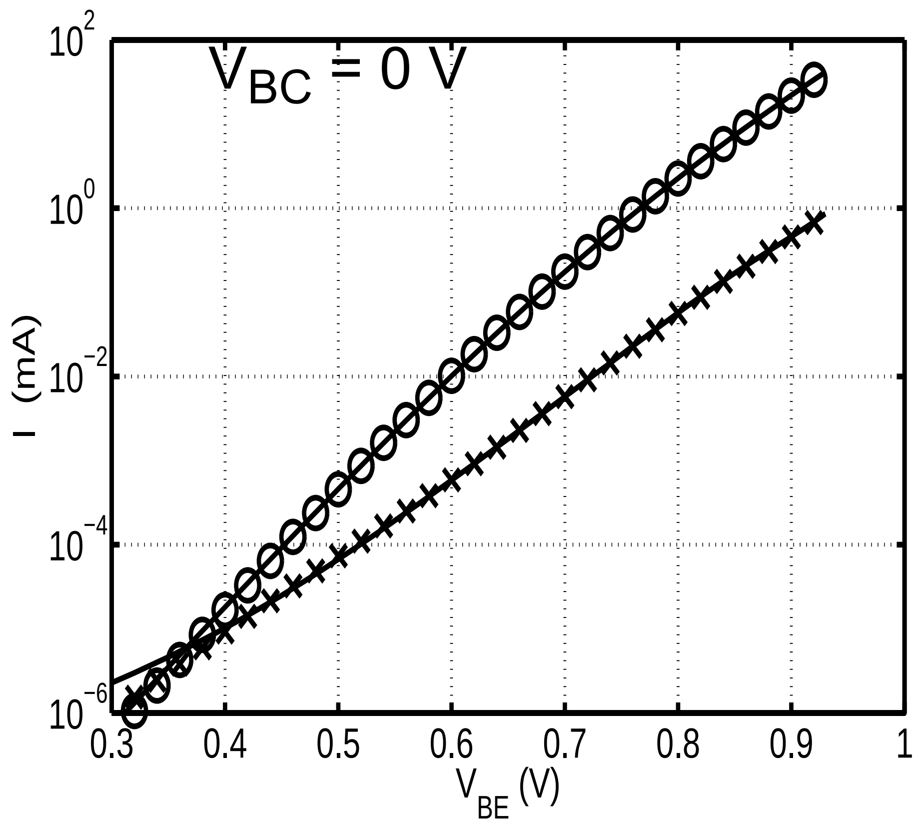
foundry process from GCS

- InGaAs/InP transistors: $f_T \approx 350$ GHz, $f_{max} \approx 400$ GHz
- no special test structures available => no scaling possible => HICUM/L0 v1.3
  - estimated base and collector resistance from sheet resistances and theory
  - measurements at various ambient temperatures for extraction of temperature related parameters
  - automated extraction with manual improvement for the remaining parameters
  - physical formulation for bias and T dependent V_{ER} (important for compositional grading)

Experimental results

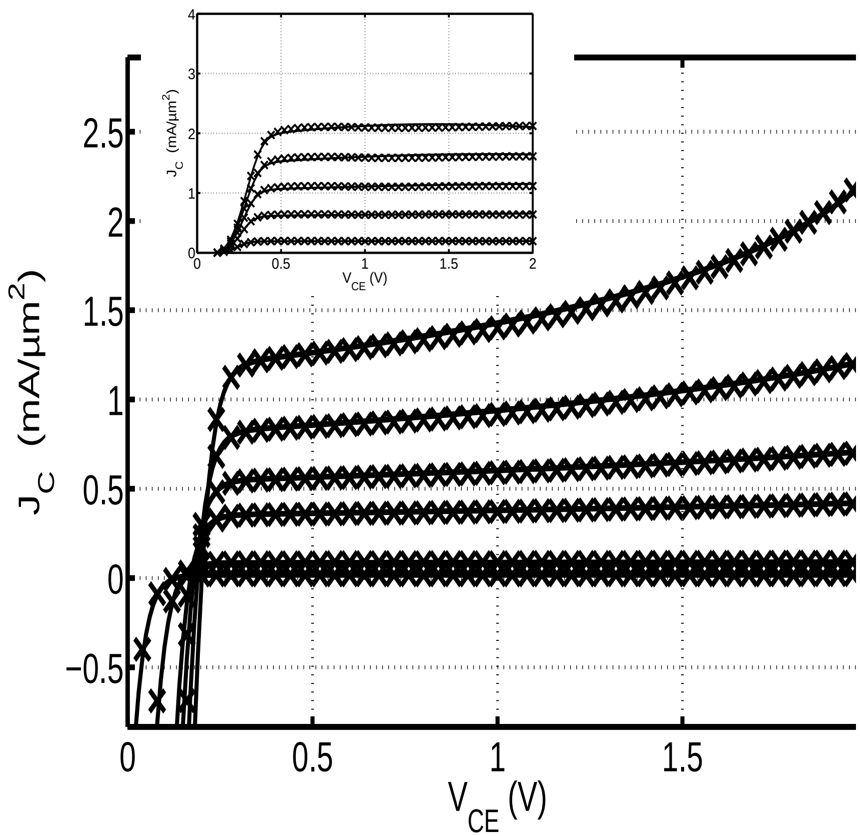
emitter window area A_{E0} = 0.8 x 10 μm^2

forward Gummel characteristics



(requires addition of $I_{BC,rec}$, a_{jC} variable)

forward output characteristics

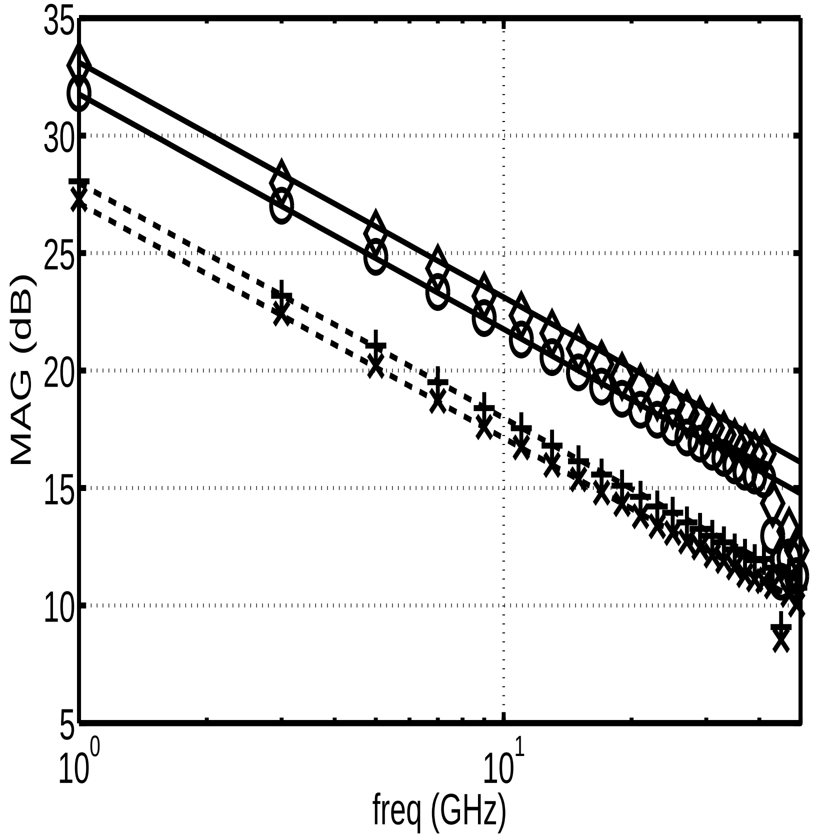


V_{BE} = [0.7, 0.76, 0.82, 0.84, 0.86, 0.88] V

=> good agreement over wide bas range

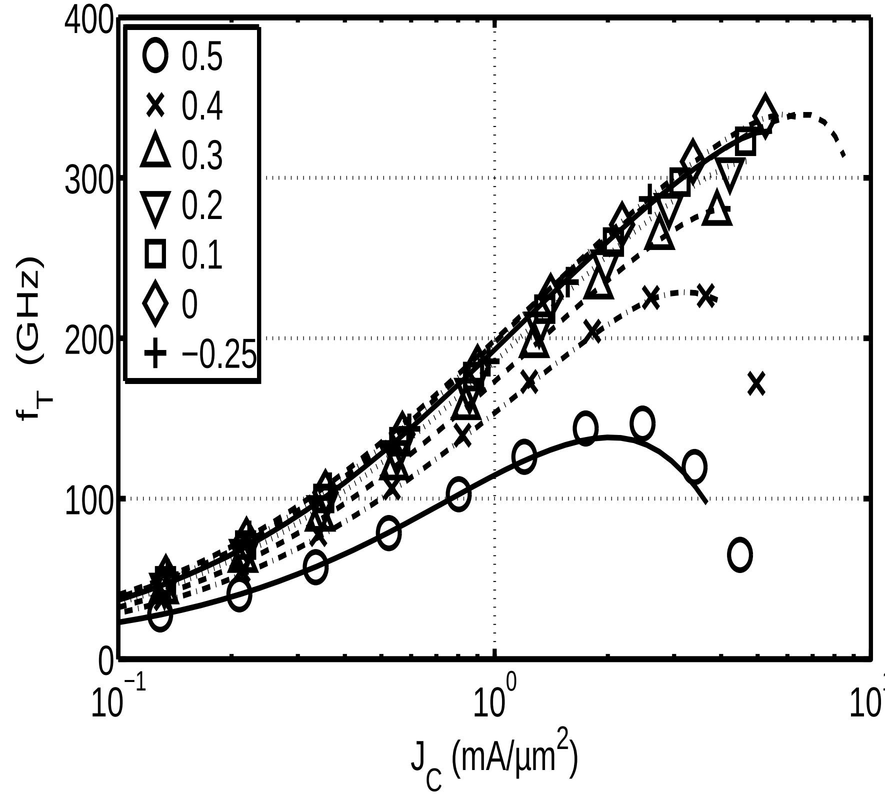
Experimental results

maximum available gain



J_C = {0.89, 5.94} and {0.93, 6.32} mA/µm²
V_{BC} = {0, -0.25}V

transit frequency f_T



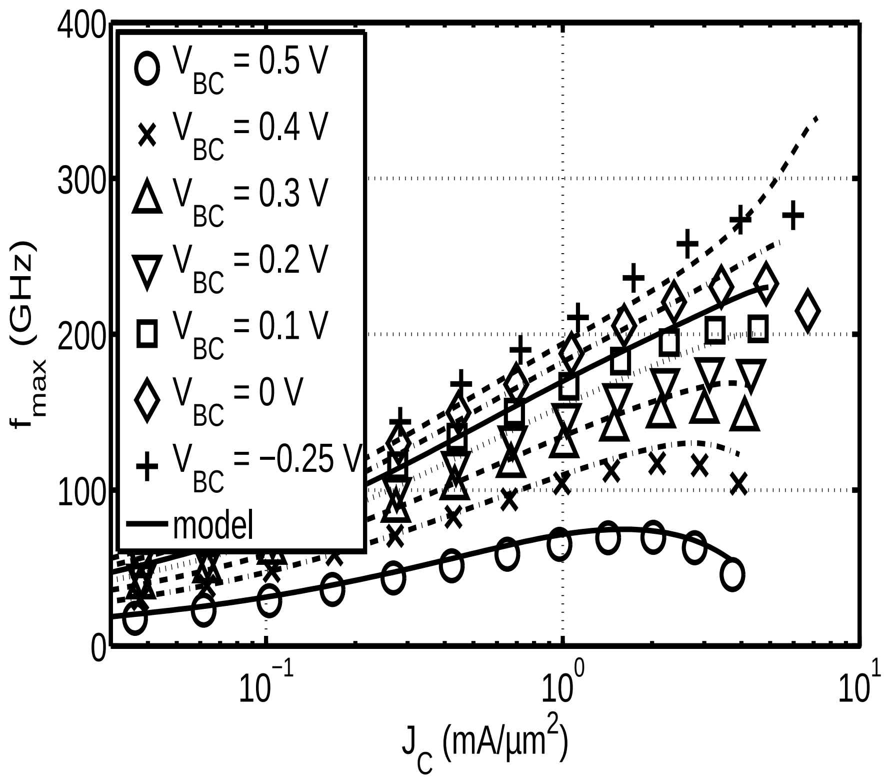
V_{BC} = [-0.25, 0, 0.1, 0.2, 0.3, 0.4, 0.5] V

=> acceptable agreement without invoking special "III/V" effects

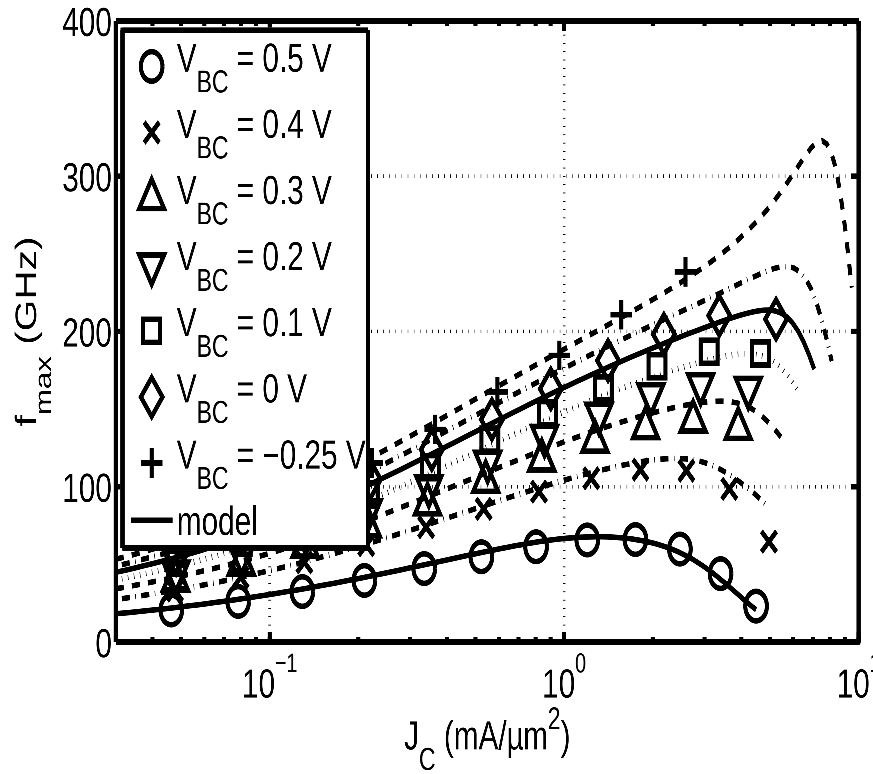
Experimental results

Maximum oscillation frequency

0.8 x 3 μm^2



0.8 x 10 μm^2



=> acceptable agreement without invoking special "III/V" effects

Conclusion

- improved transfer current formulation
  - reverse Early effect includes compositional grading in BE junction => capture $g_m V_T / I_C$ drop
  - first closed-form solution for low to high-current injection in HBTs
- temperature dependence for new and update for existing parameters

  => all new features have been made available in new HICUM/L0v1.3 code
- L0 parameters can be obtained automatically from "L2-to-L0" converter
- Application to mm-wave SiGe and InP HBTs
  => good agreement for small- and large-signal data
- next version 1.31 will also include vertical NQS effects
  - for complete compatibility with SGPM
  - both transfer current *and* charge are included (for correct phase shift in y_{21} *and* y_{11})

  => complete downward compatibility to SGPM allows replacing SGPM

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