Application of HICUM/L2 v2.30 to advanced multi-100GHz SiGe HBTs

A. Pawlak[1)], M. Schröter[1),2)]

[1)]Chair for Electron Devices and Integr. Circuits, Univ. of Technol. Dresden, Germany

[2)]ECE Dept., University of California San Diego, La Jolla, CA, USA

pawlak@iee.et.tu-dresden.de, mschroter@ieee.org

http://www.iee.et.tu-dresden.de/iee/eb/eb_homee.html

Bipolar Arbeitskreis, Crolles, Oktober 2010

Outline

- Preconditions
- Extraction step - low current region
- Extraction step - output characteristics
- Extraction step - high current region
- Model results
- Summary

Preconditions

- Model parameters
  - Adopted parameters (including temperature dependences) for all resistances and thermal resistance from [3].
  - Copied values for parasitic capacitances and parameters for I_{CK} from [3].
  - Performed extraction for capacitances and transit times.
  - Single transistor extraction => $C_{jEp0}=C_{jCx0}=0$
  - Mixed parameters for base current.
  - Avalanche parameters taken from [3], adjusted to own BC-capacitance.
  - No extraction for substrate transistor and coupling.
- Model code
  - Including a temperature dependent RTH as in Level0 and [2].
  - Disabled temperature dependence of τ_{ef0}
    (formulation of transit time under investigation)

Extraction step - low current region

- Simplification for transfer current (at V_{BC} = 0)

$$i_T = \frac{c_{10}}{Q_{p0} + h_{jEi}Q_{jEi}} \exp\left(\frac{V_{BE}}{V_T}\right) \quad \text{with} \quad h_{jEi} = f(h_{jEi0}, a_{hjE})$$

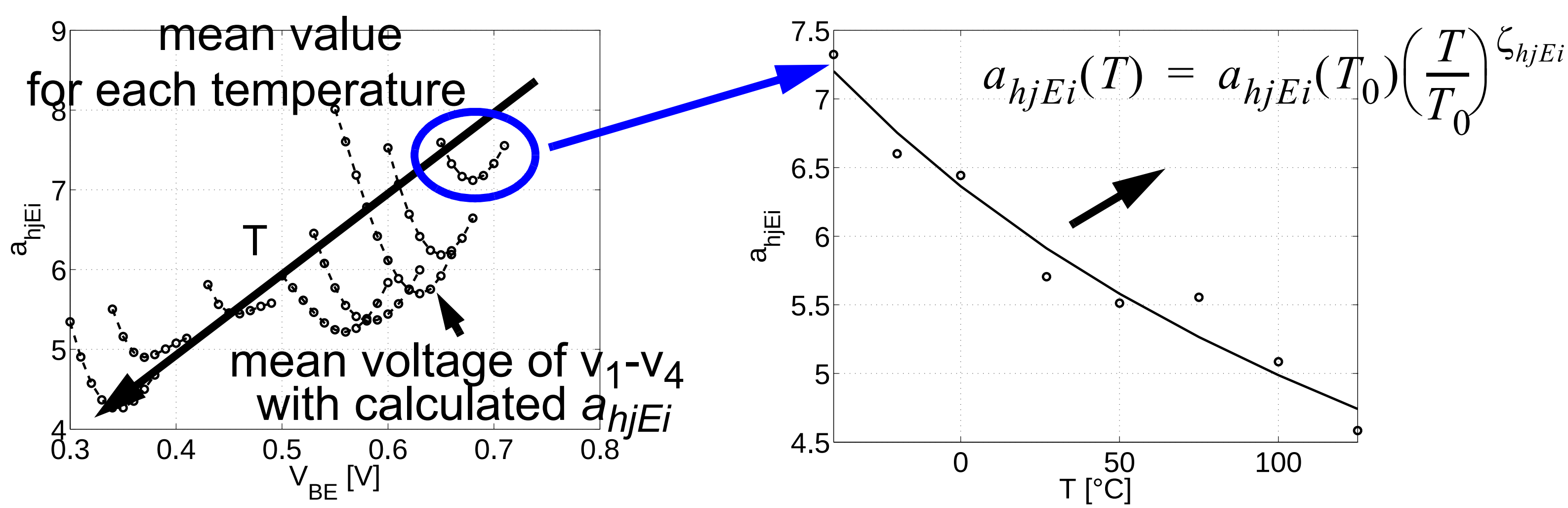
- Negligible self-heating in this region
  => extraction can be done for each temperature separately.
- Required parameters: Q_{p0}, C_{jEi0}, V_{dEi}, z_{Ei}, a_{jEi}
- Unknown parameters: c_{10}, h_{jEi0}, a_{hjEi}
- Two separate steps: first for a_{hjEi}, second for c_{10} and h_{jEi0}
- With $I_S = c_{10}/Q_{p0}$, $h(V_{BE}) = \frac{h_{jEi}(V_{BE})}{h_{jEi0}}$, $V_{Er} = \frac{Q_{p0}}{h_{jEi0}C_{jEi0}}$ follows

$$i_T = \frac{I_S}{1 + \frac{h(V_{BE})v_j(V_{BE})}{V_{Er}}} \exp\left(\frac{V_{BE}}{V_T}\right) \quad \Rightarrow \quad V_{Er} + hv_j = \frac{V_{Er}I_s \exp(V_{BE}/V_T)}{i_T}$$

- With four combinations of $I_C(V_{BE})$ => nonlinear equation for a_{hjEi}

$$\frac{h(v_1, a_{hjei})v_j(v_1) - h(v_2, a_{hjEi})v_j(v_2)}{h(v_3, a_{hjEi})v_j(v_3) - h(v_4, a_{hjEi})v_j(v_4)} = \frac{\left(\frac{\exp(v_1/V_T)}{i_1} - \frac{\exp(v_2/V_T)}{i_2}\right)}{\left(\frac{\exp(v_3/V_T)}{i_3} - \frac{\exp(v_4/V_T)}{i_4}\right)}$$

- a_{hjEi} now can be calculated by solving the non-linear equation
  - Differences between voltages may not be too small to avoid errors due to noise.
  - In practical application, ΔV=30 mV between each voltage was sufficient.
  - Step can be repeated for several combinations of voltages.

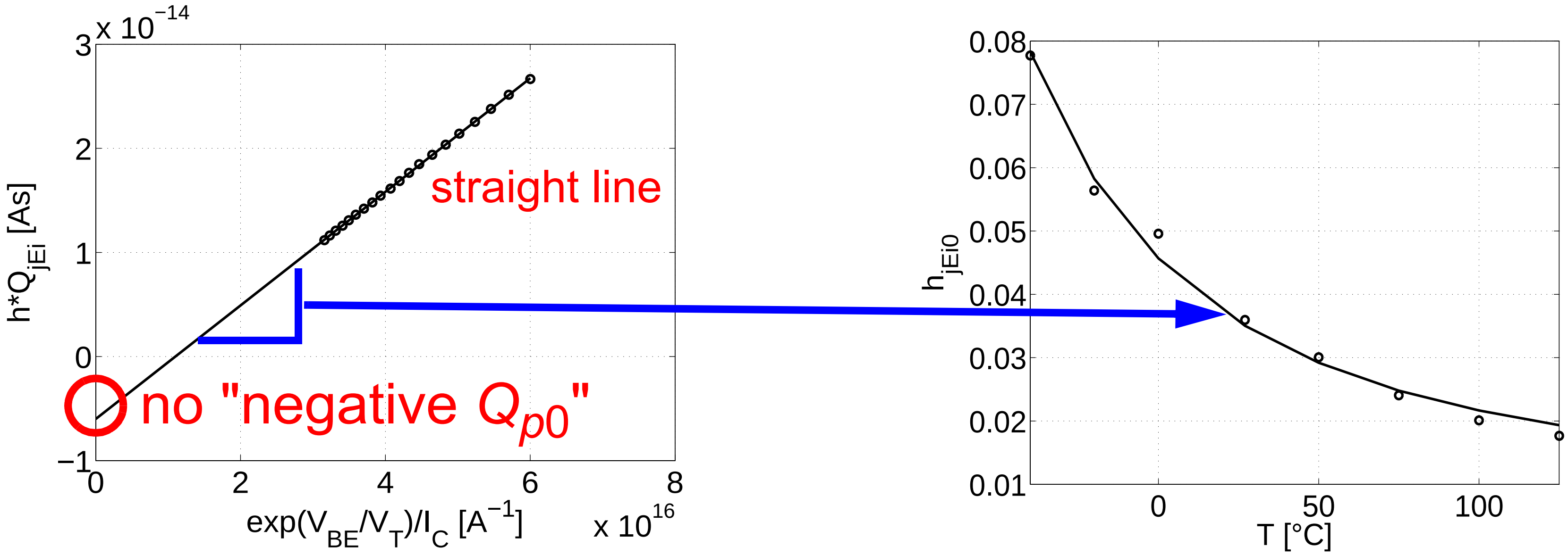


- Extraction for h_{jEi0} and c_{10} based on extended extraction, related to [1].
  - Rewriting transfer current

$$hQ_{jEi} = -\frac{Q_{p0}}{h_{jEi0}} + \frac{c_{10}}{h_{jEi0}} \frac{\exp(V_{BE}/V_T)}{i_T} \qquad \text{with}$$

$$h_{jEi0}(T) = h_{jEi0}(T_0)\exp\left(\frac{\Delta V_{gBE}}{V_T}\left(\frac{T}{T_0}-1\right)+r_{ahjEi}(a_{hjEi}(T_0)-a_{hjEi}(T))\right)$$

  - Results for 27 °C (same for all temperatures)



=> Temperature dependence as predicted!

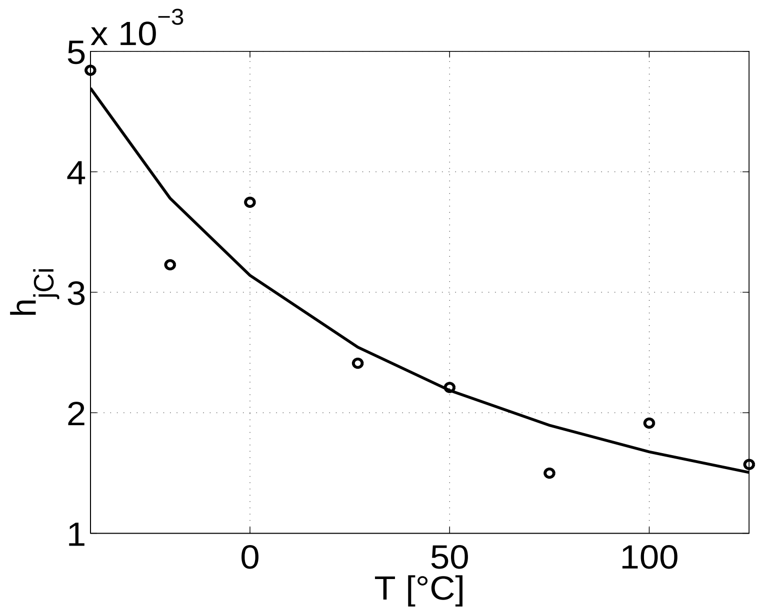
Extraction step - output characteristics

- h_{jCi} based on extraction shown in [1].
- Possible temperature dependence of h_{jCi} (as suggested by Z.H./D.C.)
- Following equation:

$$h_{jCi}(T) = h_{jCi}(T_0)\exp\left(\frac{\Delta V_G}{V_T}\left(\frac{T}{T_0} - 1\right)\right)$$

with ΔV_g=-50 mV

- Yet to be verified by device simulation.
- Temperature dependencs not included since no visible effect on I_C and g_m.



Extraction step - high current region

- Required parameters
  - Transit time including temperature dependence.
  - External resistances including temperature dependence.
  - Thermal resistance.
- For reliable results, device temperature needs to be calculated
  - Model used: $\Delta T = i_T V_{CEi} R_{th}$ with $i_T = I_C$ from measurements
  - Therefore, the non-linear equation

$$\Delta T - I_C(V_{CE} - I_C r_{Cx}(\Delta T) - I_E r_E(\Delta T)) R_{th} = 0$$

  must be solved in each operating point.
- Using these values, the final Q_{pT} is calculated

$$Q_{pT} = \frac{c_{10}(T)\exp(V_{BEi}/V_T)}{I_C}, \quad T = T_0 + \Delta T$$

- Calculation of the final minority charge for each operating point

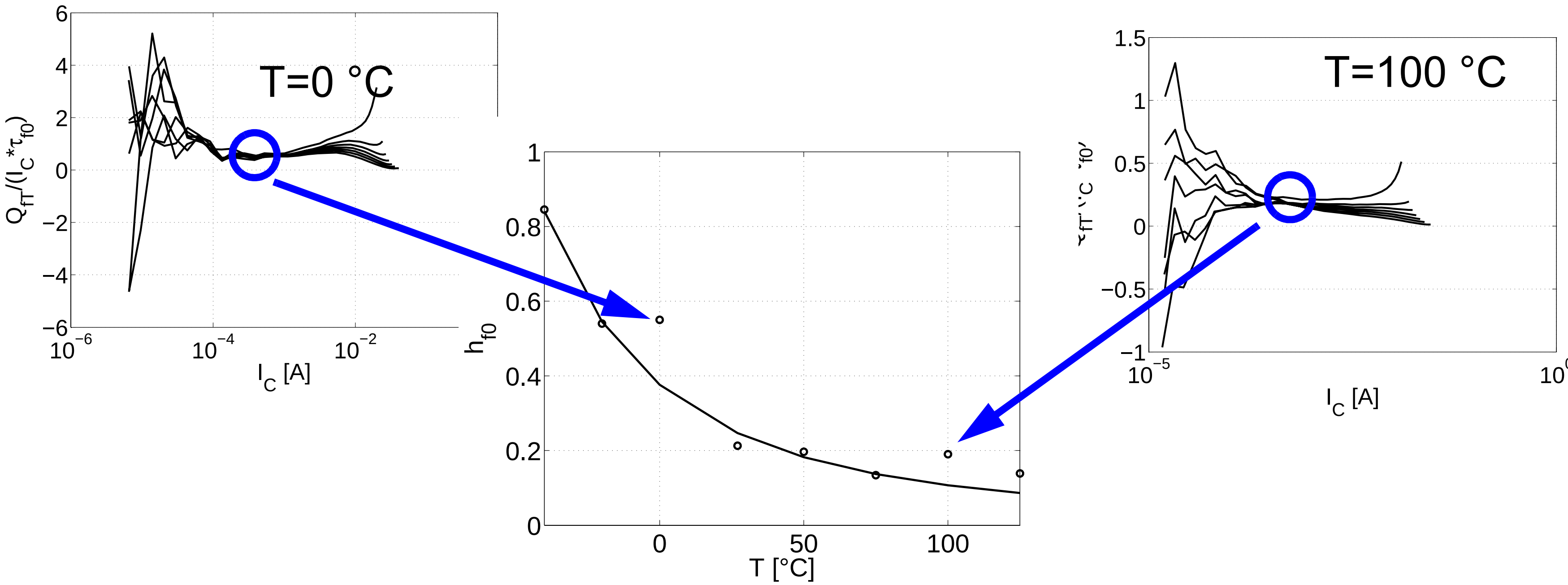
$$Q_{fT} = Q_{pT} - Q_{p0}(T) - h_{jEi}(V_{BEi}, T)Q_{jEi}(V_{BEi}, V_T) - h_{jCi}Q_{jCi}(V_{BCi}, T)$$

Components (@ $V_{CEi} > 8V_T$)

Corresponding transit times are low for low currents

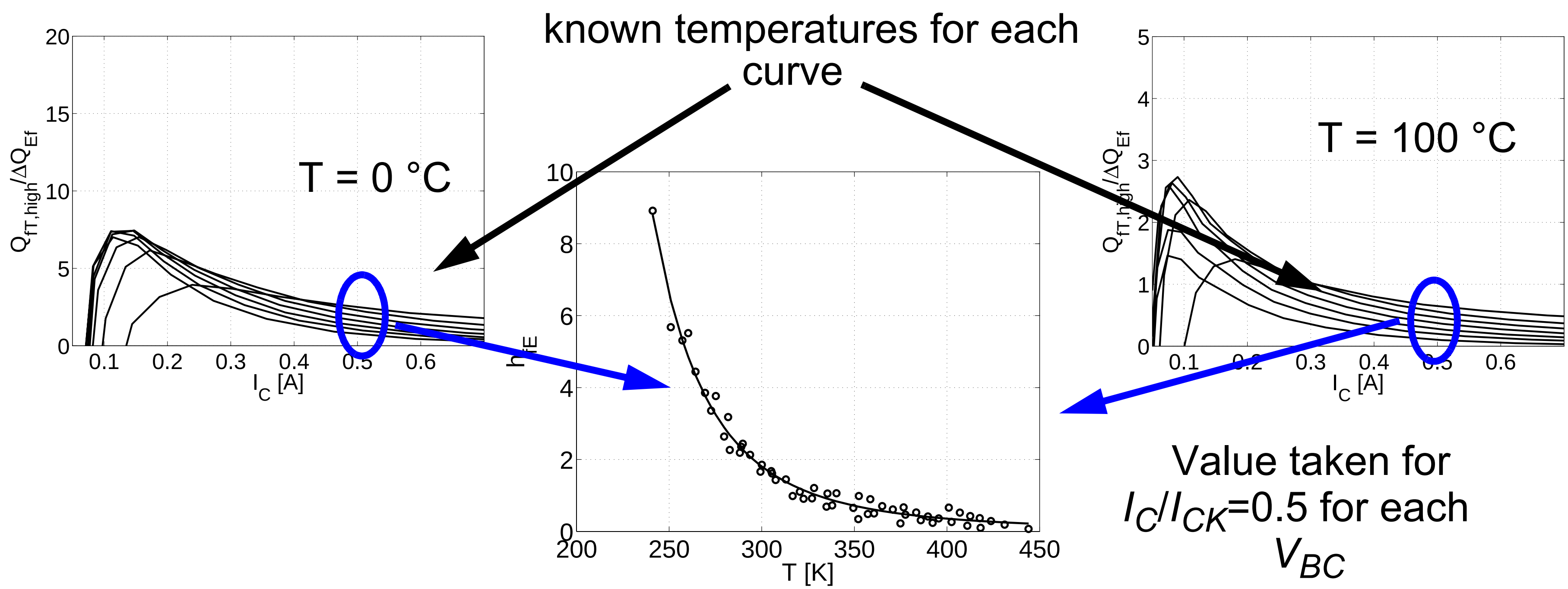
Everything known including temperature dependences

$$Q_{fT} = h_{f0}\tau_{f0}i_{Tf} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}\Delta Q_{Cf} \quad \Rightarrow \quad \lim_{i_T \to 0} \frac{Q_{fT}}{i_T \tau_{f0}} = h_{f0}$$



- Extraction of h_{fE} also by subtracting all known parts from Q_{pT} (including $h_{f0}{}^{*}\tau_{f0}$)
- Emitter charge ($i_{Tf} = i_C$): $\Delta Q_{Ef} = \Delta\tau_{Ef}\dfrac{i_C}{1+g_{\tau fe}}$ with $\Delta\tau_{Ef} = f\left(\dfrac{i_C}{I_{CK}}, T\right)$
- For $\dfrac{I_C}{I_{CK}}$ not larger than 0.5 => ΔQ_{Bf} and ΔQ_{Cf} negligible => $Q_{fT} = h_{f0}\tau_{f0}i_{Tf} + h_{fE}\Delta Q_{Ef}$

=> $Q_{fT,\,high} = Q_{fT} - h_{f0}\tau_{f0}i_C$ and $h_{fE} = \dfrac{Q_{fT,\,high}}{\Delta Q_{Ef}}$, $h_{fE}(T) = h_{fE}\exp\left(\dfrac{v_{gB}-v_{gE}}{V_T}\left(\dfrac{T}{T_0}-1\right)\right)$



Model results

Comparison for all temperatures

- Experimental results @ VBC=[-0.5 0 0.5] V
- HICUM/L2 v2.24G dashed lines
- HICUM/L2 v2.30 solid lines

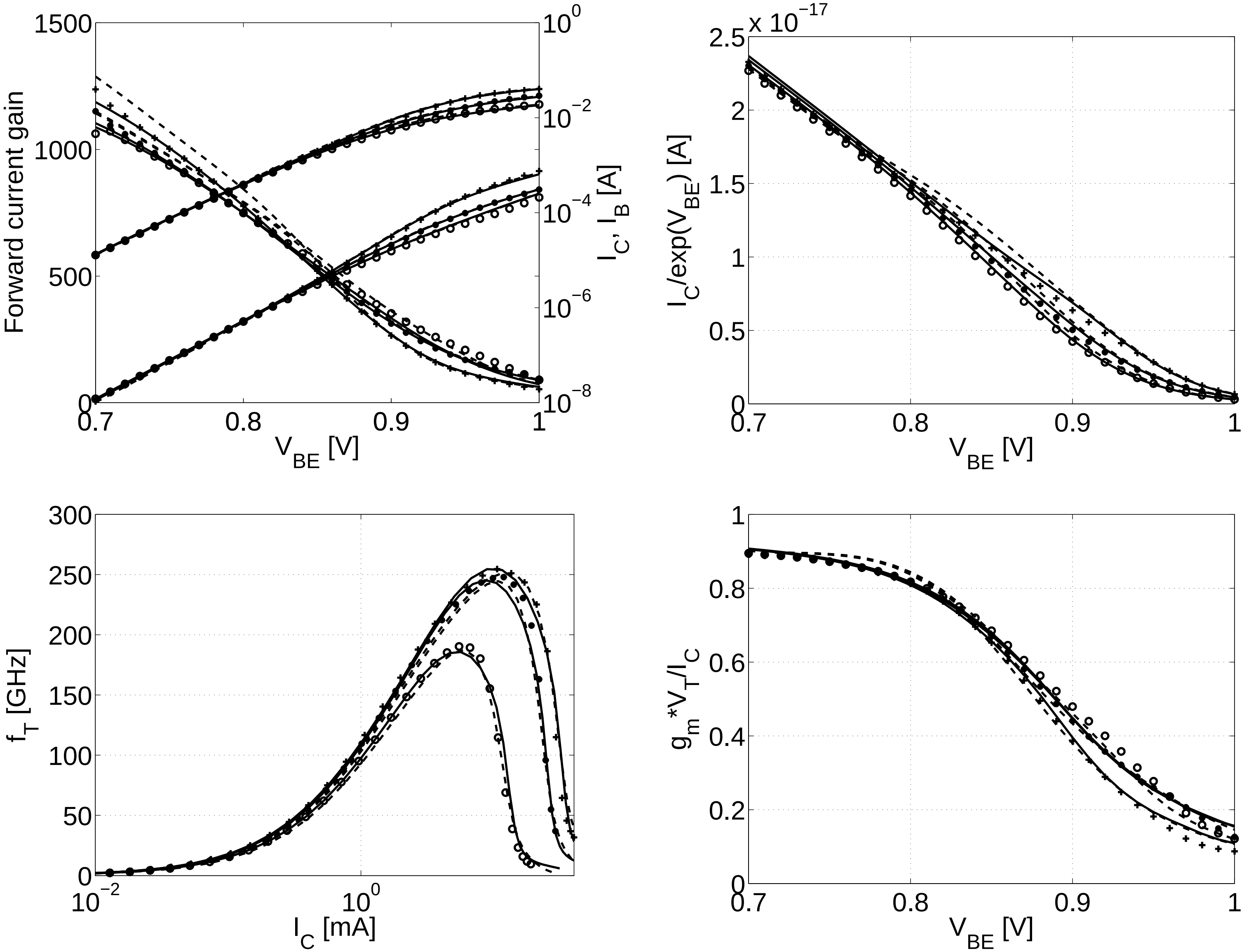
Notes

- No fine-tuning of parameters relating to the GICCR, except for c_{10} for high temperatures and I_{BEis}.

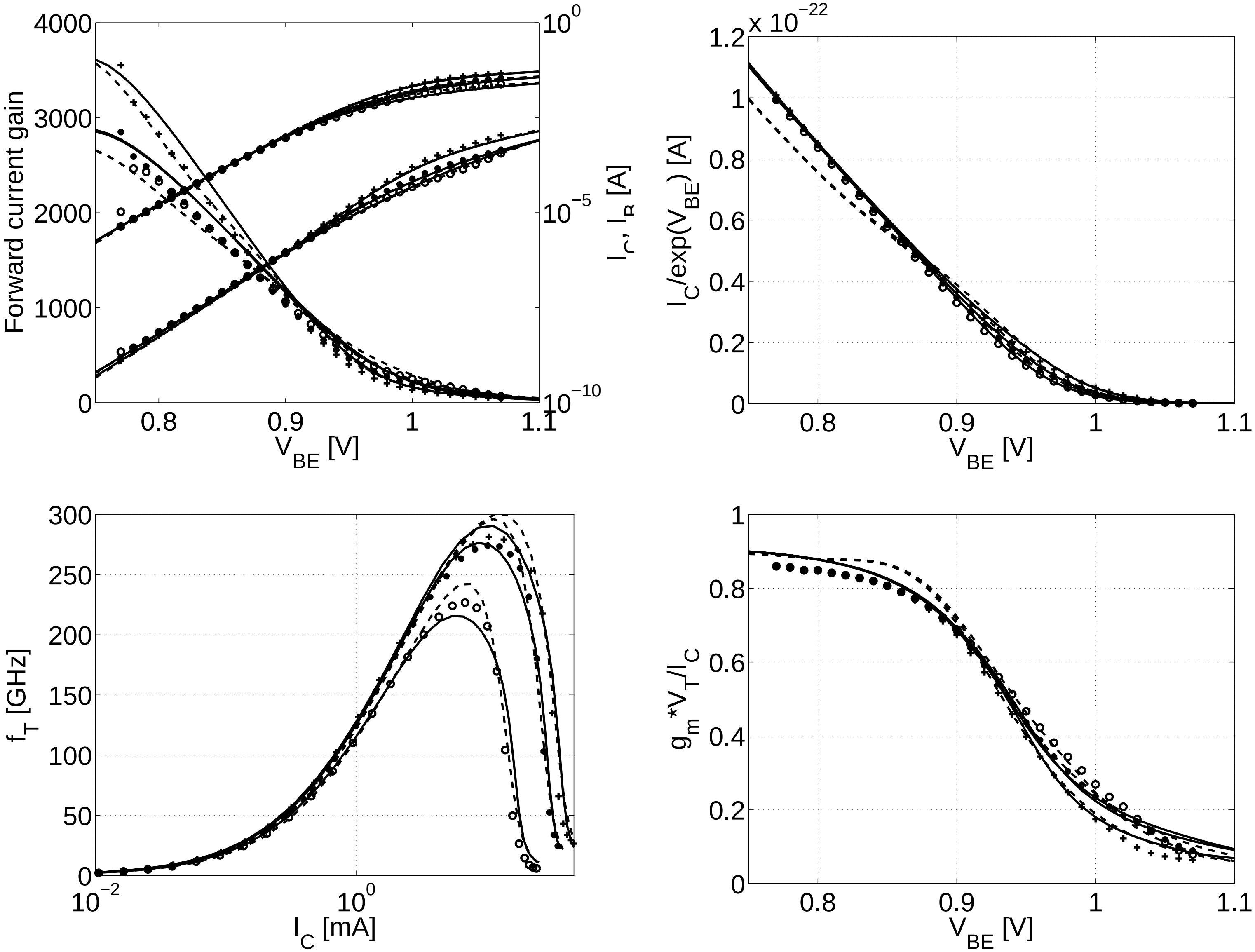
=> Automatic extraction possible

- Added normalized transconductance due to its importance for circuit design
- Shown g_m corresponds to Re(Y_{21}) @ 1 GHz.
- Simulated f_T from spot frequency method 1 GHz.

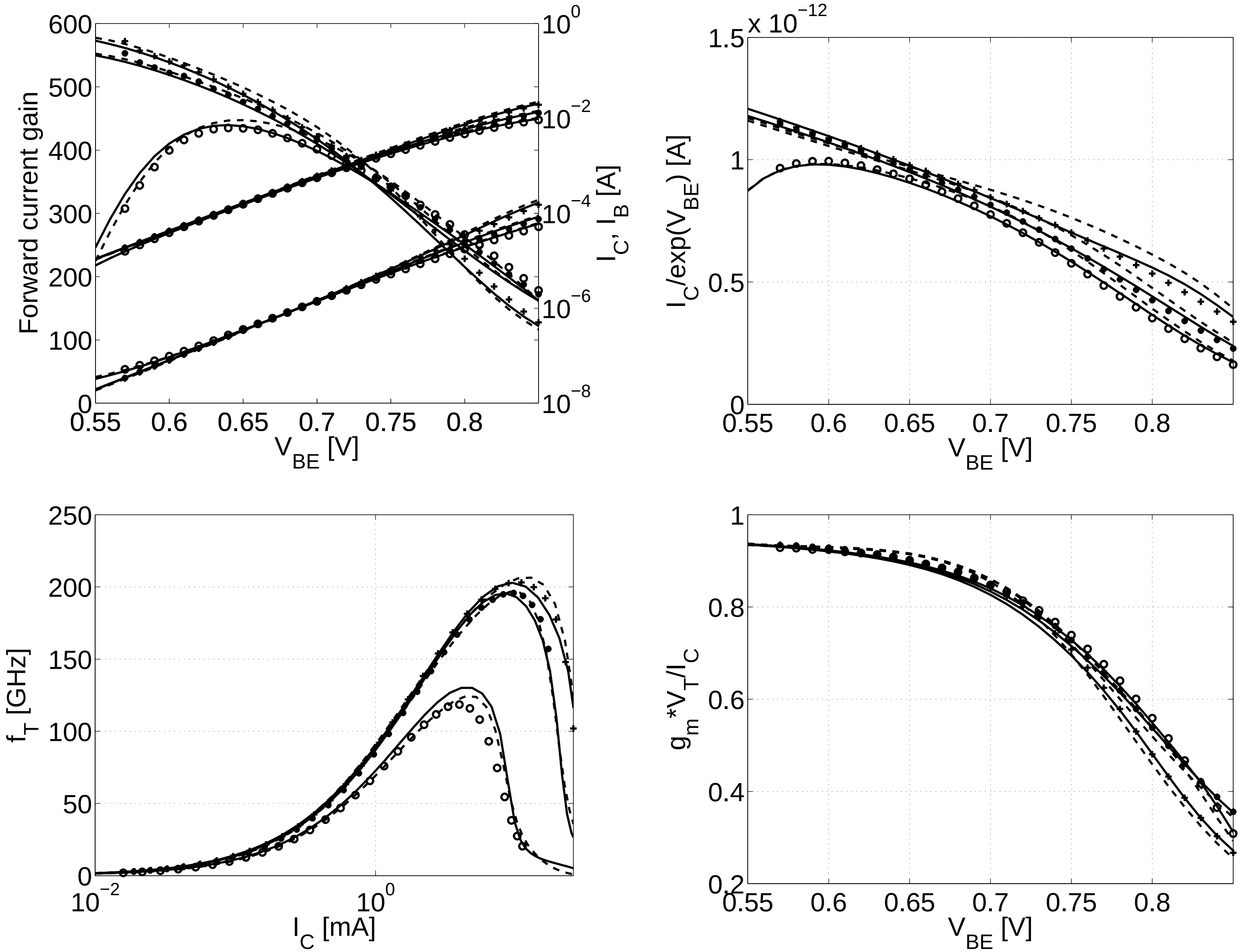
Reference temperature: T=27 °C



Low temperature: T=-40 °C



High temperature: T=125 °C



Summary

- Very good match of I_C for all temperatures and operating ranges.
- Small differences in current gain almost always caused by parasitic base current.
- Very good results for f_T and g_m.

=> excellent simultaneous match of DC and AC characteristics

- Using HICUM/L2 v2.30
  - Physics-based parameters with predicted temperature dependence.
  - Reliable extraction methods for all new parameter exist.
  - Very good results even for single transistor extraction.

=> CONCLUSION:

HICUM/L2 v2.30 is suitable for advanced SiGe-HBTs with equations and parameters that are directly related to the vertical structure of the device.

Acknowledgments

Special thanks to:

- Didier Céli (ST) for providing experimental results and model cards
- Zoltan Huszka (AMS) for code and support on HICUM/L2 v2.24G
- Christian Raya (XMOD) for comments on emitter transit time

This work was supported by:

- EC IP DotFive project
- DFG
- BMBF

Reference

[1] D. Berger, D. Céli, M. Schröter, M. Malorny, T. Zimmer, B. Ardouin, „HICUM Parameter Extraction Methodology for a single Transistor Geometry“, IEEE BCTM 6.3, 2002, 116-119.

[2] Z. Huszka, D. Céli and E. Seebacher, “A Novel Low-Bias Charge Concept for HBT/BJT Models Including Heterobangap and Temperature Effects - Part I: Theory”, IEEE Trans. Electron. Dev., reviewers proposed for publication.

[3] Z. Huszka, D. Céli and E. Seebacher, “A Novel Low-Bias Charge Concept for HBT/BJT Models Including Heterobangap and Temperature Effects - Part II: Implementation, Parameter Extraction and Verification”, IEEE Trans. Electron. Dev., reviewers proposed for publication.