Automated Transit Time and Transfer Current Extraction

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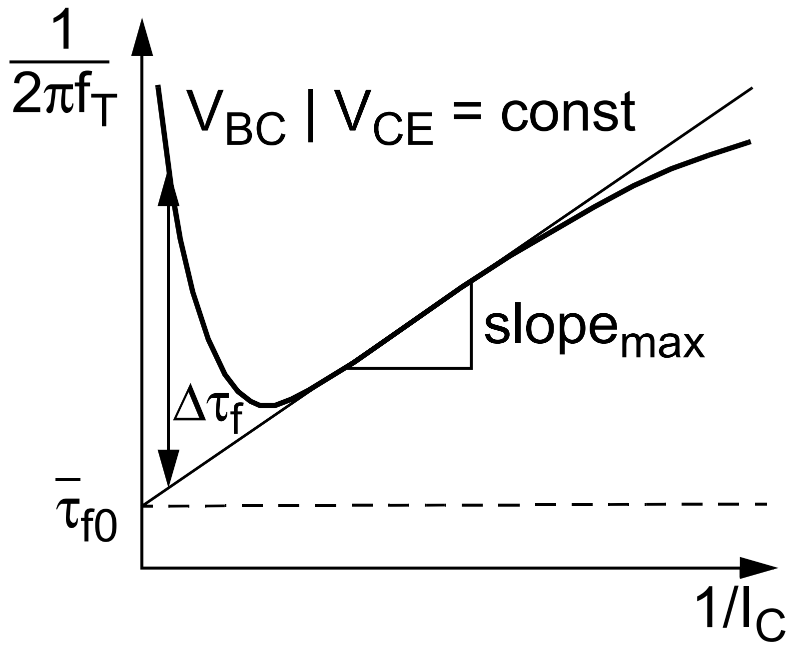
Outline

- Introduction & motivation
- Method overview
- Extraction procedure (τ_f)
- Extraction procedure (I_T)
- Results
- Conclusion

Introduction

- Classical approach for transit time (τ_f) extraction yields inaccurate results
  - perform example extraction (e.g. [1]) based on simulation data

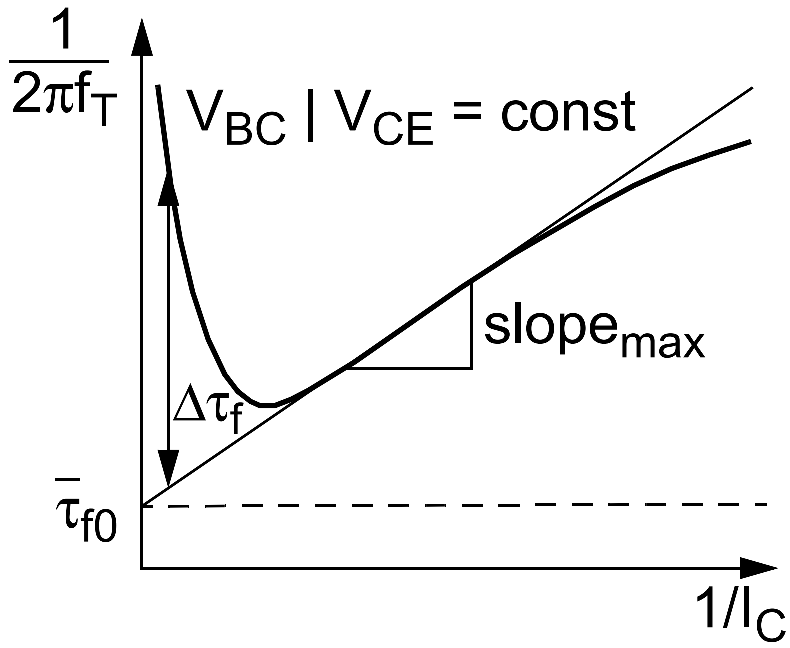


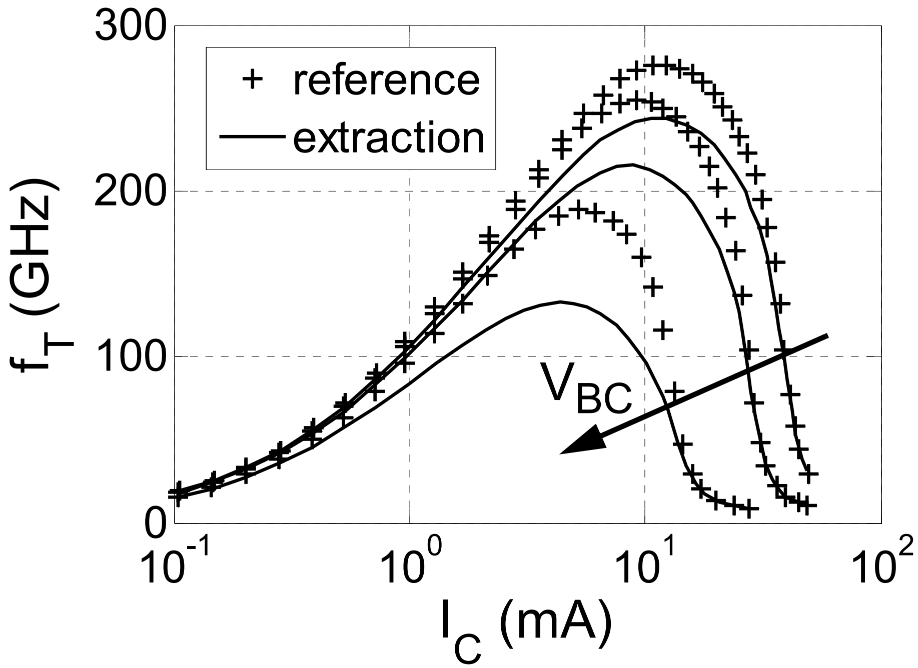
Classical method:
extrapolate $\bar{\tau}_{f0}$ data from f_T vs. $1/I_C$

[1] B. Ardouin et al., “Transit time parameter extraction for the HICUM bipolar compact model”, in Proc. IEEE BCTM, pp. 106 - 109, 2001.

Introduction

- Classical approach for transit time (τ_f) extraction yields inaccurate results
  - perform example extraction (e.g. [1]) based on simulation data





=> discrepancy caused by inaccurate τ_f determination

Motivation

- Accuracy
  - classical approach for transit time (τ_f) extraction yields inaccurate results
- Handle complexity
  - large number of involved HICUM parameters: 33 in total
  - self-heating (SH), base current (I_B) and τ_f affect transfer current (I_T) at high current densities
- Flexibility
  - approach in [2] is a closed-form analytical system
  - model related adjustments are ment to be easy
- Automation
  - optimum condition: “One-click” extraction

[2] M. Malorny, M. Schroter, “Analytical Method for Calculating Elements of an Arbitrary Equivalent Circuit”, MIXDES, pp. 79 - 84, 2004.

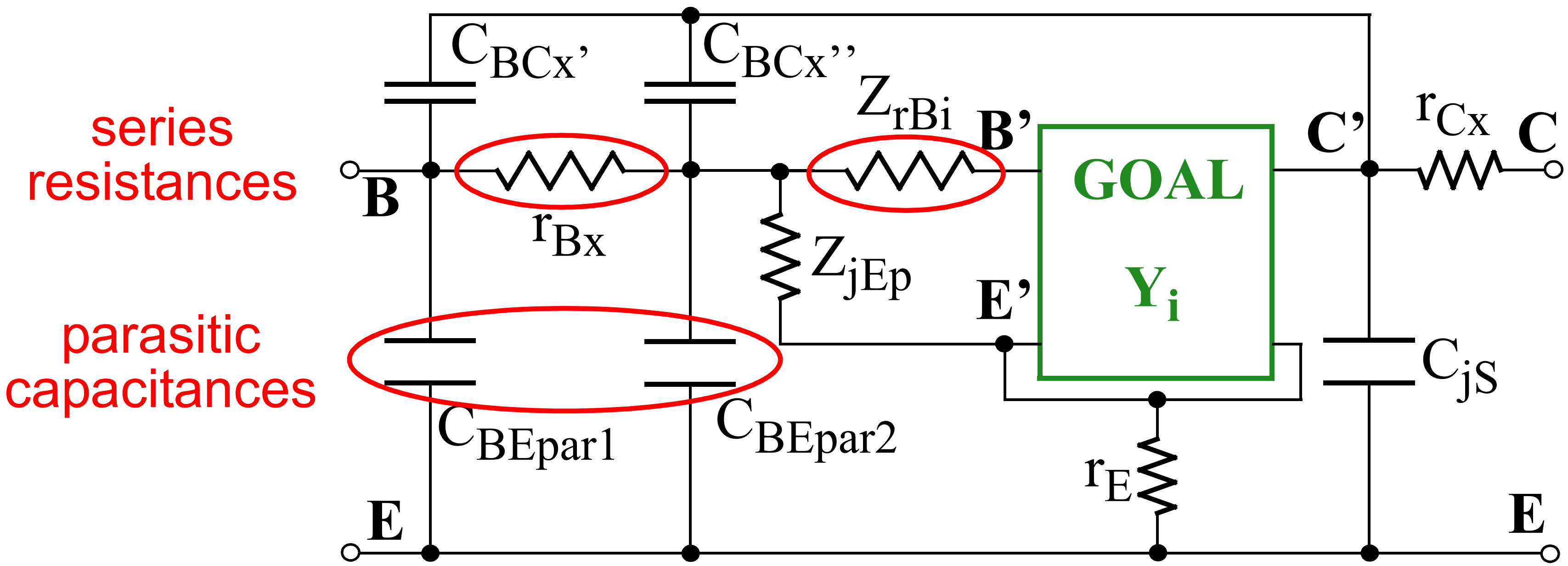
Method overview

- Transit time is associated with intrinsic transistor
  - external elements influence extraction process

  => Deembedding of external elements necessary

- Small-signal common-emitter equiv. circuit of HICUM
  - substrate transistor, -diode and -network, NQS deactivated

  => negligible for forward active region & medium frequencies



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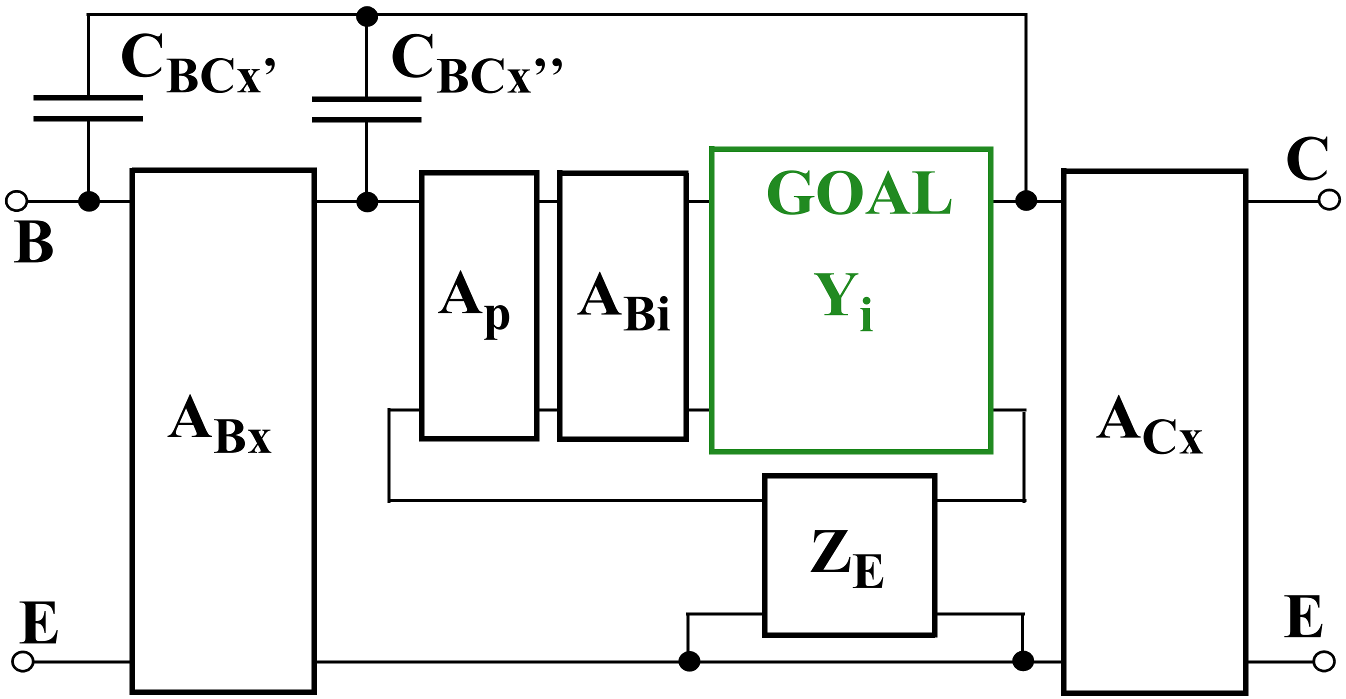
Deembedding procedure

- Express suitable sets of elements by sub-two-port
  => various options for arranging two-ports



two-ports of $C_{BC'}$ and $C_{BC''}$ not shown

- Further details on deembedding

[3] T. Rosenbaum et al., “Automated Transit Time and Transfer Current Extraction for Single Transistor Geometries”, in Proc. IEEE BCTM, pp. 106 - 109, 2013.

Extraction procedure (τ_f)

- Result of deembedding & internal transistor analysis

master equation: $$\boxed{\tau_{fit}} = \frac{\Im\{y_{i11} + y_{i21}\}}{g_m \omega} = \tau_f + \frac{C_{\tau f0}(\tau_{f0}) + C_{jEi}}{g_m}$$

with $$C_{\tau f0} = I_{Tf} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}}$$ and $$g_m \cong Re\{y_{i21}\}, \quad I_{Tf} \cong I_C$$

- Equation contains 21 parameters in total

=> least square fit is likely to fail

- Proposed solution
  - split up τ_f into distinct regions

=> apply fit to smaller parameter-subsets

=> couple subsets (loop) for final solution

Self heating

- Strongly affects high current region (extr. of I_{CK} & I_C)
  - calculate internal device temperature

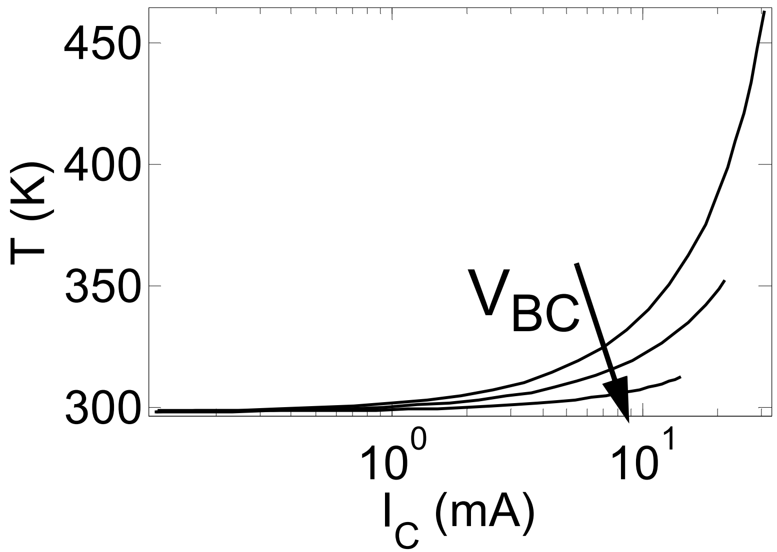
$$I_C V_{C'E'}(T) R_{th}(T) - T + T_0 = 0$$

$$\text{with} \quad V_{C'E'}(T) = V_{CE} - I_C r_{Cx}(T) - I_E r_E(T)$$

=> Solve implicit equation w.r.t. T

Required preextracted parameters

- r_{Cx}, r_{th} & r_E
- corresponding temp. coeff.



=> Include SH by considering T_j in every extraction step

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Master equation

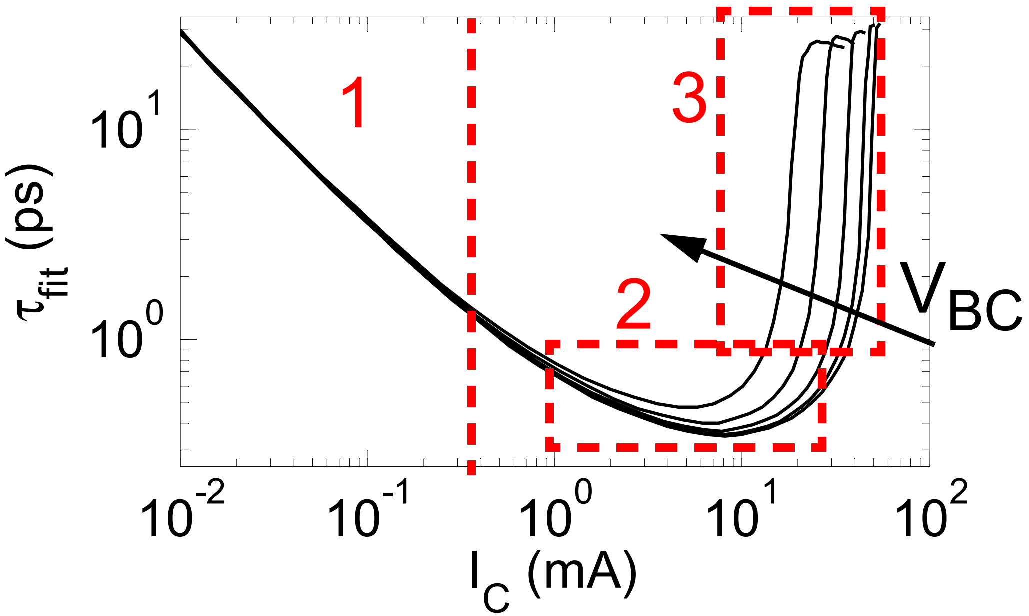
- Handling the master equation

$$\boxed{\tau_{fit}} = \tau_f + \frac{C_{\tau f0}(\tau_{f0}) + C_{jEi}}{g_m}$$ => key to successful extraction

- Result of deembedding process: τ_{fit}

three distinct regions

- 1: C_{jEi} / g_m dom.
- 2: τ_{f0} dom.
- 3: $\Delta\tau_f$ dom.



=> extraction split up should be possible

=> run loop over regions for interaction

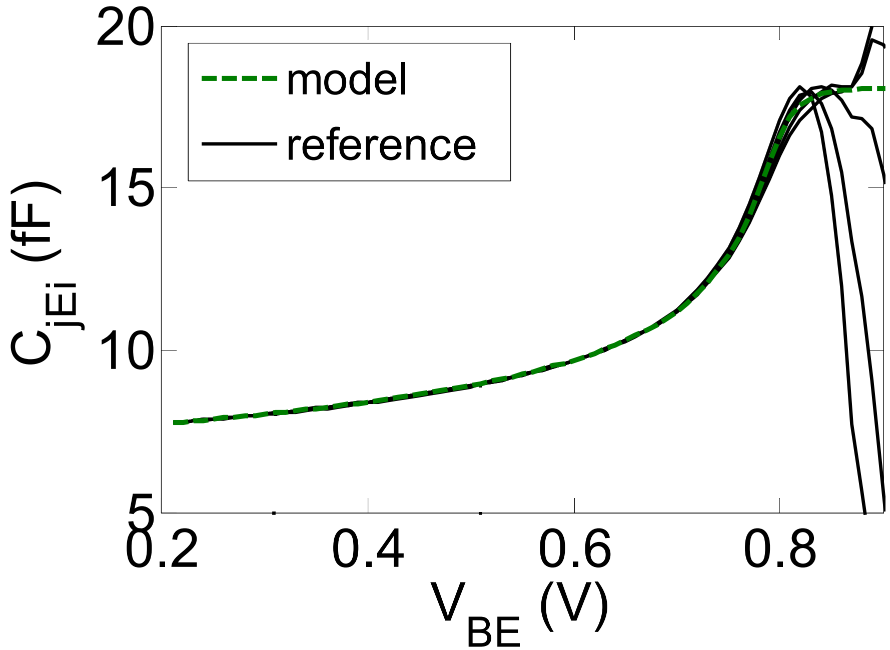
Region 1 of τ_{fit}

- R1 can be used to extract parameters for C_{jEi}
  - rearrange master equation for capacitance

$$C_{jEi} = (\tau_{fit} - \tau_f)g_m - C_{\tau f0}(\tau_{f0})$$

First iteration
- τ_f & $C_{\tau f0}$ unknown
=> set to Zero

Global loop
- insert τ_f & $C_{\tau f0}$
=> allows parameter interaction



- Usual measurement range: $V_{BE} > 0.7$ V
  - allows to tune a_{jEi} & (V_{DEi})
- All parameters for C_{jEi} can be adjusted for TCAD data

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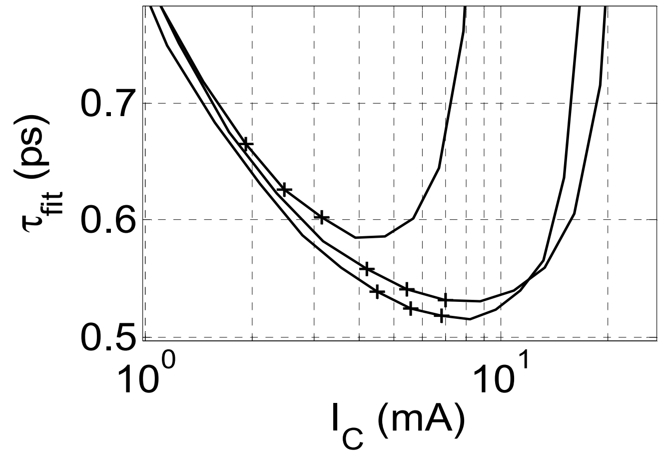
Region 2 of τ_{fit}

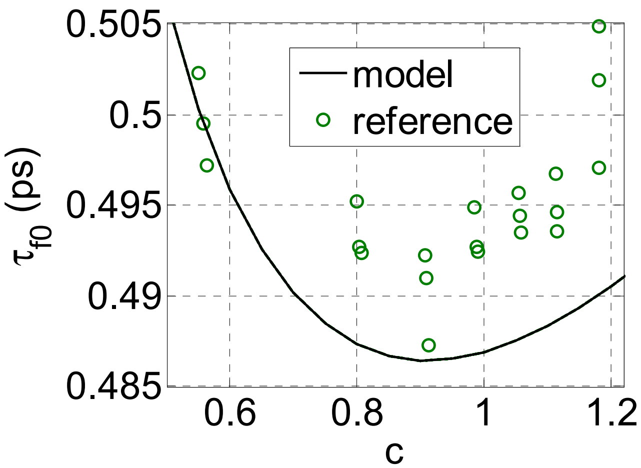
- R2 is influenced by C_{jEi} & $\Delta\tau_f$!
  - how to select appropriate data for τ_{f0}?

  => select lhs of min(τ_{fit})

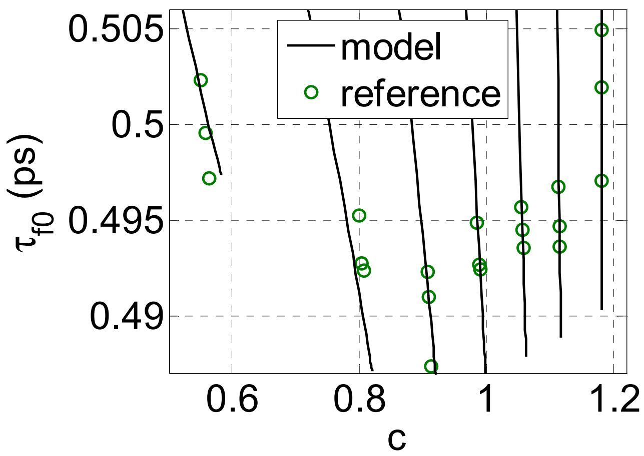


- Rearrange master equation

$$\tau_{f0} = \tau_{fit} - C_{jEi}/g_m - C_{\tau f0}/g_m - \Delta\tau_f$$



without SH



with SH

=> SH can already be observed for τ_{f0} extraction

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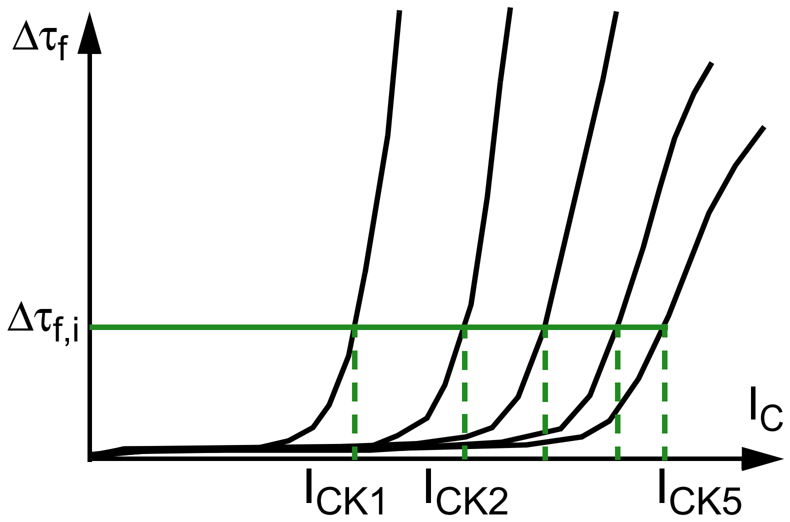
Region 3 of τ_{fit}

- Rearrange master equation for $\Delta\tau_f$

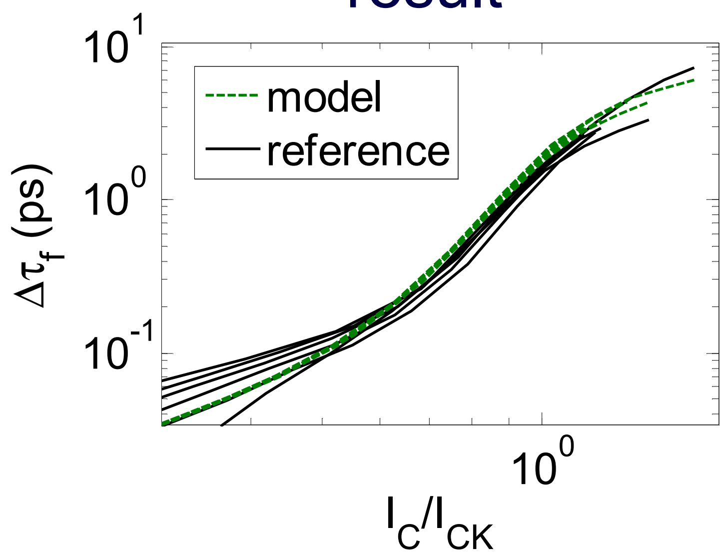
$$\Delta\tau_f = \tau_{fit} - C_{jEi}/g_m - C_{\tau f0}/g_m - \tau_{f0}$$

- How to extract the critical current?
  - obtain starting values first: e.g. standard method of [1]

method



result



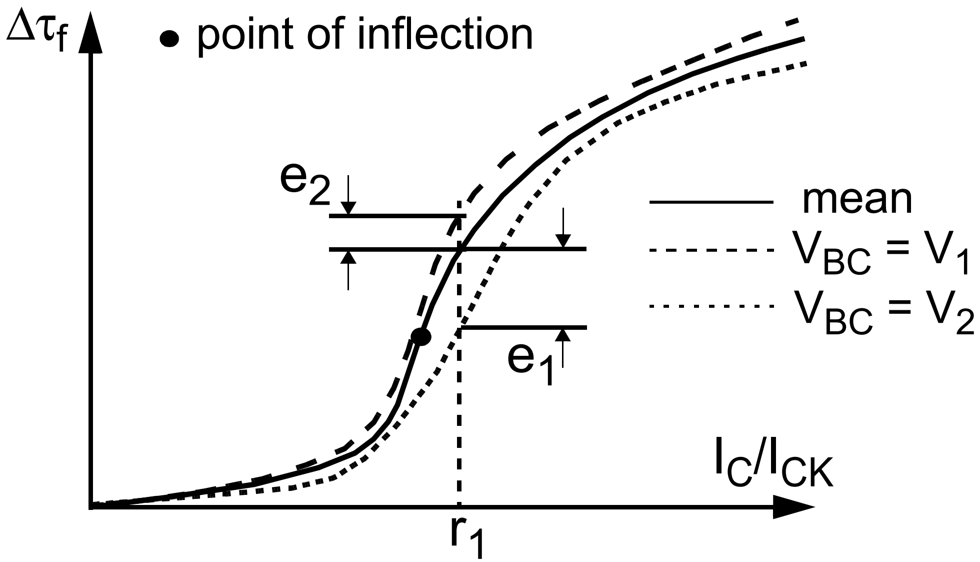
- Extracted values for I_{CKi} correspond to V_{CEi}

=> delivers first parameter set for further evaluation

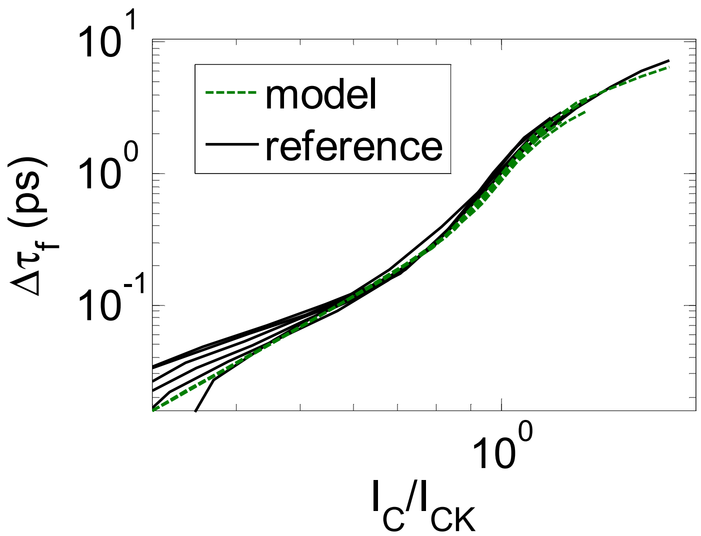
Critical current

- Further improvements possible?
  - for negligible SH: $\Delta\tau_f(I_C/I_{CK})$ curves must superimpose

method



result



- Advantages
  - no need for inception point, good medium current accuracy
  - amount of selected data increases

- But: might involve some errors in high current region due to SH

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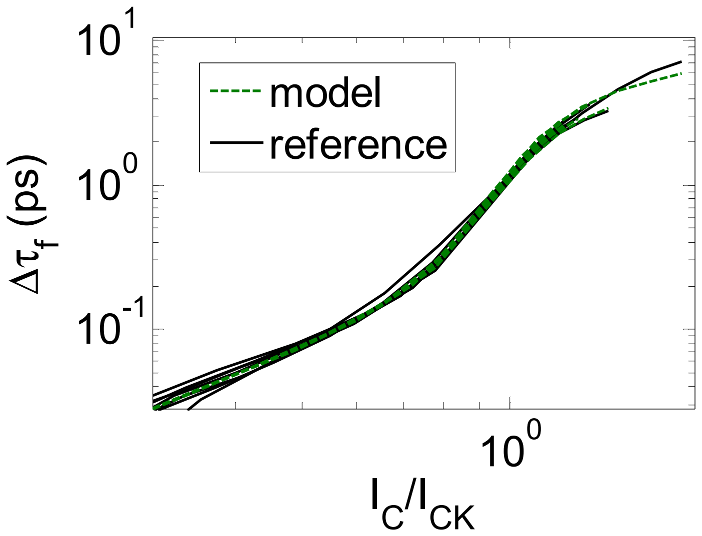
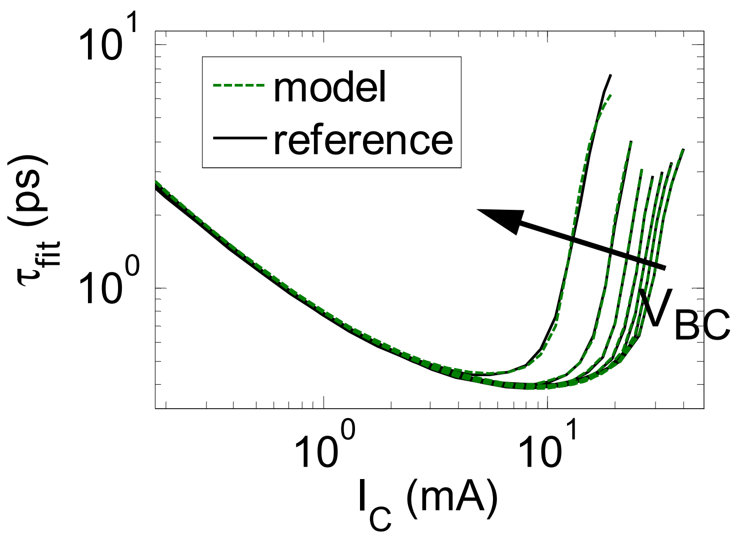
Extraction result for τ_{fit}

- Final step of $\Delta\tau_f$ extraction
  - previous step provides parameters sufficient for optimization
  - run optimization on $\Delta\tau_f(I_{CK},\tau_{hcs},\tau_{ef0})$ directly

$\Delta\tau_f$ result



τ_{fit} result



- Repeat steps for region 1 - 3
  - allow for parameter interaction (C_{jEi} <-> τ_{f0} <-> $\Delta\tau_f$)

=> τ_{fit} is reproduced

Extraction procedure (I_T)

- Low current description in HICUM

$$I_{Tf} = \frac{c_{10}}{Q_{p0} + h_{jEi}(V_{BEi})Q_{jEi}} \exp\left(\frac{V_{BEi}}{V_T}\right)$$

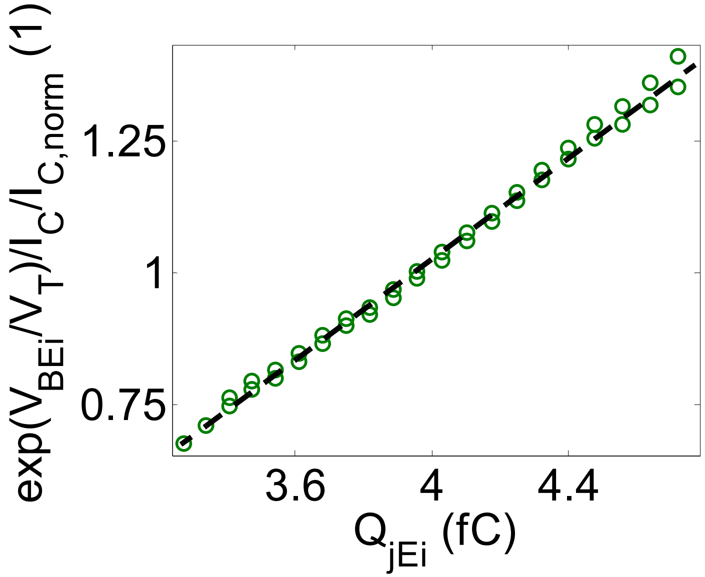
- Standard extraction of c_{10} & h_{jEi}

straight line? $$\frac{\exp(V_{BEi}/V_T)}{I_C} = \frac{Q_{p0}}{c_{10}} + \frac{h_{jEi}(V_{BEi})Q_{jEi}}{c_{10}}$$

Did extraction work?

- not enough information to assess extraction result

=> check $g_{m,norm}$



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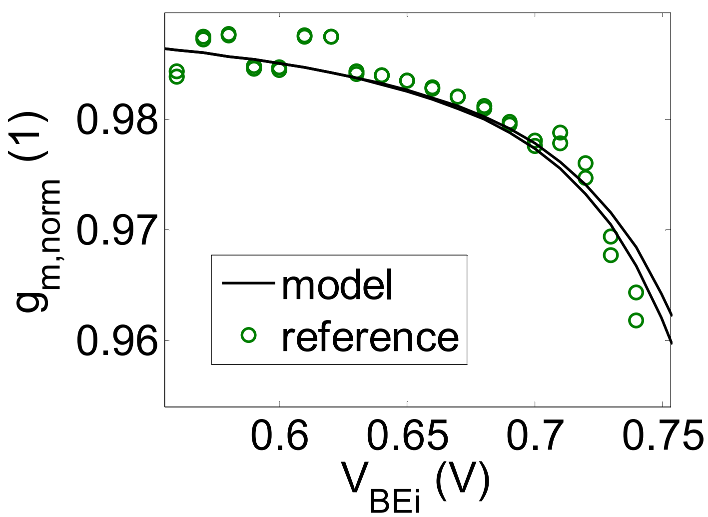
Normalized transconductance ($g_{m,norm}$)

- Definition

$$g_{m,\,norm} = V_T \frac{g_m}{I_C} \quad \text{and} \quad \frac{\partial}{\partial V_{BEi}} \ln(I_C) = \frac{1}{I_C} \frac{\partial I_C}{\partial V_{BEi}} = \frac{g_m}{I_C}$$

- Maximum value

$$g_{m,\,ideal} = I_C / V_T \;\; \Rightarrow \;\; g_{m,\,norm,\,max} = 1$$



Benefit

- larger sensitivity on change of h_{jEi} than standard method

=> use for optimization of a_{hjEi}

Extraction of high current weight factors

- Issue with calculating h_{fE}, h_{fC}
  - transit time depends on I_T and vice versa

- Usual approach
  - $I_T = I_{C,meas}$ assumed for calculating τ_f
  - but especially in the high current range:
    small errors cannot be avoided

  => leads to inconsistent determination of h_f and wrong results

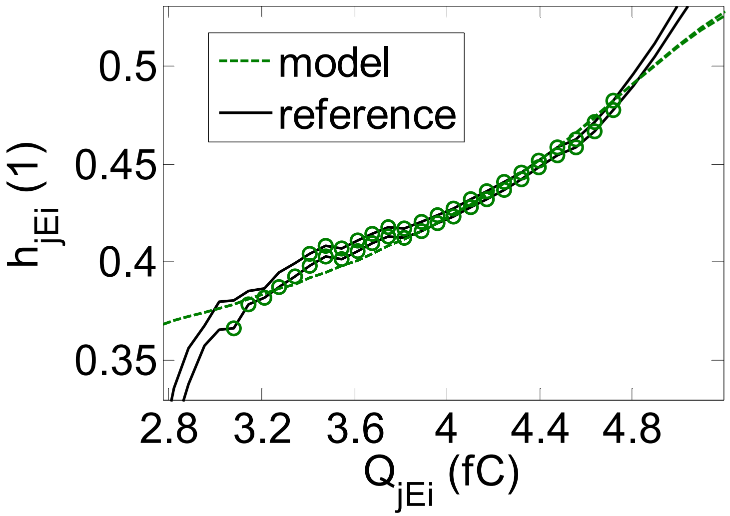
- Tedious approach
  - solve simplified HICUM transfer current equation
    - keep initially calculated internal voltages
    - keep initially calculated internal temperature

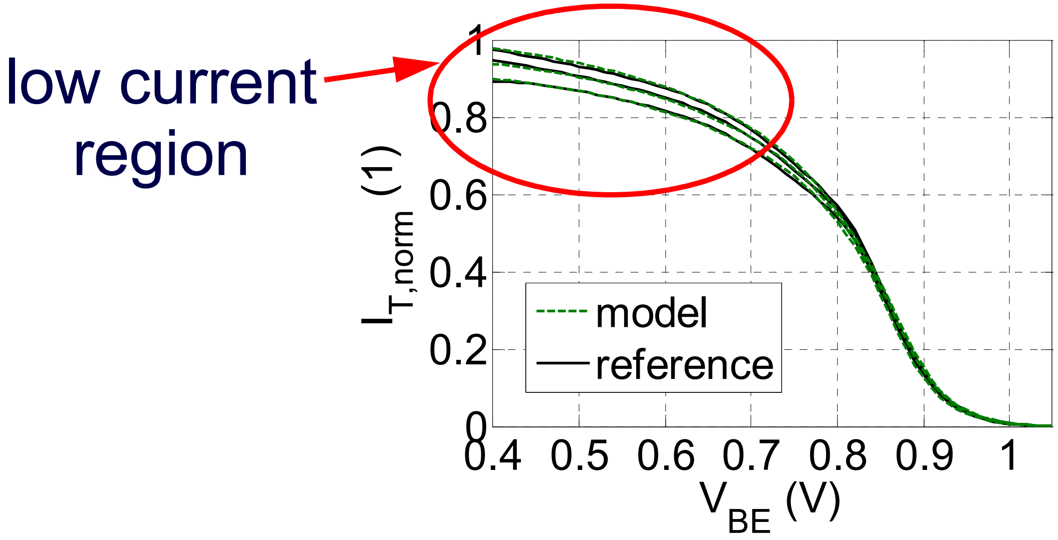
  - solve transfer current equation w.r.t. $Q(\tau_f)$

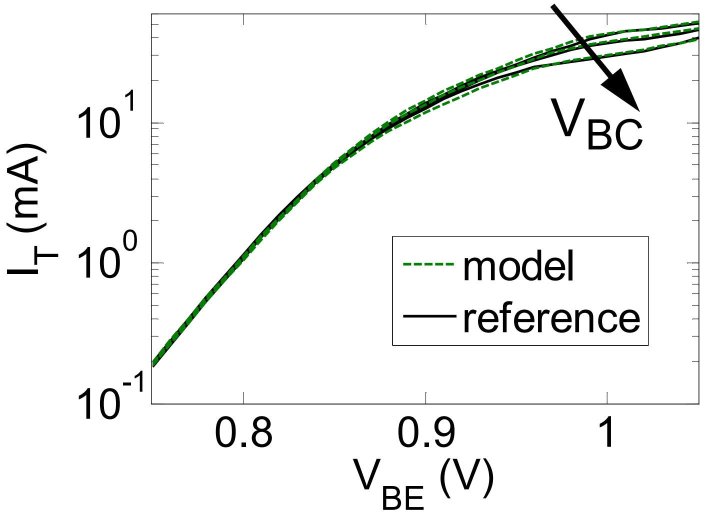
=> consistent data for τ_f & I_T

Transfer current result

- Overview of characteristics







Used extraction approach

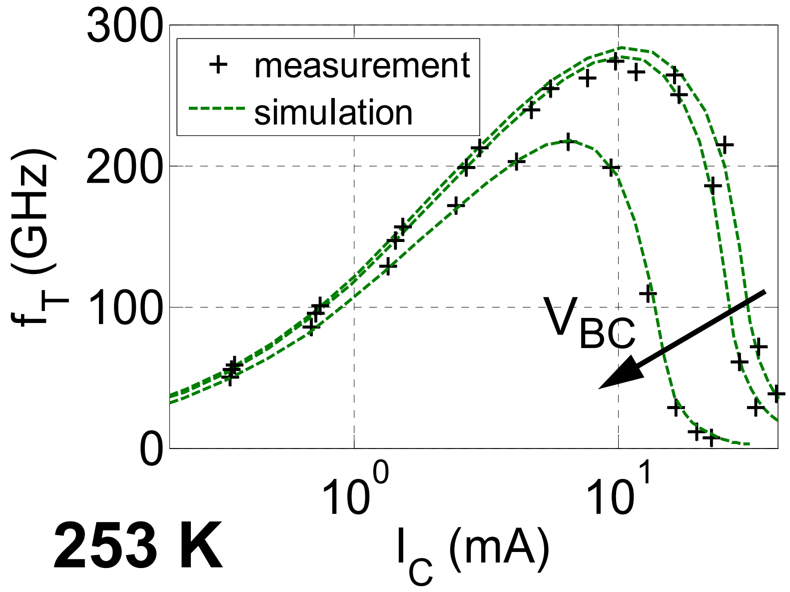
- standard method for c_{10} & h_{jEi}
- optimize a_{hjEi} on $g_{m,norm}$

=> loop for consistency

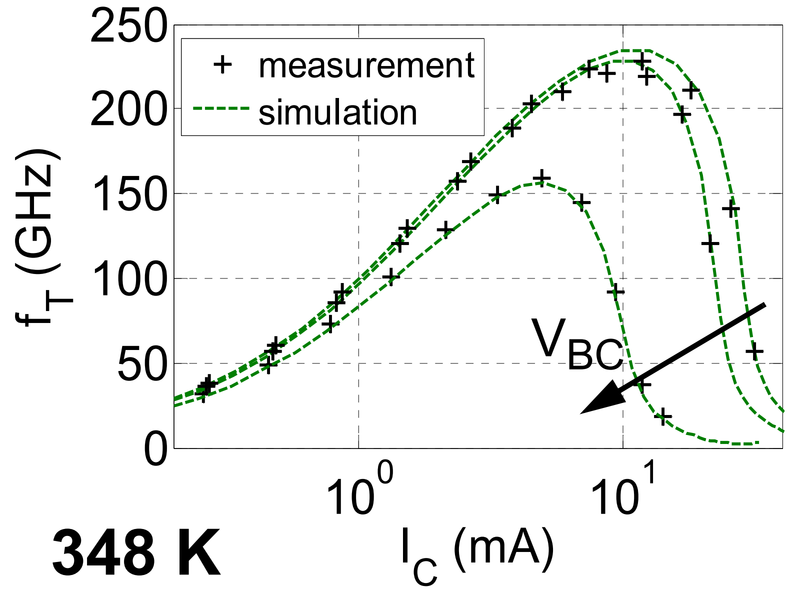
=> strategy is confirmed working

Results: ST BiCMOS9MW

transit frequency



253 K



348 K

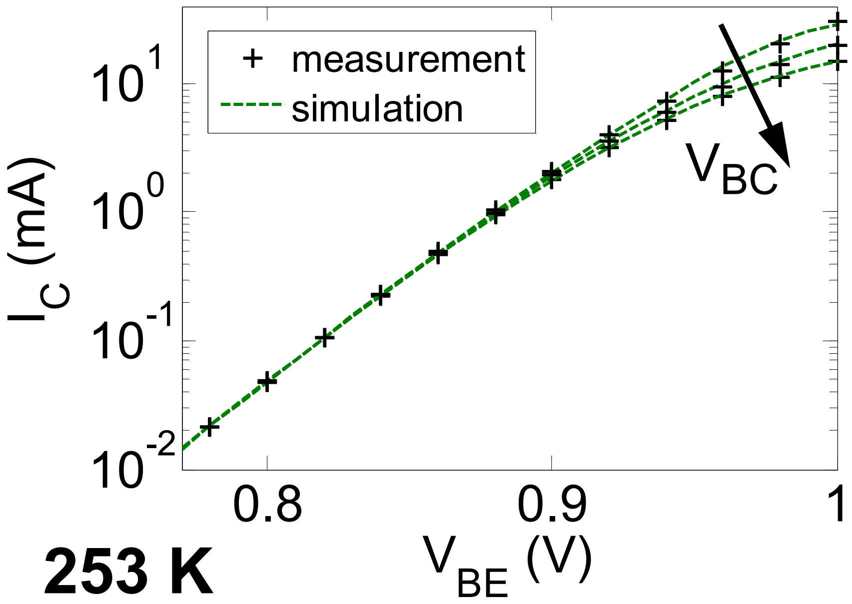
V_{BC} = [0.5, 0, -0.5] V

=> excellent agreement for whole bias range & temperatures

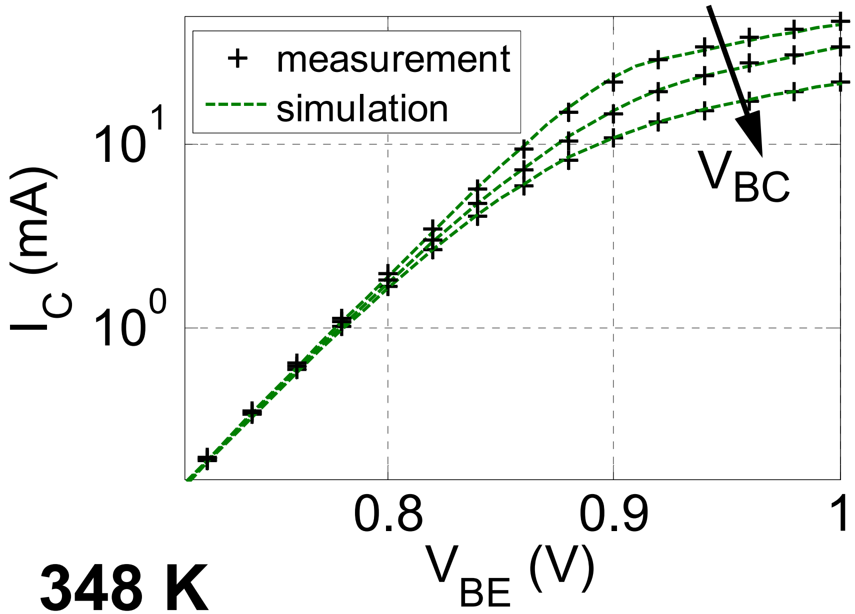
[4] G. Avenier et al., “0.13 um SiGe BiCMOS technology fully dedicated to mm-wave applications”, IEEE Journal of Solid-State Circuits, vol. 44, pp. 2312-2321, 2009.

Results: ST BiCMOS9MW

transfer current



253 K



348 K

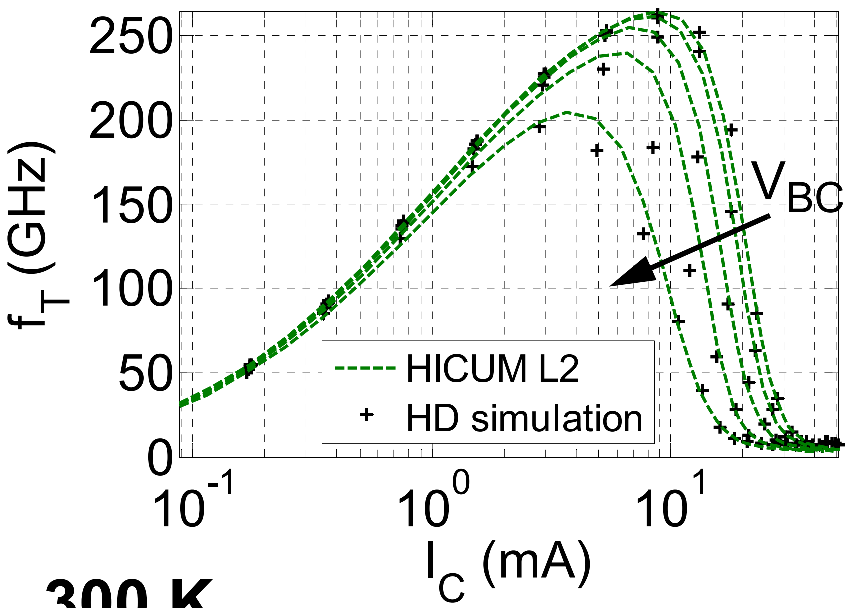
V_{BC} = [0.5, 0, -0.5] V

=> results are similar to those obtained from time consuming manual fine tuning

[4] G. Avenier et al., “0.13 um SiGe BiCMOS technology fully dedicated to mm-wave applications”, IEEE Journal of Solid-State Circuits, vol. 44, pp. 2312-2321, 2009.

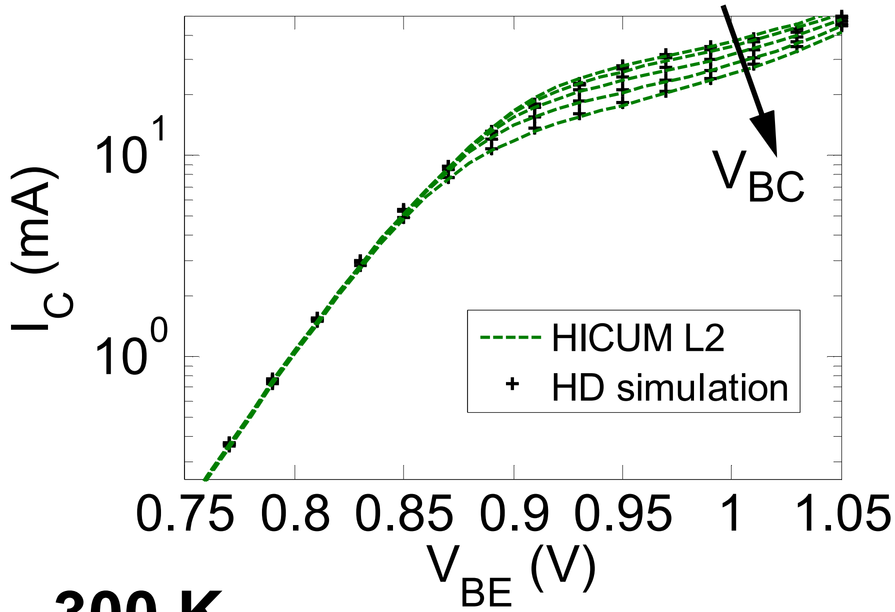
Results: TCAD (1D HD-simulation)

transit time



300 K

transfer current



300 K

V_{BC} = [0.5, 0.3, 0, -0.3 -0.5] V

=> method suitable for automated extraction
from device simulation

Conclusion

- Standard determination method for τ_f insufficient

  => τ_f cannot be accessed directly using f_T

- Problem can be solved by careful "deembedding" down to intrinsic transistor Y-parameters and an advanced extraction strategy
  - consistent model representation necessary (HICUM/L2 here)
  - self heating included for all bias points

- Method was shown to be consistent and accurate
  - extraction fully adapted to HICUM/L2 v2.32
  - method also suitable for other models
  - Method is very useful for automated extractions from device simulations

- Method implemented in Matlab based tool
  - batch & GUI mode available

Thank you for your attention!

Appendix

$$C_{dEb} = \left.\frac{dQ_f}{dV_{B'E'}}\right|_{V_{C'E'}} = \frac{\partial Q_f}{\partial I_{Tf}} \cdot \frac{\partial I_{Tf}}{\partial V_{B'E'}} + \frac{\partial Q_f}{\partial \tau_{f0}} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}} + \frac{\partial Q_f}{\partial I_{CK}} \cdot \frac{\partial I_{CK}}{\partial V_{B'E'}}$$

$$= \tau_f \cdot S_{fb} + I_{Tf} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}} + 0$$

- Special term is visible in all frequency ranges [5], about 1% of tf at low currents
- Term is caused by implementation in Verilog-A and physically correct

[5] T. Rosenbaum, “Evaluation of methods for parameter extraction of recent heterostructure bipolar transistors”, Diploma (MSEE) thesis, CEDIC, TU-Dresden, 2011.

GUI interface