Barrier modeling and extraction

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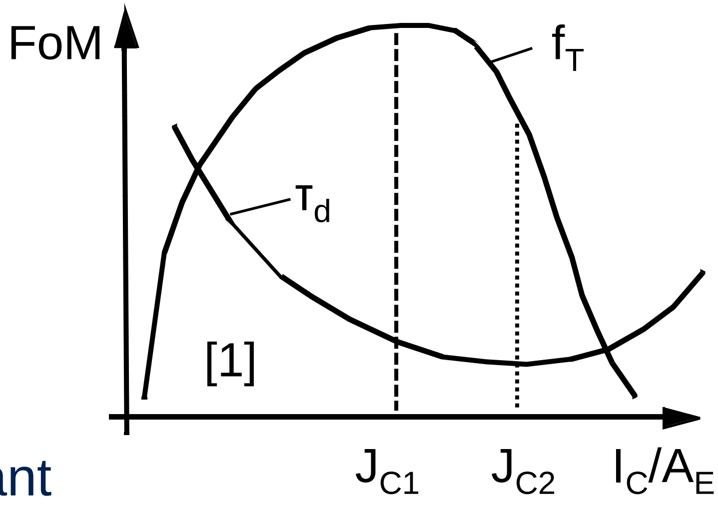
Outline

- Introduction
- Physical background
- HICUM implementation
- Empirical approach
- Conclusion

Introduction

- Circuit design relies on simulation
  => necessity for correct models
- Circuit type aim
  - e.g. speed, gain, linearity, power consumption
- Modeling of high currents
  - becomes important for circuits where gate delay (τ_d) is important
  - e.g. for optic communication (frequency dividers, multiplexers…)
- Gate delay
  - minimum of τ_d at larger current densities
- Digital logic
  - Current mode logic (CML)
    => „transient use“, large signal operation



⇒ makes modeling of high currents important

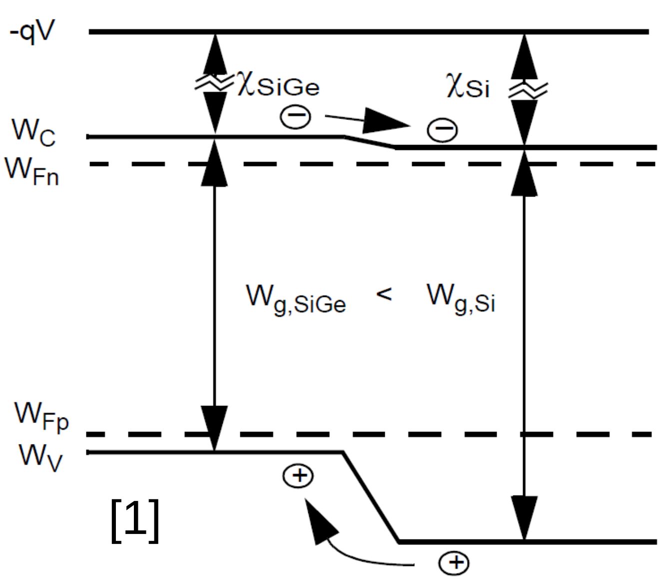
[1] M. Schroter, A. Chakravorty, “Compact hierarchical modeling of bipolar transistors with HICUM”, World Scientific, Singapore, 2010.

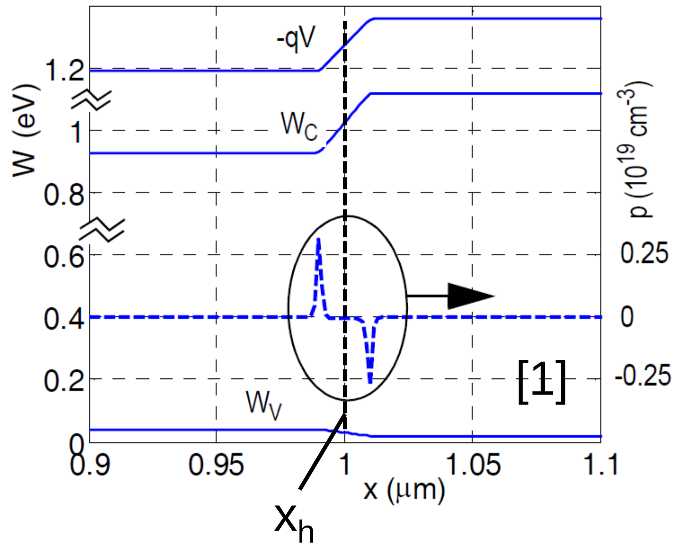
SiGe/Si heterojunction

- Band diagram view
  - combined view for p or n doped structure
  - immediately after bringing the materials in contact

  => no charge balance has taken place
- Conditions for final band diagram
  - $W_{C|V} - W_{Fn|Fp} \approx const(x)$, (defined by doping) if effective carrier densities are equal
  - Fermi level is a straight line

  => charge balance
- P doped semiconductor (rhs figure)
  - holes move from Si -> SiGe
    => electric field => potential drop
    => valence band adjustment
- N doped semiconductor
  - only small band changes ($\chi_{SiGe} \approx \chi_{Si}$)
    => nearly no change to original band diagram





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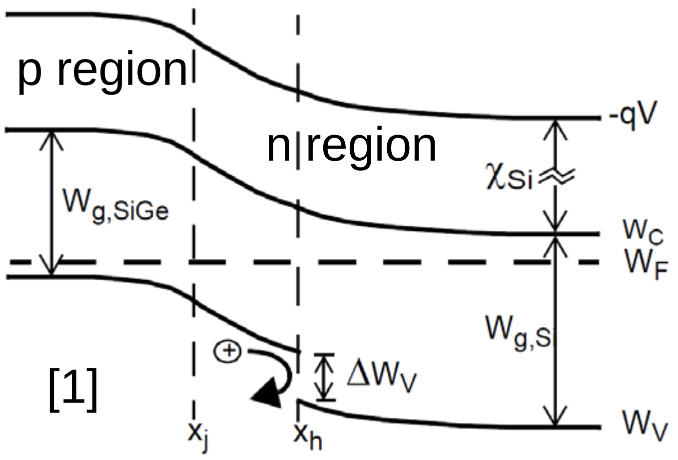
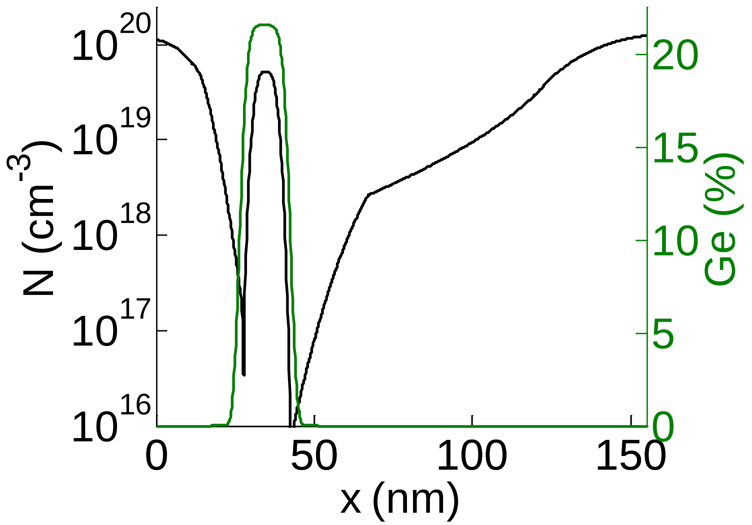
Heterojunction in pn diode

- pn diode heterojunction
  - **low current densities**:
    - Ge causes change in valence band
    => barrier for hole flow
    => decreases hole injection
  - conditions for electrons:
    - no jump of W_C visible at x_h
    (covered by: $\chi_{SiGe} \approx \chi_{Si}$ & el. field)

  => 2 major discontinuities in valence band for HBTs



- Profile under investigation
  - exemplary HBT profile with max. Ge concentration of ~20%
  - expected outcome for band diagram
    - jumps at BE- & BC-SCR probably not visible
    (fairly high doping & small structure)
    => large electric field



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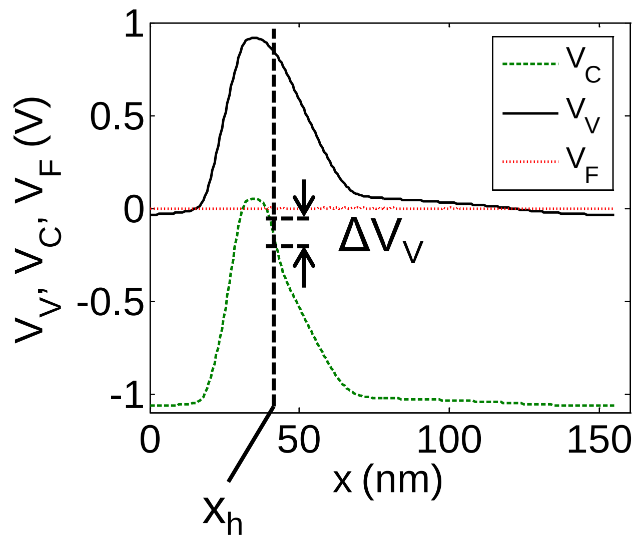
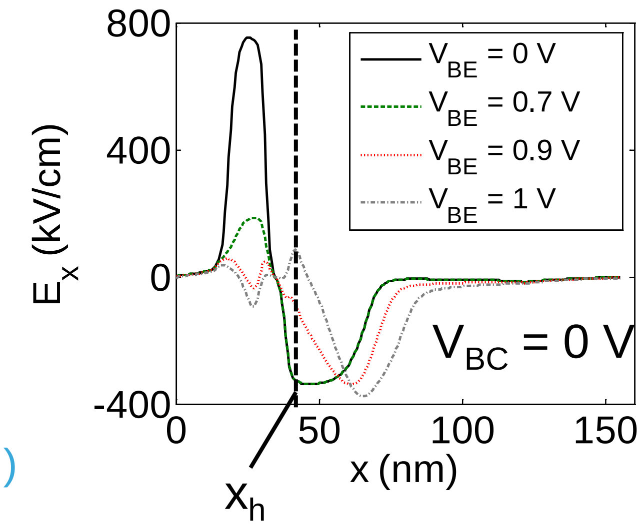
Investigated HBT

- Band diagram at 0V
  - large doping
    => shifts fermi level into V_C | V_V
  - hard to notice qualitative differences to standard BJT
  - most of the Ge-influence is covered by electric field
  - barrier for hole injection into C visible

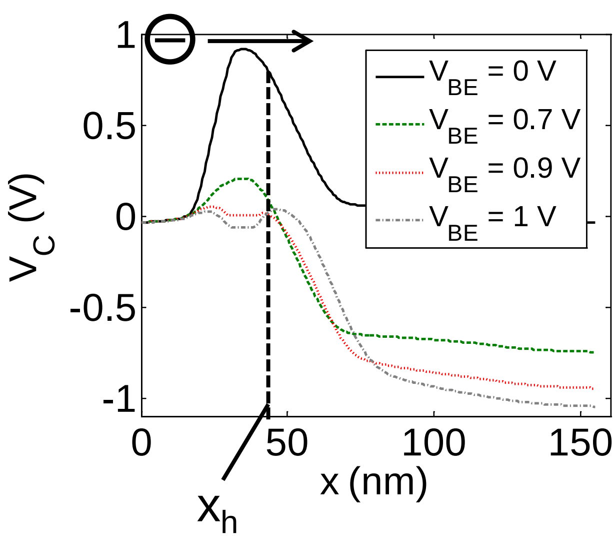


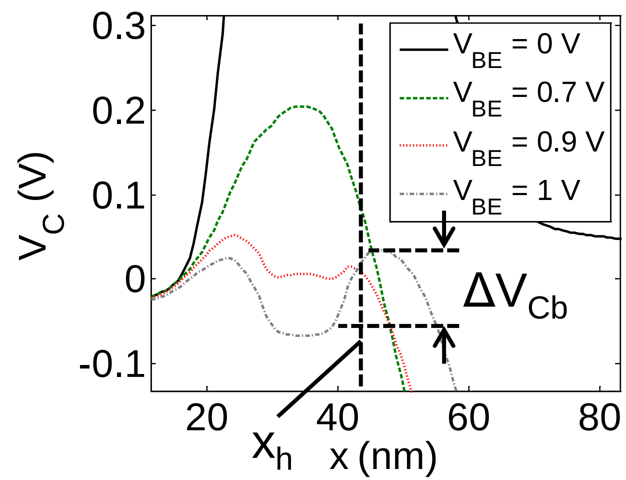
- Electric field for various I_C
  - for low currents
    $E_x < 0$ in BC-SCR
  - field at heterojunction
    - reverses at large currents (**retarding field**)
    => injection of holes into C
    and barrier for electrons
  - barrier is mainly current dependent (V_{BC} = 0!)



Collector barrier effect

- Retarding field
  - leads to deterioation of transistor performance
  - observed retarding field is also visible in band edges
- Conduction band for various I_C (V_{BC} = 0)
  - low currents: electrons can enter C without barrier (see figure on lhs)
  - medium currents: band edge flattens at x_h
  - large currents: slope of band edge at is inversed
    => formation of barrier => oppose electron flow
  - step height ΔV_{Cb}
    corresponds to change in conduction band at x_h





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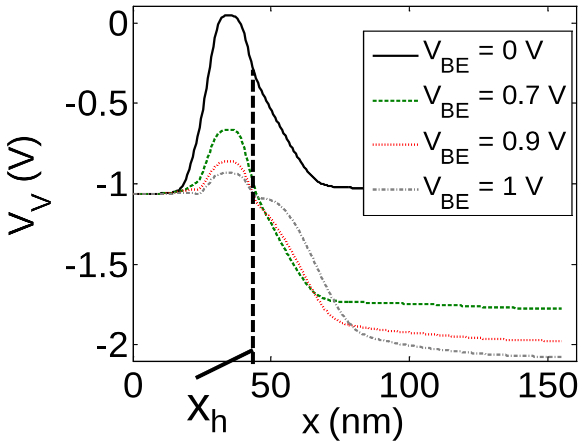
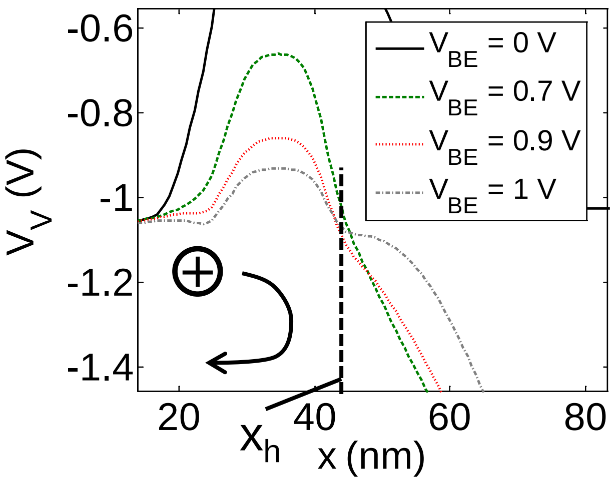
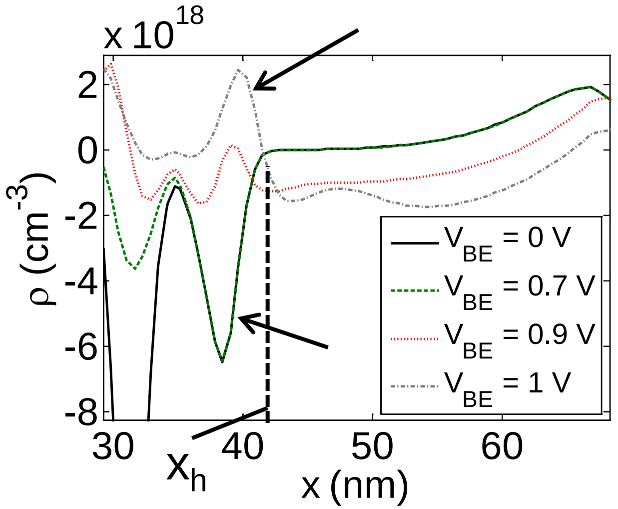
Collector barrier effect

- Valence band for various I_C (V_{BC} = 0)
  - at low - medium currents: injection of holes prevented (see figure on rhs)
  - at larger currents: step in V_V decreases (but still prevents hole injection)





- Space charge
  - low currents: ionized doping of base visible (negative peak in base)
  - space charge disappears with increasing current
  - high currents: positive charge within [x_{jC} x_h] ionized doping of collector



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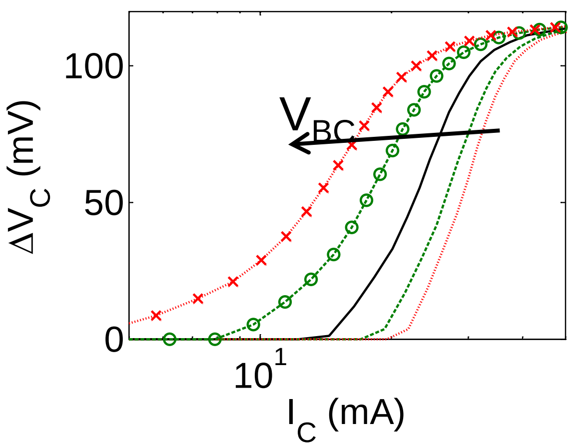
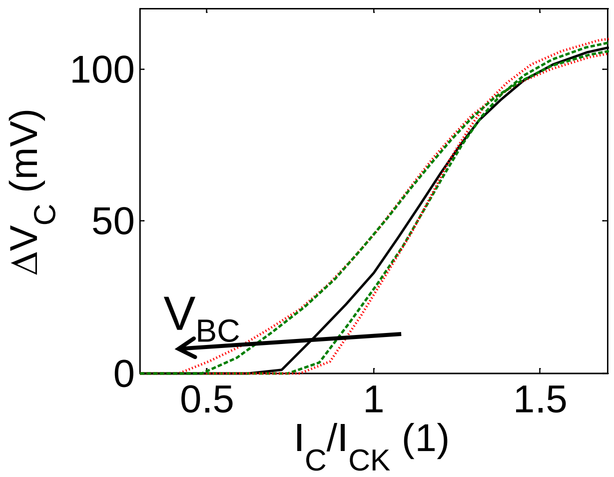
Conduction band step ΔV_C

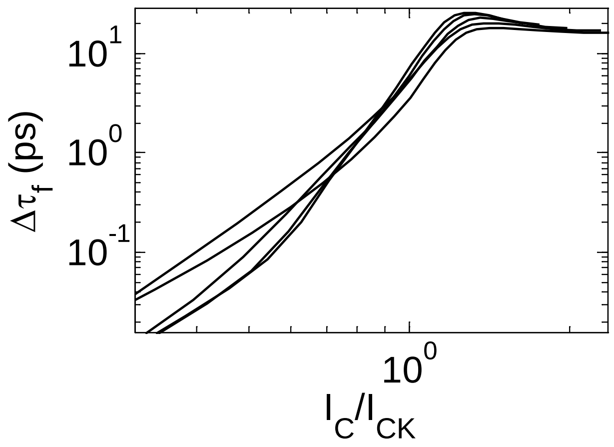
- Evaluation for V_{BC} = [-0.5 -0.3 0.0 0.3 0.5] V
  - ΔV_{Cb} directly from device simulation (conduction band jump)
  - Run extraction for determining I_{CK}





=> onset and slope for ΔV_{Cb} varies with V_{BC}

=> maximum value varies ~ 5 mV with V_{BC}



- Expected transit time behavior
  - $\tau_f \sim \exp(\Delta V_{Cb})$ ([1])

$\Rightarrow$ $\Delta\tau_f(V_{BC})$ dependence should be amplified

- Prediction is confirmed

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Barrier model descriptions

- Physical result for band offset, [1]
  - no limit for high currents
  - only applicale for $I_T > I_{lim}$

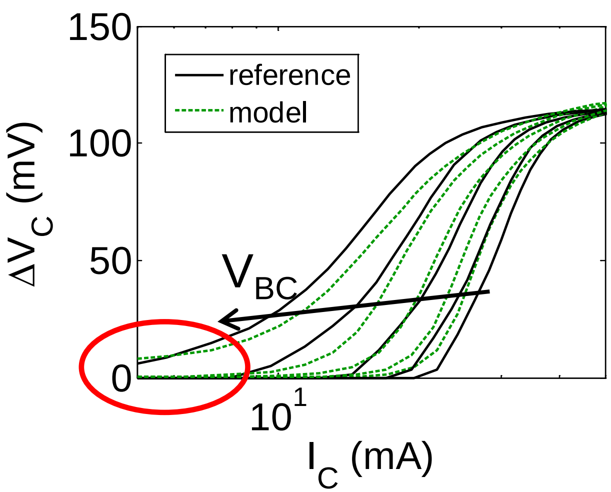
  => cannot be applied

$$\Delta V_{Cb} = \Delta V_V + V_T \ln\left[\left(\frac{I_T}{I_{\lim}}\left(1+\frac{V_{\lim}}{V_T}\frac{w_i}{w_{Ci}}\right)-1\right)\frac{N_{Ci}}{N_B}\right]$$

- HICUM implementation for band offset
  - empirical approach
  - triggered by critical current
  - $\Delta V_{Cb} = V_{cbar}$ for high currents

$$\Delta V_{Cb} = V_{cbar}\exp\left(-\frac{2}{i_{bar}+\sqrt{i_{bar}^2+a_{cbar}}}\right), \quad i_{bar} = \frac{I_{Tf}-I_{CK}}{i_{cbar}}$$

- Apply to 1D data
  - description is applicable ☺
  - accuracy is sufficient ☺ (considering that a high current effect is modeled)
  - ΔV_{Cb} assumes constant value for low currents and positive V_{BC} ☹



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HICUM barrier charge description

- Transit time charge description for high currents
  - consists of
    - E related charge
    - C+B related charge (merged in ΔQ_{fh})
    - barrier charge

$$\Delta Q_f = \Delta Q_{Ef} + \Delta Q_{Bf,bar} + \Delta Q_{fh}$$

- Barrier associated charge
  - result of physical deriviation for C side of neutral B region (see [1], chapter 4.4.2.1)

$$\Delta Q_{Bf,bar} = I_{Tf} t_{hcs} \left(1 - f_{thc}\right) \left[\exp\left(\frac{\Delta V_C}{V_T}\right) - 1 \right]$$

- Non-barrier charge ΔQ_{fh}
  - „delayed“ by barrier
  - turning off C barrier drops exp() part from description

$$\Delta Q_{fh} = I_{Tf} t_{hcs} w^2 \exp\left(\frac{\Delta V_C - V_{Cbar}}{V_T}\right)$$

- Corresponding transit times
  - derivative of ΔQ_{fh} | $\Delta Q_{Bf,bar}$ w.r.t. I_{Tf} leads to corresponding expression…

Behavior of barrier description

- Barrier related base transit time limit for high currents (I_{Tf} >> I_{CK})
  - … is not Zero

$$\Delta t_{Bf,\lim} = t_{hcs}\left(1 - f_{thc}\right)\left[\exp\left(v_{cbar}/V_T\right) - 1\right]$$

- $\Delta\tau_{fh}$ behavior
  - Related transit time for high currents (I_{Tf} >> I_{CK})
    - $\tau_{fh,lim} = \tau_{hcs}$
  - Total transit time for high currents (I_{Tf} >> I_{CK})
    - $\tau_{fh,tot} = \tau_{hcs} + \tau_{Bf,lim}$

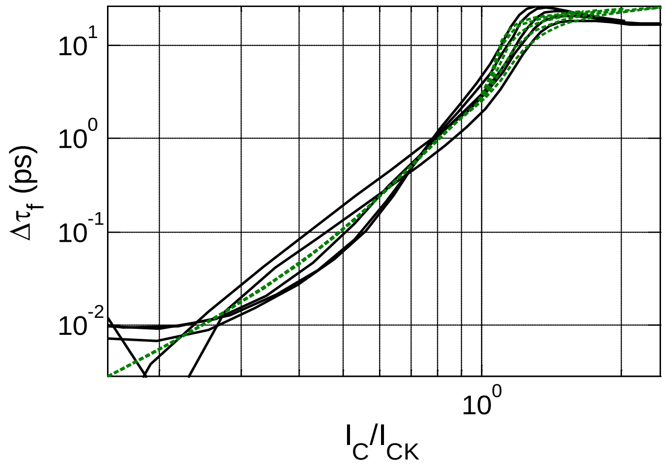
⇒ Overshoot **cannot** simply be de-/activated (sum of transit time ≠ thcs!)

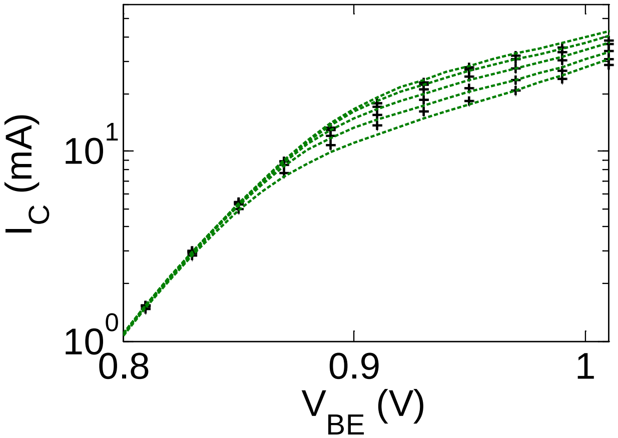
⇒ Barrier- and non-barrier transit time must be extracted simultaneously (hard to conduct) ☹

- Perform extraction on example transistor

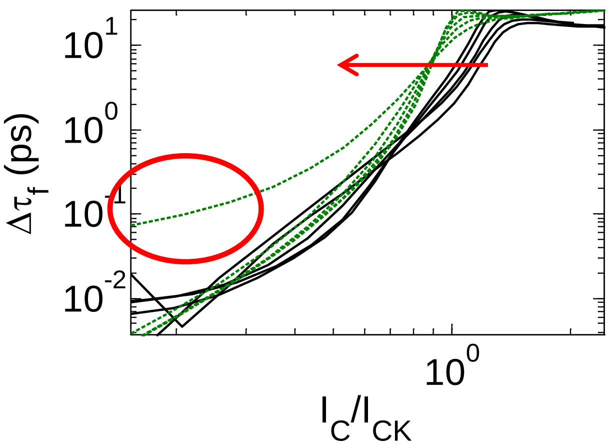
Example extraction

- Automated adjustment fails
  - Overshoot is not reproduced





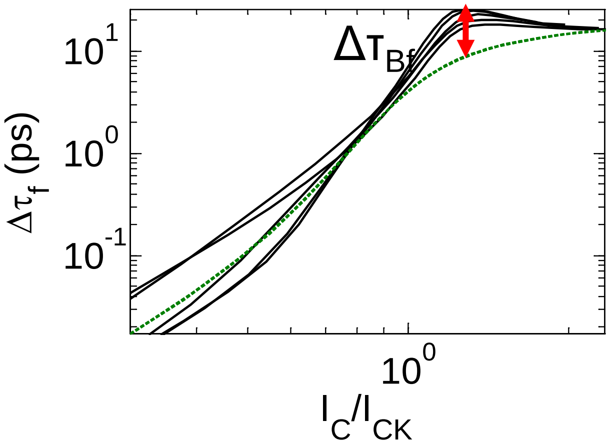
- Manual adjustment
  - To cover the transit time overshoot, acbar needs to be increased
  - Problem with this change:
    - I_{CK} is shifted (can be compensated by change of r_{ci0} and $\Delta\tau_{ef}$)
    - low I_C/I_{CK} ratios for positive V_{BC} affected ☹ (as already observed for ΔV_{Cb})

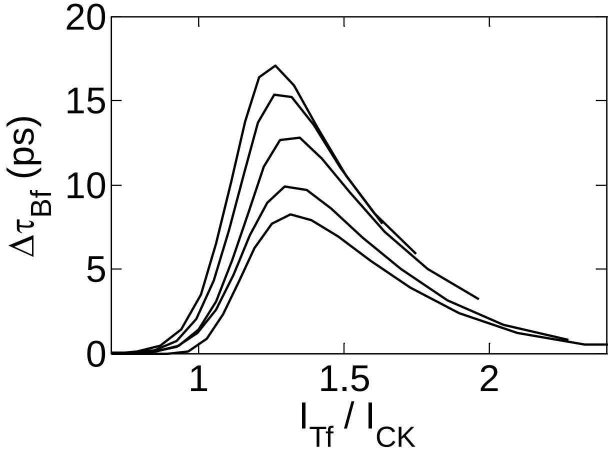


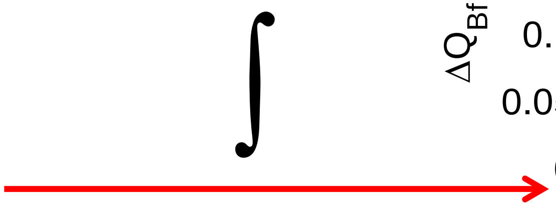
Empirical approach

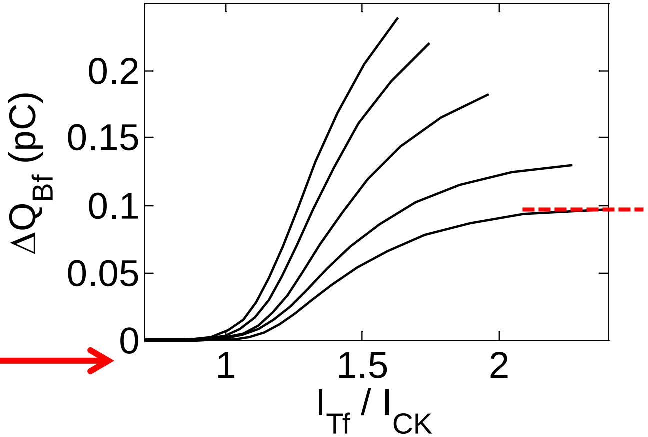
- Use example transistor to generate overshoot data
  - adjust standard HICUM (without overshoot) to match characteristics
    => Analyze **additional** transit time increase/overshoot (red arrow)

- Difference to current HICUM implementation
  - model dedicated to overshoot only
  - makes extraction easier ☺
  - allows to turn on/off overshoot ☺
  - attempt to fix low current influence for large acbar
  - loosens physical relation to BC barrier effect ☹
    (constant charge for high currents)









Constraints of description

- Requirements for description
  - Be able to turn overshoot off while still maintaining correct characteristics for medium currents and for $I_C >> I_{CK}$

  => Overshoot transit time must disappear for too low & too high I_C/I_{CK} ratios
- Review of equation
  - General charge description is plausible

$$\Delta Q_{Bf,bar} = I_{Tf} t_{hcs} \left(1 - f_{thc}\right) \left[\exp\left(\frac{\Delta V_C}{V_T}\right) - 1 \right]$$

  - But: I_{tf} causes ΔQ_{Bf} to increase linearily for large currents (assuming ΔV_C = const)

  => not suitable for empirical appoach ($\Delta Q_{Bf,ov}$ needs to be const. for large currents)
  => Replace I_{Tf} by I_{CK}
  - Leave out f_{thc} term, as overshoot corresponds fully to barrier effect

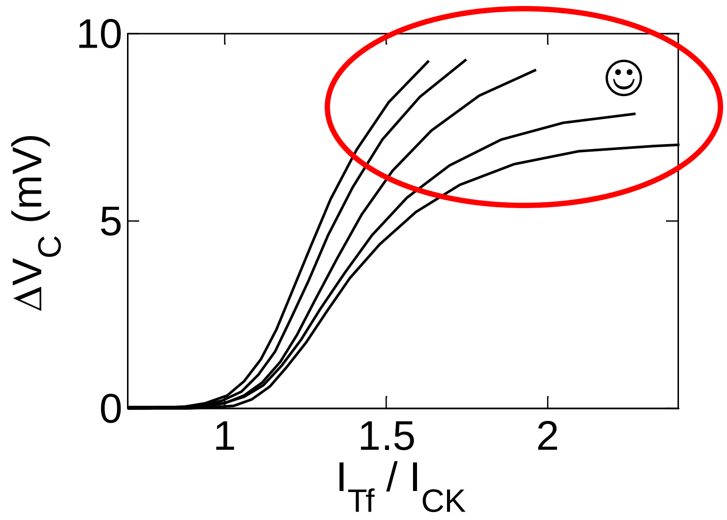
$$\Delta Q_{Bf,ov} = I_{CK} t_{hcs} \left[\exp\left(\frac{\Delta V_C}{V_T}\right) - 1 \right]$$

=> Rearrange for ΔV_C

Conduction band offset

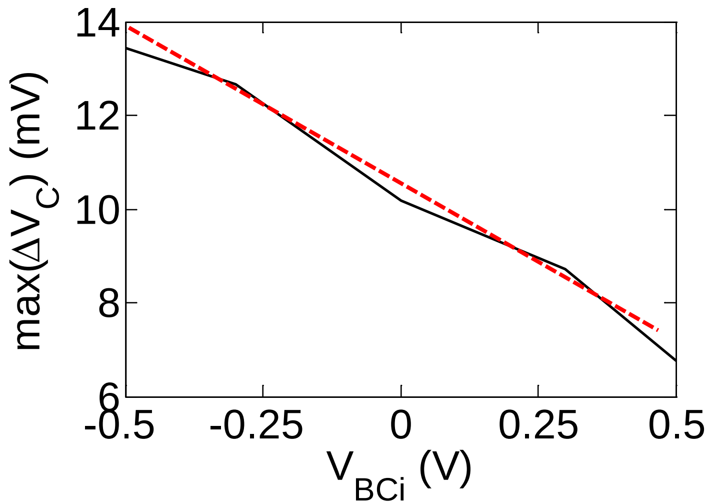
- Convert charge into ΔV_C
  - Insert charge & critical current into equation

$$\Delta V_C = \ln\left(\frac{\Delta Q_{Bf,ov}}{I_{CK} t_{hcs}} + 1\right) V_T$$



- Constraints for ΔV_C
  - ΔV_C must be Zero for low I_{Tf} / I_{CK}
  - max(ΔV_C) depends on V_{BC}
  - reference data increases to constant value

- Maximum of ΔV_C
  - linear dependence is sufficient for device simulation



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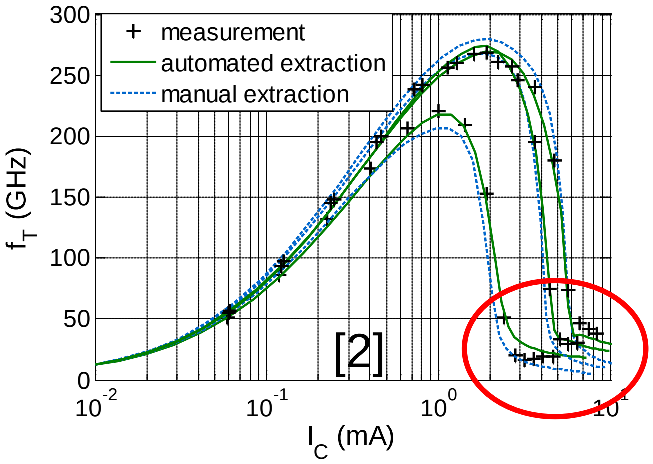
Maximum of conduction band offset

- Maximum of ΔV_C depends on V_{BC}
  - Decreasing offset for increasing V_{BC}?
  - 1D device simulation indicated this behavior
  - results for recent technology indicates contrary behavior



⇒ Description should be flexible enough for both cases

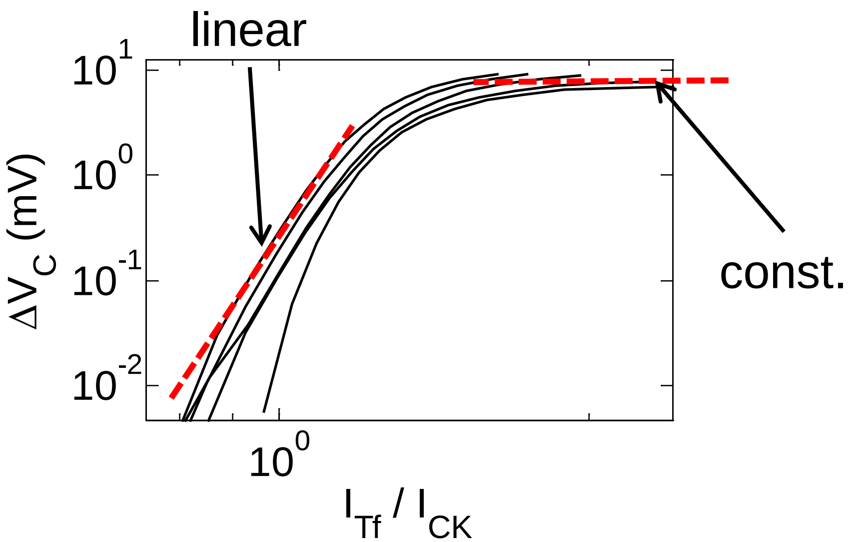
[2] T. Rosenbaum et al., "Automated Transit Time and Transfer Current Extraction for Single Transistor Geometries", Proceedings IEEE BCTM, 2013.

Starting point for ΔV_C model

- Hyperbolic smoothing function

$$y = \left(x + \sqrt{x^2 + a} \right) / 2$$

  - numerically stable
  - smooth transition behavior
  - widely used in HICUM



- Proposed equation

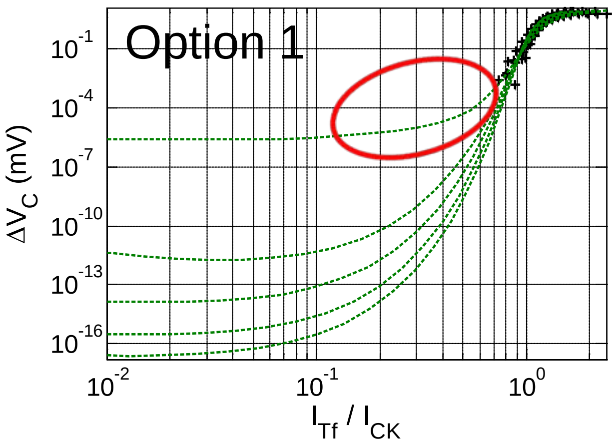
$$\Delta V_{Cb} = V_{cbar} \exp\left[\left(i_{bar} + \sqrt{i_{bar}^2 + a_{cbar}} \right) / -2 \right]$$

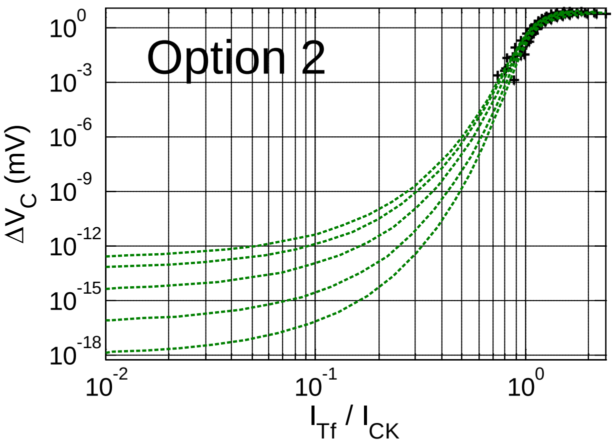
- 2 options for i_{bar}

$$i_{bar} = \left(I_{CK} - I_{Tf} \right) / i_{cbar}$$

$$i_{bar} = \left(1 - I_{Tf} / I_{CK} \right) m_{cbar}$$

  - option 1 causes problems for medium currents and positive V_{BC}





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Extraction results

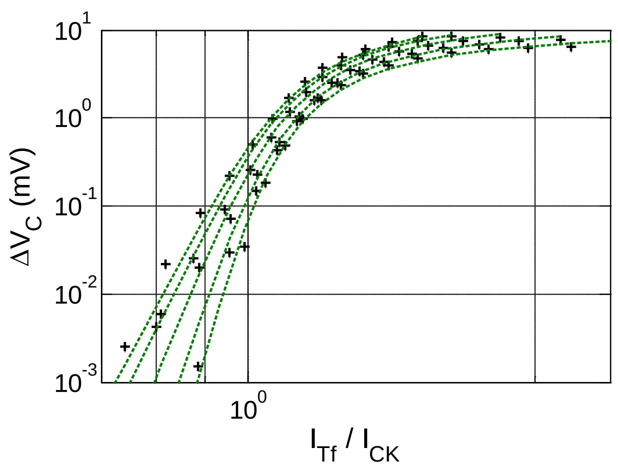
- Influence of V_{BC} on extracted parameters
  - v_{Cbar}, m_{Cbar}, and a_{Cbar} depend on V_{BC}! ☹

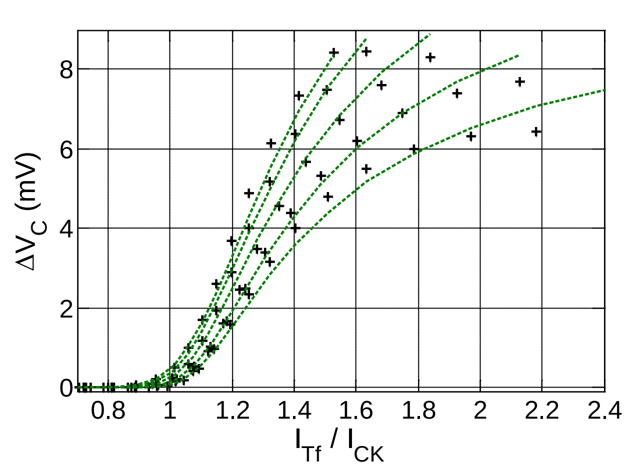
=> change description

=> additional parameter c_{Cbar} ☹

$$\Delta V_{Cb} = V_{cbar} \exp\left[\left(i_{bar} + \sqrt{i_{bar}^{2} + a_{cbar} / c^{cbar}}\right) / -2\right] c^{cbar}$$

- Results
  - good agreement & correct trend, some deviations

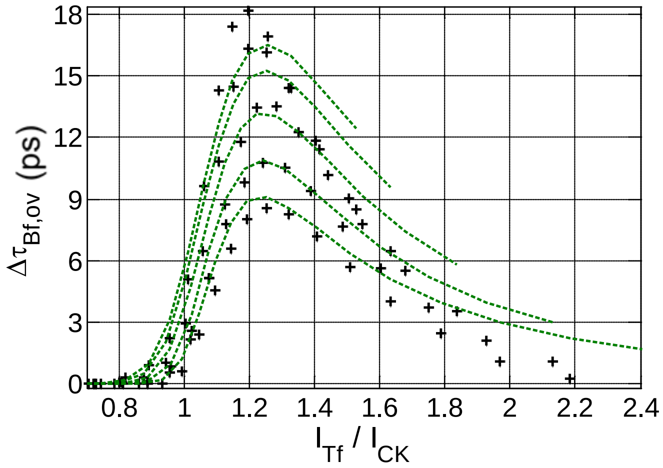


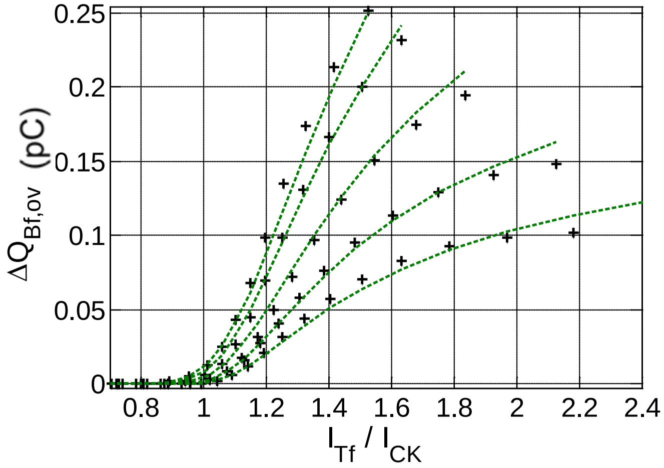


  - ideas for different smoothing function?
    - would need something that fades faster to v_{Cbar} at large currents
    - could smooth twice, but description is already complicated enough

Comparison with reference

- More results
  - transit time overshoot is reference
    - corresponding charge was determined by numeric integration





  - $\Delta\tau_{Bf,ov}$ tends to zero for large currents ☺
    but: transition could be faster…
  - c_{Cbar} can be tuned to achieve different V_{BC} behavior
    - c_{Cbar} = 0 -> no V_{BC} dependence

- Another approach?

Adjusting equation for high currents

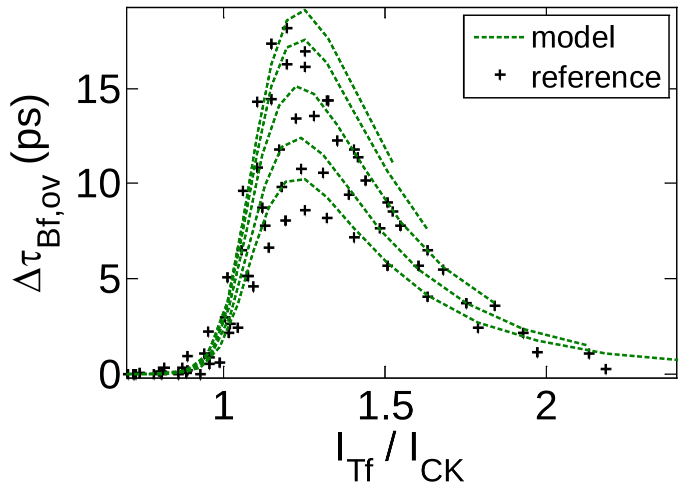
- Final description

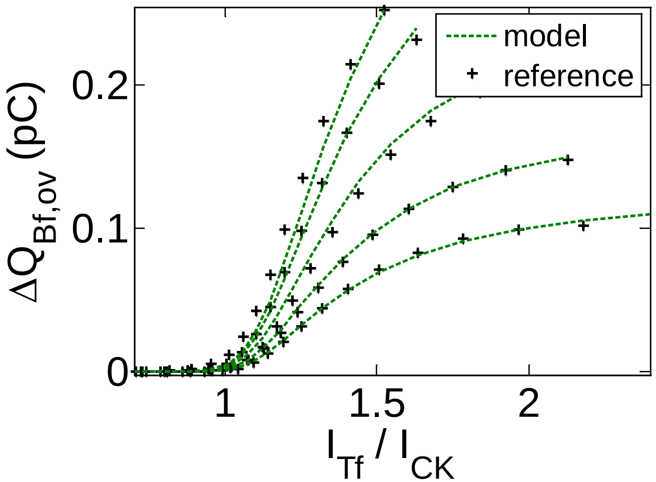
$$\Delta V_{Cb} = V_{cbar} \exp\left[\left(i_{bar} + \sqrt{i_{bar}^{2} + a_{cbar}(I_{CK}/I_{Tf})^{cbar}}\right)/-2\right] c^{cbar}$$

$$i_{bar} = \left(1 - I_{Tf}/I_{CK}\right) m_{cbar}$$

  - additional I_{CK}/I_{Tf} term helps to make $t_{Bf,ov}$ tend faster to zero at large currents

- Results





  - improved agreement for high current data ☺
  - next step: embedd in extraction flow

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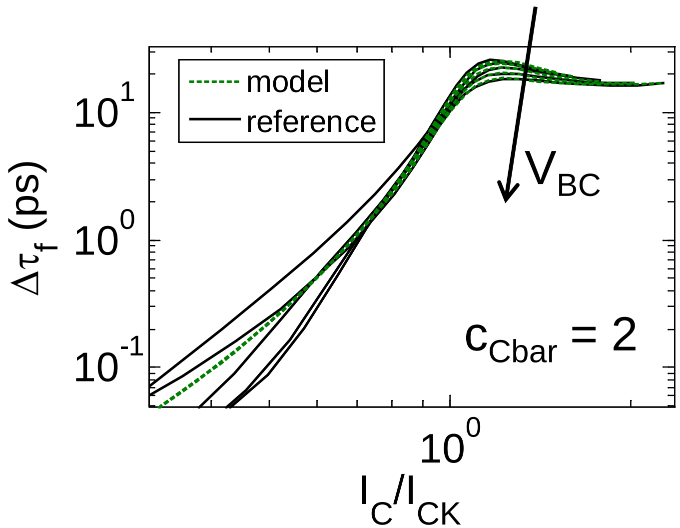
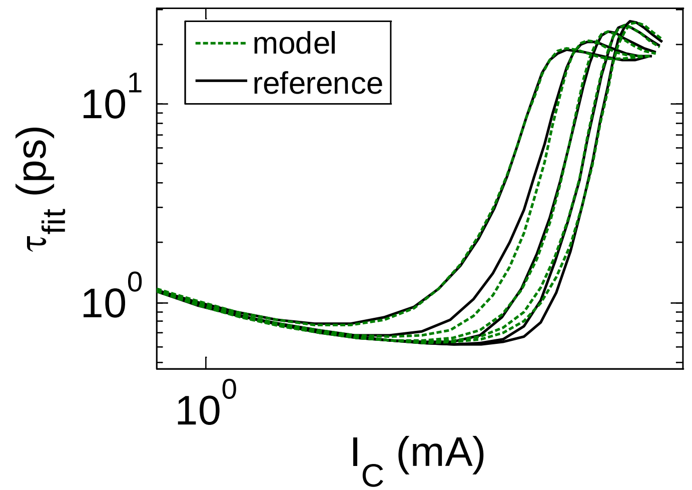
Total transit time comparison

- Extraction tool extension
  - implementation of revised overshoot equations
  - corresponding parameters c_{Cbar}, a_{Cbar}, v_{Cbar} and m_{Cbar} are automatically adjusted
- Results for 1D simulation (reference profile)

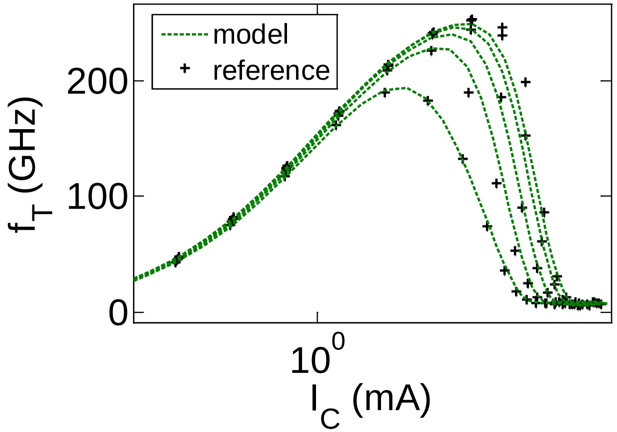


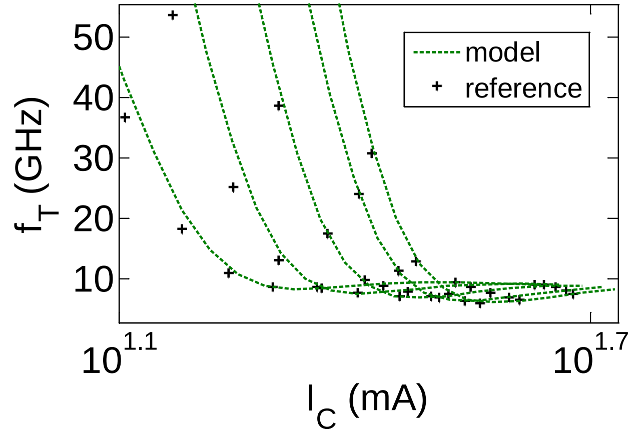


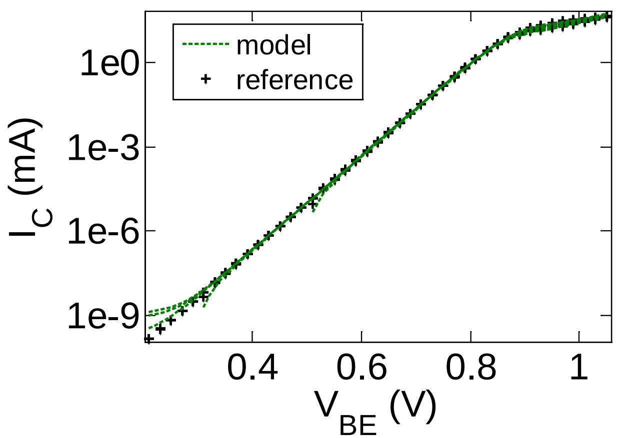
  - very good agreement between simulation and mode

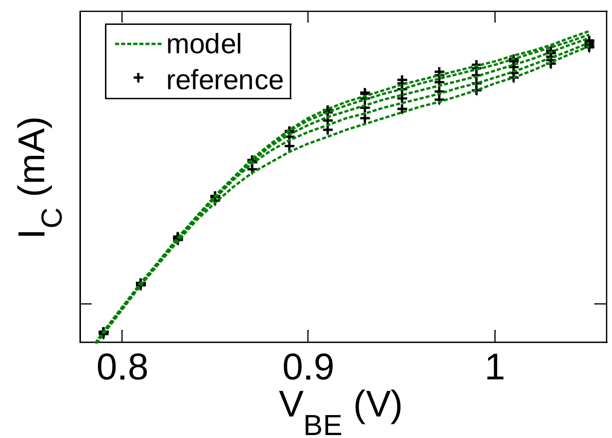
HICUM simulations for example

- Implementation
  - equations for charges and transit time were implemented in HICUM
  - extracted parameters inserted for simulation









Charges & base current

- Collector related charge

$$\Delta Q_{fh,C} = I_{Tf} t_{hcs} w^2 f_{thc}$$

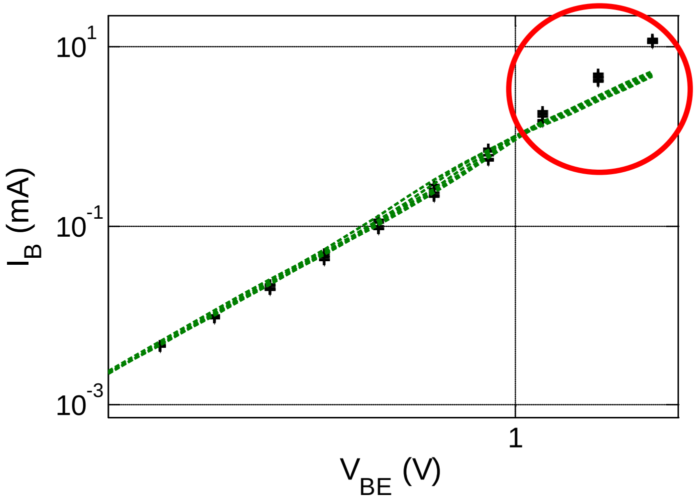
- Base related charge

$$\Delta Q_{fh,B} = I_{Tf} t_{hcs} w^2 (1 - f_{thc}) + \Delta Q_{Bf,ov}$$

$$\Delta Q_{Bf,ov} = I_{CK} t_{hcs} \left[\exp\left(\frac{\Delta V_C}{V_T} \right) - 1 \right]$$

- Base current
  - tried various combinations of tbhrec
  - accuracy did not improve ☹

=> further investigations to be done



Conclusion

- Introduction on heterostructure barriers
  - analysis of band diagram for p/n doped semiconductor
  - analysis of collector barrier effect
- Investigation of barrier description in HICUM
  - … revealed problems for large values of acbar and positive VBC (corresponds to an artifact of barrier current)
- Empirical model for transit time overshoot
  - simplifies extraction
  - allows to turn on/off overshoot
  - but: loosens physical relation to BC barrier effect (charge is related to overshoot instead of barrier)
  - model was implemented in extraction tool and HICUM .va for comparison purposes

$\Rightarrow$ results show excellent agreement for transit time

- Base current behavior is yet to be investigated

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Thank you for your attention!