A HICUM extension for medium current densities

A. Pawlak[1)], M. Schröter[1),2)], J. Krause[1)]

[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

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OUTLINE

- Introduction
- Observation of the effect
- HICUM extension
- Implementation and results
- Summary and outlook

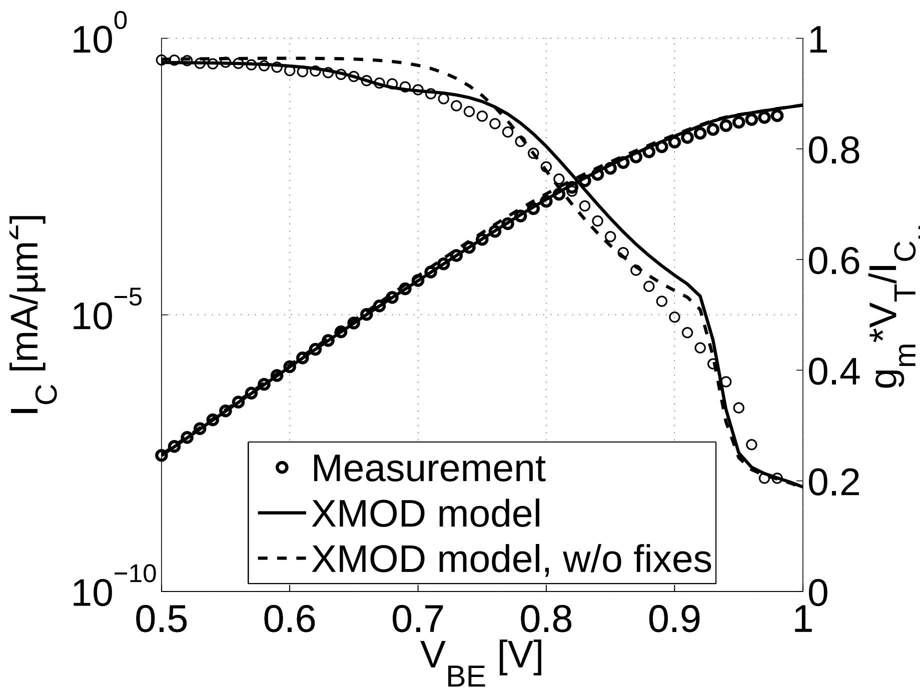
Introduction

- Goals: apply and verify HICUM Level 2, Version 2.23 to advanced SiGe HBTs with (f_T,f_{max})>300 GHz
- DotFive (http://www.dotfive.eu/): development of SiGe HBTs with 500 GHz operating frequency $\rightarrow$ need of accurate compact model
- Especially for DotFive transistors insufficient accuracy with HICUM for transfer current at medium current injection (using meaningful parameters)
- Quick fixes are available at expense of non-physical formulations and parameters
- Need for a physics-based model formulation
    - Small number of parameters
    - extraction as simple as possible
- Presented here:
    - HICUM extension in the formulation of the transfer current
    - physics-based equation with only two additional parameters

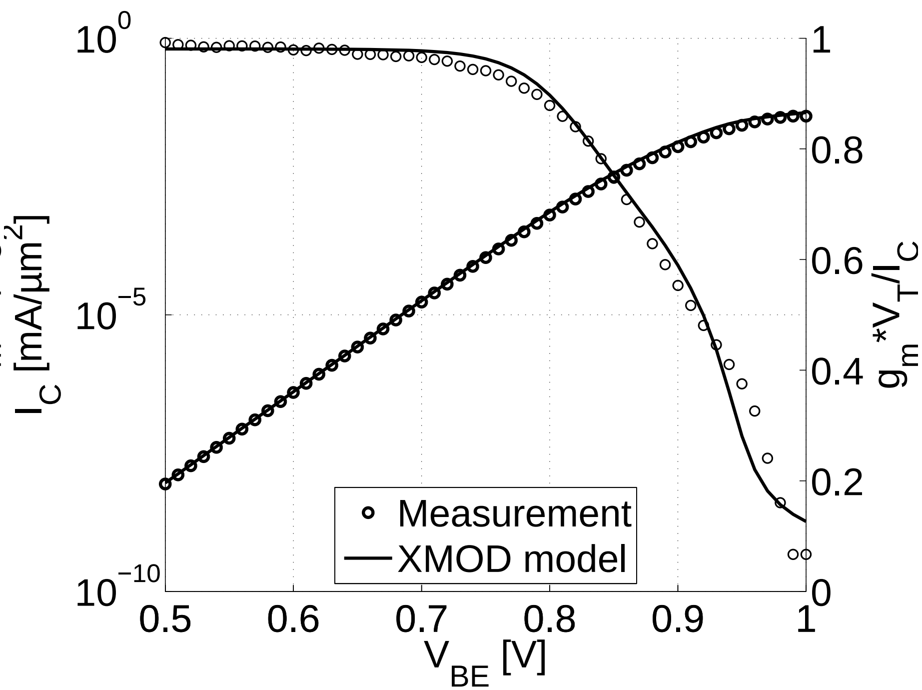
Observation of the effect

measurements on DotFive transistors

ST process



IFX process

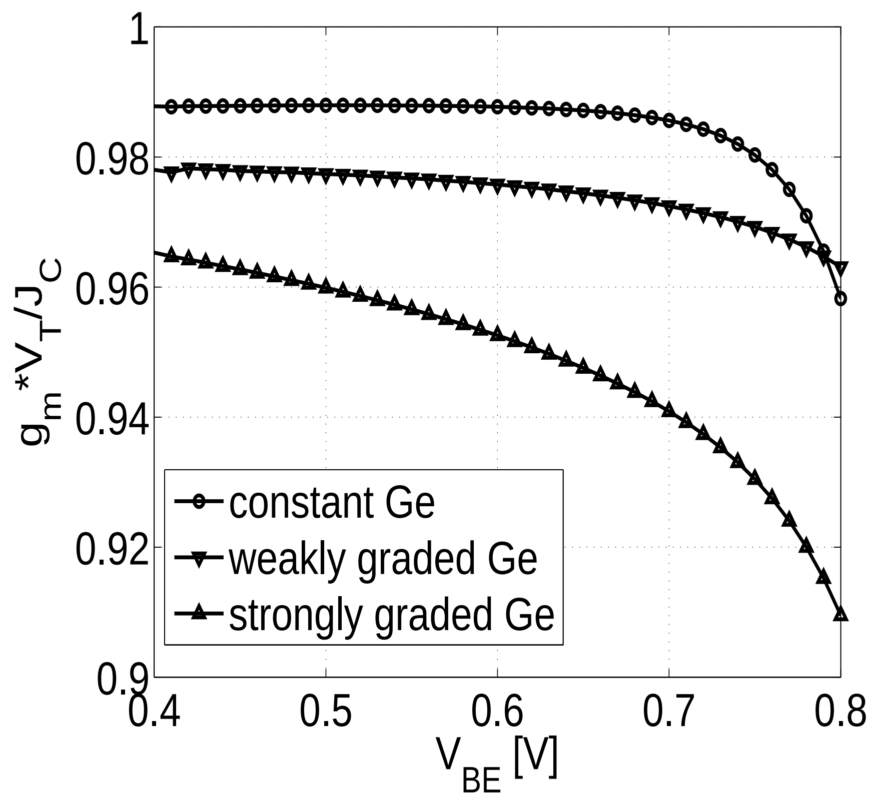


- No reasonable approximation for g_m possible
  - Fits only possible with non-physical parameters, e.g. “DC-capacitance”, i.e. adjusting capacitance parameters to DC collector current rather than to C(V)-measurement

Observation of the effect

1D device simulations

- The effects occurring in measurements could be reproduced by 1D device simulations
  - Strength of effect strongly depends on the Germanium gradient in the BE-SCR
  - HBTs with constant Germanium can easily be modeled with compact models
  - Strongly graded Germanium reduces g_m even for low voltages



- A reduction of g_m for medium current densities in modern SiGe-HBTs was observed
  - Cannot be modeled with compact models and physically meaningful parameters
  - Several quick-fixes were introduced, but in general on mathematical basics, not on physical

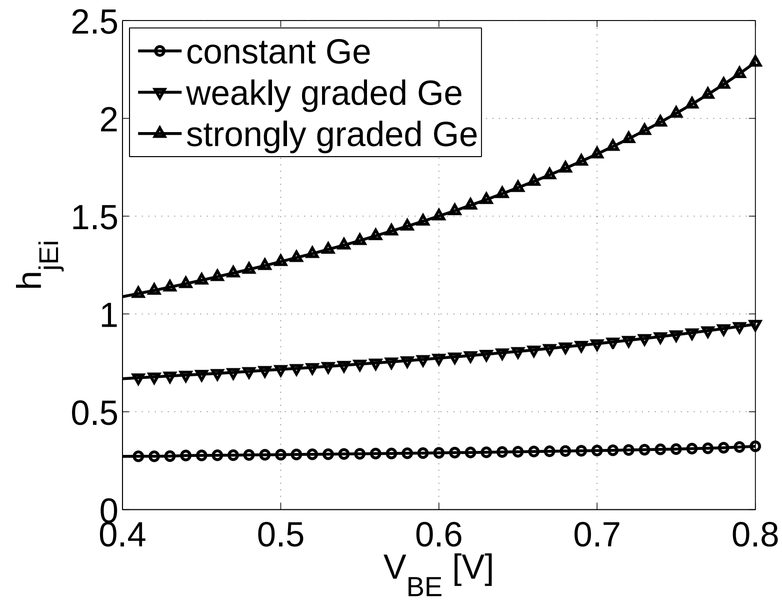
HICUM extension

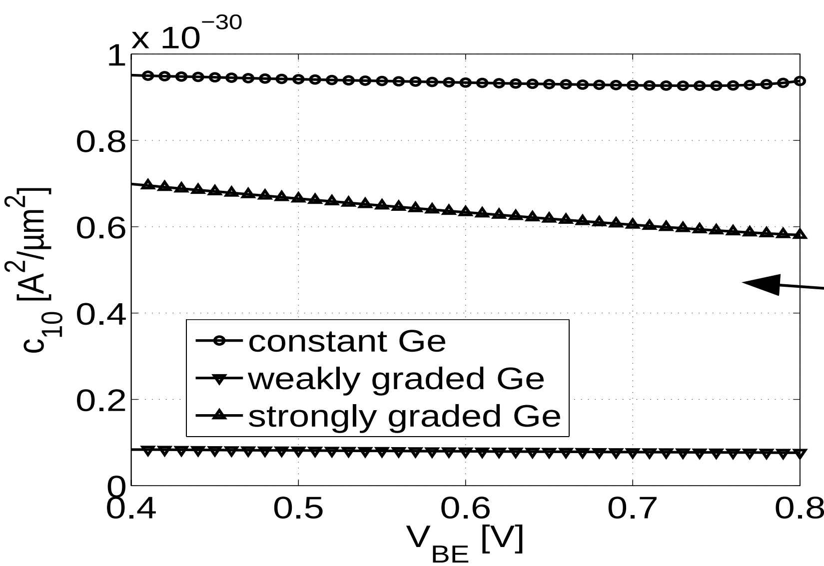
GICCR

- Background GICCR, simplification V_{BC}=0 V and low injection

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

- Simulation results for weighting factor h_{jEi}:
  - Constant value for constant germanium in BE-SCR
  - Strong bias dependence for graded Ge-content



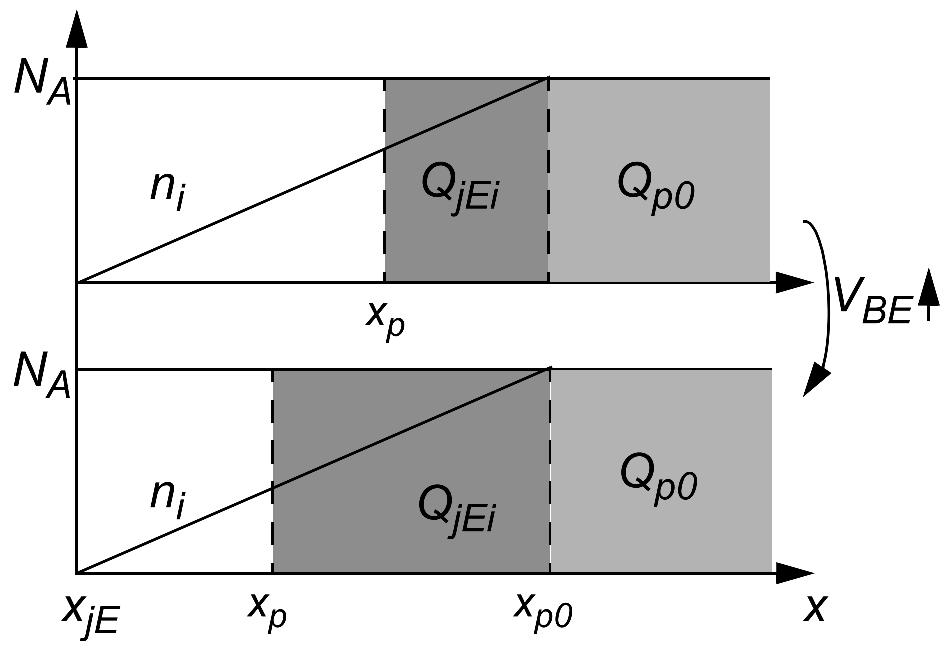


- Results for c_{10}, i.e. c_0/h_0
  - Also increasing bias dependence for graded germanium content
  - Can only be caused by electron mobility, since it is only calculated by weighting p0, i.e. hole density at equilibrium

HICUM extension

background

- Bias dependence of h_{jEi} by
  - electron mobility → weak influence
  - intrinsic carrier density → strong influence
    - HOW? n_i is independent to the operating point
    - BUT! width of space charge region is not



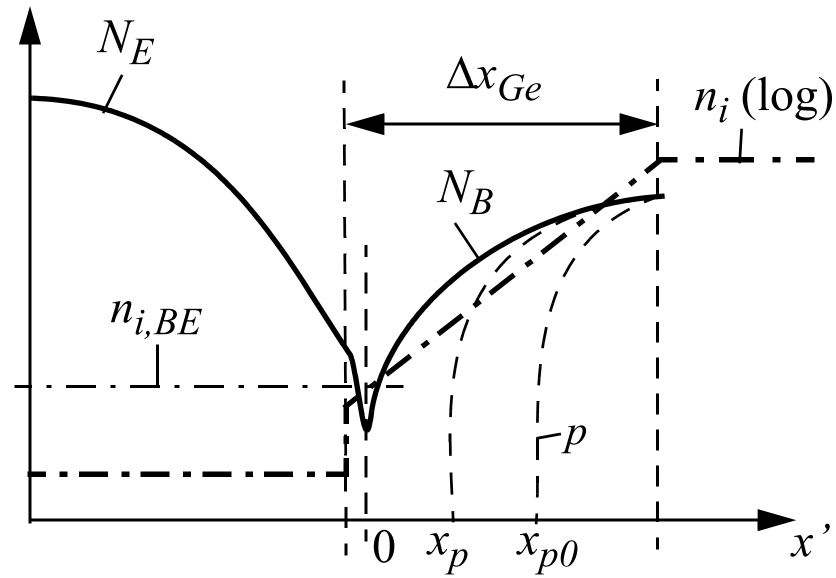
- Dependence on n_i
  - Graded germanium → graded n_i
  - Space charge width increases with V_{BE}
  - Average n_i decreases with increasing space charge
  - Leading to an increasing weighting factor

- Bias dependence of c_{10} can be covered by appropriate parameters

HICUM extension

model equations

- Assumption
  - Abrupt doping profile
  - No mobile carriers in the BE SCR
  - Graded germanium content across whole SCR for V_{BE}=0 V



- Calculation of the SC

$$Q_{jEi} = q\int_{x_p}^{x_{p0}} N_B dx \quad \text{with} \quad x_p = x_{p0}\sqrt{1-\frac{V_{BE}}{V_{DEi}}}$$

- Intrinsic carrier density

$$n_i = n_{i,BE}\exp\left(\frac{x'}{a_{ni}}\right) \quad \text{for } 0<x'<x_{p0}$$

HICUM extension

model equations

- Weighting factor h_{jEi}

$$h_{jEi} = \frac{q\int_{x_p}^{x_{p0}} \frac{\overline{\mu_{n0} n_i^2}}{\mu_n n_i^2} N_B dx'}{q\int_{x_p}^{x_{p0}} N_B dx'} = \frac{c}{n_{i,BE}^2} \frac{\int_{x_p}^{x_{p0}} \exp\left(\frac{-2x'}{a_{ni}}\right) dx'}{\int_{x_p}^{x_{p0}} dx'} = \frac{c \cdot a_{ni}}{2n_{i,BE}^2} \frac{\exp\left(-\frac{2x_p}{a_{ni}}\right) - \exp\left(-\frac{2x_{p0}}{a_{ni}}\right)}{x_{p0}\left(1 - \sqrt{1 - \frac{V_{BE}}{V_{DEi}}}\right)}$$

with $$h_{jEi0} = \lim_{V_{BE} \to 0} h_{jEi} = \frac{c}{n_{i,BE}^2} \exp\left(-\frac{2x_{p0}}{a_{ni}}\right)$$

this leads to $$h_{jEi} = h_{jEi0} \frac{\exp\left(\frac{2x_{p0}}{a_{ni}}\left(1 - \sqrt{1 - \frac{V_{BE}}{V_{DEi}}}\right)\right) - 1}{\frac{2x_{p0}}{a_{ni}}\left(1 - \sqrt{1 - \frac{V_{BE}}{V_{DEi}}}\right)} = h_{jEi0} \frac{\exp(u) - 1}{u}$$

HICUM extension

generalization

- Replacing the square root by the HICUM parameter z_{Ei}

$$h_{jEi} = h_{jEi0}\frac{\exp\left(a_{hjEi}\left(1-\left(1-\frac{V_{BE}}{V_{DEi}}\right)^{z_{Ei}}\right)\right)-1}{a_{hjEi}\left(1-\left(1-\frac{V_{BE}}{V_{DEi}}\right)^{z_{Ei}}\right)}$$

- Model parameters
  - V_{DEi} and z_{Ei}, already used in HICUM, extracted by C(V)-measurements for BC-short
  - HICUM parameter h_{jEi} reused as h_{jEi0}, weighting factor for very low V_{BE}
  - newly introduced parameter a_{hjei}

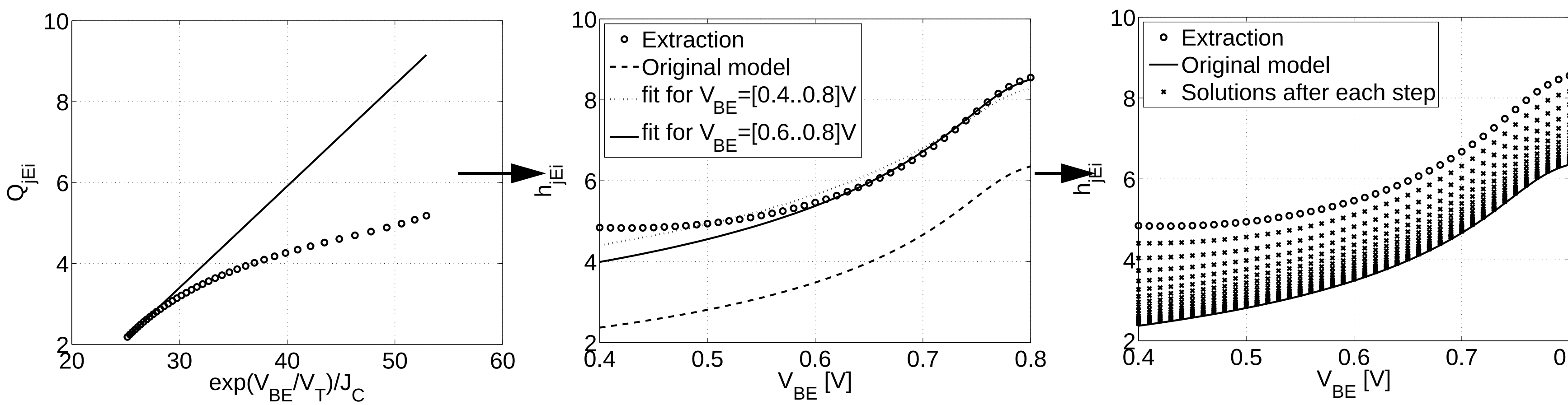
$$a_{hjEi} = \frac{2x_{p0}}{a_{ni}} \approx \frac{\sqrt{\frac{2\varepsilon}{q}\frac{N_E V_{DEi}}{N_B(N_B+N_E)}}}{\Delta x_{Ge}}\frac{\Delta V_G}{V_T} \quad \text{with} \quad \Delta V_G \approx 75mV/10\%$$

HICUM extension

extraction methodology (I)

- Starting point -> standard extraction for c_{10} and h_{jEi}, Q_{p0} known from device simulation or tetrode structures, C_{jEi} parameters known from C(V)-measurements
  - Known to lead to a negative h_{jEi} (for high V_{BE})
  - Use V_{BE} as low as possible to avoid this (works otherwise as well) to get a starting solution for $c_{10} \rightarrow$ (1)
  - Calculate $h_{jEi}(V_{BE})$ with known Q_{jEi} and I_C, c_{10} and Q_{p0} and use a fitting procedure for the model equation (for high voltages) $\rightarrow$ (2)
  - Calculate a new c_{10} with h_{jEi} from model equation for low $V_{BE} \rightarrow$ iterate for $c_{10} \rightarrow$ (3)

(1) (2) (3)



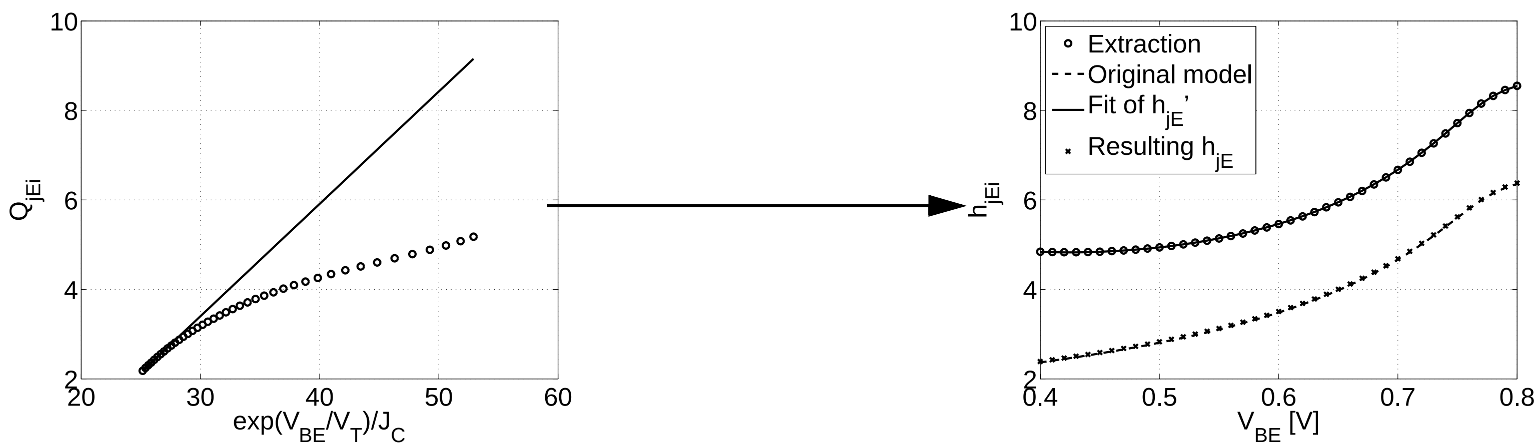
HICUM extension

extraction methodology (II)

- Same basics as methodology (I) but without the iteration
  - "False" extracted $c_{10}' = c_{10} * h_0'$ leads to a weighting factor for Q_{p0}
  - But in transfer equation, there is no weighting factor $\rightarrow$ influence on $h_{jEi}(V_{BE})$-curve

$$\frac{c_{10}'}{h_0' Q_{p0} + h_{jEi}' Q_{jEi}} = \frac{c_{10} h_0'}{h_0' Q_{p0} + h_{jEi} h_0' Q_{jEi}} = \frac{c_{10} h_0'}{Q_{p0} + \left(h_{jEi} h_0' + (h_0' - 1) \frac{Q_{p0}}{Q_{jEi}} \right) Q_{jEi}}$$

  - Extraction of the $h_{jEi}(V_{BE})$ curve $\rightarrow$ fitting with known Q_{p0} and Q_{jEi}

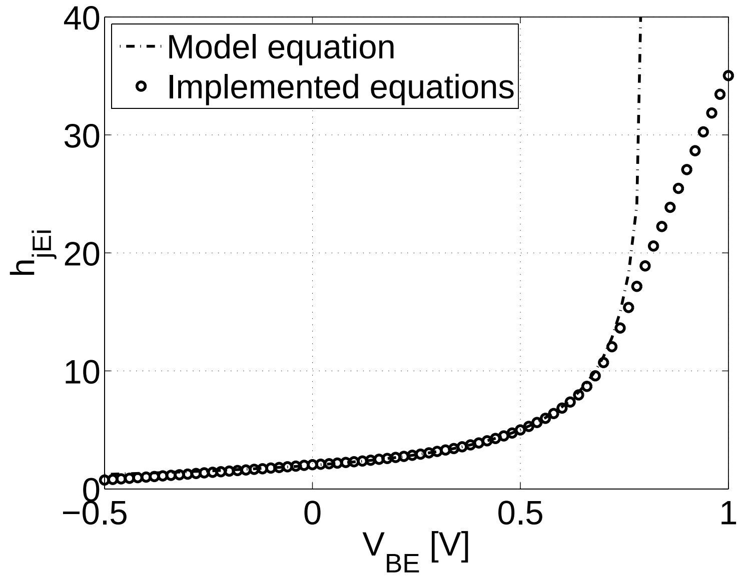


Implementation and results

model equation

- VerilogA code for HICUM Level 2, Version 2.24
- Implementation of bias dependent h_{jEi}
  - calculation as function of V_{BEi}
  - numerical problems for $V_{BEi} \geq V_{DEi}$ and $V_{BEi} = 0\ V$
  - Fixed by linearization for $V_{BEi} \rightarrow 0$ and $V_{BEi} = V_{fEi}$

    with $V_{fEi} = V_{DEi}[1 - a_{jEi}^{-(1/z_{Ei})}]$, limitation voltage for C_{jEi}
  - Turned on for a_{hjEi}>0, turned off for a_{hjEi}=0



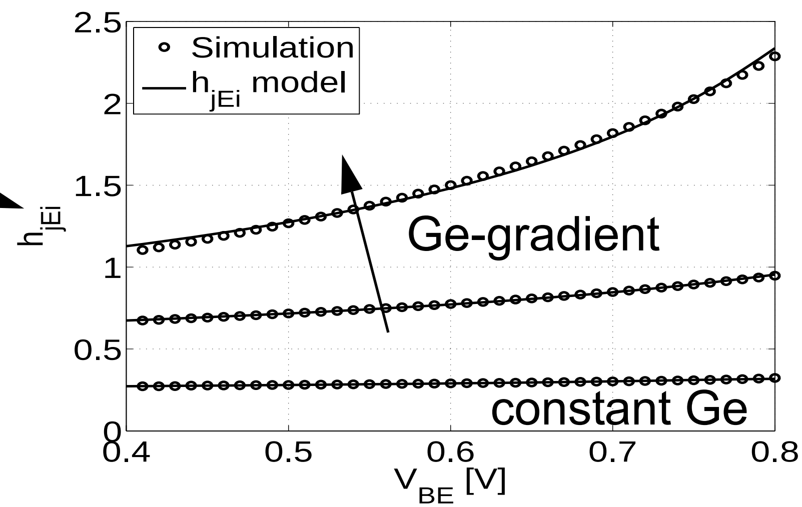
- and an additional parameter h_{f0}

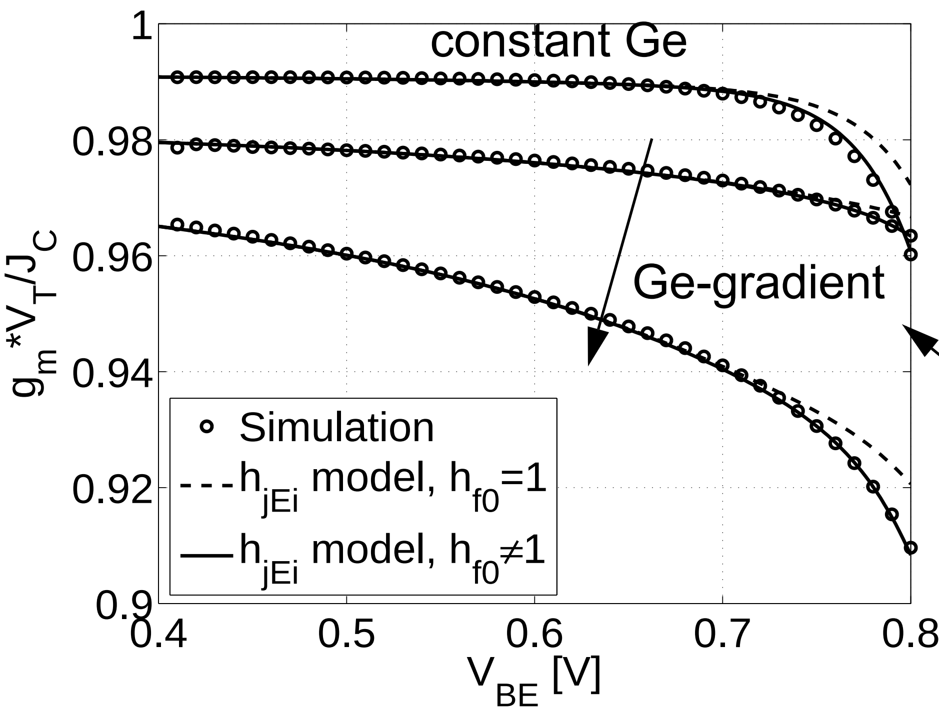
$$Q_{f,T} = h_{f0}Q_{f0} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}\Delta Q_{Cf}$$

Implementation and results

device simulations

- Very good results for modeling simulated values of h_{jEi}

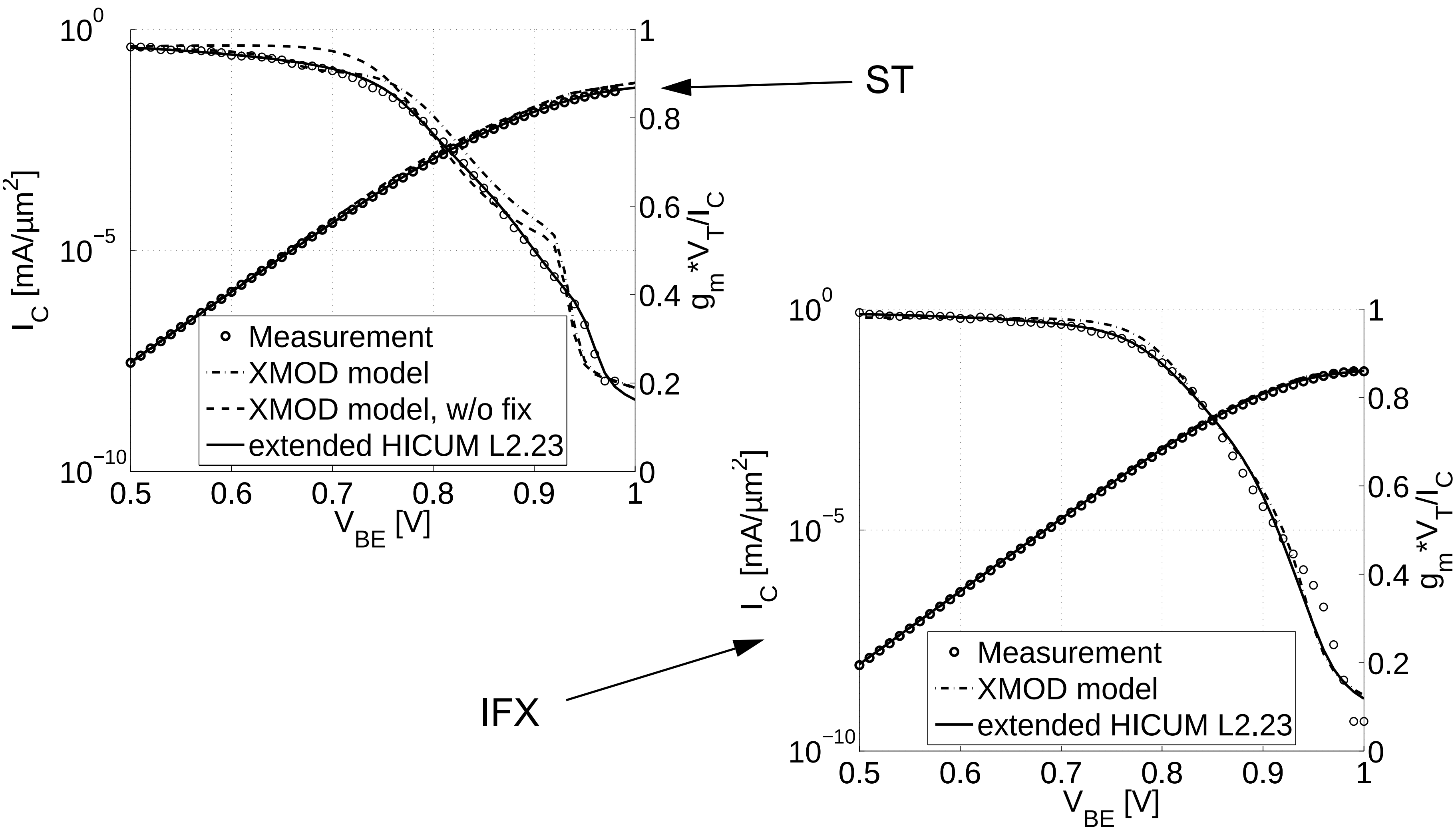




- Combination of $h_{jEi}(V_{BE})$ and h_{f0} results in an accurate description of g_m for low and medium injection

Implementation and results

experimental results: DotFive transistors



Summary and outlook

→ Development of a physics-based equation for h_{jEi} with one additional parameter

→ Introduction of a weighting factor for the low-current minority charge

→ Very accurate results for simulation and measurement

• To be done yet: further verifications (distortion, numerical stability, temperature dependence of parameters)

Acknowledgment

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- DFG

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Additional slides

influence of bias dependence of electron mobility on h_{jEi}

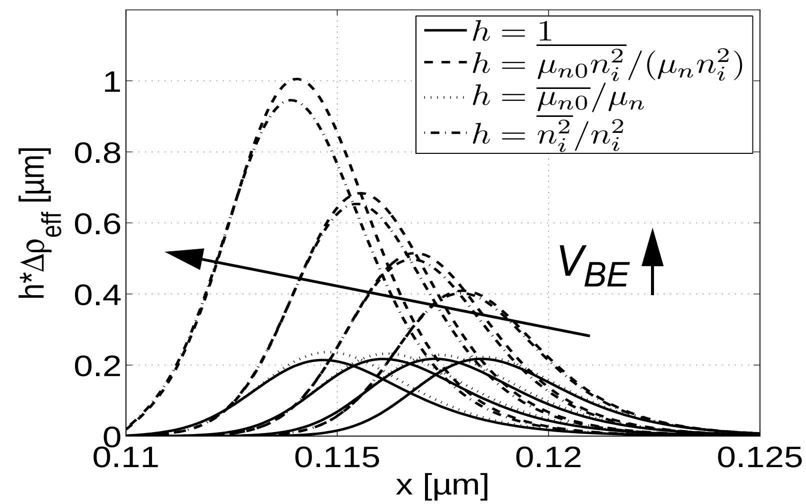
- Space charge

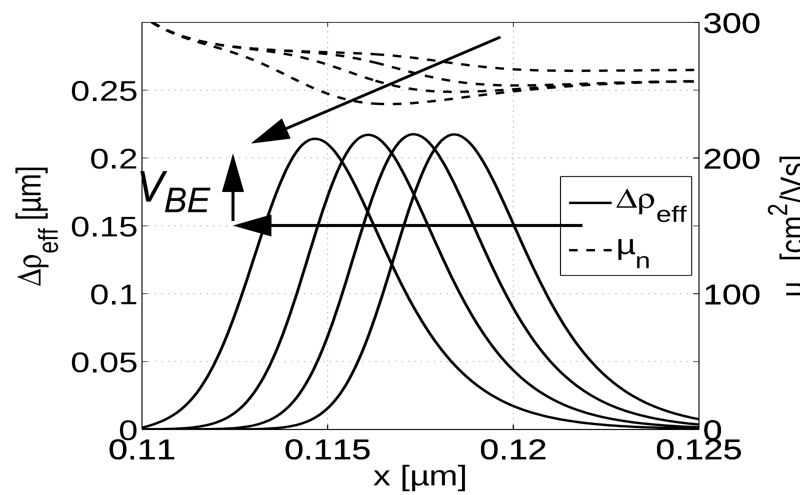
$$\Delta\rho = q[(p-p_0)-(n-n_0)]$$

- Effective increase of space charge

$$\Delta\rho_{eff} = \frac{\Delta\rho(V_{BE})-\Delta\rho(V_{BE}-dV_{BE})}{Q_{jEi}(V_{BE})-Q_{jEi}(V_{BE}-dV_{BE})}$$

- For profile with strong Ge-gradient:
  - effective increase of space charge is almost constant, moves towards junction
  - Strong increase for weighted space charge
  - Almost constant when weighted with mobility only, strong increase when weighted with n_i
  - Electric field and mobility “moves” together with $\Delta\rho_{eff}$





Additional slides

background for h_{f0}

- Weighting factor increases with Ge-gradient, approximately 1 for constant Germanium
- Assumption: Q_{f0} is weighted equal to Q_{p0}
  - Incorrect value for Q_{p0} but correct value for τ_{f0}, weighting needed for either of them
  - Incorrect value for c_{10}, needed weighting for Q_{p0} modeled with $h_{jEi}(V_{BE})$, weighting for Q_{f0} is needed
- Assumption: different weighting for Q_{p0} and Q_{f0}
  - Caused by increasing minorities in base near the BE-junction
  - Different weighting due to gradient of n_i

Additional slides

quick-fixes by XMOD

- Quick-fix for medium injection
- DC-capacitance, extraction of parameters for C_{jEi} based on transfer current for high V_{BE}, based on C(V) for low V_{BE}
- Adjusting τ_0 to get correct transit times
- Leads to “bumps” in g_m, since C_{jEi} formulation leads to a constant value for high voltages