Charge partitioning of the intrinsic HBT according to the TICCR

M. Krattenmacher, M. Schröter

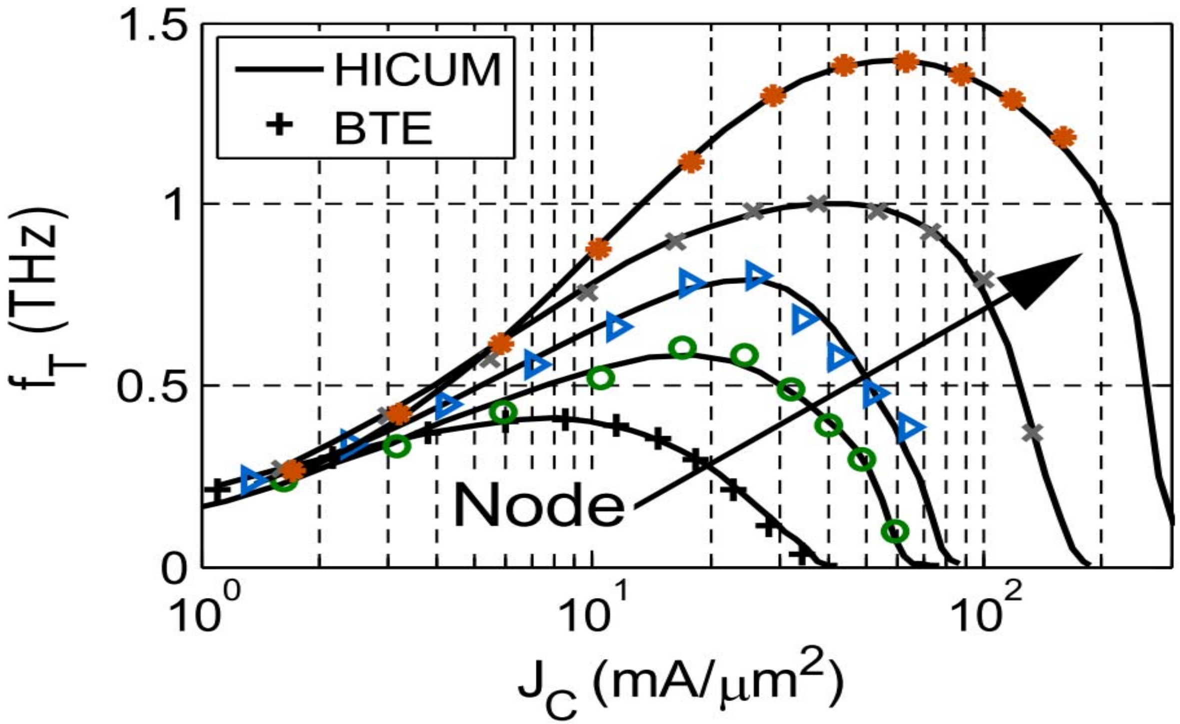
18th HICUM Workshop,
Rohde & Schwarz, Munich, Germany
June 19th, 2018

Content

- Introduction
- Compact modeling approach
- Comparison to device simulation
- Summary

Introduction

Motivation of this work



Modeling in the terahertz gap?

Predictions of dynamic behavior of charges on physical basis necessary!

[1] M. Schröter, T. Rosenbaum, P. Chevalier, B. Heinemann, S. P. Voinigescu, E. Preisler, J. Böck, and A. Mukherjee, „SiGe HBT technology: Future trends and TCAD-based roadmap", Proc. of the IEEE, vol. 105, no. 6, pp. 1068-1086, 2017.

The Transient Integral Charge-Control Relation (TICCR)

- TICCR [2] yields closed-form analytical solution for 1D current densities:

$$j_C(t) = j_T(t) - q\int_0^{x_{bl}} \eta_C\left(R + \frac{\partial n}{\partial t}\right) dx$$

$$j_E(t) = j_T(t) + q\int_0^{x_{bl}} \eta_E\left(R + \frac{\partial n}{\partial t}\right) dx$$

- common transfer current component equal to GICCR (except for h_f)

$$j_T(t) = qV_T\mu_{nr}n_{ir}^2 \frac{\exp\left(\frac{v_{B'E'}}{V_T}\right) - \exp\left(\frac{v_{B'C'}}{V_T}\right)}{\int_0^{x_{bl}} h_v h_g p\, dx}$$

=> can be directly applied to HICUM

=> Focus here on time dependent terms of TICCR current density

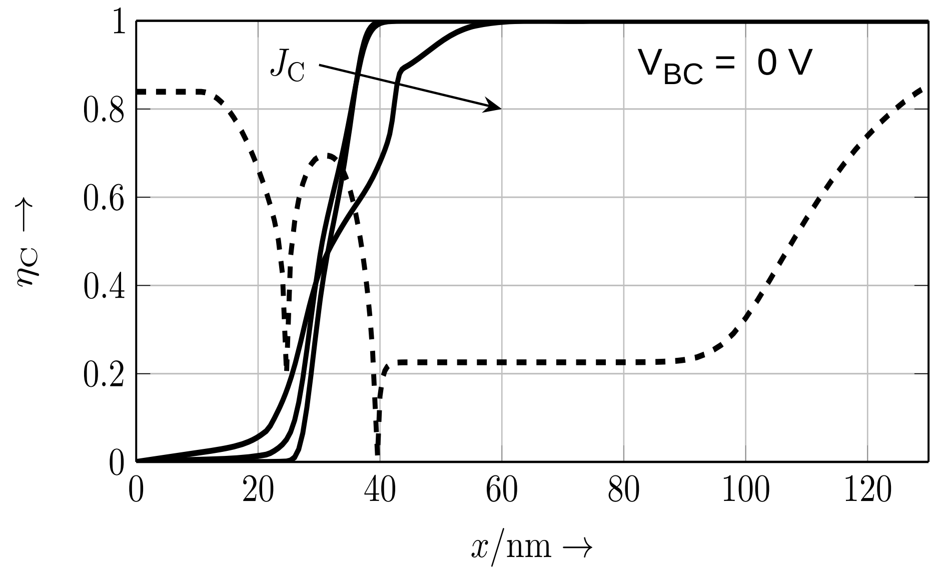
[2] H. Klose and A. Wieder, „The transient integral charge control relation: A novel formulation of the currents in a bipolar transistor," IEEE Trans. Electron Dev., vol. 34, no. 5, pp. 1090-1099, 1987.

Charge partitioning

- partitioning functions:

$$\eta_C(t) = \frac{\int_0^x h_v h_g p \, d\xi}{\int_0^{x_{bl}} h_v h_g p \, dx}$$

$$\eta_E(t) = 1 - \eta_C$$



with GICCR weight functions

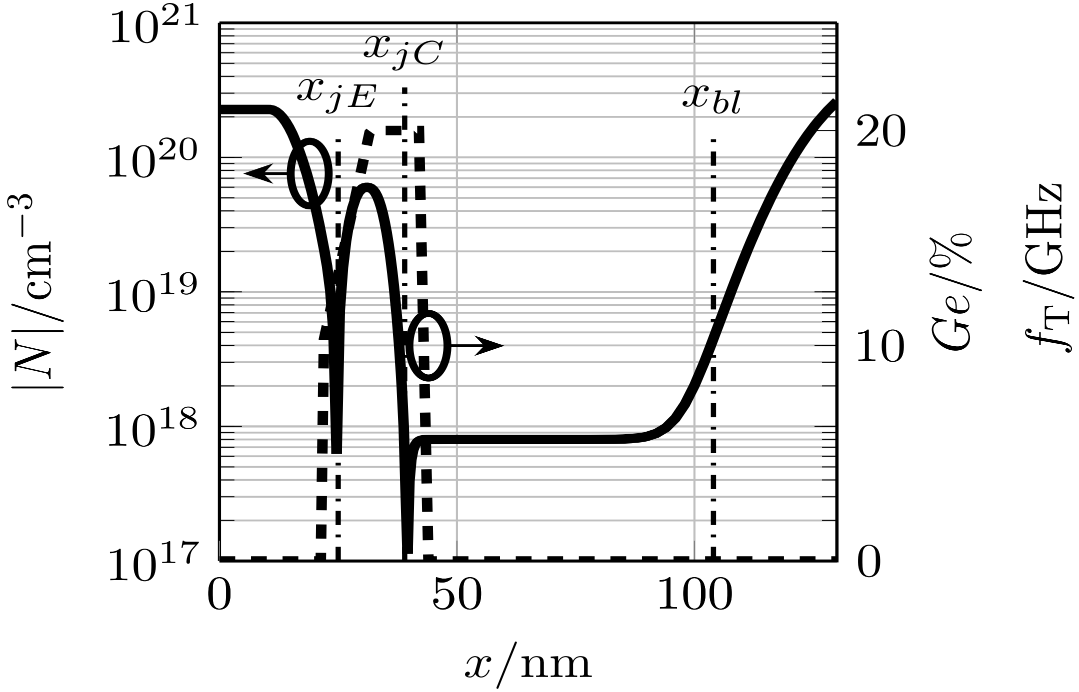
$$h_v(t) = \exp\left(\frac{v_{B'E'}(t) - \varphi_p(x, t)}{V_T}\right). \quad h_g(t) = \frac{\mu_{nr} n_{ir}^2}{\mu_n(x, t) n_i^2(x)}$$

=> η_C (η_E) determines fraction of charge that is supported by C (E) terminal during dynamic operation

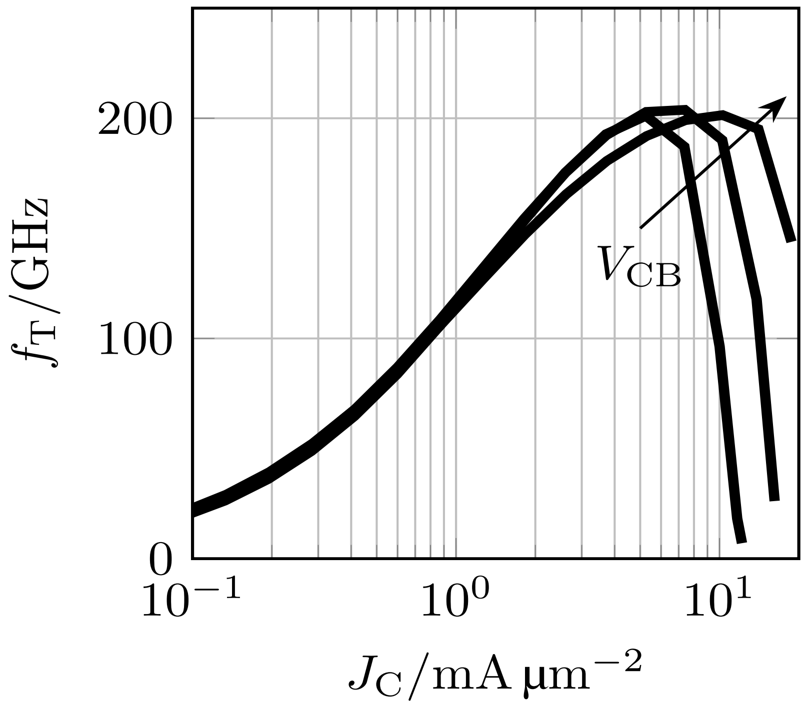
- weak bias dependence up to medium J_C

Selected transistor structure

1D doping profile [3]



transit frequency

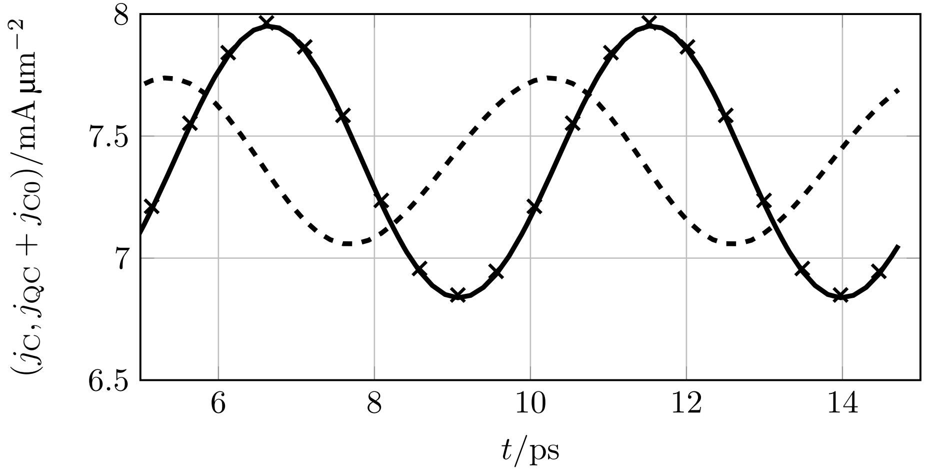


- Integration limits of the TICCR according to [3]
- DD transport dominant
  - for more advanced structures => use augmented DD transport

[3] M. Schroter, S. Lehmann, and A. Pawlak, „Why is there no internal collector resistance in HICUM?", IEEE Bipolar/BiCMOS Circ. and Technol. Meeting (BCTM), pp. 142-145, 2016.

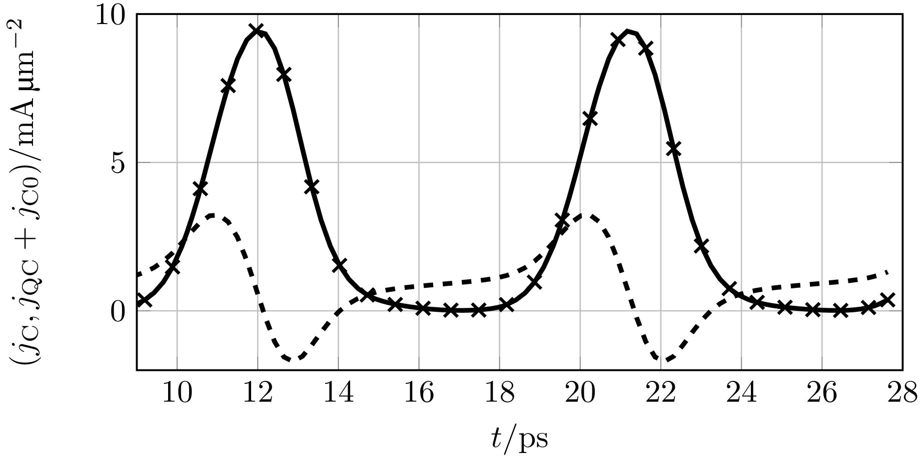
Comparison of TICCR with device simulation

- sinusoidal monofrequent input signal with frequency f
- small-signal operation
  - OP: (J_C, V_{BC}) = (7.39 mA/µm^2, 0V) => peak f_T
  - f = 203 GHz (= peak f_T)
  - 2.5 mV V_{BE} amplitude



- large-signal operation
  - OP: (J_C, V_{BC}) = (1.26 mA/µm^2, 0 V)
  - $f = f_T$ = 131 GHz
  - 70 mV V_{BE} amplitude

  => max. $j_C(t)$ = 1.5 $J_C(f_{T,peak})$!



- excellent agreement for small-signal and large-signal case

  => reference for compact model related simplifications

Compact modeling approach

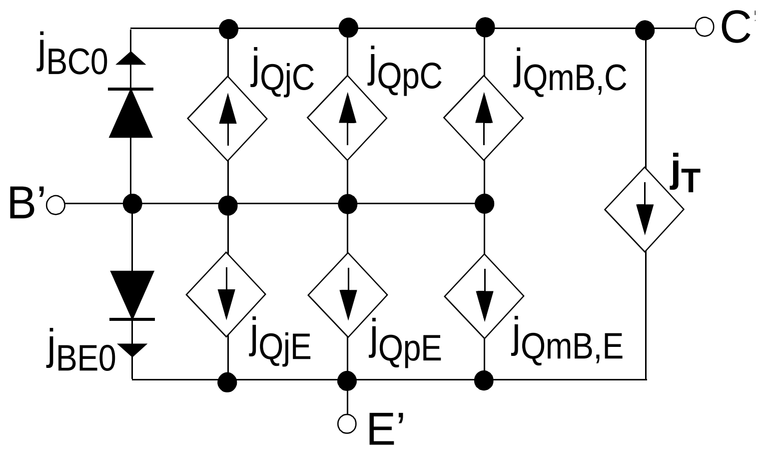
Simplifications of TICCR charge description

Assumptions

- quasi-static carrier distribution => charge, GICCR
- negligible recombination => collector charging current density:

$$j_{QC} = q\int_0^{x_{bl}} \eta_C \frac{\partial n}{\partial t} dx$$

- η_C = 1 for BC region => components



$$j_{QjC} = \frac{\partial \bar{Q}_{jC}}{\partial t} = q\int_{x_{jC}}^{x_{bl}} \frac{\partial(\Delta n - \Delta p)}{\partial t} dx$$

$$j_{QpC} = \frac{\partial \bar{Q}_{pC}}{\partial t} = q\int_{x_{jC}}^{x_{bl}} \frac{\partial \Delta p}{\partial t} dx$$

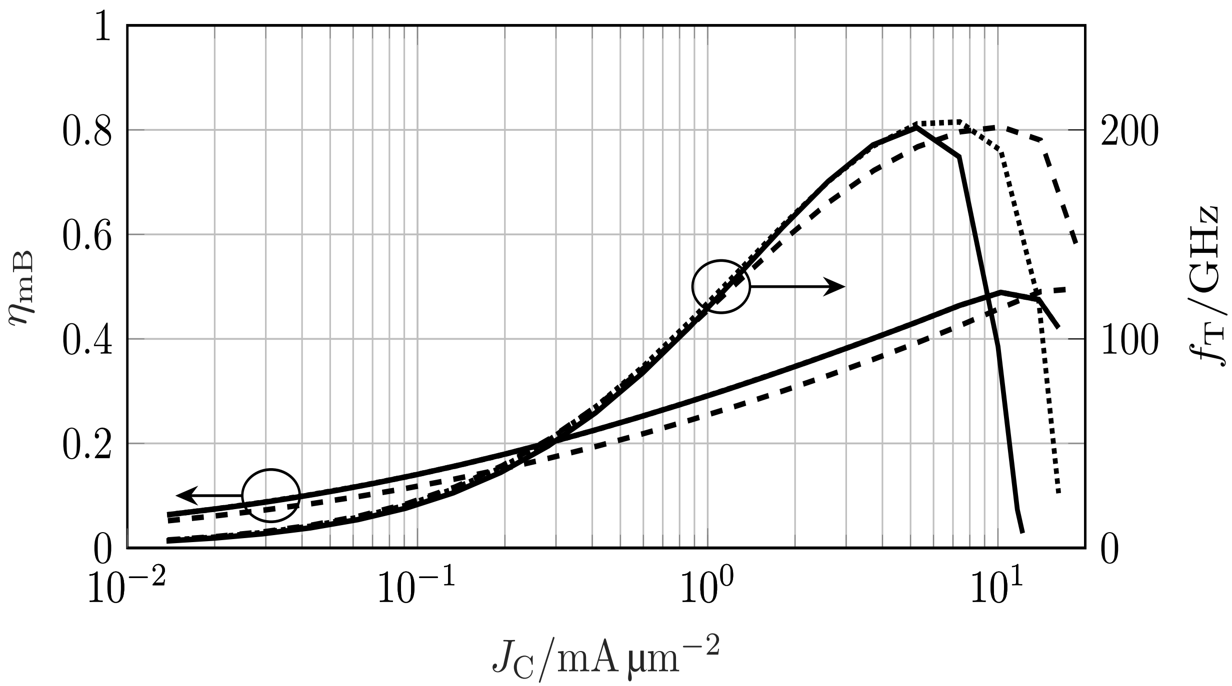
- assume $\eta_C = \eta_{mB} < 1$ for base region only:

$$j_{QmB,\,C} = \eta_{mB}\frac{\partial \bar{Q}_{mB}}{\partial t} \quad \text{with} \quad \eta_{mB} = \int_{x_{jE}}^{x_{jC}} \eta_C \Delta n dx \Big/ \int_{x_{jE}}^{x_{jC}} \Delta n dx$$

Base charge partitioning factor

$$\eta_{mB} = \frac{\int_{x_{jE}}^{x_{jC}} \eta_C \Delta n dx}{\int_{x_{jE}}^{x_{jC}} \Delta n dx}$$

- V_{BC}/V = 0.5,0 (...), -1.2 (- -)
- f_T curve added for reference

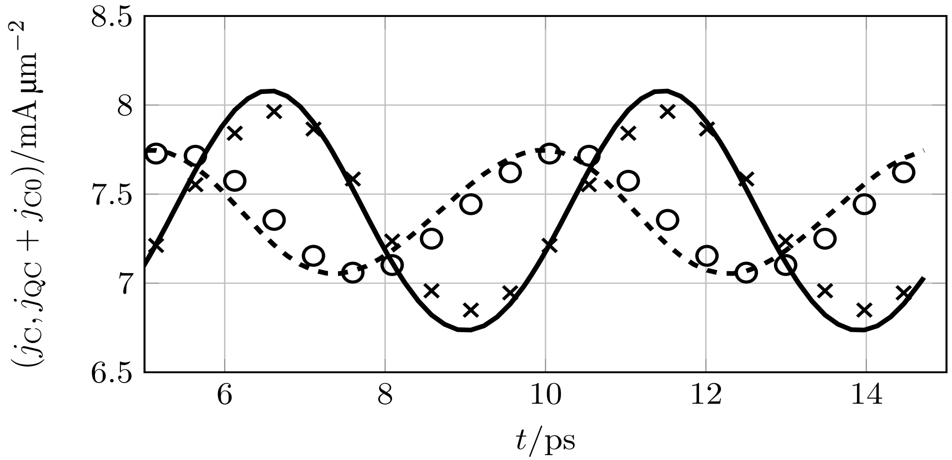


=> η_{mB} depends on J_C, but only slight function of V_{BC}

- analytical formulation for bias dependence yet to be developed
  - excess phase shift = atan($\omega\eta_{mB}C_{dE}/g_m$) = atan($\omega\eta_{mB}\tau_f$) => $\eta_{mB} = \alpha_{IT}$
- existing compact models use bias independent partitioning factor (e.g. fixed value 1/3 in MEXTRAM)

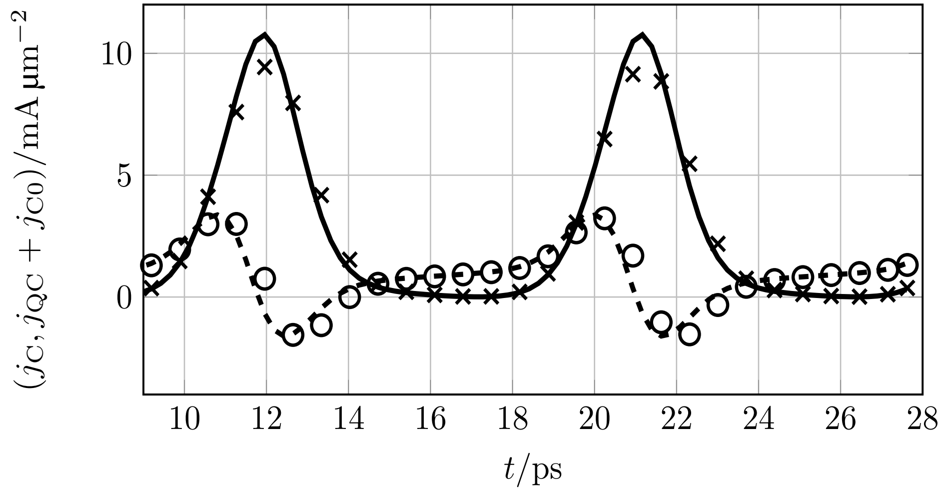
Comparison to device simulation

- sinusoidal monofrequent input signal with frequency *f*
  => same conditions as before



- small-signal operation: model ...
  - amplidute higher
  - phase shifts

- large-signal operation: model ...
  - amplitude overshoot
  - phase shift during turn-off

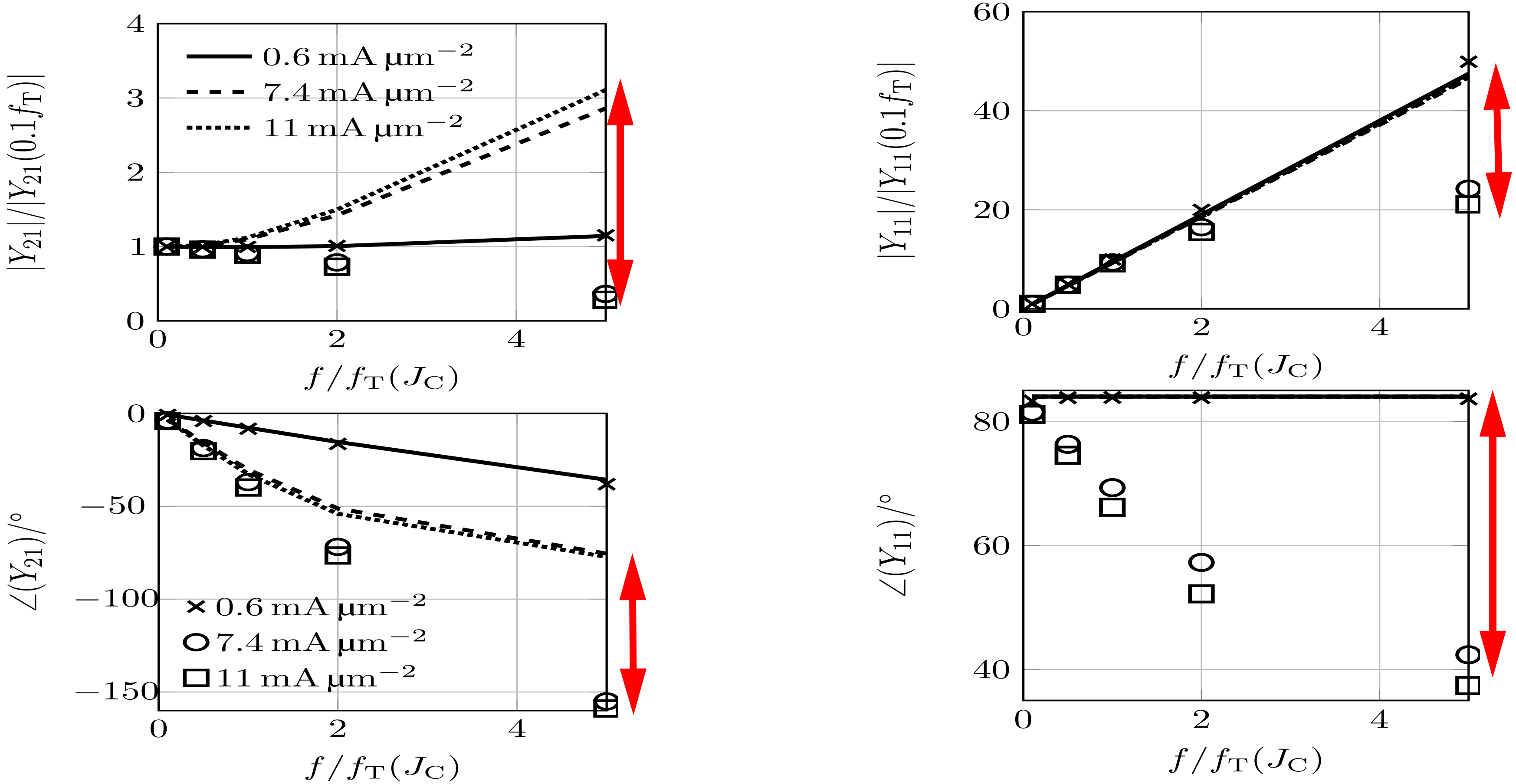


- causes for deviations?
  - dynamic j_C component phase shift
  - other?

=> charge partitioning alone is not sufficient for accurately capturing dynamic collector terminal currant!

Frequency domain results

...indicating cause of observed deviations

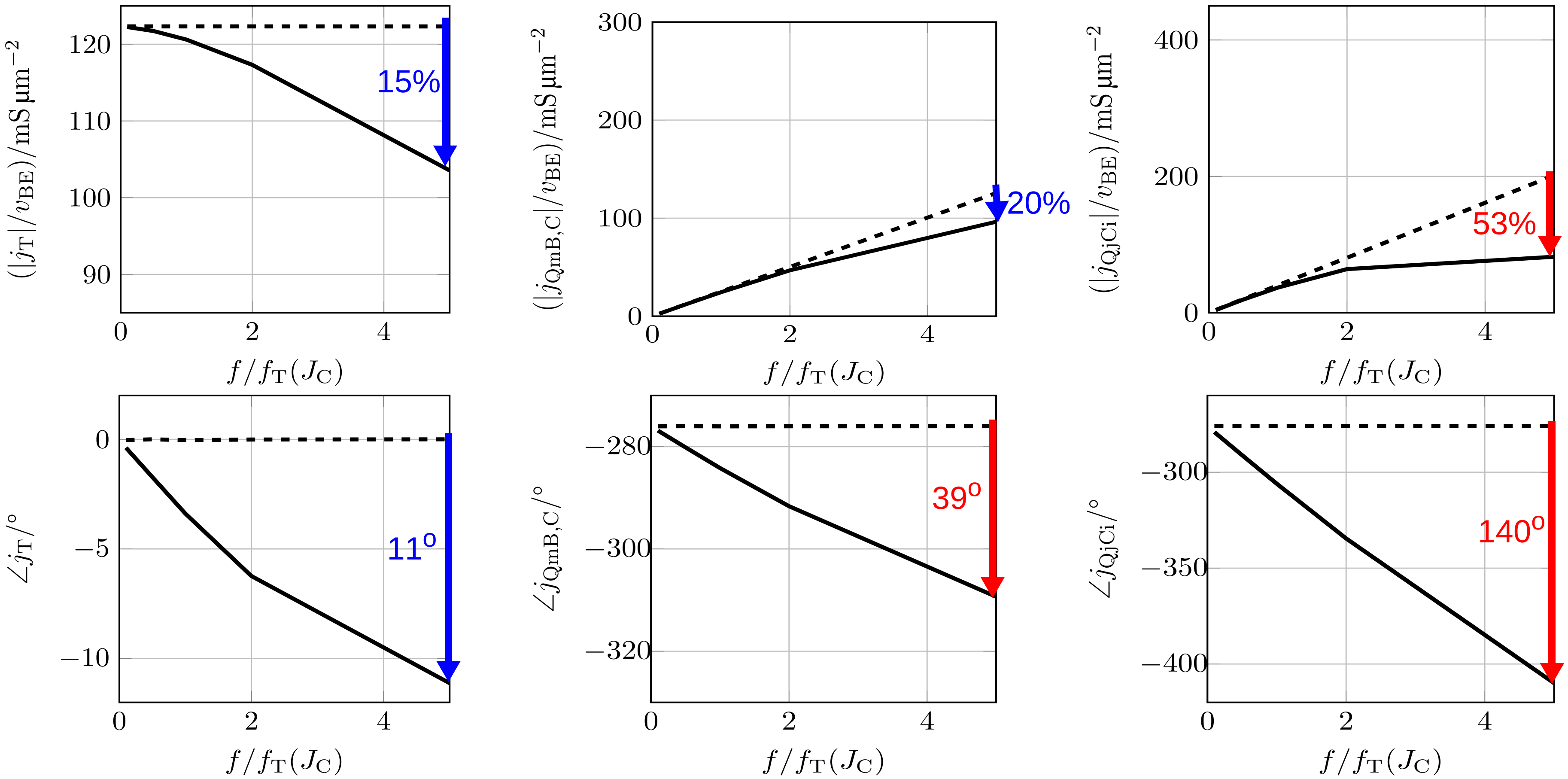


- accurate at low forward bias, but significant deviations at high bias

=> charge partitioning misses phase shift in ***mobile*** charge!

Deviations at higher harmonics

comparison of TCAD vs. CP model with charges from q.s. simulation



- relatively weak frequency dependence of transfer current
- significant frequency dep. of BC depletion charge (SCR modulation!)

Summary

- TICCR offers exact solution of drift-diffusion-based charging currents
  => use as reference for 1D compact model development
- Using quasi-static charges, TICCR based charge-partitioning shows high accuracy up to $f_{T,1D}$, but large deviations for harmonics from 2 $f_{T,1D}$ on
- Base charge partitioning factor depends on J_T

=> charge-partitioning model must include phases of charges!

Outlook

- Measurements of HV devices to validate predictions experimentally
- Develop (i) bias dependent base charge partitioning factor and
  (ii) representation of additional phase shift in BC depletion current
- Replace gyrator adjunct EC in HICUM by new analytical charge partitioning
  => allows to delete two nodes

=> runtime reduction!

Acknowledgments

German Science Foundation DFG SCHR695/16

Ecsel project TARANTO