SELECTED RESULTS OF HICUM PARAMETER EXTRACTION FOR InP HBTS

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M. Müller and M. Schröter

Chair for Electron Devices and Integrated Circuits
Technical University Dresden

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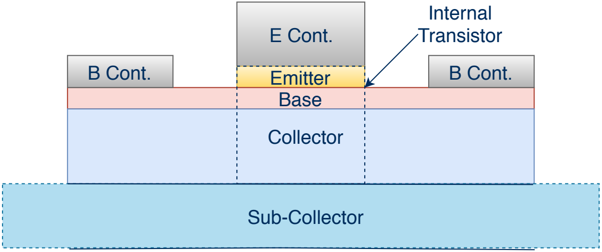
- Motivation
- Mesa Process Overview
- Scaling
- Internal f_{T}
- PDK model vs. HICUM
- Conclusion
- Current Research at CEDIC

InP HBTs show promising electrical properties, but often models are

- not scalable [1].
- not accurate enough [2].
- not accounting for special III-V physics [1].

Goals today:

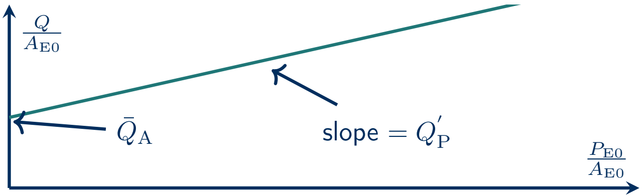
- highlight special modeling issues for InP HBTs
- demonstrate geometry scalable HICUM/L2 applicability
- point out open research questions



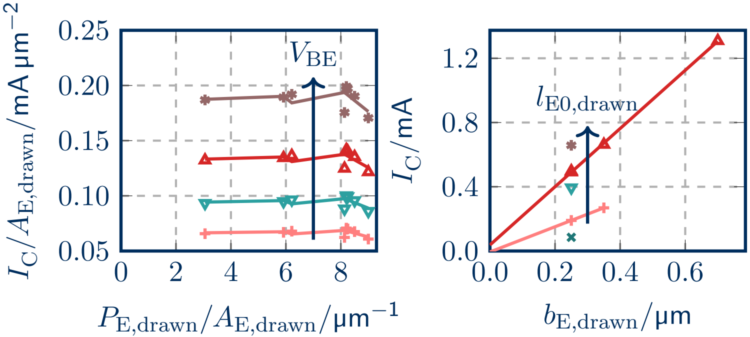
Sketch of mesa process cross section.

- process herein: $f_{\mathrm{T}} \approx 300\,\mathrm{GHz}$ InP Mesa HBT
- large external BC area $\rightarrow C_{\mathrm{BCx}}, I_{\mathrm{BCx}}$ large
- drawn emitter dimensions not accurate enough for classical PoA analysis
- few different sheet resistances

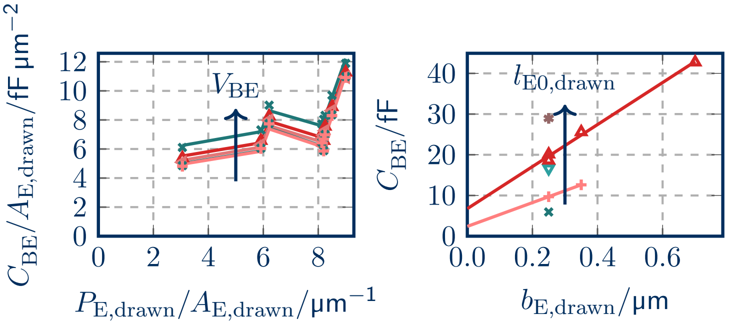
- any quantity Q given as $Q = \bar{Q}_\mathrm{A} A_\mathrm{E0} + Q'_\mathrm{P} P_\mathrm{E0}$
- it follows that $\frac{Q}{A_\mathrm{E0}} = \bar{Q}_\mathrm{A} + Q'_\mathrm{P} \frac{P_\mathrm{E0}}{A_\mathrm{E0}}$



- straight line for every operating point
- slope and y-axis intercept of line allow to separate Q into $\bar{Q}_\mathrm{A}$ and Q'_P
- positive y-axis intercept if $Q > 0$



- left: I_C over $\frac{P_{E,drawn}}{A_{E,drawn}}$ for different V_{BE} in low bias region
- right: I_C over $b_{E,drawn}$ for different $l_{E,drawn}$ at $V_{BE} = 0.7\,V$
- I_C scales linearly along both l_{E0} and b_{E0}, however (slightly) different slopes
- negative y-axis intercept

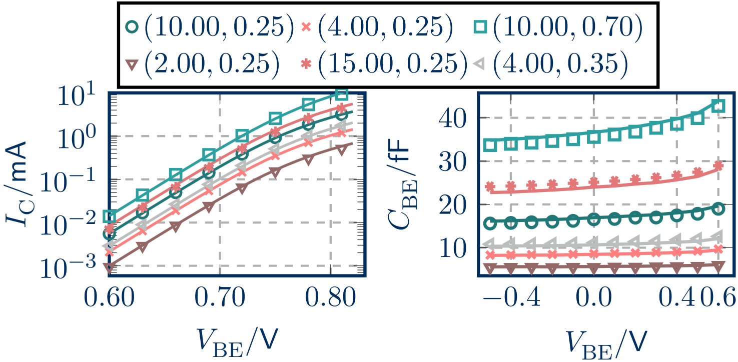


- left: C_{BE} over $\frac{P_{\mathrm{E,drawn}}}{A_{\mathrm{E,drawn}}}$ for different V_{BE} in low bias region
- right: C_{BE} over $b_{\mathrm{E,drawn}}$ for different $l_{\mathrm{E,drawn}}$ at $V_{\mathrm{BE}} = 0.7\,\mathrm{V}$
- C_{BE} scales linearly along both l_{E0} and b_{E0}, however different slopes
- positive y-axis intercept

"Classic" PoA analysis $Q = \bar{Q}_\mathrm{A} A_\mathrm{E0} + Q'_\mathrm{P} P_\mathrm{E0}$ does not work!
Bilinear scaling ansatz works:

$$
\begin{aligned}
Q &= \bar{Q}_\mathrm{A} l_\mathrm{E0} b_\mathrm{E0} + 2Q'_\mathrm{l} l_\mathrm{E0} + 2Q'_\mathrm{b} b_\mathrm{E0} + 4Q_\mathrm{c} \\
l_\mathrm{E0} &= l_\mathrm{E,drawn} + \Delta l \\
b_\mathrm{E0} &= b_\mathrm{E,drawn} + \Delta b
\end{aligned}
$$

- Q variables operating point dependent
- $(\Delta l, \Delta b)$ account for inaccuracy in $(l_\mathrm{E0}, b_\mathrm{E0})$ and do not depend on operating point.
- overdetermined and ill-posed equation system (if enough geometries available)
- suitable choice to determine $(\Delta l, \Delta b) \rightarrow I_\mathrm{C}$
- Δl and/or Δb from TEM (if possible) $\rightarrow$ reduced complexity of equation system

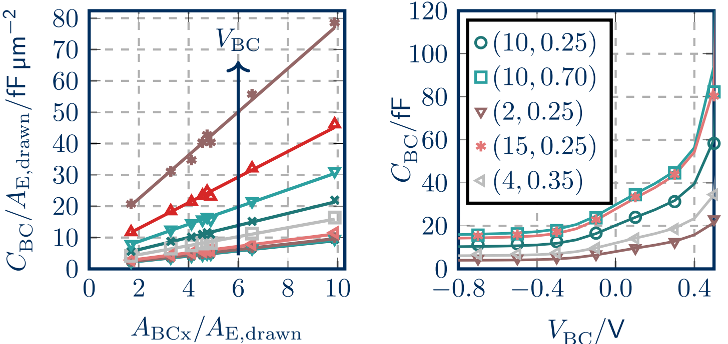


- I_C (left) and C_{BE} (right) @$V_{BC} = 0$ V for CBEBC devices with different (l_{E0}, b_{E0}) in µm
- shown are HICUM simulations
- parameter extraction with DMT
- scaling with TRADICA

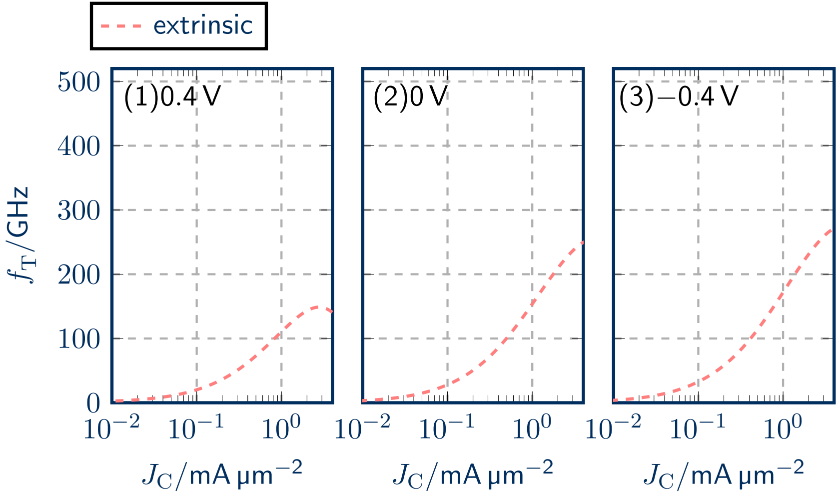
- C_{BC} dominated by external part
- PoA "classic" and bilinear ansatz do not work for C_{BC}.
- C_{BC} originates mainly from A_{E0} and the BC-Mesa area $A_{\mathrm{BCx}} \rightarrow$ ansatz:

$$C_{\mathrm{BC}} = \bar{C}_{\mathrm{BC,A}} A_{\mathrm{E0}} + \bar{C}_{\mathrm{BC,Ax}} A_{\mathrm{BCx}}$$

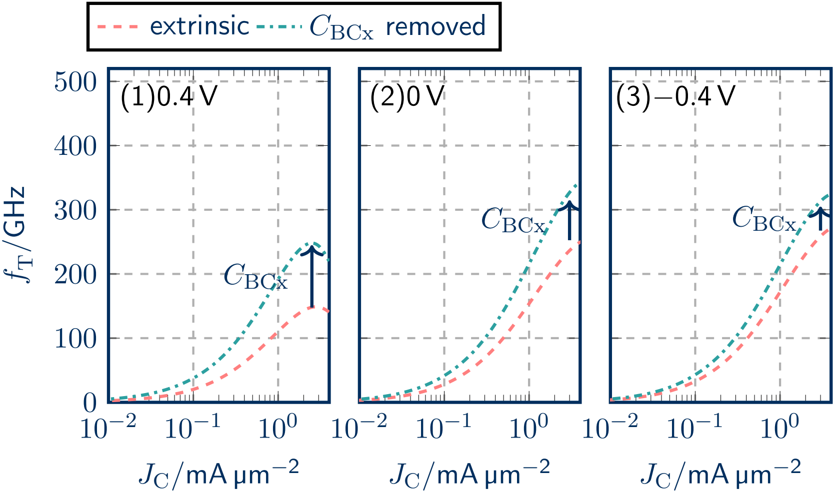
- A_{BCx} as a function of transistor geometry known from layout
- (possible) double plateau behavior in C_{BC}
- compact formulation from [3] available in experimental HICUM version



- left: C_{BC} as a function of $\frac{A_{\mathrm{BCx}}}{A_{\mathrm{E,drawn}}}$ for different V_{BC} @$V_{\mathrm{BE}} = 0\,\mathrm{V}$
- right: C_{BC} simulated vs. measured for different $(l_{\mathrm{E0}}, b_{\mathrm{E0}})$ in µm @$V_{\mathrm{BE}} = 0\,\mathrm{V}$
- accurate results possible
- external mesa area related part dominates C_{BC}



relation between internal and external f_T by removing different model elements at three V_{BC} → what happens here?



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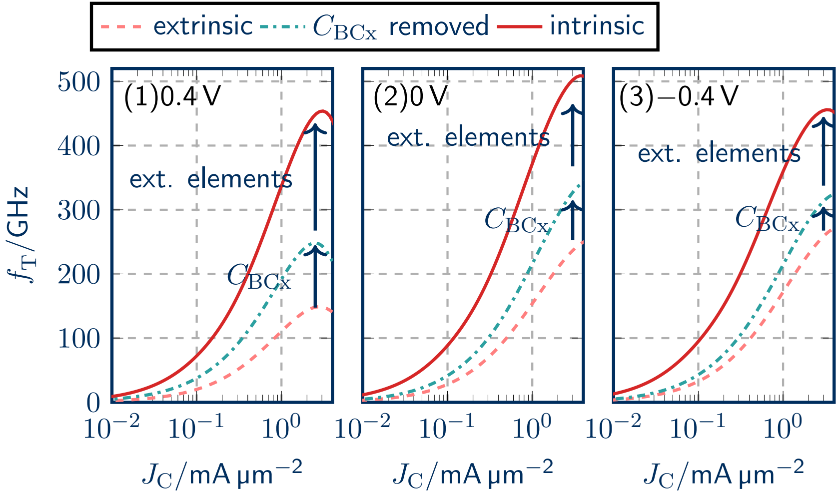

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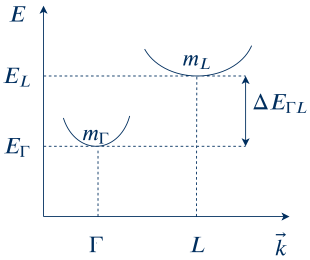
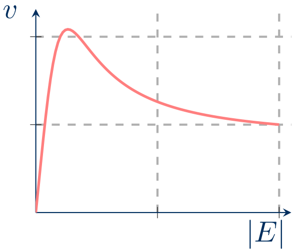


sketch of InP band structure



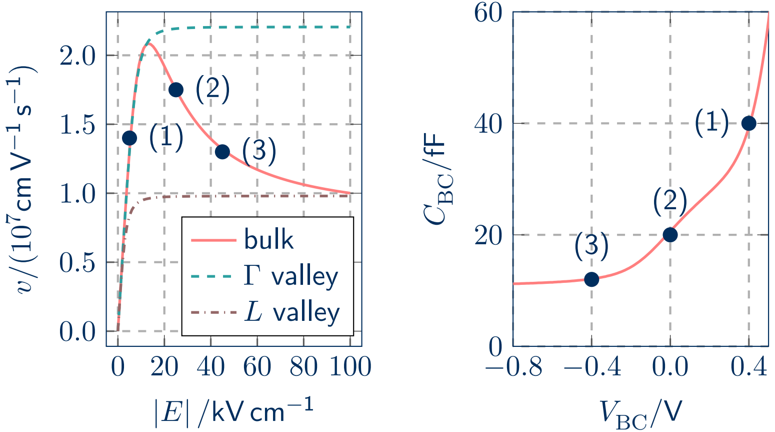
resulting $v(E)$ relationship

- at low energies most carriers are in Γ valley $\rightarrow$ high mobility
- with increasing energy carriers scatter into L valley $\rightarrow$ total mobility decreases
- since $\frac{dv}{d|E|} < 0$ this effect is called Negative Differential Mobility (NDM) effect

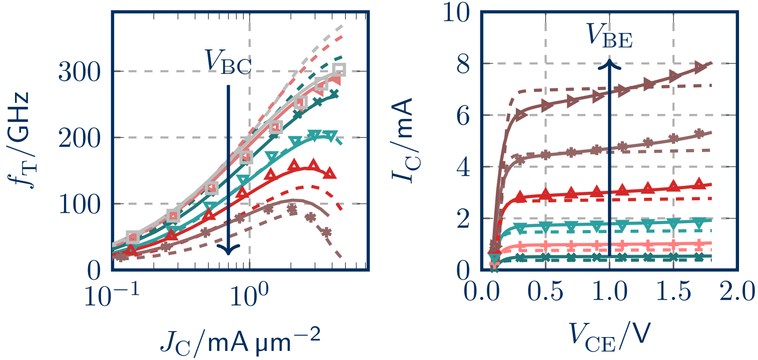
- dependence of f_{Ti} on V_{BC}:

$$\frac{1}{2\pi f_{\mathrm{Ti}}} = \tau_{\mathrm{f}} + \frac{C_{\mathrm{jei}} + C_{\mathrm{jci}}}{g_{\mathrm{m}}} \quad \text{and} \quad \tau_{\mathrm{f}} \propto v_{\mathrm{n,collector}}^{-1}$$

- V_{BC} dependence of f_{Ti} mainly from $v_{\mathrm{n,collector}}$ and C_{jc}
- currently no TCAD simulations possible $\rightarrow$ can only speculate [4]!
- work on multi-valley in-house TCAD simulator ongoing $\rightarrow$ verify physics-based τ_{BC} model accounting for NDM effect [5]



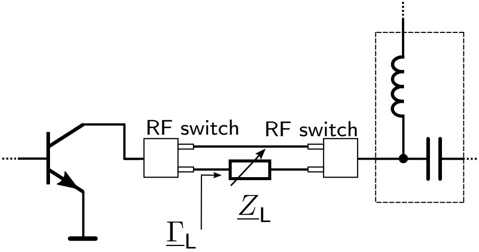
- left: InP Bulk velocity field curve with parameters from [4] and sketched (!) velocities in each valley
- right: Measured C_{BC}@$V_{\mathrm{BE}} = 0\,\mathrm{V}$



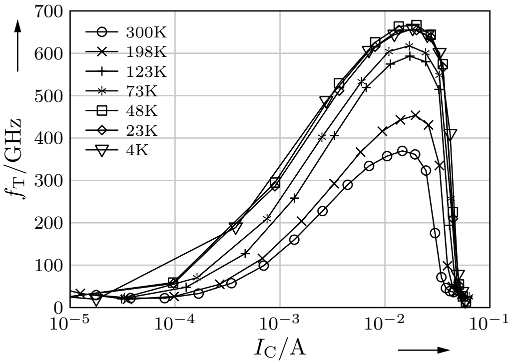
- Measured (symbols), HICUM (lines) and PDK model (dashed lines) f_T (left) and I_C (right).
- PDK model has no self heating (?)
- PDK model is not scalable

- process is scalable
- HICUM can be used to model the process.
- special issues: bilinear scaling, C_{BC} formulation, NDM effect
- f_{T} at low V_{BC} could be better $\rightarrow$ improved τ_{f} model required
- f_{max} not yet satisfactory $\rightarrow$ reason currently under investigation

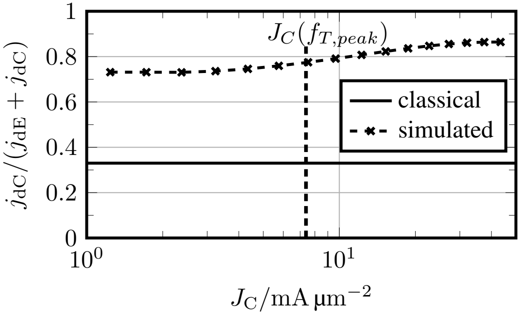
- researcher: Dipl.-Ing. Christoph Weimer
- dynamic large-signal voltage swings beyond breakdown voltages
- impact on the degradation of the static and dynamic behavior of SiGe HBTs



- researcher: M.Sc. Xiaodi Jin
- compact modeling and measurement of SiGe HBTs at cryogenic temperatures



- researcher: Dipl.-Ing. Mario Krattenmacher
- compact modeling of non-quasi-static effects in highly scaled SiGe HBTs
- physics based vertical diffusion charge partitioning



[1] T. Nardmann, *Physics-Based Compact Modeling and Parameter Extraction for Inp Heterojunction Bipolar Transistors with Special Emphasis on Material-Specific Physical Effects and Geometry Scaling*. Books on Demand, 2017, ISBN: 9783744872805.

[2] K. Eriksson, "InP DHBT Amplifiers and Circuit Packaging up to Submillimeter-Wave Frequencies", PhD thesis, Chalmers University of Technology, 2015.

[3] T. Nardmann, M. Schroter, and P. Sakalas, "A Multiregion Approach to Modeling the Base-Collector Junction Capacitance", *IEEE Transactions on Electron Devices*, vol. 63, no. 9, pp. 3808–3811, 2016.

[4] G. Wedel, T. Nardmann, and M. Schroter, "On the use of Drift-Diffusion and Hydrodynamic Transport Models for Simulating the Negative Differential Mobility Effect", in *2018 IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS)*, IEEE, 2018.

[5] M. Schroter, T. Nardmann, and G. Wedel, "A Closed-Form Solution for the Low-Current Collector Transit Time in Group IV and Group III-V HBTs", *IEEE Transactions on Electron Devices*, vol. 64, no. 8, pp. 3346–3352, 2017.