Advanced Modeling of Silicon-Germanium HBTs

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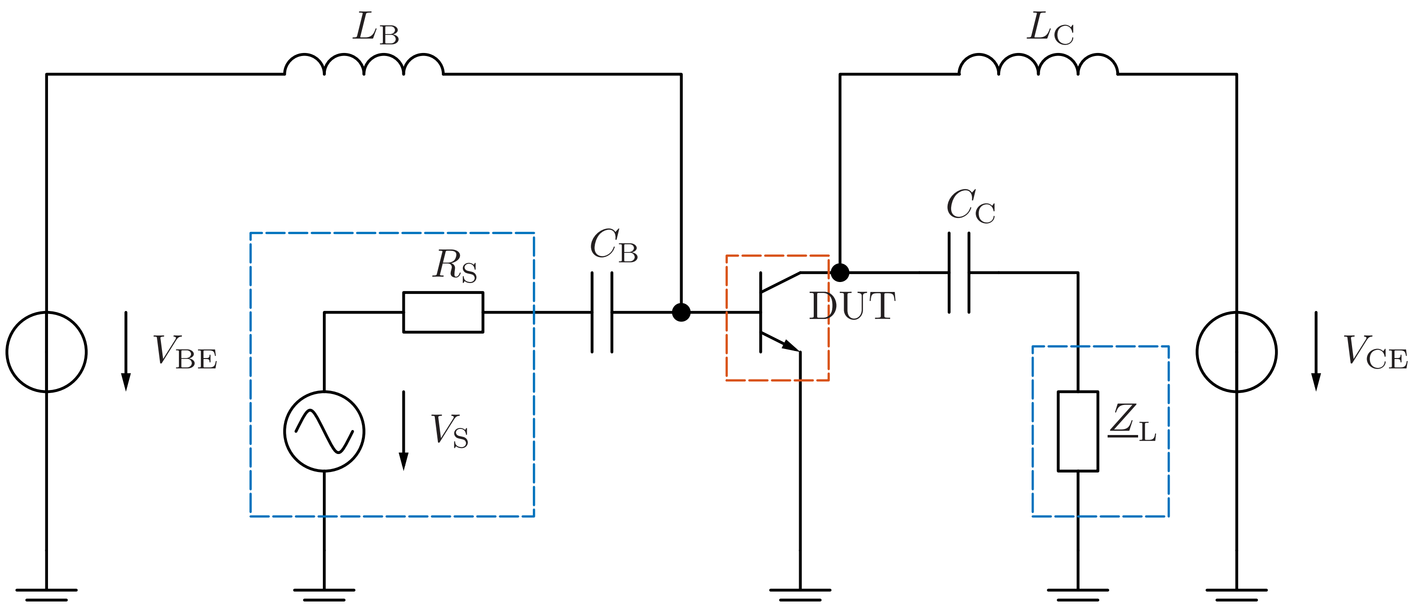
Overview

- Nonlinear modeling
- Transfer current equation
- Electrical field in the collector
- Substrate coupling
- Parameter extraction
  - Weight factors
  - Non-ideal scaling
  - Emitter and thermal resistance

Nonlinear modeling

- Simple PA circuit with power source and load impedance

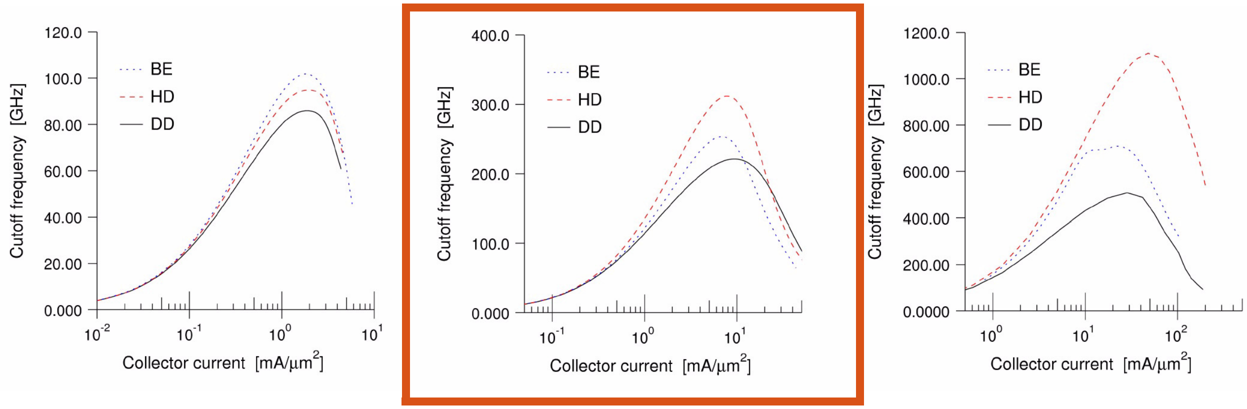


transistor DUT simulated as

either numerical 1D device
or compact model HICUM/L2

Numerical device

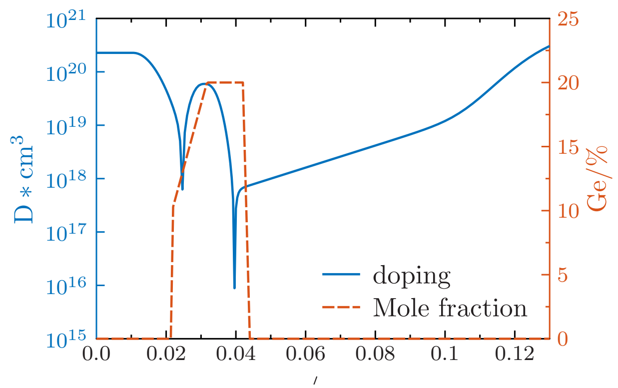
- Drift-Diffusion simulation for profile with f_T=250 GHz



[S.-M. Hong, C. Jungemann, "Electron transport in extremely scaled SiGe HBTs," BCTM 2009, S. 67-74.]

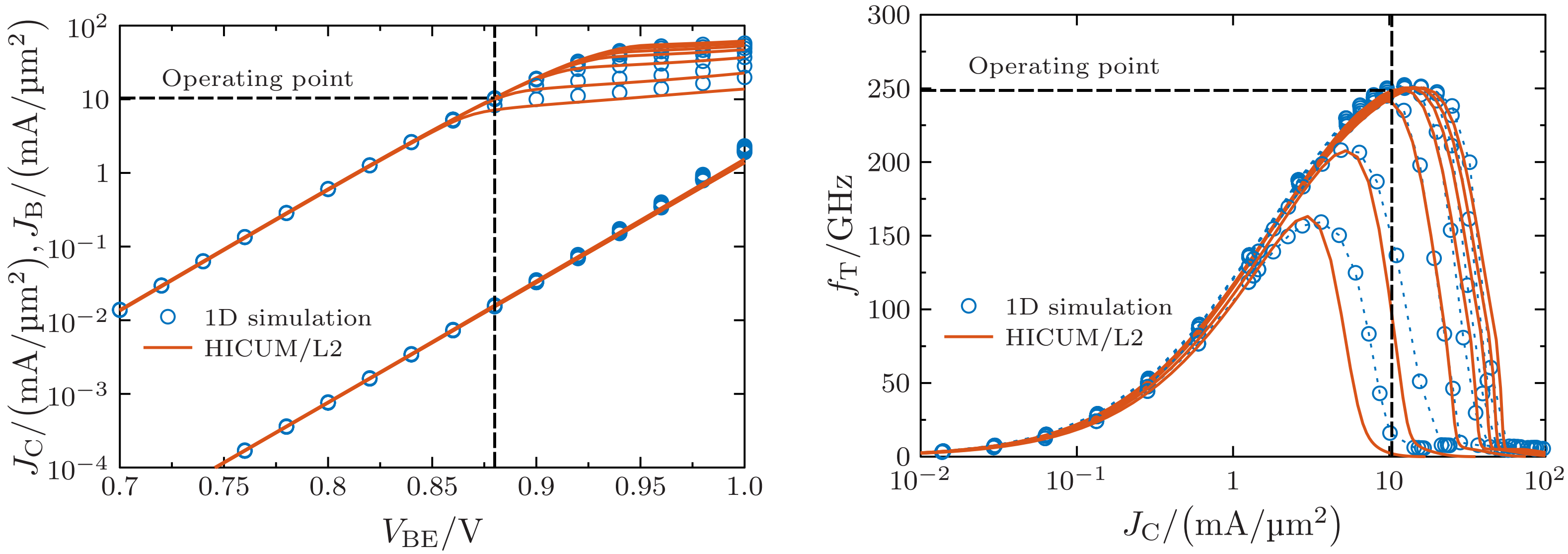
=> limits of DD model

length of internal transistor:	130 nm
base width:	15 nm
internal collector width:	70 nm
maximum base doping:	$6*10^{19}$ cm^{-3}
J_C @ $f_{T,peak}$:	10 mA/µm^2
B_{VCE0} @ V_{BE}=0.7 V:	1.5 V



Parameter extraction

- Usage of latest available version
  - extraction based on standard characteristics (DC, small signal AC)

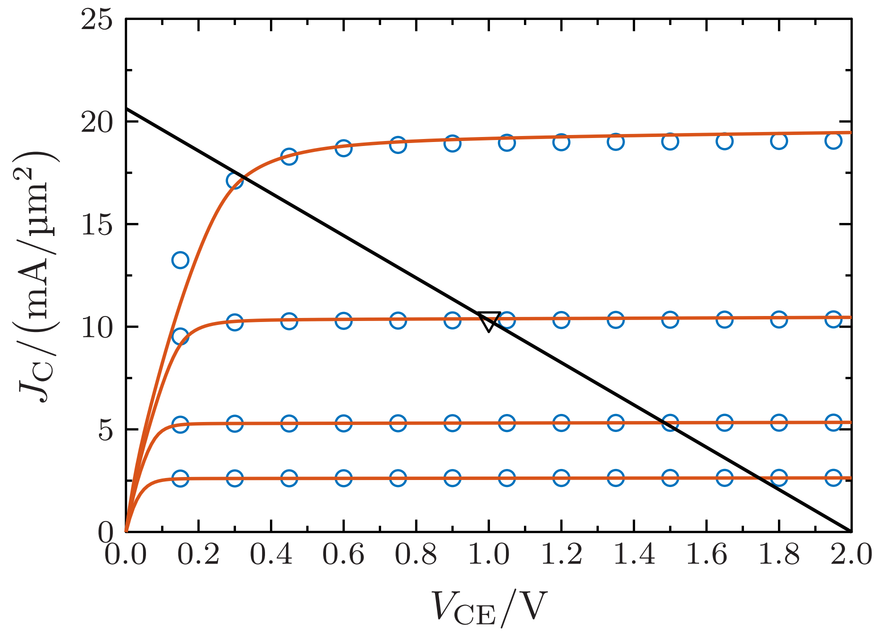


  - extraction of all parameter corresponding to 1D transistor

Power amplifier

- Operating point close to $f_{\mathrm{T,peak}}$

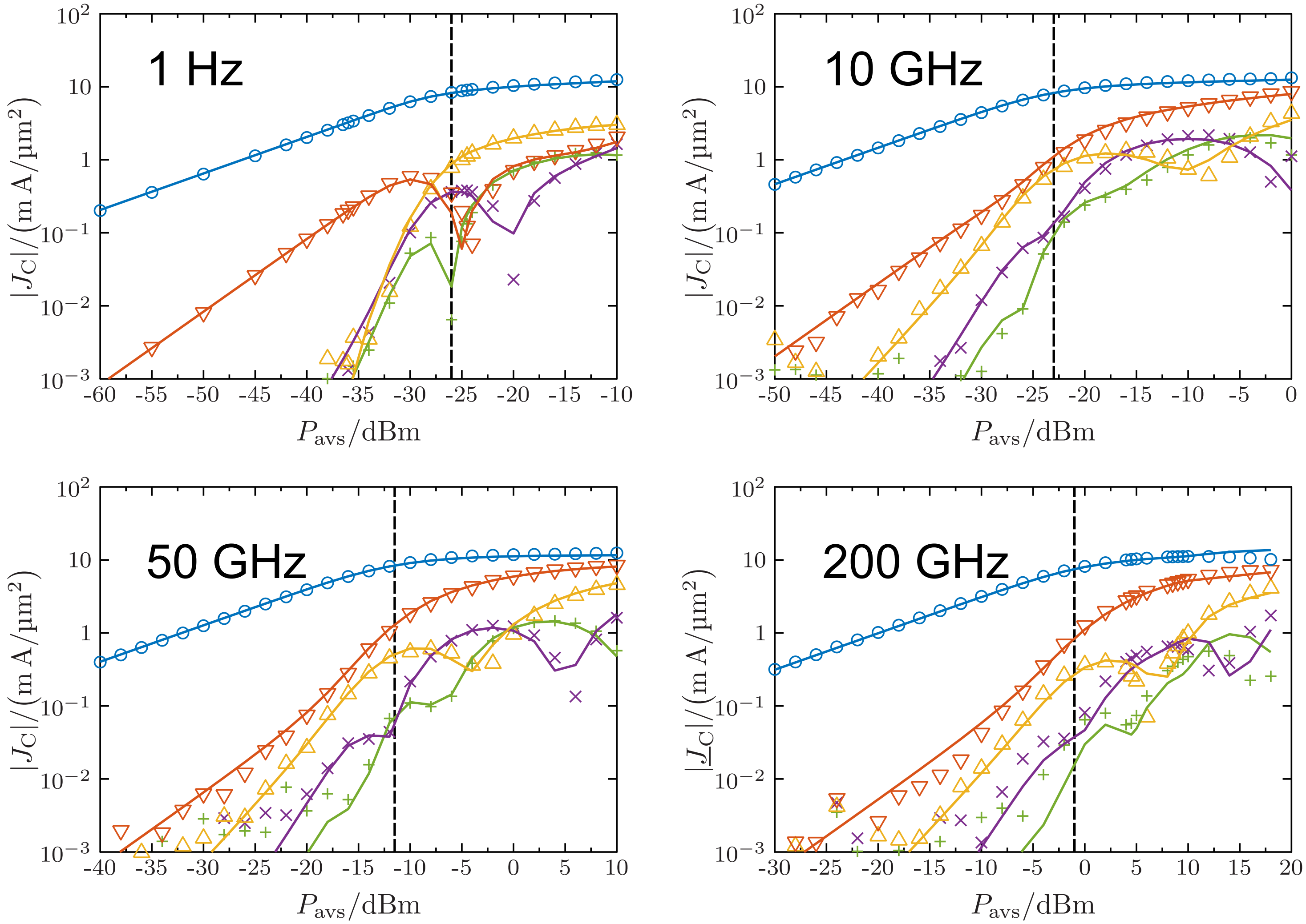
=> strong impact of high current effects



- 1D transistor used with A_{E}=1 µm^2 => Load resistance: RS=100 Ω

close enough to 50 Ω => realistic environment

Frequency domain results



Nonlinear modeling

- Accurate non-linear large-signal modeling with HICUM/L2
  - up to very high frequencies far beyond $f_{T,peak}$

=> Which physical effects are significant?

- Discussed here:

High-current effects

  - compression at high input power

=> saturation

=> transfer current modeling

  - high-current effects in charges due to strong increase of carrier-densities

=> impact on I_C (via $Q_{p,T}$)

=> impact on Q_f

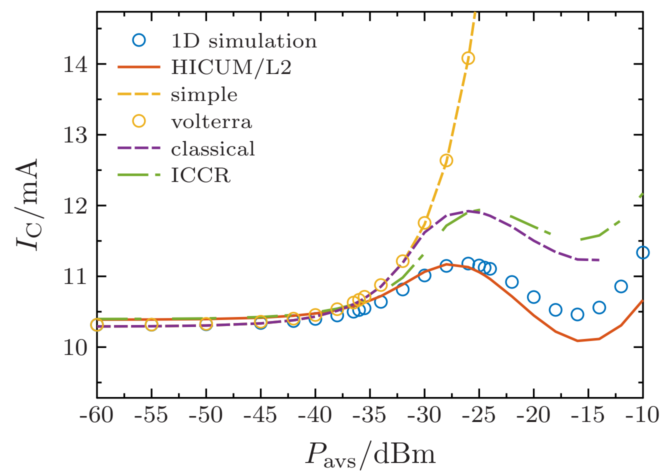
Impact

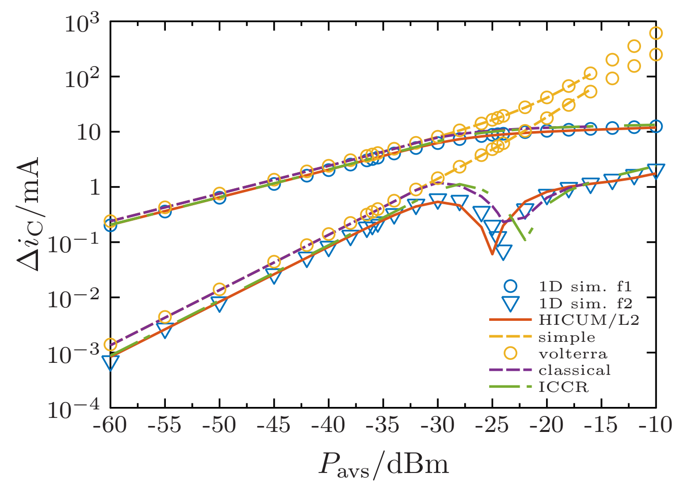
- Transfer current modeled by:

simple equation: $I_T = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$ (no saturation, no BC related current)

classical equation: $I_T = I_S\left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right)\right]$ (saturation, const. I_S)

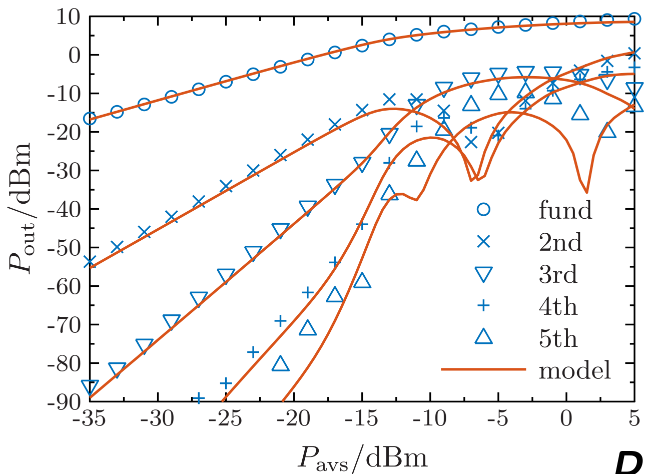
ICCR: $Q_{p,T} = Q_{p0} + Q_{j,T} + h_{f0} i_{Tf} \tau_{f0}$ (no high-current effects on I_T)

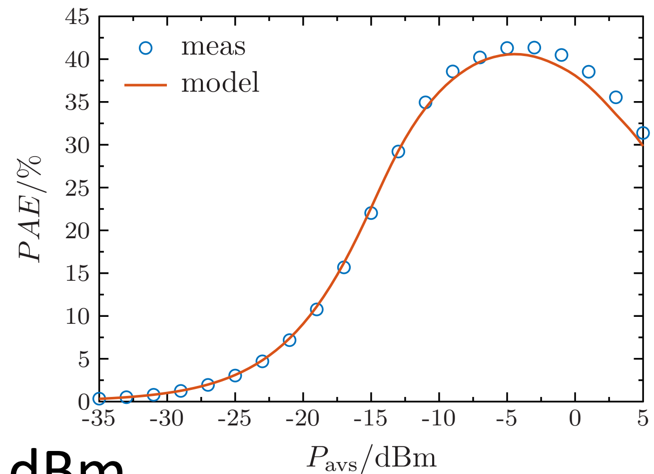




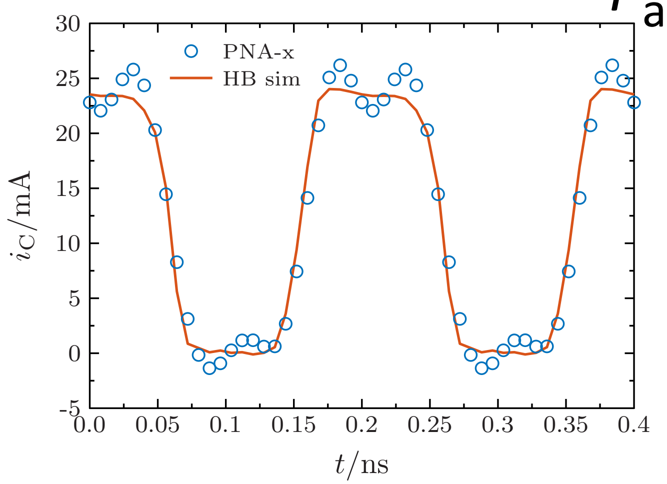
Selected Results (IHP)

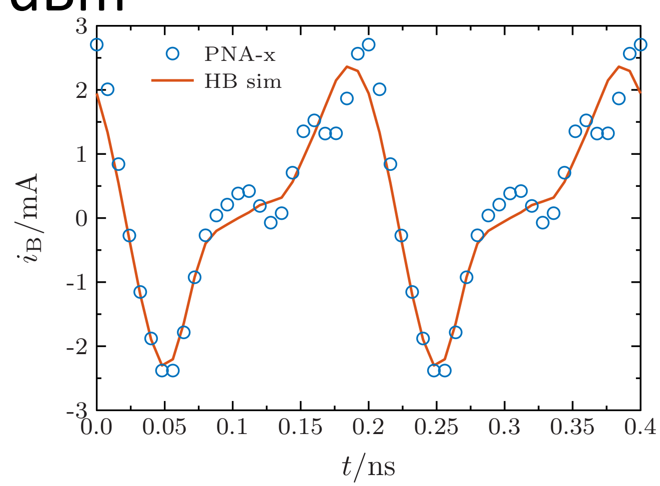
Large-signal: V_{BE}=0.875 V, V_{CE}=1 V, JC=5 mA/µm^2, f_0=5 GHz,





P_{avs}=-5 dBm





Transfer current equation

$$I_T = \frac{qA_E V_T \overline{\mu_{nr} n_{ir}^2}}{\int h(x)p(x)dx}\left[\exp\left(\frac{V_{B'E'}}{V_T}\right) - \exp\left(\frac{V_{B'C'}}{V_T}\right)\right]$$

- Weighted hole charge

$$Q_{p,T} = Q_{p0} + h_{jEi}Q_{jEi} + h_{jCi}Q_{jCi} + h_{f0}i_{Tf}\tau_{f0} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}Q_{pC}$$

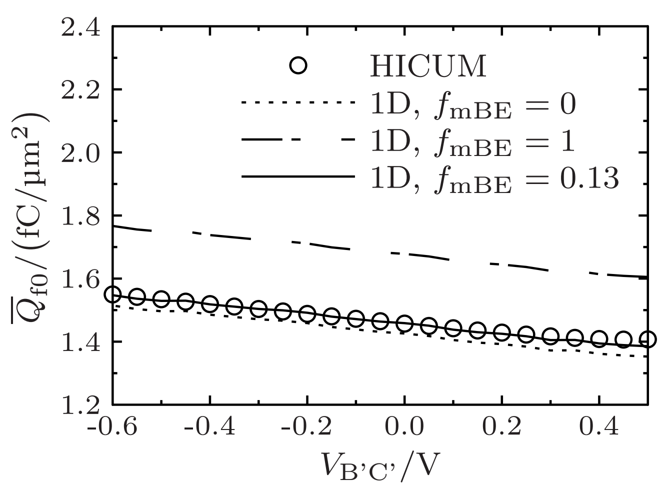
Bias dependence of h_{f0}

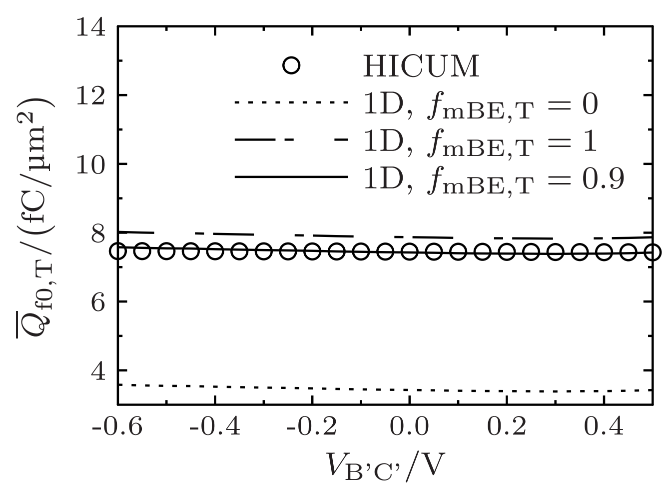
- Charge

$$Q_{f0} = Q_{mE} + f_{mBE} Q_{mBE} + Q_{mB} + Q_{pBC}$$

- versus weighted charge

$$Q_{f0,T} = \frac{h_{mE} Q_{mE} + f_{mBE,T} h_{mBE} Q_{mBE} + h_{mB} Q_{mB} + h_{pBC} Q_{pBC}}{h_{00}}$$

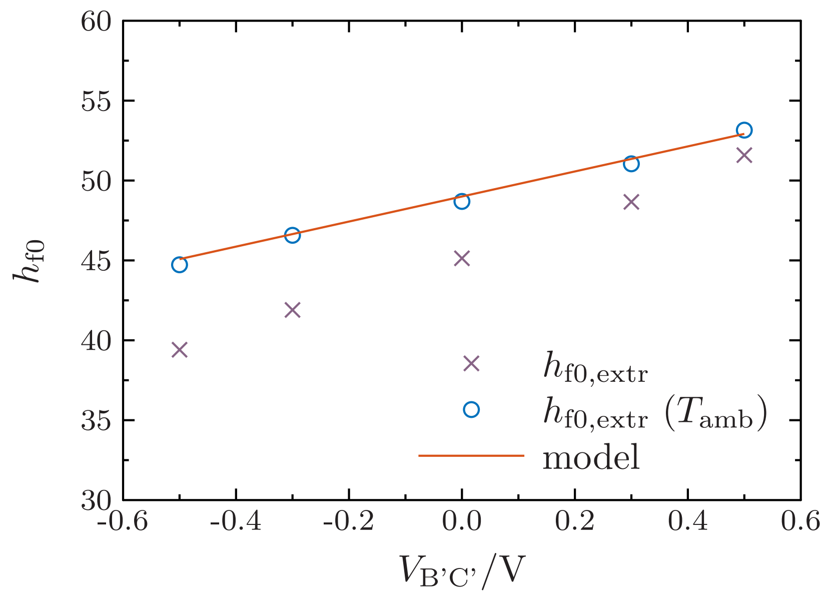


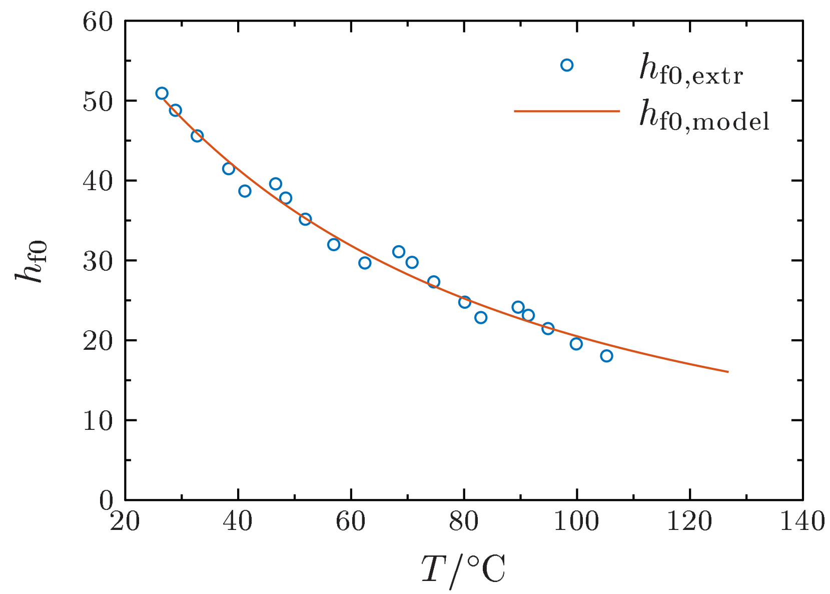


Extraction

- Extraction methods have been successfully applied to measured HBTs
  - physics-based parameter values

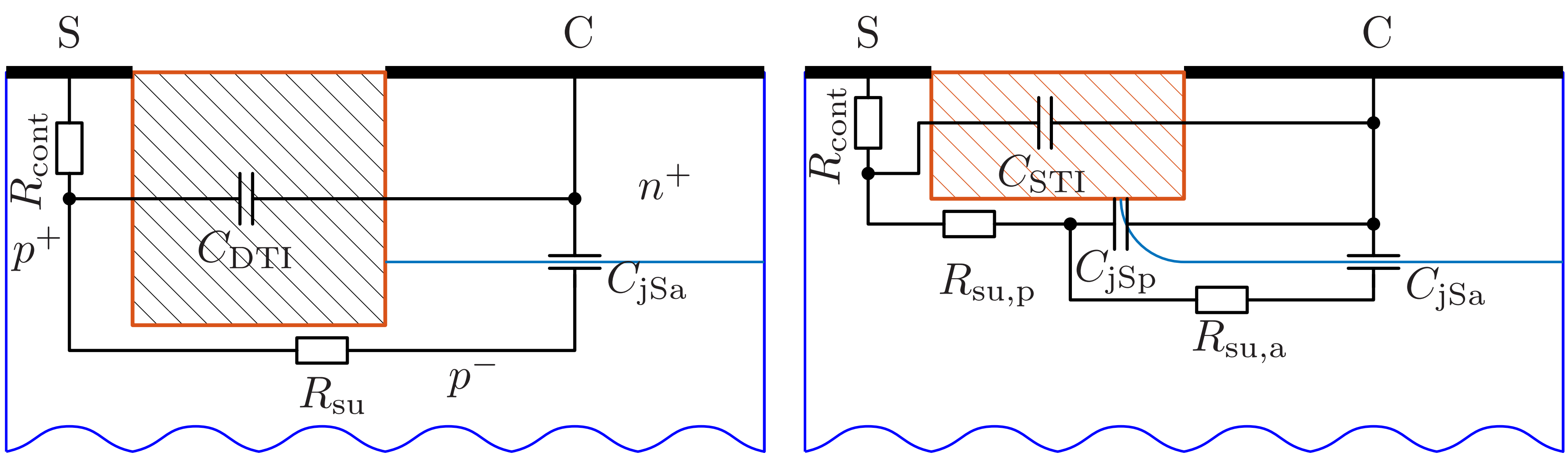
=> Verification of model equations





Substrate-coupling

- Simplified cross-sections
  - DTI isolation of transistors <=> only STI

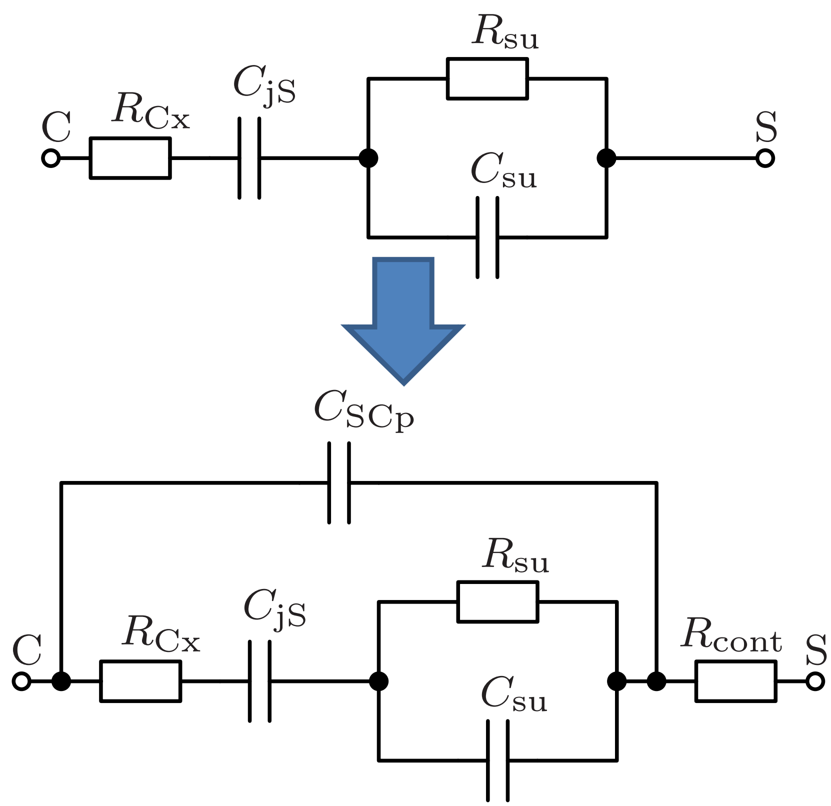


=> different bias- and temperature-dependence

=> different scaling behavior

Equivalent circuit

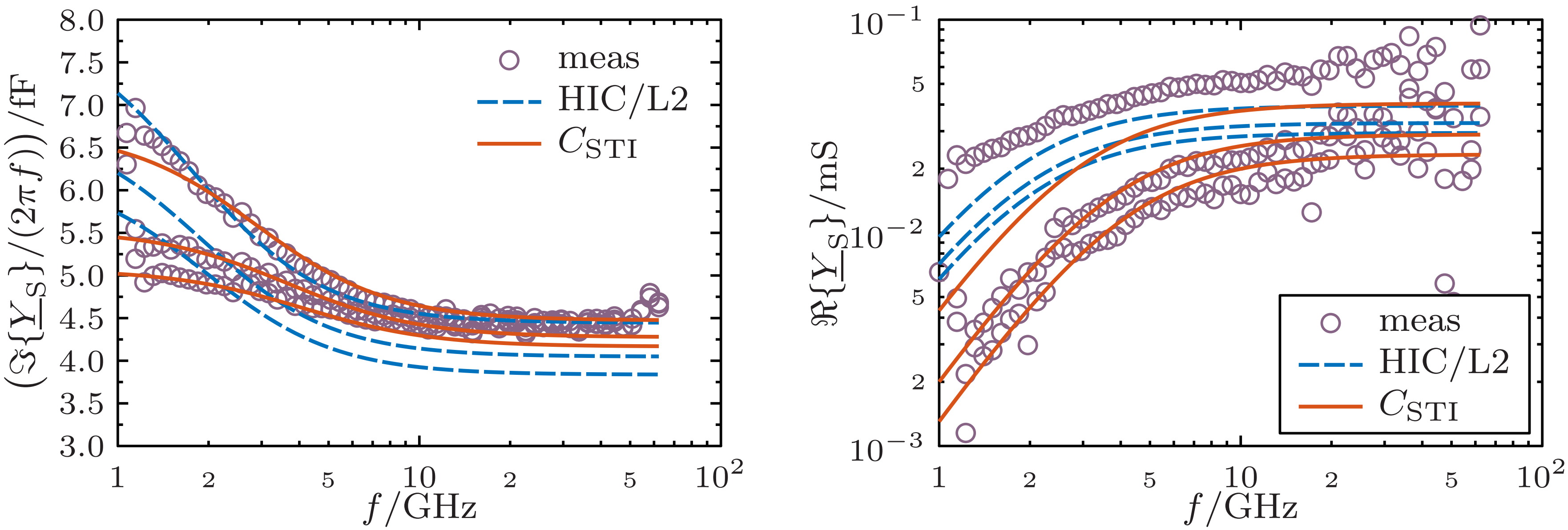
Additional peripheral capacitance



- improved scaling capabilities
- bias and temperature dependence

Application

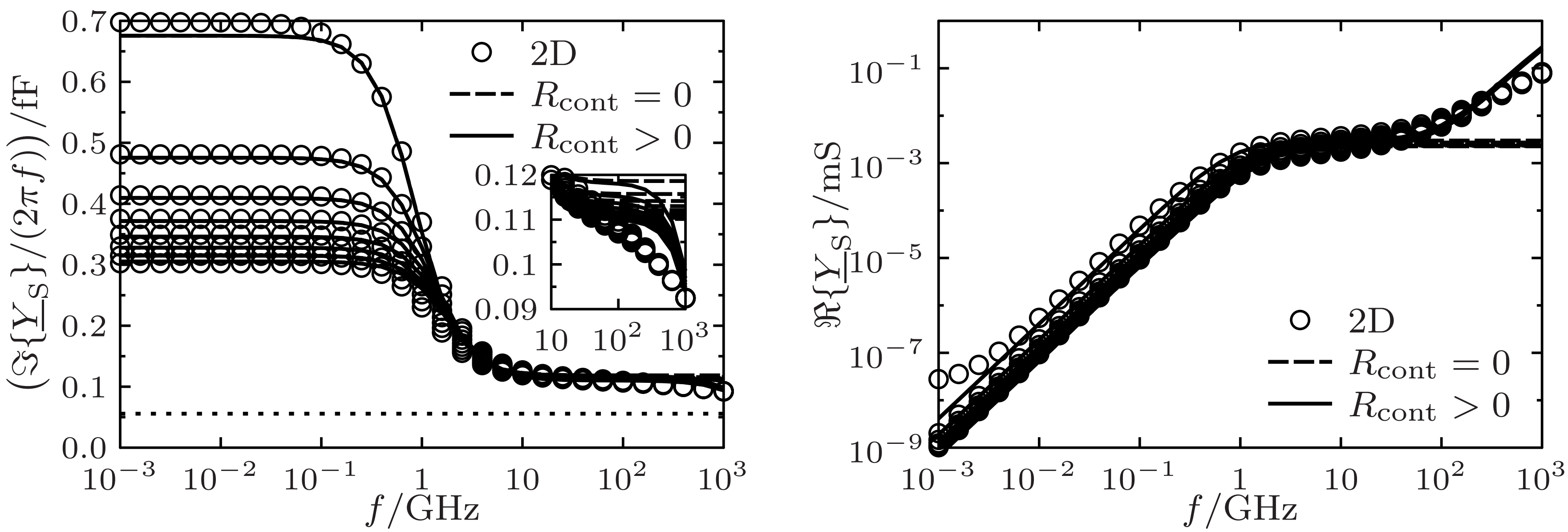
experimental results



=> improvements by adding trench capacitance

Application

2D simulations



=> highly accurate modeling up to very high frequencies

(additional series resistance added)

General scaling

- Bilinear scaling equation

$$Q = \overline{Q_A}A + Q_b'b + Q_l'l + Q$$

  - applied to currents and capacitances
  - but also to resistances

=> using partially inverse dimensions

- Emitter resistance: b = 1/b_E, l = 1/l_E
- Base and collector resistance: b = b_E, l = 1/l_E

Thank you for your attention!