Temperature dependent modeling of sub-mm-wave SiGe HBT

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OUTLINE

- Introduction
- Model evaluation over a wide range of temperatures
- Comparison between a-DD simulation and measure-ments
- Conclusions

Introduction

- SiGe HBTs have found widespread application in many fields requiring high-frequency performance, such as
  - automotive radar
  - mm-wave imaging (e.g. security scanners)
  - satellite communication
  - geothermal wells
- SiGe HBTs have also shown excellent performance over a wide range of temperatures including cryogenics

=> new DFG project:

- Investigation and extension of augmented drift-diffusion device simulation for a temperature range between 4 K and 450 K, enabling ...
  - compact model development
  - model verification at temperatures beyond room temperature for high-speed applications
- Investigation and extension of HICUM for temperature range of [4, 450] K, enabling ...
  - circuit design over a wide range of temperatures and applications

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Measured Devices

(present status)

- Technology: early IHP process version of DOTSEVEN project
  - SG13G2 backend

- b_{E0} = (130, 180, 390, 780) nm in CBEBC configuration
- l_{E0} = 10.16 μm

- Displayed figures from transistor with b_{E0} = 130 nm
  - further results are available for other widths

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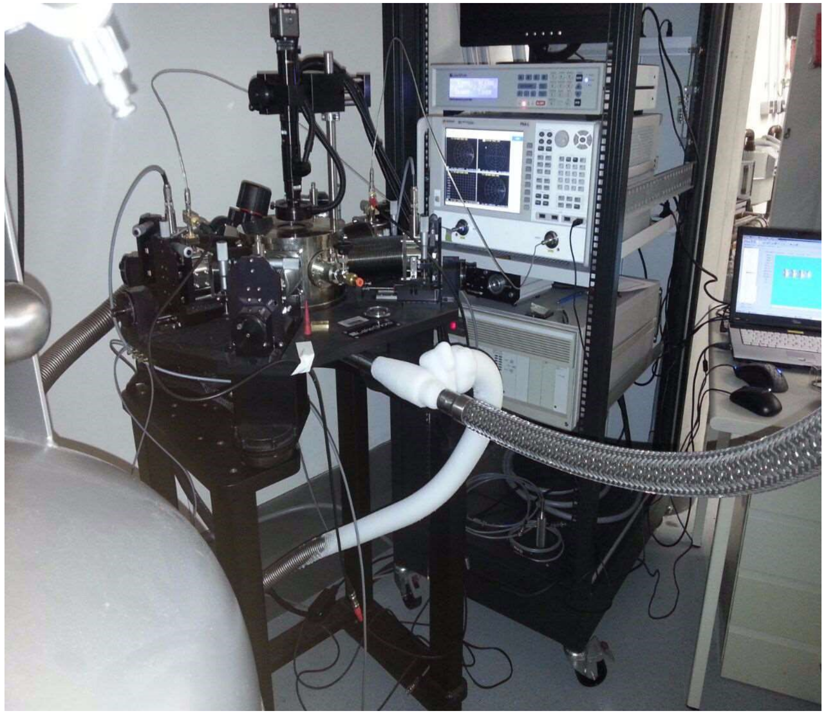
Measurement set-up

Probe station

- At 0 °C and above: thermal chuck
- Cryogenic temperatures:
  - **picoprobe Model 67 "High Performance"** with CS-5 calibration substrate specially for cryo chamber
  - vacuum required to avoid freezing of water (T<273.15K) and gases (like nitrogen for T<77K)
  - Lakeshore TTPX cryogenic probe station
  - cooling with liquid helium



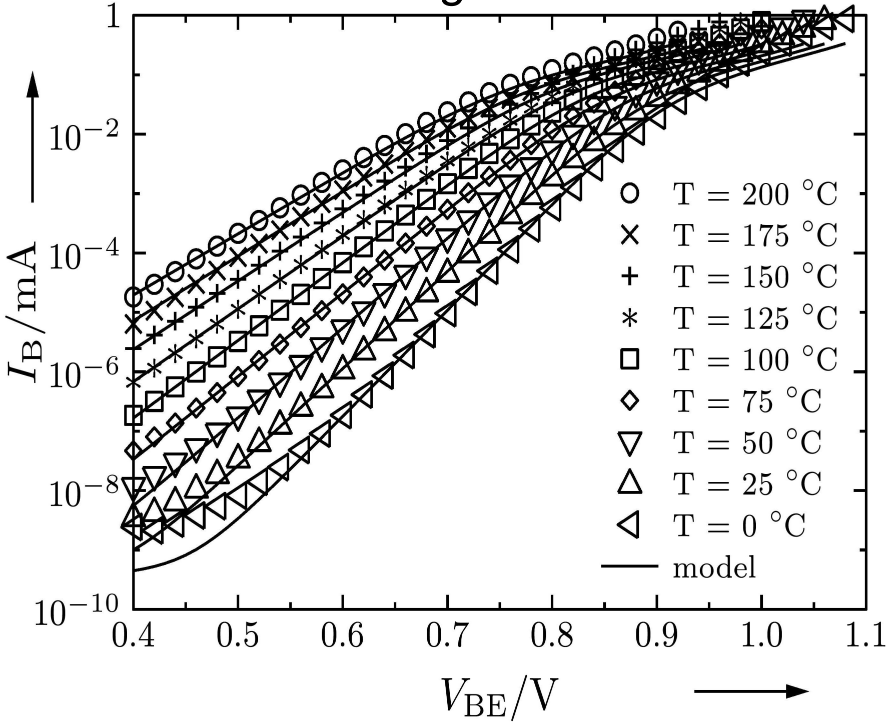
Electrical equipment

- DC/HF: Hewlett-Packard 4142B Modular DC Source/Monitor
- S-Parameters: Keysight N5235A PNA-L Microwave Network Analyzer

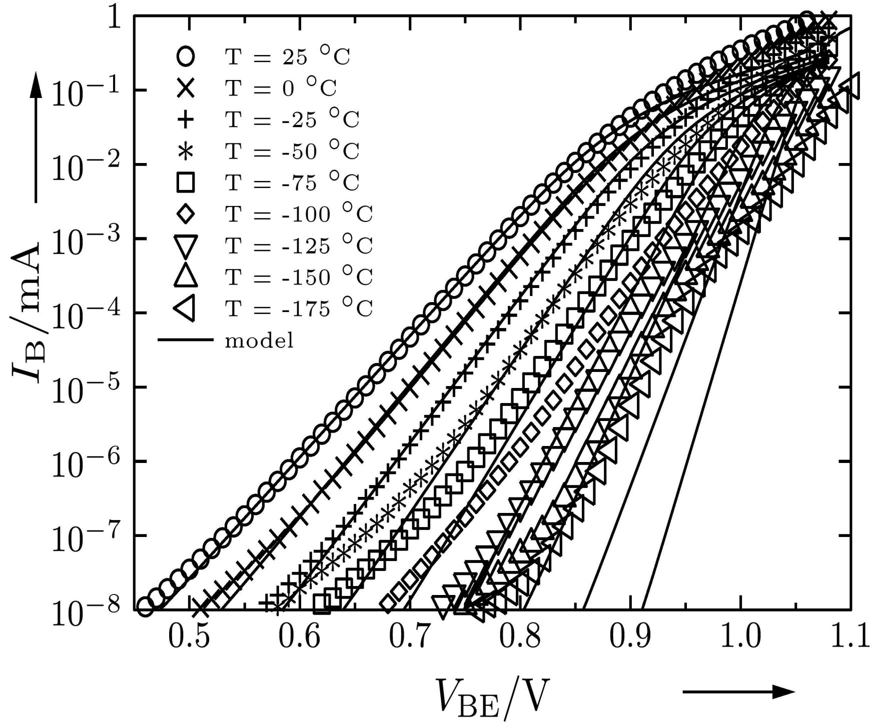
Model evaluation over a wide range of temperatures

Base current

"high" *T*



"low" *T*



- Base current decreases as temperature decreases ($E_g(T)$)
- Model shows overall agreement with measured I_B from -75°C to 200°C
- Deviation for 25°C and 0°C at low bias is related to bias-tee leakage
- Deviations increase below -75°C: measurements are strongly non-ideal

=> Physical cause for deviations at low *T* are under investigation

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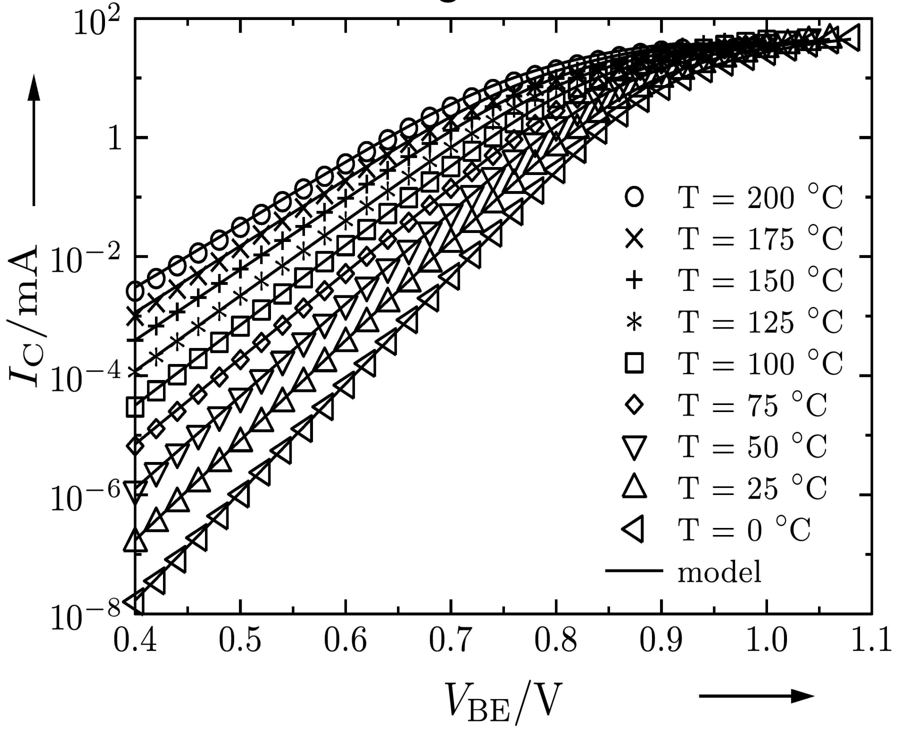
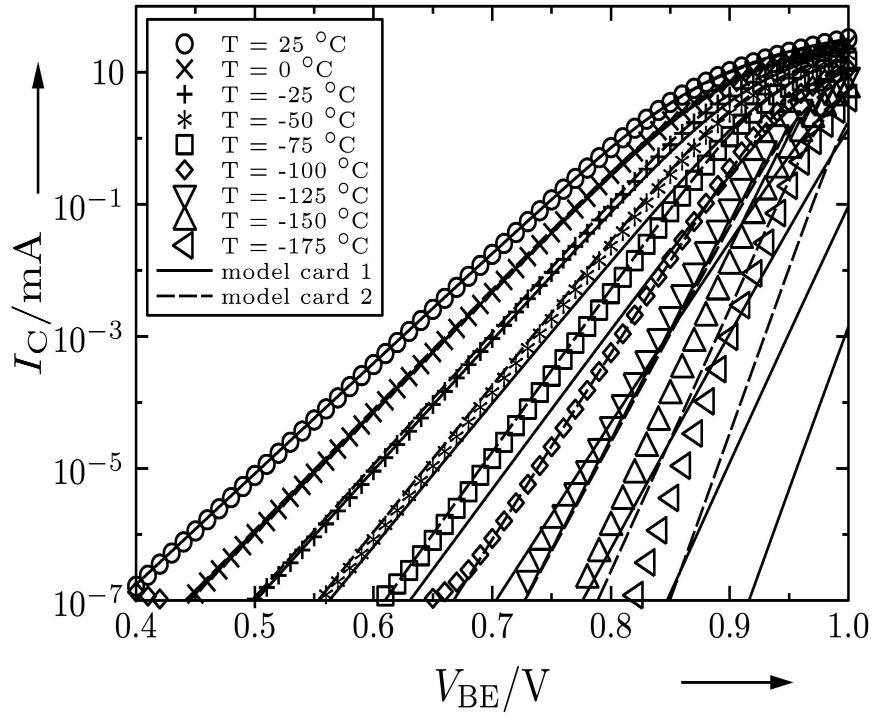
Collector current

"high" T



"low" T



- Two different model parameter sets
  - (1) card 1: agrees well with measurements in [-50, 200] °C range
  - (2) card 2: after fine-tuning $\Delta V_{gBE}(T)$, good agreement in [-125, 200] °C range
- Below -125°C => large(r) deviations

  => Physical cause for deviations low T are under investigation

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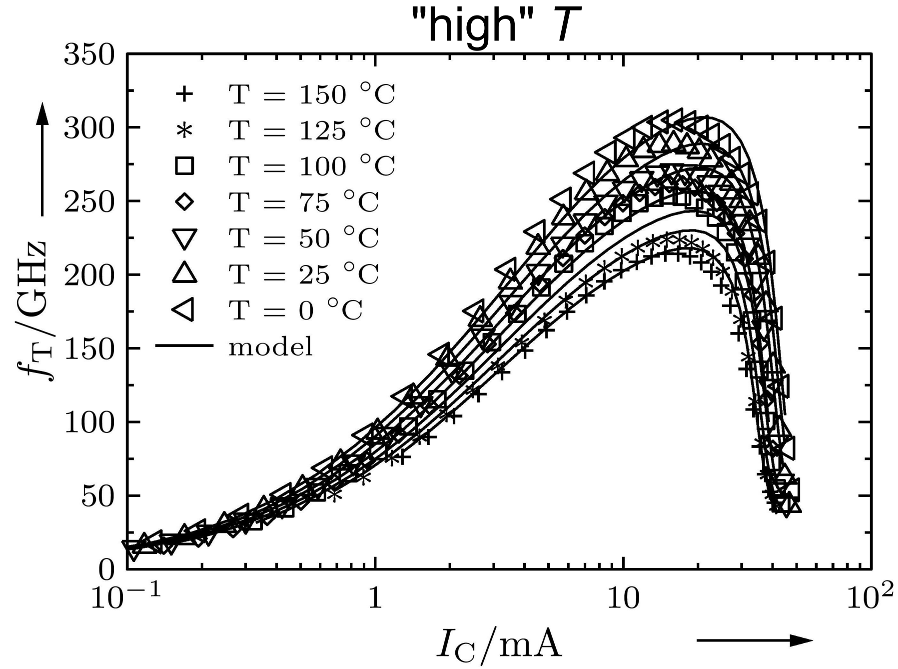
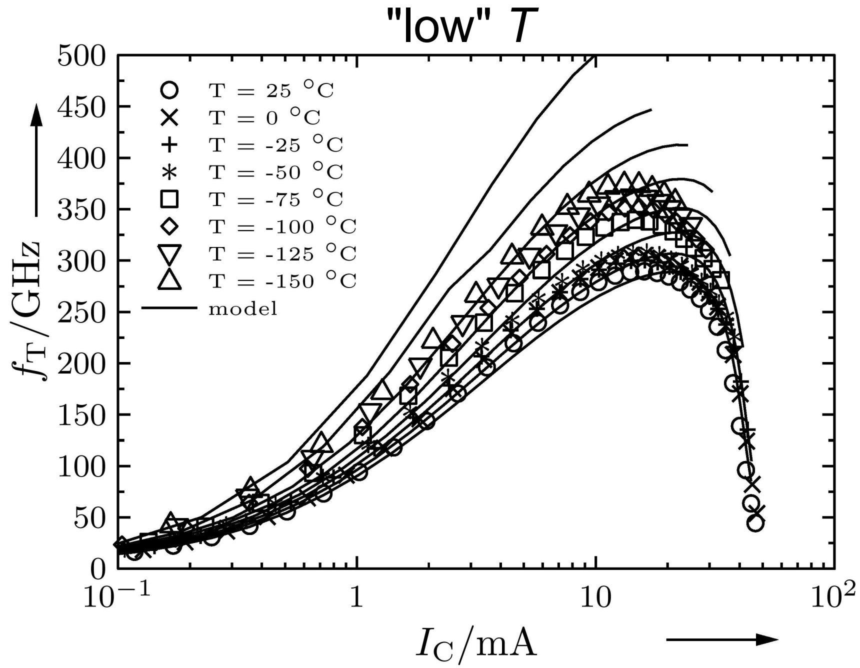
Transit frequency



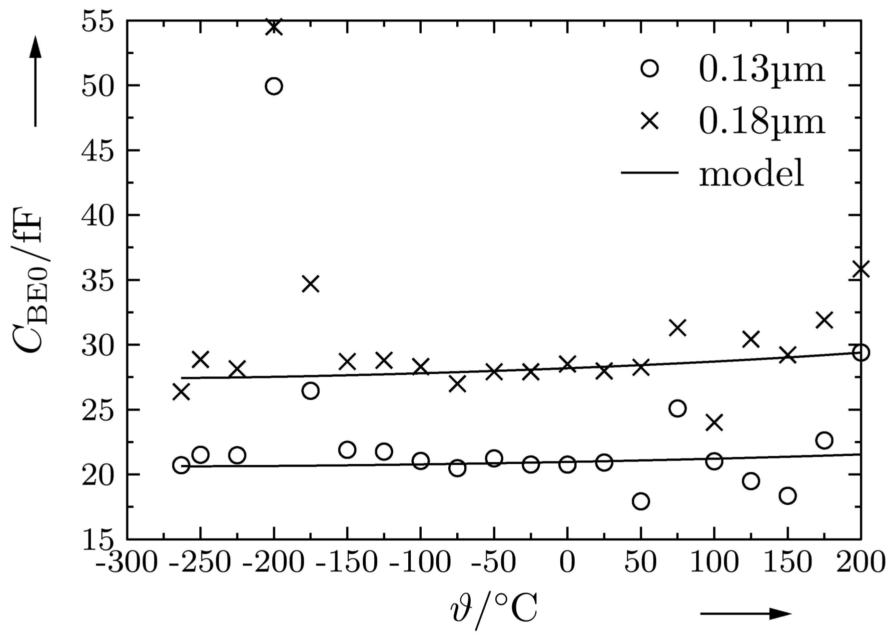


- f_T increases as temperature decreases due to increased g_m
- Model agrees reasonably well with measurements in (0,150)°C range
  - need dedicated parameter extraction for these samples
  - measurement issues at *T* (175°C and 200°C, not shown here) for this device (not observed)
- At low temperatures => larger deviations already at low current densities
  => *T* dependence of depletion capacitances?

=> under investigation

Base-Emitter capacitance

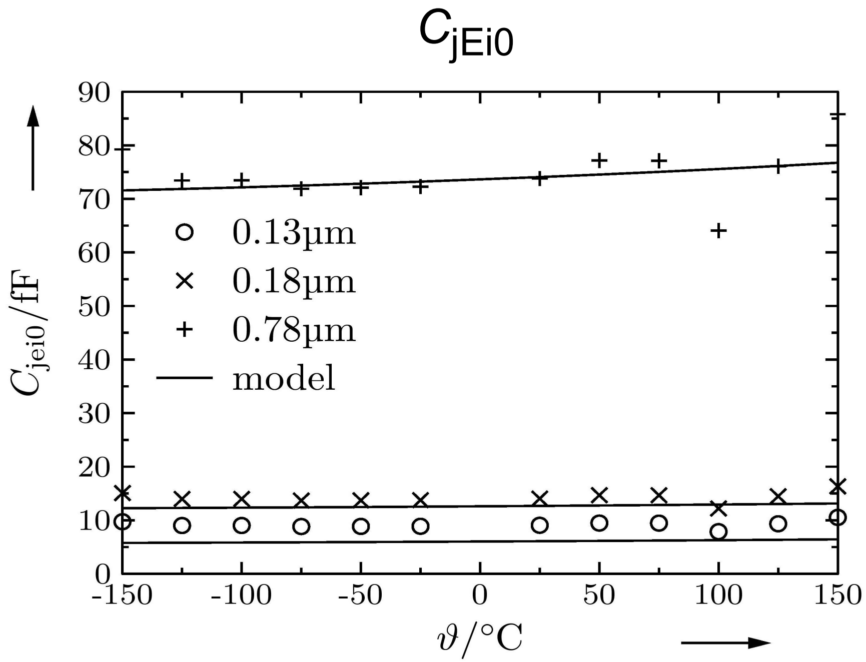
- symbols: measurement data
  lines: HICUM/L2
- At low bias:
  $C_{BE0} = C_{jEi0} + C_{jEp0} + C_{BEpar}$
- C_{BEpar} is assumed to be temperature independent
- Extraction of depletion capacitance focuses on operating range [-0.5, 0.5] V

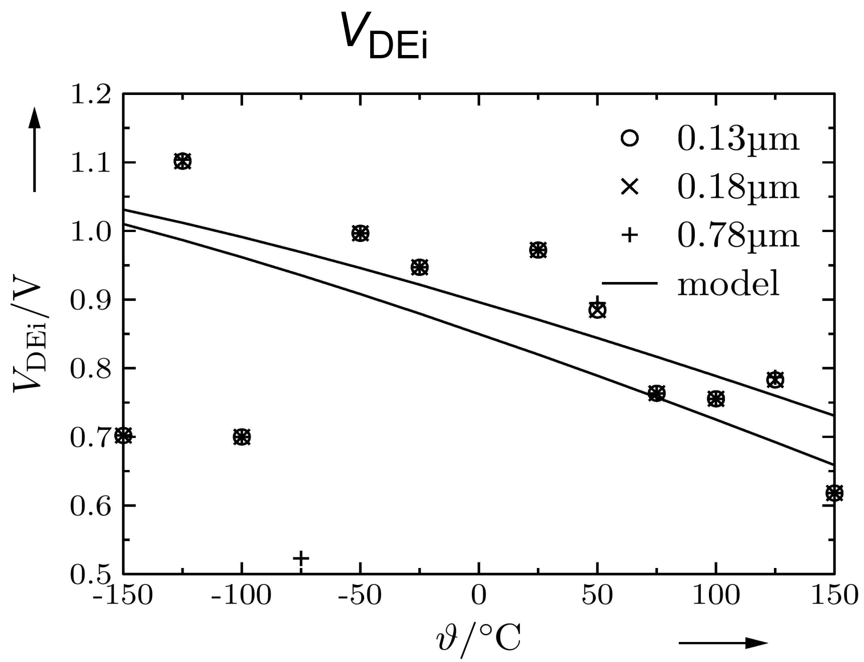


- Measurements down to -263.15°C were made only for two devices
- Capacitance decreases slightly towards lower T
- Model agrees well with measured capacitance data
  - measurement issues at 200°C, 175°C, -175°C and -200°C
    => under investigation

=> Capacitance data do not confirm model f_T at low bias

BE depletion capacitance





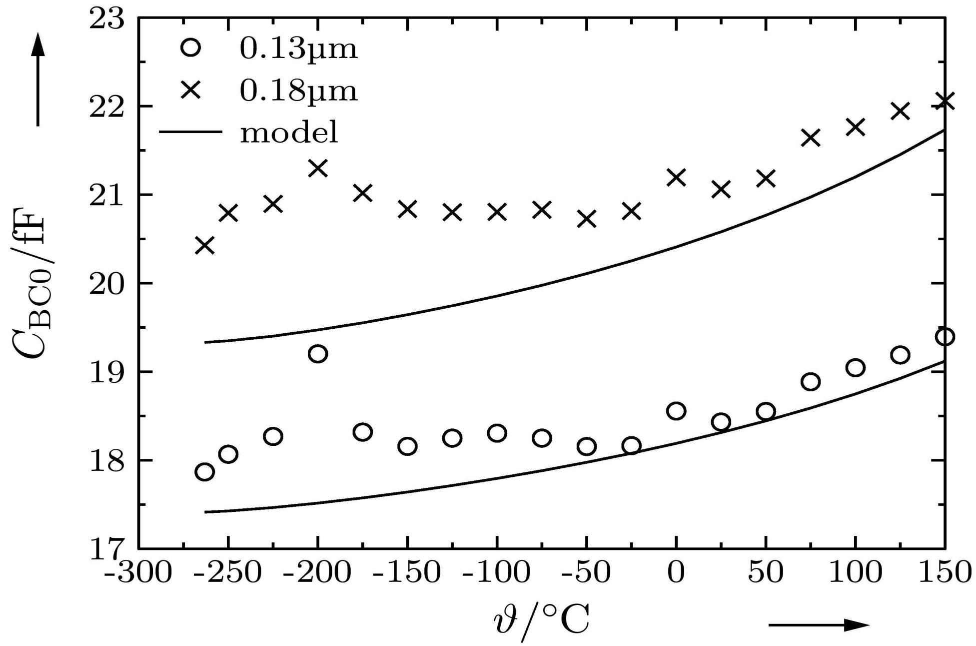
- Good agreement for C_{jEi0}
  - measurement data for all geometries incomplete at T < -150 ^{o}C
- Modeled V_{DEi} shows expected T dependence
  - V_{DEi} of smallest device (0.13 µm) fine tuned (due to measurement issues at very low T)
- C_{jEi0} decreased slightly towards lower T

=> additional measurements at very low T are required

Base-Collector capacitance

$C_{BC0} = C_{jCi0} + C_{jCx0} + C_{BCpar}$

- symbols: measurement data
  lines: HICUM/L2
- C_{BCpar} assumed to be temperature independent

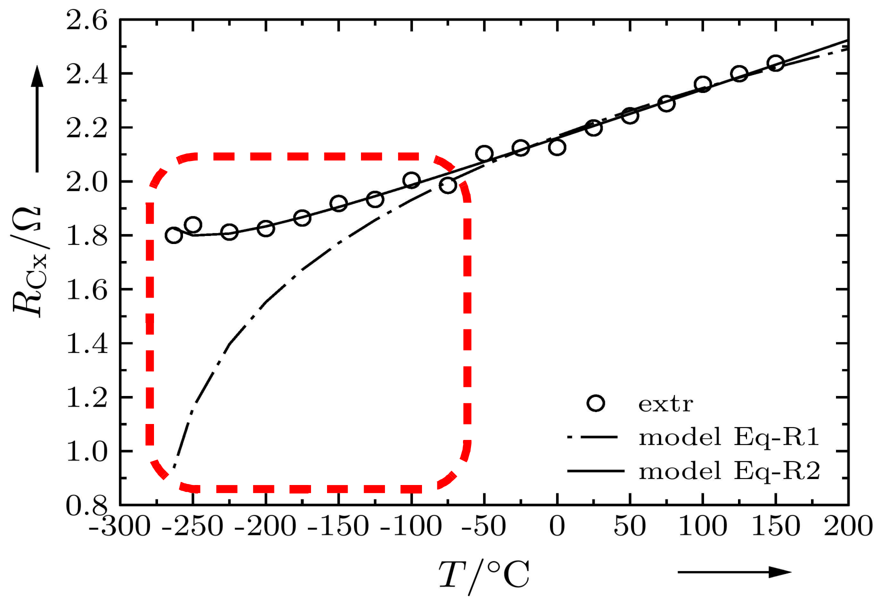


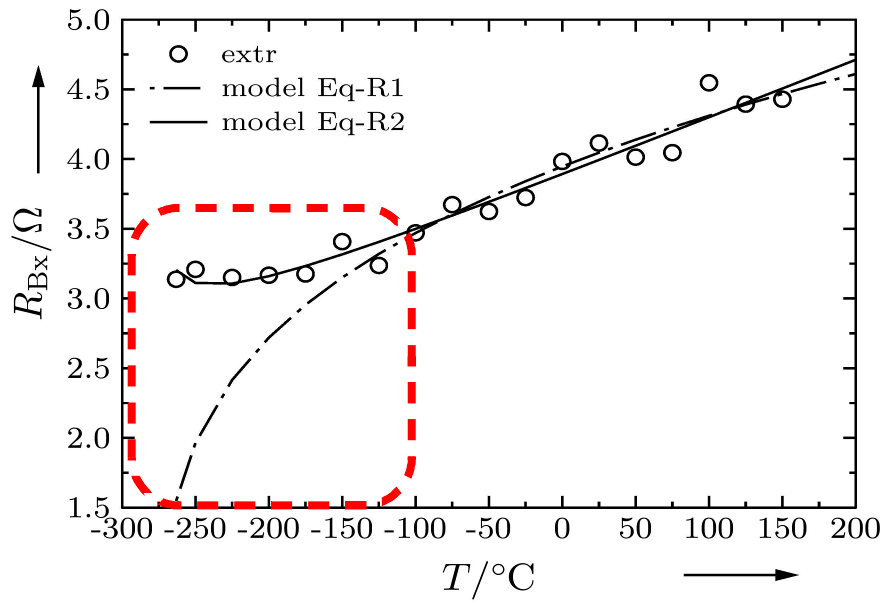
- Weaker decrease of C_{BC0} towards low temperature
- Model underestimates extracted C_{BC0} at low T
  => appears to be cause of higher f_T of compact model

=> Observed deviation is under investigation

Series Resistance

model vs. experimental results





- HICUM expression for temperature dependence of series resistances

$$R_x(T) = R_x(T_0)\left(\frac{T}{T_0}\right)^{\varsigma_{rx}} \text{ with } x = \{\mathrm{E, Cx, Bx, Bi0}\} \qquad \text{(R1)}$$

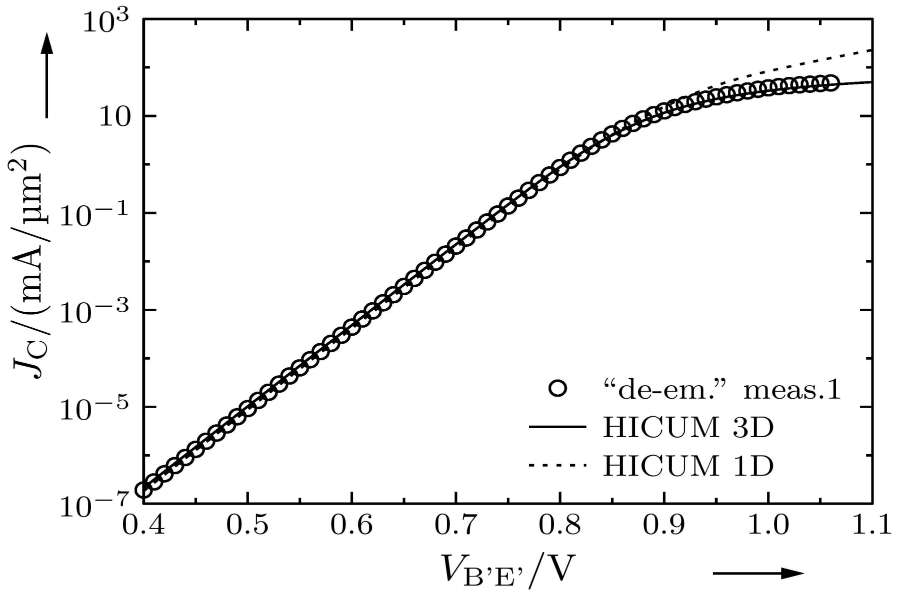
  - $R_x(T_0)$: resistance at reference T_0, ζ_{rx} depends on doping concentration

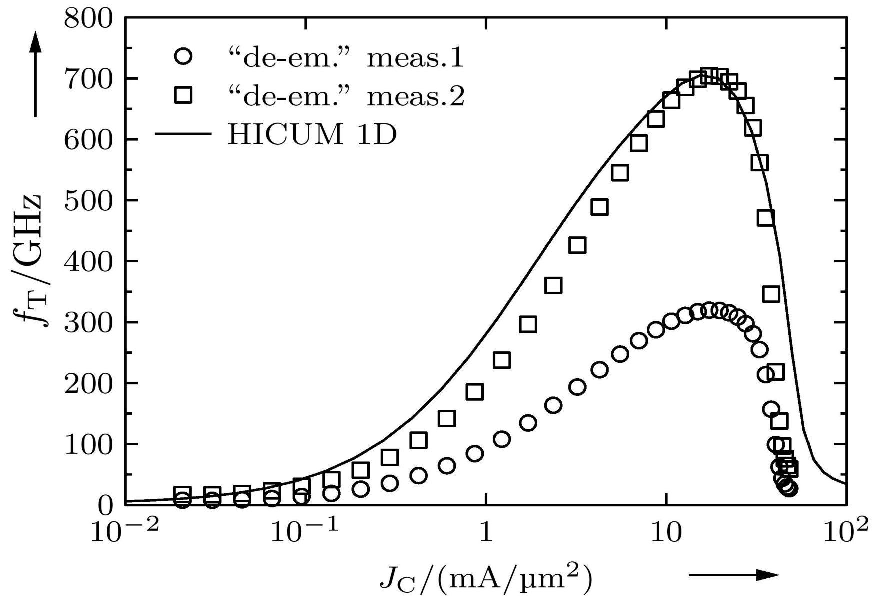
- Modification for very low T: $R_x(T) = R_x(T_0)\left(\frac{T}{T_0}\right)^{\varsigma_{rx}}(1 + a_{rx}\Delta T) \qquad \text{(R2)}$

Comparison between a-DD Simulation and measurements

Comparison between HICUM 1D and "de-em" measurements

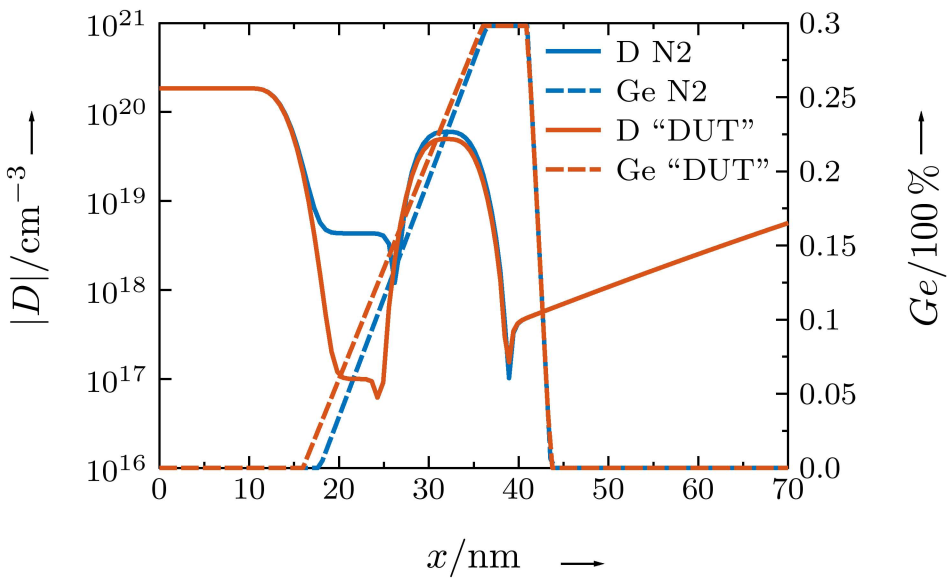
"de-em" of measurement for 1D case





- 1D HICUM parameter set for "de-embedding" 1D behavior from measured terminal data
  - "de-em. meas.1": only for I_C
  - "de-em. meas.2": for both I_C and f_T
- Adjust a-DD simulator model parameters & doping profile to match de-embedded 1D J_C and f_T
  - Example for modified DD parameters: $v_{s,n}$ = 2.4*10^7 cm/s (from 1.07*10^7 cm/s)

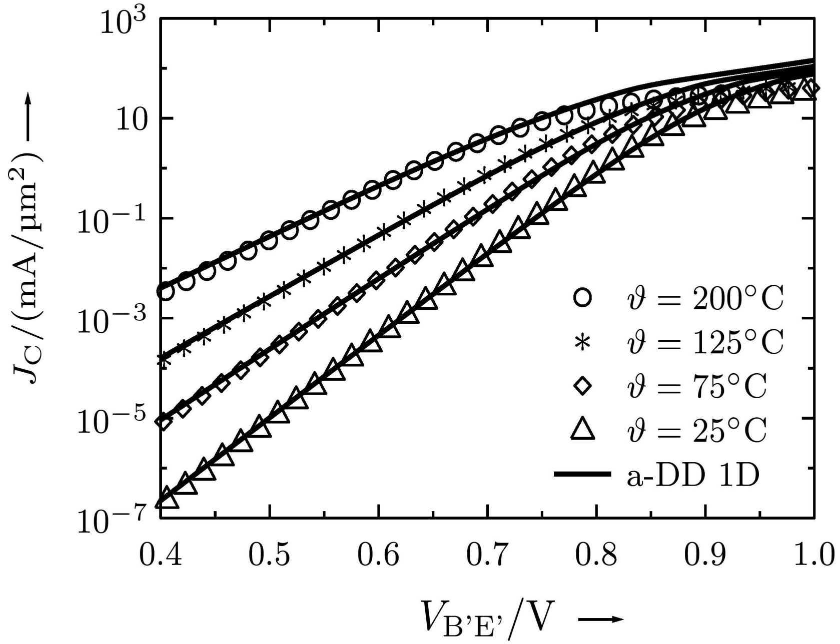
Simulated 1D doping and Ge profiles

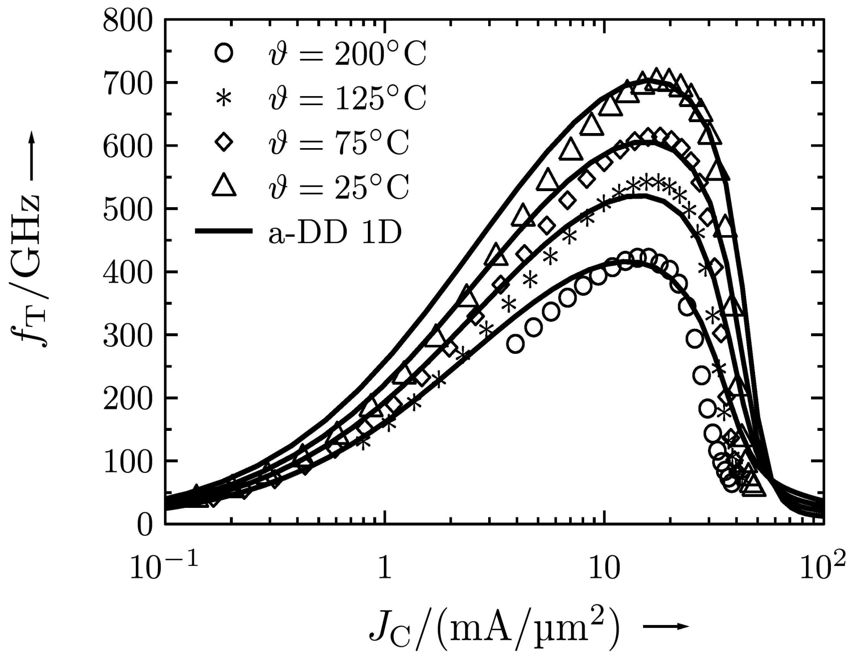


- Initial profile: N2 of DOTSEVEN
- Modification of initial profile based on 1D depletion capacitances, transit time and DC collector current density
- Not the actual device profile but has similar electrical behavior as the measurements
  => can be used for comparing characteristics with measurements at cryogenic temperatures

Collector current density and transit frequency at high *T*

Comparison between a-DD simul. and "de-embedded" measurement



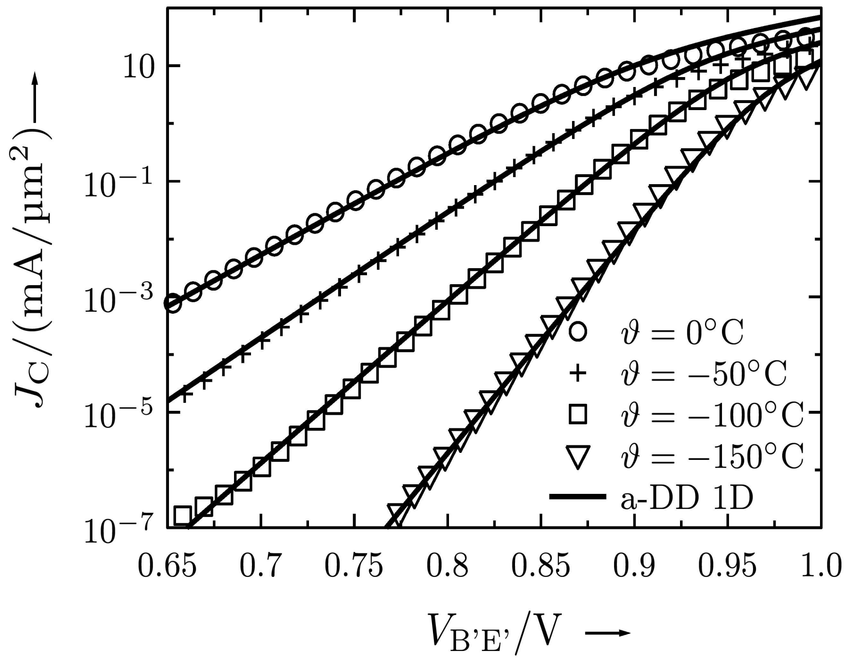


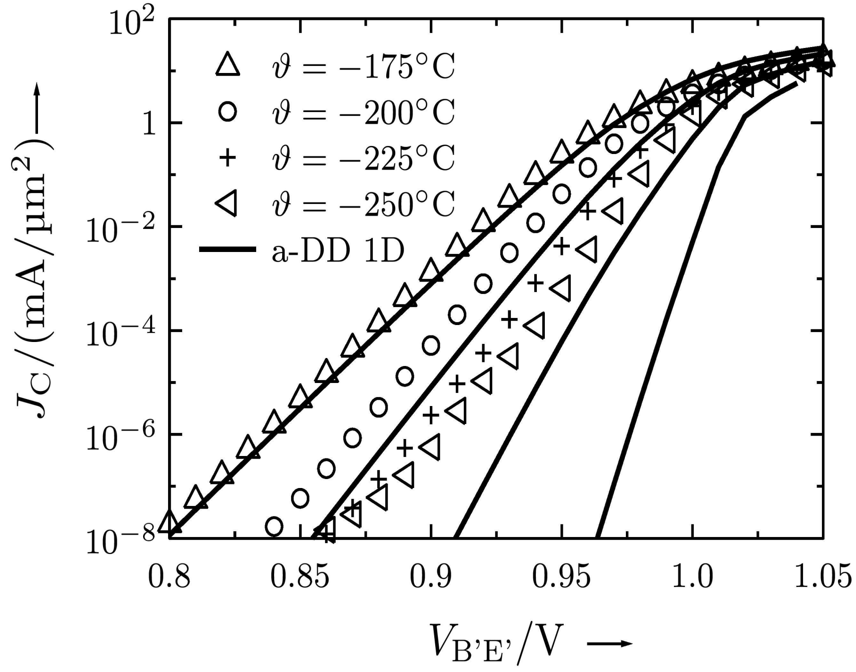
- a-DD simulator calibration based on peak f_T only
- Small discrepancy in J_C at high bias due to bias dependent current spreading

=> overall good agreement between calibrated a-DD device simulation and measured characteristics at room and high temperatures

Collector current density at low *T*

Comparison between a-DD simul. and "de-embedded" measurement



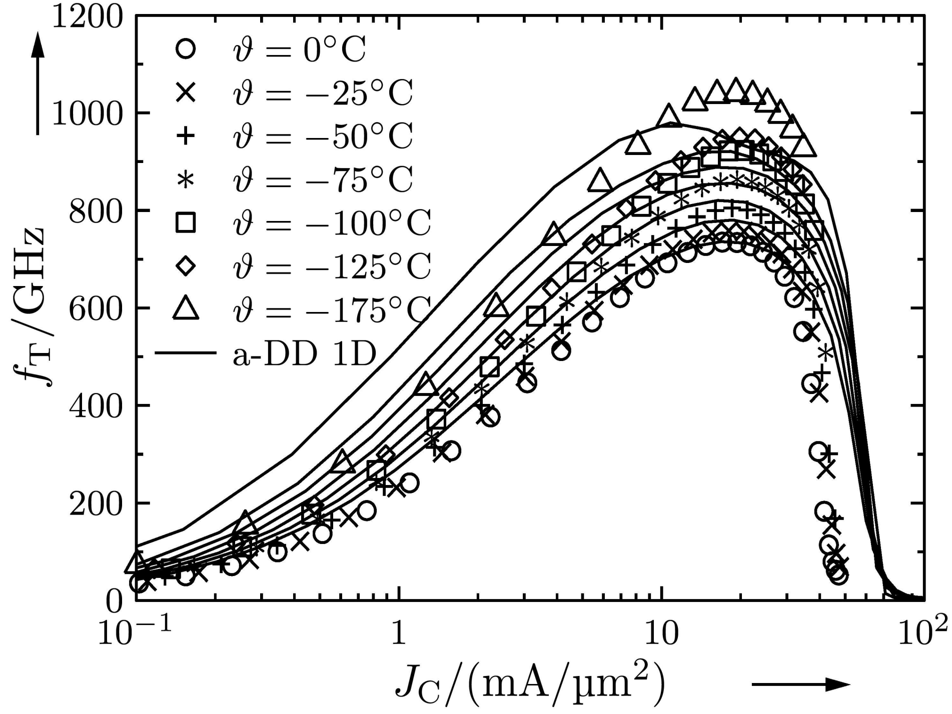


=> good agreement at *T* down to -175°C, but deviations below -175°C

- possible causes for deviation (under investigation):
  - present DD transport (model) at very low temperatures requires additional trap-assisted tunneling current through base region
  - Note: freeze-out unlikely to occur due to large doping concentrations

Transit frequency at low *T*

Comparison between a-DD simul. and "de-embedded" measurement



=> good agreement at *T* down to -125°C, deviations below -125°C

- $f_{T,max}$ of a-DD is lower than measurement at -175°C
- measurement issues at -150°C and below -175°C and not shown

Conclusions

- DC/HF measurements of (f_T,f_{max}) = (300,500) GHz SiGe HBTs over a wide range of temperatures (incl. cryogenic region)
- Extension of T dependent series resistance expression toward very low temperature for saturation of resistance
- Good agreement between HICUM/L2 and measurements, except below
  - -125 °C for I_C
  - 0 °C for f_T
  - -50 °C for I_B
- Numerical simulation (DEVICE) with augmented drift-diffusion transport parameters and adjusted doping profile agrees well with measurements from
  - -175 °C to 200 °C for $J_{C,}$ deviations at T < -175 °C possibly due to TAT current through the base
  - -125°C to 200°C for f_T

Future work

- Investigate physical causes for observed deviations at low T
- develop physics-based extensions for transfer and base current, charges

Acknowledgments

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