Breakdown mechanisms in advanced SiGe HBTs: scaling and TCAD calibration

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Bipolar **A**rbeits**K**reis
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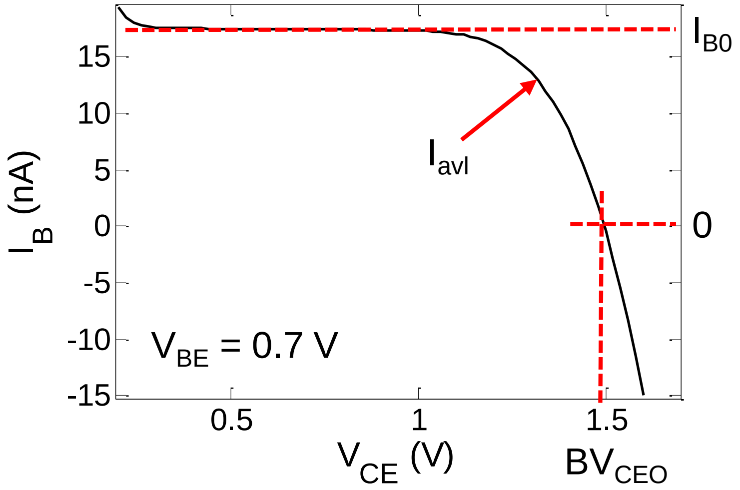
Outline

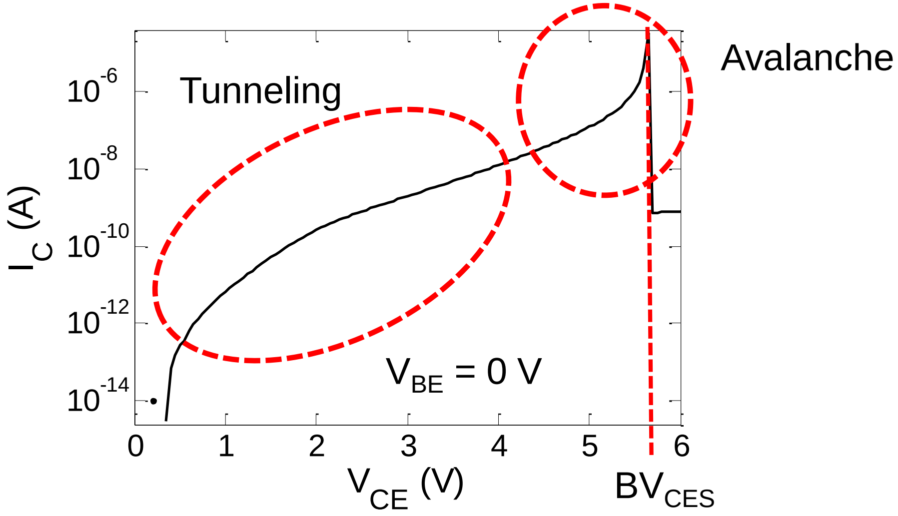
- Introduction
  - Figures of merit for breakdown characterization
  - P/A scaling and determination of I_{avl} from measurements
- TCAD calibration of impact ionization
  - Calibration of impact ionization parameters
- Tunneling current scaling
  - Well proximity effect
  - Determination of BV_{CES} with TCAD
- Conclusion

Introduction

- Breakdown voltages
  - Are defined for different bias conditions
  - BV$_{CEO}$
    - Sweep V$_{CB}$ until Base current reversal at fixed V$_{BE}$ (e.g. V$_{BE}$ = 0.7 V)
  - BV$_{CES}$
    - Sweep V$_{CB}$ until breakdown of BC diode for V$_{BE}$ = 0 V
  - BV$_{CBO}$
    - Sweep V$_{CB}$ until breakdown of BC diode for floating Emitter contact (I$_E$ = 0 A)
- Examples



$$I_{avl} = |I_B - I_{B0}|$$

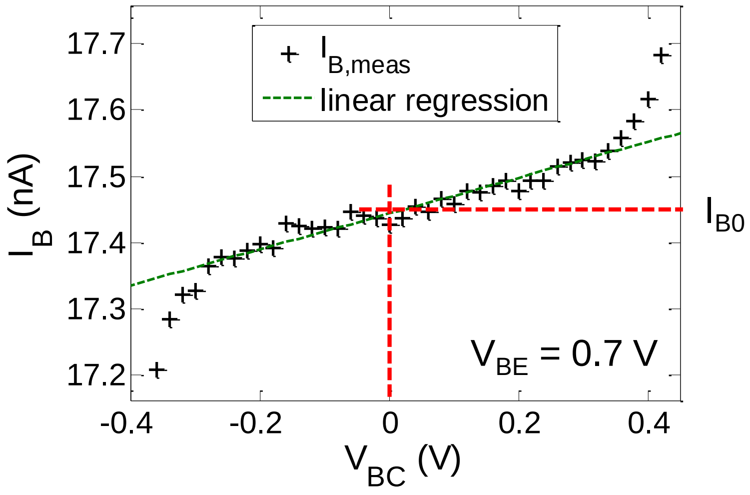


Avalanche current separation

- Zoom-in of Base current of BV$_{CEO}$ measurement
  - Zero volt Base current
    - Marks reference point of separation
  - Current for positive bias (V$_{BC}$ > 0.4 V)
    - Is influenced by injection
  - Voltage dependence of current
    - Linear dependence (-0.3 V < V$_{BC}$ < -0.3 V)
    - Is caused by neutral base recombination

    ⇒ taken into account by linear model

$$I_{B,NBR} = I_{B0}(1 + m_{NBR}V_{BC})$$



- Calculation of I$_{avl}$ and I$_T$
  - Linear fit with measurement data to determine m$_{NBR}$
  - Avalanche and transfer current calculation

$$I_{avl} = \left|I_B - I_{B,NBR}\right| \qquad I_T = I_C - I_{avl}$$

  - For TCAD calibration
    - Area related components necessary

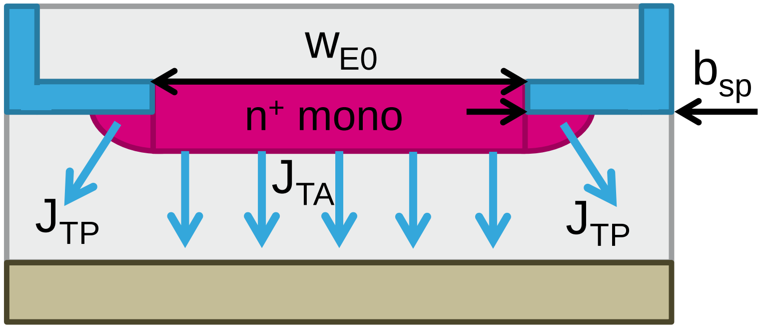
    ⇒ perform P/A separation

P/A separation

- P/A concept
  - Description for total transfer current

$$I_T = J_{TA} A_{E0} + J_{TP} P_{E0}$$

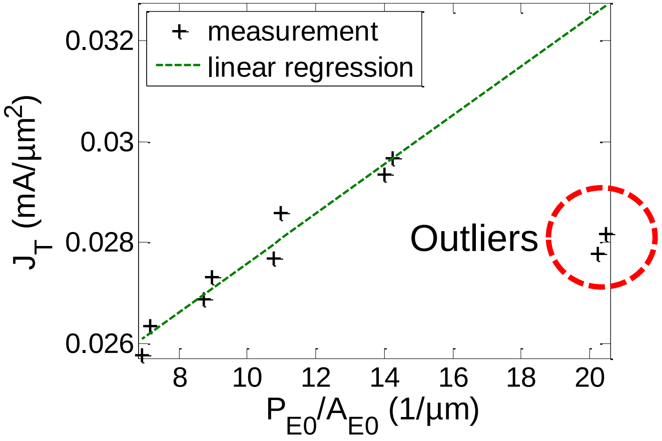
  - Current components
    - J_{TA} is assumed to be constant over w_{E0}
    - J_{TP} is associated with perimeter



- Example extraction
  - Current separation leads to straight line

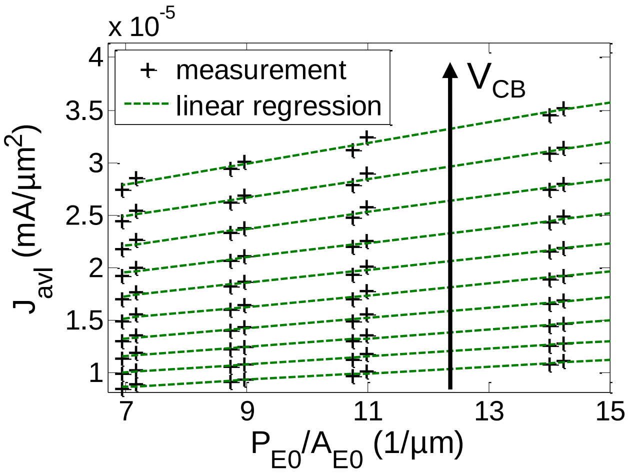
$$\frac{I_T}{A_{E0}} = J_{TA} + J_{TP} \frac{P_{E0}}{A_{E0}}$$

    - Slope of extrapolation corresponds to J_{TP}
    - Intercept of extrapolation with $P_{E0}/A_{E0} = 0$ corresponds to J_{TA}



⇒ allows determination of current components for each bias point by linear regression

TCAD reference data



- Area related avalanche current
  - J_{avlA} is the result of P/A separation of I_{avl}
    - Method applied analog to I_T
  - Is J_{avlA} suitable for TCAD calibration?
- Physical background of Impact Ionization (II)
  - Highly energetic electrons hit electrons in valence band

  $\Rightarrow$ bound electrons in valence band can get knocked out of its state causing the generation of electron hole pairs (EHP)

  $\Rightarrow$ consecutive collisions lead to avalanche (electrons are **multiplied**)
- Multiplication factor
  - Definition

$$M = 1 + \frac{I_{avl}}{I_T}$$

  - Process of impact ionization is associated to transfer current

  $\Rightarrow$ an error of I_T will impact I_{avl}

  $\Rightarrow$ use multiplication factor M to calibrate TCAD instead of I_{avl}

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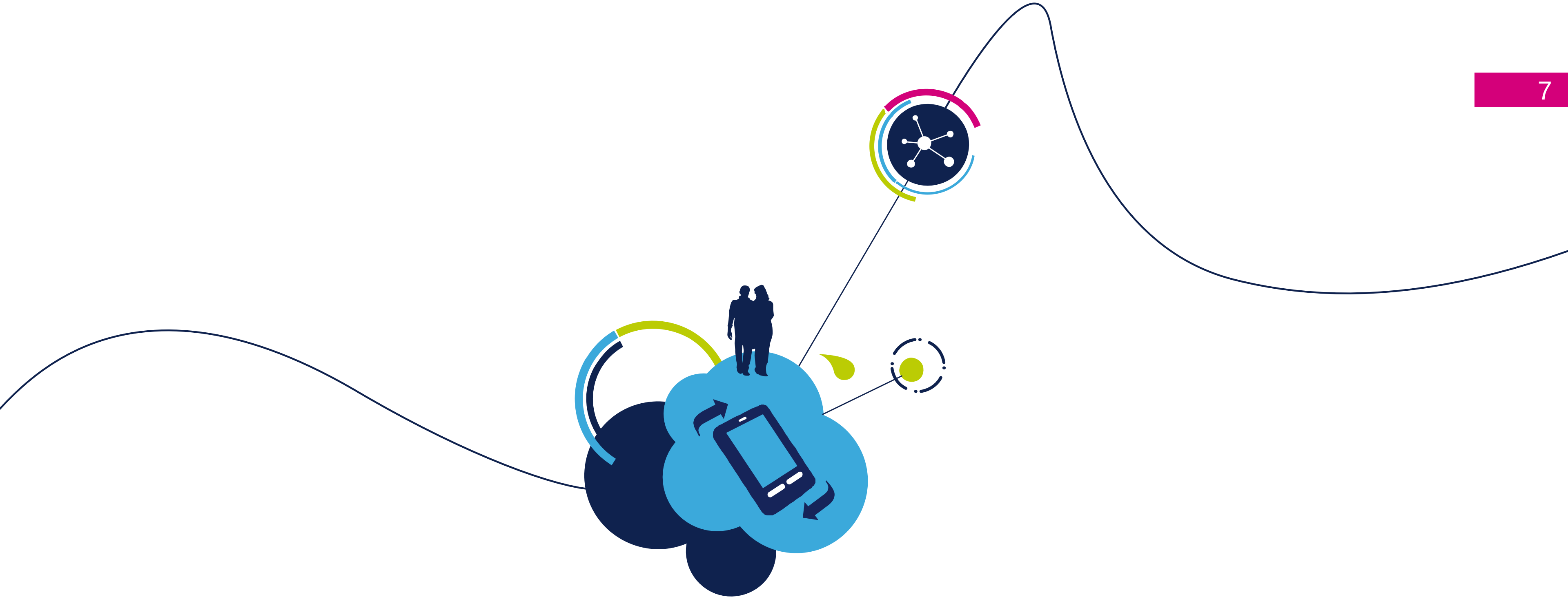
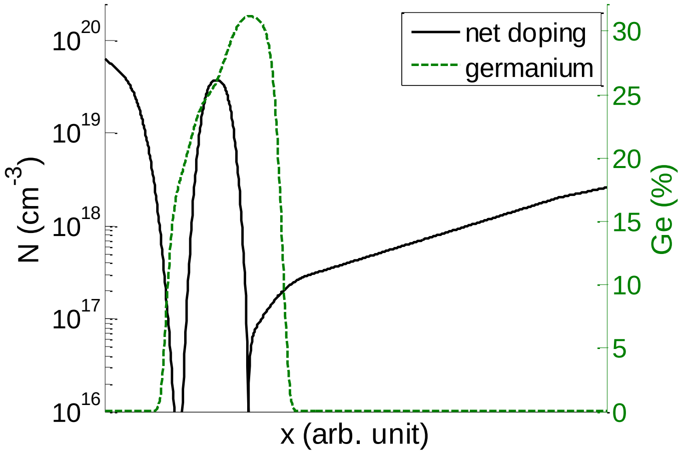


TCAD calibration of impact ionization

Starting point

- Calibrated 1D doping profile
  - See reference [1]
- TCAD environment
  - In-house HD simulator of TU-Dresden with 1D simulation capability



- Avalanche model for electrons (HD)
  - Generation rate is associated to carrier temperature

$$G_{avl,n} = nAexp\left(-B\,\frac{E_G}{k_B T_n}\right)$$

  - Model parameters A and B are to be calibrated
- Adjustment procedure
  - Run optimization on A and B for best agreement with measurement data

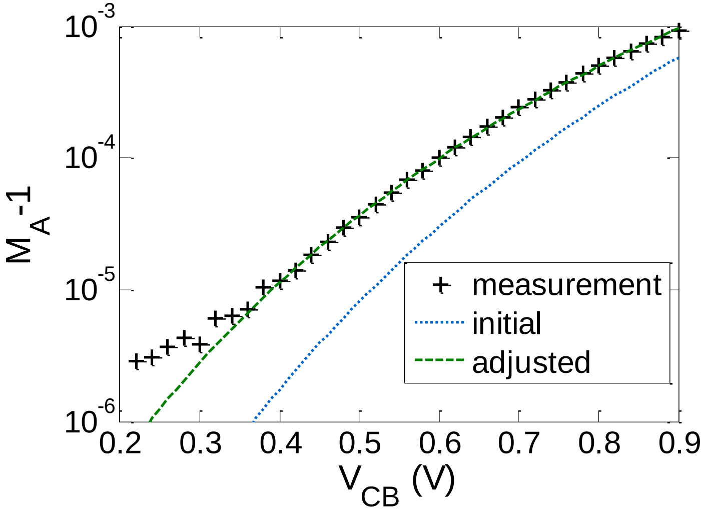
[1] T. Rosenbaum et al., “Calibration of 1D Doping Profiles of SiGe HBTs”, accepted paper for Proc. IEEE BCTM, 2015.

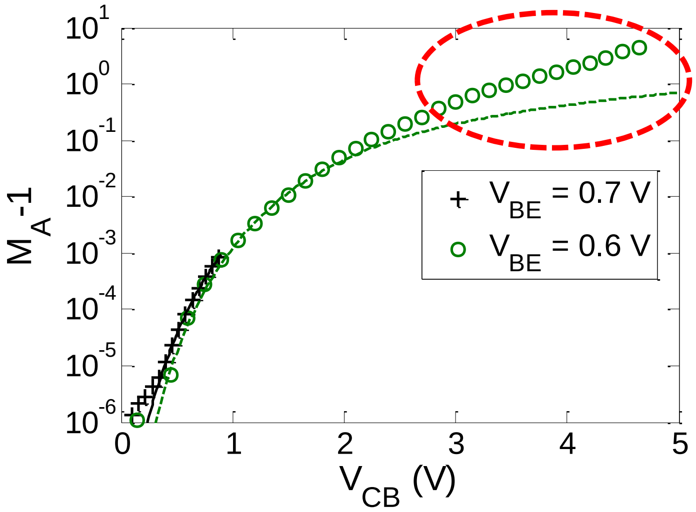
Parameter adjustment

- Comparison
  - M_A denotes multiplication factor of area component
  - Initial parameters
    - A = 2.514e+015 1/s, B = 4.869
  - Adjusted parameters for best fit
    - A = 1.770e+014 1/s, B = 3.668

⇒ very good agreement for analyzed bias range

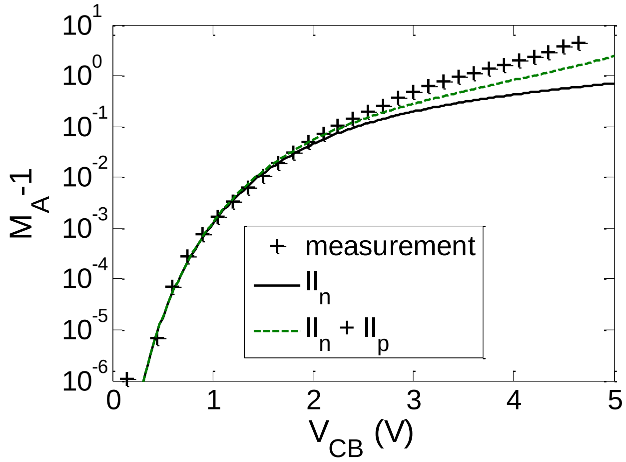
- Extended bias range
  - Forced V_{BE} measurement available up to V_{CB} = 5 V (single transistor data only)
    - V_{BE} = 0.6 V
    - Need to assume identical scaling to obtain M_A
  - Good agreement with measurement data up to V_{CB} = 2 V
    - Markers correspond to meas
    - Lines correspond to simulation
  - Deviation for V_{CB} > 3 V ?

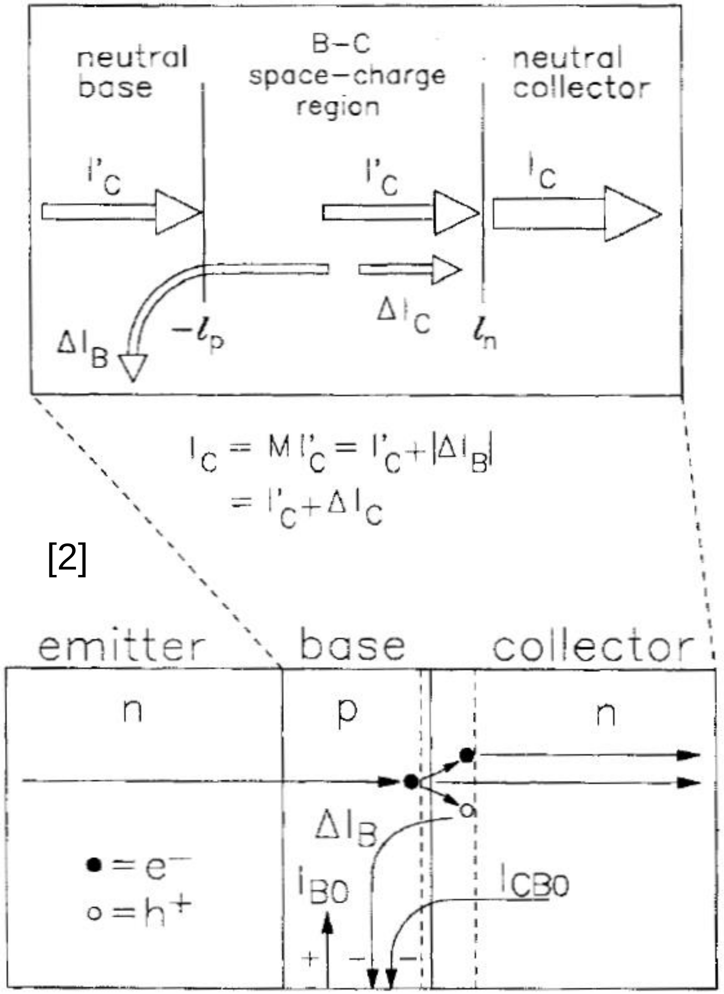




Including impact ionization of holes

- Electron hole pair (EHP) generation
  - Can also be triggered by holes
  - Is the process relevant for npn transistors?
    - At low electric fields the EHP generated by holes is negligible as the amount of holes is small
    - For large electric fields holes of EHP generated by electrons can cause an avalanche
- Simulation rerun improves result
  - Avalanche for holes activated
    - Using standard parameters





[2]

[2] C. Canali et al., “Experimental and Monte Carlo analysis of impact-ionization in AlGaAs/GaAs HBTs”, IEEE Transaction on Electron Devices, 1996.

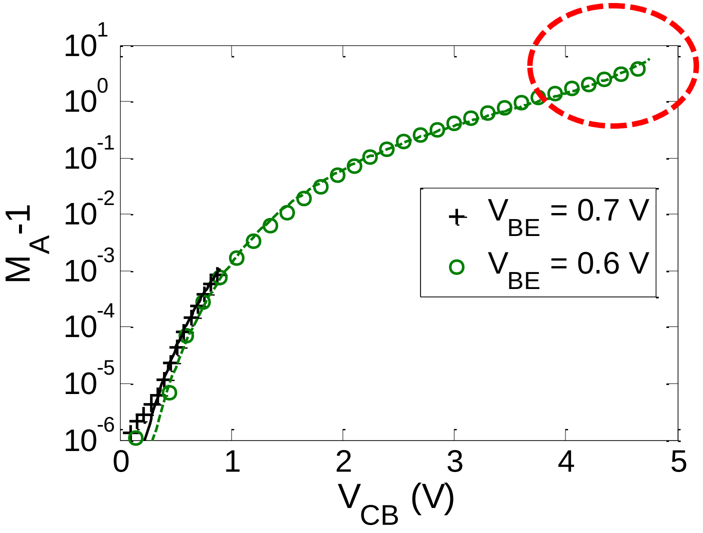
Final calibration result

- Final steps for calibration of avalanche parameters
  1. Adjust hole parameters for extended measurement range
  2. Check agreement for standard range and re-adjust parameters for electrons
  3. Loop for best fit
  - For holes, DD transport is assumed => different II description
- Avalanche model for holes (DD)

$$G_{avl,p} = p v_{sp} a_p exp\left(-\frac{F_p}{grad[\varphi_p]}\right)$$

- Comparison
  - Initial parameters
    - A = 2.514e+15 1/s, B = 4.869
      a_p = 1.582e+06 1/cm, F_p = 2.036e+06 V/cm
  - Adjusted parameters for best fit
    - A = 1.250e+14 1/s, B = 3.552
      a_p = 1.3213e+06 1/cm, F_p = 1.2938e+06 V/cm

$\Rightarrow$ good agreement for whole bias range
- Both V_{BE} = 0.6 and V_{BE} = 0.7 V are captured reasonably well
- Onset of breakdown is captured (see red circle)



BV_{CEO} vs. B_f comparison

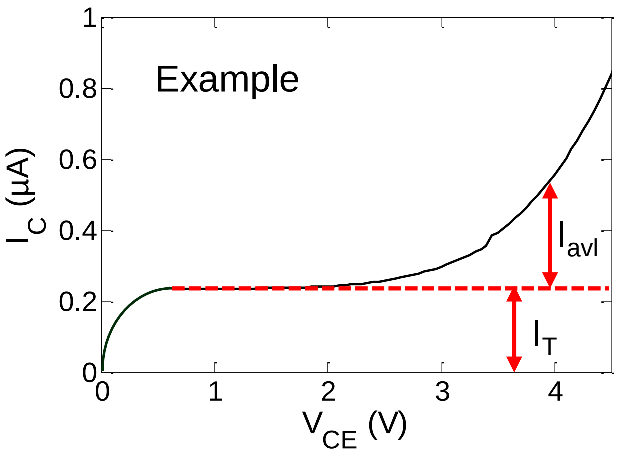
- TCAD limits
  - Base current is usually insufficiently accurate
    - Caused by recombination component of E contact and maturity of the process

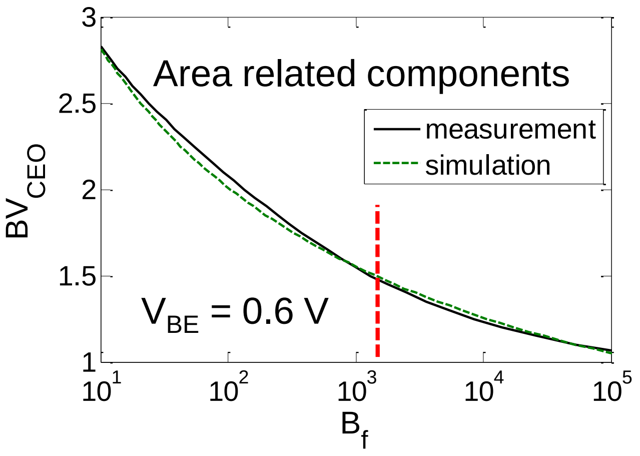
  ⇒ typically, I_B cannot be determined reliably from TCAD simulations

  ⇒ workaround for BV_{CEO} required
- Plot breakdown voltage vs. current gain
  - Assuming breakdown at an arbitrary V_{CE}
    - I_{avl} must be as large as I_B at breakdown condition

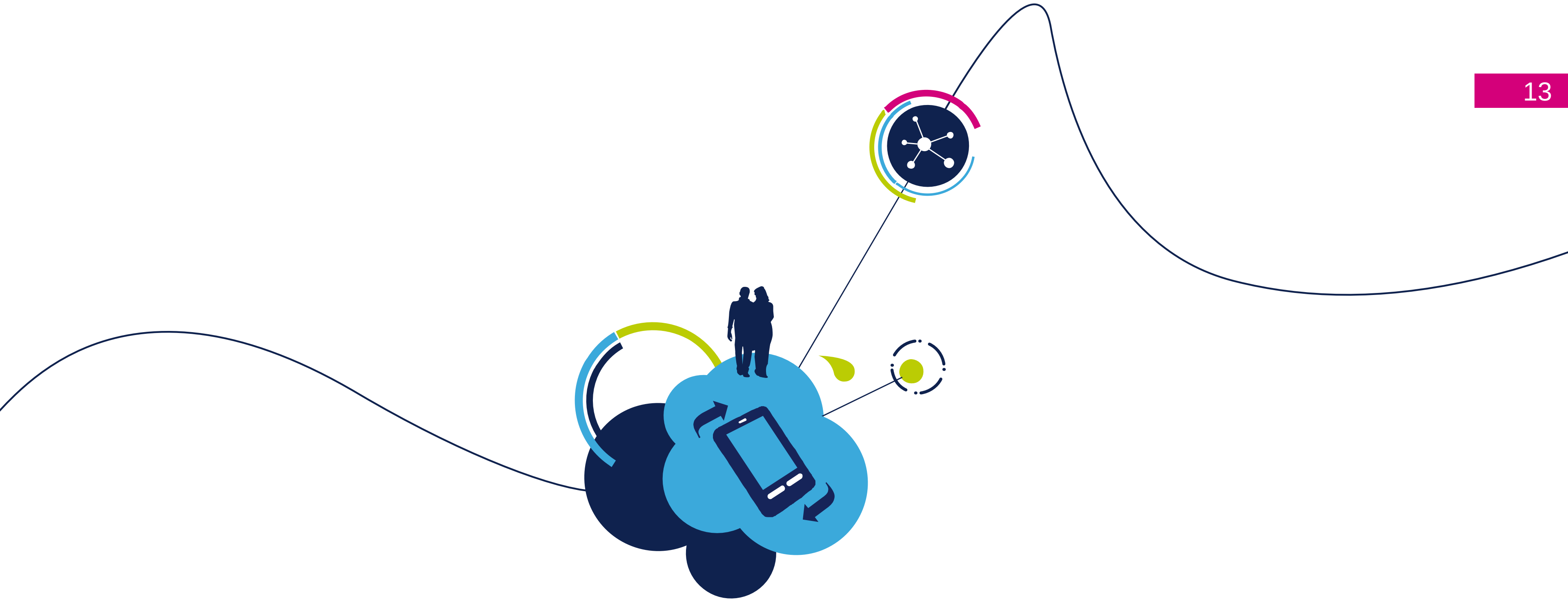
    ⇒ calculate B_f from I_{avl} and I_T

$$\frac{I_T}{I_{avl}}\bigg|BV_{CEO} = \frac{I_B B_f}{I_B} = B_f$$





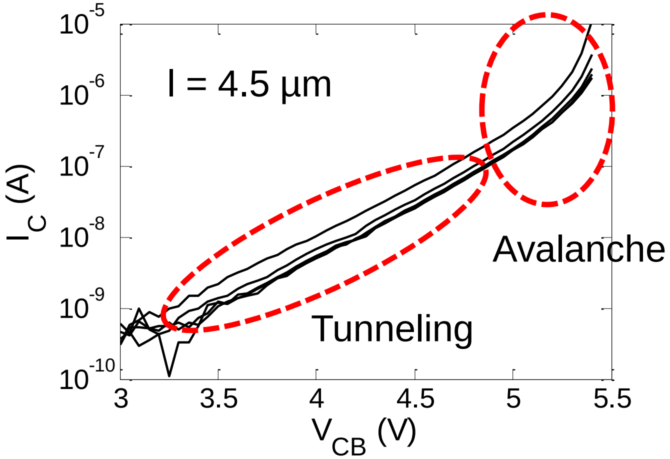
  - Good agreement with measurement data
    - BV_{CEO} = 1.49 V (sim) vs. 1.48 V (meas)

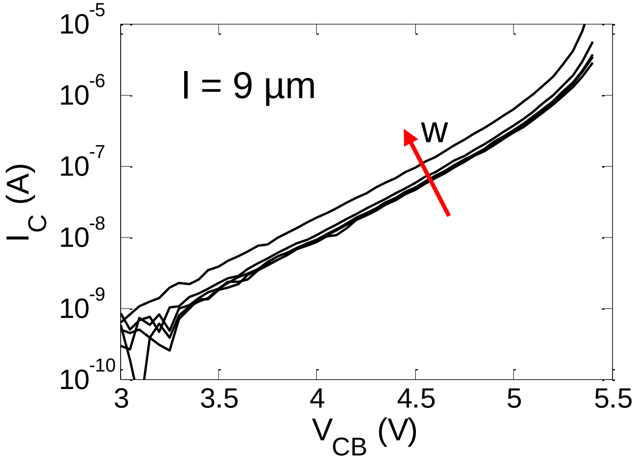


Tunneling current scaling

P/A separation

- Measurement data overview
  - V_{BE} = 0 V, V_{CB} sweep until breakdown
    - BE diode deactivated, BC diode in reverse operation
    - Leads to tunneling and avalanche current of BC diode





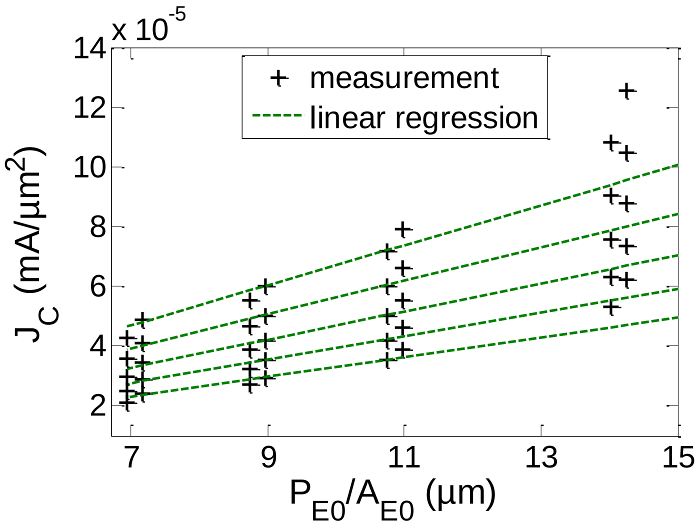
- Unexpected device behavior
  - Increasing current with decreasing width,
    or (if excluding smallest width) no dependence of I_C with Emitter width
- Tunneling current
  - Seems to be associated with transistor periphery
  - Increased Collector doping at periphery?

Well proximity effect

- Linear regression on measurement data
  - Leads to negligible area component I_{tunA}
    - Smallest transistor widths excluded from fit

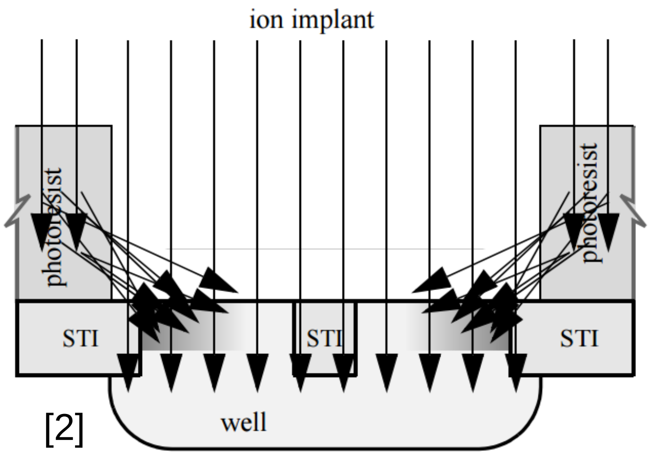
  ⇒ tunneling current is a perimeter associated phenomenon

  ⇒ indicator for increased Collector doping at periphery



- Well proximity effect (WPE)
  - Name originates from well implant of CMOS processes
    - Implant is used to protect devices from latch-up effect
  - Implanted ions scatter from photoresist
    - Ions are embedded at lateral photoresist boundary
    - Ions contribute to peripheral doping profile
  - For SiGe HBTs, the WPE affects the SIC implant

  ⇒ ions are attached to Collector periphery



[2]

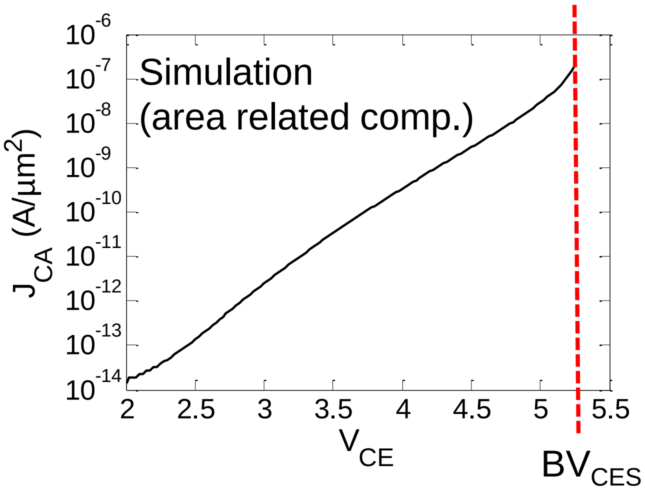
[3] P. G. Drennan et al., “Implications of Proximity Effects for Analog Design”, IEEE 2006 Custom Integrated Circuits Conference, 2006.

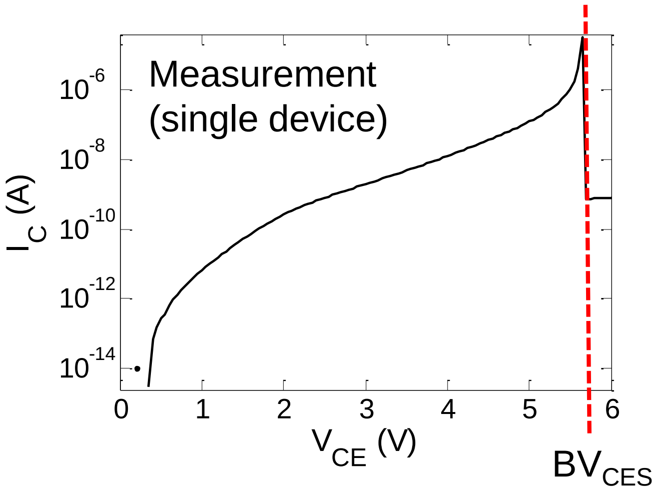
Calibration of tunneling parameters

- Feasibility
  - Used process does not exhibit an area related tunneling component
  - Peripheral doping profiles are not known accurately
    - Process-TCAD does not take into account the WPE

  $\Rightarrow$ calibration of tunneling is **not feasible**

- Assuming standard parameters for tunneling mechanisms
  - Avalanche, trap-assisted tunneling (TAT) and band-to-band (B2B) tunneling taken into account for simulations





  - Similar breakdown voltages
    - 5.3 V (sim.) vs. 5.7 V (meas.)
    - But: tunneling current cannot be compared (single transistor vs. area component)

Sensitivity analysis

- Tunneling current parameter influence
  - Parameters determine shape of $I_C(V_{CE})$ curve (V_{BE} = 0 V)
  - But at breakdown condition: carrier impacts multiply infinitely

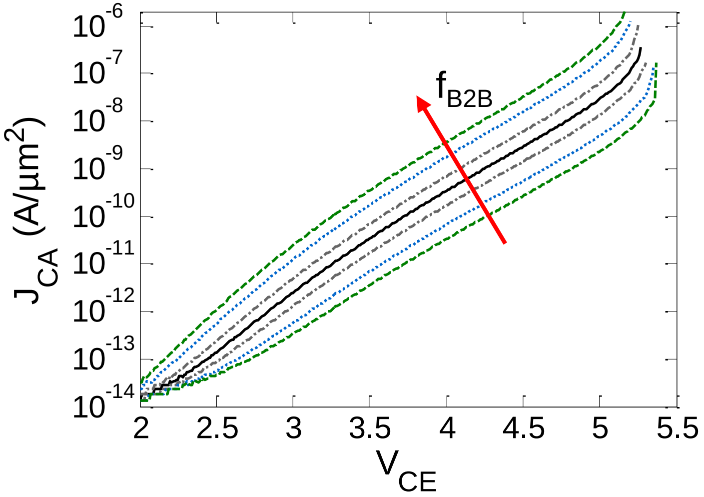
  ⇒ tunneling parameters should not play a major role, as already a small amount of carriers will trigger breakdown

- Band to band tunneling model
  - Field dependent description
    - Parameters f_{B2B}, γ_{B2B} and b_{B2B}

$$G_{B2B} = -f_{B2B}\frac{|F|^{\gamma_{B2B}}}{\sqrt{V_g}}exp\left(-b_{B2B}\frac{V_g^{3/2}}{|F|}\right)$$

- TCAD analysis
  - f_{B2B} variation (span of 2 decades)
    - Minimum value: 3.5e20
    - Reference value: 3.5e21
    - Maximum value: 3.5e22
  - BV_{CES} variation
    - 5.20 V … 5.37 V

  ⇒ variation relatively small, but standard parameter set should be taken into account



Conclusion

- Introduction on breakdown of SiGe HBTs
  - Physical mechanisms
    - Impact ionization, tunneling
  - Corresponding figures of merit
    - BV_{CEO}, BV_{CES}
- TCAD calibration of an advanced SiGe HBT technology [4]
  - P/A separation of measurement data
  - Calibration of impact ionization parameters
    - Both holes and electron parameters adjusted to measurements
  - Suitability for future doping profiles yet to be verified
- Tunneling current scaling
  - Well proximity effect
  - Determination of BV_{CES} with TCAD successful
    - Sensitivity analysis of tunneling on BV_{CES}

[4] P. Chevalier et al. « A 55 nm Triple Gate Oxide 9 Metal Layers SiGe BiCMOS Technology Featuring 320 GHz fT / 370 GHz fMAX HBT and High-Q Millimeter-Wave Passives ». Proc. IEEE IEDM, 2014.

References

[1] T. Rosenbaum et al., “Calibration of 1D Doping Profiles of SiGe HBTs”, accepted paper for Proc. IEEE BCTM, 2015.

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