Extraction of Parasitic Substrate PNP Parameters (and even more) of NPN Devices Without Access to the Substrate Terminal

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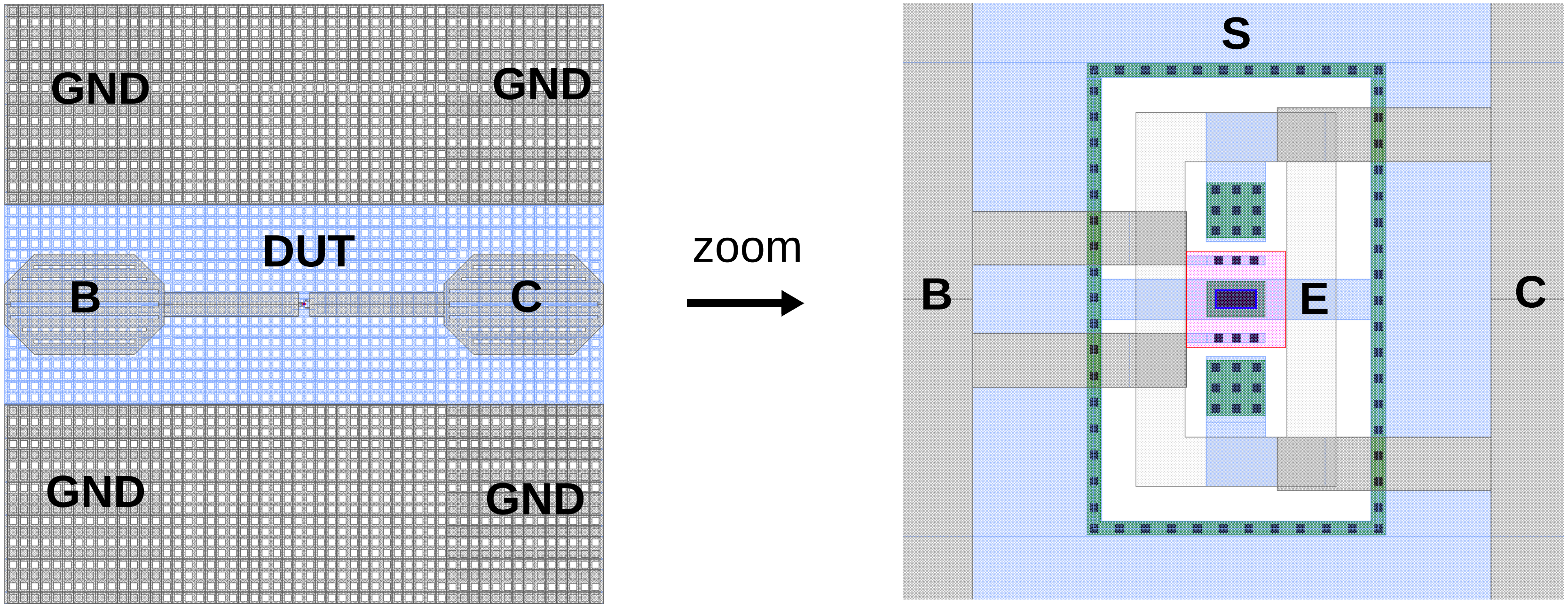
Outline

- Purpose
- Theory
- Measurement set up
- Extraction flow
- Summary
- Conclusion

Purpose

- In order to avoid the duplication of test structures (DC and RF structures)
  - For saving silicon area
  - To reduce the time of measurement and the quantity of stored data (only RF structures are measured)
  - To preserve the data consistency (DC and RF measurements performed on the same device)
- Measurements for bipolar parameter extraction are performed only on RF test structures with common emitter configuration using G.S.G RF probes
- In this configuration the emitter and the substrate are shorted to the ground and therefore the substrate current cannot be measured

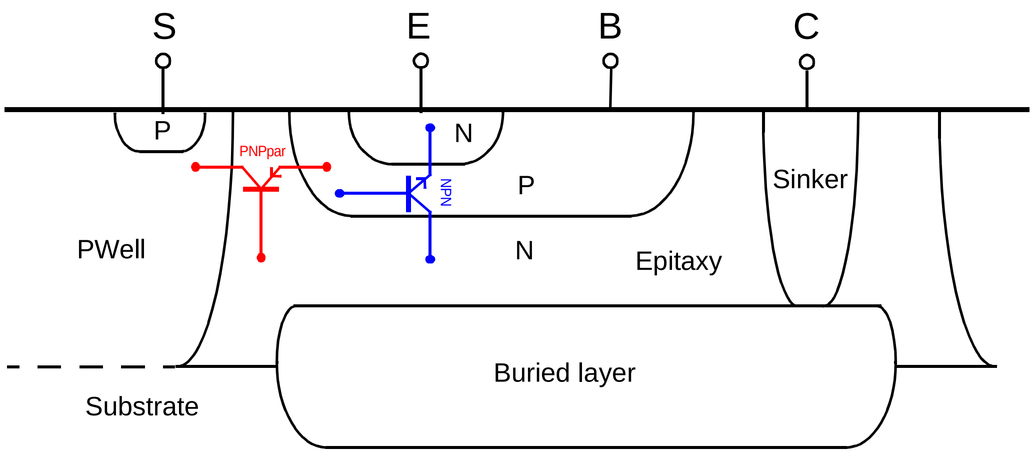


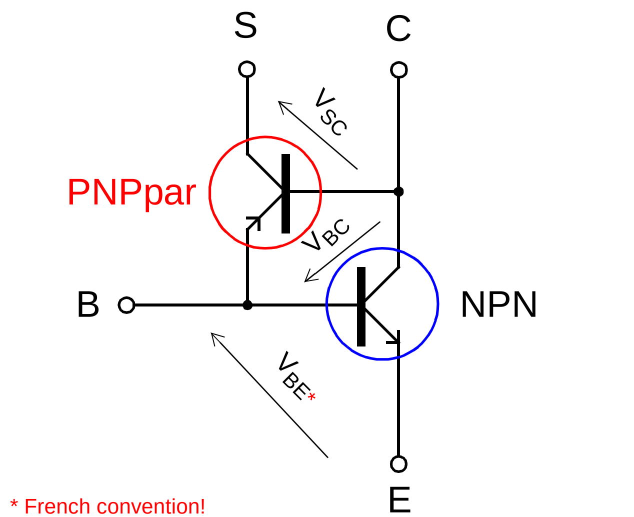
Theory

- In aim of this study, in complement to [1], [2] and [3], is to provide a methodology for the DC parameter extraction (i) of the parasitic PNP (associated to vertical isolated NPN devices), (ii) of the BC diode of the NPN and (iii) the BE tunneling current, only from measurements of the base and collector currents.

- The proposed method is independent of the model (SGP with SUBCKT, HICUM/L2, HICUM/L0, MEXTRAM, VBIC)
  - Results using HICUM/L2 and HICUM/L0 are shown

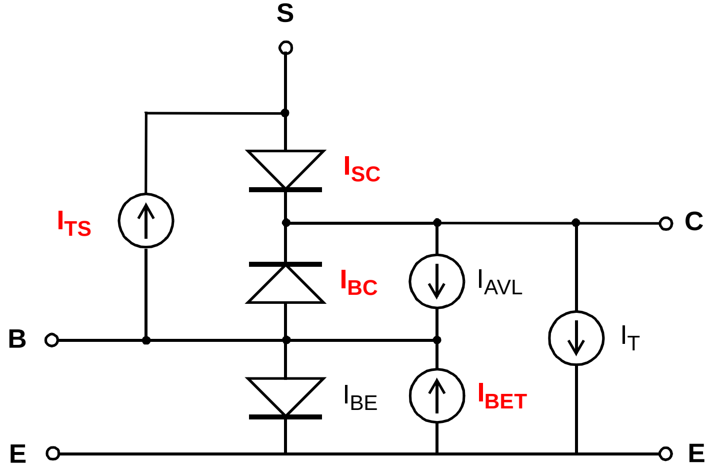
- To all vertical isolated integrated bipolar devices is associated a parasitic bipolar to the substrate
  - Substrate PNP for NPN devices
  - Niso NPN for vertical PNP devices

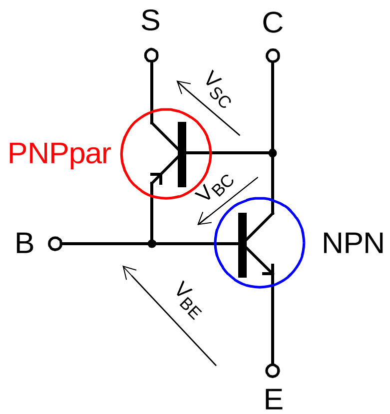




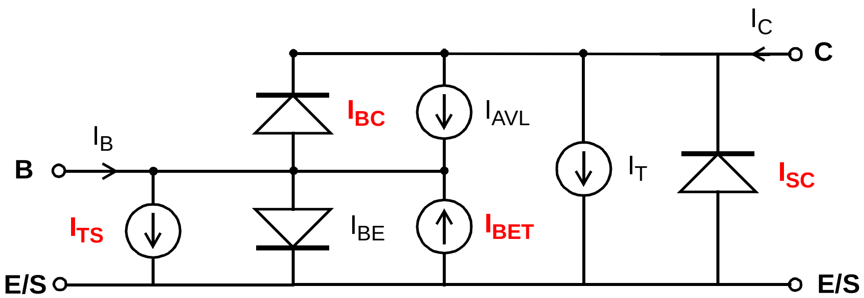
Theory

- Parameter extraction at low densities of current in order to avoid voltage drop in series resistances, high-injection and shelf-heating effects
- Simplified HICUM/L2 equivalent circuit





- Commun emitter configuration with the emitter and the substrate connected to the ground



- I_{BE} et I_{BC} are respectively the total (bottom and lateral) current of BE and BC junctions
- I_{SC} is the current of the CS junction
- I_T is the transfer current of the NPN
- I_{BET} is the BE tunneling current
- I_{AVL} is the BC weak avalanche current
- I_{TS} is the transfer current of the substrate PNP
- The parameters of all currents in red have to be determined

Theory

Expression of the internal currents

- **Diode BE**

$$I_{BE} \approx I_{SBE} \cdot \left(e^{\frac{V_{BE}}{M_{BE} \cdot V_T}} - 1 \right) \quad (1)$$

where I_{SBE} is the equivalent saturation current of the BE junction and M_{BE} the equivalent BE non-ideality factor

- **Diode BC**

$$I_{BC} \approx I_{SBC} \cdot \left(e^{\frac{V_{BC}}{M_{BCI} \cdot V_T}} - 1 \right) \quad (2)$$

where I_{SBC} is the equivalent saturation current of the BC junction and M_{BCI} the BC non-ideality factor.

Assuming the same non-ideality factor M_{BCI} for the internal and external components of the BC current, I_{SBC} can than splited into internal and external part using the BC diode partition factor X_{JBC}

$I_{BCIS} = (1 - X_{JBC}) \cdot I_{SBC}$ and $I_{BCXS} = X_{JBC} \cdot I_{SBC}$

- **Transfer current of the NPN**

$$I_T \approx I_S{}^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) \quad (3)$$

where $I_S{}^*$ is the equivalent saturation current of the NPN including the modulation with V_{BE} and V_{BC}

Theory

- **Transfer current of the parasitic PNP substrate**

$$I_{TS} = I_{TSS} \cdot \left(e^{\frac{-V_{BEpnp}}{M_{SF} \cdot V_T}} - e^{\frac{-V_{BCpnp}}{M_{SF} \cdot V_T}} \right) \tag{4}$$

where I_{TSS} is the saturation current substrate PNP and M_{SF} the non-ideality factor of the substrate transfert current

$$\begin{cases} -V_{BEpnp} = V_{BCnpn} = V_{BC} \\ -V_{BCpnp} = V_{SCnpn} = V_{SE} + V_{EC} = 0 + V_{BC} - V_{BE} = V_{BC} - V_{BE} \end{cases}$$

leads to final expression for I_{TS}

$$I_{TS} = I_{TSS} \cdot e^{\frac{V_{BC}}{M_{SF} \cdot V_T}} \cdot \left(1 - e^{\frac{-V_{BE}}{M_{SF} \cdot V_T}} \right) \tag{5}$$

- **CS diode**

$$I_{SC} = I_{SCS} \cdot \left(e^{\frac{-V_{BCpnp}}{M_{sc} \cdot V_T}} - 1 \right) = I_{SCS} \cdot \left(e^{\frac{V_{SCnpn}}{M_{sc} \cdot V_T}} - 1 \right) \tag{6}$$

leads to final expression for I_{SC}

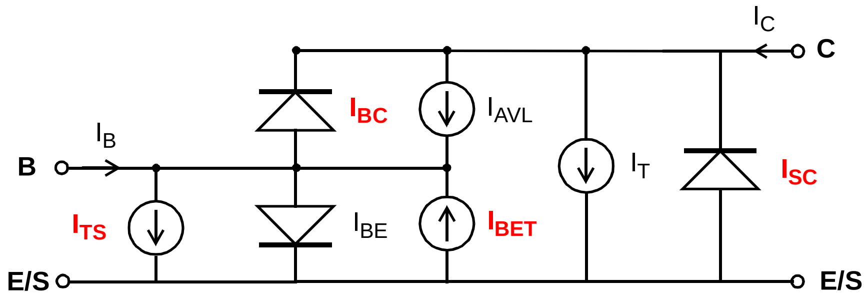
$$I_{SC} = I_{SCS} \cdot \left(e^{\frac{V_{BC}}{M_{sc} \cdot V_T}} \cdot e^{\frac{-V_{BE}}{M_{sc} \cdot V_T}} - 1 \right) \tag{7}$$

Theory

- **BC weak avalanche current**

$I_{AVL} = 0$ for positive V_{BC}

$I_{AVL} = f(V_{BE}, V_{BC})$ for negative V_{BC}



- **BE tunneling current**

$I_{BET} = 0$ for positive V_{BE}

$I_{BET} = g(V_{BE})$ for negative V_{BE}

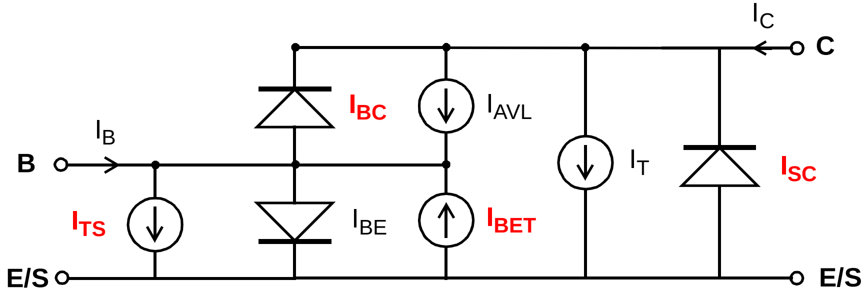
$g(V_{BE})$ depends on two model parameters that need to be extracted, the BE tunneling saturation current I_{BETS} and the exponent factor for the tunneling current A_{BET}.

Theory

Expression of the terminal currents I_B and I_C

- **Base current I_B**

$$I_B = I_{BE} + I_{BC} + I_{TS} - I_{BET} - I_{AVL} \tag{8}$$



From the previous formulations of the currents we can write

$$I_B = I_{SBE} \cdot \left(e^{\frac{V_{BE}}{M_{BE} \cdot V_T}} - 1 \right) + I_{SBC} \cdot \left(e^{\frac{V_{BC}}{M_{BCI} \cdot V_T}} - 1 \right) + I_{TSS} \cdot e^{\frac{V_{BC}}{M_{SF} \cdot V_T}} \cdot \left(1 - e^{\frac{-V_{BE}}{M_{SF} \cdot V_T}} \right) - g(V_{BE}) - f(V_{BE}, V_{BC}) \tag{9}$$

It may be noted that I_B is only a fonction of V_{BE} and V_{BC}

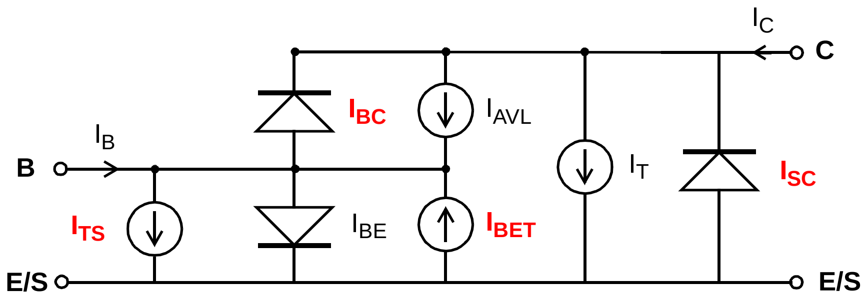
- In a first step, we assume that all non-ideality factors are identical and close to one.That allows to determine initial guess for saturation currents before global optimization

$$I_B = I_{SBE} \cdot \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \left[I_{TSS} \cdot \left(1 - e^{\frac{-V_{BE}}{V_T}} \right) + I_{SBC} \right] \cdot e^{\frac{V_{BC}}{V_T}} - I_{SBC} - g(V_{BE}) - f(V_{BE}, V_{BC}) \tag{10}$$

Theory

- **Collector current I_C**

$$I_C = I_T + I_{AVL} - I_{BC} - I_{SC} \quad (11)$$



From the previous formulations of the currents we can write

$$I_C = I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) + f(V_{BE}, V_{BC}) - I_{SBC} \cdot \left(e^{\frac{V_{BC}}{M_{BCI} \cdot V_T}} - 1 \right) - I_{SCS} \cdot \left(e^{\frac{V_{BC}}{M_{sc} \cdot V_T}} \cdot e^{\frac{-V_{BE}}{M_{sc} \cdot V_T}} - 1 \right) \quad (12)$$

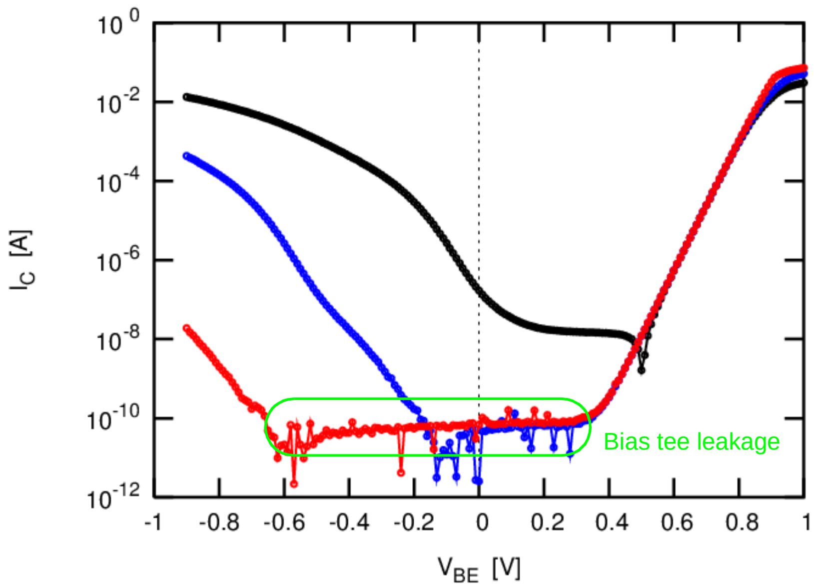
It may be also noted that I_C is only a fonction of V_{BE} and V_{BC}

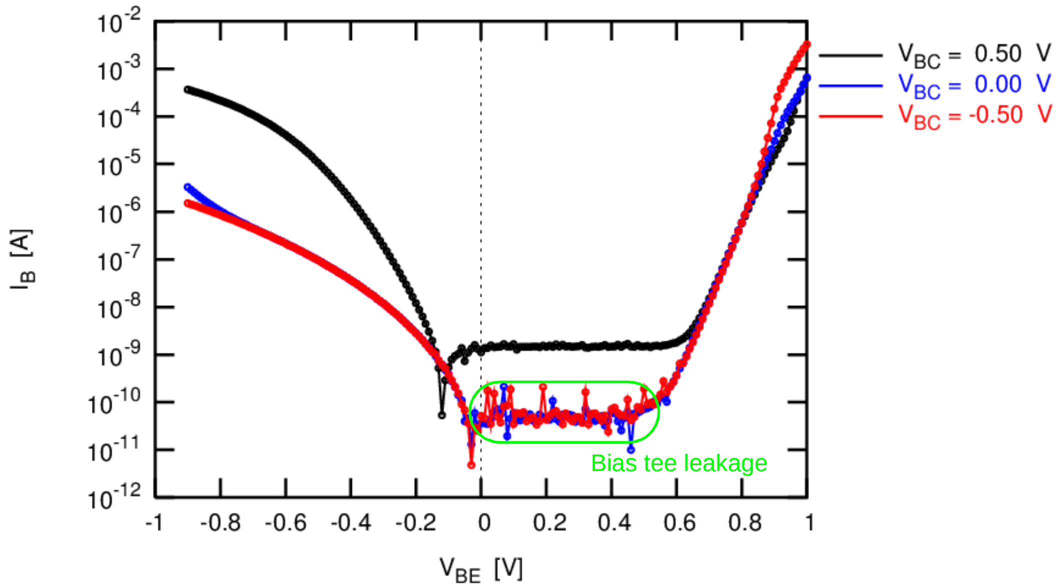
- In a first step, we assume that all non-ideality factors are identical and close to one.That allows to determine initial guess for saturations current before global optimization

$$I_C = I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) + f(V_{BE}, V_{BC}) - \left(I_{SBC} + I_{SCS} \cdot e^{\frac{-V_{BE}}{V_T}} \right) \cdot e^{\frac{V_{BC}}{V_T}} + I_{SBC} + I_{SCS} \quad (13)$$

Measurement setup

- Gummel plot (I_C and I_B) at several V_{BC} with V_{BE} swept from negative value to positive value
  - V_{BEmin} = -1 V to V_{BEmax} = 1 V (step 10 mV)
  - 3 VBC
    - one positive (saturation) 0.5 or 0.6V
    - V_{BC} = 0 V
    - One close to $-BV_{CEO} + V_{BEmax}$





Extraction flow

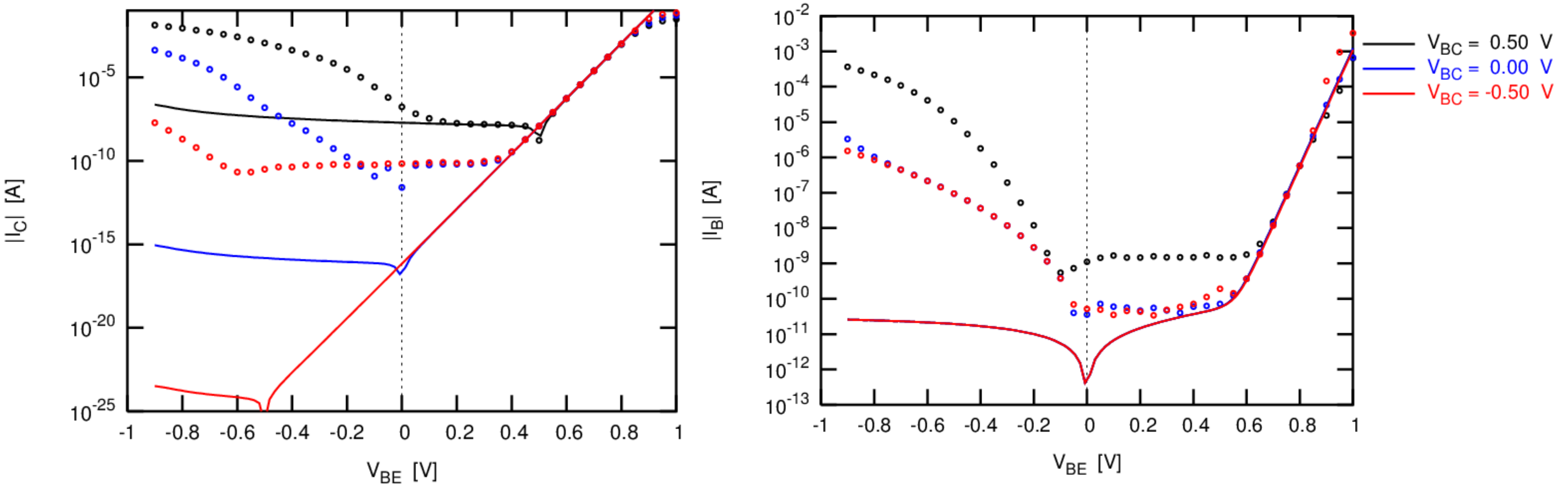
Prerequisite

- Model parameters, in forward mode and at low currents densities of the transfer current I_T and of the base current I_{BE}, are known.
- Model parameters of the weak avalanche current are known.

→ see various methods presented at AKB or HICUM workshops

- https://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_events.html
- https://www.iee.et.tu-dresden.de/iee/eb/forsch/AK-Bipo/ak_bipo_bei.html

Results before PNP substrate, BC diode and BE tunneling current parameter extraction



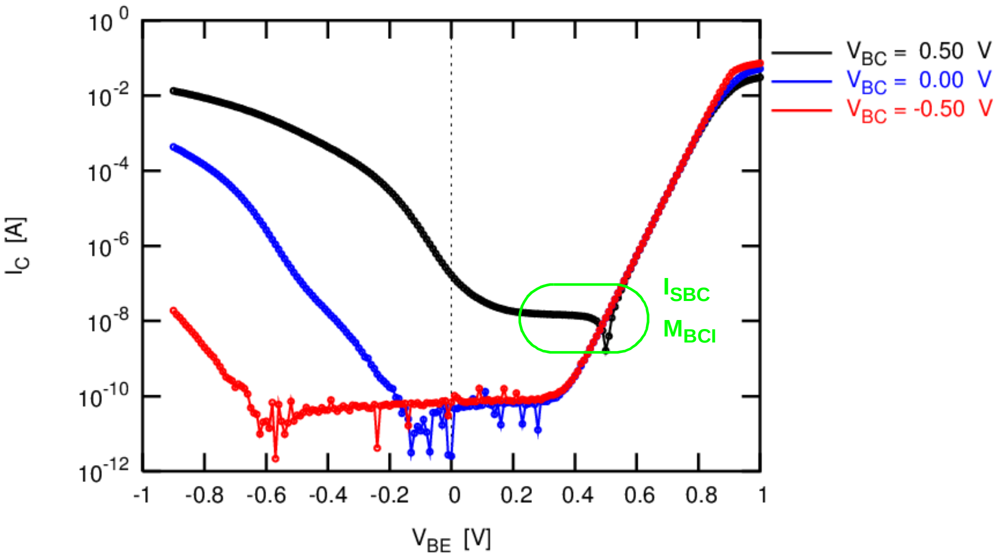
Step 1: I_{SBC}, M_{BCI}

- BC diode parameter extraction: $\mathbf{I_{SBC}}$ and $\mathbf{M_{BCI}}$
  - **From I_C vs. V_{BE} at positive V_{BE} and positive V_{BC}** equation (13) can be simplified

$$I_C = I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) + f(V_{BE}, V_{BC}) - \left(I_{SBC} + I_{SCS} \cdot e^{\frac{-V_{BE}}{V_T}} \right) \cdot e^{\frac{V_{BC}}{V_T}} + I_{SBC} + I_{SCS} \quad (14)$$

and from (12)

$$I_C = I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) - I_{SBC} \cdot e^{\frac{V_{BC}}{M_{BCI} \cdot V_T}} \quad (15)$$



- In this operating bias range, the only unknown parameters are those of the BC diode I_{SBC} and M_{BCI}
- I_{SBC} and M_{BCI} are determined using non-linear least squares method with the initial guess

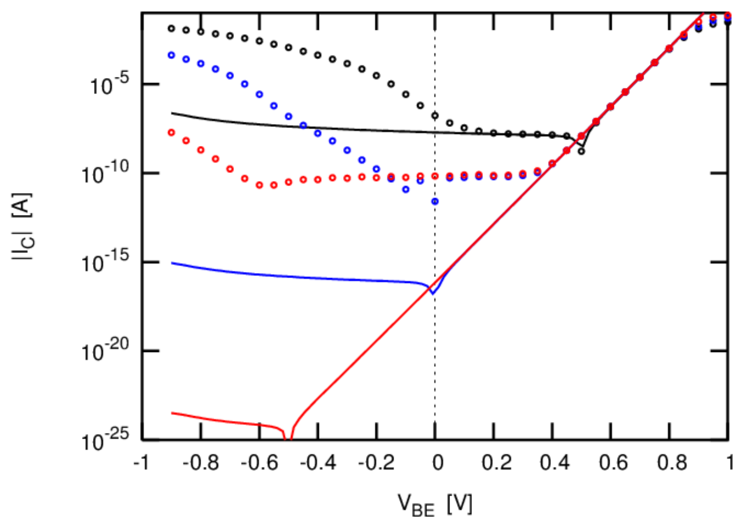
$$\begin{cases} M_{BCI} = 1 \\ I_{SBC} = \dfrac{I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) - I_C}{e^{\frac{V_{BC}}{V_T}}} \end{cases}$$

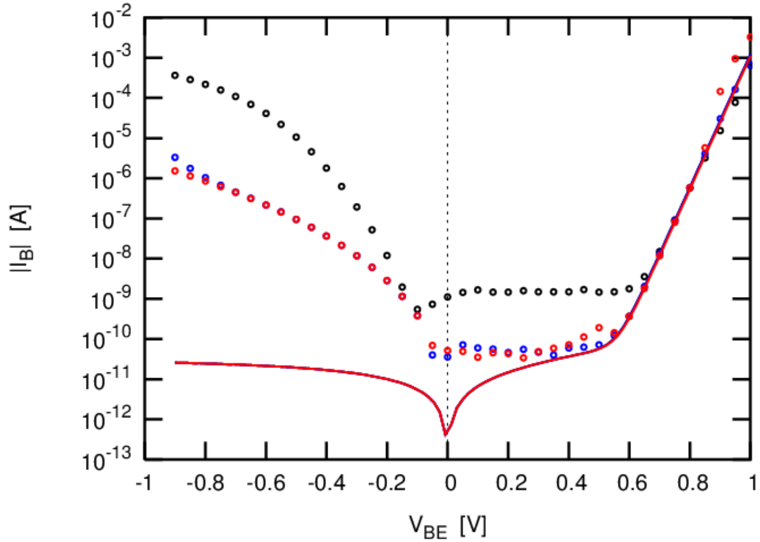
Step 1: I_{SBC}, M_{BCI}

Results

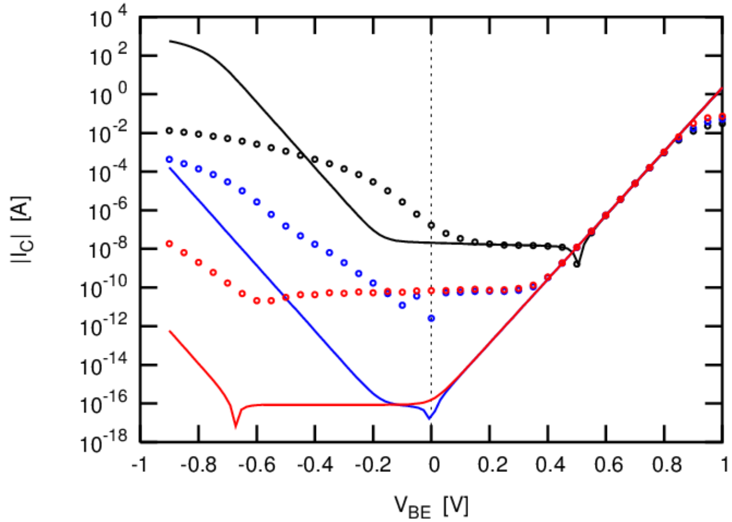
- **Extraction on I_C for V_{BEmin} = 0.2 V and V_{BEmax} = 0.6 V at V_{BC} = 0.5 V**

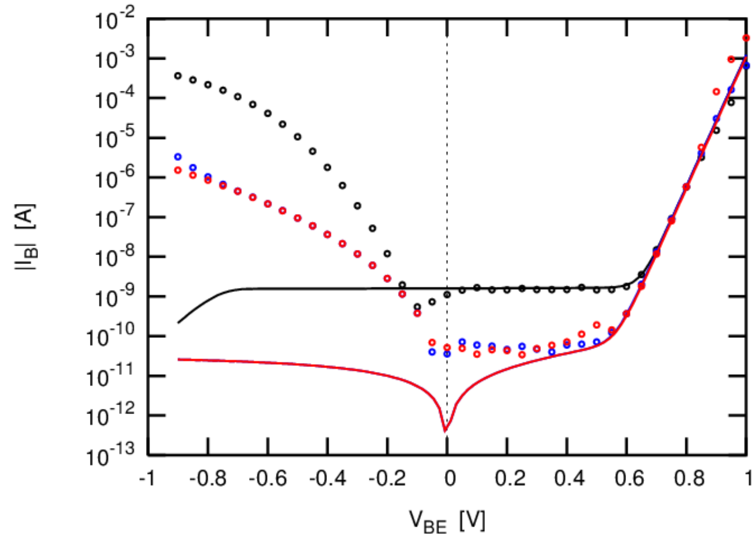
Before





After





Step 1a : I_{SBC}, M_{BCI}

- Alternative to step 1
  - **From I_B vs. V_{BE} at positive V_{BE} and V_{BC}** equation (10) can be simplified

$$I_B = I_{SBE} \cdot \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \left[I_{TSS} \cdot \left(1 - e^{\frac{-V_{BE}}{V_T}} \right) + I_{SBC} \right] \cdot e^{\frac{V_{BC}}{V_T}} - I_{SBC} - g(V_{BE}) - f(V_{BE}, V_{BC}) \quad (16)$$

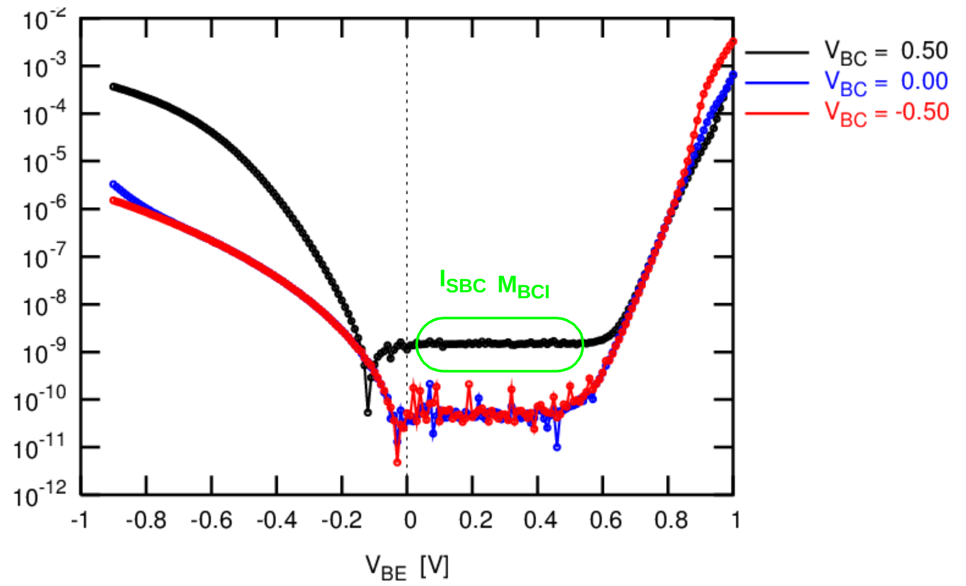
and from (9)

$$I_B = I_{SBE} \cdot e^{\frac{V_{BE}}{M_{BE} \cdot V_T}} + I_{SBC} \cdot e^{\frac{V_{BC}}{M_{BCI} \cdot V_T}} \quad (17)$$

  - In this operating bias range, the only unknown parameters are those of the BC diode I_{SBC} and M_{BCI}

  - I_{SBC} and M_{BCI} are determined using non-linear least squares method with the initial guess

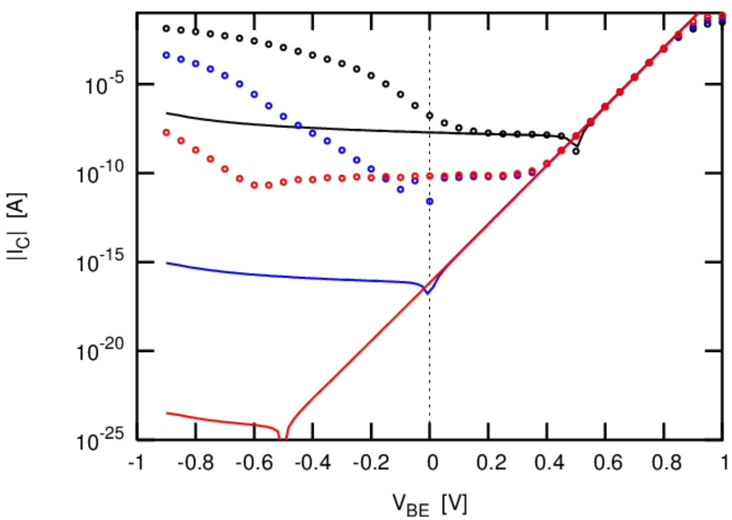
$$\begin{cases} M_{BCI} = 1 \\ I_{SBC} = \dfrac{I_B - I_{SBE} \cdot e^{\frac{V_{BE}}{M_{BE} \cdot V_T}}}{e^{\frac{V_{BC}}{V_T}}} \end{cases}$$



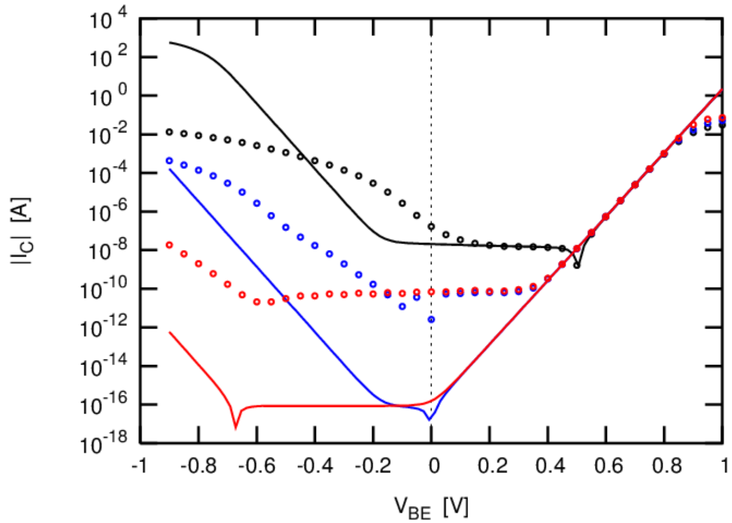
Step 1a : I_{SBC}, M_{BCI}

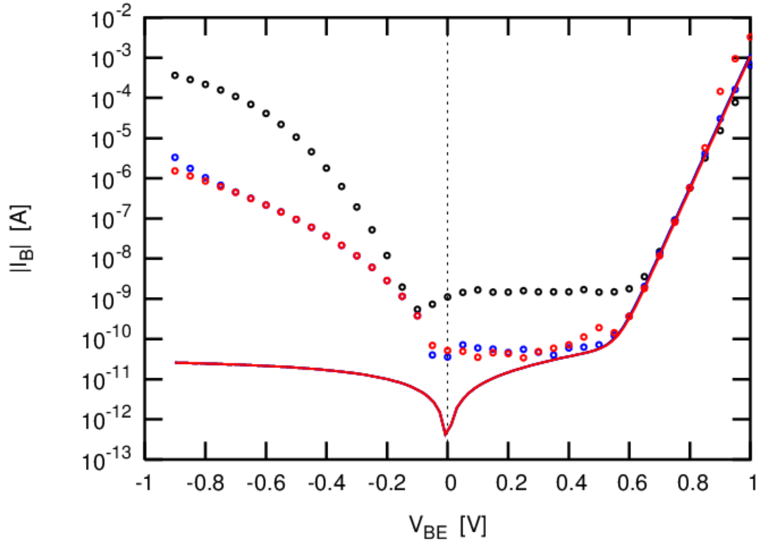
- Results
  - **Extraction on I_B for V_{BEmin} = 0.2 V and V_{BEmax} = 0.6 V at V_{BC} = 0.5 V**

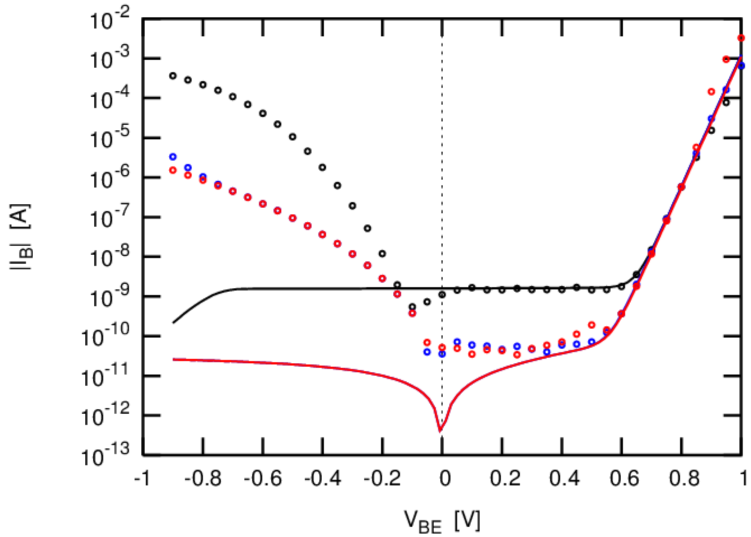
Before



After







Step 2 : I_{SCS}, M_{SC}

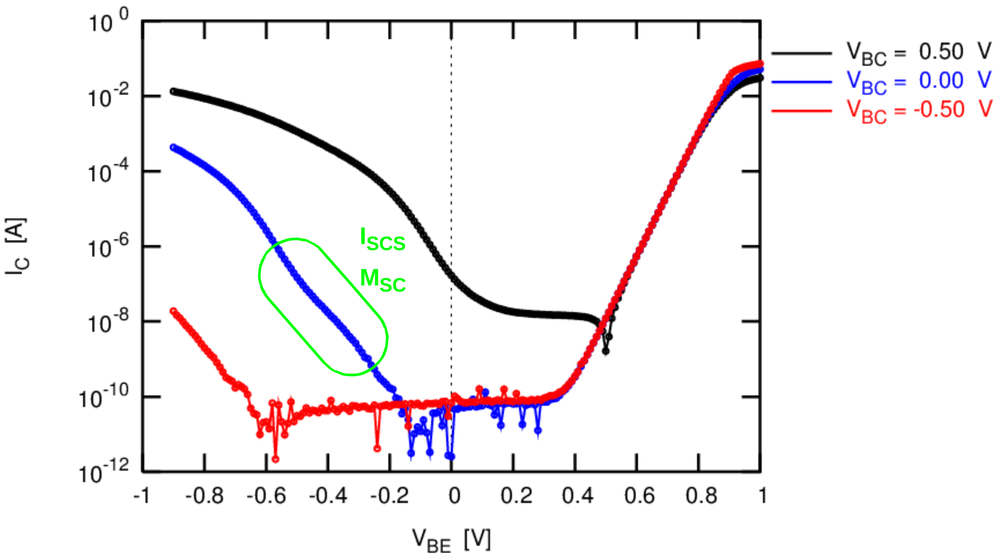
- CS diode parameter extraction: **I_{SCS} and M_{SC}**
  - **From I_C vs. V_{BE} at negative V_{BE} and V_{BC} = 0 V** equation (13) can be simplified

$$I_C = I_S^* \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) + f(V_{BE}, V_{BC}) - \left(I_{SBC} + I_{SCS} \cdot e^{\frac{-V_{BE}}{V_T}} \right) \cdot e^{\frac{V_{BC}}{V_T}} + I_{SBC} + I_{SCS} \qquad (18)$$

and from (12)

$$I_C = -I_{SCS} \cdot e^{\frac{-V_{BE}}{M_{sc} \cdot V_T}} \qquad (19)$$

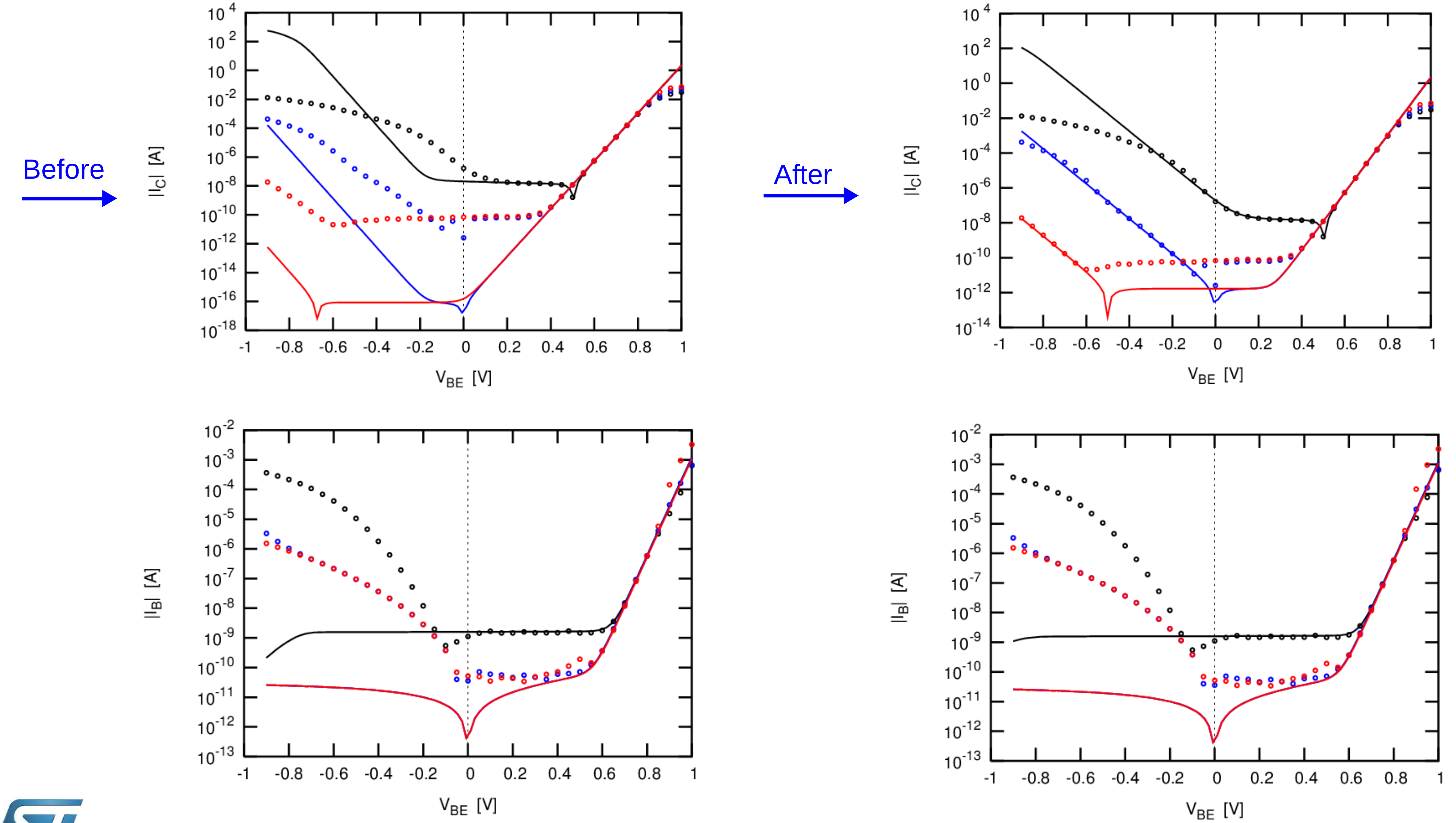
- In this operating bias range, I_C depends only on the parameters of the CS diode I_{SCS} and M_{SC}
- I_{SCS} and M_{SC} are determined using non-linear least squares method with the initial guess deduced from linear regression of $\ln|I_C|$ vs. $-V_{BE}$



Step 2 : I_{SCS}, M_{SC}

Results

- **Extraction on I_C for V_{BEmin} = -0.2 V and V_{BEmax} = -0.6 V at V_{BC} = 0 V**



Step 3 : I_{TSS}, M_{SF}

- Transfer current of the parasitic PNP parameter extraction: **I_{TSS} and M_{SF}**
  - **From I_B vs. V_{BE} at negative V_{BE} and V_{BC} = 0.5 V** equation (10) can be simplified

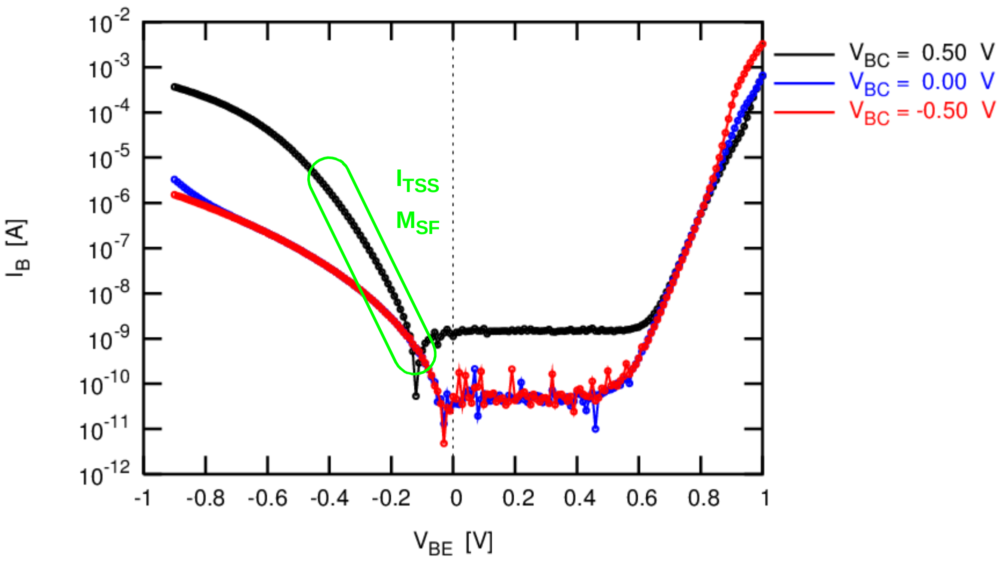
$$I_B = I_{SBE} \cdot \left(e^{\frac{V_{BE}}{V_T}} - 1\right) + \left[I_{TSS} \cdot \left(1 - e^{\frac{-V_{BE}}{V_T}}\right) + I_{SBC} \right] \cdot e^{\frac{V_{BC}}{V_T}} - I_{SBC} - g(V_{BE}) - f(V_{BE}, V_{BC}) \quad (20)$$

and from (9)

$$I_B \approx -I_{TSS} \cdot e^{\frac{-V_{BE}}{M_{SF} \cdot V_T}} \cdot e^{\frac{V_{BC}}{M_{SF} \cdot V_T}} \quad (21)$$

- In this operating bias range, I_B depends only on the parameters of the transfer substrate current parameters I_{TSS} and M_{SF}

- I_{TSS} and M_{SF} are determined using non-linear least squares method with the initial guess deduced from linear regression of $\frac{|I_B|}{e^{\frac{V_{BC}}{V_T}}}$ vs. -V_{BE} in semi-log scale, assuming M_{SF} close too 1.

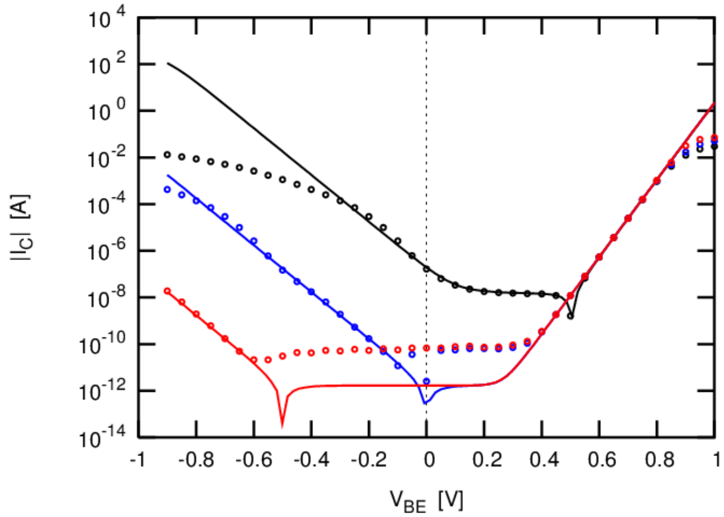


Step 3 : I_{TSS}, M_{SF}

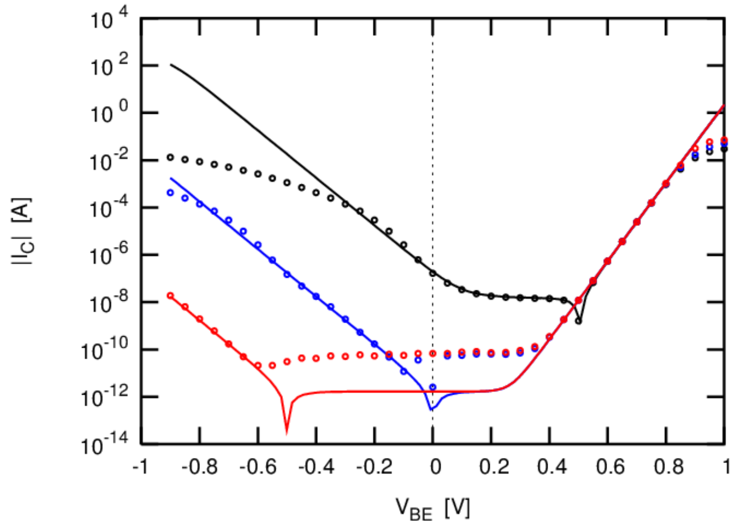
Results

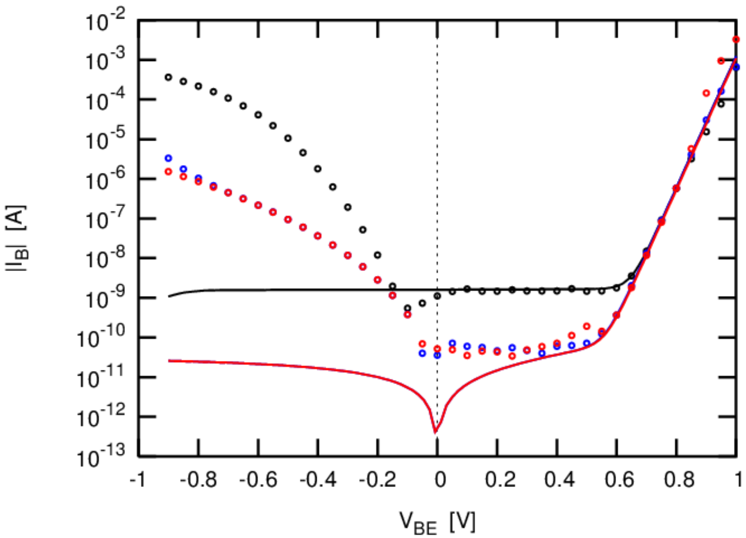
- **Extraction on I_B for V_{BEmin} = -0.4 V and V_{BEmax} = 0 V at V_{BC} = 0.5 V**

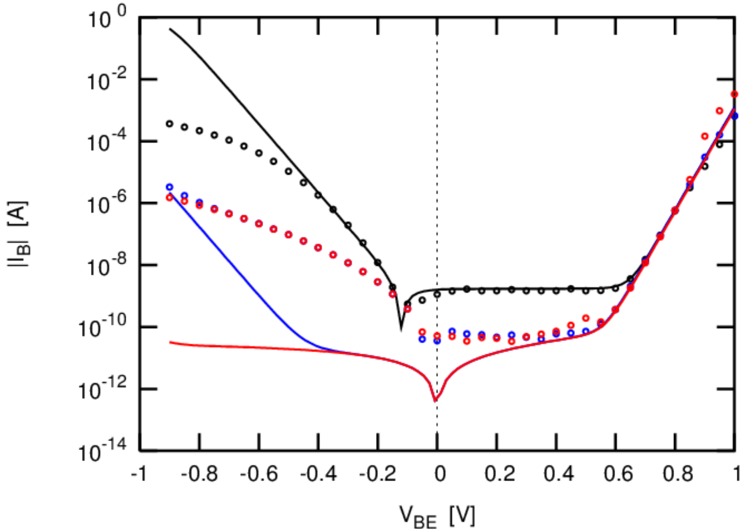
Before



After







Step 4 and last step : I_{BETS}, A_{BET}

- BE tunneling current parameter extraction: $\mathbf{I_{BETS}}$ and $\mathbf{A_{BET}}$
  - **From I_B vs. V_{BE} at negative V_{BE} and negative V_{BC}** equation (10) can be simplified

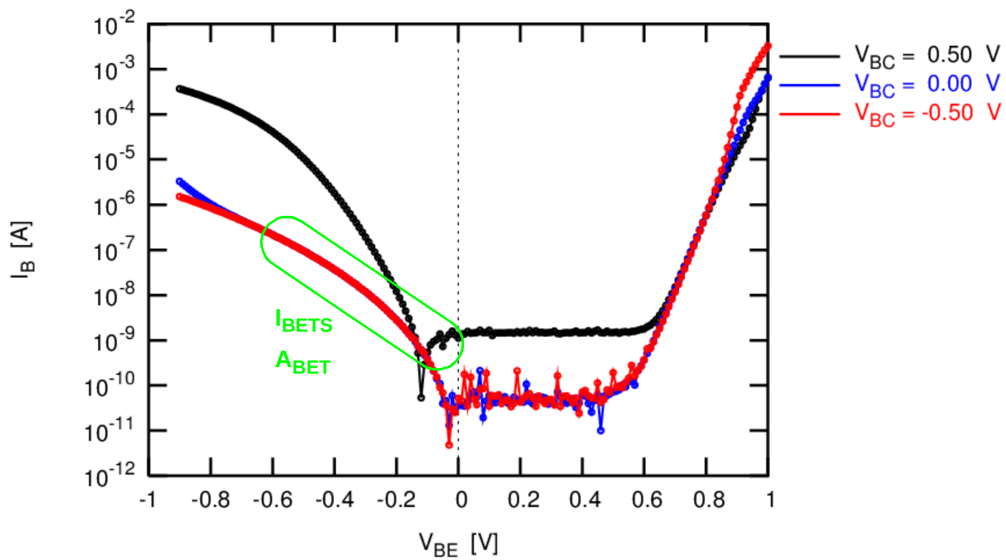
$$I_B = I_{SBE}\cdot\left(\cancel{e^{\frac{V_{BE}}{V_T}}}-1\right)+\left[I_{TSS}\cdot\left(\cancel{1}-e^{\frac{-V_{BE}}{V_T}}\right)+\cancel{I_{SBC}}\right]\cdot\cancel{e^{\frac{V_{BC}}{V_T}}}-\cancel{I_{SBC}}-g(V_{BE})-\cancel{f(V_{BE},V_{BC})} \quad (22)$$

and from (9)

$$I_B \approx -g(V_{BE}) \quad (23)$$

- In this operating bias range, I_B depends only on the parameters of the tunneling current I_{BETS} and M_{SF}

- I_{BETS} and A_{BET} are determined using non-linear least squares method with the initial guess:
  I_{BETS} = 0.01 and A_{BET} = 10.

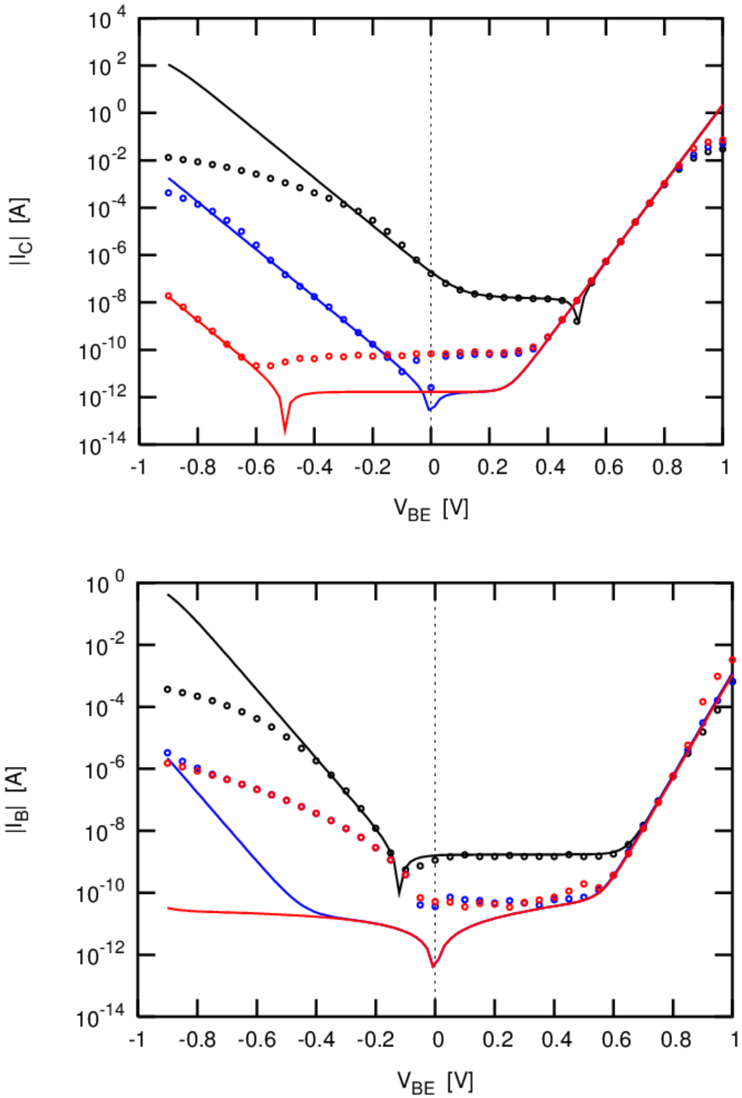


Step 4 : I_{BETS}, A_{BET}

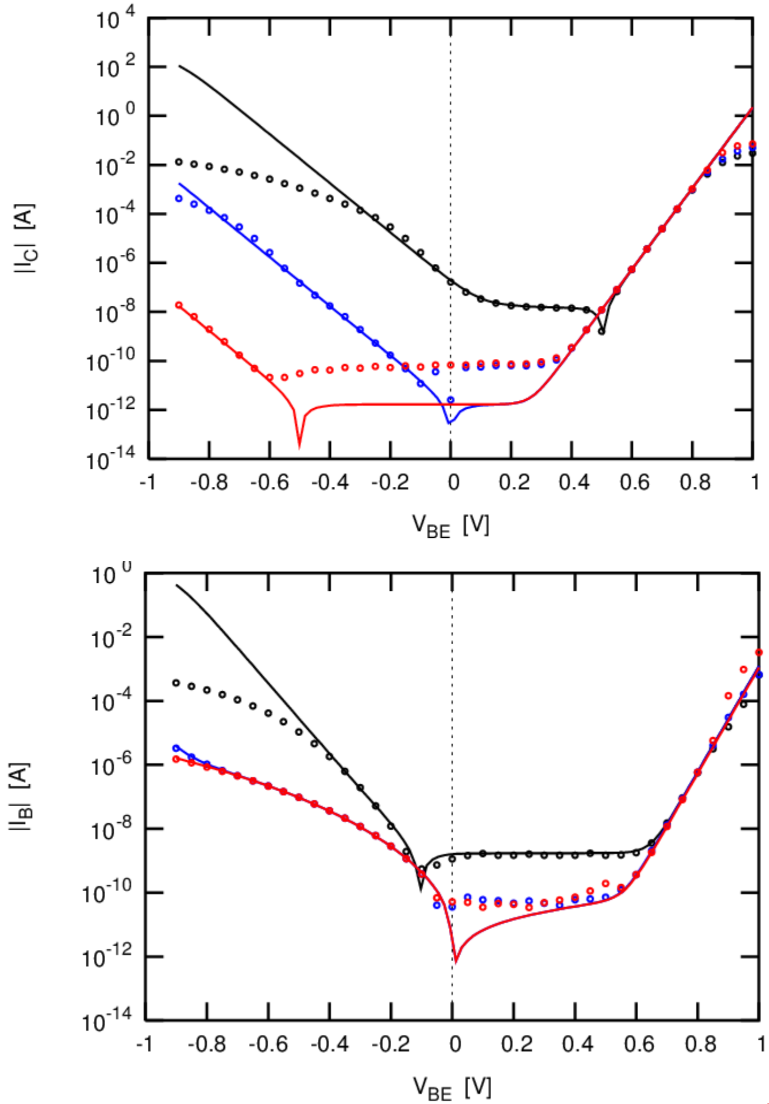
Results

- **Extraction on I_B for V_{BEmin} = -0.8 V and V_{BEmax} = -01 V at V_{BC} = -0.5 V**

Before



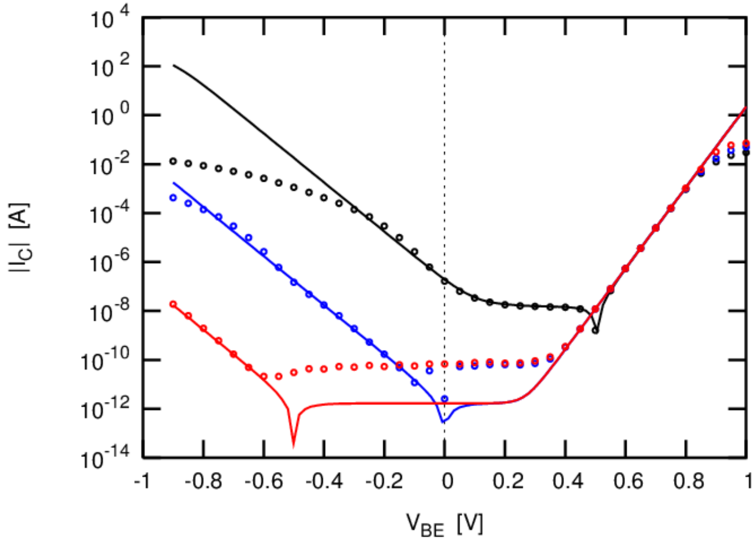
After

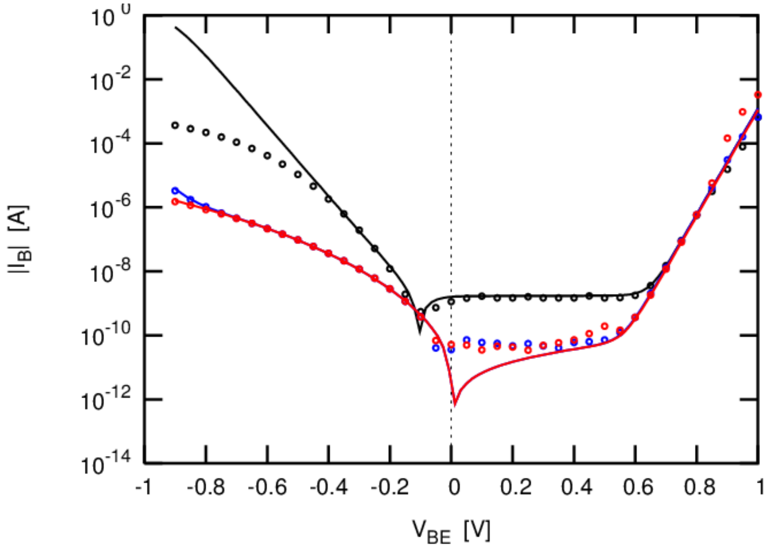


Same extraction flow applied to HICUM/L0

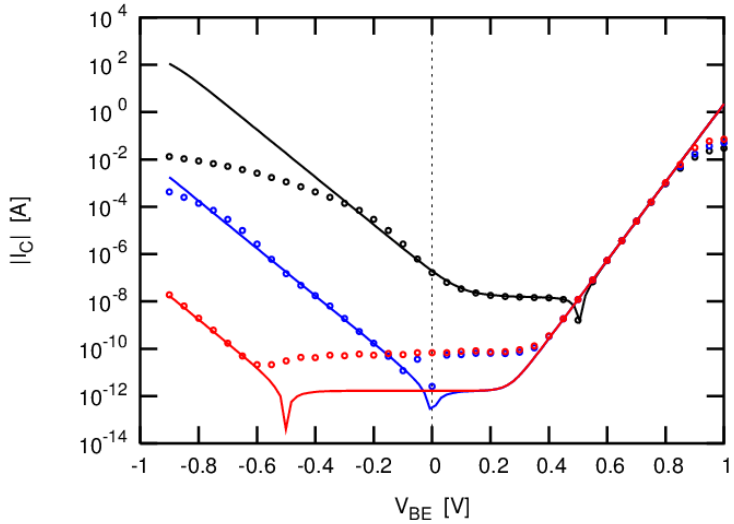
- Identical results excepted for I_B for negative V_{BE} due to the absence of tunneling current in HICUM/L0

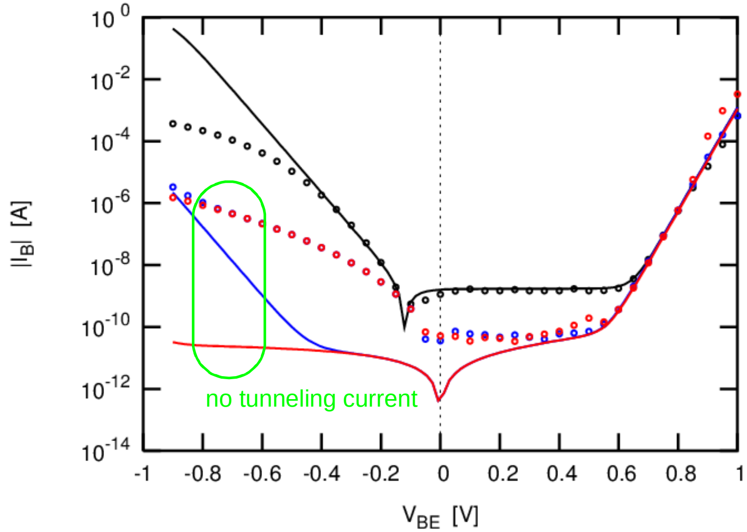
HICUM/L2





HICUM/L0

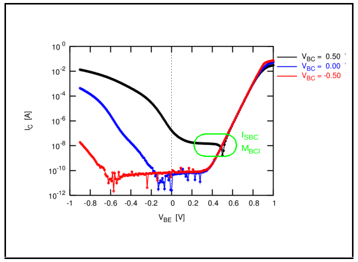




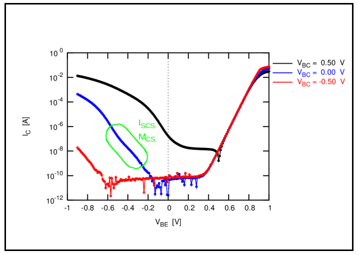
Extraction flow summary

- 4 steps parameter extraction

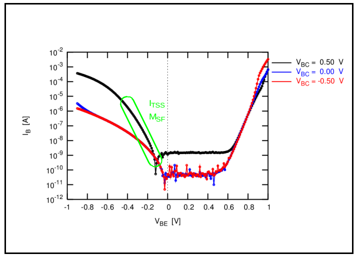
1 — **BC diode** I_{SBC}, N_{BCI} — **I_C vs. V_{BE}** $V_{BE} > 0$ $V_{BC} > 0$



2 — **CS diode** I_{SCS}, N_{SC} — **I_C vs. V_{BE}** $V_{BE} < 0$ $V_{BC} = 0$

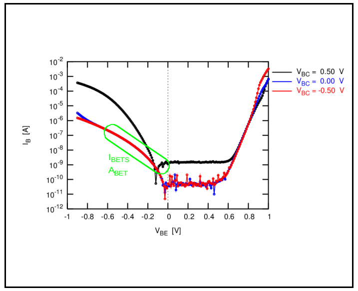


3 — **PNP substrate transfer current** I_{TSS}, M_{SF} — **I_B vs. V_{BE}** $V_{BE} < 0$ $V_{BC} > 0$

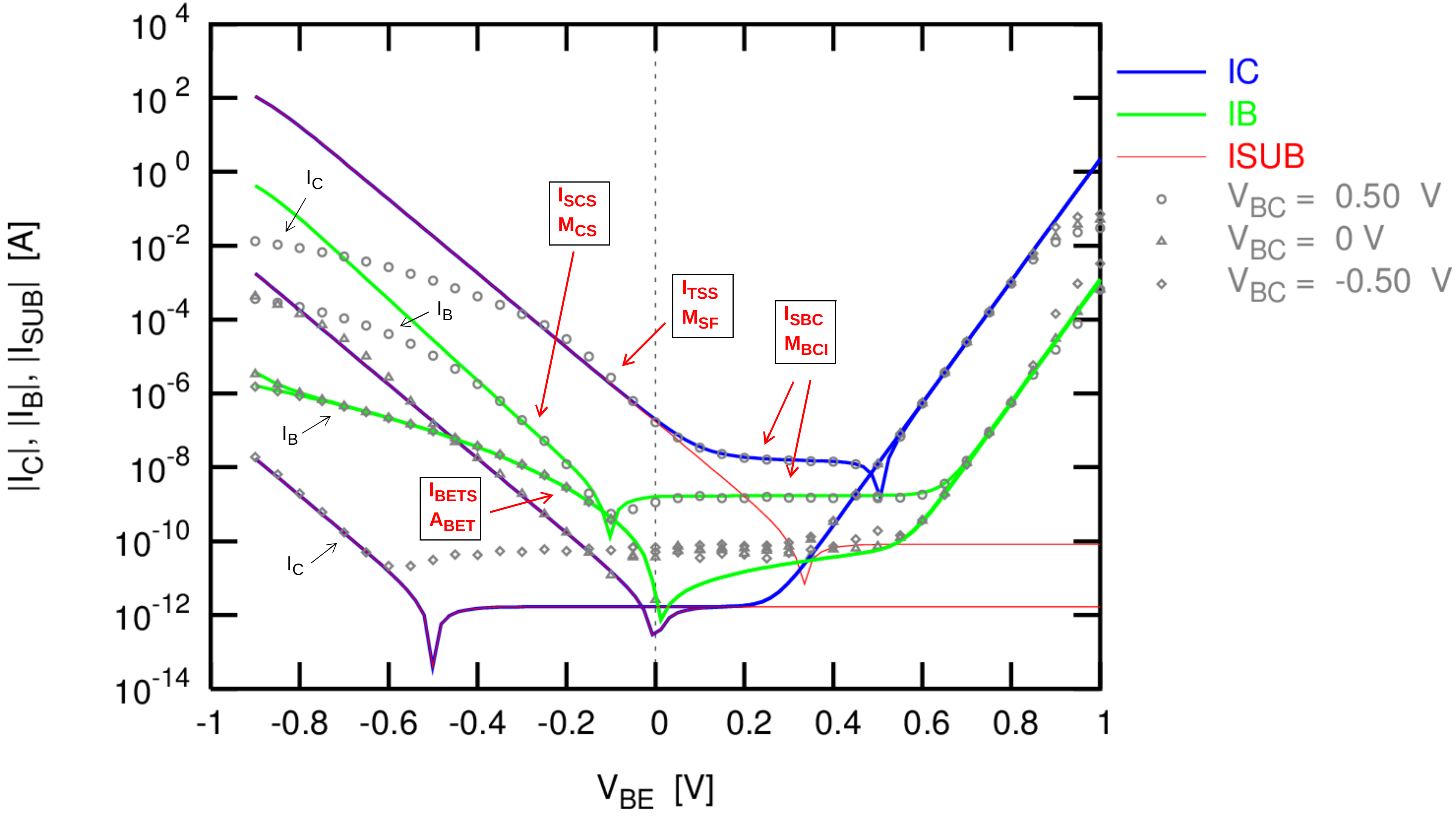


HICUM/L2 only

4 — **BE tunneling current** I_{BETS}, A_{BET} — **I_B vs. V_{BE}** $V_{BE} < 0$ $V_{BC} < 0$



Extraction flow summary



Conclusion

- In common emitter configuration, with the substrate terminal connected to the emitter, from the formulation of the base and collector current, depending of the bias condition
  - Positive or negative V_{BE}
  - Positive V_{BC} or V_{BC} = 0 V (or negative V_{CB})

  it is possible to isolate without any ambiguity
  - The components of the parasitic PNP
  - The CS diode
  - The BC diode
  - The BE tunneling current
- Then, their associated parameters can be easily determined using both direct extraction (initial guess) and global optimization
- The proposed method is independent of the model and can be applied for HICUM/L2, HICUM/L0, MEXTRAM, VBIC, SGP with SUBCKT
  - Note that only HICUM/L2 and MEXTRAM allow to model the BE tunneling current in reverse
- It has been used successfully for various NPN devices (high speed, medium voltage, high voltage) and isolated vertical PNP transistors

References

[1] F. Pourchon, D. Céli, "Parasitic Substrate PNP Modeling without Access to the Substrate Terminal", CMRF Workshop, October 2005.

[2] F. Pourchon, D. Céli, C. Raya, "Improved Methodology for Modeling the Parasitic Substrate PNP without Access to the Substrate Terminal", 6th HICUM Workshop, June 2006.

[3] Z. Huszka, "The *fo* Method for the Determination of I_{BC} and I_{TS} parameters", Private communication, July 2007.