How to Avoid HICUM/L2 v2.24  ?

Application to low collector current parameter extraction at room temperature

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*23rd **A**rbeits**K**reis **B**ipolar*
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Outline

- Introduction
- Direct extraction of low collector current parameters at room temperature
- The dangers of global optimization
- Possible workarounds
- Summary

Introduction

- HICUM/L2 v2.24* is certainly the best physics based bipolar model available today in circuit simulators [1]

- But, on the other hand, HICUM/L2 is also certainly the only physics based bipolar model which can be fitted with unphysical parameters!...

- Demonstration...
  - Application to the determination of the low collector current parameters C_{10}, Q_{P0}, H_{JEI} (equivalent to I_S and V_{AR} of the SGPM) for advanced SiGe HBTs developed in the framework of DOTFIVE project [2].

* In all this document, for simplicity HICUM/L2 v2.24 will be maned HICUM/L2

C_{10}, Q_{P0}, H_{JEI} direct extraction procedure

- Extraction flow (single-geometry approach) [3]

1	BE junction capacitance parameter extraction
2	Split of the BE junction capacitance
3	$\mathbf{C_{10}}$ and $\mathbf{Q_{P0}}$ extraction assuming $\mathbf{H_{JEI}}$=1

BE Junction capacitance parameter extraction

- For each V_{BE}, the BE junction capacitance is determined from *cold* S-parameters measurements, in a given frequency range, using (average value)

$$C_{jBE} = \frac{Im(Y_{11e} + Y_{12e})}{\omega}$$

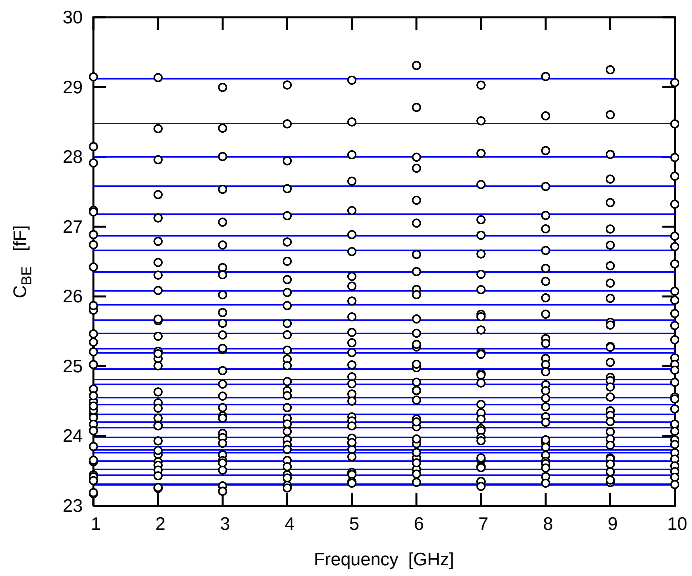
- The parasitic capacitances $\mathbf{C_{PE}}$ (backend and spacer capacitances) are determined from CAD tools.

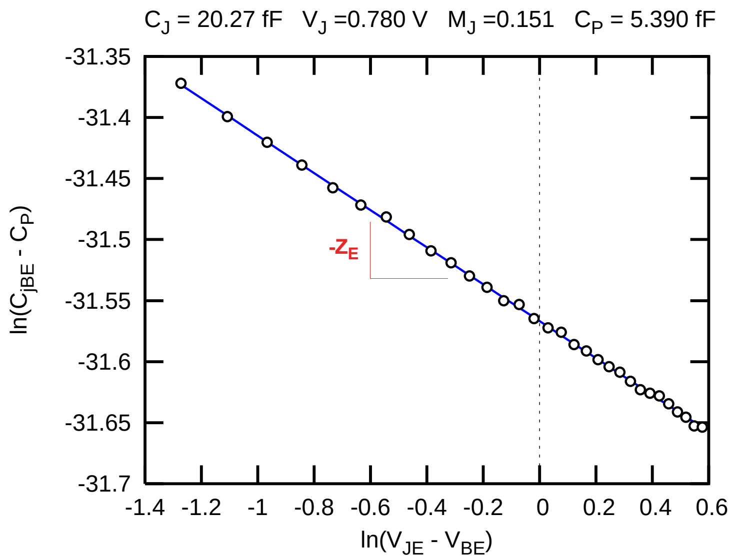
- The model parameters, $\mathbf{C_{JE0}}$, $\mathbf{V_{DE}}$ and $\mathbf{Z_E}$ of the BE depletion capacitance are directly extracted from a linear regression on the characteristic [4]

$$\ln(C_{meas} - \mathbf{C_{PE}}) = \ln(\mathbf{C_{JE0}} \cdot \mathbf{V_{DE}}^{\mathbf{Z_E}}) - Z_E \cdot \ln(\mathbf{V_{DE}} - V_{BE})$$

$\mathbf{C_{PE}}$ and $\mathbf{V_{DE}}$ are chosen by dichotomy in order to maximize the magnitude of the correlation coefficient |r|, than $\mathbf{Z_E}$ is deduced from the *slope* and $\mathbf{C_{JE0}}$ from the y *intercept*

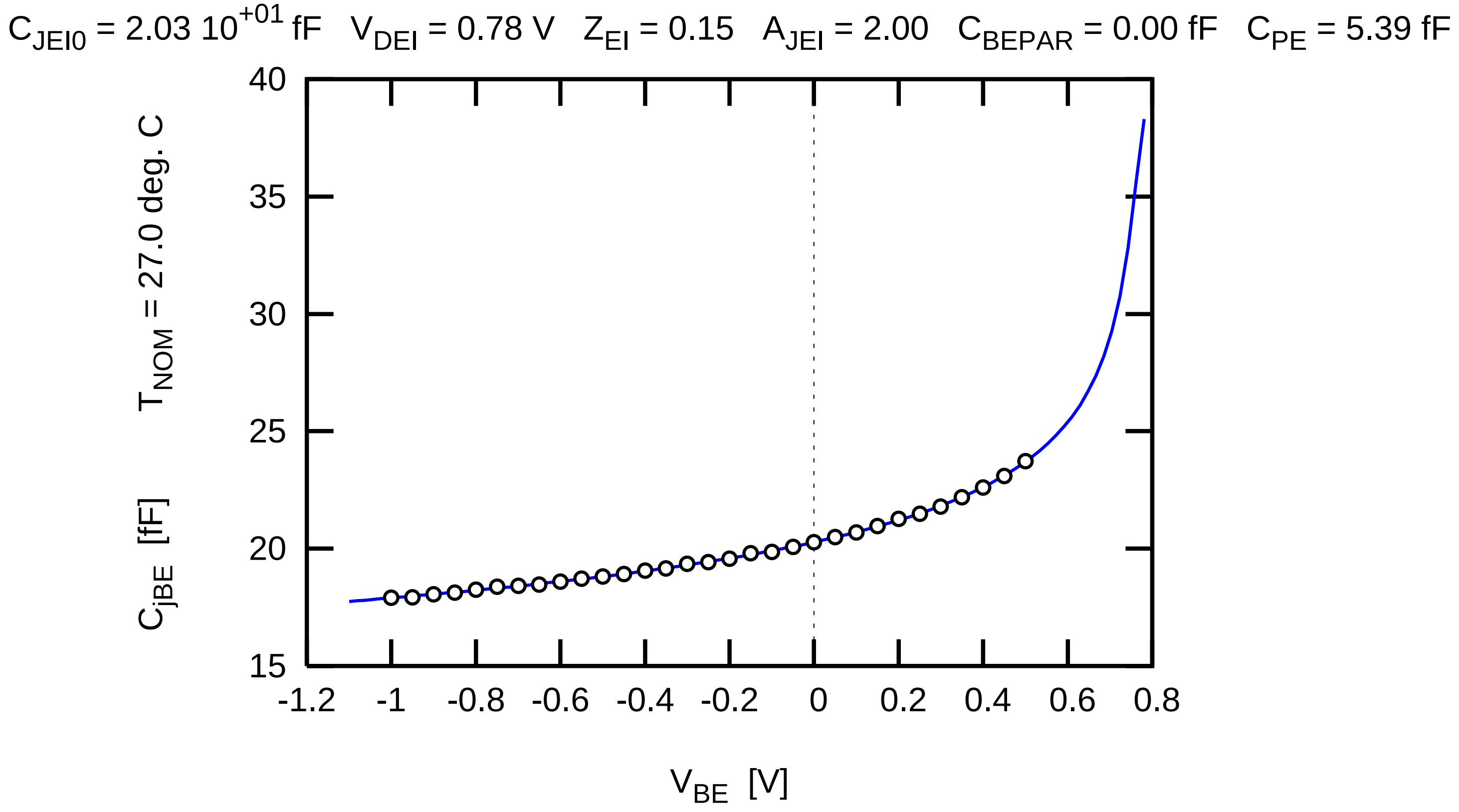
$$\begin{cases} \mathbf{Z_E} = -\text{slope} \\ \mathbf{C_{JE0}} = \dfrac{e^{\text{intercept}}}{\mathbf{V_{DE}}^{\mathbf{Z_E}}} \end{cases}$$





Results

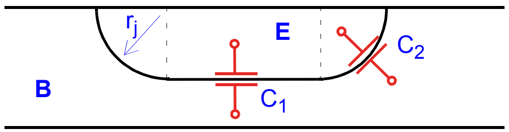
- Very accurate C(V) curve is obtained with the extracted parameters



Split of the BE junction capacitance

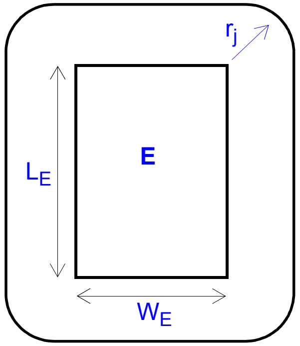
- As the parameters are extracted on a single-geometry device, some assumptions are done for the split (intrinsic/extrinsic part) of the BE capacitance
  - We assume that the area component C_{JEA} is the same for the area and peripheral parts.
  - The split of the BE junction capacitance can be then defined by

$$\begin{cases} C_1 = X_{JBE} \cdot C_{jBE} = C_{JEA} \cdot A_E \\ C_2 = (1 - X_{JBE}) \cdot C_{jBE} = C_{JEP} \cdot P_E = C_{JEA} \cdot \frac{\pi}{2} \cdot r_j \cdot P_E \end{cases}$$



that leads to

$$X_{JBE} = \frac{1}{1 + \frac{\pi}{2} \cdot r_j \cdot \frac{P_E}{A_E}}$$



$$\begin{cases} P_E = 2 \cdot (L_E + W_E) \\ A_E = L_E \cdot W_E \end{cases}$$

  - Application

r_j (nm)	17.1
L_E (µm)	9.86
W_E (µm)	0.13
X_{JBE}	0.705
C_1 (fF)	14.29
C_2 (fF)	5.98

C_{10} and Q_{P0} parameter extraction

- Expression of the collector current at low current densities and V_{BC} = 0V

$$I_C \approx I_{TF} \approx \frac{\mathbf{C_{10}} \cdot e^{\frac{V_{BE}}{V_T}}}{\mathbf{Q_{P0}} + H_{JEI} \cdot Q_{JEI}} \qquad (1)$$

- Extraction strategy
  - From (1) we can write

$$\mathbf{Q_{P0}} + H_{JEI} \cdot Q_{JEI} = \frac{\mathbf{C_{10}} \cdot e^{\frac{V_{BE}}{V_T}}}{I_C} \text{ and finally } \boxed{Q_{JEI} = \frac{\mathbf{C_{10}}}{H_{JEI}} \cdot \frac{e^{\frac{V_{BE}}{V_T}}}{I_C} - \frac{\mathbf{Q_{P0}}}{H_{JEI}}} \qquad (2)$$

  - The internal BE depletion charge Q_{JEI} can be computed from the BE depletion capacitance

$$Q_{JEI} = \int_0^{V_{BE}} C_{JEI}(V)dV \text{ which gives after integration}$$

$$Q_{jEi} = \mathbf{C_{jEi0}} \cdot \left\{ \frac{\mathbf{V_{DEi}}}{1 - \mathbf{Z_{Ei}}} \cdot \left[1 - \left(1 - \frac{V_j}{\mathbf{V_{DEi}}}\right)^{1 - \mathbf{Z_{Ei}}}\right] + \mathbf{A_{jEi}} \cdot (V_{BE} - V_j) \right\}$$

where the auxiliary voltage V_j is equal to V_{BE} in reverse and low forward bias.

C_{10} and Q_{P0} parameter extraction

• Therefore, from (2), at low current densities, the internal BE depletion charge Q_{JEI} vs. the quantity $e^{\frac{V_{BE}}{V_T}}/I_C$ is linear.

• The *slope* allows to determine $\mathbf{C_{10}/H_{JEI}}$ and the *intercept* $\mathbf{Q_{P0}/H_{JEI}}$.

First

• Despite $\mathbf{H_{JEI}}$ affect I_C at low-medium current densities (equation (1)), to our knowledge, $\mathbf{H_{JEI}}$ can not be determined in this range of currents. As consequence, only the ratios $C_{10^*}=\mathbf{C_{10}/H_{JEI}}$ and $Q_{PO^*}=\mathbf{Q_{P0}/H_{JEI}}$ can be extracted.

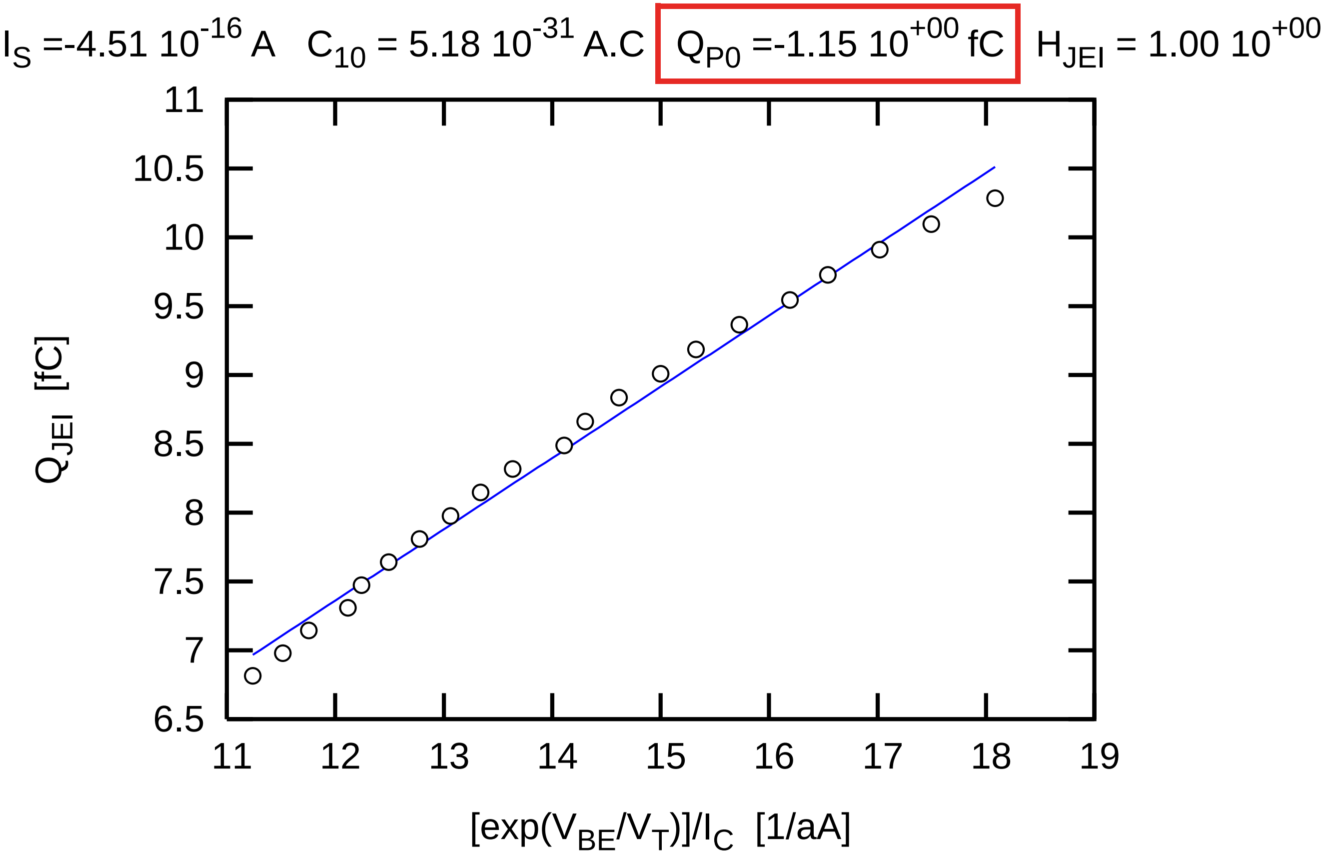
• This method is very sensitive to the temperature which must be accurately known (regulated thermochuck).

Second

• This method has been applied with success for several ST technologies. But, for devices having similar performances than DOTFIVE technology, this method fails and gives a negative $\mathbf{Q_{P0}}$ value (y intercept). Therefore the saturation current $\mathbf{I_S=C_{10}/Q_{P0}}$ cannot be determined.

Results

- Direct extraction gives negative Q_{P0} value



Global optimization

- As direct extraction failed: *an inadequate extraction strategy being always possible*, global optimization (Simplex algorithm) is used.

- Optimization of C_{10}, Q_{P0} and H_{JEI} on the semi-normalized collector current I_{CN}, at low and medium current densities and V_{BC} = 0V
  - T0 (low current transit time) and emitter resistance extracted in previous step.

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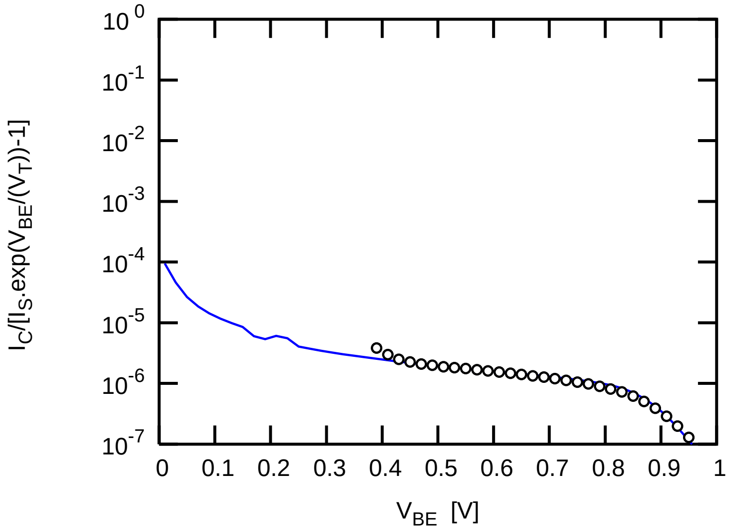
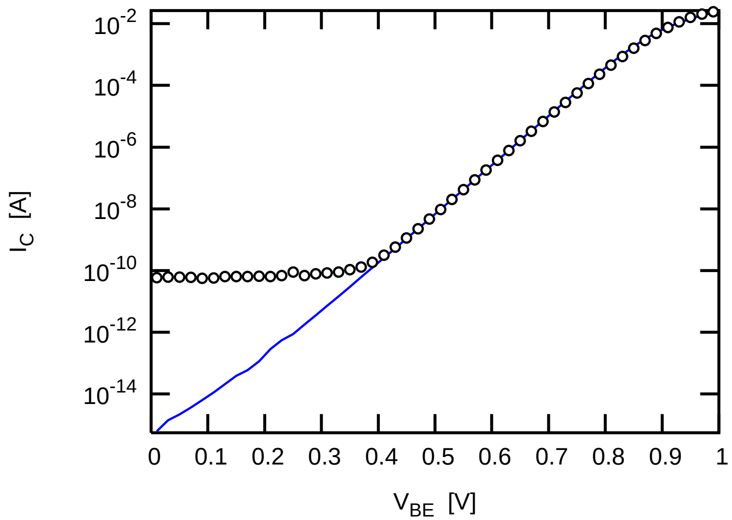
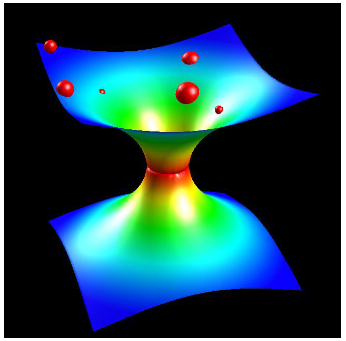
- Perfect results are obtained, with very small *rms* error.

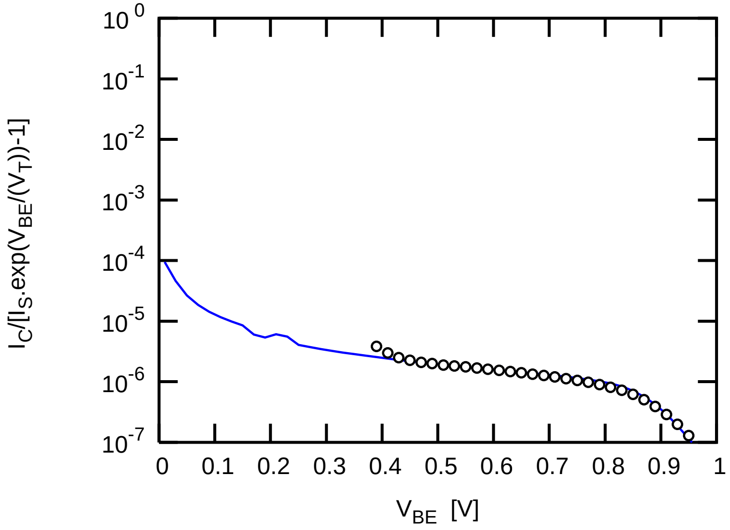


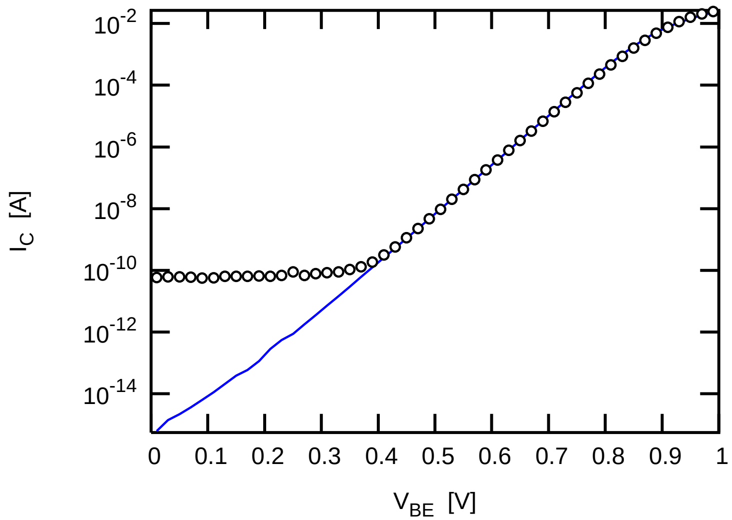


Global optimization

- But in fact we fell in the HICUM's black hole







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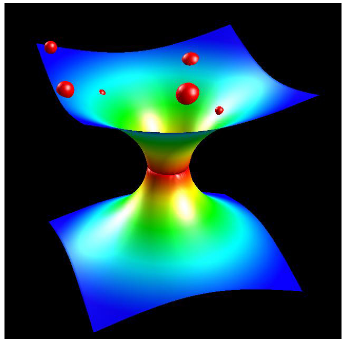
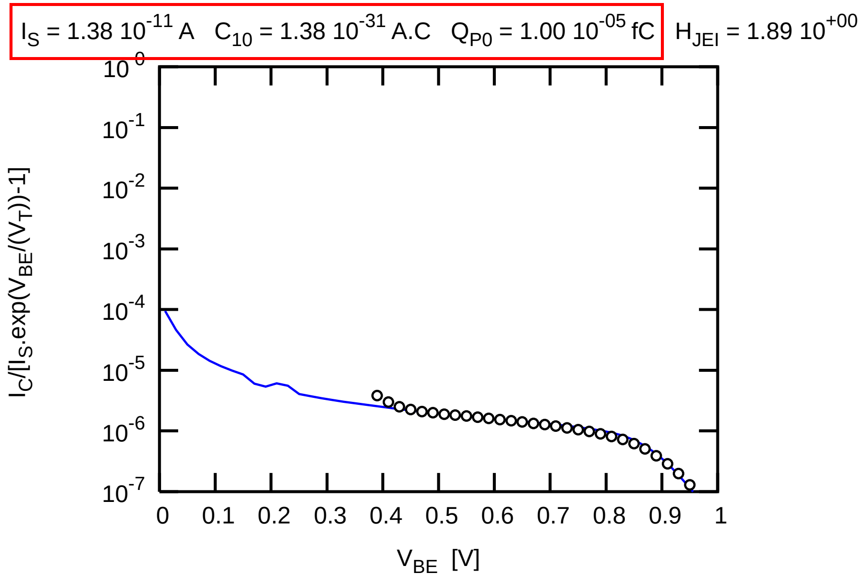
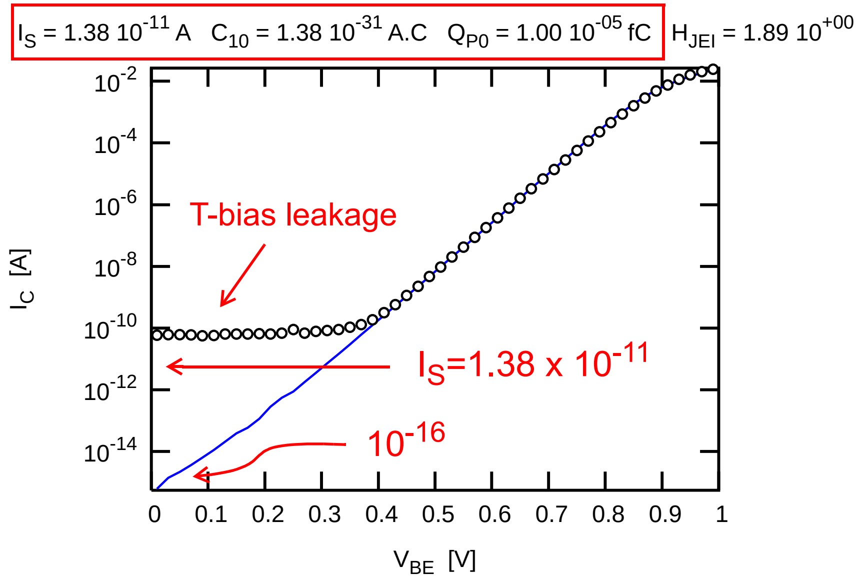




- A terrible trap for modeling engineers
  - **Physics based model**
  - **Very good fit**
  - **Unphysical model parameters**
  - **$Q_{P0} = 10^{-20}$ underestimated**
  - **I_S overestimated**

$$I_S = \frac{C_{10}}{Q_{P0}} = \mathbf{1.38 \times 10^{-11} A}$$



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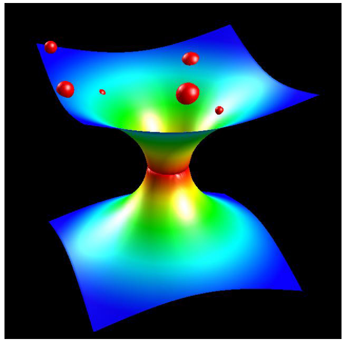

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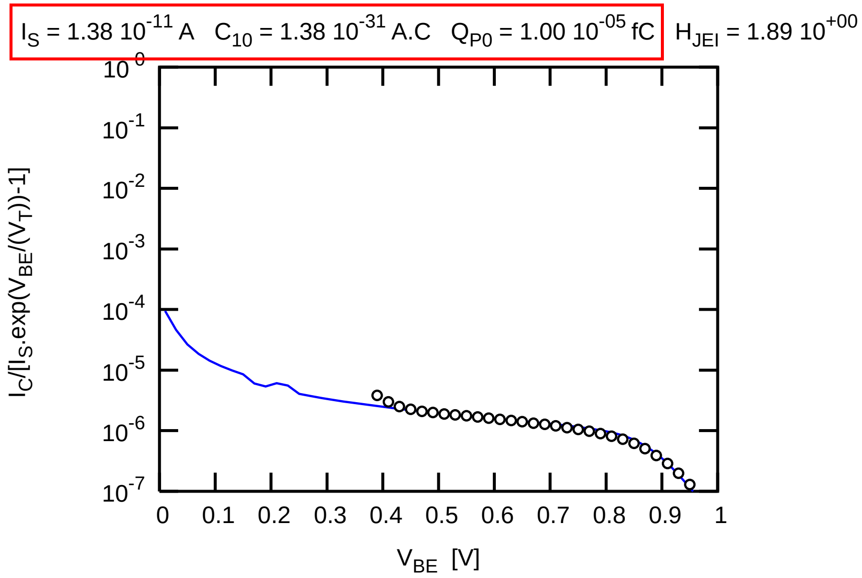
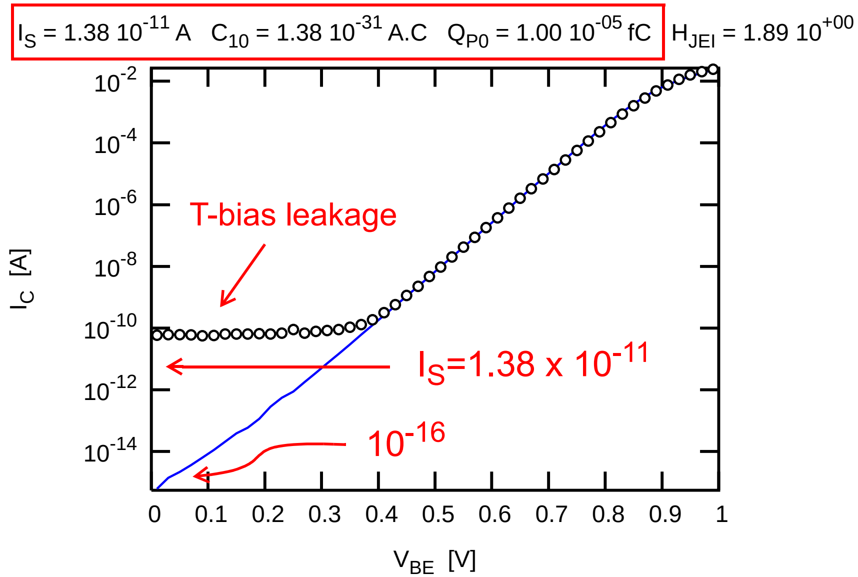
- How to avoid this trap?



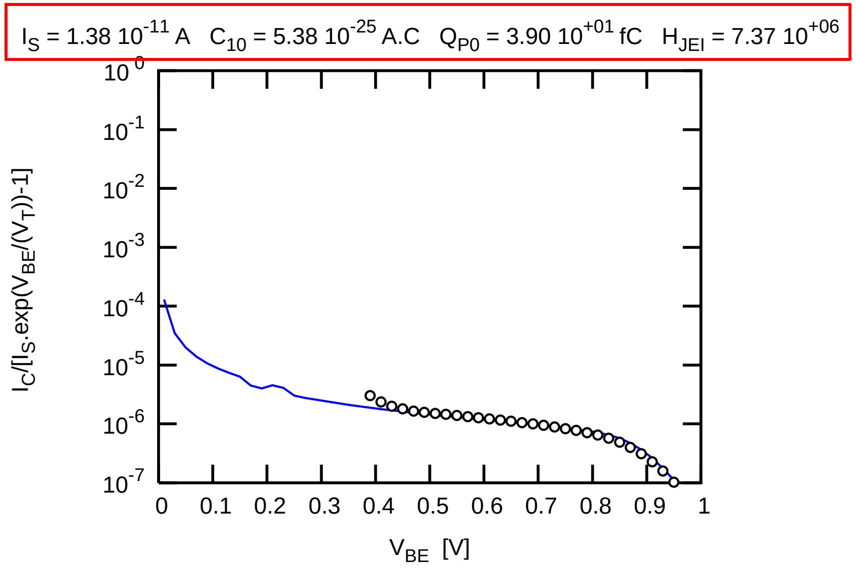


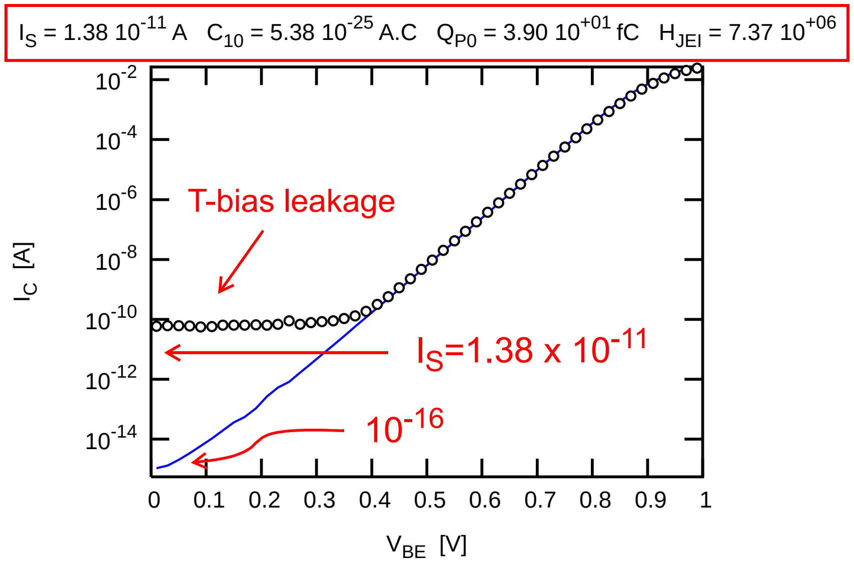
Other trials

- As Q_{P0} was underestimated, Q_{P0} is now fixed to the value deduced from tetrode measurement, as suggested by TuD, (Q_{P0} = 39 fC) and only C_{10} and H_{JEI} are optimized

- Same anomaly
  - **Physics based model**
  - **Very good fit**
  - **Unphysical model parameters**
  - **Same C_{10}/Q_{P0} and H_{JEI}/Q_{P0} ratios**
  - **I_S overestimated**

$$I_S = \frac{C_{10}}{Q_{P0}} = \mathbf{1.38 \times 10^{-11} A}$$



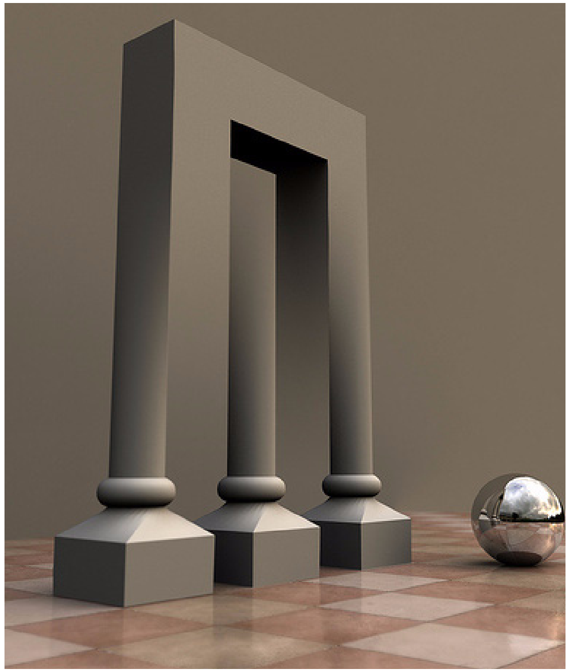


Explanation

- Why global optimization fails?
- C_{10}, Q_{P0}, H_{JEI} are optimized from the semi-normalized collector current I_C over $\exp(V_{BE}/V_T)$ at low and medium current densities and V_{BC} = 0V

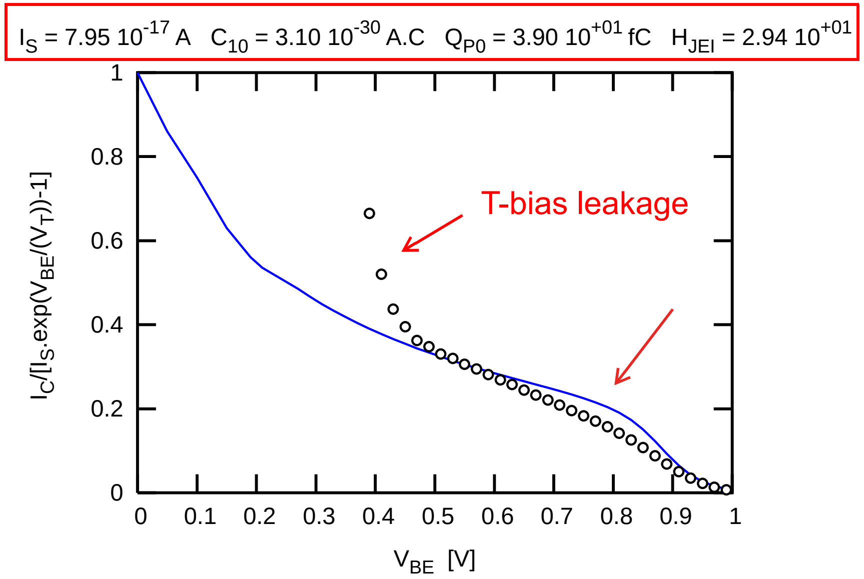
$$\bullet \quad \frac{I_C}{e^{\frac{V_{BE}}{V_T}}} = \frac{C_{10}}{Q_{P0} + H_{JEI} \cdot Q_{JEI}} = \frac{\frac{C_{10}}{Q_{P0}}}{1 + \frac{H_{JEI}}{Q_{P0}} \cdot Q_{JEI}} = \frac{\mathbf{A}}{1 + \mathbf{B} \cdot Q_{JEI}}$$

- Global optimization will give only the ratio **A** = C_{10}/Q_{P0} and **B** = H_{JEI}/Q_{P0}, with the impossibility to distinguish C_{10} from Q_{P0} and H_{JEI} from Q_{P0} (2 equations, 3 variables)
- This is confirmed from the trials we have done, an infinity of C_{10}, Q_{P0}, H_{JEI} parameters can be found given the same accuracy (but with non-physical parameters) if the ratios **A** and **B** are preserved.
- We hope that this *ambiguity* will be remove in the future HICUM/L2 releases. Solutions are possible [6], [7].



Other trials

- As an unphysical value is obtained for I_S, now I_S is fixed (y-intercept, 79.5 aA), Q_{P0} is also fixed to the value deduced from tetrode measurement (Q_{P0} = 39 fC) and only H_{JEI} is optimized
  - C_{10} is automatically calculated from $C_{10} = I_S.Q_{P0}$



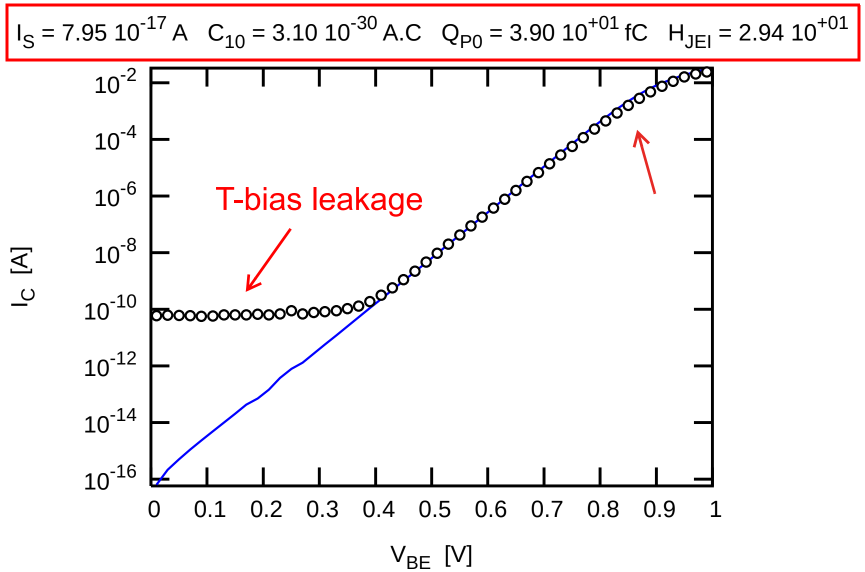
- And now?
  - **Physics based model**
  - **Physical parameters**

    I_S = 79.5 aA

    $C_{10} = 3.1 \times 10^{-30}$ A.C

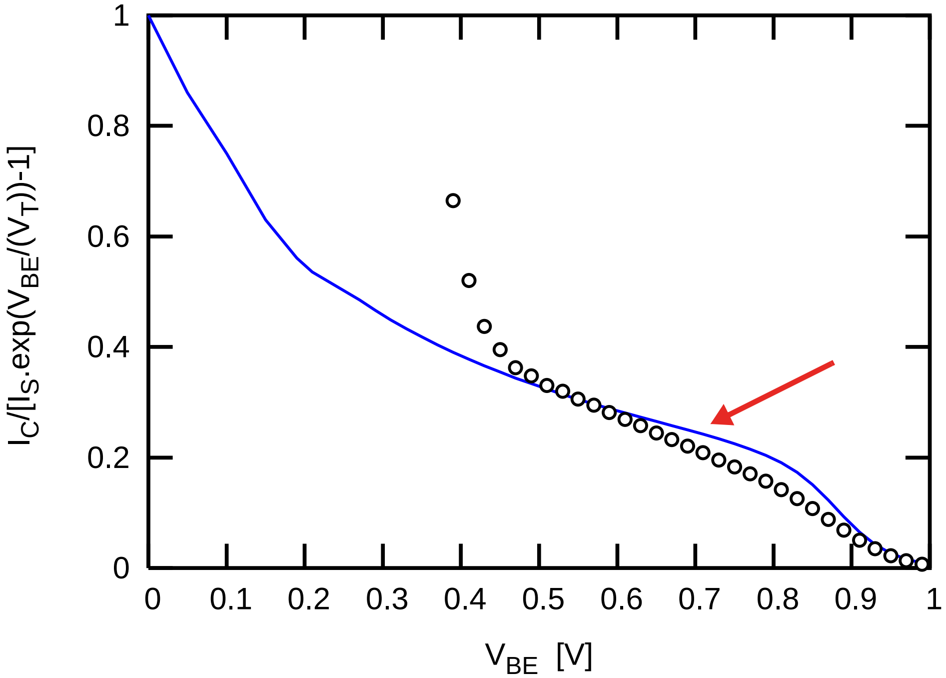
    Q_{P0} = 39 fC

    H_{JEi} = 31.1
  - **Poor accuracy, especially where the transistor will be used (around the f_T peak)**



Conclusion

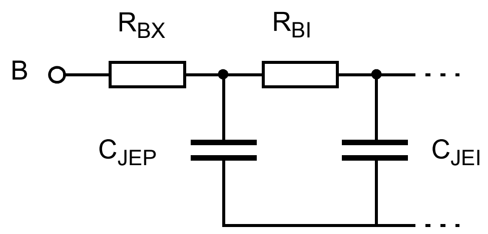
- For advanced HBTs like DOTFIVE devices, the collector current cannot be accurately reproduced with physics based parameters (C_{10}, Q_{P0}, H_{JEI}) using HICUM/L2.
- Before the availability of new HICUM release, workarounds must be found to solve this important model issue.
- The slope of the normalized collector current is too small.



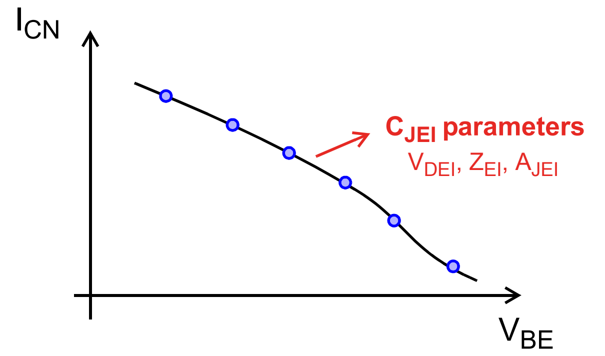
- How to improve (increase) the slope of the normalized collector current?
- 2 possibilities
  - Play withe the charges Q_{JEI}
  - Play with the non-ideality factor M_{CF}

First workaround

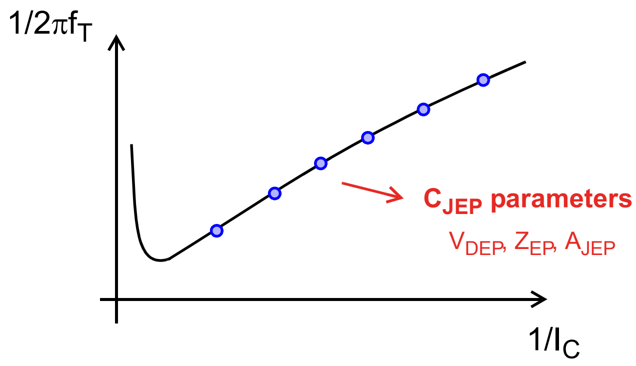
- The principle was first suggested by Z. Huszka [5]
- Use the fact that the BE junction capacitance can be splitted in 2 parts (Intrinsic C_{JEI} and extrinsic C_{JEP})



- C_{JEI} and its associated parameters are used for modeling the $I_C(V_{BE})$ characteristic at low current densities



- C_{JEP} and its associated parameters are used for modeling the f_T characteristic at low current densities

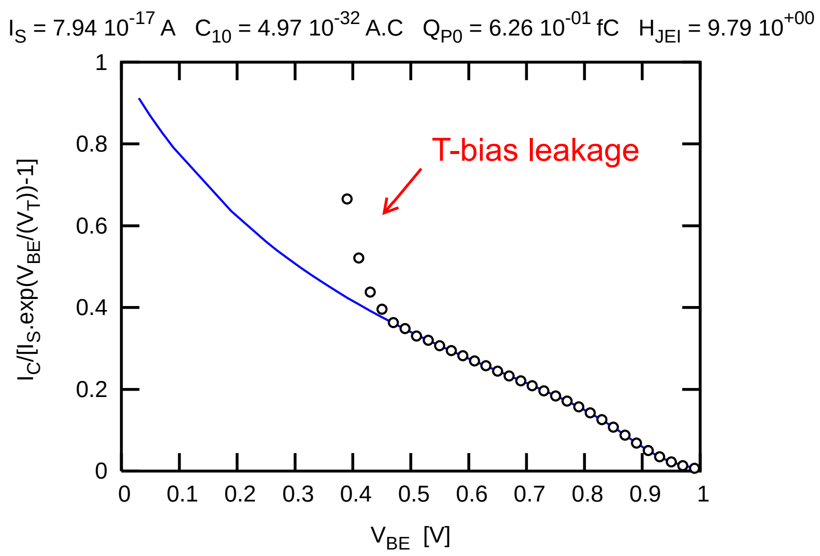


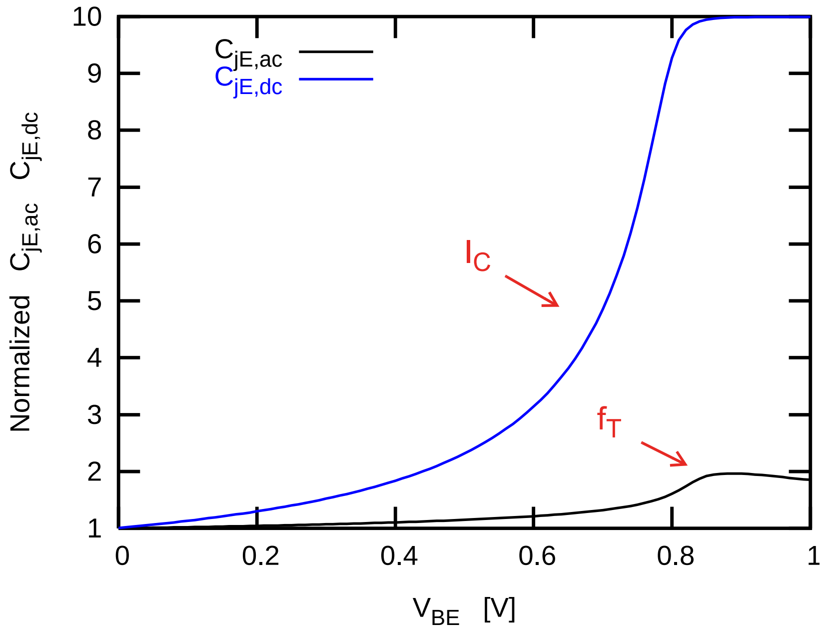
- For that C_{JEI0} must be fixed to a small value in order that the DC capacitance parameters of C_{JEI} do not affect the f_T characteristics

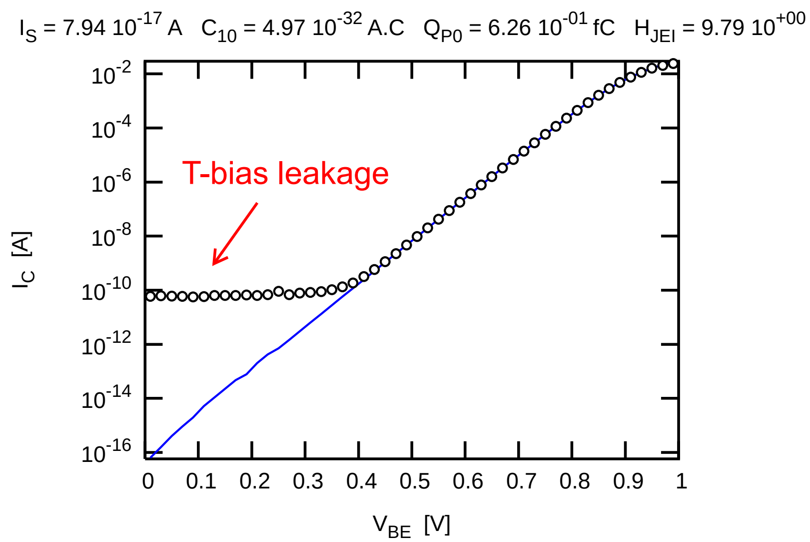
$$\begin{cases} C_{JEI0} = 0.1 \times C_{JE0\_total} \\ C_{JEP0} = 0.9 \times C_{JE0\_total} \end{cases}$$

First workaround

- Very accurate results are obtained with phisical model parameters
- Today used in all ST model libraries
- Possible limitation (f_{max} modeling): R_{BI} must be small, that is the case today for our advanced HBTs. Still valid for THz devices?



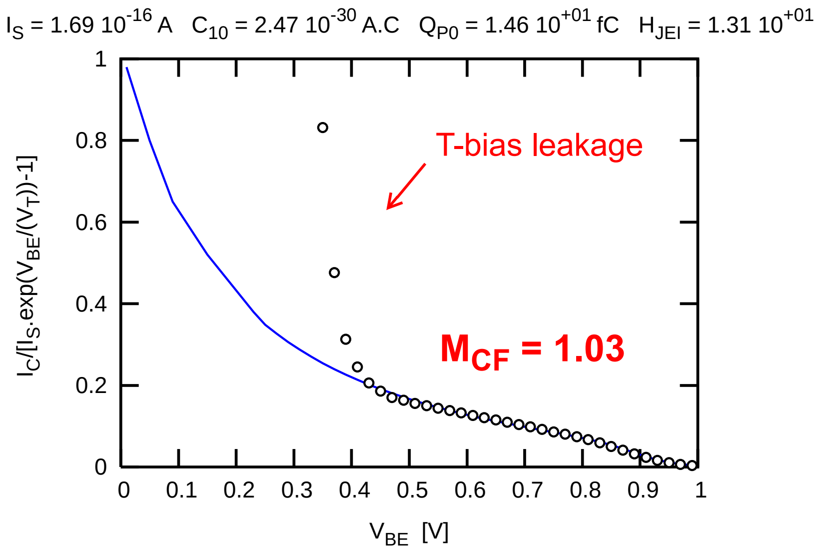




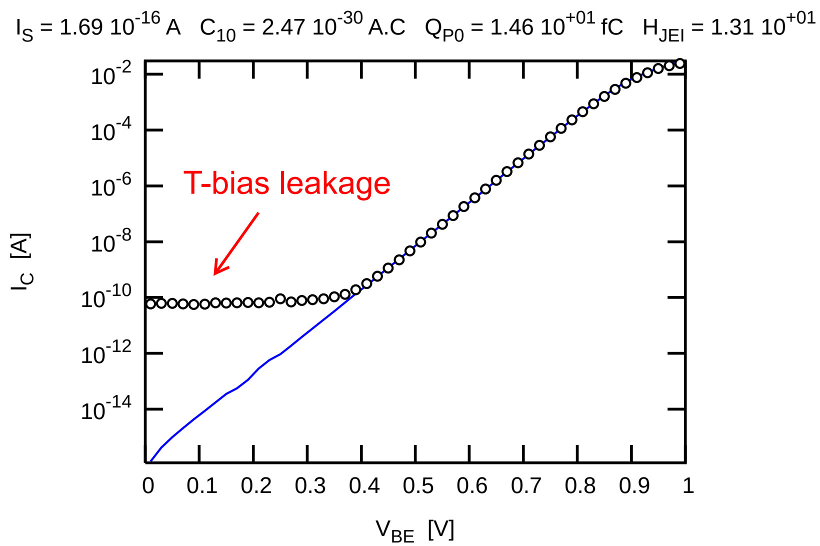
Second workaround

- The second possibility to improved (increase) the slope of the semi-normalized collector current is to introduce the non-ideality factor M_{CF}

  - $$I_C = \frac{C_{10}\cdot e^{\frac{V_{BE}}{\mathbf{M_{CF}}\cdot V_T}}}{Q_{P0}+H_{JEI}\cdot Q_{JEI}} \Leftrightarrow \frac{I_C}{e^{\frac{V_{BE}}{V_T}}} = \frac{C_{10}\cdot e^{\frac{V_{BE}}{V_T}\left\{\frac{1}{\mathbf{M_{CF}}}-1\right\}}}{Q_{P0}+H_{JEI}\cdot Q_{JEI}}$$



- Global optimization of C_{10}, Q_{P0}, H_{JEI}, M_{CF} at low and medium current densities (V_{BE} = 0.45-0.85 V)
  - Medium currents allow to determine Q_{P0} (transit time parameters known).
  - Low current densities allow to determine $C_{10,}$ H_{JEI}, M_{CF}
  - Very good accuracy as with workaround 1, but with a different set of model parameter (C_{10}, Q_{P0}, H_{JEI})
  - Q_{P0} closer than tetrode measurement (but not mandatory)
  - I_S (C_{10}/Q_{P0}) similar.
  - **Warning:** *in order to avoid an offset on the $I_C(V_{CE})$ characteristics at I_C=0, M_{CR} parameter* ***MUST*** *be set to M_{CF}. Unfortunately this parameter does not exist in HICUM/L2*



Comments

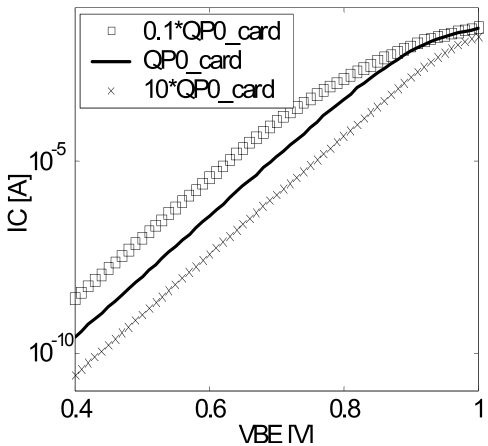
- Despite these 2 workarounds solve the limitations of HICUM/L2 v2.24, for advanced multi-100GHz SiGe HBTs, at room temperature,
- unfortunately, the temperature dependence issue of the collector current (critical for bandgap applications) is not solved with these approaches [6], [7].
- Other workarounds are needed in order to make H_{JEI} (workaround 1) or M_{CF} (workaround 2) temperature dependent
  - Temperature laws (quadratic law with 2 TCs) described outside the model using simulator script

Summary

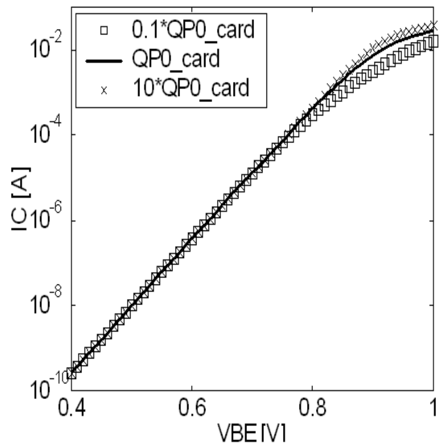
- For HICUM/L2, the coupling between C_{10}, Q_{P0}, H_{JEI} is a Nightmare for modelling engineers and still an issue for reliable (physical and accurate) parameter extraction.

- A solution was proposed at the last HICUM WS to overcome this problem [6]

Old formulation - strong impact of Q_{P0}



New formulation - impact of Q_{P0} only at high currents

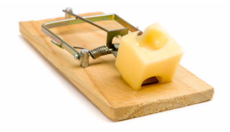


- Strong limitations of HICUM/L2 v2.24 for modeling advanced SiGe HBT's

- Workaround are proposed to solve these problems at room temperature but still exist at other temperatures

Summary

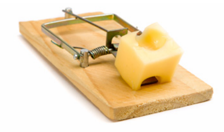
- New official HICUM/L2 release *will have to take into account all these limitations with minimizing all extraction*



- Solutions were presented at the last HICUM WS [6], [7], [8]

- In the meantime, daily modeling engineer activities will still look like this...

Summary

- New official HICUM/L2 release *will have to take into account all these limitations with minimizing all extraction* 
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References

[1] M. Schröter, A. Chakravorty, "*Compact Hierarchical Bipolar Transistor Modeling with HICUM*", World Scientific, Singapore, ISBN 978-981-4273-21-3, 2010.

[2] *http://www.dotfive.eu/*

[3] D. Berger, D. Céli, M. Schröter, M. Malorny, T. Zimmer, B. Ardouin, "*HICUM Parameter Extraction Methodology for Single Transistor Geometry*", proceedings of the BCTM, pp. 116-119, September 2002.

[4] Y. Getreu, "*Modeling the Bipolar Transistor*", Tektronic.Inc, PP. 166-168, 1979.

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