How to Avoid HICUM/L2 v2.24 ?

Application to low collector current parameter extraction at room temperature

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Outline

- Introduction
- Direct extraction of low collector current parameters at room temperature
- The dangers of global optimization
- Possible workarounds
- Summary
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 $C_{10}$, $Q_0$, $H_{JEI}$ (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. $C_{10}$ and $Q_{P0}$ extraction assuming $H_{JEI}=1$
BE Junction capacitance parameter extraction

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

\[
C_{\text{JBE}} = \frac{\text{Im}(Y_{11e} + Y_{12e})}{\omega}
\]

• The parasitic capacitances \( C_{\text{PE}} \) (backend and spacer capacitances) are determined from CAD tools.

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

\[
\ln(C_{\text{meas}} - C_{\text{PE}}) = \ln(C_{\text{JE0}} \cdot V_{\text{DE}}^{Z_E}) - Z_E \cdot \ln(V_{\text{DE}} - V_{\text{BE}})
\]

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

\[
\begin{align*}
Z_E &= -\text{slope} \\
C_{\text{JE0}} &= e^{\frac{\text{intercept}}{Z_E}} V_{\text{DE}}
\end{align*}
\]
Very accurate $C(V)$ curve is obtained with the extracted parameters

- $C_{JEI0} = 2.03 \times 10^{+01} \text{ fF}$
- $V_{DEI} = 0.78 \text{ V}$
- $Z_{EI} = 0.15$
- $A_{JEI} = 2.00$
- $C_{BEPAR} = 0.00 \text{ fF}$
- $C_{PE} = 5.39 \text{ fF}$
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 $C_{JE_A}$ is the same for the area and peripheral parts.
- The split of the BE junction capacitance can be then defined by

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

that leads to

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

- Application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_j$ (nm)</td>
<td>17.1</td>
</tr>
<tr>
<td>$L_E$ (µm)</td>
<td>9.86</td>
</tr>
<tr>
<td>$W_E$ (µm)</td>
<td>0.13</td>
</tr>
<tr>
<td>$X_{JBE}$</td>
<td>0.705</td>
</tr>
<tr>
<td>$C_1$ (fF)</td>
<td>14.29</td>
</tr>
<tr>
<td>$C_2$ (fF)</td>
<td>5.98</td>
</tr>
</tbody>
</table>
Expression of the collector current at low current densities and $V_{BC} = 0V$

\[ I_C \approx I_{TF} \approx \frac{C_{10} \cdot e}{Q_{P0} + H_{JEI} \cdot Q_{JEI}} \]  

(1)

**Extraction strategy**

- From (1) we can write

\[ Q_{P0} + H_{JEI} \cdot Q_{JEI} = C_{10} \cdot \frac{e}{I_C} \]  

and finally

\[ Q_{JEI} = C_{10} \cdot \frac{e}{I_C} - \frac{Q_{P0}}{H_{JEI}} \]  

(2)

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

\[ Q_{JEI} = \int_0^{V_{BE}} C_{JEI}(V)dV \]  

which gives after integration

\[ Q_{JEI} = C_{JE0} \cdot \left\{ \frac{V_{DEI}}{1 - Z_{EI}} \cdot \left[ 1 - \left( 1 - \frac{V_j}{V_{DEI}} \right)^{1 - Z_{EI}} \right] + A_{JE} \cdot (V_{BE} - V_j) \right\} \]

where the auxiliary voltage $V_j$ is equal to $V_{BE}$ in reverse and low forward bias.
**C\textsubscript{10} and Q\textsubscript{P0} parameter extraction**

- Therefore, from (2), at low current densities, the internal BE depletion charge $Q\textsubscript{JEI}$ vs. the quantity $\frac{V\textsubscript{BE}}{V\textsubscript{T}}/I\textsubscript{C}$ is linear.

- The *slope* allows to determine $C\textsubscript{10}/H\textsubscript{JEI}$ and the *intercept* $Q\textsubscript{P0}/H\textsubscript{JEI}$.

**First**

- Despite $H\textsubscript{JEI}$ affect $I\textsubscript{C}$ at low-medium current densities (equation (1)), to our knowledge, $H\textsubscript{JEI}$ can not be determined in this range of currents. As consequence, only the ratios $C\textsubscript{10^*}=C\textsubscript{10}/H\textsubscript{JEI}$ and $Q\textsubscript{P0^*}=Q\textsubscript{P0}/H\textsubscript{JEI}$ 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 $Q\textsubscript{P0}$ value (y intercept). Therefore the saturation current $I\textsubscript{S}=C\textsubscript{10}/Q\textsubscript{P0}$ cannot be determined.
Results

- Direct extraction gives negative $Q_{P0}$ value

\[
I_S = 4.51 \times 10^{-16} \text{ A} \quad C_{10} = 5.18 \times 10^{-31} \text{ A.C} \quad Q_{P0} = -1.15 \times 10^{+00} \text{ fC} \quad H_{JEI} = 1.00 \times 10^{+00}
\]
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 $V_{BC} = 0V$
  - $T_0$ (low current transit time) and emitter resistance extracted in previous step.
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 $V_{BC} = 0\text{V}$
  - To (low current transit time) and emitter resistance extracted in previous step.

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

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

\[
I_C/[I_S \exp(V_{BE}/(kT))-1]
\]

\[
V_{BE} [V] = 1.38 \times 10^{-11} \text{A}
\]

\[
C_{10} = 1.38 \times 10^{-31} \text{A.C}
\]

\[
Q_{0} = 1.00 \times 10^{-5}
\]

\[
H_{J_{EI}} = 1.89 \times 10^{00}
\]
Global optimization

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

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

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

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

- A terrible trap for modeling engineers
  - Physics based model
  - Very good fit
  - Unphysical model parameters
  - \( Q_P = 10^{-20} \) underestimated
  - \( I_S \) overestimated
  \[ I_S = \frac{C_{10}}{Q_{P0}} = 1.38 \times 10^{-11} \text{A} \]
- How to avoid this trap?
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

\[ I_S = \frac{C_{10}}{Q_{P0}} = 1.38 \times 10^{-11} \text{A} \]
Why global optimization fails?

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

- Global optimization will give only the ratio $A = C_{10}/Q_{P0}$ and $B = H_{JEl}/Q_{P0}$, with the impossibility to distinguish $C_{10}$ from $Q_{P0}$ and $H_{JEl}$ from $Q_{P0}$ (2 equations, 3 variables).

- This is confirmed from the trials we have done, an infinity of $C_{10}$, $Q_{P0}$, $H_{JEl}$ 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 removed in the future HICUM/L2 releases. Solutions are possible [6], [7].

\[
\frac{I_C}{e^{V_{BE}/V_T}} = \frac{C_{10}}{Q_{P0} + H_{JEl} \cdot Q_{JEl}} = \frac{C_{10}}{Q_{P0}} \cdot \frac{1}{1 + \frac{H_{JEl}}{Q_{P0}} \cdot Q_{JEl}} = A + B \cdot Q_{JEl}
\]
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 $C_{10} = I_S \cdot Q_{P0}$

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)
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 with the charges $Q_{JEI}$
- Play with the non-ideality factor $M_{CF}$
The principle was first suggested by Z. Huszka [5]

Use the fact that the BE junction capacitance can be split into 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

\[
\begin{align*}
C_{JEI0} &= 0.1 \times C_{JE0\_total} \\
C_{JEP0} &= 0.9 \times C_{JE0\_total}
\end{align*}
\]
First workaround

- Very accurate results are obtained with physical model parameters
- Today used in all ST model libraries
- Possible limitation ($f_{\text{max}}$ modeling): $R_{BI}$ must be small, that is the case today for our advanced HBTs. Still valid for THz devices?
The second possibility to improve (increase) the slope of the semi-normalized collector current is to introduce the non-ideality factor $M_{CF}$:

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

- 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.
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 $H_{JE1}$ (workaround 1) or $M_{CF}$ (workaround 2)
temperature dependent

- Temperature laws (quadratic law with 2 TCs) described outside the model using simulator script
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...
New official HICUM/L2 release will have to take into account all these limitations with minimizing all extraction.

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


