4th European HICUM Workshop

HICUM Model and Scaling Laws Issues

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HICUM Model and Scaling Laws Issues

HICUM Model Issues

- Temperature dependence of the base current.
- Temperature dependence of the neutral emitter storage time.
- Temperature dependence of the zero bias hole charge.
- Temperature dependence of the low-current forward transit time.
- Bump on $I_C(V_{CE})$ characteristics in saturation region.
- Effect of the reverse transit time T_R.
- HICUM implementation issues in cicuit simulators.
- Status of HICUM Level 0.

HICUM Scaling Laws (or Parameter Extraction) Issues

- Split of the BE junction capacitance.
- Split of the BC junction capacitance.
- Weak avalanche current.
- Forward transit time for small devices.

HICUM Model Issues

Temperature Dependence of the Base Current.

- The HICUM temperature dependence of the base saturation current I_{BS} is derived from the temperature dependence of the saturation current I_S and of the forward current gain B_F as follows

$$I_{BS}(T) = \frac{I_S(T)}{B_F(T)}$$

In HICUM (version 2.1) the temperature dependence of I_S is similar to the one of the SGP model with $X_{TI} = 3$.

On the other hand, the temperature dependence of B_F is linear with the temperature

$$B_F(T) = B_F(T_0) \cdot (1 + A_{LB} \cdot (T - T_0))$$

This formulation is too simple and not physical, as shown in the next section.

Finally, the temperature dependence of the base saturation current can be written (non ideality factor assumed to be equal to 1)

$$\boxed{I_{BS}(T) = I_{BS}(T_0) \cdot \left(\frac{T}{T_0}\right)^{A_{CT}} \cdot \exp\left\{\left(\frac{V_{GB}}{V_{T0}} - T \cdot A_{LB}\right) \cdot \left(1 - \frac{T_0}{T}\right)\right\}}$$

with $A_{CT} = 3$ in HICUM version 2.1.

- More physics based formulation of the forward current gain temperature dependence

As the forward current gain is proportional to $e^{-\frac{\Delta_{VG}}{V_T}}$, where Δ_{VG} is the difference between the bangap voltage in the base and in the emitter, $\Delta_{VG} = V_{GB} - V_{GE}$, its temperature dependence can be written

$$B_F(T) = B_F(T_0) \cdot \exp\left\{\frac{\Delta_{VG}}{V_{T0}} \cdot \left(1 - \frac{T_0}{T}\right)\right\} \text{ or } B_F(T) = B_F(T_0) \cdot \exp\left\{A_{LB} \cdot \left(1 - \frac{T_0}{T}\right)\right\} \text{ with } A_{LB} = \frac{\Delta_{VG}}{V_{T0}}$$

Therefore, the temperature dependence of the base saturation current can be written (non ideality factor assumed to be equal to 1)

$$\boxed{I_{BS}(T) = I_{BS}(T_0) \cdot \left(\frac{T}{T_0}\right)^{A_{CT}} \cdot \exp\left\{\left(\frac{V_{GB}}{V_{T0}} - A_{LB}\right) \cdot \left(1 - \frac{T_0}{T}\right)\right\}}$$

We can notice that this formulation is similar to the HICUM model, with $\mathbf{A_{LB}}$ instead of $\mathbf{T \cdot A_{LB}}$.

✓ Suggested model

- In order to have a more physics based temperature dependence of the base current, and to take into account both the temperature dependence of the base and emitter Gummel numbers

$$B_F(T) = \frac{N_{GE}(T)}{N_{GB}(T)}$$

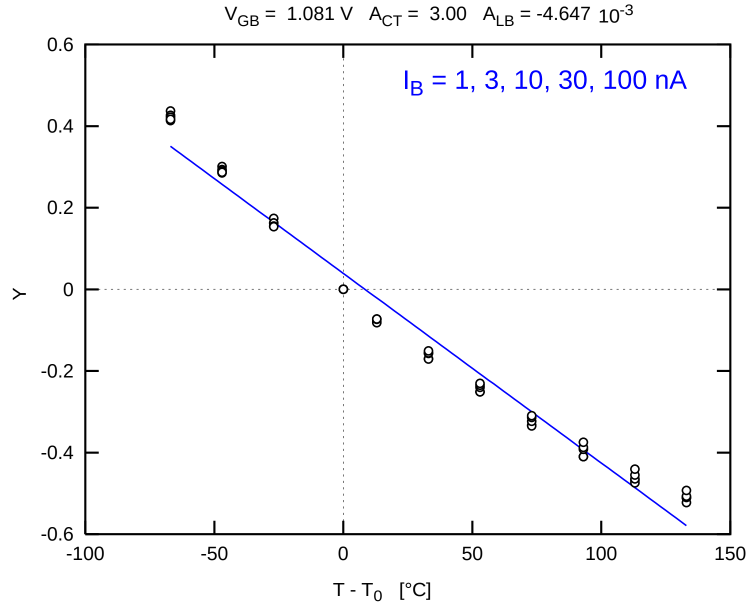
we suggest to use the following model which is in fact already implemented in other BJT models like VBIC or MEXTRAM

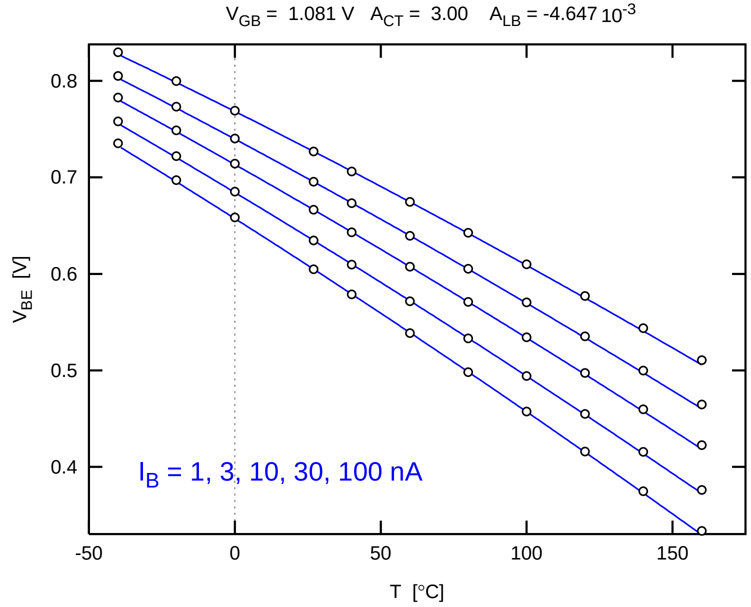
$$B_F(T) = B_F(T_0) \cdot \left(\frac{T}{T_0}\right)^{\mathbf{A_{BT}}} \cdot \exp\left\{\mathbf{A_{LB}} \cdot \left(1 - \frac{T_0}{T}\right)\right\}$$

- The temperature dependence of the base saturation current can, in this case, be written (non ideality factor assumed to be equal to 1)

$$\boxed{I_{BS}(T) = I_{BS}(T_0) \cdot \left(\frac{T}{T_0}\right)^{\mathbf{A_{CT}} - \mathbf{A_{BT}}} \cdot \exp\left\{\left(\frac{V_{GB}}{V_{T0}} - \mathbf{A_{LB}}\right) \cdot \left(1 - \frac{T_0}{T}\right)\right\}}$$

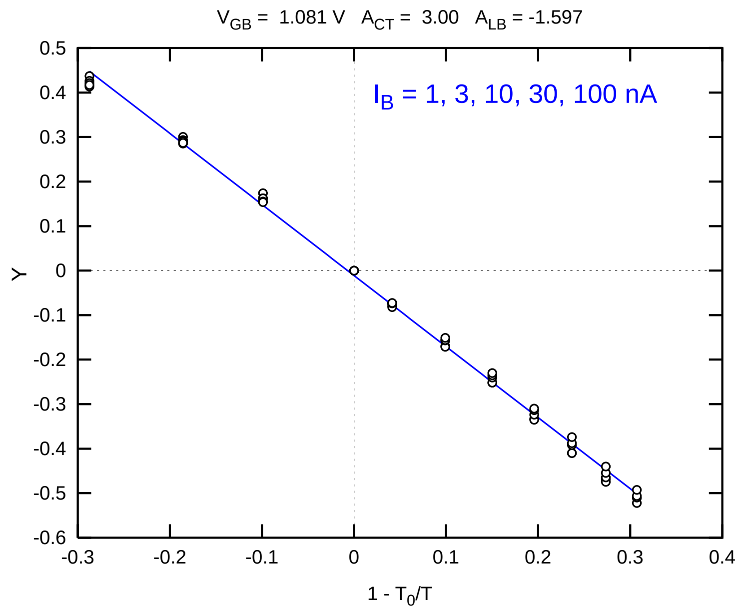
- Validation on experimental results

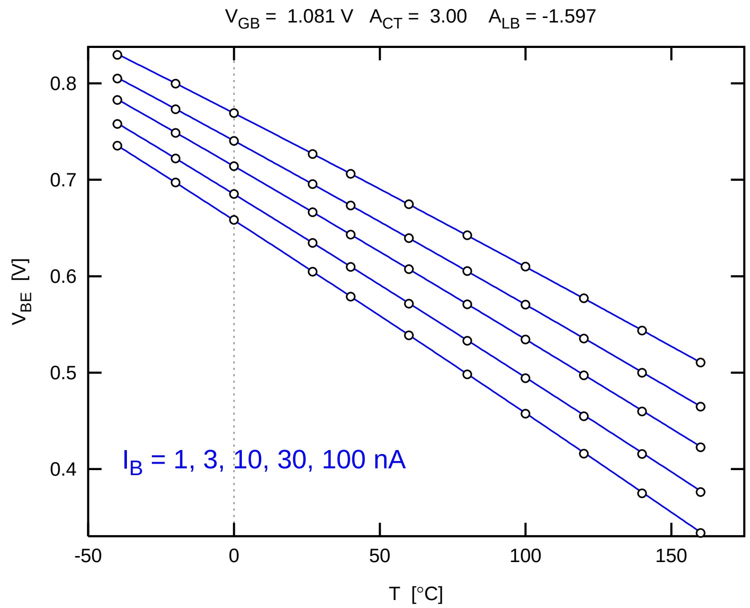




HICUM Version 2.1

Deviation greater than 5mV at extreme temperatures





Proposed Model with $A_{BT} = 0$

Deviation lower than 1.5mV in all the temperature range

Temperature Dependence of the Neutral Emitter Storage Time.

- The temperature dependence of the neutral emitter storage time T_{EF0} is given by

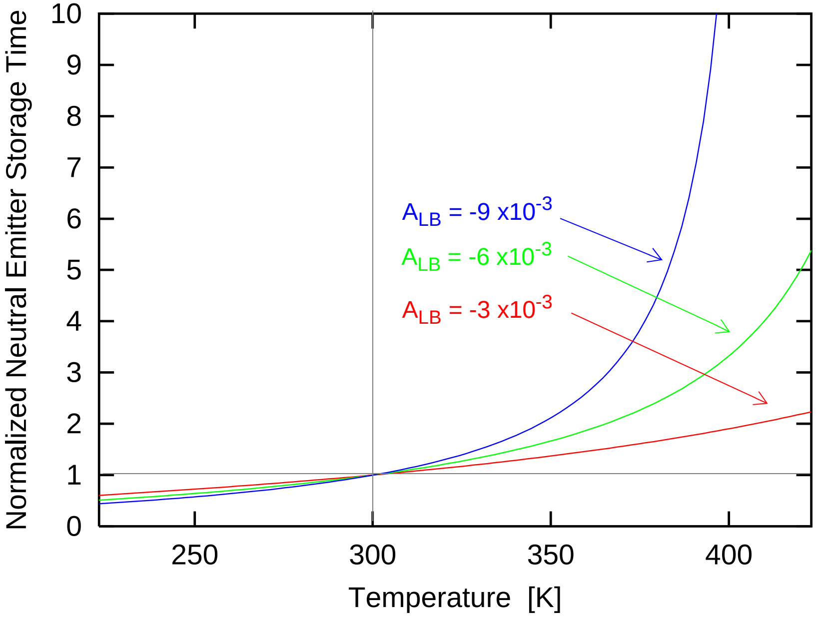
$$T_{EF0}(T) = T_{EF0}(T_0) \cdot \frac{T/T_0}{1 + (A_{LB} \cdot (T - T_0))}$$

There is a numerical issue when $A_{LB} \cdot (T - T_0) = -1$.

To overcome this issue, in HICUM the following expression is used

$$T_{EF0}(T) = T_{EF0}(T_0) \cdot \frac{T/T_0}{\frac{1 + A_{LB} \cdot (T - T_0) + \sqrt{(1 + A_{LB} \cdot (T - T_0))^2 + \mathbf{10^{-6}}}}{2}}$$

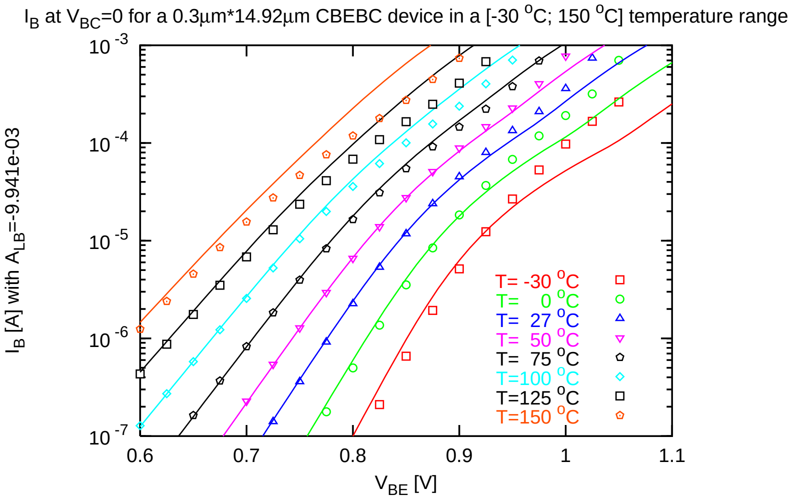
The smoothing function in the denominator avoids numerical problem at extreme temperatures (very low or high, depending on the sign of A_{LB} and on its value)

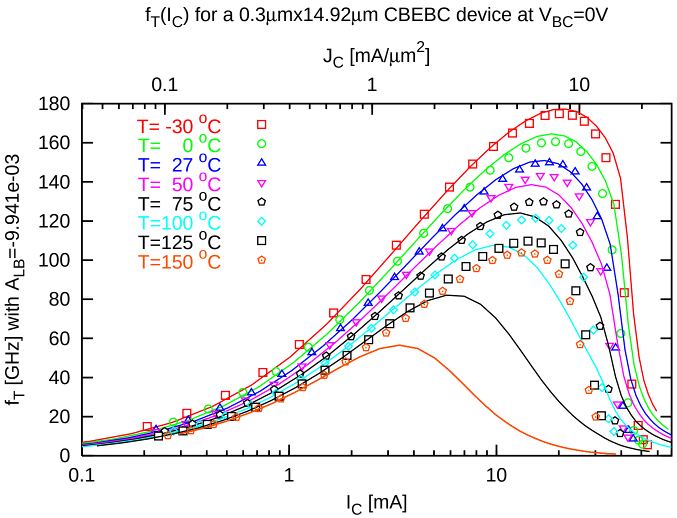


But, when the sign of $1 + A_{LB} \cdot (T - T_0)$ changes, the decrease of the smoothing function is too abrupt and T_{EF0} increases too rapidly. Consequently f_T decreases too much in comparison with measurements.

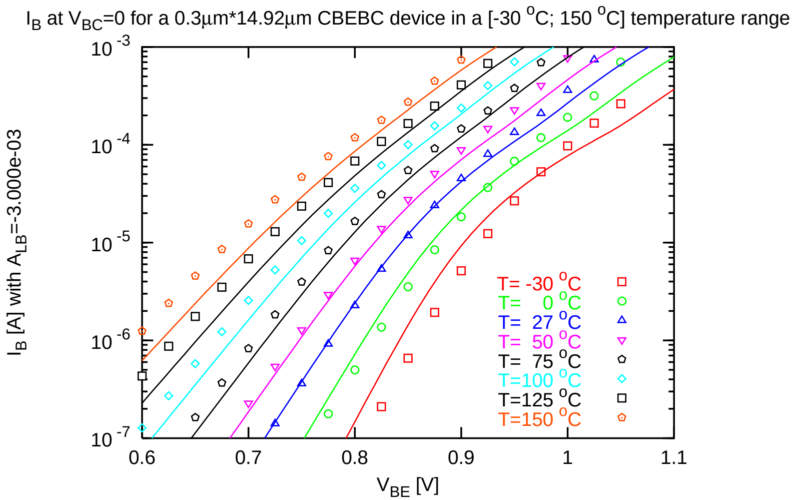
To solve this important issue, it is necessary to modify this smoothing function or to find a more physical law for the temperature dependence of T_{EF0} and perhaps, decouple the temperature dependence of T_{EF0} from the temperature dependence of the current gain.

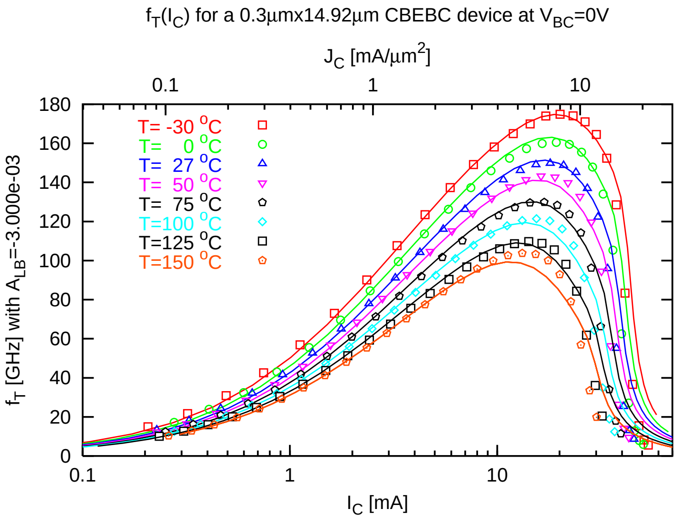
● Today, the only way to correct this issue is to alter the value of A_{LB}. In this case the temperature dependence of f_T is correct but not the one of the base current.





$A_{LB} = -9.94 \times 10^{-3}$





$A_{LB} = -3.00 \times 10^{-3}$

Temperature Dependence of the Zero Bias Hole Charge.

- In the formulation of the temperature dependence of Q_{P0} given by

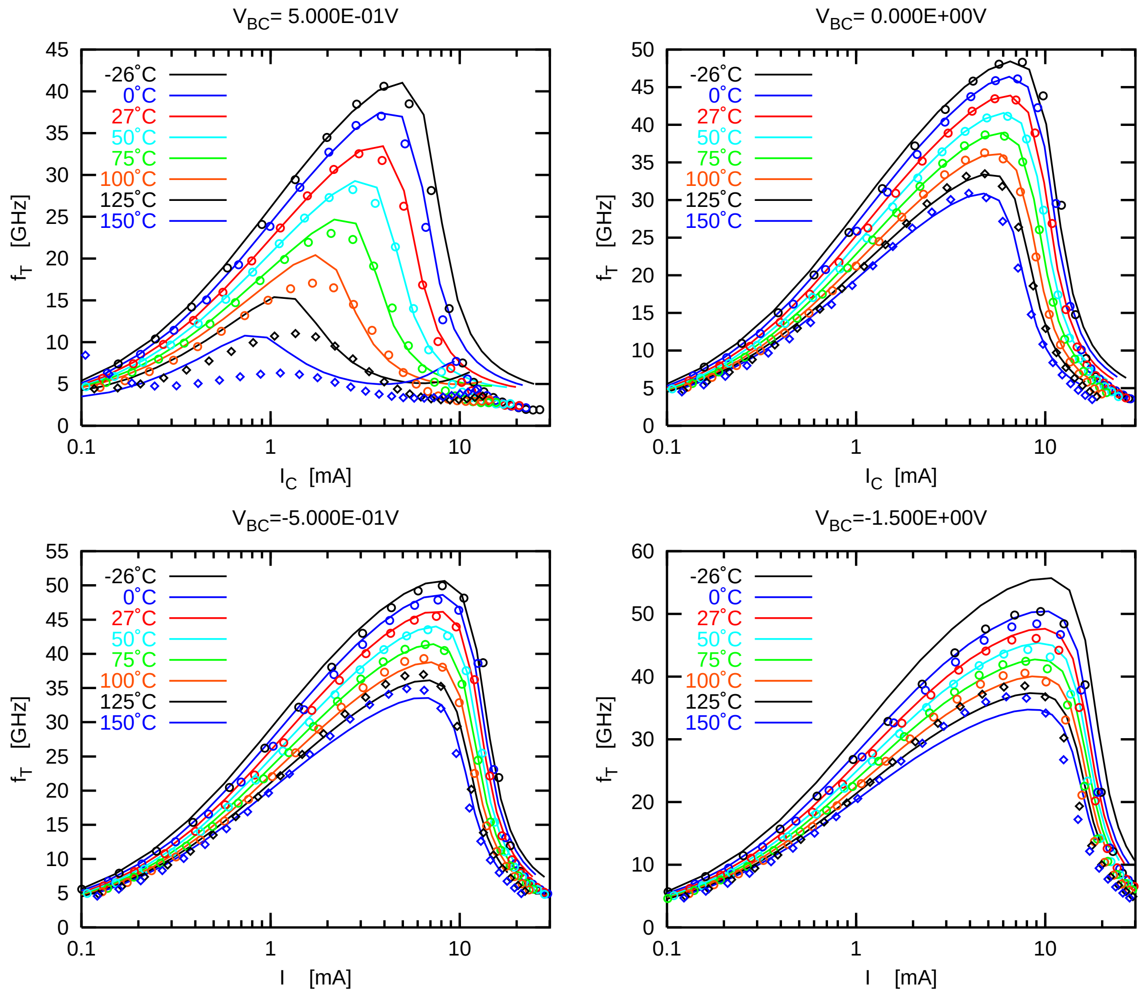
$$Q_{P0}(T) = Q_{P0}(T_0) \cdot \left[1 + \frac{Z_{EI}}{\mathbf{2}} \cdot \left\{1 - \frac{V_{DEI}(T)}{V_{DEI}(T_0)}\right\}\right]$$

the factor **2** is arbitrary.

A model parameter could be preferable, otherwise there is no way to alter the temperature dependence of Q_{P0}.

Temperature Dependence of the Low-Current Forward Transit Time.

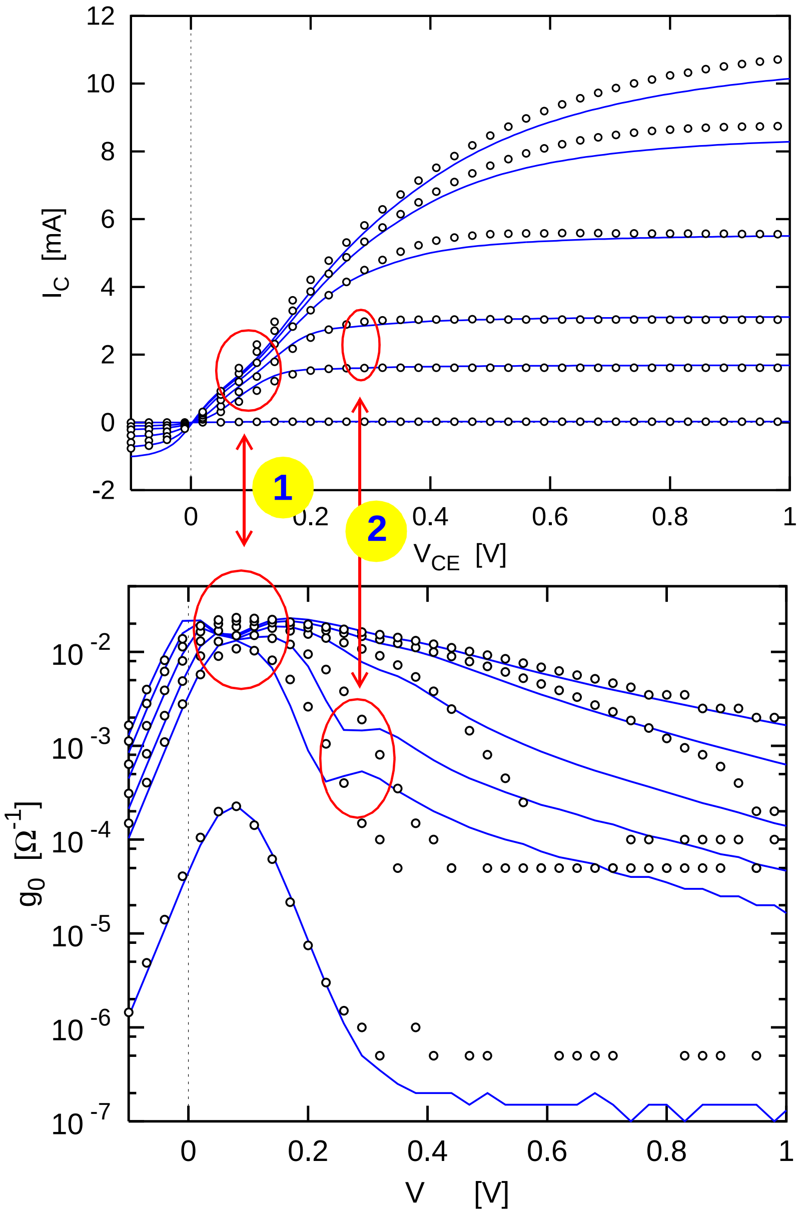
- In HICUM, only the low-current forward transit time at V_{BC}=0V, T_0, is temperature dependent. Experimentally, we notice a variation of D_{T0H} and T_{BVL} with the temperature. Is it an extraction issue or a limitation of HICUM?. To be investigated.



Self-heating included

← Model limitation or extraction issue?

Bump on $I_C(V_{CE})$ Characteristics in Saturation Region.



1 *'Bump'* in hard-saturation region, at medium and high current densities.

- Cannot be corrected by increasing V_{DCI} or/and V_{DCX}.
- The cause of this *'bump'* is not clearly identified. Is it due to a wrong combination of model parameters, or is it a limitation of the HICUM model for linking the quasi-saturation and saturation region?.
- To be analysed, which parameters are responsible of this *'bump'*.
- Could be affect the convergence of the model?.

2 *'Discontinuity'* in quasi-saturation region, at medium current densities.

- Can be corrected by increasing V_{DCI} or/and V_{DCX}.
- Nevertheless, an improvement of the formulation of the BC junction capacitance in forward mode would be better.
- Is it planned to modify the model equations?.

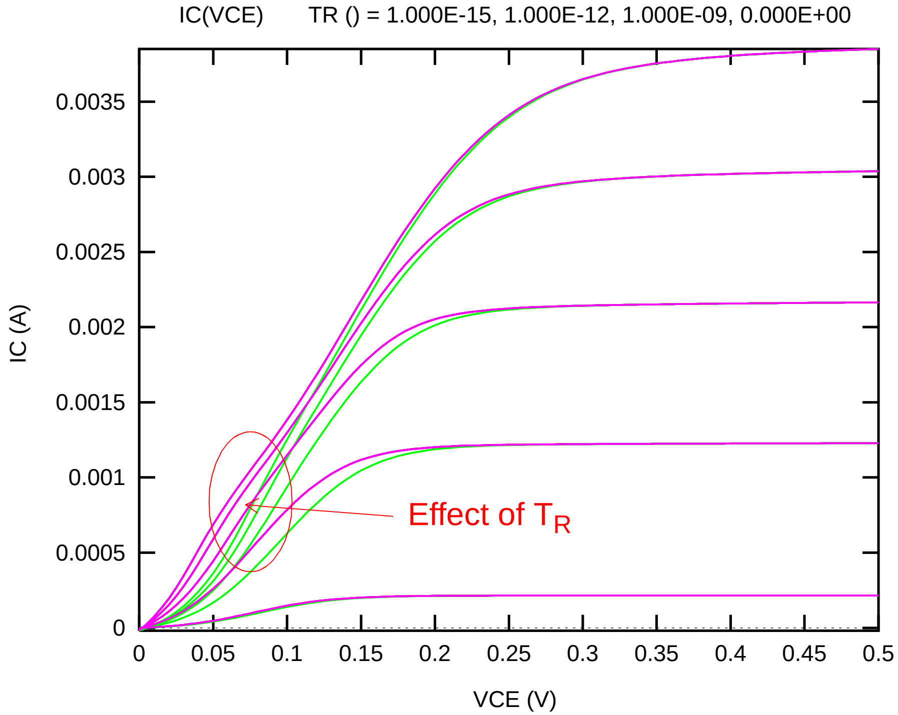
Effect of the Reverse Transit Time T_R

- Strange behaviour of the output characteristics in the saturation region when T_R parameter is specified:
  - $T_R = 0$ no effect on the output characteristics (it is natural)
  - If T_R is different of zero, important and same effects on the output characteristics whatever the value of T_R (1 fs, 1ps, 1 ns).
- Is it normal?
- Can we really use TR in HICUM?
- Some EDA vendors have modified the expression of the BC diffusion capacitance as follows

$$C_{DBC} = T_R \cdot \left.\frac{dI_{TR}}{dV_{CE}}\right|_{V_{BE}} \quad \text{instead of}$$

$$C_{DBC} = T_R \cdot \left.\frac{dI_{TR}}{dV_{CE}}\right|_{V_{BE}} + T_F \cdot \left.\frac{dI_{TF}}{dV_{CE}}\right|_{V_{BE}} \quad \text{(HICUM 2.1)}$$

- Is it justified?
- Is this modification have been done by all EDA vendors?
- HICUM code and documentation have to be updated.



HICUM Implementation Issues in Circuits Simulators

- For the first time (Q1 2004) we have delivered to design kit model libraries based on HICUM. The main supported circuit simulators being: ADS, APLAC, ELDO, HSPICE, SPECTRE...

- The feedback of internal and external customers were not good:
  - Too CPU time increase in comparison with STBJT model (SPICE Gummel-Poon model like including base push-out effect and BC breakdown...).
  - Important convergence issues in transient analysis and large signal simulations, especially with APLAC, ELDO and SPECTRE.

- Some CAD vendors provided *patches* solving these issues:
  - Correction of the *incomplete* or *wrong* derivatives (temperature, NQS effects...)
  - Modification of the HICUM equations (BC diffusion capacitance: T_F contribution removed, ...)

- Convergence and CPU time were improved (but not totally solved, simple CML ring oscillator still does not converge in some simulators), and now we ask the following questions:
  - Where is the reference code of HICUM?
  - Are we certain that all convergence issues are completely solved?.
  - Are we certain that all EDA vendors have made the same corrections (model equations, derivatives,...) and implemented the same code without new bugs?

- In order to answer all these questions, and to avoid these kind of issues in future (bad reputation for HICUM: very accurate model but unusable), we request to M. Schroter to become again the owner of the code, that is to say, we request a new HICUM version (version 2.1 dated December 2000 is now obsolete) that solve all these existing issues (code formulation and derivatives...).

- This work could be partially founded by the CMC and by companies supporting HICUM.

Status of HICUM Level 0.

- Maturity of the model, accuracy in comparison with HICUM Level 2.
- Status of the code: CPU time, convergence in comparison with HICUM Level 2.
- Implementation in circuit simulators: which ones, when?.
- ST request: to add the parasitic PNP substrate inside the model, otherwise it is not possible to accurately fit the output characteristics in the saturation region.
  A solution could be the use of a sub-circuit, but lower CPU time (more node to be solve) and possible convergence issue (all parameters of the parasitic PNP not defined).

HICUM Scaling Laws Issues

Split of the BE junction capacitance

- Depending on the process and on the architecture of the device, the scaling laws used in TRADICA could give negative peripheral BE junction capacitance, it is the case when the γ (ratio of the peripheral specific junction capacitance to the area specific junction capacitance) associated to the junction capacitance is lower than the γ (ratio of the peripheral collector current density to the area collector current density) associated to the collector current. How to solve this issues?.

Split of the BC junction capacitance

- How to split accurately the BC junction capacitance between the internal and external part?
  The fit obtained on the Y_{12} parameter demonstrates that this partionning is not always enough accurate (the internal part of the BC junction capacitance is often underestimated).

BC weak avalanche parameters

- In HICUM the weak avalanche current is given by

$$I_{AVL} = I_{TF} \cdot F_{AVL} \cdot (V_{DCI} - V_{BCi}) \cdot \exp\left\{-\frac{Q_{AVL}}{C_{JCI} \cdot (V_{DCI} - V_{BCi})}\right\}$$

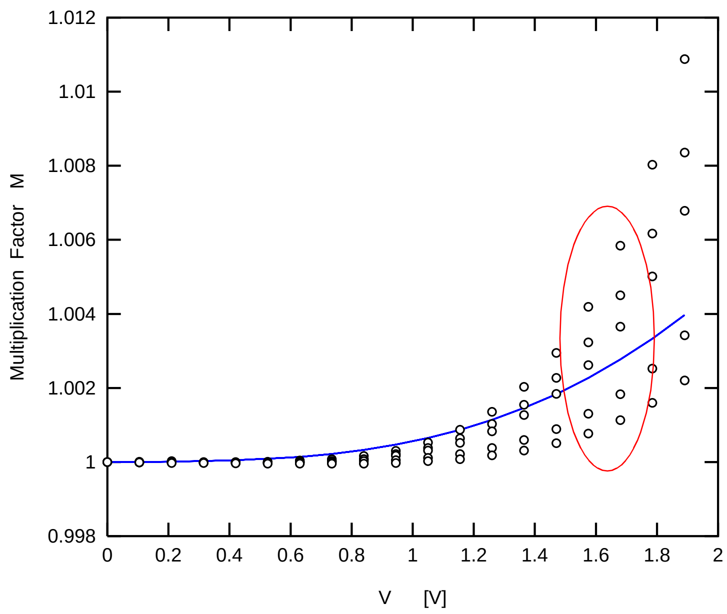
If it is assumed that C_{JCI}, Q_{AVL} and I_{TF} are only proportional to the effective emitter area, I_{AVL} is also proportional only to the effective emitter area.

- From $I_C = I_{C0} + I_{AVL} = M \cdot I_{C0}$ we can deduce that the multiplication factor M is geometry independent

$$M = 1 + \frac{I_{AVL}}{I_{C0}} = \underbrace{F_{AVL} \cdot (V_{DCI} - V_{BCi}) \cdot \exp\left\{-\frac{Q_{AVL}}{C_{JCI} \cdot (V_{DCI} - V_{BCi})}\right\}}_{\text{geometry independent}}$$

- But experimentally, it is not the case.

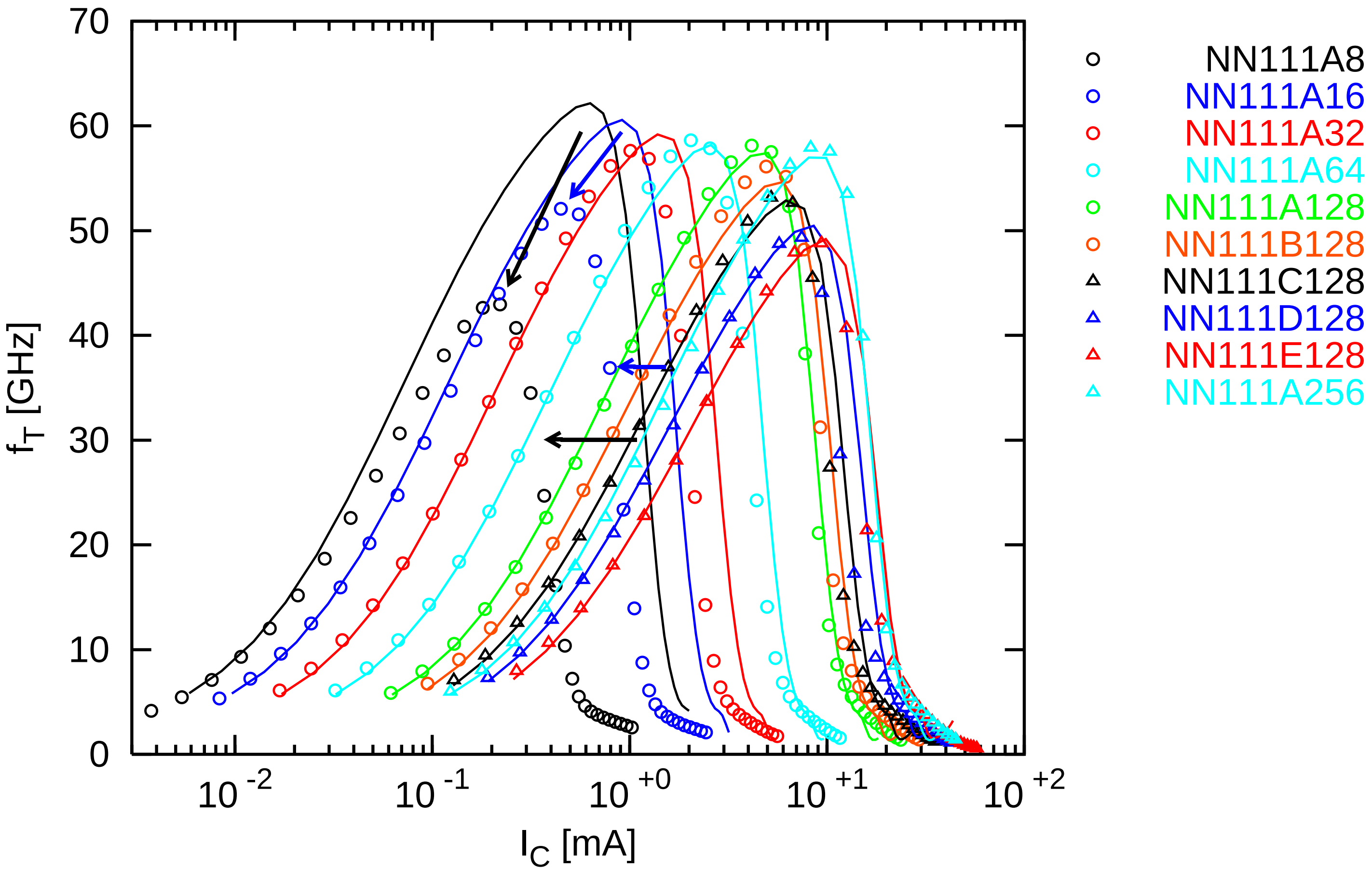
- How to solve this scaling issue of the avalanche current (TRADICA)?



Multiplication factor for transistors with different emitter length and width

Transit time scaling laws

- Depending on the process, it is difficult to accurately fit the f_T characteristics for devices with small emitter length. Is it an extraction issue (I_{CK} overestimated for small devices) or the scalling law for R_{CI0} has to be improved (one δ_C for each direction)?.
- Is it a problem of non-scalable process?.
- Is there a solution in TRADICA to solve this issue?. How?.



Summary of Main ST Requirements

- New HICUM Level 2 version (2.2)
  - Update of the model equations and of the code corresponding to the corrections done by EDA vendors for solving all convergence issues.
  - Reference code needed.
- New HICUM Level 2 version (2.3)
  - Correction of the temperature scaling laws (especially for I_B and T_{EF0}).
  - Other physical effects to be improved?...
- Level 0 status and implementation in circuits simulators
- Improvement of HICUM Scaling laws and guidelines for the extraction of some specific parameters