# HICUM/L2 version 2.30: Release Notes

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# 1 Introduction

HICUM/L2 version 2.30 has been developed to a large extent within the framework of the European DOTFIVE project. This HICUM/L2 version has been improved from its present official version (v2.24) in order to meet the requirements for emerging mm-wave applications. This release note contains a brief overview of the new improvements and additions in the new model. Theoretical background of some of the new equations and the previous model versions can be found in [1].

# 2 Improvements of the model equations

This section describes the model improvements and the corresponding implemented equations in verilog-A code.

## 2.1 Formulation for the critical current ($I_{CK}$)

The new equation for the critical current is given by,

$$I_{CK} = \frac{v_{ceff}}{r_{Ci0}} \frac{1}{\left(1 + \left(\frac{v_{ceff}}{V_{lim}}\right)^{\delta_{CK}}\right)^{1/\delta_{CK}}} \left[1 + \frac{x + \sqrt{x^2 + a_{ickpt}}}{2}\right], \tag{2.1.0-1}$$

where, $\delta_{CK}$ is the new model parameter.

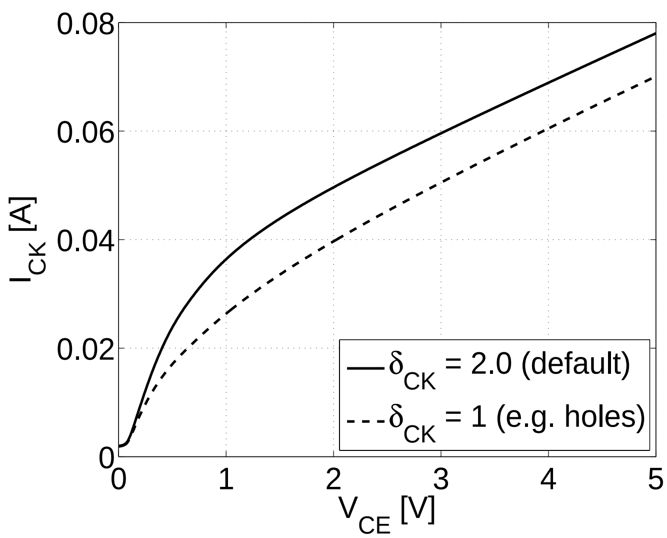


Fig. 2.1.0/1: Effect of $\delta_{CK}$ on critical current

## 2.2 Weight factors

### 2.2.1 Weight factor for low current transit time

A new weighting factor $h_{f0}$ for the low current minority charge has been introduced and the expression for *weighted* minority charge is modified as

$$Q_{f,T} = h_{f0}Q_{f0} + h_{fE}\Delta Q_{Ef} + \Delta Q_{Bf} + h_{fC}\Delta Q_{Cf} \,. \tag{2.2.1-1}$$

It should be noted that default value of $h_{f0}$ (=*1*) makes it compatible with the previous version.

The temperature dependence of $h_{f0}$ is given by,

$$h_{f0}(T) = h_{f0}(T_0)\exp\left[\frac{\Delta V_{gBE}}{V_T}\left(\frac{T}{T_0} - 1\right)\right] , \tag{2.2.1-2}$$

where, $\Delta V_{gBE}$ is the new model parameter and defined as the bandgap difference between base and BE-junction, used for $h_{jEi0}$ and $h_{f0}$.

### 2.2.2 Weight factor of BE depletion charge

It has been observed that for advanced graded SiGe-HBTs ($f_T > 200\ GHz$) there is significant decrease in $g_m$ at the medium injection. Due to presence of graded germanium in the BE-SCR, the BE-depletion charge weighting factor $h_{jEi}$ becomes bias dependent.

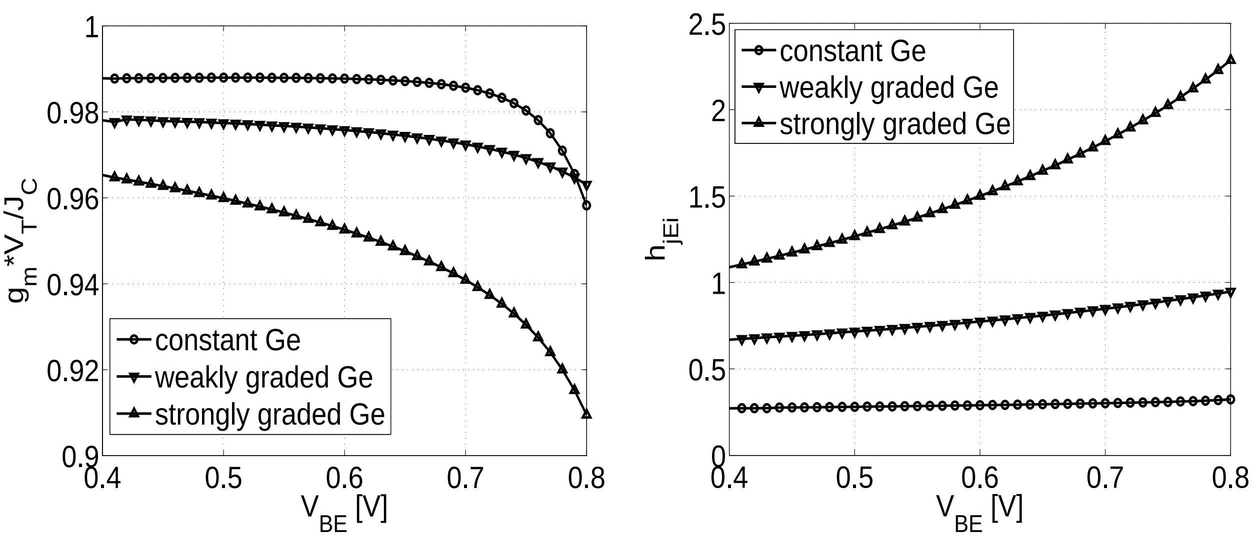


Fig. 2.2.2/1: Variation of $g_m$ and $h_{jEi}$ with bias.

In this new version the BE-depletion charge weight factor $h_{jEi}$ is modeled as bias dependent with the following equations,

$$h_{jEi} = h_{jEi0}\frac{\exp(u)-1}{u}, \tag{2.2.2-1}$$

with,

$$u = a_{hjEi}\left(1-\left(1-\frac{v_j}{V_{DEi}}\right)^{z_{Ei}}\right) . \tag{2.2.2-2}$$

Where, $a_{hjEi}$ is the new model parameter.

The junction voltage is limited to $V_{DEi}$ and 0 by,

$$x_{upp} = \frac{V_{DEi}-V_{BEi}}{r_{h_{jEi}}V_T} , \tag{2.2.2-3}$$

and

$$v_{j,upp} = V_{DEi}-r_{h_{jEi}}V_T\frac{x_{upp}+\sqrt{x_{upp}^2+a_{fi}}}{2} , \tag{2.2.2-4}$$

where, $r_{hjEi}$ is the newly introduced model parameter.

The voltage has been further limited to values greater than zero using the following equations,

$$x_{low} = \frac{v_{j,upp}-V_T}{V_T} , \tag{2.2.2-5}$$

$$v_j = V_T\left(1+\frac{x_{low}+\sqrt{x_{low}^2+a_{fi}}}{2}\right) . \tag{2.2.2-6}$$

The temperature dependence of $h_{JEi}$ and $r_{hjEi}$ is given by,

$$a_{hjEi}(T) = a_{hjEi}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{h_{jEi}}} , \tag{2.2.2-7}$$

$$h_{jEi0}(T) = h_{jEi}(T_0)\exp\left[\left(-\frac{\Delta V_{gBE}}{V_T}\right)\left(\left(\frac{T}{T_0}\right)^{\zeta_{V_{gBE}}} - 1\right)\right], \tag{2.2.2-8}$$

where, $\zeta_{hjEi}$ and $\zeta_{VgBE}$ are the fitting parameters.

It should be mentioned that, the previous weighting factor for the BE junction charge $h_{jEi}$ has been redefined as the weight factor for the BE junction charge for $V_{BEi} = 0V$.

The bias dependence and temperature dependence of $h_{jEi}$ can be completely turned off by setting $a_{hjEi}$=0.

### 2.2.3 High current weight factors

Temperature dependences for $h_{fE}$ and $h_{fC}$ have been considered in the new model,

$$h_{fE}(T) = h_{fE}(T_0)\exp\left[\frac{V_{gb} - V_{ge}}{V_T}\left(\frac{T}{T_0} - 1\right)\right] \tag{2.2.3-1}$$

and

$$h_{fC}(T) = h_{fC}(T_0)\exp\left[\frac{V_{gb} - V_{gc}}{V_T}\left(\frac{T}{T_0} - 1\right)\right]. \tag{2.2.3-2}$$

In order to enable full backward compatibility to previous versions of HICUM, the parameter *flcomp* needs to be set to *2.3* or more to turn on these models.

## 2.3 Transit times

The formulation for the transit time has been extended with a model describing the barrier effect at the collector-side heterojunction. Additionally, the temperature dependence of the emitter transit time has been turned off.

### 2.3.1 Barrier voltage

In this HICUM version, the barrier related term is calculated by the bias dependent barrier voltage,

$$\Delta V_{cBar} = V_{cBar}\exp\left(-\frac{2}{i_{Bar} + \sqrt{i_{Bar}^2 + a_{cBar}}}\right), \tag{2.3.1-1}$$

with,

$$i_{Bar} = \frac{i_{Tf} - I_{CK}}{i_{cBar}} . \tag{2.3.1-2}$$

Hence three new model parameters have been introduced, $V_{cBar}$, $a_{cBar}$ and $i_{cBar}$. Also, setting, $V_{cBar} = 0$ makes entire barrier extension turn-off.

### 2.3.2 Barrier related minority charge

The high current minority charge expression has been extended by adding the barrier related part,

$$Q_{f,h} = \Delta Q_{Ef} + \Delta Q_{Bf,b} + \Delta Q_{Bf,c} + \Delta Q_{Cf,c} . \tag{2.3.2-1}$$

The new formulation for the barrier related minority charge reads as follows,

$$\Delta Q_{Bf,b} = \tau_{Bfvs} i_{Tf}\left[\exp\left(\frac{\Delta V_{cBar}}{V_T}\right) - 1\right], \tag{2.3.2-2}$$

with the already existing parameter, $\tau_{Bfvs} = (1 - f_{\tau hc})\tau_{hCs}$.

### 2.3.3 High current charges

Considering the “Kirk effect” the following expression can be obtained

$$\Delta Q_{fh,c} = \tau_{hCs} i_{Tf} w^2 \exp\left(\frac{\Delta V_{cBar} - V_{cBar}}{V_T}\right) . \tag{2.3.3-1}$$

The high current collector charge including current spreading can be expressed as

$$\Delta Q_{Cf,c} = \tau_{pCs} i_{Tf} \exp\left(\frac{\Delta V_{cBar} - V_{cBar}}{V_T}\right) \begin{cases} 2\dfrac{f_{Ci}\ln\left(\dfrac{1+\zeta_b w}{1+\zeta_l w}\right) - f_{Cb} + f_{Cl}}{\zeta_b - \zeta_l} & , \quad l_{E0} > b_{E0} \\ \dfrac{1+\zeta_b w/3}{1+\zeta_b w} w^2 & , \quad l_{E0} = b_{E0} \end{cases} . \tag{2.3.3-2}$$

### 2.3.4 Emitter transit time

The temperature dependence of the emitter transit time has been removed. However, setting *fl-comp* to *2.2* or lower, the former existing equation will still be available.

## 2.4 Lateral non-quasi-static (NQS) effect

The formulation has been switched back to that of HICUM/L2v2.23, i.e, *"ddx"* operator is being used to calculate the value of $C_{Rbi}$ from which required charge $Q_{Rbi}$ is calculated considering the proper node voltage.

## 2.5 Temperature dependence of thermal resistance

In this version the thermal resistance ($R_{th}$) has been modeled as temperature dependent. The temperature dependence can be directly calculated by the following formulation,

$$R_{th}(T) = R_{th}(T_0)\left(\frac{T}{T_0}\right)^{\zeta_{rth}}, \tag{2.5.0-1}$$

where, $\zeta_{rth}$ is the temperature coefficient of $R_{th}$ and a new model parameter.

## 2.6 Temperature dependence of internal BE recombination current

The current equation has been modified, within the existing simplifying assumptions, by replacing "*1/2*" with "*1/*$m_{REi}$",

$$I_{REiS}(T) = I_{REiS}(T_0)\left(\frac{T}{T_0}\right)^{\frac{m_g}{m_{REi}}} \exp\left[\frac{1}{m_{REi}} \cdot \frac{V_{gBEeff}}{V_T}\left(\frac{T}{T_0} - 1\right)\right]. \tag{2.6.0-1}$$

## 2.7 Temperature dependence of peripheral BE recombination current

In the same way the with peripheral BE recombination current has been modified,

$$I_{REpS}(T) = I_{REpS}(T_0)\left(\frac{T}{T_0}\right)^{\frac{m_g}{m_{REp}}} \exp\left[\frac{1}{m_{REp}} \cdot \frac{V_{gBEeff}}{V_T}\left(\frac{T}{T_0} - 1\right)\right]. \tag{2.7.0-1}$$

Setting $m_{REi} = 2$ and $m_{REp} = 2$ yields the formulation of previous model versions.

## 2.8 Noise source of the emitter resistance

Based on measurements presented in [2] an additional flicker noise contribution has been introduced for the series emitter resistance $RE$. The total noise contribution becomes,

$$\overline{I_{rE}^2} = \frac{Kf_{rE} \cdot I_E^{Af_{rE}}}{f} + \frac{4kT}{r_E} , \qquad (2.8.0\text{-}1)$$

where, the first component represents the flicker noise and second the thermal noise.

## 2.9 Newly added model parameters

The following table summarizes the new model parameters that have been added along with their definition.

Table 2.9.0/1:

| Parameter | Default | Description |
|---|---|---|
| $\delta_{CK}$ | 2 | Fitting factor for $I_{CK}$ |
| $a_{hjEi}$ | 0 | Parameter describing the slope of $h_{jEi}(V_{BE})$ |
| $r_{hjEi}$ | 1 | Smoothing parameter for $h_{jEi}(V_{BE})$ at high voltage. |
| $\Delta V_{gBE}$ | 0 | Bandgap difference between base and BE-junction, used for $h_{jEi0}$ and $h_{f0}$. |
| $\zeta_{hjEi}$ | 1 | Temperature coefficient for $a_{hjEi}$. |
| $\zeta_{VgBE}$ | 1 | Temperature coefficient for $h_{jEi0}$. |
| $h_{f0}$ | 1 | Weight factor for the low current minority charge. |
| $V_{cBar}$ | 0 | Barrier voltage |
| $a_{cBar}$ | 1 | Smoothing parameter for barrier voltage. |
| $i_{cBar}$ | 1 | Normalization parameter |
| $\zeta_{rth}$ | 1 | Temperature coefficient for $R_{th}$ |
| $Kf_{rE}$ | 0 | $R_E$ flicker noise coefficient |
| $Af_{rE}$ | 2 | $R_E$ flicker noise exponent factor |

# 3 Reference

[1] M. Scorcher and A. Chakravorty, “Compact hierarchical modeling of bipolar transistors with HICUM”, World Scientific, Singapore, ISBN 978-981-4273-21-3, 2010.

[2] N. Derrier, “Limitations of Bipolar Compact Models for Low Frequency Noise Application to HICUM"