# Extension of HICUM/L2 Avalanche Model at High Current: Proposal

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#### **Overview**

- To the designer requests, extension of HICUM/L2 avalanche model at high-injection levels
  - For more details see [1]
- Impact of the new model parameters on electrical characteristics
- Test and validation with various circuit simulators
- Verilog-A code is available on request



#### **Motivation**

- The increasing of RF performances (f<sub>T</sub>, f<sub>max</sub>) of HBTs leads to a decreasing of the breakdown voltages (BV<sub>CBO</sub>, BV<sub>CEO</sub>)
- In consequence, designers are often obliged to bias the transistor beyond the BV<sub>CEO</sub> (BV with open base, never happens in real circuit)
- They ask for a better model beyond BV<sub>CEO</sub>
- It is especially the case for HV HBTs, where the high-injection effects are important because of the low doped collector
  - $\bullet$  Variation of  $\mathsf{BV}_\mathsf{CEO}$  with current densities
  - Not taken into account with the existing HICUM/L2 model

Modulation of  $BV_{CEO}$  with current densities for HV device

- Measurement (circles)
- HICUM/L2 (dashed lines)
- Proposal (lines)





## Model equations (1/2)

#### Weak avalanche model

• HICUM/L2 revision before 2.4.0

$$I_{AVL} = g \cdot I_{T}$$

 $I_T$  is the transfer current

• The avalanche factor g is given by

$$g = \mathbf{F}_{\mathbf{A}\mathbf{V}\mathbf{L}} \cdot (V_{DCI} - V_{B'C'}) \cdot e^{\frac{-\mathbf{Q}_{\mathbf{A}\mathbf{V}\mathbf{L}}}{(V_{DCI} - V_{B'C'}) \cdot C_{JCI}}}$$

• This model allows to model accurately the BV<sub>CEO</sub> of the transistor at low and medium current densities.

#### Strong avalanche model

- From HICUM/L2 2.4.0
- Allows to accurately model the avalanche current up to (or close to) the BV<sub>CBO</sub> of the transistor
- $\bullet$  Safeguard for designers when reaching the  $\mathsf{BV}_{\mathsf{CBO}}.$

$$\mathbf{I}_{AVL} = \frac{\mathbf{g}}{1 - \mathbf{K}_{AVL} \cdot \mathbf{g}} \cdot \mathbf{I}_{T}$$
(3)

The model parameter K<sub>AVL</sub> allows to turn off the strong avalanche effect (K<sub>AVL</sub> = 0), or to fine-tune the avalanche current in order to have the good value for BV<sub>CBO</sub> (K<sub>AVL</sub> ∈ (0, 3]) of the transistor at low and medium current densities.



(2)

## Model equations (2/2)

- Prevention of numerical overflow
  - To prevent numerical issue, the denominator of (3) is limited to values greater than zero using the smoothing function

$$\frac{1 - \mathbf{K}_{\mathbf{AVL}} \cdot \mathbf{g} + \sqrt{\left(1 - \mathbf{K}_{\mathbf{AVL}} \cdot \mathbf{g}\right)^2 + 0.01}}{2}$$
(4)





#### Extension at high-injection level (1/4)

- The 2 previous formulations (1) and (3) are only valid at low and medium current densities. At high-current densities, the injected electrons n, in the collector can no longer be neglected.
- The result is a modulation of the electric field, in the vertical collector under the emitter, with the collector current according to the Poisson's equation

$$\frac{\partial \mathsf{E}}{\partial \mathsf{x}} = \frac{\mathsf{q} \cdot (\mathsf{N}_{\mathsf{epi}} - \mathsf{n})}{\varepsilon_{\mathsf{si}}}$$
(5)

• Example of electric field variation in case of constant collector doping and  $V_{CB} = 2V$ .







#### Extension at high-injection level (2/4)

Assuming saturation velocity (we are close to BV<sub>CEO</sub>, the electric field is strong enough),
 (5) can be re-written

$$\frac{\partial E}{\partial x} = \frac{q \cdot N_{epi}}{\epsilon_{si}} \cdot \left\{ 1 - \frac{I_T}{I_{LIM}} \right\}$$
(6)

• where  $I_{LIM}$  corresponds to the transfer current when  $n = N_{epi}$  (slope of the electric field = 0)  $I_{LIM} = q \cdot N_{epi} \cdot v_{sn} \cdot A_E$ 

Solving the Poisson's equation (6), for I<sub>T</sub> < I<sub>LIM</sub> and I<sub>T</sub> > I<sub>LIM</sub>, we can demonstrate [1], that the avalanche factor g (2) must be corrected by a factor F<sub>COR</sub> (see (12) and (13) slide 8)

$$\begin{cases} F_{CORL} = \sqrt{1 - \frac{I_{T}}{I_{LIM}}} & \text{for} & I_{T} < I_{LIM} \\ F_{CORH} = \sqrt{\frac{I_{T}}{I_{LIM}} - 1} & \text{for} & I_{T} > I_{LIM} \end{cases}$$
(8)

In case of non constant collector doping, I<sub>LIM</sub> is approximated by

$$I_{\text{LIMeff}} = D_{\text{AVL}} \cdot I_{\text{LIM}} + H_{\text{AVL}} \cdot I_{\text{T}}$$
(9)
• where  $D_{\text{AVL}}$  and  $H_{\text{AVL}}$  are two additional model parameters.

• **D**<sub>AVL</sub> = **0** is used as a flag to turn off the new formulation.



6/30

(7)

#### Extension at high-injection level (3/4)

In order to connect F<sub>CORL</sub> and F<sub>CORH</sub>, the following function is used [1]





#### Extension at high-injection level (4/4)

Final expression of the avalanche current at low and high V<sub>CB</sub>, at low and high-currents

$$I_{AVL} = \frac{g}{1 - K_{AVL} \cdot g} \cdot I_{T}$$
(11)

with

$$g = \mathbf{F}_{AVL} \cdot (V_{DCI} - V_{B'C'}) \cdot e^{\frac{-\mathbf{Q}_{AVL}}{\mathbf{F}_{COR} \cdot (V_{DCI} - V_{B'C'}) \cdot C_{JCI}}}$$
(12)

and the correction factor

$$\mathbf{F}_{\mathbf{COR}} = \sqrt{\mathbf{S}_{\mathbf{M}} \cdot \ln\left\{\mathbf{e}^{\frac{\mathbf{C}_{\mathbf{A}\mathbf{VL}} \cdot \mathbf{C}_{\mathsf{JCI}}}{\mathbf{S}_{\mathbf{M}} \cdot \mathbf{C}_{\mathsf{JCI0}}} - 2 + 2 \cdot \cosh\left(\frac{1 - \frac{\mathbf{I}_{\mathsf{T}}}{\mathbf{I}_{\mathsf{LIMeff}}}{\mathbf{S}_{\mathbf{M}}}\right)\right\}}$$
(13)

with

$$\mathbf{I}_{\text{LIMeff}} = \mathbf{D}_{\text{AVL}} \cdot \mathbf{I}_{\text{LIM}} + \mathbf{H}_{\text{AVL}} \cdot \mathbf{I}_{\text{T}}$$
(14)

#### Comments

• I<sub>LIM</sub> is not an HICUM model parameter. It can be calculated from (see Appendix A)

$$I_{\text{LIM}} = \frac{V_{\text{LIM}}}{R_{\text{CIO}}}$$
(15)



# Impact of $\mathsf{D}_{\mathsf{AVL}}$ on $\mathsf{F}_{\mathsf{COR}}$

- D<sub>AVL</sub> allows to enable (D<sub>AVL</sub>≠0) or disable (D<sub>AVL</sub> = 0) the high-injection effects on the avalanche current
- If D<sub>AVL</sub>≠0, D<sub>AVL</sub> allows to shift the abscissa of the stationary point of F<sub>COR</sub>(I<sub>T</sub>) characteristic, which is by default (D<sub>AVL</sub> = 1) at I<sub>T</sub> = I<sub>LIM</sub> = V<sub>LIM</sub>/R<sub>CI0</sub>





## Impact of $H_{AVL}$ on $F_{COR}$

- H<sub>AVL</sub> has two effects
  - It shifts the abscissa of the stationary point of the  $F_{COR}(I_T)$  characteristics (like  $D_{AVL}$ ), which is by default  $(H_{AVL} = 0)$  at  $I_T = I_{LIM} = V_{LIM}/R_{CI0}$
  - It changes the slope of  $F_{COR}(I_T)$  in the high-current region ( $I_T > I_{LIMeff}$ )





# Impact of $C_{\text{AVL}}$ on $F_{\text{COR}}$

- $C_{AVL}$  allows to fix the minimum value of  $F_{COR}$  at  $I_T = I_{LIMeff}$
- Increasing C<sub>AVL</sub>, increases the minimum value of F<sub>COR</sub>





# Impact of $S_M$ on $F_{COR}$

- S<sub>M</sub> is a smoothing factor allowing to connect  $F_{CORL}$  and  $F_{CORH}$  at  $I_T = I_{LIMeff}$
- We suggest to use the default value  $S_M = 0.1$





## Verilog-A code and model parameters

13/30

Verilog-A available on request for testing



#### Base-collector avalanche current parameters

Parameter	Definition	Default	Range	Unit	Factor	Comments
F <sub>AVL</sub>	Factor for avalanche current	0	[0:inf)	V <sup>-1</sup>		HICUM/L2 v2.4.0
Q <sub>AVL</sub>	Charge for avalanche current	0	[0:inf)	С	М	HICUM/L2 v2.4.0
K <sub>AVL</sub>	Flag and factor for turning strong avalanche on or off	0	[0:3]	-		HICUM/L2 v2.4.0
D <sub>AVL</sub>	Correction factor for ${\rm I}_{\rm LIM}$ (case of non-uniform collector doping)	0	[0:inf]	-		new
H <sub>AVL</sub>	Factor for current dependence of I <sub>LIM</sub> (case of non-uniform collector doping)	0	[0:10]	-		new
S <sub>M</sub>	Smoothing factor to link $F_{COR}$ equations before and after $I_{LIMeff}$	0.1	(0:1]	-		new
C <sub>AVL</sub>	Factor to define the value of $F_{COR}$ at $I_T = I_{LIMeff}$	1	[0:10]	-		new



## Verilog-A code validation (1/2)

- The new model formulation was implemented in Verilog-A code from the version 2.4.0 of HICUM/L2
- The new model has been extensively tested with commercial simulator (ELDO) and open source free circuit simulator QucsStudio [2]
- In few words, why to have used QucsStudio?
  - Free circuit simulator
  - Easy to use and powerful GUI to build the netlist and to analyze the results
  - High quality plots which can be directly used in presentations or reports
  - Verilog-A compilation on the fly as commercial tools
  - Good convergence
  - Many interesting features which are even not available in commercial simulators
    - Possibility to optimize model parameters
    - Manual tuning with sliders
    - Numerical data processing using Octave
    - DC, AC, S-parameter, transient and Harmonic Balance analysis
    - System simulations...



## Verilog-A code validation (2/2)

Example of tuning with sliders





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#### **Backward compatibility**

- If the new model is not enabled, D<sub>AVL</sub> = 0 there is a total backward compatibility with HICUM/L2 v2.4.0.
- I<sub>B</sub> vs. V<sub>CB</sub> characteristics, for several value of V<sub>BE</sub>. The points correspond to HICUM/L2 v2.4.0 and the lines to the proposed model.





## New formulation vs. HICUM/L2 v2.4.0 formulation (1/2)

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17/30
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- I<sub>B</sub> and I<sub>C</sub> vs.  $V_{CB}$  at constant  $V_{BE}$ 
  - The new model formulation allows to take into account the shift of BV<sub>CEO</sub> at high-currents due to the modulation of the collector electric field in high-injection





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## New formulation vs. HICUM/L2 v2.4.0 formulation (2/2)

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18/<u>30</u>
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I<sub>B</sub> and I<sub>C</sub> vs.  $V_{CB}$  at constant  $V_{BE}$  for a wider range of  $V_{BE}$ 



# Impact of K<sub>AVL</sub>

- I<sub>B</sub> and I<sub>C</sub> vs. V<sub>CB</sub> at low V<sub>BE</sub> (0.7 V) for several value of K<sub>AVL</sub> (0 to 1, step 0.2)
- K<sub>AVL</sub> allows to tune the value of BV<sub>CBO</sub>
  - $\bullet$  BV\_{CBO} decreases if  $K_{AVL}$  increases





# Impact of D<sub>AVL</sub>

- I<sub>B</sub> and I<sub>C</sub> vs. V<sub>CB</sub> at constant V<sub>BE</sub> (0.7 V and 0.9V) for  $D_{AVL} = 0.5, 1, 2$
- D<sub>AVL</sub> allows to fine-tune the value of I<sub>LIM</sub> for the current dependence of BV<sub>CEO</sub> at high currents









# Impact of H<sub>AVL</sub>

- I<sub>B</sub> and I<sub>C</sub> vs. V<sub>CB</sub> at constant V<sub>BE</sub> (0.7 V and 0.9V) for H<sub>AVL</sub> = 0, 0.5, 1
- H<sub>AVL</sub> allows to shift the value of BV<sub>CEO</sub> at high currents
  - $\bullet$  BV  $_{CEO}$  decreases if H  $_{AVL}$  increases







# Impact of C<sub>AVL</sub>

- I<sub>B</sub> and I<sub>C</sub> vs. V<sub>CB</sub> at constant V<sub>BE</sub> (0.7 V and 0.9V) for  $C_{AVL} = 1, 0.5, 0.3$
- C<sub>AVL</sub> allows to shift the value of BV<sub>CEO</sub> at high currents
  - $BV_{CEO}$  decreases if  $C_{AVL}$  increases. Low values of  $C_{AVL}$  have no impact on  $BV_{CEO}$







## Impact of S<sub>M</sub>

- $I_B$  and  $I_C$  vs.  $V_{CB}$  at constant  $V_{BE}$  (0.7 V and 0.9V) for  $S_M = 1, 0.5, 0.1$
- S<sub>M</sub> is a smoothing factor allowing to link to the characteristics of the avalanche current before and after ILIMeff
  - The impact of S<sub>M</sub> on the simulated characteristics is low. It is advised to keep S<sub>M</sub> to its default value 0.1







#### Impact on runtime (1/2)

- DC simulations at 27°C with ELD0 using Verilog-A codes
  - HICUM/L0 v2.4.0
  - High-current effects on avalanche current implemented from HICUM/L0 v2.4.0 Verilog-A code
- Output characteristics I<sub>C</sub> vs. V<sub>CE</sub> (from 0V beyond BV<sub>CB0</sub>) at constant V<sub>BE</sub>
  - Without self-heating in order to see only the impact of the avalanche model at high currents
  - Total of simulated bias points 200.000
    - 1000  $V_{CE}$  (from 0 to 16 V)
    - + 200  $V_{\text{BE}}$  (from 0.2 to 0.9 V)

## Runtime results

HICUM/L2 v2.4.0 BV with high-current effects	HICUM/L2 v2.4.0				
Eldo interactive runs completed.	Eldo interactive runs completed.				
There are no simulation error(s) nor warning(s).	There are no simulation error(s) nor warning(s).				
***> 2-Nov-2018 10:51:16 - GLOBAL CPU TIME 10mn 16s 040ms <***	***> 2-Nov-2018 15:03:37 - GLOBAL CPU TIME 27mn 59s 730ms <***				

10-2

10<sup>-1</sup>

10-8

10-10

10<sup>-12</sup> 10<sup>-14</sup> 10<sup>-16</sup> 10<sup>-18</sup>

0

10<sup>-2</sup>

10-6

10-8

10-12

10<sup>-14</sup> 10<sup>-16</sup> 10<sup>-18</sup>

0

<u>م</u> 10<sup>-10</sup>

8

V<sub>CE</sub> [V]

10

12

12

10

V<sub>CE</sub> [V]

14 16

14 16

I<sub>B</sub> [A]

BV extension at high currents is 2.7 time faster than existing HICUM//L2 v2.4.0 version



HICUM/L2 v2.40

#### Extension with high-current effects on avalanche current

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## Impact on runtime (2/2)

- Output characteristics  $I_C$  vs.  $V_{CE}$  (from 0V beyond  $BV_{CB0}$ ) at constant  $V_{BE}$ 
  - Total of simulated bias points 200.000
    - 1000 V<sub>CE</sub>
    - 200 V<sub>BE</sub>

life.augmented



#### Parameter extraction guidelines (1/2)



- Step 1
  - Direct extraction of  $Q_{AVL}$  and  $F_{AVL}$  at low  $V_{BE}$  and close to the  $BV_{CE0}$  (domain where  $I_B$  becomes negative) as described in [3] and [4].
  - D<sub>AVL</sub> set to 0

#### Step 2

- Optimization of  $K_{AVL}$  at low  $V_{BE}$  and high  $V_{CB}$  close to the  $BV_{CBO}$  [4].
- D<sub>AVL</sub> set to 0

#### Step 3

- At this stage, self-heating parameters (R<sub>TH</sub> and thermal coefficients) are assumed to be known
- SM is set to 0.1
- $D_{AVL}$  (and possibly  $C_{AVL})$  is optimized at high  $V_{BE},$  before  $I_{LIM},$  and high  $V_{CB}\,[1]$
- H<sub>AVL</sub> set to 0







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#### Parameter extraction guidelines (2/2)



- Step 4
  - $H_{AVL}$  (and possibly  $C_{AVL})$  is optimized at high  $V_{BE},$  after  $I_{LIM},$  and high  $V_{CB}\,[1]$
- Comments
  - Step 3 and 4 can be repeated several times if needed





#### Summary

- An extension of HICUM/L2 avalanche model at high-injection levels is proposed based on [1]
- The new approach is explained and the implementation in Verilog-A code is validated with ELDO and QucsStudio [2]
  - Total backward compatibility with HICUM/L2 v2.4.0 if the additional parameters are not specified (default values)
  - No converge issue and better runtime than HICUM/L2 v2.4.0
- Validation of the new model can be found in [1] showing excellent agreement versus experimental data
- Verilog-A code available on request for evaluation
- If you are interested in this new formulation, please contact the HICUM developer Michael Schröter (michael.schroeter@tu-dresden.de), and ask him for its implementation in an official future HICUM revision



## Appendix A: Calculation of ILIM

- The current I<sub>LIM</sub> used in the model formulation is not a model parameter. It can be computed from the HICUM model parameter R<sub>CI0</sub> and V<sub>LIM</sub> as follows
  - I<sub>LIM</sub> corresponds to the case where n = Nepi. From (5), the electric field is horizontal and therefore

$$\mathsf{E}_{\mathsf{LIM}} = -\rho_{\mathsf{epi}} \cdot \mathsf{J}_{\mathsf{LIM}} = \frac{-\rho_{\mathsf{epi}} \cdot \mathsf{I}_{\mathsf{LIM}}}{\mathsf{A}_{\mathsf{E}}} \tag{A.1}$$

 $\rho_{epi}$  is the resistivity of the collector under the emitter and  $A_E$  the emitter area.

 The corresponding potential (integral of the electric field) is given by

$$V_{LIM} = -E_{LIM} \cdot W_{epi} = \frac{\rho_{epi} \cdot W_{epi}}{A_E} \cdot I_{LIM}$$
(A.2)



• By definition,  $\frac{\rho_{epi} \cdot W_{epi}}{A_E}$  is the vertical resistance of the collector under the emitter R<sub>CI0</sub>, leading to the expression of I<sub>LIM</sub>  $I_{LIM} = \frac{V_{LIM}}{R_{CI0}}$ (A.3)



#### References

- [1] M. Jaoul, C. Maneux, D. Céli, M. Schröter, T. Zimmer, "A Compact Formulation for Avalanche Multiplication in SiGe HTBs at High-Injection Levels", TED, accepted to be published.
- [2] QucsStudy, a free and powerful circuit simulator, November 2018, http://dd6um.darc.de/QucsStudio/about.html
- [3] D. Céli, M. Jaoul, N. Derrier, "A Study of HICUM Avalanche Model Beyond BV<sub>CEO</sub>", 16<sup>th</sup> HICUM Workshop, Munich, May 2016.
- [4] M. Jaoul, D. Céli, C. Maneux, M. Schröter, A. Pawlak, "Avalanche Compact Model Featuring SiGe HBTs Characteristics up to BV<sub>CBO</sub>", ESSDERC, Leuven, 2017.

