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 ($f_T$, $f_{\text{max}}$) of HBTs leads to a decreasing of the breakdown voltages ($\text{BV}_{\text{CBO}}$, $\text{BV}_{\text{CEO}}$)

- In consequence, designers are often obliged to bias the transistor beyond the $\text{BV}_{\text{CEO}}$ (BV with open base, never happens in real circuit)

- They ask for a better model beyond $\text{BV}_{\text{CEO}}$

- It is especially the case for HV HBTs, where the high-injection effects are important because of the low doped collector
  - Variation of $\text{BV}_{\text{CEO}}$ with current densities
  - Not taken into account with the existing HICUM/L2 model

![Modulation of $\text{BV}_{\text{CEO}}$ with current densities for HV device](image)

- Measurement (circles)
- HICUM/L2 (dashed lines)
- Proposal (lines)
Model equations (1/2)

**Weak avalanche model**

- HICUM/L2 revision before 2.4.0

\[ I_{AVL} = g \cdot I_T \]  

(1)

- \( I_T \) is the transfer current

- The avalanche factor \( g \) is given by

\[ g = F_{AVL} \cdot (V_{DCI} - V_{B'C'}) \cdot e^{\frac{-Q_{AVL}}{(V_{DCI} - V_{B'C'}) \cdot C_{JCI}}} \]  

(2)

- This model allows to model accurately the \( BV_{CEO} \) 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 \( BV_{CBO} \) of the transistor

- Safeguard for designers when reaching the \( BV_{CBO} \).

\[ I_{AVL} = \frac{g}{1 - K_{AVL} \cdot g} \cdot I_T \]  

(3)

- The model parameter \( K_{AVL} \) allows to turn off the strong avalanche effect \( (K_{AVL} = 0) \), or to fine-tune the avalanche current in order to have the good value for \( BV_{CBO} \) \( (K_{AVL} \in (0, 3]) \) of the transistor at low and medium current densities.
Prevention of numerical overflow

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

\[
1 - K_{AVL} \cdot g + \sqrt[2]{\left(1 - K_{AVL} \cdot g\right)^2 + 0.01} \over 2
\]

(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

\[
\frac{\partial E}{\partial x} = \frac{q \cdot (N_{epi} - n)}{\varepsilon_{si}}
\]

(5)

- Example of electric field variation in case of constant collector doping and \( V_{CB} = 2V \).
Assuming saturation velocity (we are close to $BV_{CEO}$, the electric field is strong enough), (5) can be re-written

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

- where $I_{LIM}$ corresponds to the transfer current when $n = N_{epi}$ (slope of the electric field $= 0$)
  $$I_{LIM} = q \cdot N_{epi} \cdot v_{sn} \cdot A_E$$  \hspace{1cm} (7)

Solving the Poisson’s equation (6), for $I_T < I_{LIM}$ and $I_T > I_{LIM}$, we can demonstrate [1], that the avalanche factor $g$ (2) must be corrected by a factor $F_{COR}$ (see (12) and (13) slide 8)

$$F_{CORL} = \sqrt{1 - \frac{I_T}{I_{LIM}}} \quad \text{for} \quad I_T < I_{LIM}$$

$$F_{CORH} = \sqrt{\frac{I_T}{I_{LIM}} - 1} \quad \text{for} \quad I_T > I_{LIM}$$  \hspace{1cm} (8)

In case of non constant collector doping, $I_{LIM}$ is approximated by

$$I_{LIMeff} = D_{AVL} \cdot I_{LIM} + H_{AVL} \cdot I_T$$  \hspace{1cm} (9)

- where $D_{AVL}$ and $H_{AVL}$ are two additional model parameters.
- $D_{AVL} = 0$ is used as a flag to turn off the new formulation.
In order to connect $F_{CORL}$ and $F_{CORH}$, the following function is used [1]

$$F_{COR} = \sqrt{S_M \cdot \ln \left( \frac{C_{AVL} \cdot C_{JCl}}{S_M \cdot C_{JCl0}} \cdot 2 + 2 \cdot \cosh \left( \frac{1 - \frac{I_T}{I_{LIMeff}}}{S_M} \right) \right)}$$

where $S_M$ and $C_{AVL}$ are 2 smoothing parameters (10)
Extension at high-injection level (4/4)

- Final expression of the avalanche current at low and high \( V_{CB} \), at low and high-currents

\[
I_{AVL} = \frac{g}{1 - K_{AVL} \cdot g} \cdot I_T
\]  \hspace{1cm} (11)

with

\[
g = F_{AVL} \cdot (V_{DCI} - V_{B'C'}) \cdot e^{F_{COR} \cdot (V_{DCI} - V_{B'C'}) \cdot C_{JCI}}
\]  \hspace{1cm} (12)

and the correction factor

\[
F_{COR} = \sqrt{S_M \cdot \ln \left( e^{\frac{c_{AVL} \cdot C_{JCI}}{S_M \cdot C_{JCI0}}} - 2 + 2 \cdot \cosh \left( \frac{1 - \frac{I_T}{I_{LIMeff}}}{S_M} \right) \right)}
\]  \hspace{1cm} (13)

with

\[
I_{LIMeff} = D_{AVL} \cdot I_{LIM} + H_{AVL} \cdot I_T
\]  \hspace{1cm} (14)

- Comments
  - \( I_{LIM} \) is not an HICUM model parameter. It can be calculated from (see Appendix A)

\[
I_{LIM} = \frac{V_{LIM}}{R_{CI0}}
\]  \hspace{1cm} (15)
Impact of $D_{AVL}$ on $F_{COR}$

- $D_{AVL}$ allows to enable ($D_{AVL} \neq 0$) or disable ($D_{AVL} = 0$) the high-injection effects on the avalanche current.
- If $D_{AVL} \neq 0$, $D_{AVL}$ allows to shift the abscissa of the stationary point of $F_{COR}(I_T)$ characteristic, which is by default ($D_{AVL} = 1$) at $I_T = I_{LIM} = V_{LIM}/R_{Cl0}$

<table>
<thead>
<tr>
<th>$H_{AVL}$</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_M$</td>
<td>0.1</td>
</tr>
<tr>
<td>$C_{AVL}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

![Graph showing the impact of $D_{AVL}$ on $F_{COR}$]
Impact of $H_{AVL}$ on $F_{COR}$

- $H_{AVL}$ 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 $I_T = I_{LIM} = V_{LIM}/R_{Cl0}$
  - It changes the slope of $F_{COR}(I_T)$ in the high-current region ($I_T > I_{LIMeff}$)

<table>
<thead>
<tr>
<th>$D_{AVL}$</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_M$</td>
<td>0.1</td>
</tr>
<tr>
<td>$C_{AVL}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Impact of $C_{AVL}$ on $F_{COR}$

- $C_{AVL}$ allows to fix the minimum value of $F_{COR}$ at $I_T = I_{LIMeff}$
- Increasing $C_{AVL}$, increases the minimum value of $F_{COR}$

<table>
<thead>
<tr>
<th>$D_{AVL}$</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{AVL}$</td>
<td>0</td>
</tr>
<tr>
<td>$S_M$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

![Graph showing the impact of $C_{AVL}$ on $F_{COR}$]
Impact of $S_M$ on $F_{COR}$

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

<table>
<thead>
<tr>
<th>$D_{AVL}$</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{AVL}$</td>
<td>0</td>
</tr>
<tr>
<td>$C_{AVL}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

![Graph showing the impact of $S_M$ on $F_{COR}$]
Verilog-A code and model parameters

- Verilog-A available on request for testing
  
  didier.celi@st.com

- Base-collector avalanche current parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Default</th>
<th>Range</th>
<th>Unit</th>
<th>Factor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAVL</td>
<td>Factor for avalanche current</td>
<td>0</td>
<td>[0:inf]</td>
<td>V^{-1}</td>
<td></td>
<td>HICUM/L2 v2.4.0</td>
</tr>
<tr>
<td>QAVL</td>
<td>Charge for avalanche current</td>
<td>0</td>
<td>[0:inf]</td>
<td>C</td>
<td>M</td>
<td>HICUM/L2 v2.4.0</td>
</tr>
<tr>
<td>KAVL</td>
<td>Flag and factor for turning strong avalanche on or off</td>
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<td>[0:3]</td>
<td>-</td>
<td></td>
<td>HICUM/L2 v2.4.0</td>
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<tr>
<td>DAVL</td>
<td>Correction factor for I_{LIM} (case of non-uniform collector doping)</td>
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<td>[0:inf]</td>
<td>-</td>
<td></td>
<td>new</td>
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<tr>
<td>HAVL</td>
<td>Factor for current dependence of I_{LIM} (case of non-uniform collector doping)</td>
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<td>[0:10]</td>
<td>-</td>
<td></td>
<td>new</td>
</tr>
<tr>
<td>SM</td>
<td>Smoothing factor to link F_{COR} equations before and after I_{LIMeff}</td>
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<td>(0:1)</td>
<td>-</td>
<td></td>
<td>new</td>
</tr>
<tr>
<td>CAVL</td>
<td>Factor to define the value of F_{COR} at I_T = I_{LIMeff}</td>
<td>1</td>
<td>[0:10]</td>
<td>-</td>
<td></td>
<td>new</td>
</tr>
</tbody>
</table>
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...
Example of tuning with sliders
Backward compatibility

- If the new model is not enabled, $D_{AVL} = 0$ there is a total backward compatibility with HICUM/L2 v2.4.0.
- $I_B$ vs. $V_{CB}$ characteristics, for several value of $V_{BE}$. 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)

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$

  - The new model formulation allows to take into account the shift of $BV_{CEO}$ at high-currents due to the modulation of the collector electric field in high-injection.
New formulation vs. HICUM/L2 v2.4.0 formulation (2/2)

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$ for a wider range of $V_{BE}$
Impact of $K_{AVL}$

- $I_B$ and $I_C$ vs. $V_{CB}$ at low $V_{BE}$ (0.7 V) for several values of $K_{AVL}$ (0 to 1, step 0.2)
- $K_{AVL}$ allows to tune the value of $BV_{CBO}$
  - $BV_{CBO}$ decreases if $K_{AVL}$ increases

C:/Users/dieder.celli/Quics/hicuml2V2p41/pr/BV1-HL2-241-v1-QuicsStudio.sch
Impact of $D_{AVL}$

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$ (0.7 V and 0.9 V) for $D_{AVL} = 0.5, 1, 2$
- $D_{AVL}$ allows to fine-tune the value of $I_{LIM}$ for the current dependence of $BV_{CEO}$ at high currents
Impact of $H_{AVL}$

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$ (0.7 V and 0.9V) for $H_{AVL} = 0, 0.5, 1$
- $H_{AVL}$ allows to shift the value of $BV_{CEO}$ at high currents
  - $BV_{CEO}$ decreases if $H_{AVL}$ increases
Impact of $C_{AVL}$

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$ (0.7 V and 0.9 V) for $C_{AVL} = 1, 0.5, 0.3$
- $C_{AVL}$ allows to shift the value of $BV_{CEO}$ at high currents
  - $BV_{CEO}$ decreases if $C_{AVL}$ increases. Low values of $C_{AVL}$ have no impact on $BV_{CEO}$
Impact of $S_M$

- $I_B$ and $I_C$ vs. $V_{CB}$ at constant $V_{BE}$ (0.7 V and 0.9V) for $S_M = 1, 0.5, 0.1$
- $S_M$ is a smoothing factor allowing to link to the characteristics of the avalanche current before and after $I_{LIMeff}$
  - The impact of $S_M$ on the simulated characteristics is low. It is advised to keep $S_M$ 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 $I_C$ vs. $V_{CE}$ (from 0V beyond $BV_{CB0}$) at constant $V_{BE}$
  - 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 $V_{BE}$ (from 0.2 to 0.9 V)

- Runtime results

<table>
<thead>
<tr>
<th>HICUM/L2 v2.4.0 BV with high-current effects</th>
<th>HICUM/L2 v2.4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eldo interactive runs completed.</td>
<td>Eldo interactive runs completed.</td>
</tr>
<tr>
<td>There are no simulation error(s) nor warning(s).</td>
<td>There are no simulation error(s) nor warning(s).</td>
</tr>
</tbody>
</table>

- $BV$ extension at high currents is **2.7 time faster** than existing HICUM//L2 v2.4.0 version
Impact on runtime (2/2)

- Output characteristics $I_C$ vs. $V_{CE}$ (from 0V beyond $BV_{EB0}$) at constant $V_{BE}$
  - Total of simulated bias points 200,000
    - 1000 $V_{CE}$
    - 200 $V_{BE}$

HICUM/L2 v2.40
CPU time 27 mn

Extension with high-current effects on avalanche current
CPU time 10 mn
Parameter extraction guidelines (1/2)

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

- **Step 2**
  - Optimization of $K_{AVL}$ at low $V_{BE}$ and high $V_{CB}$ close to the $BV_{CBO}$ [4].
  - $D_{AVL}$ set to 0

- **Step 3**
  - At this stage, self-heating parameters ($R_{TH}$ 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]
  - $H_{AVL}$ set to 0
Parameter extraction guidelines (2/2)

- **Step 4**
  - $H_{AVL}$ (and possibly $C_{AVL}$) is optimized at high $V_{BE}$, after $I_{ILIM}$, 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 $I_{\text{LIM}}$

The current $I_{\text{LIM}}$ used in the model formulation is not a model parameter. It can be computed from the HICUM model parameter $R_{\text{Cl0}}$ and $V_{\text{LIM}}$ as follows

- $I_{\text{LIM}}$ corresponds to the case where $n = \text{Nepi}$. From (5), the electric field is horizontal and therefore

$$E_{\text{LIM}} = -\rho_{\text{epi}} \cdot J_{\text{LIM}} = \frac{-\rho_{\text{epi}} \cdot I_{\text{LIM}}}{A_{E}} \quad (A.1)$$

$ho_{\text{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

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

- By definition, $\frac{\rho_{\text{epi}} \cdot W_{\text{epi}}}{A_{E}}$ is the vertical resistance of the collector under the emitter $R_{\text{Cl0}}$, leading to the expression of $I_{\text{LIM}}$

$$I_{\text{LIM}} = \frac{V_{\text{LIM}}}{R_{\text{Cl0}}} \quad (A.3)$$
References


