Investigation on Bias Dependence of Critical Current $I_{CK}$ in HICUM Models

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Outline

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Motivation

- Study of the bias dependence of the critical current $I_{CK}$ after to have observed a bump on the output characteristics (quasi-saturation region) with both HICUM/L2 and HICUM/L0

- In HICUM models (Level 2 and Level 0), the critical current $I_{CK}$ characterizes the onset of high-injection effects in the collector
  - Quasi-saturation effect
  - Kirk effect
**$I_{CK}$ formulation**

- From HICUM/L2 v2.31 (similar equation in HICUM/L0, the bias dependence of $I_{CK}$ is given by

\[
I_{CK} = \frac{V_{Ceff}}{R_{Cl0}} \cdot \frac{1}{1 + \left( \frac{V_{Ceff}}{V_{LIM}} \right)^{\frac{1}{D_{ELCK}}} \left( 1 + \frac{V_{Ceff}}{V_{LIM}} \right)^{\frac{1}{D_{ELCK}}}} \cdot \left( \frac{V_{Ceff} - V_{LIM}}{V_{PT}} + \sqrt{\left( \frac{V_{Ceff} - V_{LIM}}{V_{PT}} \right)^2 + \epsilon} \right)
\]

- The smoothing function $1 + \frac{V_{Ceff} - V_{LIM}}{V_{PT}} + \sqrt{\left( \frac{V_{Ceff} - V_{LIM}}{V_{PT}} \right)^2 + \epsilon}$, with smoothing factor $\epsilon = 0.001$, is used to connect the cases of low and high-electric fields in the collector.

- $V_{Ceff}$ is the *effective* collector voltage defined by

\[
V_{Ceff} = \left( \frac{V_{C} - V_{T}}{V_{T}} + \left( \frac{V_{C} - V_{T}}{V_{T}} \right)^2 + 1.921812 \right) \cdot V_{T}
\]

with $V_{C} = V_{CEi} - V_{CES}$
The bias dependence of $I_{CK}$ is characterized by the following model parameters:

- $R_{CI0}$ internal total vertical collector resistance under the emitter
- $V_{LIM}$ voltage separating ohmic and saturation region of carrier velocity $V_{LIM} = E_{LIM} \cdot W_{Ci}$
- $V_{PT}$ collector punch-through voltage $V_{PT} = \frac{q \cdot N_{Ci}}{2\varepsilon_{si}} \cdot W_{Ci}$
- $V_{CES}$ collector-emitter saturation voltage
- $D_{ELCK}$ field dependent mobility in the collector

From (1), the bias dependence of the critical current $I_{CK}$ can be split in 3 parts:

- $I_{CKL}$, $I_{CK}$ at low collector voltage
- $I_{CKHL}$, $I_{CK}$ at high collector voltage but lower than $V_{LIM}$
- $I_{CKHH}$, $I_{CK}$ at high collector voltage greater than $V_{LIM}$
From (1), I_{CKL} can be written:

\[ I_{CKL} \approx \frac{V_{\text{Ceff}}}{R_{C10}} = \frac{V_{\text{CEi}} - V_{\text{CES}}}{R_{C10}} \quad V_{\text{CEi}} > V_T \]

Model parameters:

\[
\begin{align*}
V_{\text{CES}} &= 1 \text{ mV} \\
R_{C10} &= 10 \Omega \\
V_{\text{LIM}} &= 0.5 \text{ V} \\
V_{\text{PT}} &= 1 \text{ V} \\
D_{\text{ELCK}} &= 2
\end{align*}
\]
\( I_{CK} \) at high collector voltage with \( V_{Ce} < V_{LIM} \)

- From (1), \( I_{CKL} \) can be written

\[
I_{CKL} \approx \frac{V_{CEi} - V_{CES}}{R_{Cl0}} \cdot \frac{1}{1 + \left( \frac{V_{CEi} - V_{CES}}{V_{LIM}} \right)^{D_{ELCK}^{D_{ELCK}}}} \quad V_{CEi} < V_{LIM}
\]

- Model parameters

\[
\begin{align}
V_{CES} &= 1 \text{ mV} \\
R_{Cl0} &= 10 \Omega \\
V_{LIM} &= 0.5 \text{ V} \\
V_{PT} &= 1 \text{ V} \\
D_{ELCK} &= 2
\end{align}
\]
\( I_{CK} \) at high collector voltage with \( V_{C_{eff}} > V_{LIM} \)

- From (1), \( I_{CKHH} \) can be written

\[
I_{CKHH} \approx \frac{V_{LIM}}{R_{CI0}} \times \left\{ 1 + \frac{V_{CEi} - V_{CES} - V_{LIM}}{V_{PT}} \right\}
\]

\( V_{CEi} > V_{LIM} \)

- Model parameters

\[
\begin{align*}
V_{CES} &= 1 \text{ mV} \\
R_{CI0} &= 10 \Omega \\
V_{LIM} &= 0.5 \text{ V} \\
V_{PT} &= 1 \text{ V} \\
D_{ELCK} &= 2
\end{align*}
\]
Bias dependence of $I_{CK}$ vs. $V_{CEi}$

$$I_{CK} = \frac{V_{Ceff}}{R_{Cl0}} \cdot \frac{1}{1 + \left\{ \frac{V_{Ceff}}{V_{LIM}} \right\}^{D_{ELCK}}} \cdot \left\{ 1 + \left( \frac{V_{Ceff} - V_{LIM}}{V_{PT}} \right)^{\frac{1}{2}} \right\}^{\frac{V_{Ceff} - V_{LIM}}{V_{PT}}} + \epsilon$$

- Model parameters
  - $V_{CES} = 1 \text{mV}$
  - $R_{Cl0} = 10 \Omega$
  - $V_{LIM} = 0.5 \text{V}$
  - $V_{PT} = 1 \text{V}$
  - $D_{ELCK} = 2$

![Graph showing bias dependence of $I_{CK}$ vs. $V_{CEi}$](image)
Bias dependence of $I_{CK}$ vs. $V_{CEi}$

- Model issue
  - Inflection point (bump) at $V_{CEi} = V_{LIM}$ (connection between $I_{CKHL}$ and $I_{CKHH}$)
  - This bump is also visible on output characteristics in the quasi-saturation region (see slide 2)
A possible solution to remove this bump is to increase the smoothing factor $\varepsilon$ of equation (1)

- $\varepsilon$ set to 0.1 instead of 0.001
Proposal and validation

- Same effect on the output characteristics, the increase of $\varepsilon$ allows to correct the bump in quasi-saturation region.
Proposal and validation

- Impact on $f_T$ characteristics

Similar (or even better) accuracy are obtained with increasing of $\varepsilon$ ($I_{CK}$ parameters re-extracted)

- Comments to HICUM users
  - Due to the strong impact of the self-heating, direct extraction of $I_{CK}$ parameters, as described in literature, is very difficult, or even impossible...
  - Alternative solution?
The critical current $I_{CK}$ can be split in 3 components

- One at low $V_{CEi}$
- A second at high $V_{CEi}$ but lower than $V_{LIM}$
- And a third at high $V_{CEi}$ greater than $V_{LIM}$

We clearly shown that the smoothing function used for the transition between $V_{CEi}$ lower than $V_{LIM}$ and $V_{CEi}$ greater than $V_{LIM}$ is not enough soft.

We propose to increase the smoothing factor $\varepsilon$ in order to remove the bump on the $I_{CK}$ vs. $V_{CEi}$ characteristics.

- with the possibility (to be discussed) to add a model parameter ($A_{CK}$) which could be adjusted by users like $A_{HC}$

Doing that, the bump often observed on $I_C$ vs. $V_{CE}$ characteristics, after the optimization of $I_{CK}$ parameters, is also no more visible.

Users and developers feedback requested for approval and implementation in next HICUM releases for both HICUM/L2 and HICUML/L0