HICUM/L0: Improvement of the injection width description
Outline

- Improvement of the transfer current modeling (Review)
- Investigation of quasi saturation modeling
- Improvement of the injection width description
- Modeling results
- Summary
Improvement of the transfer current modeling

Motivation:
Avoidance of negative slope in the simulated collector current of the HICUM/L0 model

Reason for negative slope:
Usage of the low transfer current $I_{tfl}$ for the calculation of the injection width $w$ and the normalized hole charge $q_{pT,T}$
Improvement of the transfer current modeling

Development of improved model equations for $qpT,T$ and $w$:
- Do not need $Itfl$
- Have a non-iterative solution

\[
q_{pT,T} = \frac{q_j}{2} + \sqrt{\left(\frac{q_j}{2}\right)^2 + q_{m_{new}}}
\]
\[
q_j = \frac{q_{jci}}{VEF} + 1
\]
\[
q_{m_{new}} = \frac{Itfi}{IQF} + \frac{Itri}{IQR} + \frac{Itfi}{IQFH} \cdot w^2 + \left(\frac{Itfi^2}{Ick} \cdot \frac{TFH}{IQFH}\right)^{2/3}
\]
\[
a_{new} = 1 - \frac{Ick}{Itfi} \sqrt{q_{m_{new}}(a)}
\]
\[
a_{new} = \frac{1}{(1 + Ick / \sqrt{Itfi \cdot IQFH})}
\]
\[
w_{new} = \frac{a_{new} + \sqrt{a_{new}^2 + AHC}}{1 + \sqrt{1 + AHC}}
\]
Improvement of the Transfer Current Modeling

Using the improved model equations:
- The collector current can be modeled sufficient using IQFH and TFH
- In no case a negative slope occurs in the collector current

However:
The modeling of the quasi saturation is not sufficient

Further investigation is necessary
Investigation of the quasi saturation modeling

As in HICUM/L2, also in HICUM/L0 the quasi saturation should be modeled by the critical current $I_{ck}$. Where $I_{ck}$ should act as a limit to the high current range.

Using the improved model equations:

- $I_{ck}$ is directly reflected on the output characteristic.
- In particular for the collector-base-charge term: $I_{tf - cb} = \sqrt{I_{tf} \cdot IQFH} + I_{ck}$
Investigation of the quasi saturation modeling

Reason for this behavior:
The intersection between \( q_{p,T,T} \) and \( w \), was not regarded at the
calculation of \( q_{p,T,T} \). \( w \) was regarded as a constant.

\[
q_{p,T,T} = 1 + \frac{q_{jCi}}{VEF} + \frac{Itr}{IQF} + \frac{Itr}{IQR} + \frac{Itf^2}{Ick IQFH} + \frac{w(If)^2}{IQFH}
\]

Taking into account the intersection between \( w \) and \( q_{p,T,T} \) by
inserting the unlimited injection width \( a=1-Ick/Itf \) for \( w \), leads to:

\[
q_{p,T,T} = 1 + \frac{q_{jCi}}{VEF} + \frac{Itf}{IQF \cdot q_{p,T,T}} + \frac{Itri}{IQR \cdot q_{p,T,T}} + \frac{Itf}{IQFH q_{p,T,T}} \left( 1 - \frac{ick}{itf} \cdot \sqrt{q_{p,T,T}} \right) + \frac{Itf^2}{Ick IQFH q_{p,T,T}^2}
\]

Solvable for \( q_{p,T,T} \), but:
• the solution is not unique
• poles and nulls can appear

Not usable for a implementation
Improvement of the injection width description

Therefore the calculation of $q_{pT,T}$ stays the same:

$$q_{pT,T} = \frac{q_j}{2} + \sqrt{\left(\frac{q_j}{2}\right)^2 + q_{m_{new}}}$$

$$q_j = \frac{q_{jci}}{VEF} + 1$$

$$q_{m_{new}} = \frac{Itfi}{IQF} + \frac{Itri}{IQR} + \frac{Itfi}{IQFH} \cdot \frac{w^2}{\sqrt{\left(\frac{Itfi^2}{Ick} \cdot \frac{TFH}{IQFH}\right)^{2/3}}}$$

But, calculation of $w$ is improved:

$$a_{new} = 1 - \frac{Ick}{Itfi} \sqrt{q_{m_{new}}(a)}$$

$$a_{new} = 1 - \frac{Ick}{Itfi} \cdot q_{pT,T_{-cb}}$$

$q_{pT,T_{-cb}}$ takes into account the interaction of $w$ and $q_{pT,T}$.
Improvement of the injection width description

For derivation the new assumption for $q_{pT,T_{cb}}$, simplified only the collector-base charge term is regarded.

\[
q_{pT,T_{cb}} = 1 + \frac{I_{tfi}}{I_{QFH} \cdot q_{pT,T}} \cdot w^2 \approx 1 + \frac{I_{tfi}}{I_{QFH} \cdot q_{pT,T_{cb}}} \cdot w^2
\]

Inserting the unlimited injection width $a$, makes it possible to consider the dependence from $w$ on $q_{pT,T}$

\[
q_{pT,T_{cb}} = 1 + \frac{I_{tfi}}{I_{QFH} \cdot q_{pT,T_{cb}}} \left(1 - \frac{i_{ck}}{i_{tfi}} \cdot q_{pT,T_{cb}}\right)^2
\]

However, by using the unlimited injection width again nulls an pols can occur in the solution
Improvement of the injection width description

Therefore the following conversion for $w$ is done:
- to limit the injection width
- to be able to isolate the variable $q_{pT,T_{(cb)}}$

$$a = 1 - \frac{ick}{itfi} \cdot q_{pT,T_{(cb)}} = 1 - \frac{ick}{itfi} \cdot q_{pT,T_{(cb)}} - q_{pT,T_{(cb)}} + q_{pT,T_{(cb)}} = 1 + q_{pT,T_{(cb)}} \left(1 - \frac{ick}{itfi}\right) - q_{pT,T_{(cb)}}$$

Inserting the limited ideal injection width $w_i$ for $a_i$ in $w$,

$$a_i = 1 - \frac{Ick}{Itfi} \quad \text{and} \quad w_i = \frac{a_i + \sqrt{a_i^2 + AHC}}{1 + \sqrt{1 + AHC}}$$

Leads to:

$$w^* = q_{pT,T} \cdot w_i + 1 - q_{pT,T} = 1 + q_{pT,T} (w_i - 1)$$
Improvement of the injection width description

Inserting this assumption of $w^*$ in $q_{pT,T_{cb}}$, makes it possible to isolate $q_{pT,T_{cb}}$

\[
q_{pT,T_{cb}} = 1 + \frac{I_{tf}}{I_{QFH} \cdot q_{pT,T_{cb}}} (1 + q_{pT,T_{cb}} (w_i - 1))^2
\]

And leads to a quadratic assumption for $q_{pT,T_{cb}}$ with the following unique solution:

\[
q_{pT,T_{cb}} = \frac{1 + 2 \cdot (1 - w_i) \cdot \frac{I_{tf}}{I_{QFH}} + \sqrt{1 + 4 \frac{I_{tf}}{I_{QFH}} \cdot w_i}}{2 \left(1 - \frac{I_{tf}}{I_{QFH}} (w_i - 1)^2\right)}
\]

This solution can be implemented in a simulator and therefore is usable for the calculation of $w_{new}$

\[
a_{new} = 1 - \frac{I_{ck}}{I_{tf}} \cdot q_{pT,T_{cb}} \quad w_{new} = \frac{a_{new} + \sqrt{a_{new}^2 + AHC}}{1 + \sqrt{1 + AHC}}
\]
The critical current $I_{ck}$ behaves as expected as a limit between the high and low current range.
Modeling results

Using the improved injection width description the collector current and the quasi saturation can be modeled well.
Modeling results

However, the ac- and dc- modeling is mostly decoupled in HICUM/L0 by $I_{ck}$ still a coupling exists.

Therefore it is difficult to get a fit sufficient fit for the $f_t$-characteristic and the quasi saturation in parallel at a single transistor extraction.

Suggestion: Doubling of the parameters VLIM, RCI0 and AHC
Modeling results

With the doubled parameter set the quasi saturation and the ft-characteristic can be modeled sufficient.

But further question to investigate:

What is the reason for the difference in the model parameters?
Summary

- The transfer current modeling is improved to avoid the appearance of a negative slope.
- Non-iterative equations for the injection width $w$ and the normalized hole charge $q_{pT,T}$ are developed.
- Using this improved equation the collector current can be modeled sufficiently and in no case a negative slope occurs.
- However, the quasi saturation modeling is not sufficient.
- Therefore a improved description of the injection width is derived, which takes into account the intersection between $q_{pT,T}$ and $w$.
- Using this equations a good fit of the quasi saturation is possible.
- However, the dc- and ac-modeling is still coupled by $I_{ck}$ and makes it difficult to get a sufficient fit of the quasi saturation and the ft-characteristic in parallel.
- Therefore a doubling of the parameters $RC10$, $VLIM$ and $AHC$ is suggested.