

HICUM/L0: Investigation and Improvement of the DC- High Current Modeling



Never stop thinking

Outline

- Transfer current modeling in HICUM/L0
- Modeling results
- Improved model equations
- Modeling results with the improved model equations
- Investigation of the quasi saturation modeling
- Summary

Transfer current modeling in HICUM/LO

In HICUM/LO the total transfer current is calculated from the ideal transfer current it_i dividing it through the normalized hole charge $q_{pT,T}$.

$$itf = \frac{it_i}{q_{pT,T}} \quad itr = \frac{it_r}{q_{pT,T}} \quad it = itf - itr$$

$$q_{pT,T} = 1 + \underbrace{\frac{q_{jCi}}{VEF} + \frac{itf}{IQF} + \frac{itr}{IQR}}_{q_{pT,l}} + \underbrace{\frac{itf \cdot w(itf)^2}{IQFH} + \frac{itf^2}{ick} \frac{TFH}{IQFH}}_{\Delta q_{fh}}$$

$$w = \frac{a + \sqrt{a^2 + AHC}}{1 + \sqrt{1 + AHC}} \quad a = 1 - \frac{ick}{itf}$$

$q_{pT,l}$ includes the modeling of the Early effect (VEF) and the knee currents (IQR, IQF). And it nearly corresponds to the definition of the normalized base charge q_B in the SGP- model.

Δq_{fh} is derived from the base-collector charge term and emitter charge term of the forward minority charge Q_{ft} . The additional usage in $q_{pT,T}$ and the introduction of IQFH and TFH was necessary to decouple the ac- and dc- behavior in HICUM/LO. They are used to model the additional decrease of the collector current slope and the quasi saturation.

Transfer Current Modeling in HICUM/LO

Because of the decoupling, a non-iterative solution for the calculation of itf , $q_{pT,T}$ and w has to be found. Therefore the low-transfer current itl is introduced in HICUM/LO:

$$itfl = \frac{itfi}{q_{pT,l}} \quad itrI = \frac{itri}{q_{pT,l}} \quad itl = itfl - itrI$$

Simplifying the calculation of $q_{pT,T}$ by using itl instead of it ,

$$q_{pT,T} = 1 + \underbrace{\frac{q_{jCi}}{VEF} + \frac{itfl}{IQF} + \frac{itrI}{IQR}}_{q_{pT,l}} + \underbrace{\frac{itfl \cdot wI(itfl)^2}{IQFH} + \frac{itfl^2}{Ick} \frac{TFH}{IQFH}}_{\Delta qfh}$$

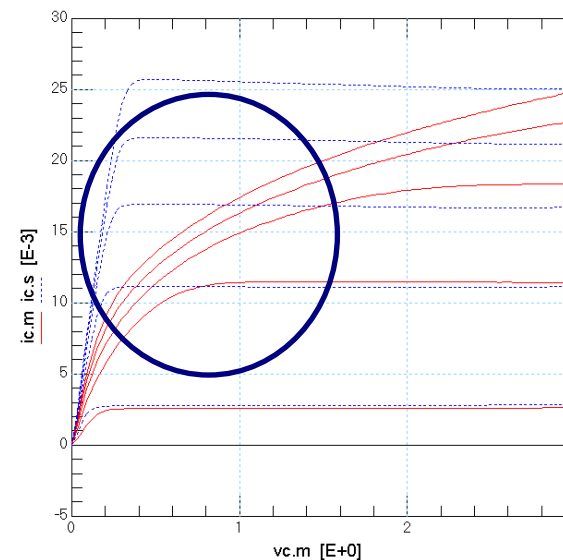
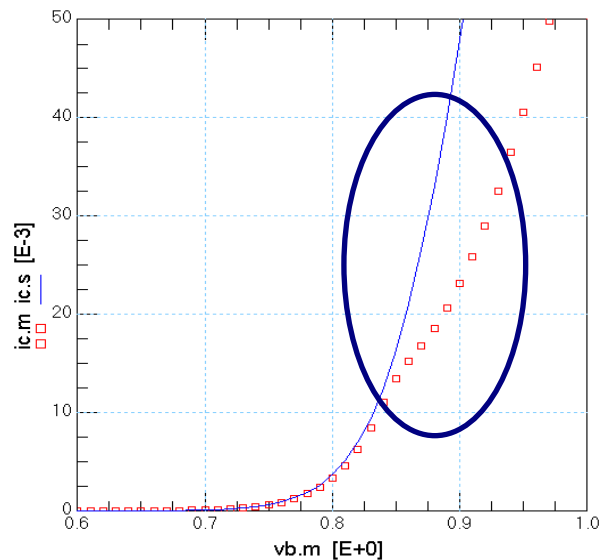
gives a quadratic assumption for $q_{pT,l}$ with the following solution:

$$q_{pT,l} = \frac{q_j}{2} + \sqrt{\left(\frac{q_j}{2}\right)^2 + q_m} \quad q_j = \frac{q_{jCi}}{VEF} + 1 \quad q_m = \frac{itfi}{IQF} + \frac{itri}{IQR}$$

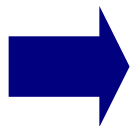
And it makes possible to calculate w and $q_{pT,T}$ without iteration.

Modeling results (Case I)

Case I: $I_{QF} = 22.22\text{m}$, $I_{QFH} \rightarrow \infty$ and $T_{FH} \rightarrow 0$, therefore the new modeling equations are not active: $itf = itfl$.



The modeling results correspond to the one, which are reached with the SGP-model. The modeling of the high current range of the collector current and the modeling of the quasi saturation are not sufficient.



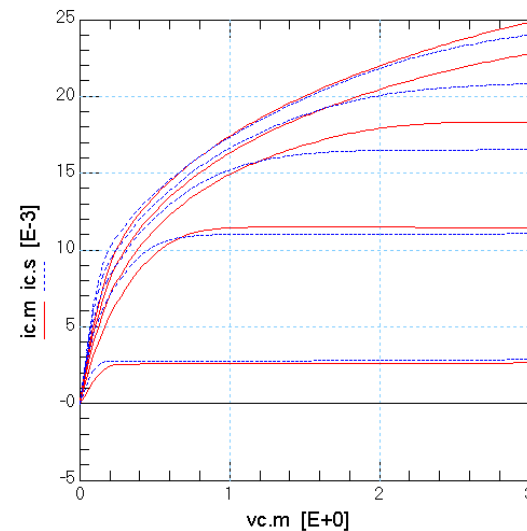
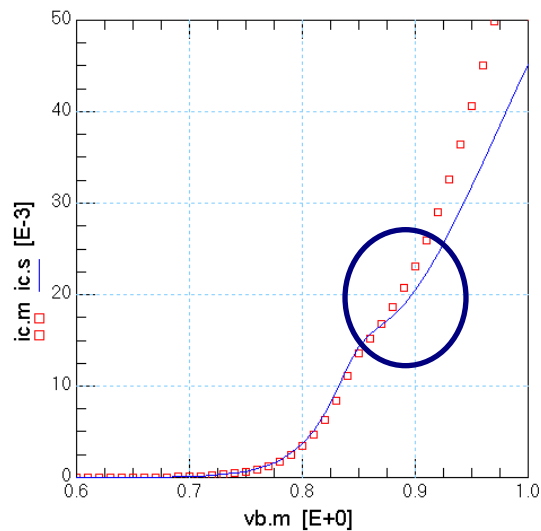
Δq_{fh} is necessary

Modeling results (Case II)

Case II: IQF=22.00m, IQFH=6.30m, TFH=2.00p

In this case the behavior at the high current range is mostly influenced by the base-collector charge term:

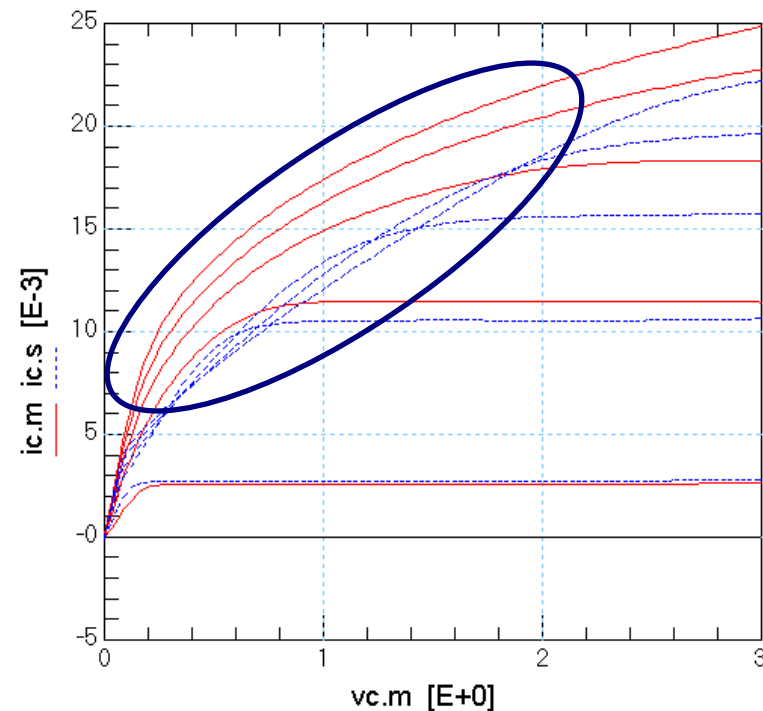
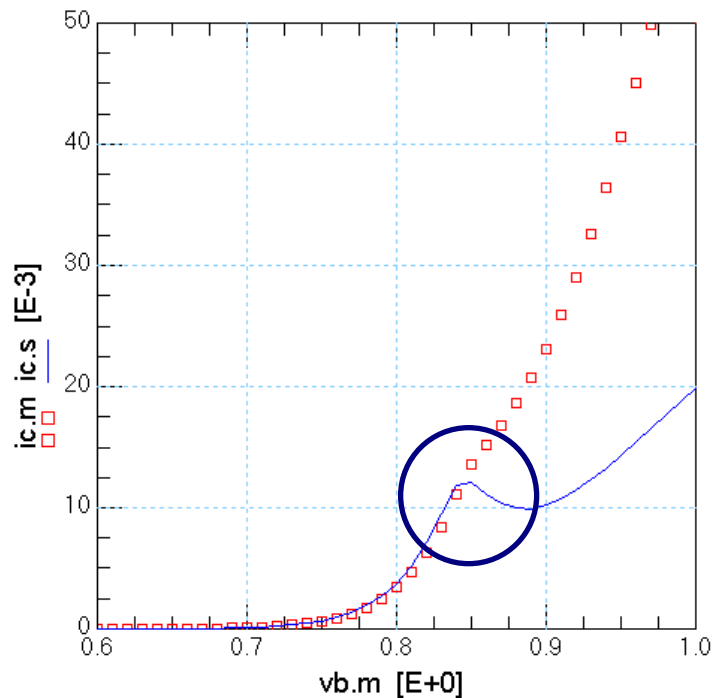
$$\Delta q_{fcb} = \frac{itfl \cdot wl(itfl)^2}{IQFH}$$



The quasi saturation looks sufficient, but a kink in the collector current occurs.

Modeling results (Case IIa)

Case IIa: IQF=22.00m IQFH=3.00m TFH=2.00p
 Compared to Case II IQFH is additionally decreased.



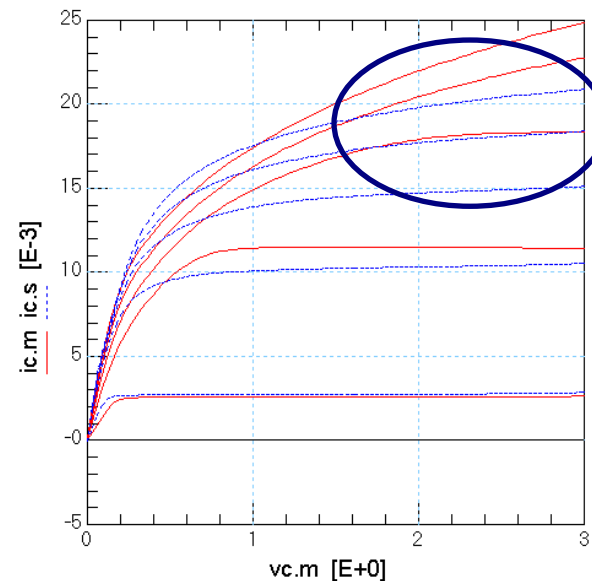
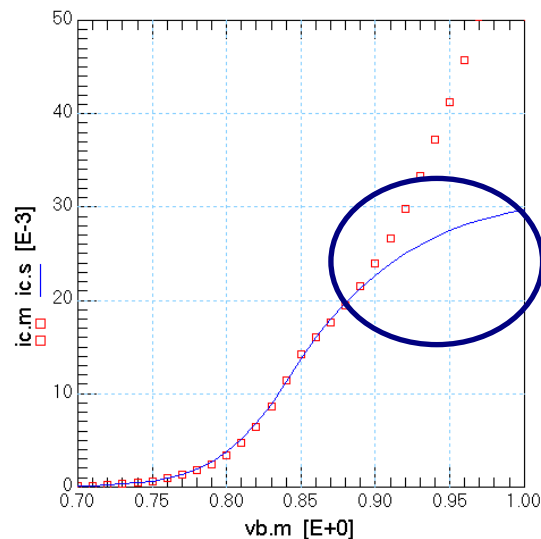
A negative slope in the collector current occurs, which is also visible in the output characteristics.

Modeling results (Case III)

Case III: IQF=22.00m, IQFH=32.20m, TFH=521.2m

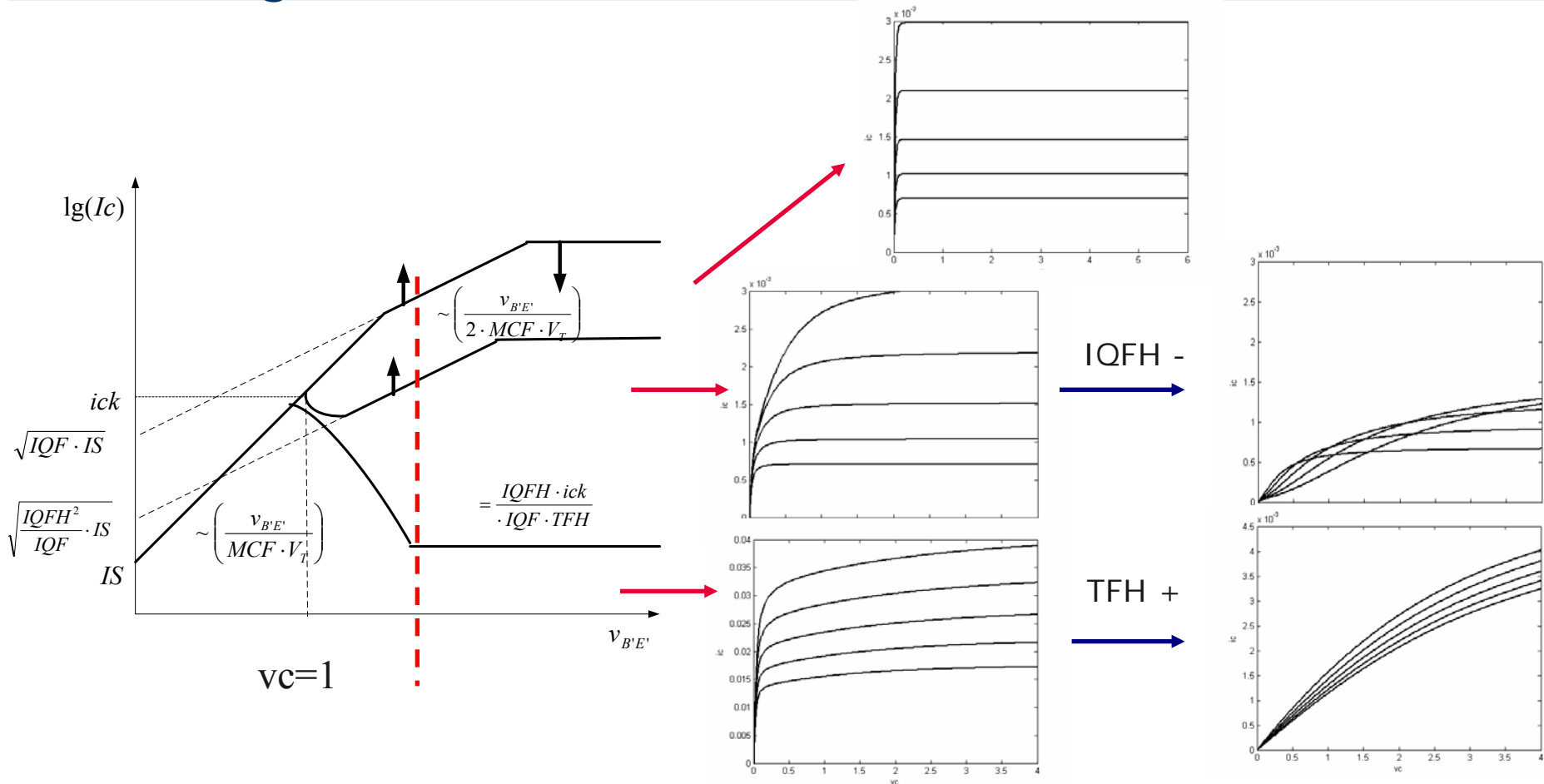
In this case the behavior in the high current range is mostly influenced by the emitter charge term:

$$\Delta q_{fhe} = \frac{itfl^2}{ick} \frac{TFH}{IQFH}$$



For low vc values the quasi saturation looks sufficient, at high vbe the collector current converges to a constant value.

Modeling results



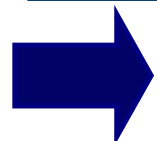
In Case II and Case III a negative slope in the collector current can occur.



The negative slope has to be avoided by improved model equations

Improved model equations

Reason for the negative slope is the usage of the low-transfer-current $itfl$ for the calculation of $q_{pT,T}$ and the injection width w_i . Due to this the injection width is calculated with an overestimated transfer current and the influence of Δq_{fh} on itf is changed.

 New model equations for $q_{pT,T}$ and w are investigated which does not need $itfl$, but also can be calculated non-iteratively.

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

$$q_j = \frac{qjci}{VEF} + 1$$

$$q_{mneu} = \frac{itfi}{IQF} + \frac{itri}{IQR} + \frac{itfi}{IQFH} \cdot w^2 + \left(\frac{itfi^2}{ick} \frac{TFH}{IQFH}\right)^{2/3}$$

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

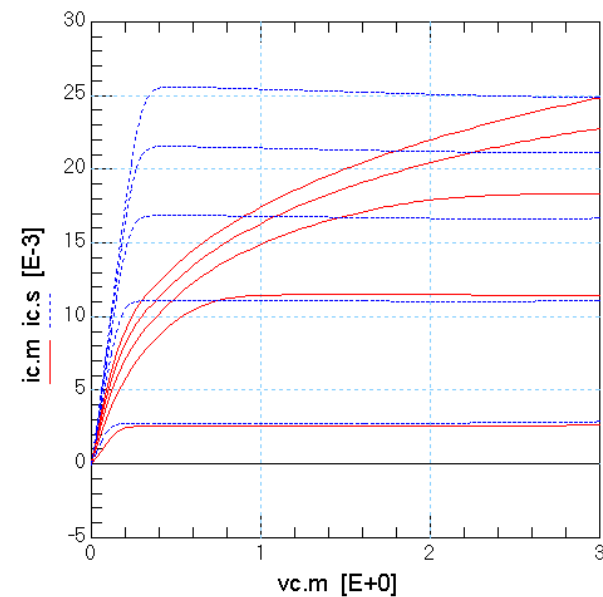
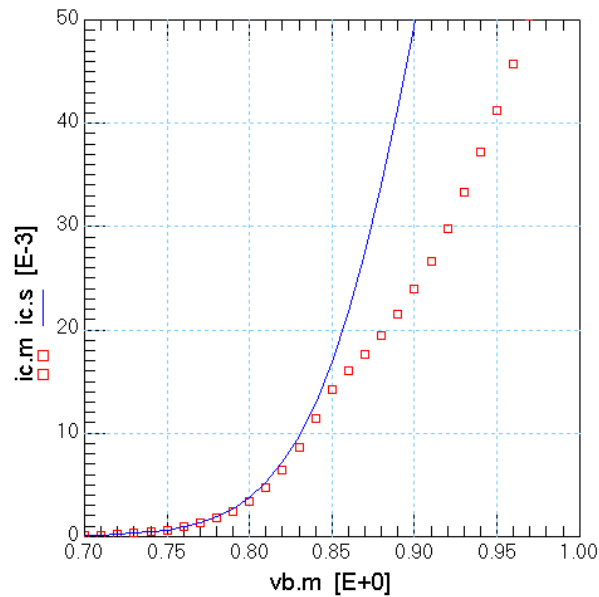
$$a_{new} = \frac{1}{(1 + Ick / \sqrt{Itfi \cdot IQFH})}$$

$$w_{new} = \frac{a_{new} + \sqrt{a_{new}^2 + AHC}}{1 + \sqrt{1 + AHC}}$$

Modeling results with the improved model equations



Case I: $IQF = 22.22\text{m}$, $IQFH \rightarrow \infty$ and $TFH \rightarrow 0$



In Case I the result for the improved model equations corresponds to one of the unimproved model equations, because there is no influence of Δq_{fh} .

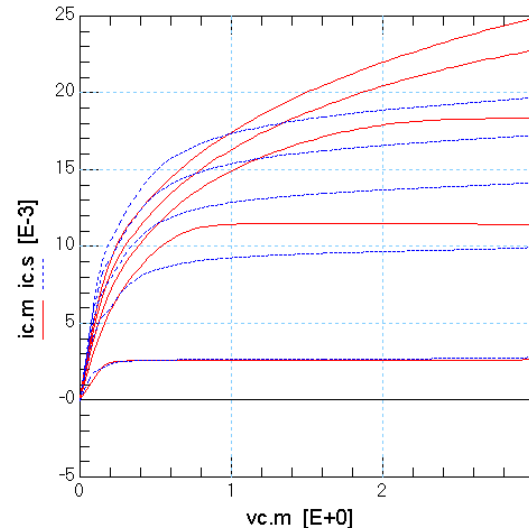
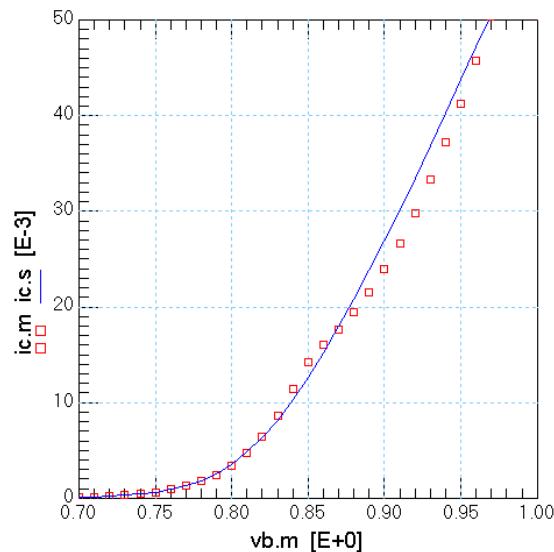
Modeling results with the improved model equations



Case II: IQF=22.00m, IQFH=2.12m, TFH=2.00p

In this case the behavior in the high current range is mostly influenced by the base-collector charge term:

$$\Delta q_{f h c b} = \frac{i t f \cdot w(i t f)^2}{I Q F H}$$



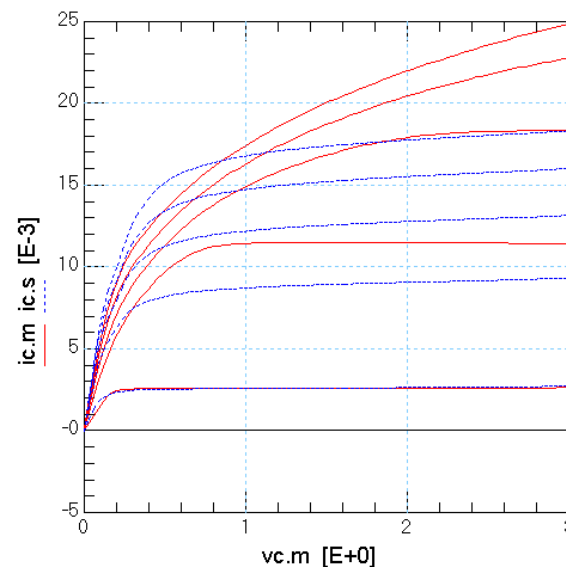
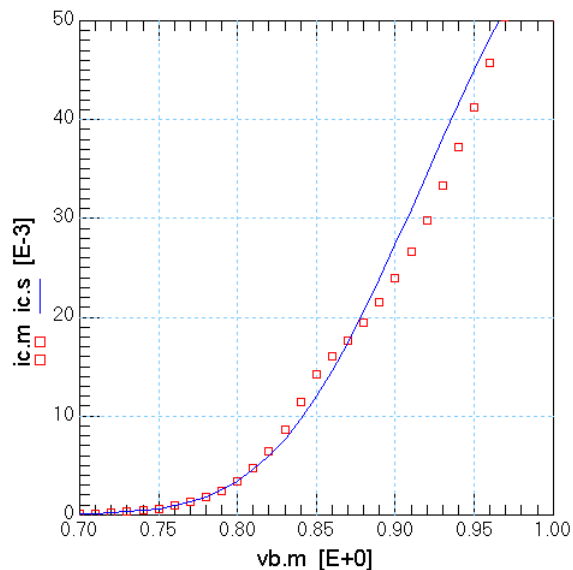
In comparison to the unimproved model equations no kink or negative slope occurs. However, the quasi saturation is a bit worse.

Modeling results with the improved model equations

Case III: IQF=22.00m, IQFH=98.20m,TFH=521.2m

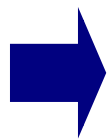
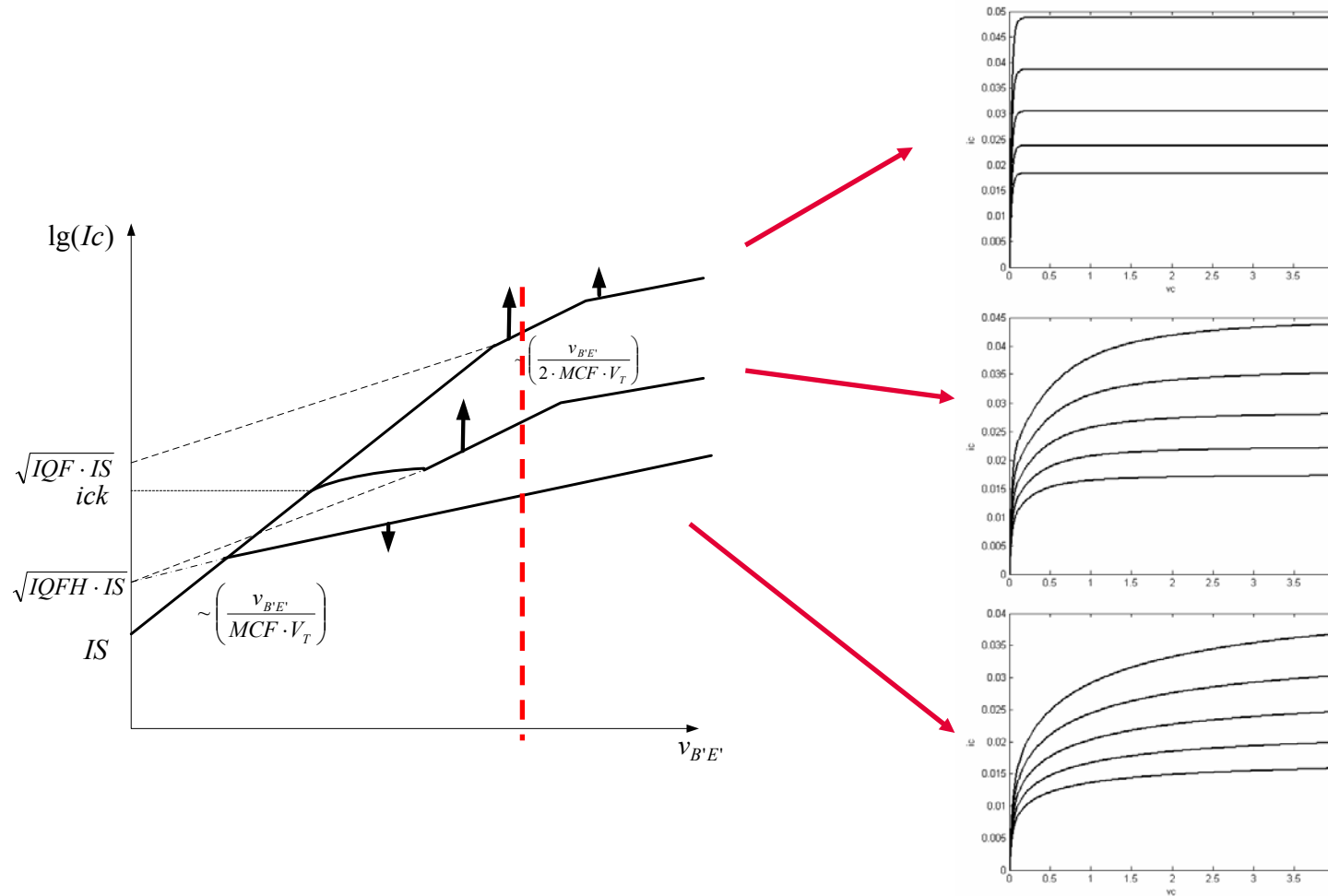
In this case the behavior in the high current range is mostly influenced by the emitter charge term:

$$\Delta q_{fhe} = \frac{itf^2}{ick} \frac{TFH}{IQFH}$$



In comparison to the unimproved model equations the collector current does not converge to a constant value. However, also in this case the quasi saturation is a bit worse.

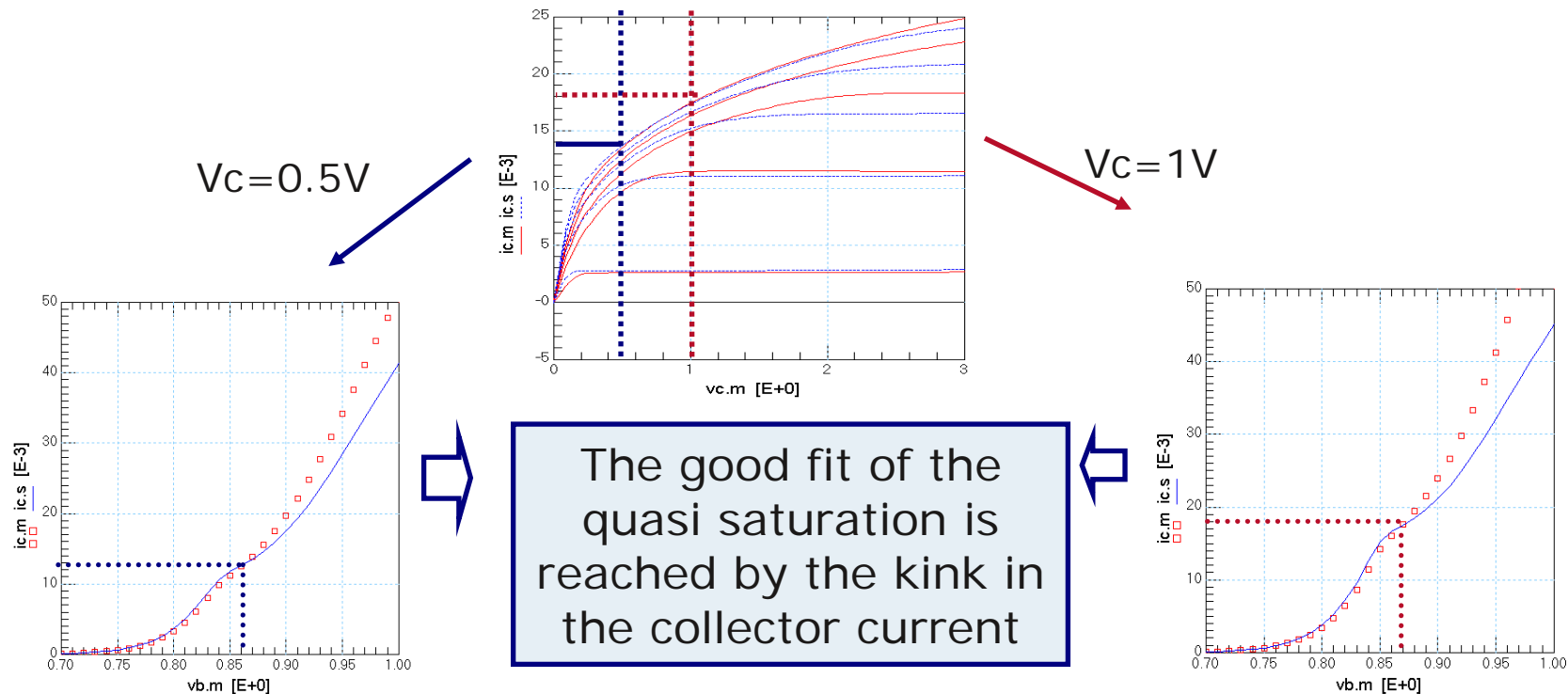
Modeling results with the improved model equations



In no case a negative slope in the collector current occurs. However, the quasi saturation is modeled worse than with the unimproved model equations.

Investigation of the quasi saturation modeling

Why does the quasi saturation look better for the unimproved model equations?



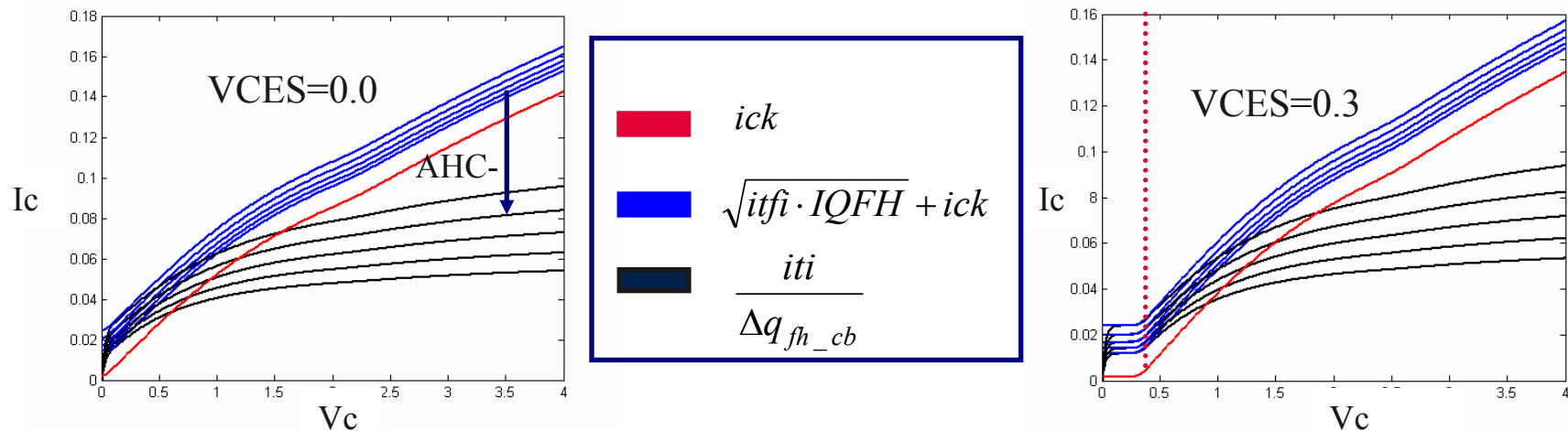
The appearance of the kink depends on ick and therefore on v_c .
 But the behavior does not reflect the v_c -dependence of the base-collector charge term and the emitter charge term.

Investigation of the quasi saturation modeling

Base-collector charge term

$$\Delta q_{fh_cb} = \frac{itf \cdot w(itf)^2}{IQFH} = \sqrt{\frac{itfi}{IQFH}} \cdot w$$

$$itf_{cb} = \frac{\sqrt{itfi \cdot IQFH}}{w} \approx \frac{\sqrt{itfi \cdot IQFH}}{a} = \frac{\sqrt{itfi \cdot IQFH}}{\left(1 - \frac{ick}{itf}\right)} = \underline{\underline{\sqrt{itfi \cdot IQFH} + ick}}$$

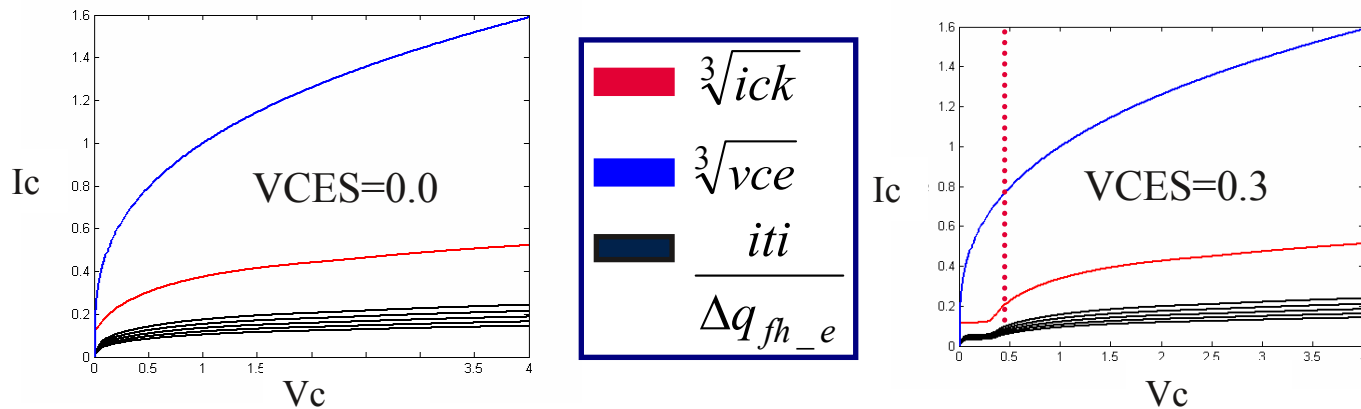


The modeling of the quasi saturation depends on the characteristic of ick . However, ick is fixed by the modeling of the ac-behavior. For $VCES > 0$ a kink in the output characteristic occurs.

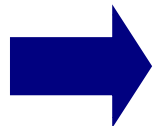
Investigation of the quasi saturation modeling

Emitter charge term

$$\Delta q_{fh_e} = \frac{itf^2 \cdot TFH}{ick \cdot IQFH} = \sqrt[3]{\frac{itfi^2 \cdot TFH}{ick \cdot IQFH}} \quad \Rightarrow \quad itf_e = \sqrt[3]{itfi \cdot ick \cdot \frac{IQFH}{TFH}}$$



The v_c -dependence of the transfer current itf_e and therefore the quasi saturation modeling is defined by the root function $\sqrt[3]{ick}$. For $VCES > 0$ a kink occurs, too.



For none of both high current terms a sufficient fit of the quasi saturation is reached. ick is directly reflected in the output characteristic which leads to a kink for $VCES > 0$. Further investigation and a modification of the model equations are necessary.

Summary

- In HICUM/L0 new dc-high current terms were introduced to model the additional decrease of the collector current slope and the quasi saturation.
- For certain values of the new model parameters IQFH and TFH a negative slope occurs in the forward transfer current *itf*.
- To avoid this behavior new model equations were developed which do not need the low transfer current *itl*.
- For the new modeling equations the modeling of the quasi saturation seems to be worse than for the unimproved ones.
- But for the unimproved model equations the quasi saturation was reached by the kink in the forward transfer current *itf*.
- The run of the quasi saturation, which is defined by the new dc-high current terms, directly reflect the characteristic of *ick*. Therefore a kink occurs in the output characteristic for $V_{CES} > 0$.
- To avoid this behavior further investigations and modifications of the model equations are necessary.