

Benchmarking the vces and vdck model variants of HICUM

15th AKB Workshop at XFAB FRA, Corbeil-Essonnes France, 9th-10th November, 2023

Letter Session

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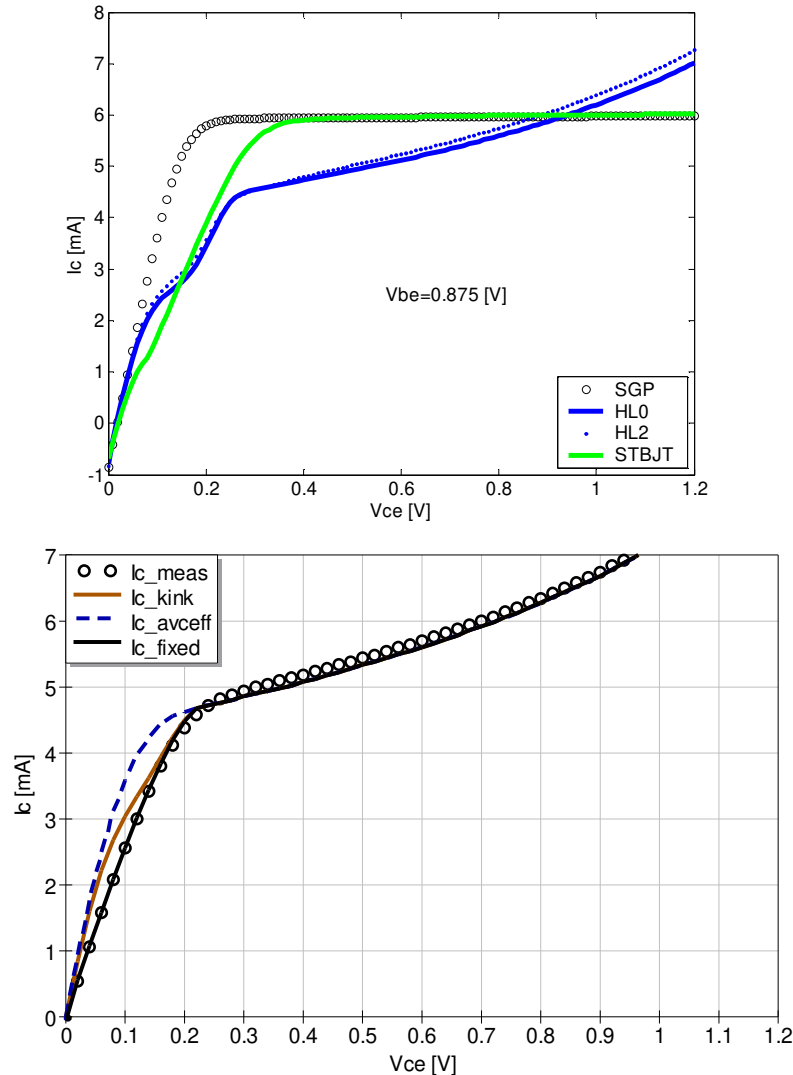
Outline

Benchmarking the vces and vdck model variants of HICUM

- a brief summary of the kink issue
- the vces and vdck models on DUT1
- FT and FMAX using the vces and vdck approaches on DUT1
- comparing the vces and vdck models on DUT2
- introduction of a new – V_{bici} related qpcc - term in the collector add'l charge
- repeating the comparisons with the qpcc approach
- an issue using the V_{bici} related qrT and qpcc terms
- fixing the problem by limiting the growth of V_{bici} (or qpcc) for $V_{ciei} < 0$
- summary

Kinks in a nutshell

Benchmarking the vces and vdck model variants of HICUM



[1] performed extractions from a hicumL2 synthetic data for various models. Simulation results with the published cards are displayed on the top figure.

SGP: QucsStudio simulation using the built in model

HL0: QucsStudio simulation using hicumL0_v2p1p1.va

HL2: QucsStudio simulation using hicumL2V3p0p0.va (synthetic)

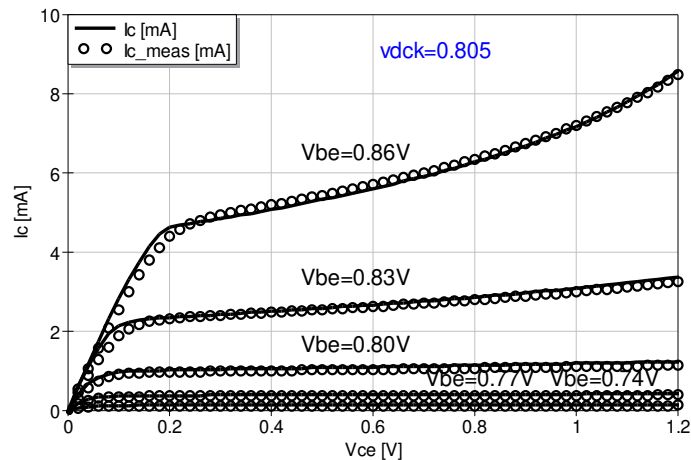
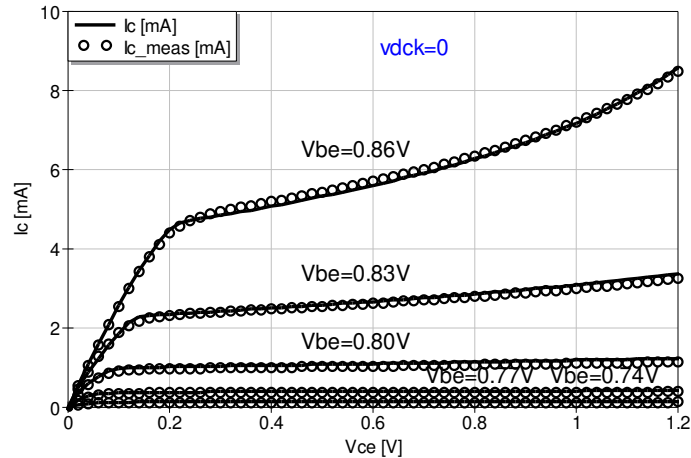
STBJT: ELDO simulation (courtesy of D. Celi, STM)

The Kirk effect is not included in SGP since the excess collector (and emitter) charges are not modeled. The high current effects are described by a single parameter IKF. At very high currents it implies a $\frac{1}{2}$ exponent in the transfer current according to conductivity modulation in the base (Webster effect). It is seen that the forward output current from each of the HL0, HL2 and STBJT cards starts from the origin with the slope of the SGP model. Generally, all kink affected simulations have a false initial section due to the low level of add'l charges in Q_{pT} .

It is confirmed by a measured device too on the left. The fixed model blends in measurements with a reduced initial slope eliminating the kink. The kink can also be „removed” by increasing the smoothing factor avceff. As shown in [2] this implies an elevated ICK so that no Kirk domain can exist any more. Actually the SGP model is returned with no additional charges. Kink is not generated but the fit to measurements gets destroyed. There is no physics behind this technique hence its application is unadvised.

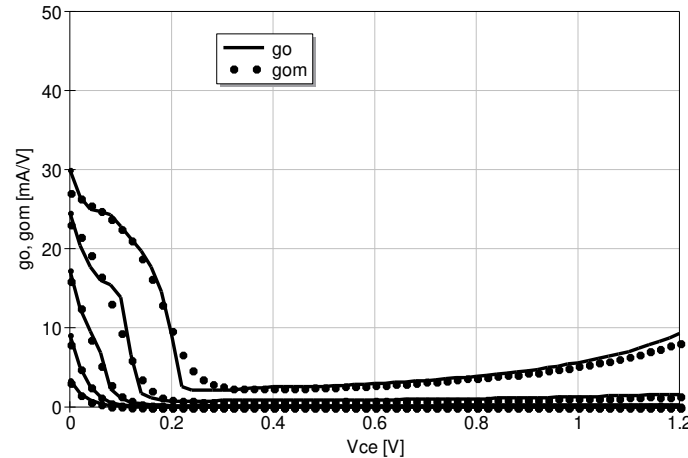
Vbe controlled forward output plots (DUT1)

Benchmarking the vces and vdck model variants of HICUM



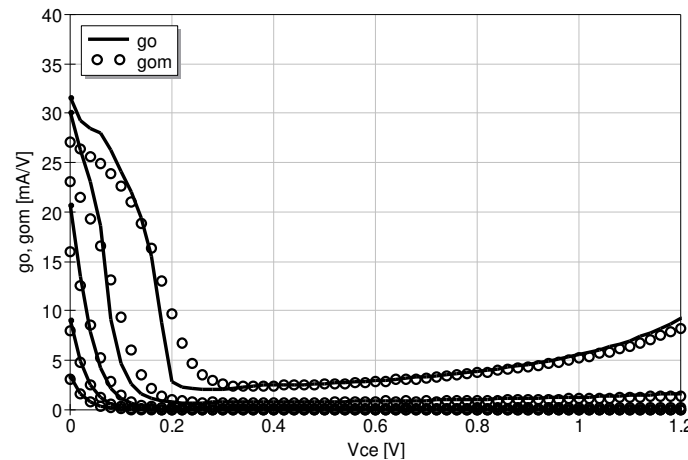
Top: vces model

Bottom: vdck model



Left: Vbe controlled fwd. output

Right: Output conductance



All simulations in this paper have been prepared by hicumL2V3p0p0.va implemented in QucsStudio. Modifications required for the analyses are detailed here and in [2]. Emphasis is placed on the detection of possible kinks by adding the corresponding output conductance plots as well.

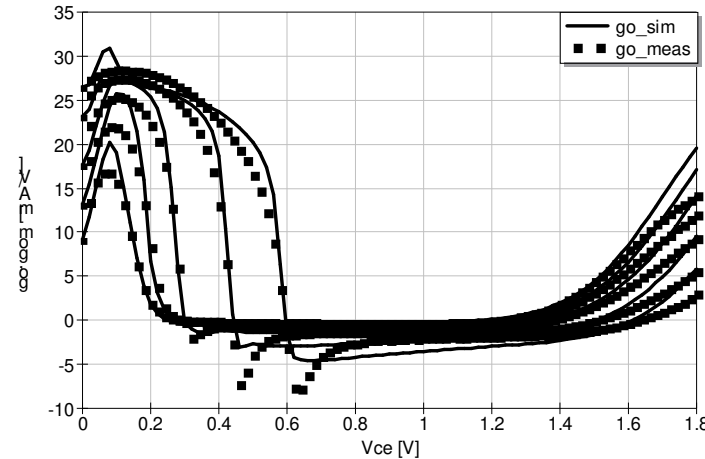
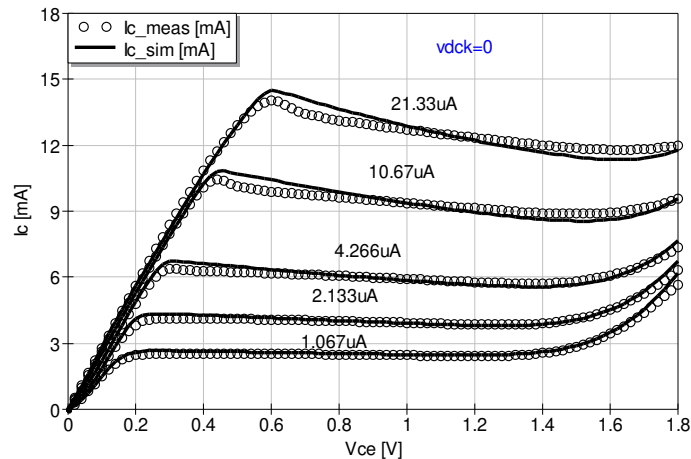
Brackets in the title mark that the name DUT1 was not shown in [2].

The top curves repeat the results of [2] with vces=61.78mV and zero Ick asymptote for $V_{ce} \rightarrow -\infty$. vdck=0 in the model automatically activates the vces mode of operation.

The lower pair of plots have been prepared using vdck=0.805V. A non-zero vdck automatically puts off the vces mode. The rest of the Ick related model parameters have been left as extracted in [2] with vces control.

Ib controlled forward output plots (DUT1)

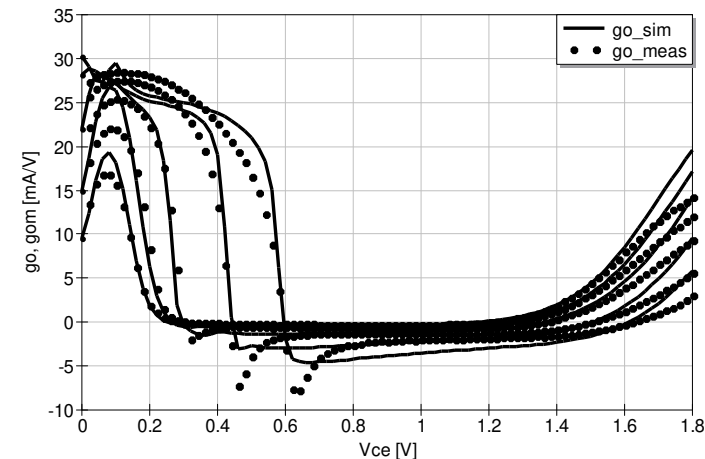
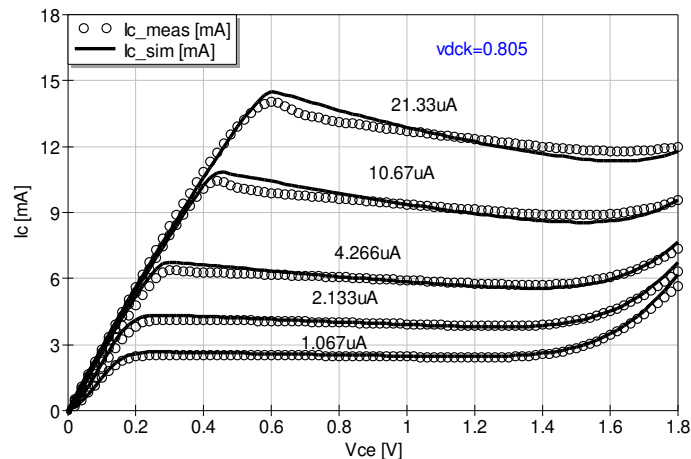
Benchmarking the vces and vdck model variants of HICUM



The top curves repeat the results of [2] with $v_{ces}=61.78$ mV and zero I_{ck} asymptote. $v_{dk}=0$ in the model automatically activates the vces mode of operation.

The lower pair of plots have been prepared using $v_{dk}=0.805$. A non-zero v_{dk} automatically puts off the vces mode. The rest of the I_{ck} related model parameters have been left as extracted in [2] with vces control.

The plots indicate that changing from the vces to the v_{dk} model affects only the output conductance g_o along the largest two branches. Strongly tolerable.



Top: vces model

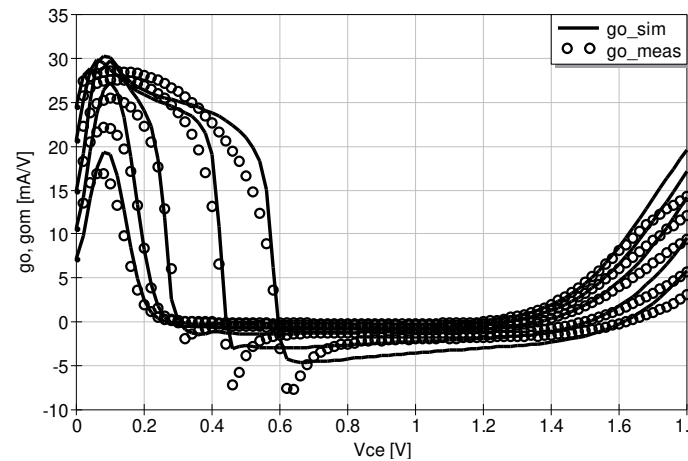
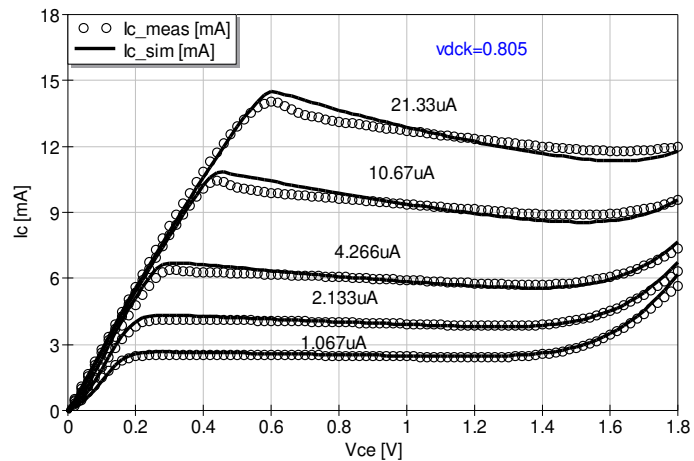
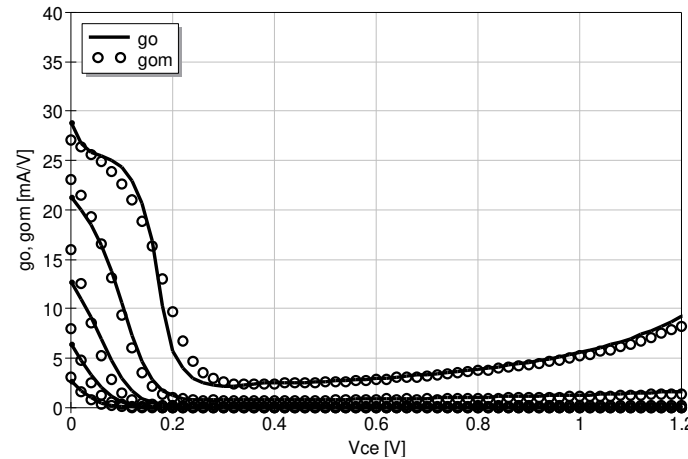
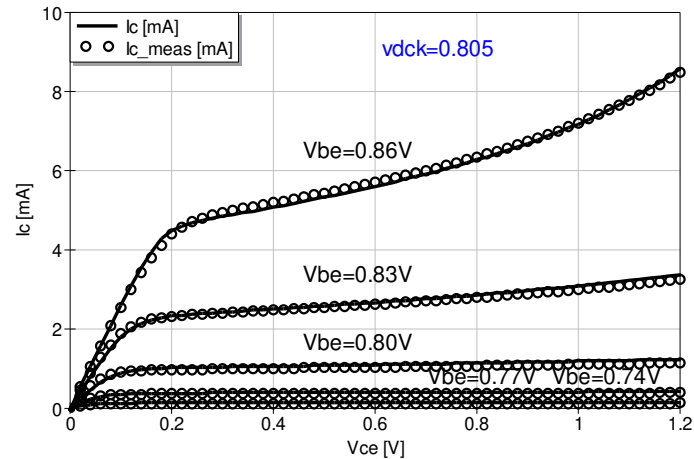
Bottom: v_{dk} model

Left: V_{be} controlled fwd. output

Right: Output conductance

Vbe controlled forward output plots (DUT1), improvement

Benchmarking the vces and vdck model variants of HICUM



There has been a slight deviation on the bottom curve of the vdck model on slide#4. It could be eliminated by setting $hf0>1$ as suggested in [2] for the case of DUT2 (top). The modification has a little effect on the current controlled plots in that it improves the smoothness of the simulated output conductance (bottom).

At this point it can be concluded from a broader perspective as if a V_{bici} related term was missing from the model.

Top: Vbe controlled fwd. output

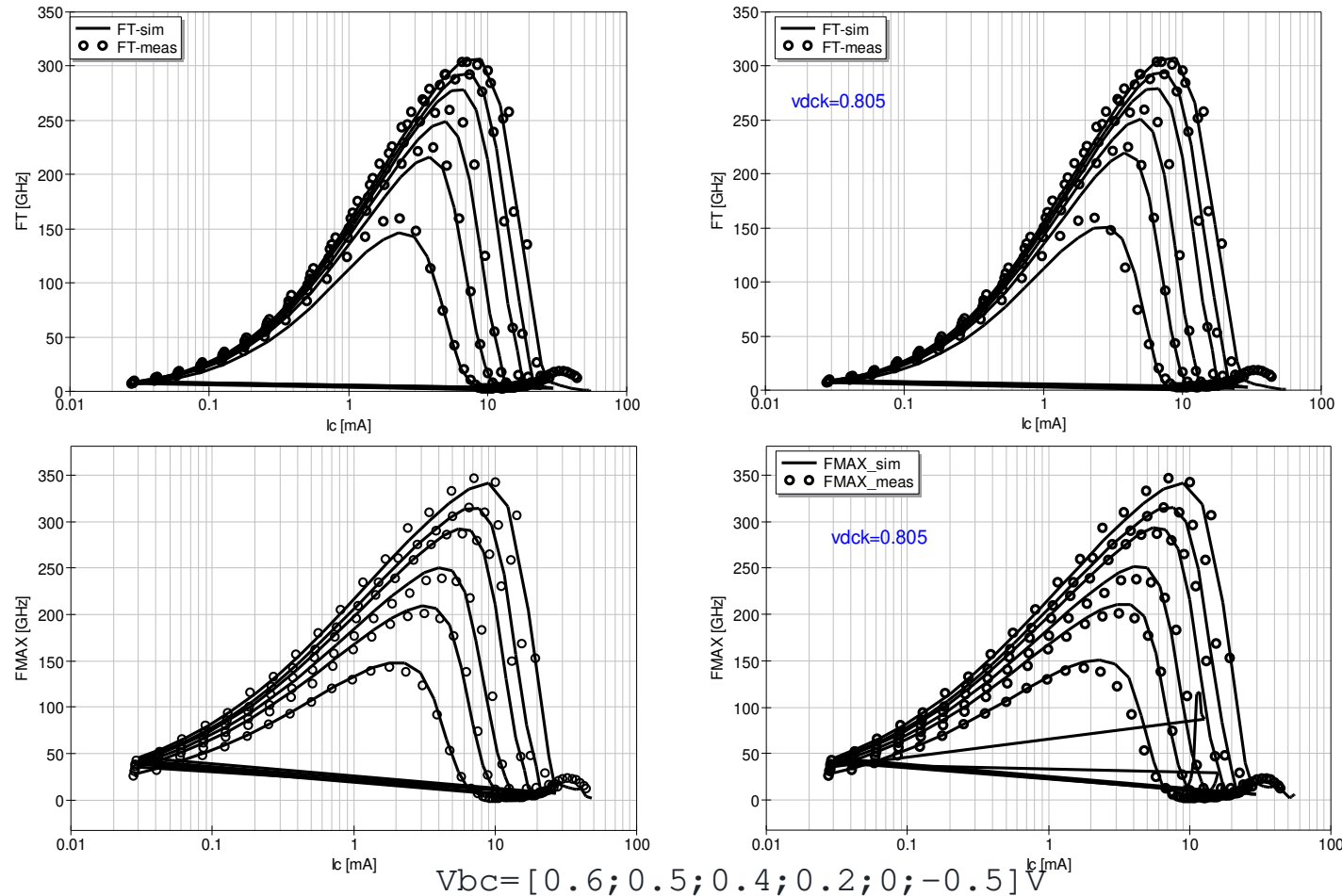
Bottom: Ib controlled fwd. output

Left: Output characteristics

Right: Output conductance

FT and FMAX, (DUT1)

Benchmarking the vces and vdck model variants of HICUM



The transit frequency practically remains the same with switching to the vdck model. There is a little difference between the FMAX plots at the $V_{bc}=0.6V$ curve, moreover simulation glitches appear in two points. The latter can often be observed on FMAX and may also come from the applied simulator.

As a summary simulated FT and FMAX behave the same in the two Ick models.

Left: vces model, [2]

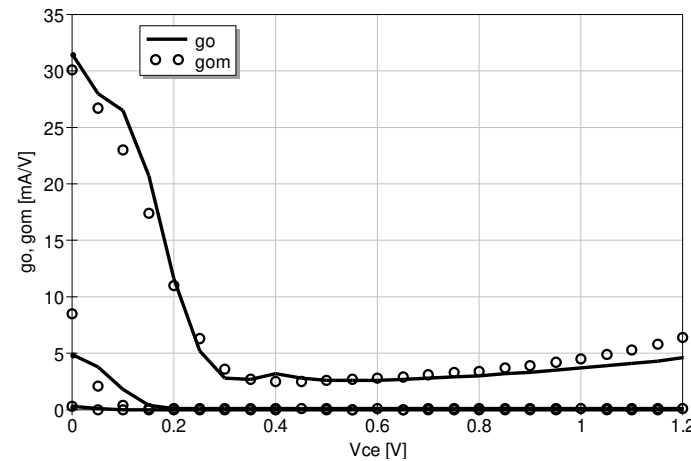
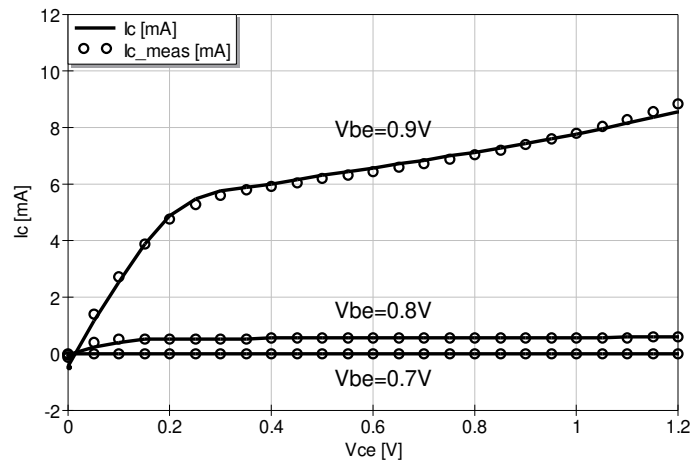
Right: model with $vdck=0.805$

Top: FT

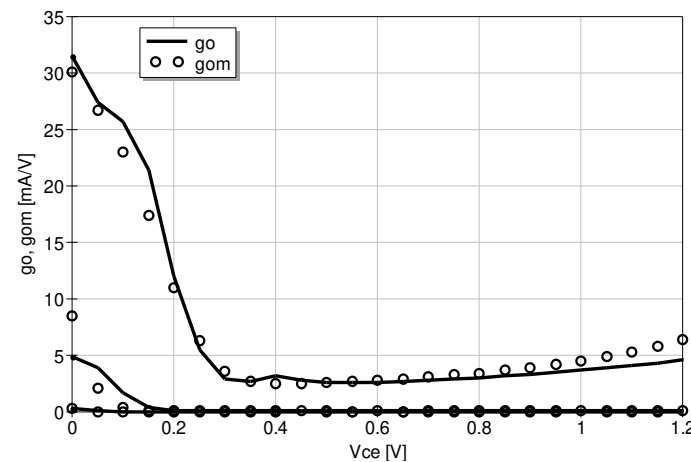
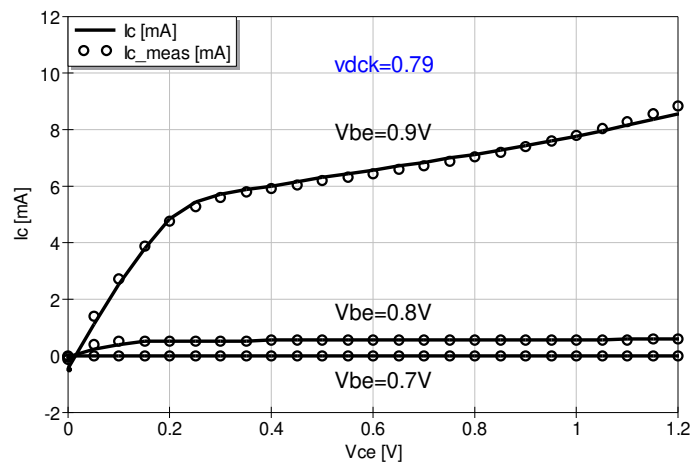
Bottom: FMAX

Vbe controlled forward output plots, DUT2

Benchmarking the vces and vdck model variants of HICUM



The top curves repeat the results of [2] with $v_{ces}=75.61\text{mV}$ and zero I_{ck} asymptote. $vdck=0$ in the model automatically activates the vces mode of operation.



The lower pair of plots have been prepared using $vdck=0.790$. A non-zero $vdck$ automatically puts off the vces mode. The rest of the I_{ck} related model parameters have been left as extracted in [2] with vces control.

Top: vces model

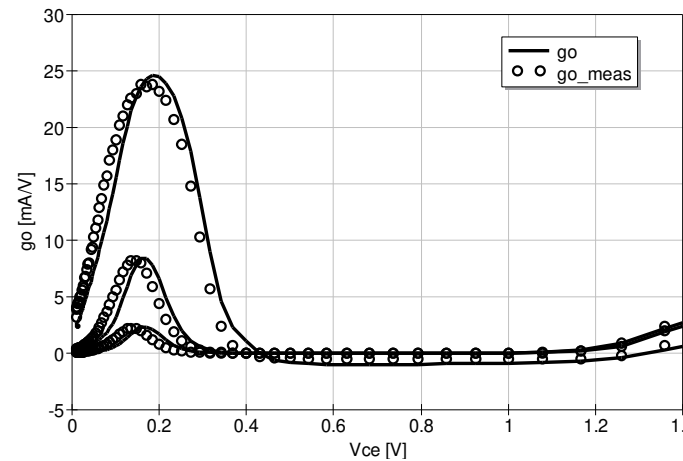
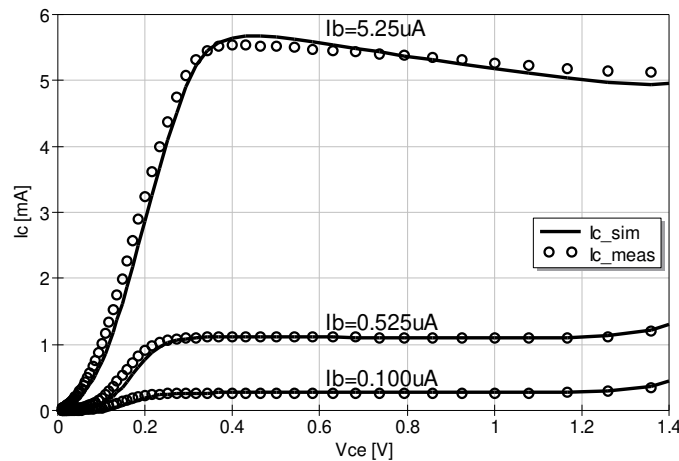
Bottom: vdck model

Left: Vbe controlled fwd. output

Right: Output conductance

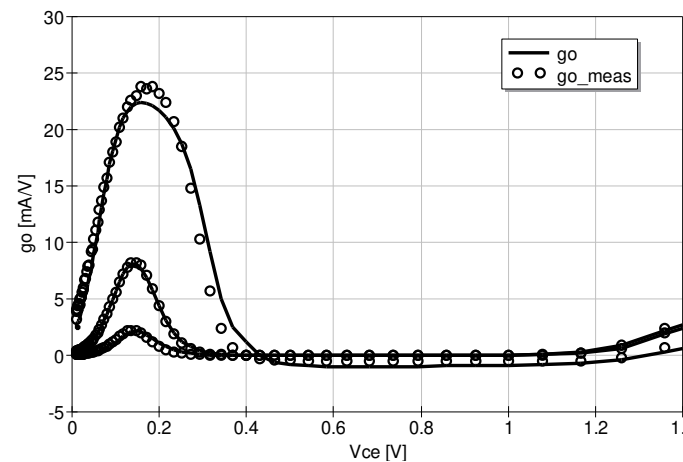
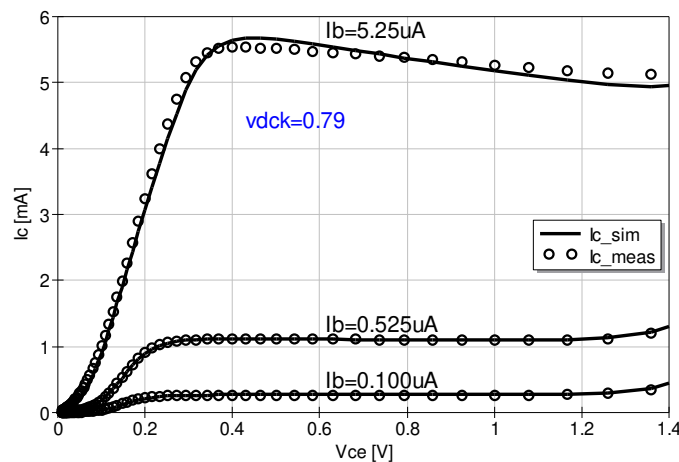
Ib controlled forward output plots, DUT2

Benchmarking the vces and vdck model variants of HICUM



The top curves repeat the results of [2] with $v_{ces}=75.61\text{mV}$ and zero I_{ck} asymptote. $vd_{ck}=0$ in the model automatically activates the vces mode of operation.

The lower pair of plots have been prepared using $vd_{ck}=0.790\text{V}$. A non-zero vd_{ck} automatically puts off the vces mode. The rest of the I_{ck} related model parameters have been left as extracted in [2] with vces control.



Note that all simulations have been performed with $hr_0>0$ confirming again the conjecture as if a V_{bici} related term missed from the model.

The deviations of the vces and vdck models are negligible.

Top: vces model

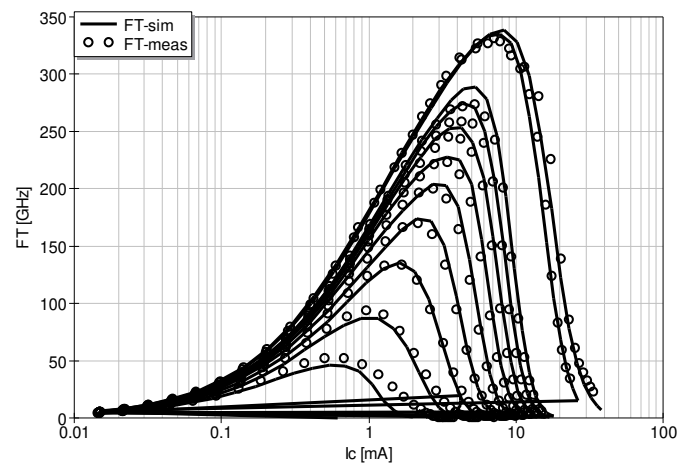
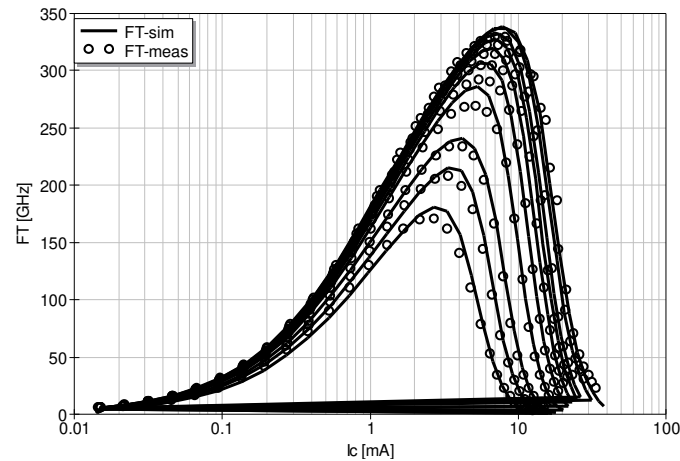
Bottom: vdck model

Left: Ib controlled fwd. output

Right: Output conductance

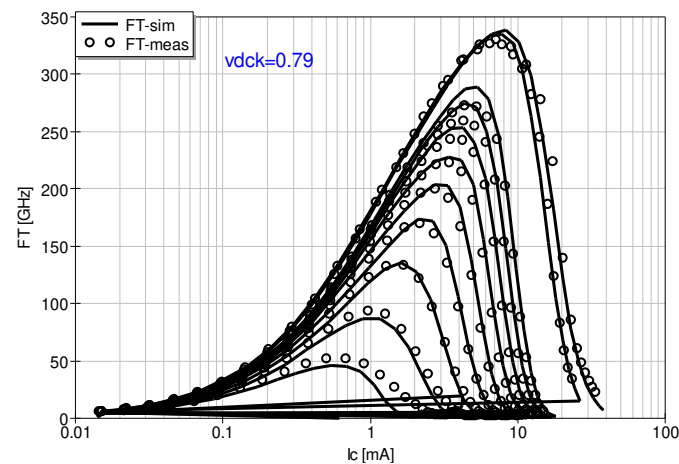
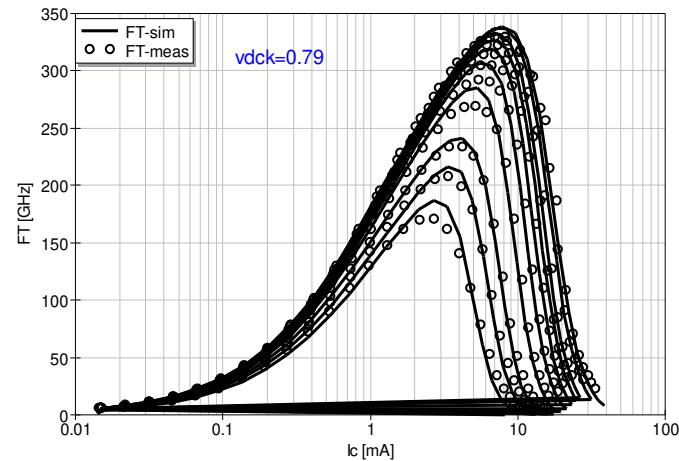
FT, DUT2

Benchmarking the vces and vdck model variants of HICUM



Top: $V_{bc}=0.6; 0.55; 0.5; 0.4; 0.3; 0.2; 0.1; 0; -0.25; -0.5$

Bottom: $V_{ce}=0.1; 0.15; 0.2; 0.25; 0.3; 0.35; 0.4; 0.45; 0.5; 1; 1.5$



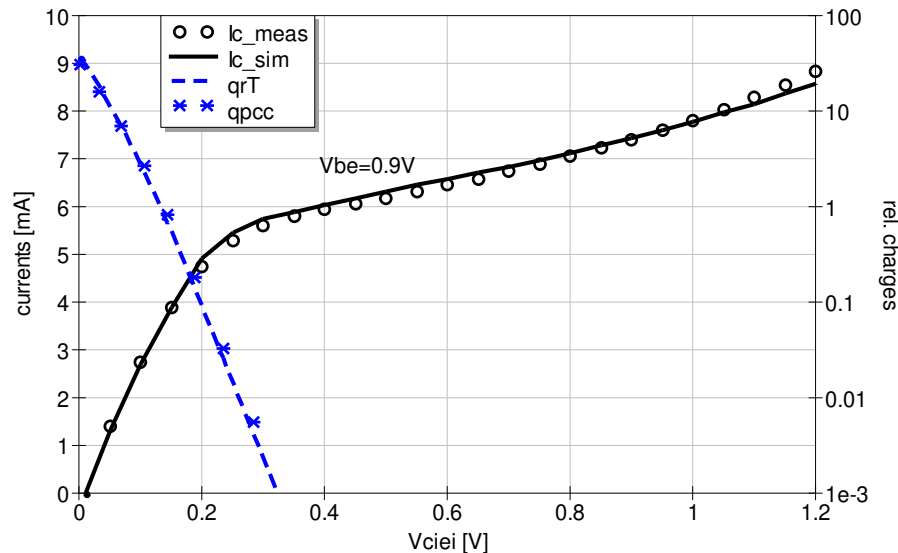
Left: vces model in [2]

Right: vdck model

There is hardly any difference seen between the vces and vdck model results. The same $vdck=0.790V$ served equally well for all the demonstrated DC and RF characteristics at invariant ICK parameters. Also the same $hr0>1$ value guaranteed the excellent agreements among the model variants.

A further corrective measure

Benchmarking the vces and vdck model variants of HICUM



DUT2 exhibited a DC misfit which could be eliminated by adapting a $hr0 > 1$ weighting factor to the reverse charge. The the dashed qrT line on the left plot removed the kink. The strictly aligning stars represent the alternative function to be discussed below.

[3] derived a - so far missing - term to the additional collector charge:

$$\bar{Q}_{pC, hc} = qp_{wi} w_{Ci} + \tau_{pCs} J_T w^2 \quad \text{with} \quad p_{wi} = \frac{N_{Ci}}{2} \left[\sqrt{1 + \left(\frac{2n_{iC}}{N_{Ci}} \right)^2 \exp\left(\frac{V_{bici}}{V_T}\right)} - 1 \right]$$

Using the proper quantities from the `hicumL2V3p0p0.va` code description one can write

$$qpc0 = \frac{A_E N_{Ci} w_{Ci}}{2}; \quad \frac{2n_{iC}(T_0)}{N_{Ci}} \cdot \frac{n_{iC}(T)}{n_{iC}(T_0)} = inci \cdot \frac{n_{iC}(T)}{n_{iC}(T_0)}; \quad \expbc = \left(\frac{2n_{iC}}{N_{Ci}} \right)^2 \exp\left(\frac{V_{bici}}{V_T}\right) = inci^2 \frac{i_{0r}}{c10}; \quad qpcc = q \cdot qpc0 \frac{\expbc}{1 + \sqrt{1 + \expbc}} \rightarrow$$

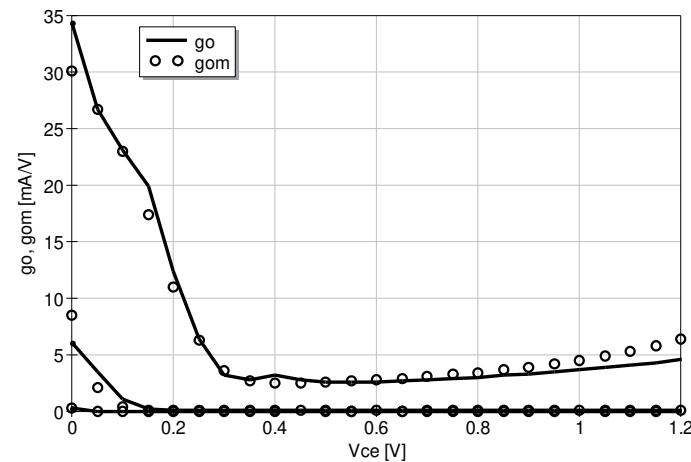
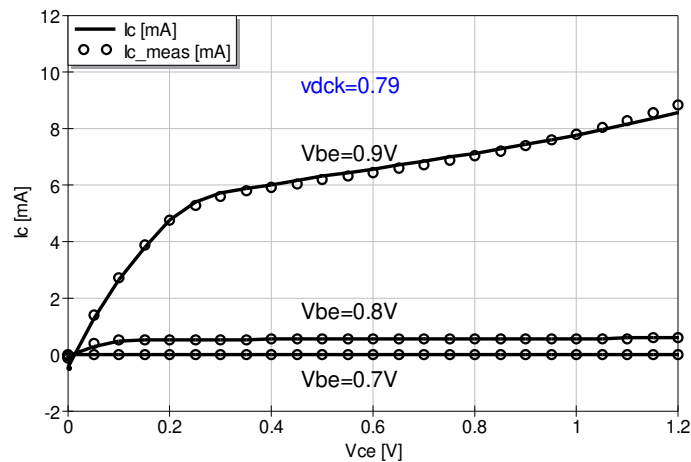
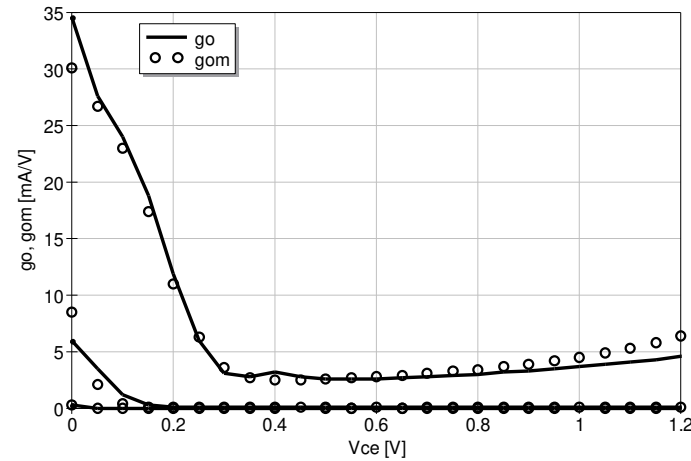
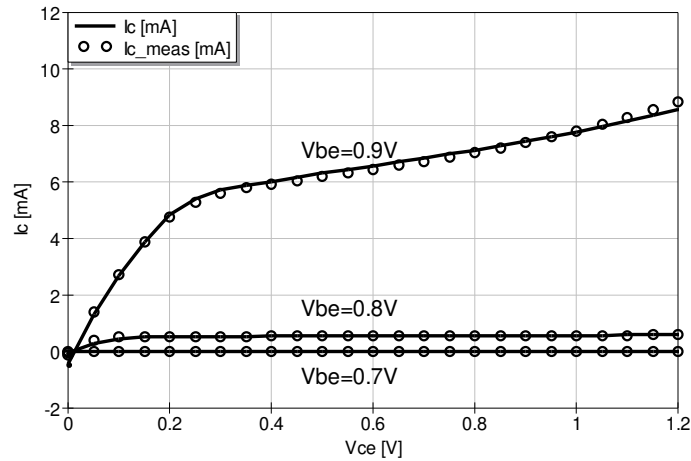
$Q_{pC, hc} = qpcc + hfc_t \cdot \tau_{pCs} i_{Tf} w^2$ has been implemented in the macro `HICQFF()` with *qpc0* and *inci* as model parameters by

```
qpccg = qpcc*FFvc_exp;\nQ_fT = hf0_t*Qf+Q_bf+hfe_t*FFdQef+hfc_t*FFdQcfc+qpccg);\n
```

No influences on the transit time, weighting factor and current spreading have been considered. The temperature dependence of n_{iC}^2 was taken equal to that of *c10*.

Vbe controlled forward output plots with qpcc, DUT2

Benchmarking the vces and vdck model variants of HICUM



Top: vces model

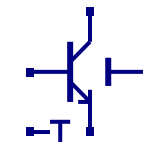
Bottom: vdck model

Left: Vbe controlled fwd. output

Right: Output conductance

These and the next plots have been prepared by an experimental model using the qpcc approach implemented as shown on the previous slide. The transistor disclosing the relevant parameters is seen below. The flcomp value serves as a switch for exporting some internal variables. As throughout this document the rest of the Ick related model parameters have been left as extracted in [2] with vces control. The zero Ick asymptote is a built-in feature.

The top curves show the vdck=0 model using vces=75.61mV while the lower pair of plots correspond to a setting of vdck=0.790V.

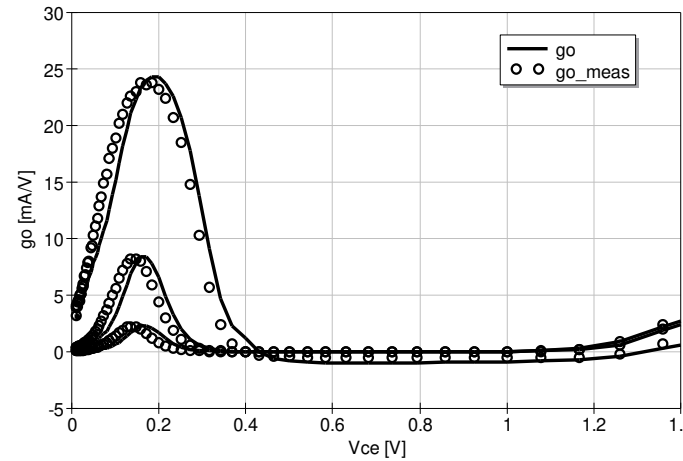
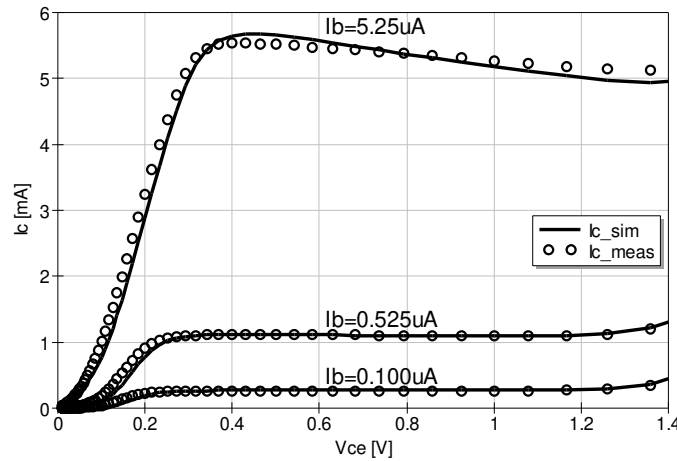


```

hicumL2V3p0p0gc
hfe=0
hfc=0
vces=0.07561
vdck=0.790
flsh=2
flcomp=20
temp=temp
qpc0=3.132e5
inci=8.283e-7
hr0=1
    
```

Ib controlled forward output plots with qpcc, DUT2

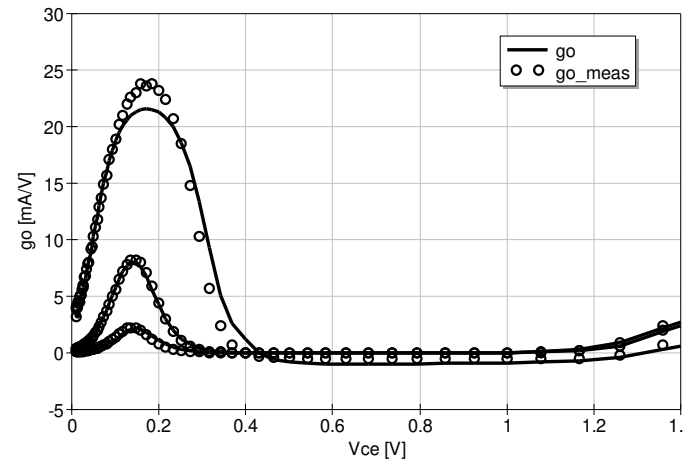
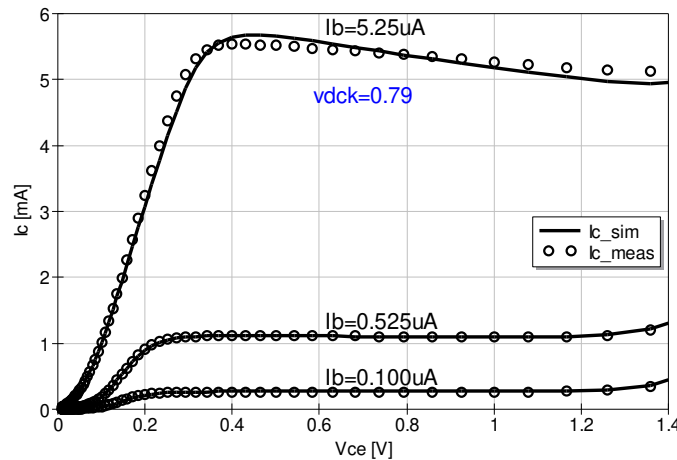
Benchmarking the vces and vdck model variants of HICUM



Top: vces=75.61mV, vdck=0

Bottom: vdck=0.790V

No difference is seen by comparing these results with those on slide#9 using hr0>1 and without qpcc.



Top: vces model

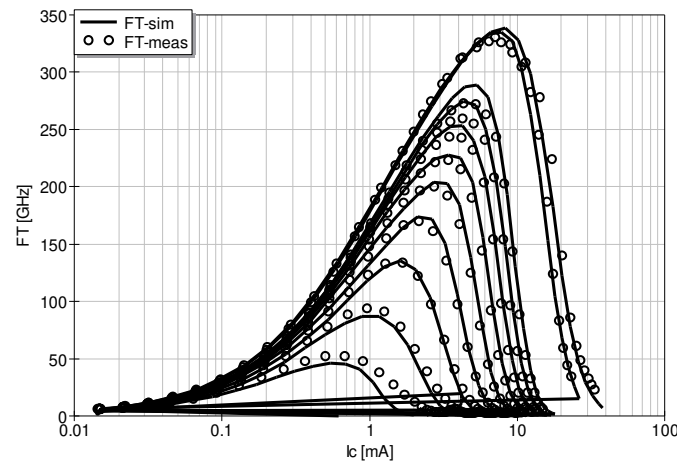
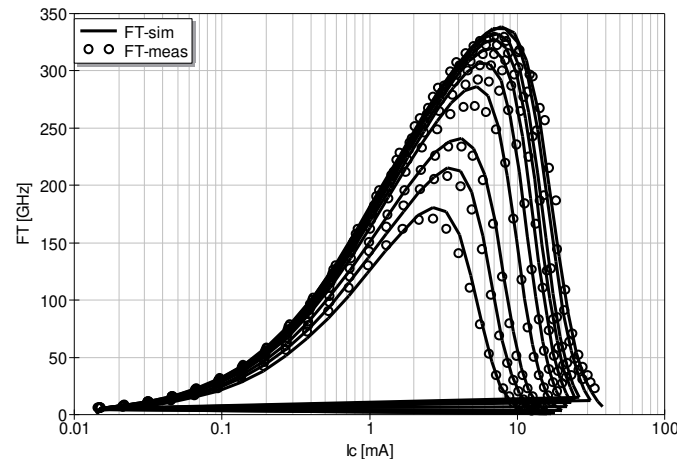
Bottom: vdck model

Left: Ib controlled fwd. output

Right: Output conductance

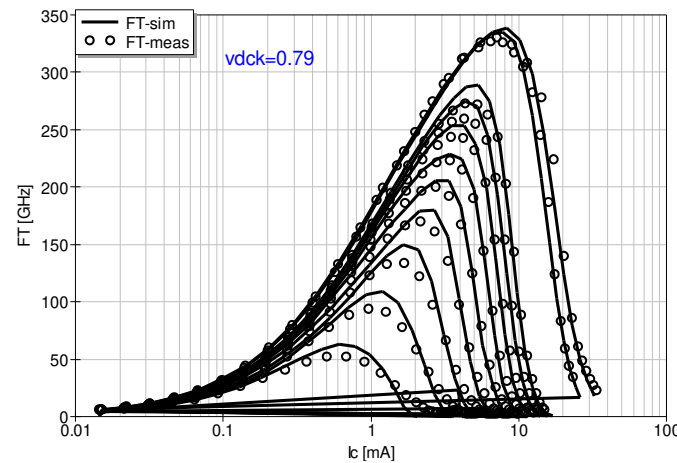
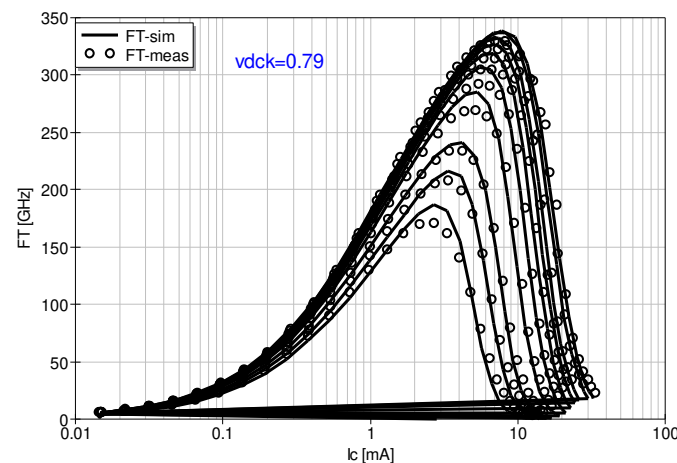
FT with qpcc, DUT2

Benchmarking the vces and vdck model variants of HICUM



Top: $V_{bc}=0.6; 0.55; 0.5; 0.4; 0.3; 0.2; 0.1; 0; -0.25; -0.5$

Bottom: $V_{ce}=0.1; 0.15; 0.2; 0.25; 0.3; 0.35; 0.4; 0.45; 0.5; 1; 1.5$



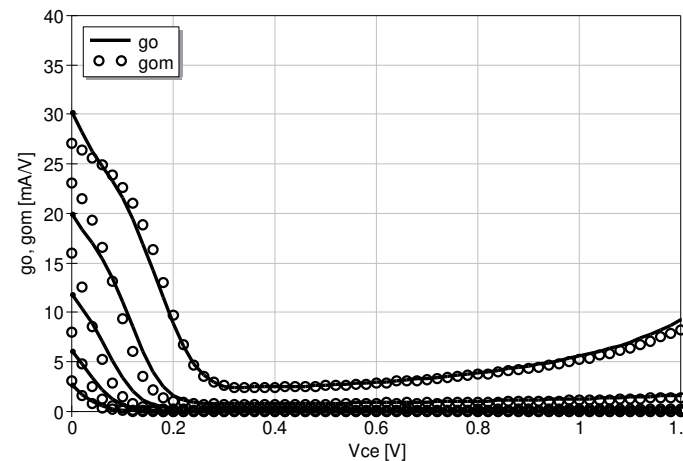
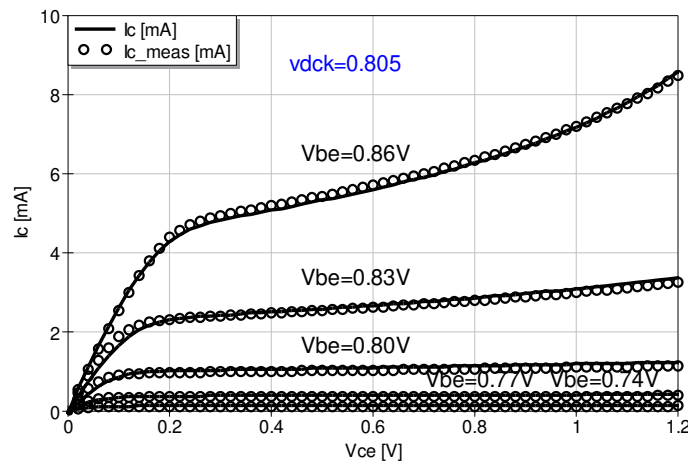
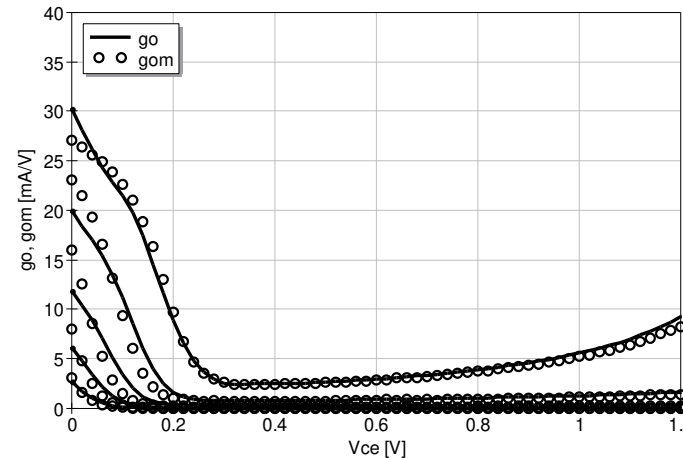
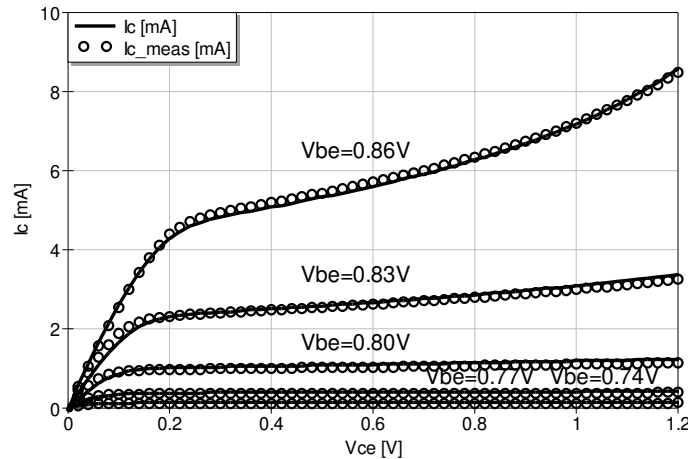
Left: vces model

Right: vdck model

As opposed to the nearly perfect fits on slide#10 with the $hr0 > 1$ approach there is a slight increase on the low V_{ce} branches of the common emitter plots using the vdck model. The deviations are highly tolerable though.

Vbe controlled forward output plots with qpcc, DUT1

Benchmarking the vces and vdck model variants of HICUM



Top: vces model

Bottom: vdck model

Left: Vbe controlled fwd. output

Right: Output conductance

Despite that the kinks on DUT1 could be eliminated without extra measures with the reverse charge i.e. using the built-in $hf0=1$ it is important to confirm that the device can be fixed with the qpcc option as well. To this end the transistor parameters have been changed as shown below.

First of all hfe and hfc were modified to zero from their finite values. In addition the $qpc0$ parameter had to be increased 5 times from its value at DUT2. Parameter $vdck$ had also been slightly increased from its former value of 0.790V to 0.805V.

No difference can be seen between the vces and vdck variants: both provide excellent fits.

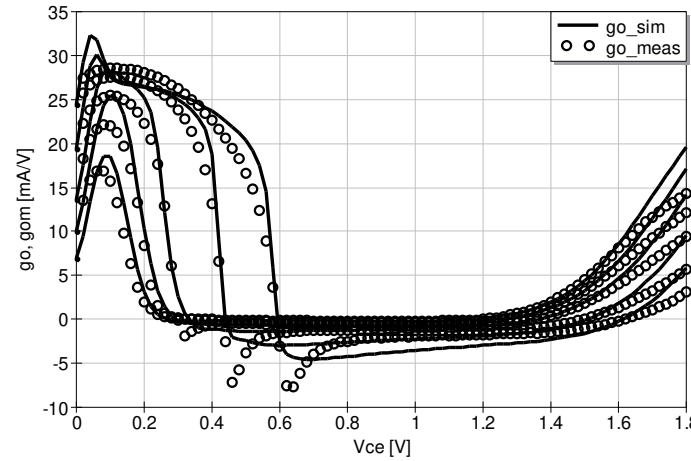
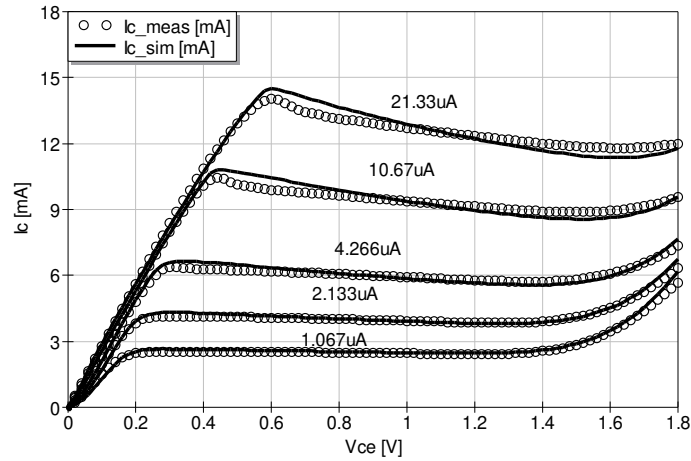
```

hicumL2V3p0p0gc
hfe=0*0.06846
hfc=0*136.8
vces=0.06178
vdck=0*0.805
flsh=2
flcomp=2
temp=temp
qpc0=5*3.132e5
inci=8.283e-7
hr0=1
    
```

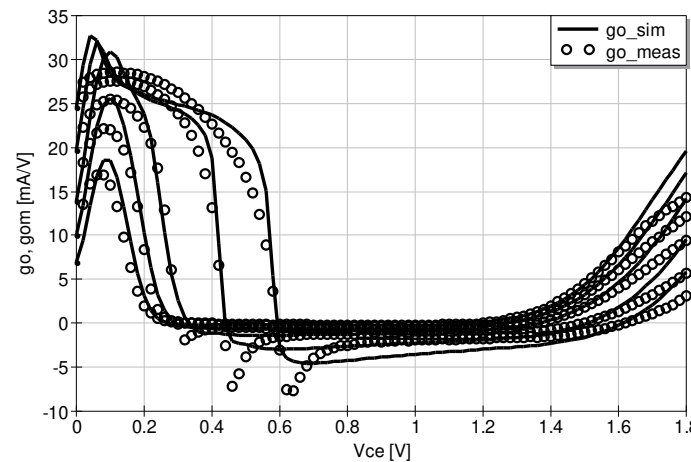
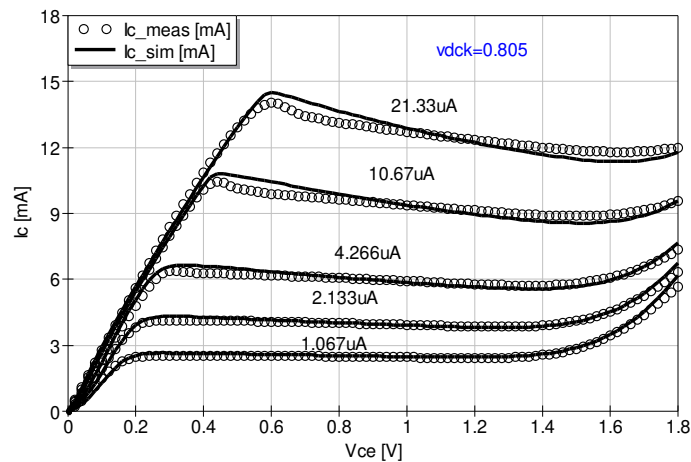


Ib controlled forward output plots with qpcc, DUT1

Benchmarking the vces and vdck model variants of HICUM



Somewhat smoother output conductance can be observed w.r.t. those on slide#5 using $hr0 > 1$ and without qpcc.



The slide intended to show FT and FMAX for comparison to slide#7 is missing. The QucsStudio simulator has not converged with the qpcc option for unknown reasons.

Top: vces model

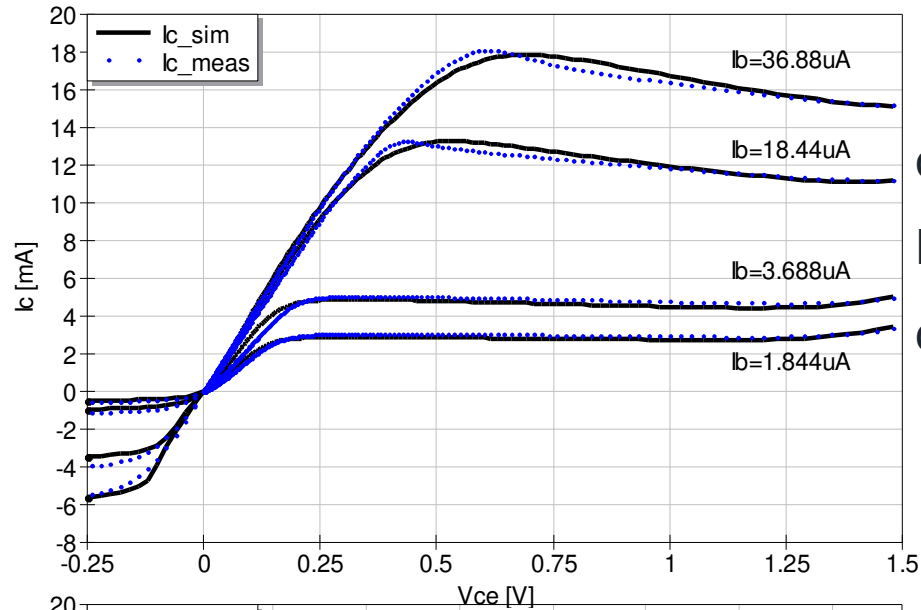
Bottom: vdck model

Left: Ib controlled fwd. output

Right: Output conductance

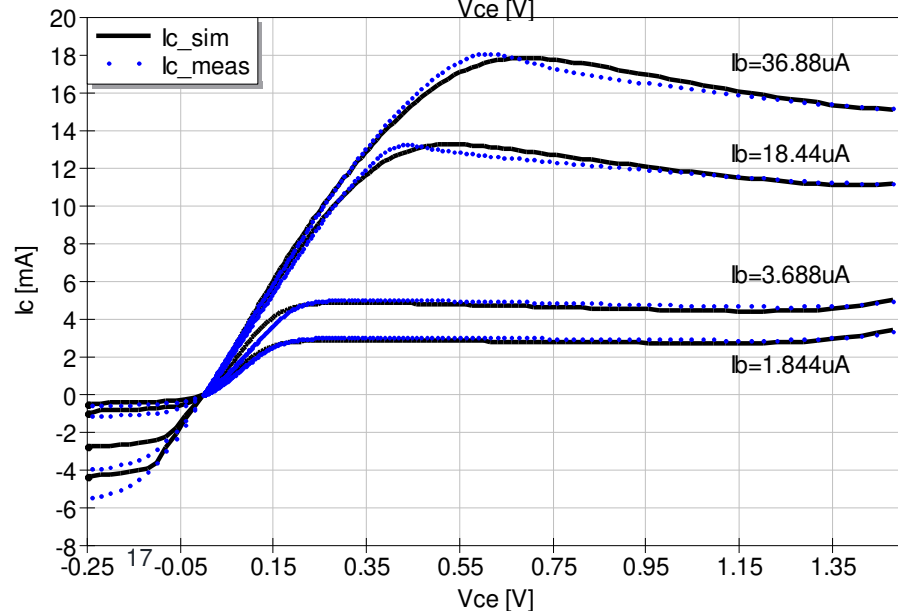
Issue with $hr0 > 1$ and $qpc0 > 0$

Benchmarking the vces and vdck model variants of HICUM

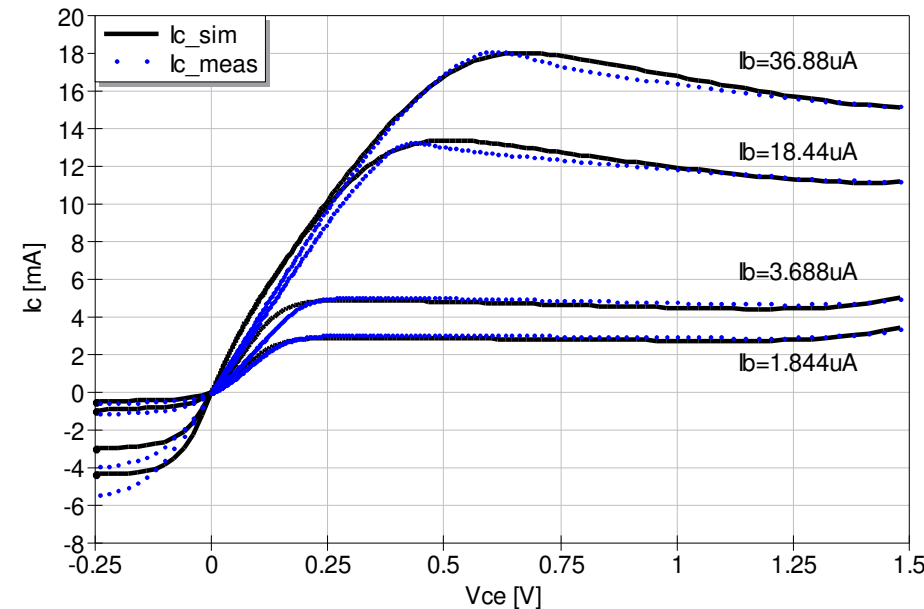


default:
 $hr0=1$
 $qpc0=0$

The kinks can be reduced or completely eliminated by either of the $hr0 > 1$ or $qpc0 > 0$ techniques. The effect of the two variants is very similar. This holds also for one of their known negative consequences as well. Particularly, the negative branches of the forward output characteristics get compressed. Even that this is not regarded an important domain of operation it highlights a model deficiency.



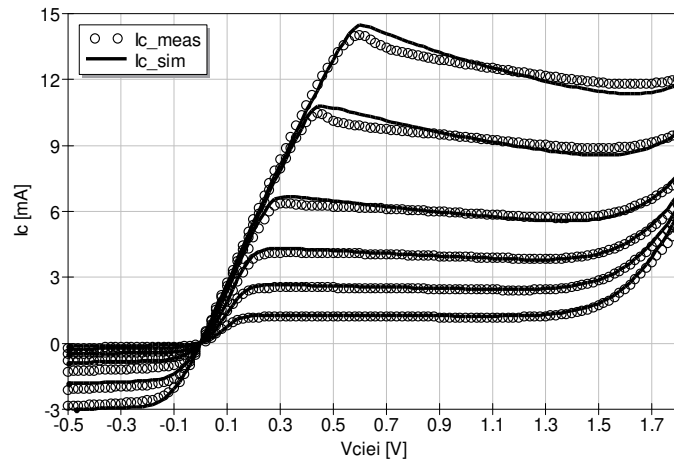
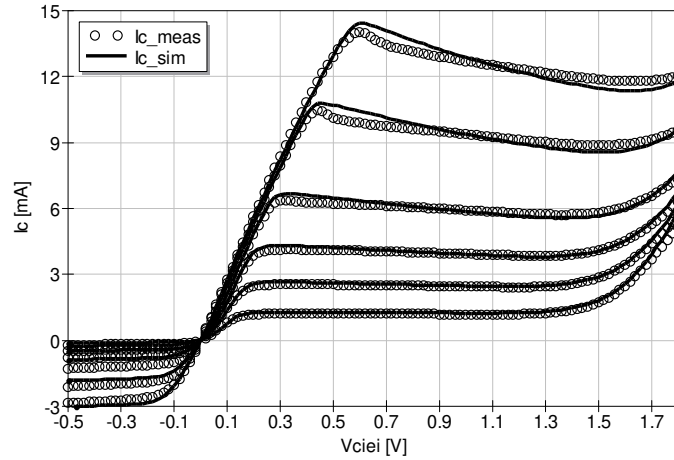
$hr0 > 1$
 $qpc0=0$



$hr0=1$
 $qpc0 > 0$

qpcc approach: Vbici limiting, DUT1

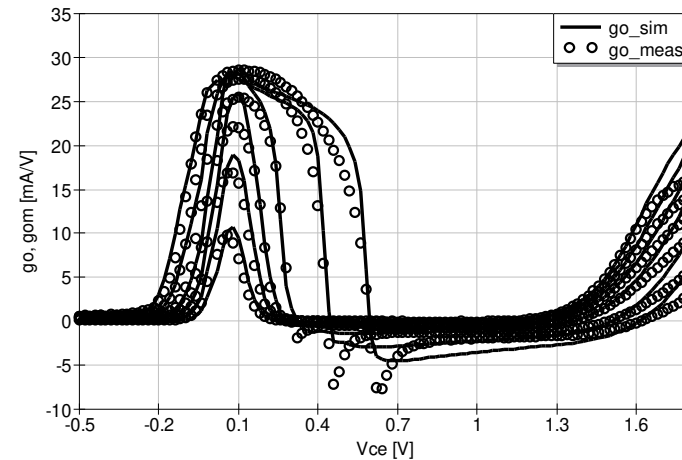
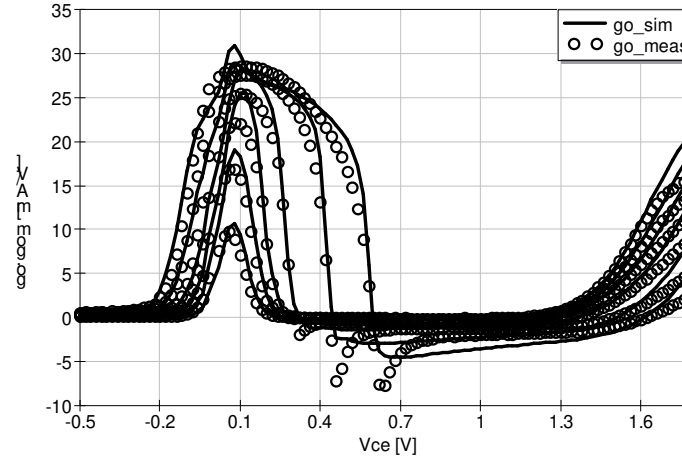
Benchmarking the vces and vdck model variants of HICUM



Top: vces model

Bottom: vdck model

limiting
to Vbiei



Left: Ib controlled fwd. output

Right: Output conductance

$$V_{bici} = V_{biei} - V_{ciei}$$

The LHS can take large values at $V_{ciei} < 0$. As there is no high current effect in reverse operation [3] V_{bici} can be limited to V_{biei} in the negative V_{ciei} domain.

$$vqpc = \frac{VT}{2} \left(\frac{V_{ciei}}{VT} + \sqrt{\left(\frac{V_{ciei}}{VT} \right)^2 + avceff} \right); \quad avceff = 1.921812$$

On slide#11 we replace

$$\expbc = inci^2 \cdot \exp\left(\frac{V_{biei} - vqpc}{VT}\right) \cdot \frac{c10_t}{c10}$$

with the limited voltage $V_{bici_lim} = V_{biei} - vqpc$

Alternatively, qpcc is put off in $V_{ciei} < 0$ with

$$swbc = \tanh\left(\frac{V_{ciei}}{0.001VT0}\right)$$

$$\expbc = inci^2 \cdot \frac{c10_t}{c10} \cdot \exp\left(\frac{swbc \cdot V_{bici}}{VT}\right)$$

The two limiting schemes provide similar results

Summary

Benchmarking the vces and vdck model variants of HICUM

- hicumL2V3p0p0 offers an alternative ICK model replacing the parameter vces by vdck
- it is an important question if the rest of the ICK parameters can remain the same as extracted with vces
- the vces variant has proved to provide excellent match to measurements
- the vdck variant is claimed to be physics based too thus the same modeling quality is expected from its use
- identical itf requires the same ICK through the invariant itf/ICK demanded by the same onset of high currents
- this ICK invariance has been demonstrated on extracted transistors in this study
- the new approach adapts $v_c = v_{dck} - V_{bici} = V_{ciei} - (V_{biei} - v_{dck})$
- $v_{ces_eff} = V_{biei} - v_{dck}$ takes different values on different fwd. output branches, a strange novelty
- the qpcc extension of two parameters has been found equivalent to the add'l qrT term [2] of one parameter
- both approaches work fine in kink removal at the cost of somewhat deteriorating the reverse output behaviour
- fixes were proposed to eliminate this problem either by limiting V_{bici} to V_{biei} or by putting off qpcc for $V_{ciei} < 0$
- making avceff a model parameter has been found unnecessary
- ICK quality can be tested by the equivalence of the vces and vdck variants (to be confirmed)

References

Benchmarking the vces and vdck model variants of HICUM

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- [2] Z. Huszka, „Analysis of the forward output kinks in HICUM,” 20th HICUM Workshop, Infineon, Neubiberg, Germany May 15/16, 2023
- [3] M. Schröter, „HICUM/L2 Model Development,” 20th HICUM Workshop, Infineon, Neubiberg, Germany, May 15/16, 2023

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Thank you!

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