Temperature Invariant Extraction of IS and VER

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Purpose

- decoupling of temperature error at *VER* extraction
- decoupling of temperature error at *IS* extraction
- determination of the measurement temperature

Outline

- equivalent circuit
- extraction equations at low currents
- analysis of the „temperature“ error
- extraction method
- results
- summary

Former Observations

Extraction of Hicum parameters *Qp0* and *C10* have been investigated in [1] from the normalized collector current

$$I_{cmeas} \cdot \exp\left(-\frac{V_{bei}}{V_T}\right)$$

„Pitfall: a small ΔT results in large ΔQp0"

Extraction of Hicum parameter *hjei* has been analyzed in [2] from the normalized collector current:

„The parameters strongly depend on temperature..."

In this paper the efforts of [3] will be extended for a more robust decoupling of the temperature error at the extraction of the reverse Early related parameters

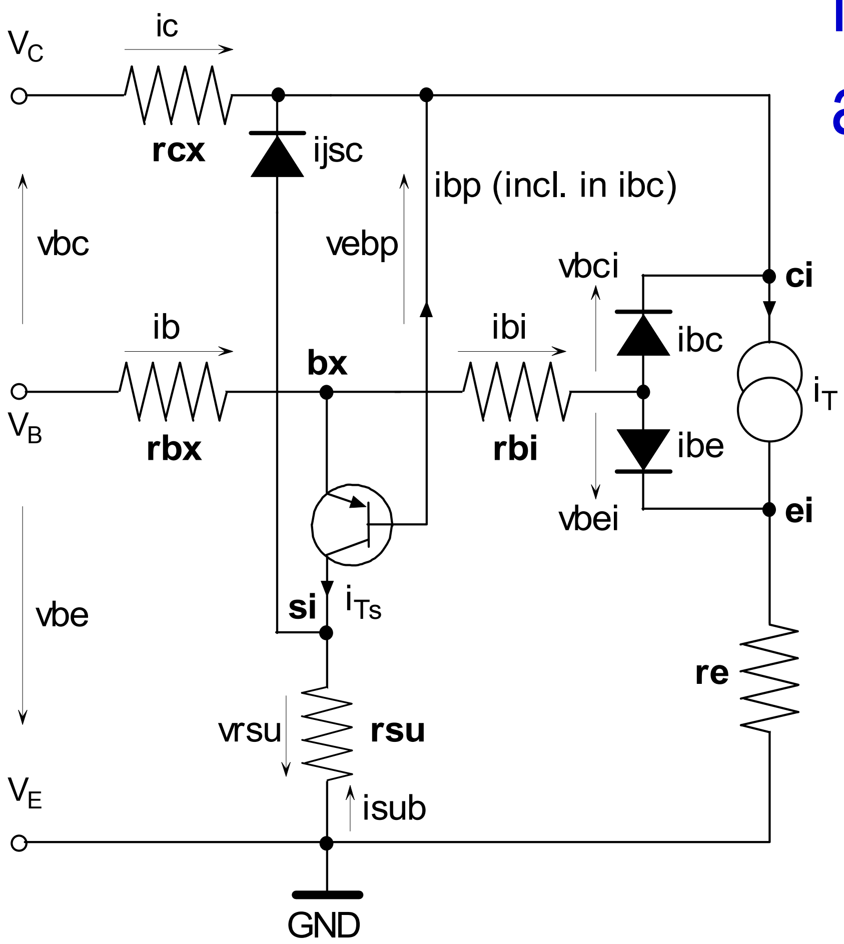
Low bias DC formulations in various models

	SGP	VBIC	HICUM/L2	MEXTRAM
$\mathbf{I_c}$	$I_c = \dfrac{I_F}{q_E}; \qquad I_F = IS \cdot \exp\left(\dfrac{V_{bei}}{N \cdot V_T}\right)$			
N	NF	NF	1	1
IS	IS	IS	$c10 \quad (IS)$	IS
$\mathbf{q_E}$	$\left(1 - \dfrac{V_{bei}}{VAR} - \dfrac{V_{bci}}{VAF}\right)^{-1}$	$1 + \dfrac{qdbe}{VER} + \dfrac{qdbc}{VEF}$	$Q_{p0} + h_{jEi} \cdot Q_{jEi} + h_{jCi} \cdot Q_{jCi}$	$1 + \dfrac{V_{tE}}{VER} + \dfrac{V_{tC}}{VEF}$

With the normalized Hicum parameters suggested in [4]: $VER = \dfrac{Q_{p0}}{hjei \cdot C_{jei0}}; \quad qdbe = \dfrac{Q_{jEi}}{C_{jei0}} \qquad VEF = \dfrac{Q_{p0}}{hjci \cdot C_{jci0}}; \quad qdbc = \dfrac{Q_{jCi}}{C_{jci0}}$

q_E is identical in VBIC, HICUM/L2 and MEXTRAM

Equivalent



Model equivalence at low bias allows using Hicum notations only

KCL on node **ci**

$$ic + ibc + ijsc - iT = 0 \tag{1}$$

with

$$ibc = ibcxs \cdot \left[\exp\left(\frac{vbci}{V_T \cdot mbcx}\right) - 1\right] \tag{2}$$

$$ijsc = iscs \cdot \left[\exp\left(-\frac{vcei}{V_T \cdot msc}\right) - 1\right] \tag{3}$$

$$i_T = \frac{IS}{q_E} \cdot \left[\exp\left(\frac{vbei}{V_T}\right) - \exp\left(\frac{vbci}{V_T}\right)\right] \tag{4}$$

IS and *VER* extraction at forward bias

At *vcb=0* and *vbe>10*V_T*=258mV* *ibc* and *ijsc* vanish in (1):

$$ic = \frac{IS}{q_E} \cdot \exp\left(\frac{vbei}{V_T}\right)$$

This provides the well known extraction formula

$$\frac{1}{IS} + \frac{1}{IS \cdot VER} \cdot qdbe(vbei) = a + b \cdot qdbe(vbei) = \frac{\exp\left(\frac{vbei}{V_T}\right)}{ic}$$

Linear regression gives *IS* and *VER*

$$IS = 1/a; \quad VER = a/b$$

Temperature induced extraction error

nominal temp.: T_n erroneous measurement reading: $T = T_n + \Delta T$

$$\exp\left(\frac{V_{bei}}{V_T}\right) = \exp\left(\frac{V_{bei}}{V_{Tn}} \cdot \frac{T_n}{T_n + \Delta T}\right) \approx \exp\left[\frac{V_{bei}}{V_{Tn}} \cdot \left(1 - \frac{\Delta T}{T_n}\right)\right] \approx \exp\left(\frac{V_{bei}}{V_T}\right) \cdot \left(1 - \frac{V_{bei}}{V_{Tn}} \cdot \frac{\Delta T}{T_n}\right)$$

Substituting, with IS_n denoting value at nominal temperature:

$$\frac{1}{IS_n} + \frac{qjei(vbei)}{IS_n \cdot VER} = \frac{\exp\left(\frac{V_{bei}}{V_{Tn}}\right)}{ic} \cdot \left(1 - \frac{\Delta T}{T_n} \cdot \frac{V_{bei}}{V_{Tn}}\right) \Rightarrow \left(\frac{1}{IS_n} + \frac{qjei(vbei)}{IS_n \cdot VER}\right) \cdot \left(1 + \frac{\Delta T}{T_n} \cdot \frac{V_{bei}}{V_{Tn}}\right) \approx \frac{\exp\left(\frac{V_{bei}}{V_{Tn}}\right)}{ic}$$

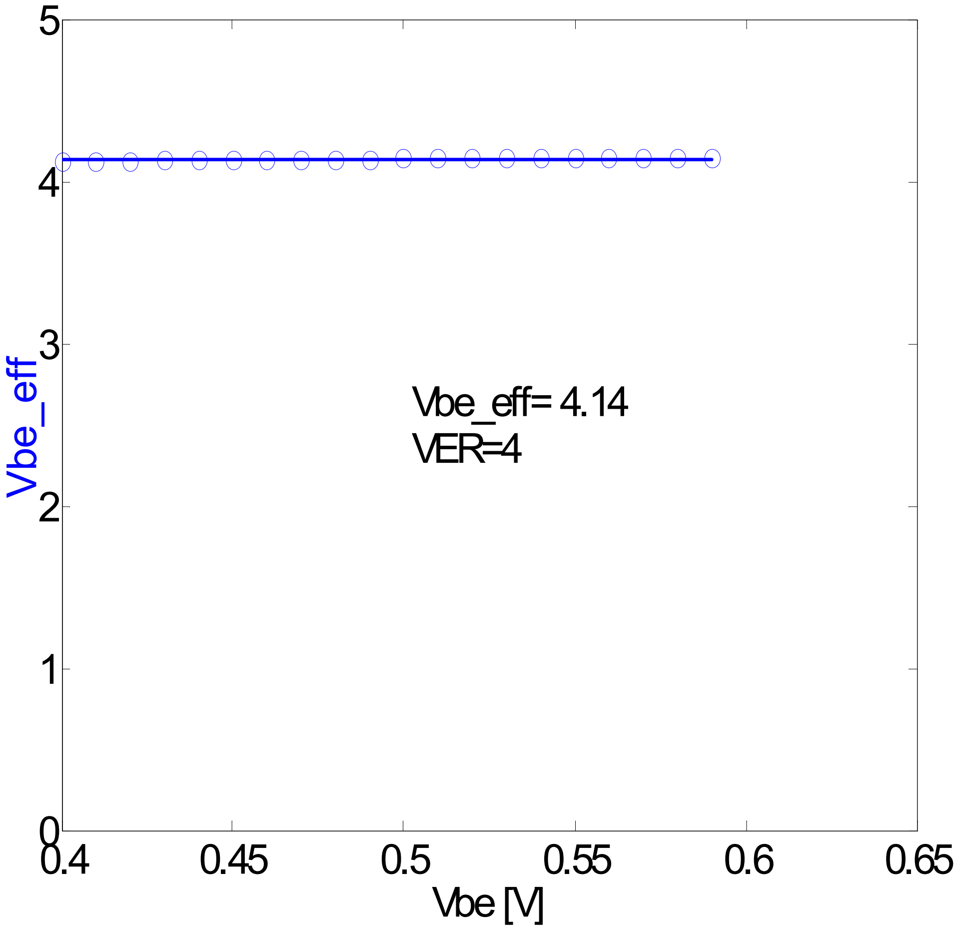
Finally:

$$\frac{1}{IS_n} + \frac{1+\delta}{IS_n \cdot VER} \cdot qjei(V_{bei}) \approx \frac{\exp\left(\frac{V_{bei}}{V_{Tn}}\right)}{ic}$$

$$\delta = \frac{\Delta T}{T} \cdot \frac{V_{be\_eff}}{V_T}; \quad V_{be\_eff} = V_{bei} + VER \cdot \frac{V_{bei}}{qjei(V_{bei})} \approx V_{bei} + VER$$

IS_n is not affected by temperature error in the first order

Temperature effect on *VER*



Extracted *VER*:

$$VER_x = \frac{VER}{1+\delta}$$

Example:

with $\Delta T=1C^0$ VER=4

δ=0.531, VER_x=2.61

***VER_x* is heavily affected by temperature error**

IS and *VER* extraction at reverse bias

For *vbci*>0 (1) and (4) can be combined to give

$$\frac{qjei(vbei)}{IS\cdot VER}+\frac{1}{IS}\left(1+\frac{qjci(vbci)}{VEF}\right)=-\frac{\exp\left(\frac{vbci}{V_T}\right)\cdot\left[1-\exp\left(\frac{vcei}{V_T}\right)\right]}{ic+ijsc+ibc}$$

The temp. effect of the [ ] term can be neglected at *vcei*<-7V_T

$$\left[\frac{qjei(vbei)}{IS_n\cdot VER}+\frac{1}{IS_n}\left(1+\frac{qjci(vbci)}{VEF}\right)\right]\cdot\left(1+\frac{\Delta T}{T_n}\cdot\frac{V_{bci}}{V_{Tn}}\right)\approx-\frac{\exp\left(\frac{vbci}{V_{Tn}}\right)\cdot\left[1-\exp\left(\frac{vcei}{V_{Tn}}\right)\right]}{ic+ijsc+ibc}$$

Linear regression w.r.t. *vbei* by fixing e.g. *vbci=0.6V*:

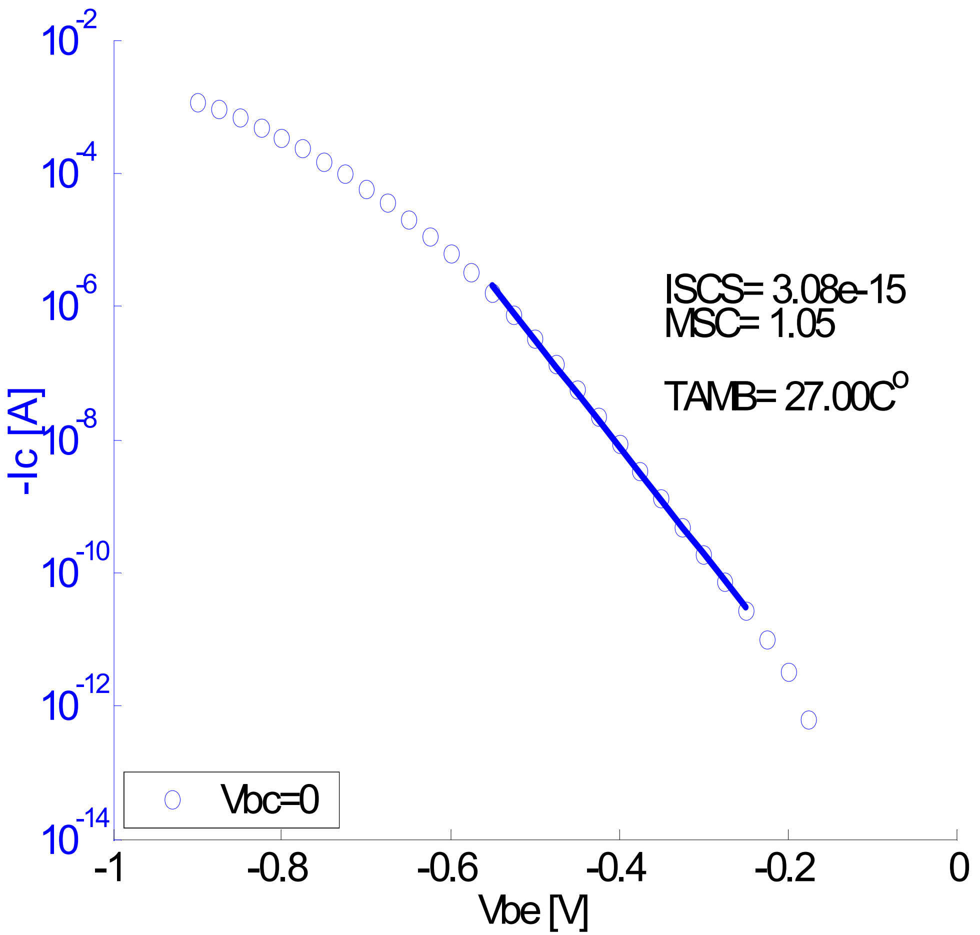
$$VER_x=VER\cdot\left(1+\frac{qjci(vbci)}{VEF}\right)$$

$$IS_{nx}^{-1}=IS_n^{-1}\cdot\left(1+\frac{qjci(vbci)}{VEF}\right)\cdot(1+\delta);\quad \delta=\frac{\Delta T}{T_n}\cdot\frac{V_{bci}}{V_{Tn}}$$

***VER* is unaffected by temperature error in the first order**

Extraction of the *ijsc* parameters

ibc becomes zero at *vcb=0* hence for *vbe<-10V$_T$=-258mV*:



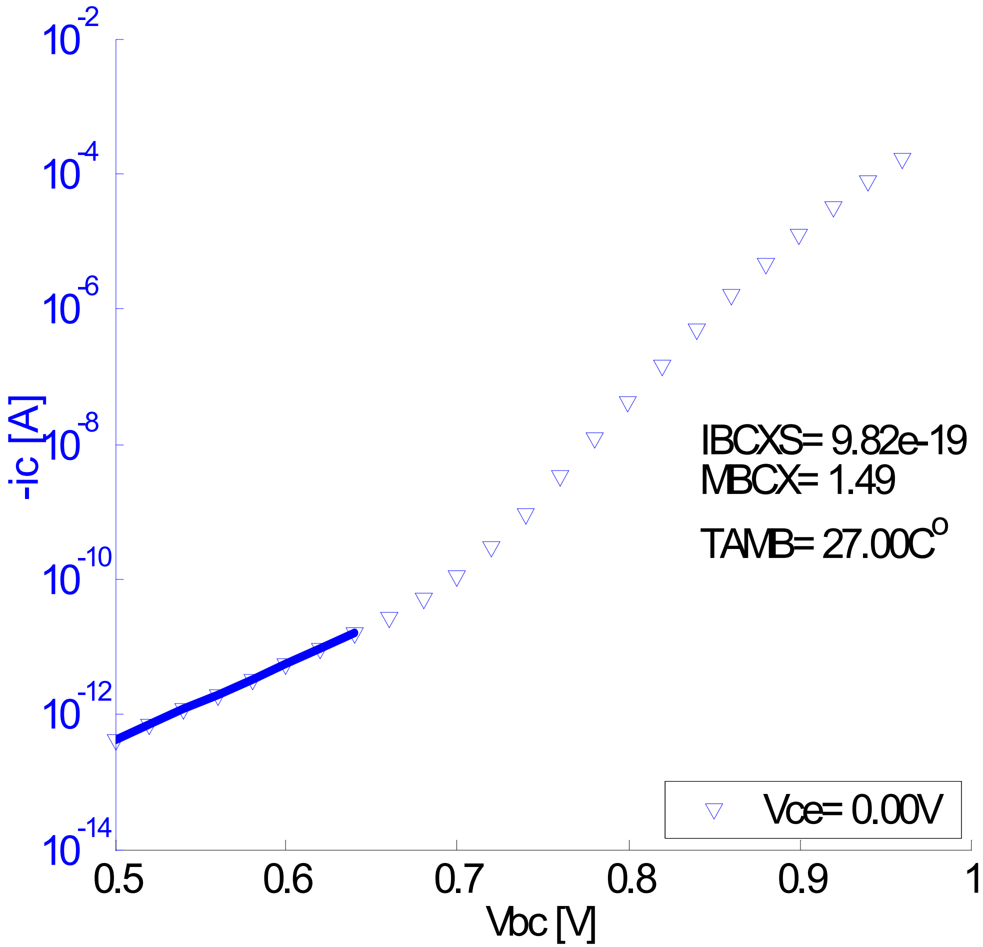
$$ic \approx -\frac{IS}{q_E} - iscs \cdot \exp\left(\frac{-vbei}{V_T \cdot msc}\right)$$

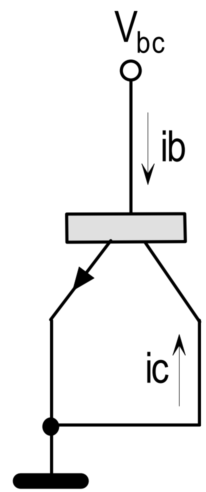
in the *vbe* range above the first term can be neglected providing the regression:

$$\ln(-ic) = \ln(iscs) + \frac{-vbei}{V_T} \cdot \frac{1}{msc}$$

Extraction of the *ibc* parameters

ijsc (3) and i_T (4) become zero at *vce=0*

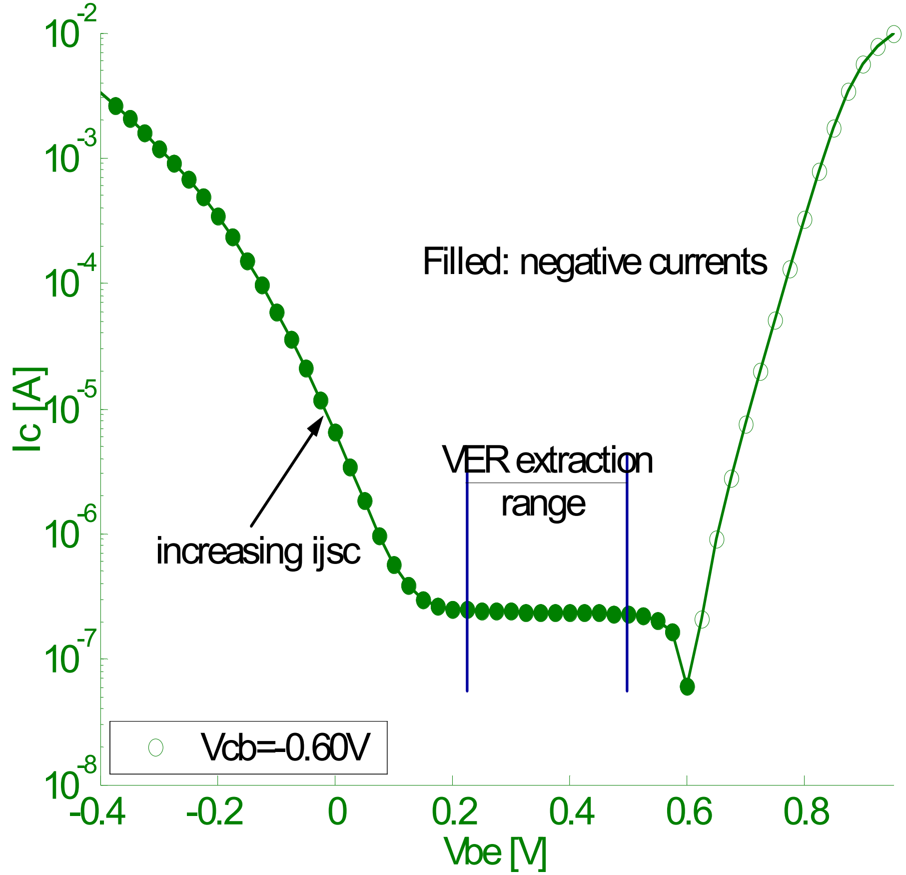




$$\ln(-ic) = \ln(ibcxs) + \frac{vbci}{V_T} \cdot \frac{1}{mbcx}$$

Substrate current parameters can be extracted from *ib* (not needed here)

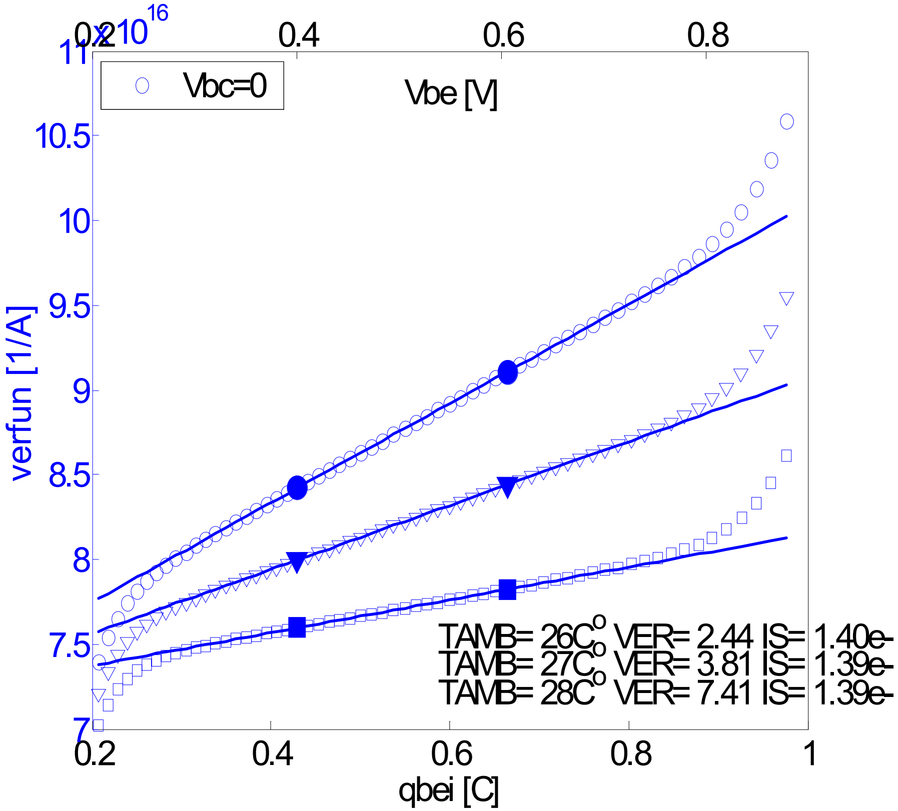
Simplified *VER* extraction

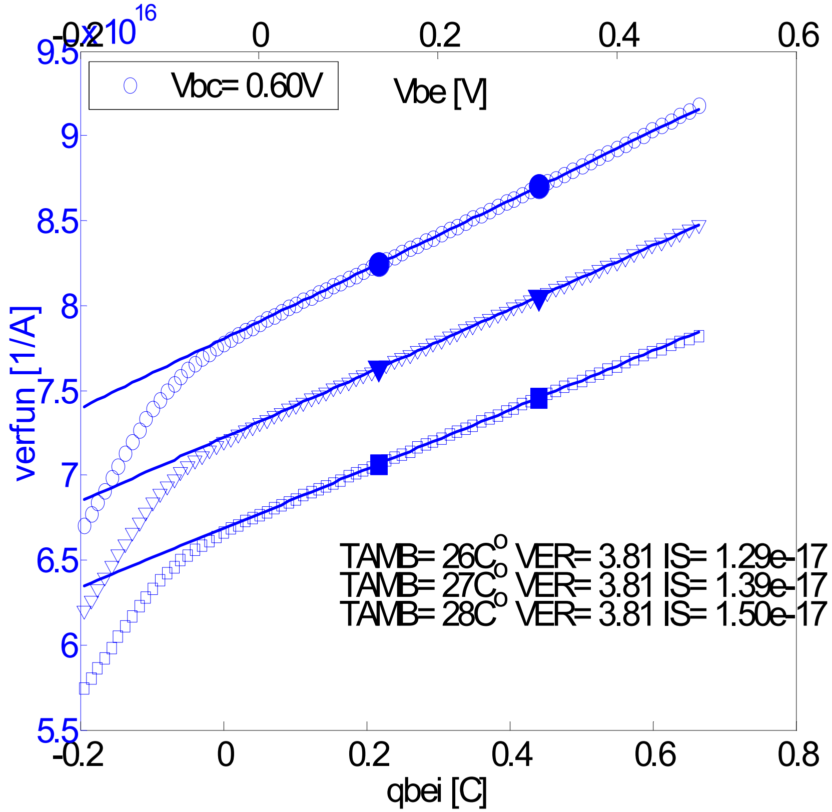


Usually there is a flat section where *ijsc* is much less than *ic* for a simplified *VER* regression with RHS:

$$-\frac{\exp\left(\frac{vbci}{V_T}\right)\cdot\left[1-\exp\left(\frac{vcei}{V_T}\right)\right]}{ic+ijsc+ibc}\approx-\frac{\exp\left(\frac{vbci}{V_T}\right)\cdot\left[1-\exp\left(\frac{vcei}{V_T}\right)\right]}{ic+ibc}$$

Comparing fwd. and rev. *IS* & *VER* extractions





Fwd.: *IS* invariant

Rev.: *VER* invariant

Extract *IS* from fwd. *VER* from rev. regression!

Determination of measurement temperature

Given *IS* and *VER* in a temperature independent manner, the low-bias normalized Early charge q_E can also be computed in a temperature independent way.

The current equation in the fwd. *VER* extraction range

$$ic = \frac{IS}{q_E} \cdot \exp\left(\frac{vbei}{V_T}\right)$$

provides the measurement temperature

$$T = \frac{q}{k} \frac{vbei}{\ln\left(\frac{ic \cdot q_E}{IS}\right)}$$

Exact *T* and *IS* allows a highly accurate extraction of temperature coefficients e.g. for bandgap designs

Summary

- a two-step *IS* & *VER* extraction method has been proposed
- temperature effects are eliminated from both parameters
- applicable to all present HBT/BJT models
- the procedure returns the measurement temperature
- allows for a more accurate *IS* tempco extraction
- parameter extraction suggested for *ijsc* and *ibc*

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References

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3. Z. Huszka and E. Seebacher, „ *Temperature Decoupled, Model Invariant Extraction of the Reverse Early Parameter*," CMRF06, 11. October 2006, Maastricht
4. Z. Huszka, „ *Normalized HICUML2 and new Advancements in TF Extraction*," Hicum WS, 18-19. June 2007, Dresden