A Novel Low-bias Charge Concept for HBT/BJT Models Including Heteroband-gap and Temperature Effects

Part II: Parameter Extraction and Verification

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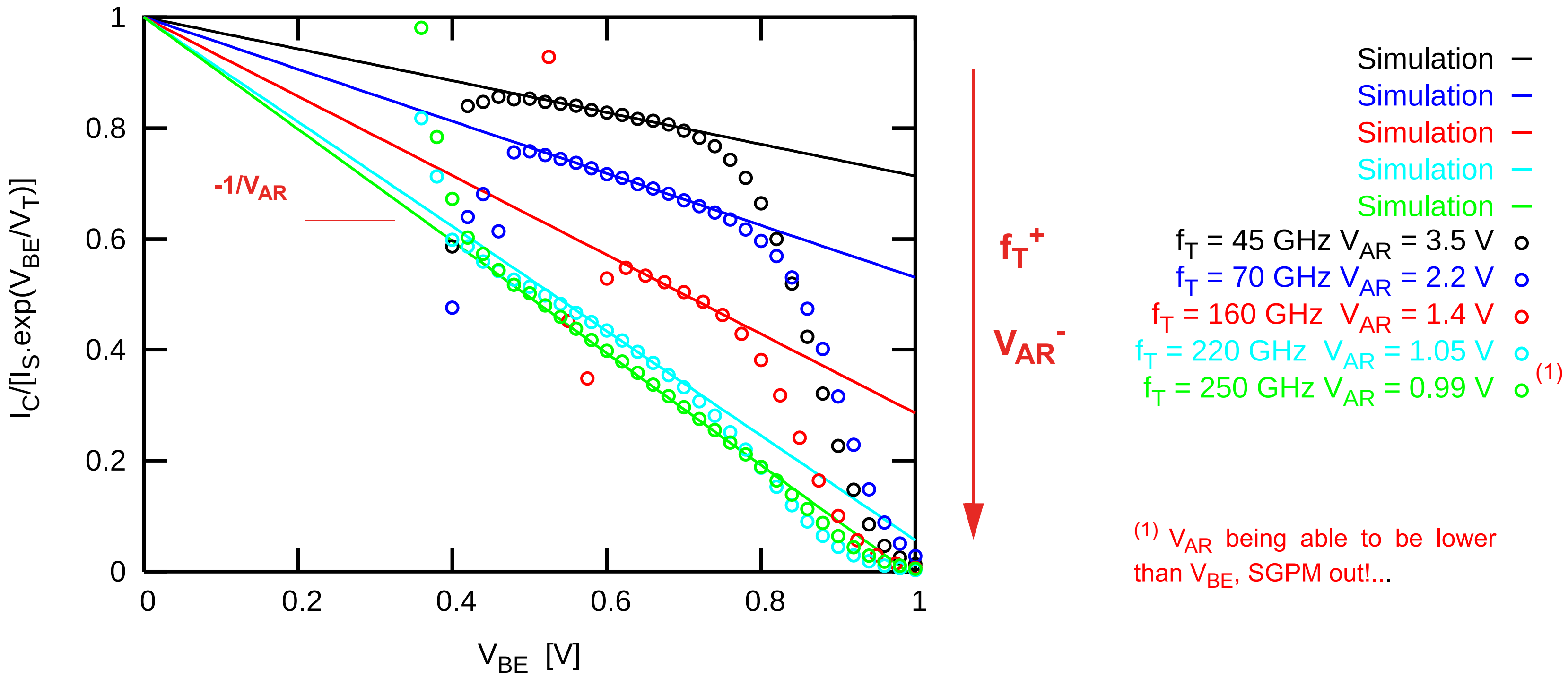
Problematics (1/2)

- In advanced HBTs the *effective* reverse Early voltage decreases drastically with the increasing of RF performances [1]

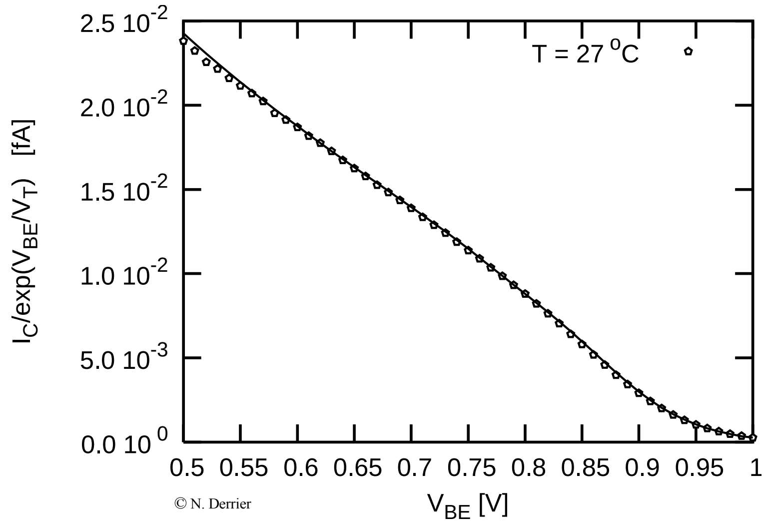
  • At low and medium current densities, the slope of the normalized collector current $I_{CN} = \dfrac{I_C}{I_S \cdot e^{\frac{V_{BE}}{V_T}}} \approx 1 - \dfrac{V_{BE}}{V_{AR}}$ versus V_{BE} gives a good approximation of the reverse Early voltage (SGPM)

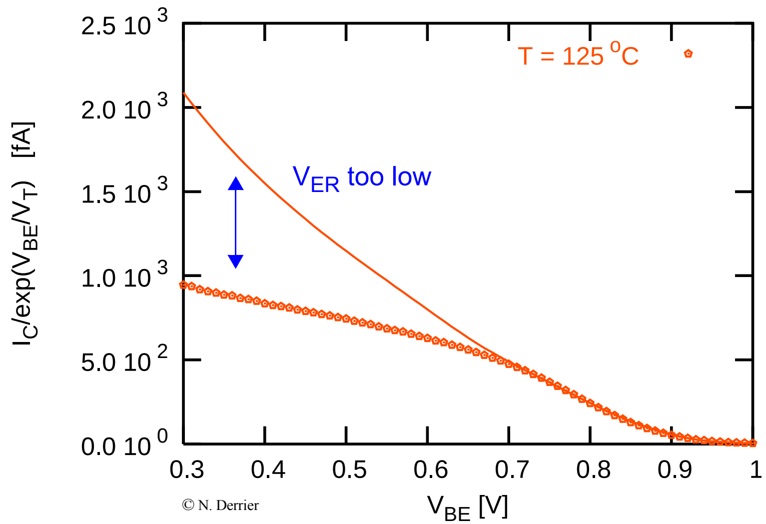


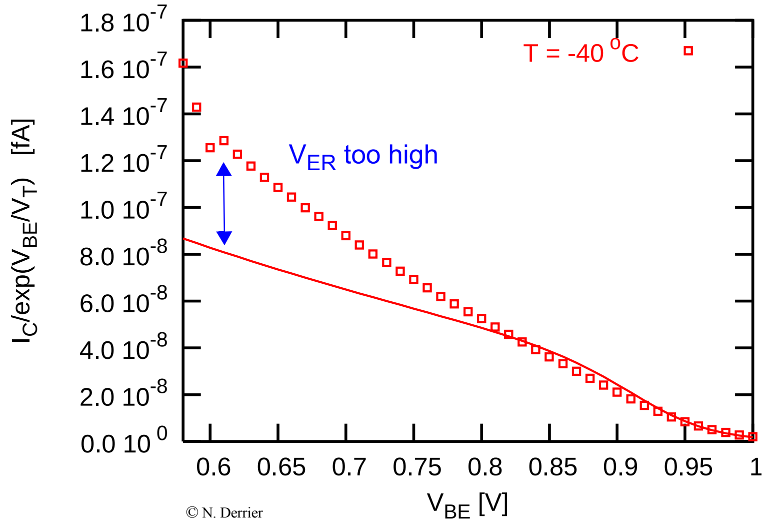
(1) V_{AR} being able to be lower than V_{BE}, SGPM out!...

Problematics (2/2)

- Moreover, this small *effective* reverse Early voltage becomes strongly temperature dependant [1]



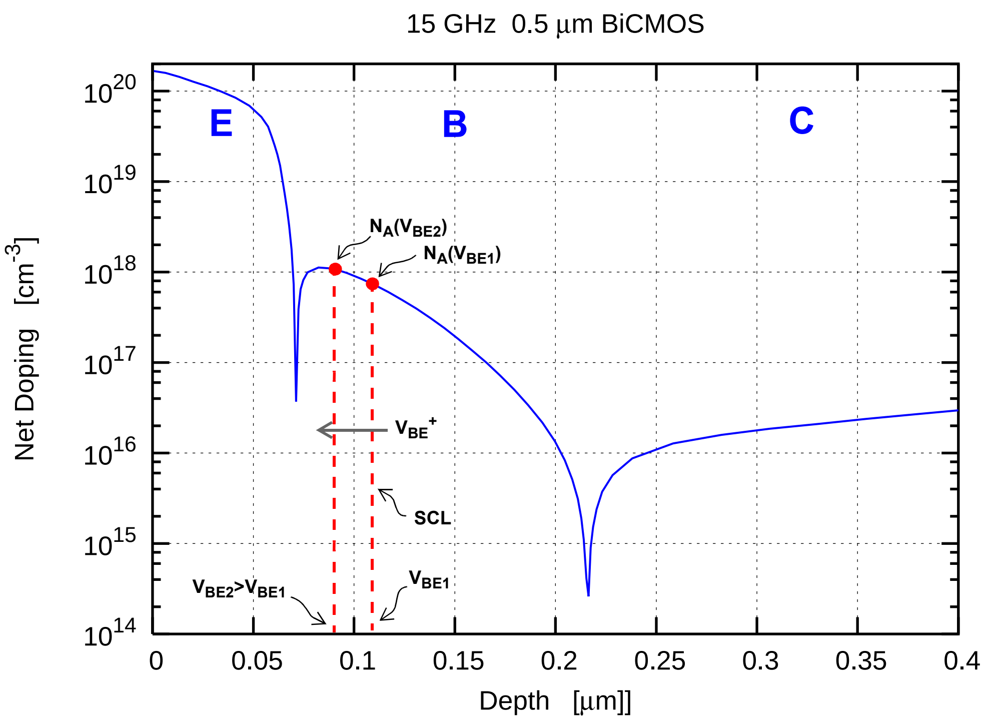




- Using HICUM/L0 v1.2, despite the very good results at room temperature, the temperature behavior of the collector current at low and medium current densities is not good.
- Underestimation of the collector current at low current densities and low temperatures (V_{ER} too high).
- Overestimation of the collector current at low current densities and high temperatures (V_{ER} too low).
- Up to now these effects are not modeled in all existing bipolar models (SGP, HICUM, MEXTRAM, VBIC)

Why V_{AR} is so small in advanced HBTs? (1/2)

- Two main reasons [2]
  - Effect of shape of the base profile



- The collector current depends on the injected electron in the base, at the EB depletion layer boundary

$$I_C \propto n_{b0}(V_{BE}) \cdot e^{\frac{V_{BE}}{V_T}} \quad \text{or} \quad I_{C*} = \frac{I_C}{e^{V_{BE}/V_T}} \propto n_{b0}(V_{BE})$$

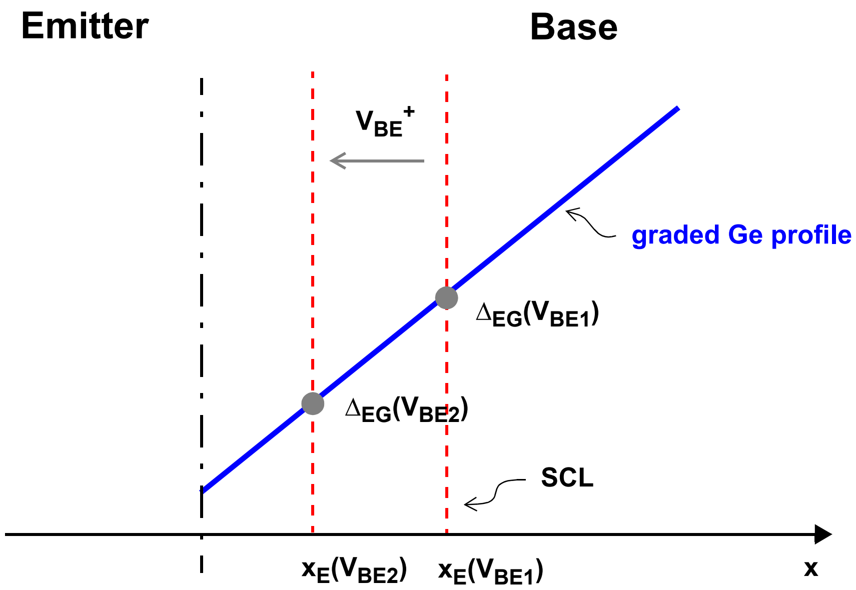
- If V_{BE} increases $N_A(V_{BE2}) > N_A(V_{BE1})$
- Since $n_{b0} \approx \frac{n_i^2}{N_A}$, we have $n_{b0}(V_{BE2}) < n_{b0}(V_{BE1})$

  and therefore $\boxed{I_{C*}(V_{BE2}) < I_{C*}(V_{BE1})}$

- Similar effect than the reverse Early effect (base width modulation with V_{BE}), where I_{C*} decreases with V_{BE}.
- This effect increases in modern HBTs due to the high stepness of the base profile.

Why V_{AR} is so small in advanced HBTs? (2/2)

- Effect of the graded Ge profile



- In HBTs, the collector current depends on the reduction Δ_{EG} of the base bandgap due to the introduction of Ge into the base

$$I_{C^*} = \frac{I_C}{e^{V_{BE}/V_T}} \propto e^{\frac{\Delta_{EG}}{V_T}}$$

- In graded Ge base profile (triangle or trapezoidal), if V_{BE} increases $\Delta_{EG}(V_{BE2}) < \Delta_{EG}(V_{BE1})$ and therefore $\boxed{I_{C^*}(V_{BE2}) < I_{C^*}(V_{BE1})}$

- This effect is responsible of the very low *effective* reverse Early voltage (decrease of I_{C^*} with V_{BE}) of advanced HBTs with high graded Ge profile in the base.

Solution?

- Used the Novel Low-bias Concept developed in [3]

- This innovator concept will be applied to
  - HICUM/L0 v1.2 → HICUM/L0 v1.2G
  - HICUM/L2 v2.24 → HICUM/L2 v2.24G

- and fully validated on 2 different technologies
  - BiCMOS9MW a 0.13µm SiGe BiCMOS dedicated to millimeter-wave applications of STMicrolectronics [8]
  - H18 HVMOS a 0.18µm high voltage process of autriamicrosystems AG [9]

Outline

- HICUM/L0 v1.2G and HICUM/L2 v2.24G new features
- Parameter extraction overview
- Experimental results and validations
- Summary

HICUM/L0 v1.2G new model parameters

- HICUM/L0 v1.2G new parameters [10] for the novel low-bias charge model

Name	Description	Default	Range	Unit	Factor
V_{ER} [1]	Normalized reverse Early Coefficient	∞	$[0:\infty)$	-	-
V_{EF} [1]	Normalized forward Early Coefficient	∞	$[0:\infty)$	-	-
D_{ELTE}	Coefficient of the zero bias emitter MRG charge temperature dependence	0	$[0:\infty)$	-	-
D_{ELTC}	Coefficient of the zero bias collector MRG charge temperature dependence	0	$[0:\infty)$	-	-
Z_{ETAVER}	Thermal coefficient of the normalized reverse Early Coefficient	0	[-10:10]	-	-
Z_{ETAVEF}	Thermal coefficient of the normalized forward Early coefficient	0	[-10:10]	-	-

[1] Existing but redefined model parameters

HICUM/L2 v2.24G new model parameters

- HICUM/L2 v2.24G new parameters [11] for the novel low-bias charge model

Name	Description	Default	Range	Unit	Factor
I_S	Saturation current (alternative to C_{10})	0	[0:1]	A	M
H_{JEI} (1)	Reverse Early factor	1	[0:100]	-	-
H_{JCI} (1)	Forward Early factor	1	[0:100]	-	-
V_{DEDC}	Built-in potential of the BE MRG (2) charge	0.9	(0:10)	V	-
Z_{EDC}	Grading factor of the BE MRG charge	0.9	[0:1)	-	-
A_{JEDC}	Ratio maximum to zero-bias value of BE MRG charge derivative	10	[1:∞)	-	-
D_{ELTAE}	Coefficient of the zero bias emitter MRG charge temperature dependence	0	[0:∞)	-	-
D_{ELTAC}	Coefficient of the zero bias collector MRG charge temperature dependence	0	[0:∞)	-	-
Z_{ETAG0}	Thermal coefficient of the 'quiescent' hole charge	0	[-10:10]	-	-
Z_{ETAGE}	Thermal coefficient of the emitter MRG charge	0	[-10:10]	-	-
Z_{ETAGC}	Thermal coefficient of the collector MRG charge	0	[-10:10]	-	-

(1) Existing but redefined model parameters

(2) Moll-Ross-Gummel

HICUM/L0 v1.2G new model equations [10] (1/3)

- Collector current at low current densities

$$I_C = \frac{\mathbf{I_S} \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right)}{1 + \frac{\Gamma_E}{\mathbf{V_{ER}}} + \frac{\Gamma_C}{\mathbf{V_{EF}}}} \quad (1)$$

- I_S, Γ_E, Γ_C, V_{ER} and V_{EF} are temperature dependent according to

• $\mathbf{I_S}(T) = \mathbf{I_S}(T_0) \cdot \left(\frac{T}{T_0}\right)^{\mathbf{Z_{ETACT}}} \cdot e^{\left(\frac{\mathbf{V_{GB}}}{V_{T0}} - \mathbf{Z_{ETAIQF}}\right) \cdot \left(1 - \frac{T_0}{T}\right)}$

$$\begin{cases} \Gamma_E(T) = \Delta_E(T) + \Phi_E(T) \\ \Delta_E(T) = \dfrac{\mathbf{D_{ELTE}}}{1 - \mathbf{Z_{EDC}}} \cdot \left[1 - \left\{\dfrac{\mathbf{V_{DEDC}}(T)}{\mathbf{V_{DEDC}}(T_0)}\right\}^{1 - \mathbf{Z_{EDC}}}\right] \\ \Phi_E(T) = \dfrac{1}{1 - \mathbf{Z_{EDC}}} \cdot \left\{\dfrac{\mathbf{V_{DEDC}}(T)}{\mathbf{V_{DEDC}}(T_0)}\right\}^{1 - \mathbf{Z_{EDC}}} \cdot \left[1 - \left\{1 - \dfrac{V_{BE}}{\mathbf{V_{DEDC}}(T)}\right\}^{1 - \mathbf{Z_{EDC}}}\right] \end{cases} \quad (2)$$

HICUM/L0 v1.2G new model equations (2/3)

- $$\begin{cases} \Gamma_C(T) = \Delta_C(T) + \Phi_C(T) \\ \Delta_C(T) = \dfrac{\mathbf{D_{ELTC}}}{1-\mathbf{Z_{CI}}} \cdot \left[1 - \left\{\dfrac{\mathbf{V_{DCI}}(T)}{\mathbf{V_{DCI}}(T_0)}\right\}^{1-\mathbf{Z_{CI}}}\right] \\ \Phi_C(T) = \dfrac{1}{1-\mathbf{Z_{CI}}} \cdot \left\{\dfrac{\mathbf{V_{DCI}}(T)}{\mathbf{V_{DCI}}(T_0)}\right\}^{1-\mathbf{Z_{CI}}} \cdot \left[1 - \left\{1 - \dfrac{V_{BE}}{\mathbf{V_{DCI}}(T)}\right\}^{1-\mathbf{Z_{CI}}}\right] \end{cases}$$

- $\Delta_i(T, V)$ i = E,C characterizes the zero bias junction
- $\Phi_i(T, V)$ i = E,C is the classical depletion charge equation normalized to $C_{J0}.V_{D0}$ $\quad \Phi_i(T, V) = \dfrac{Q_J(T, V)}{C_J(T_0, 0) \cdot V_D(T_0)}$

- $\mathbf{V_{DEDC}}(T) = \mathbf{V_{DEDC}}(T_0) - V_T \cdot \left(3 - \mathbf{F_{1VG}} \cdot \dfrac{q}{k}\right) \cdot \ln\left(\dfrac{T}{T_0}\right) + V_{GBE} \cdot \left(1 - \dfrac{T}{T_0}\right)$ with $V_{GBE} = \dfrac{\mathbf{V_{GB}} + \mathbf{V_{GE}}}{2}$

- $\mathbf{V_{DCI}}(T) = \mathbf{V_{DCI}}(T_0) - V_T \cdot \left(3 - \mathbf{F_{1VG}} \cdot \dfrac{q}{k}\right) \cdot \ln\left(\dfrac{T}{T_0}\right) + V_{GBC} \cdot \left(1 - \dfrac{T}{T_0}\right)$ with $V_{GBC} = \dfrac{\mathbf{V_{GB}} + \mathbf{V_{GC}}}{2}$

- These equations are a simplification, ONLY for extraction purposes (no change in the code), of the temperature dependence of the built-in potential valid up to $V_D \geq 0.5V$. For lower V_D values, in the model equations, there is a limitation to avoid $V_D(T) < 0$ at high temperatures.

HICUM/L0 v1.2G new model equations (3/3)

- $\mathbf{V_{ER}}(T) = \mathbf{V_{ER}}(T_0) \cdot e^{\left(1 - \frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAVER}}}$

- $\mathbf{V_{EF}}(T) = \mathbf{V_{EF}}(T_0) \cdot e^{\left(1 - \frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAVEF}}}$

- Temperature dependence of the knee current $\mathbf{I_{QF}}$

  - $\mathbf{I_{QF}}(T) = \mathbf{I_{QF}}(T_0) \cdot e^{\left(1 - \frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAIQF}}}$

- Relation between new and old Early models (see Appendix A)

  - $$\boxed{\begin{cases} V_{ER\_new} = \dfrac{V_{ER\_old}}{\mathbf{V_{DEDC}}(T_0)} \\ V_{EF\_new} = \dfrac{V_{EF\_old}}{\mathbf{V_{DCI}}(T_0)} \end{cases}}$$

  - Warning: in HICUM/L0 v1.2G, V_{ER} and V_{EF} are no more voltages, but are normalized respectively to the BE and BC built-in potential at the reference temperature T_0

HICUM/L2 v2.24G new model equations [11] (1/2)

- Collector current at low current densities
  - $$\boxed{I_C = \frac{\mathbf{C_{10}} \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}}\right)}{Q_{P0}^G + H_{JEI}^G \cdot Q_{P0} \cdot \Gamma_E(T) + H_{JCI}^G \cdot Q_{P0} \cdot \Gamma_C(T)}}$$
- Q_{P0}^G, H_{JEI}^G, H_{JCI}^G, Γ_E and Γ_C are temperature dependent according to
  - $$\begin{cases} Q_{P0}^G = \mathbf{Q_{P0}} \cdot e^{\left(1-\frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAG0}}} \\ H_{JEI}^G = \mathbf{H_{JEI}} \cdot e^{\left(1-\frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAGE}}} \\ H_{JCI}^G = \mathbf{H_{JCI}} \cdot e^{\left(1-\frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAGC}}} \\ \Gamma_E(T) = \Delta_E(T) + \Phi_E(T) \\ \Gamma_C(T) = \Delta_C(T) + \Phi_C(T) \end{cases}$$
  - The temperature dependence of $\Gamma_E(T)$ and of $\Gamma_C(T)$ are identical to those of HICUM/L0 v1.2G

HICUM/L2 v2.24G new model equations (2/2)

- Collector current at low current densities and at the reference temperature

  - $I_C = \dfrac{C_{10} \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}}\right)}{Q_{P0} + H_{JEI} \cdot Q_{P0} \cdot \Phi_E(T_0) + H_{JCI} \cdot Q_{P0} \cdot \Phi_C(T_0)}$ dividing the numerator and the denominator by Q_{P0} leads

$$\boxed{I_C = \frac{\mathbf{I_S} \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}}\right)}{1 + H_{JEI} \cdot \Phi_E(T_0) + H_{JCI} \cdot \Phi_C(T_0)}} \text{ with } \mathbf{I_S} = \frac{C_{10}}{Q_{P0}} \qquad (3)$$

- Comments

  - From equation (3) it is important to remark that the collector current at low current densities and at the reference temperature T_0 is independent on QP0. In consequence, for the first time, with the HICUM/L2 v2.24G, I_S, H_{JEI} and H_{JCI} can be now determined without any ambiguity. In this new formulation I_S is use as an alternative of C_{10}.

  - From equations (1) and (3) we can deduce

$$\boxed{\begin{cases} H_{JEI} = \dfrac{1}{\mathbf{V_{ER}}} \\ H_{JCI} = \dfrac{1}{\mathbf{V_{EF}}} \end{cases}}$$

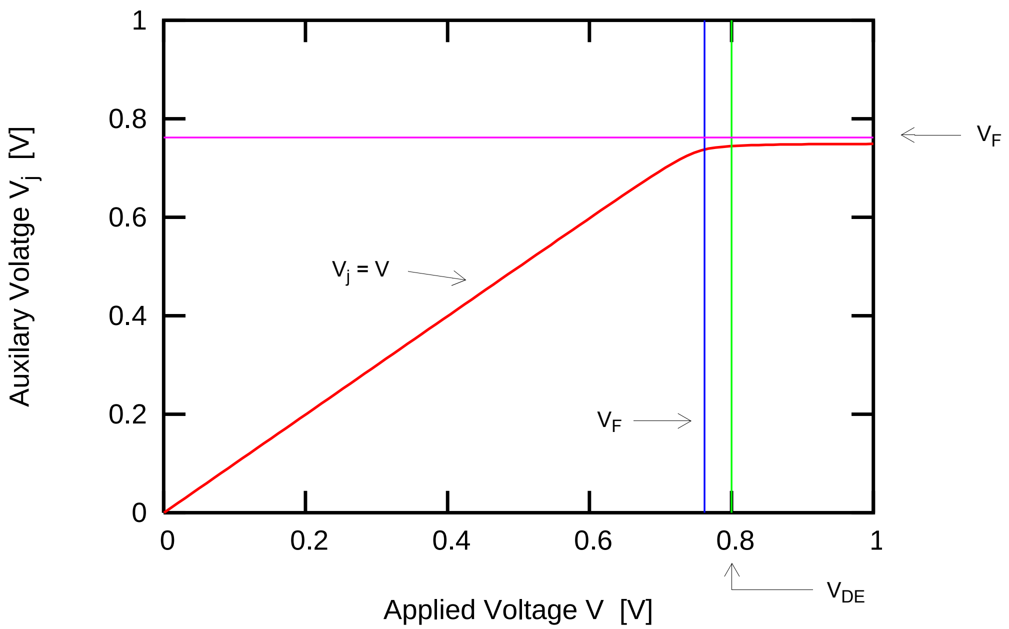
HICUM/L0 v1.2G parameter extraction overview [4] (1/9)

- I_S, V_{ER}, V_{DEDC}, (Z_{EDC}, A_{JEDC})
  - These parameters are determined from I_C vs. V_{BE} at low current density, V_{BC} = 0V and at the reference temperature T_0
  - Direct extraction method which gives enough accurate initial guess for after global optimization
  - It had been observed and demonstrated [5], [7] that

    (i) Z_{EDC} and A_{JEDC} are linked

    (ii) $Z_{EDC} \approx 1$

    (iii) Moreover, if we assume $V_F / \mathbf{V_{DEDC}} \approx 0.9$ than $\boxed{\mathbf{A_{JEDC}} \approx 10^{\mathbf{Z_{EDC}}} \text{ or } \mathbf{Z_{EDC}} \approx \log(\mathbf{A_{JEDC}})}$



- V_F is the knee voltage for the forward dependence of the junction capacitance
- For $V_{BE} < V_F$, $V_{BE\_capa} = V_{BE}$
- For $V_{BE} > V_F$, $V_{BE\_capa} = V_F \approx \mathbf{V_{DEDC}}$
- In consequence, as initial guess we chose $Z_{EDC} = 0.999$ and $A_{JEDC} = 10$

HICUM/L0 v1.2G parameter extraction overview (2/9)

- At T_0 and at low V_{BE} we have

$$I_C \approx \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 + \frac{Q_{JNOM} \cdot \Gamma_E(T_0)}{Q_{P0}}} = \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 + \frac{\Gamma_E(T_0)}{\mathbf{V_{ER}}}} \text{ with } \Gamma_E(T_0) = \Delta_E(T_0) + \Phi_E(T_0) = 0 + \Phi_E(T_0) \tag{4}$$

- Moreover

$$Q_{JE} = Q_{JNOM} \cdot \Phi_E(T_0) = \mathbf{C_{JE0}}(T_0) \cdot \mathbf{V_{DEDC}}(T_0) \cdot \Phi_E(T_0) = \int_0^{V_{BE}} C_{JE}(u)du \tag{5}$$

- At low forward V_{BE} and assuming $\mathbf{Z_{EDC}}$ close to 1, the junction capacitance is given by

$$C_{JE}(V) = \frac{\mathbf{C_{JE0}}}{\left(1 - \frac{V_{BE}}{\mathbf{V_{DEDC}}}\right)^{\mathbf{Z_{EDC}}}} = \frac{\mathbf{C_{JE0}}}{1 - \frac{V_{BE}}{\mathbf{V_{DEDC}}}} \text{ and}$$

$$\int_0^{V_{BE}} C_{JE}(u)du = -C_{JE0}(T_0) \cdot V_{DEDC}(T_0) \cdot \ln\left\{1 - \frac{V_{BE}}{V_{DEDC}(T_0)}\right\} \tag{6}$$

- Finally, from (5) and (6) we can deduce the value of $\Phi_E(T_0)$

$$\Phi_E(T_0) = \frac{\int_0^{V_{BE}} C_{JE}(u)du}{C_{JE0}(T_0) \cdot V_{DEDC}(T_0)} = -\ln\left\{1 - \frac{V_{BE}}{V_{DEDC}(T_0)}\right\} \tag{7}$$

HICUM/L0 v1.2G parameter extraction overview (3/9)

- Therefore, from (7) and (4) we can write the expression of the collector current at low current densities

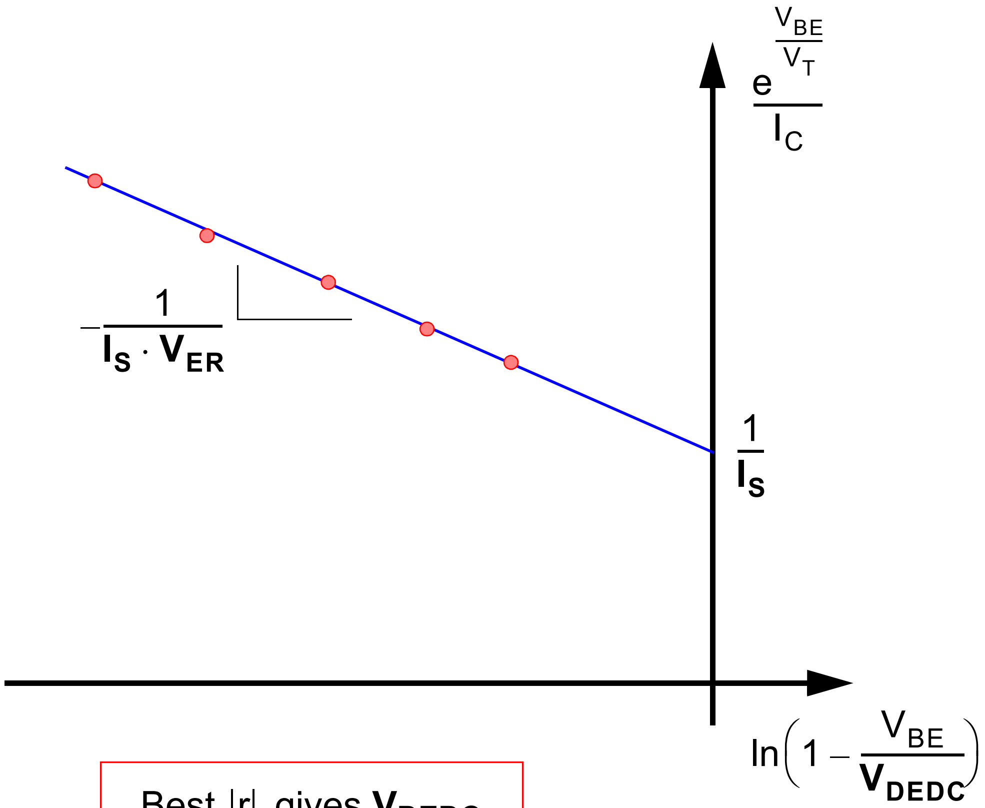
$$I_C = \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 + \frac{\Phi_E(T_0)}{\mathbf{V_{ER}}}} = \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 - \frac{1}{\mathbf{V_{ER}}} \cdot \ln\left(1 - \frac{V_{BE}}{\mathbf{V_{DEDC}} T_0}\right)} \qquad (8)$$

- Rearranging we obtain

$$\frac{e^{\frac{V_{BE}}{V_T}}}{I_C} = \frac{1}{\mathbf{I_S}} - \frac{1}{\mathbf{I_S} \cdot \mathbf{V_{ER}}} \cdot \ln\left(1 - \frac{V_{BE}}{\mathbf{V_{DEDC}}(T_0)}\right) \qquad (9)$$

- From equation (9), we chose (dichotomy method) the value of $\mathbf{V_{DEDC}}$ which gives the best correlation |r| coefficient close to 1.

- Once is $\mathbf{V_{DEDC}}$ is found, the measured data must be aligned (that validate the assumption $\mathbf{Z_{EDC}} = 1$), the intercept gives $\mathbf{I_S}$, the slope and the intercept give $\mathbf{V_{ER}}$



Best |r| gives $\mathbf{V_{DEDC}}$

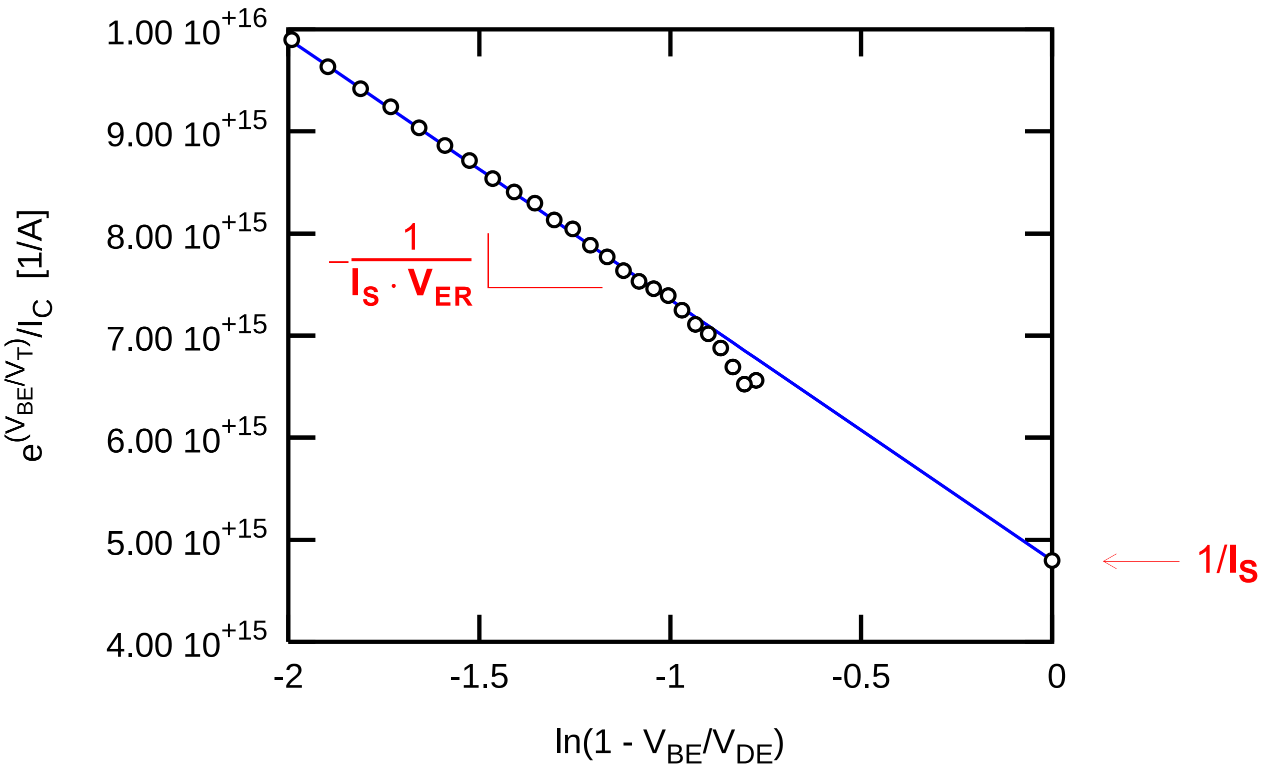
$$\mathbf{I_S} = \frac{\mathbf{1}}{\mathbf{Intercept}}$$

$$\mathbf{V_{ER}} = -\frac{\text{Intercept}}{\text{Slope}}$$

HICUM/L0 v1.2G parameter extraction overview (4/9)

- The good linearity of the experimental characteristic $\frac{e^{\frac{V_{BE}}{V_T}}}{I_C}$ vs. $\ln\left\{1-\frac{V_{BE}}{\mathbf{V_{DEDC}}(T_0)}\right\}$ validates the assumption

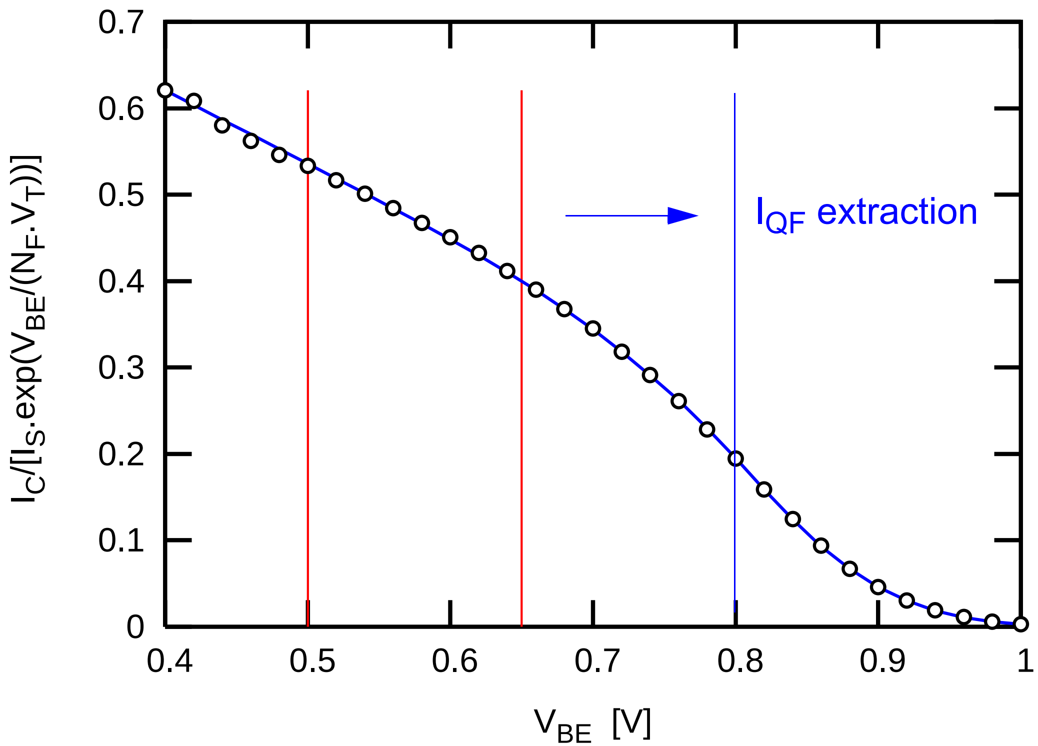
$Z_{EDC} = 0.999$ and $A_{JEDC} = 10$



HICUM/L0 v1.2G parameter extraction overview (5/9)

- I_{QF}

  - Knowing $\mathbf{I_S}$, $\mathbf{V_{ER}}$, $\mathbf{V_{DEDC}}$, the extraction of $\mathbf{I_{QF}}$ is performed on the characteristic $\frac{I_C}{e^{\frac{V_{BE}}{V_T}}}$ vs. V_{BE}, at V_{BC} = 0V, enlarging the V_{BE} range to medium current densities. Using global non-linear least-square algorithms (SIMPLEX, Levenberg-Marquardt, ...) $\mathbf{I_S}$, $\mathbf{V_{ER}}$, $\mathbf{V_{DEDC}}$ and $\mathbf{I_{QF}}$ are optimized. If needed $\mathbf{A_{JEDC}}$ can be also optimized (keeping $\mathbf{Z_{EDC}}$ fixed to 0.999).
  - As we can see accurate results are obtained



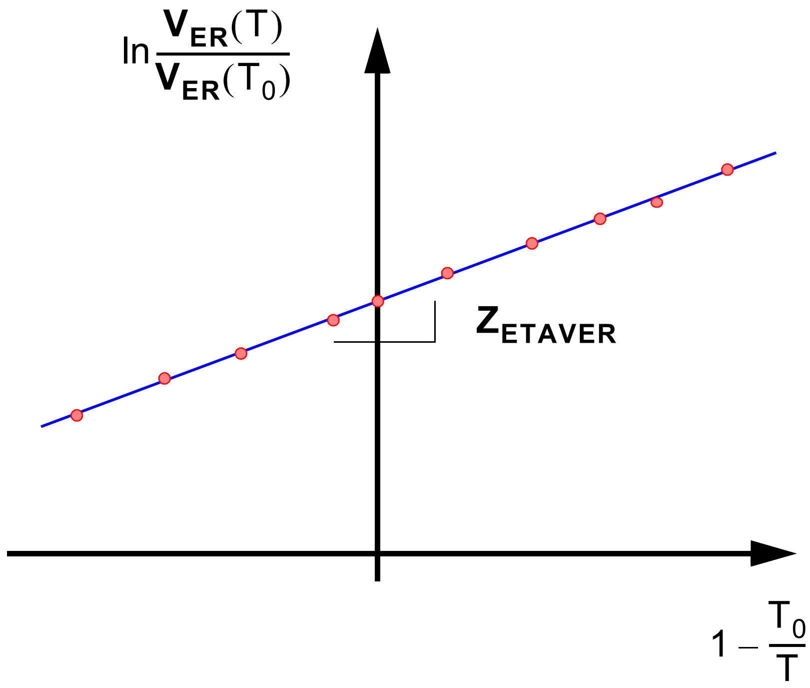
HICUM/L0 v1.2G parameter extraction overview (6/9)

- V_{EF}
  - From I_C - I_{AVL} vs. V_{BC} ($I_{AVL} = I_B(0) - I_B(V_{BC})$, at constant V_{BE} (0.7V)
  - The slope of the characteristic allows to determine V_{EF} (see Appendix C)

- Z_{ETAVER}, Z_{ETAVEF}, Z_{ETAIQF}
  - The previous extraction step are performed at each temperature allowing to have $V_{ER}(T)$, $V_{EF}(T)$, $I_{QF}(T)$ (and $I_S(T)$, $\mathbf{V_{DEDC}}(T)$) characteristics
  - From the logarithm of these data versus 1-T_0/T, the thermal coefficient can be easily determined
  - $\mathbf{V_{ER}}(T) = \mathbf{V_{ER}}(T_0) \cdot e^{\left(1-\frac{T_0}{T}\right) \cdot \mathbf{Z_{ETAVER}}} \Leftrightarrow$

$$\boxed{\ln\frac{\mathbf{V_{ER}}(T)}{\mathbf{V_{ER}}(T_0)} = \mathbf{Z_{ETAVER}} \cdot \left(1-\frac{T_0}{T}\right)}$$

  - Same procedure for $\mathbf{V_{EF}}$ and $\mathbf{I_{QF}}$



HICUM/L0 v1.2G parameter extraction overview (7/9)

- Z_{ETACT}, V_{GB}

  - $$\mathbf{I_S}(T) = \mathbf{I_S}(T_0)\cdot\left(\frac{T}{T_0}\right)^{\mathbf{Z_{ETACT}}}\cdot e^{\left(\frac{\mathbf{V_{GB}}}{V_{T0}}-\mathbf{Z_{ETAIQF}}\right)\cdot\left(1-\frac{T_0}{T}\right)} = \mathbf{I_S}(T_0)\cdot\left(\frac{T}{T_0}\right)^{\mathbf{Z_{ETACT}}}\cdot e^{\mathbf{Z_{ETAVG}}\cdot\left(1-\frac{T_0}{T}\right)} \Leftrightarrow$$

  $$\boxed{\ln\frac{\mathbf{I_S}(T)}{\mathbf{I_S}(T_0)} = \mathbf{Z_{ETACT}}\cdot\ln\frac{T}{T_0}+\mathbf{Z_{ETAVG}}\cdot\left(1-\frac{T_0}{T}\right)}$$

  - This equation is linear, $\mathbf{Z_{ETACT}}$ and $\mathbf{Z_{ETAVG}}$ can be directly determines using multi-variable linear regression

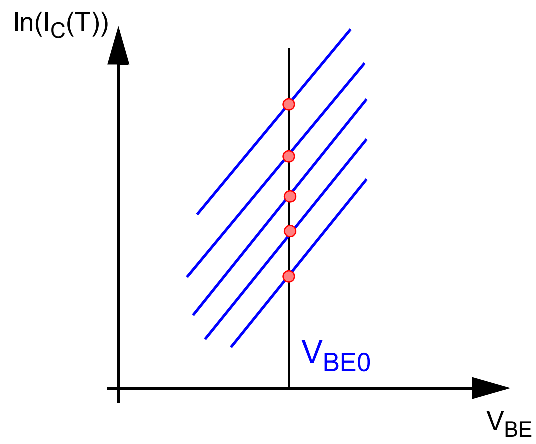
  - From $\mathbf{Z_{ETAVG}}$, it is possible to determine $\mathbf{V_{GB}}$

  $$\boxed{\mathbf{V_{GB}} = (\mathbf{Z_{ETAVG}}+\mathbf{Z_{ETAIQF}})\cdot V_{T0}}$$

HICUM/L0 v1.2G parameter extraction overview (8/9)

D_{ELTE}

- This parameter is determined from $I_C(T, V_{BE})$ at low current densities and V_{BC} = 0V
- $V_{BE} = V_{BE0}$ is chosen in order to be at low current densities for all temperatures



$$I_C(T, V_{BE0}) \approx \frac{\mathbf{I_S}(T)\cdot e^{\frac{V_{BE0}}{V_T}}}{1+\frac{\Gamma_E(T)}{\mathbf{V_{ER}}(T)}} \Leftrightarrow \frac{\mathbf{I_S}(T)\cdot e^{\frac{V_{BE0}}{V_T}}}{I_C(T, V_{BE0})} = 1+\frac{\Gamma_E(T)}{\mathbf{V_{ER}}(T)} = 1+\frac{\Delta_E(T)+\Phi_E(T)}{\mathbf{V_{ER}}(T)}$$

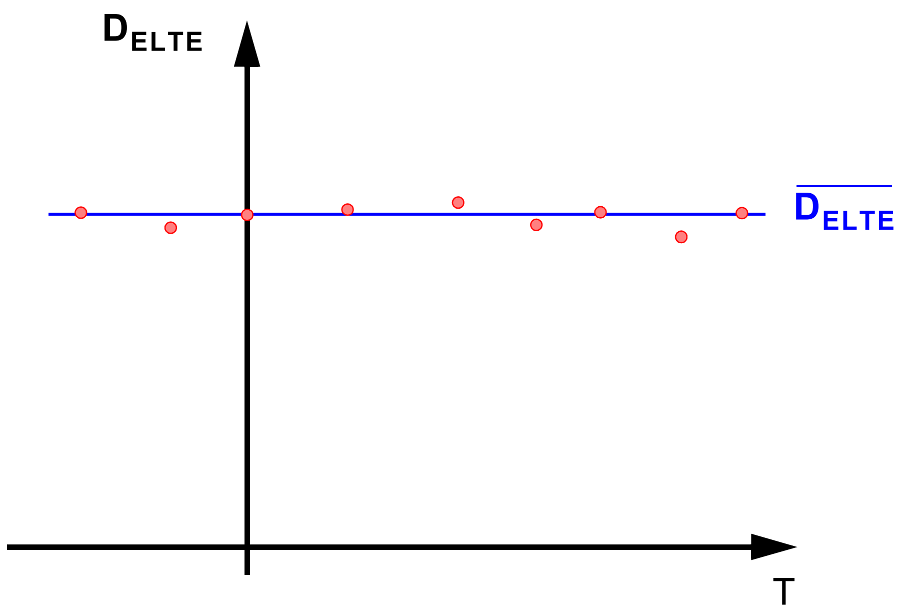
leads

$$\boxed{\Delta_E(T) = \left(\frac{\mathbf{I_S}(T)\cdot e^{\frac{V_{BE0}}{V_T}}}{I_C(T, V_{BE0})}-1\right)\cdot \mathbf{V_{ER}}(T)-\Phi_E(T)}$$

- This equation allows to compute $\Delta_E(T)$ and after to calculate $\mathbf{D_{ELTE}}$ from (2)

$$\boxed{\mathbf{D_{ELTE}} = \frac{(1-\mathbf{Z_{EDC}})\cdot\Delta_E(T)}{1-\left\{\frac{\mathbf{V_{DEDC}}(T)}{\mathbf{V_{DEDC}}(T_0)}\right\}^{1-\mathbf{Z_{EDC}}}}}$$

- From this equation, $\mathbf{D_{ELTE}}$ can be computed at each temperature. The mean value is chosen.



HICUM/L0 v1.2G parameter extraction overview (9/9)

- D_{ELTC}
  - Similar approach can be used to determine $\mathbf{D_{ELTC}}$ from $I_C(T,V_{BE},V_{BC})$. But as its value is less important than $\mathbf{D_{ELTE}}$, the procedure is not described.

HICUM/L2 v2.24G parameter extraction overview [4]

- If the new model parameters of the HICUM/L0 v1.2G have been correctly determined, the new parameter of HICUM/L2 v2.24G can be directly calculated from those of HICUM/L0 v1.2G without any extraction effort (and vice versa)

  •

$$
\begin{aligned}
Q_{p0} &= I_{QF} \cdot T_0 \\
C_{10} &= I_S \cdot Q_{P0} \\
H_{JEI} &= \frac{1}{V_{ER}} \\
H_{JCI} &= \frac{1}{V_{EF}} \\
Z_{ETAG0} &= Z_{ETAIQF} \\
Z_{ETAGE} &= Z_{ETAIQF} - Z_{ETAVER} \\
Z_{ETAGC} &= Z_{ETAIQF} - Z_{ETAVEF}
\end{aligned}
$$

- Extraction of I_S, Q_{P0}, C_{10}, H_{JEI}
  - Thanks to the new formulation of the transfer current, the *original concept* of HICIM is still fully preserved and it is now possible to extract Q_{P0}, C_{10}, H_{JEI} without ambiguity. For the first time since 2006 [2], a solution is found to break the correlation between Q_{P0}, C_{10}, H_{JEI}. HICUM/L2 parameter extraction is no more a nightmare and even becomes a pleasure and as simple as SGP model!...
  - See Appendix B for more details

Experimental results and validation

- Two technologies
  - BiCMOS9MW 0.13µm SiGe BiCMOS self-aligned technology from STMicroelectronics [8]
  - H18 HVMOS 0.18µm high voltage process from *austriamicrosystems AG* [9]

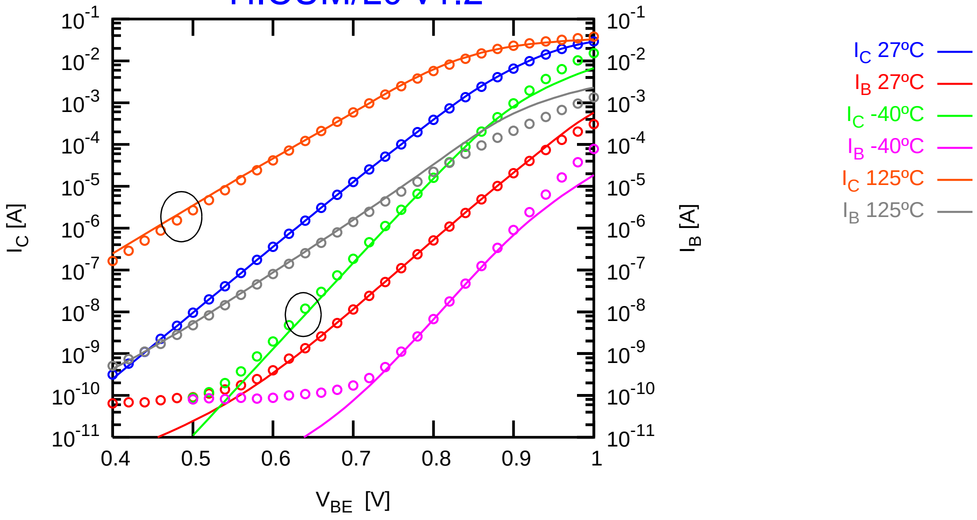
- Three models
  - HICUM/L0 v1.2
  - HICUM/L0 v1.2G
  - HICUM/L2 v2.24G

- Theory/experiment comparisons
  - Simulations with Verilog-A code and ELDO (AMS 2010.1)
  - Same results obtained with MATLAB code and NGSPICE [12]

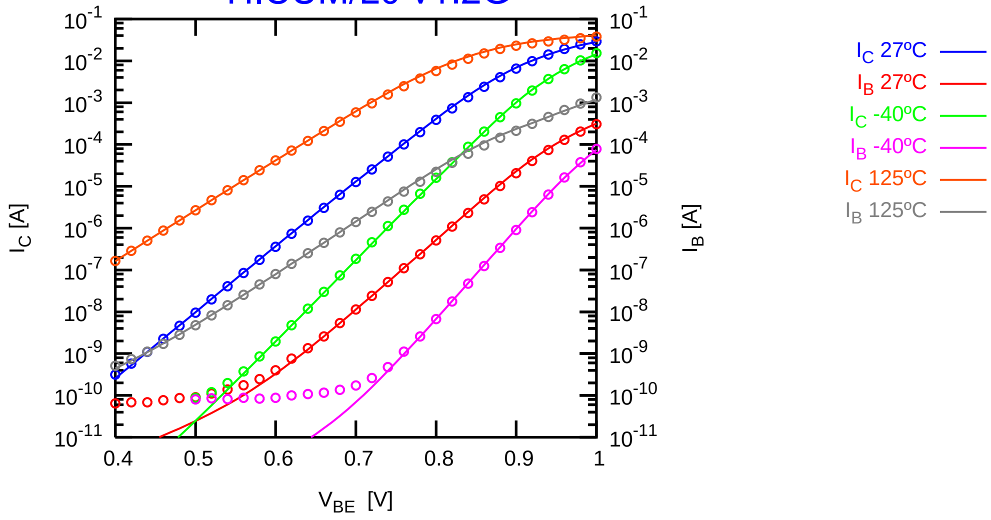
Forward Gummel plots

- Advanced HBT process f_T 250GHz [8]

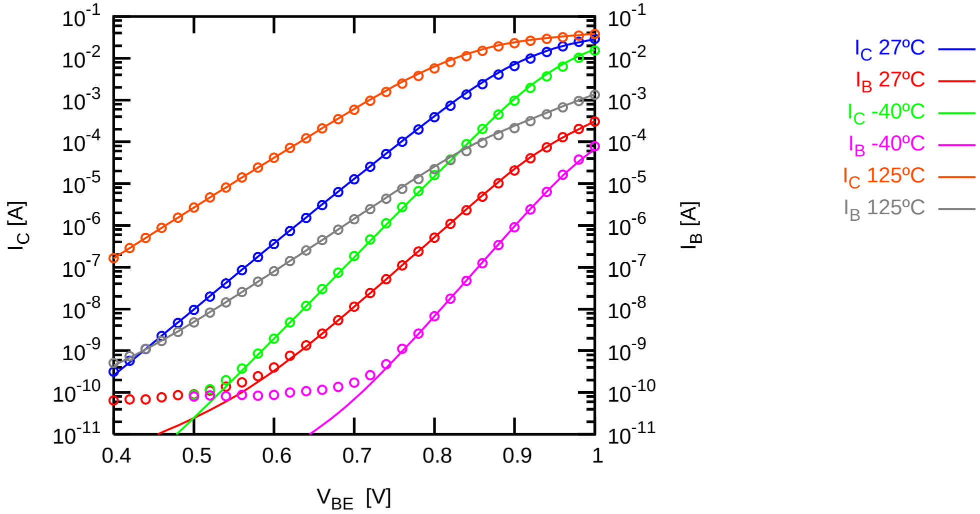
HICUM/L0 v1.2



HICUM/L0 v1.2G



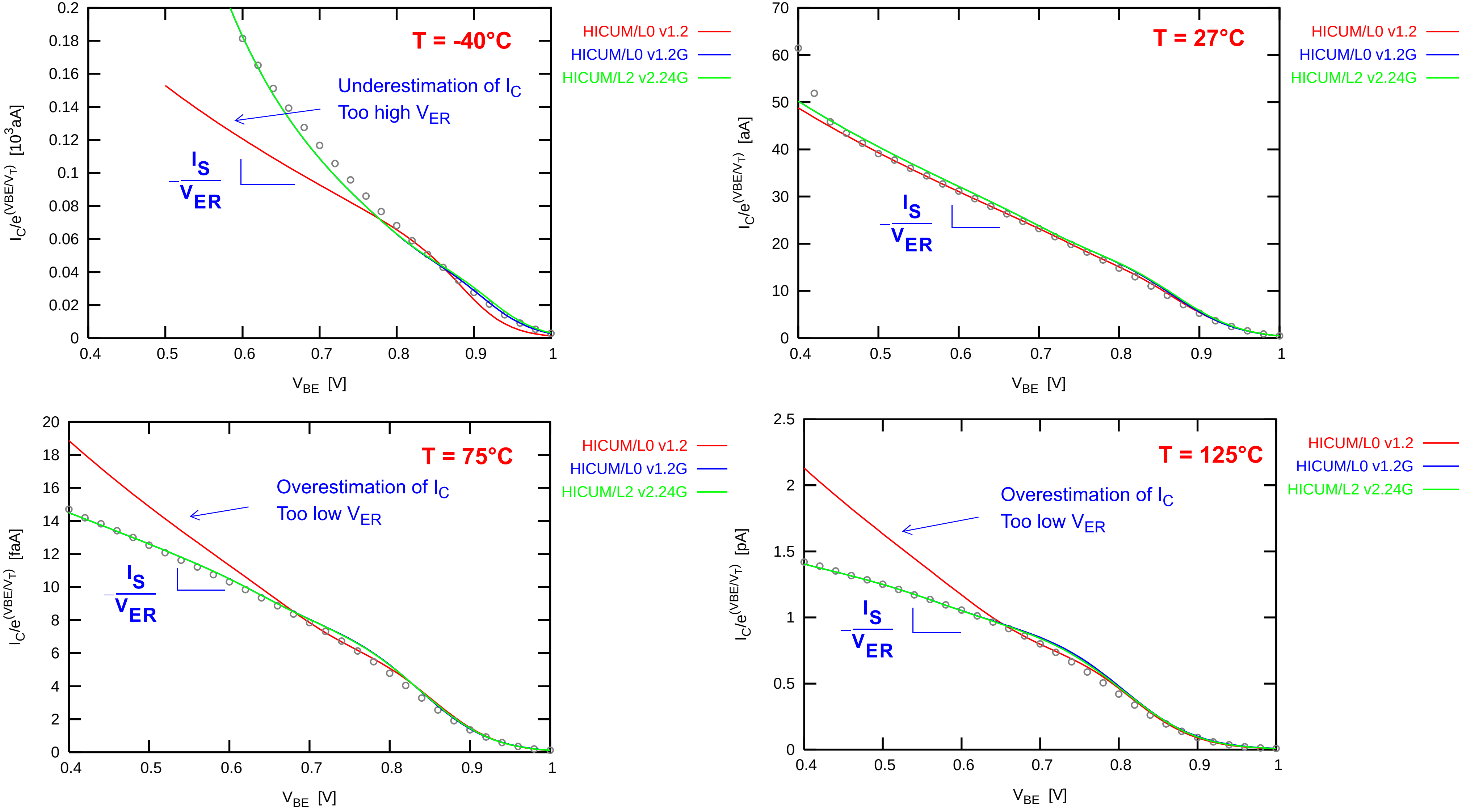
HICUM/L2 v2.24G



- HICUM/L0 v1.2 bad temperature dependence of the collector current. HICUM/L2 v2.24 give similar results (not shown) with also bad modeling at room temperature with unrealistic $\mathbf{I_S}$ ($\mathbf{C_{10}/Q_{P0}}$) value.
- HICUM/L0 v1.2G and HICUM/L2 v2.24G very good modeling of the collector current in all temperature range.
- The plots of the normalized collector current $I_C/\{\exp(V_{BE}/V_T)\}$ allows to better see the impact of the temperature on the *effective* reverse early effect and the accuracy of the new proposed models (next slide).

Collector current normalized to exp(V_{BE}/V_T)

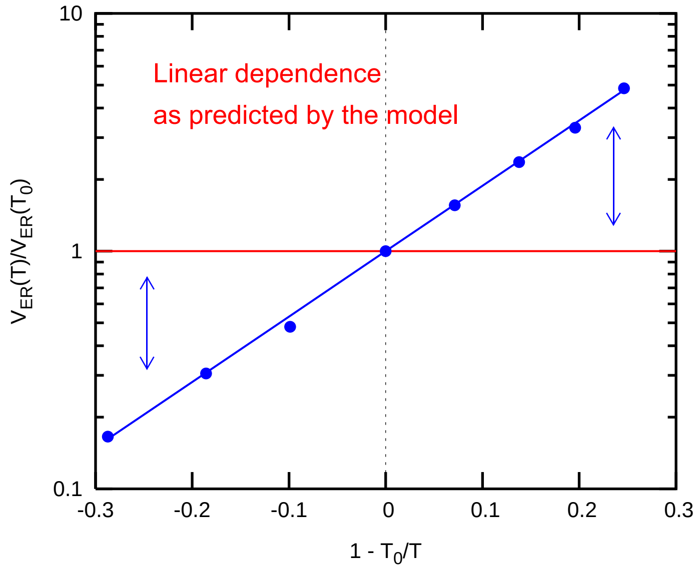
- Advanced HBT process f_T 250 GHz [8]

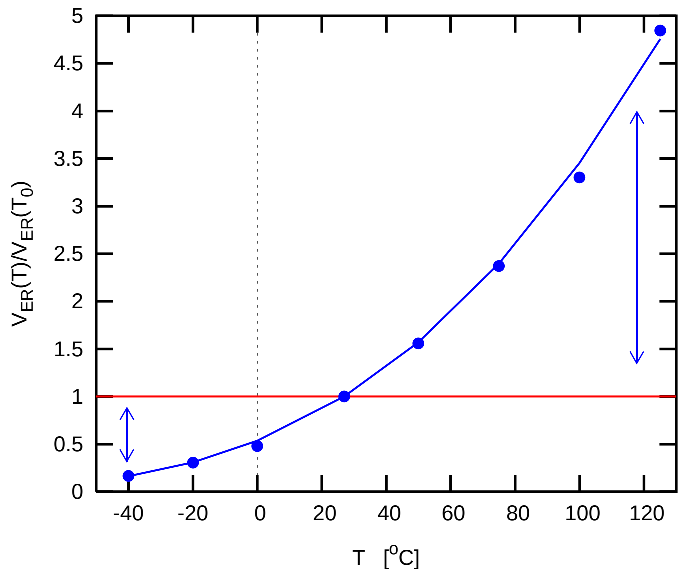


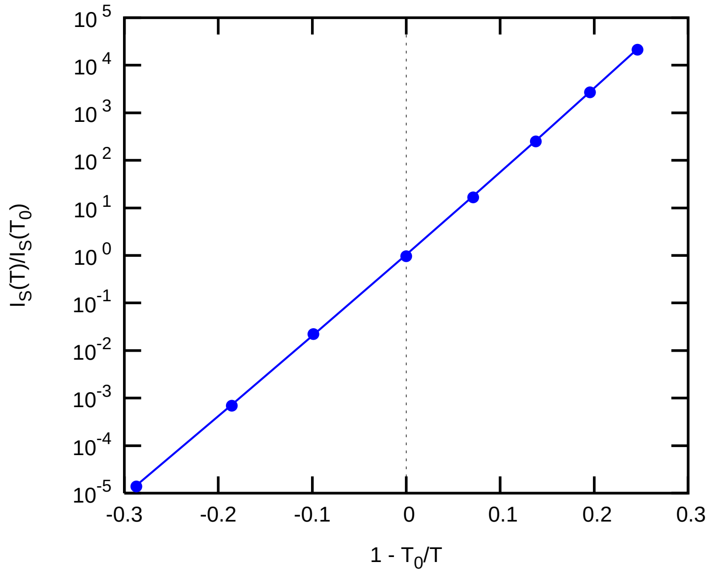
Saturation Curent and reverse Early effect (1/2)

- 0.13 µm advanced HBT process f_T 250 GHz [8]

HICUM/L0





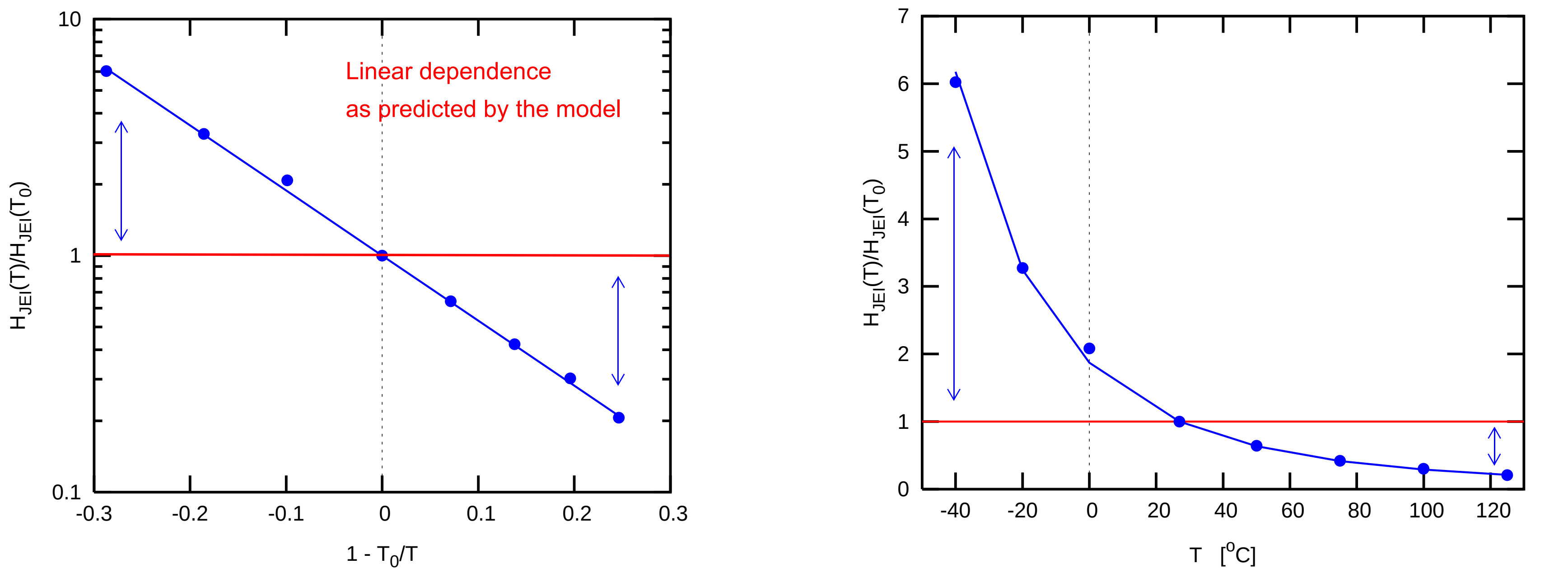


Contrary to HICUM/L0 v1.2 (red), the important temperature variation of $\mathbf{V_{ER}}$ is well described in HICUM/L0 v1.2G (blue).

Saturation Curent and reverse Early effect (2/2)

- 0.13 µm advanced HBT process f_T 250 GHz [8]

HICUM/L2

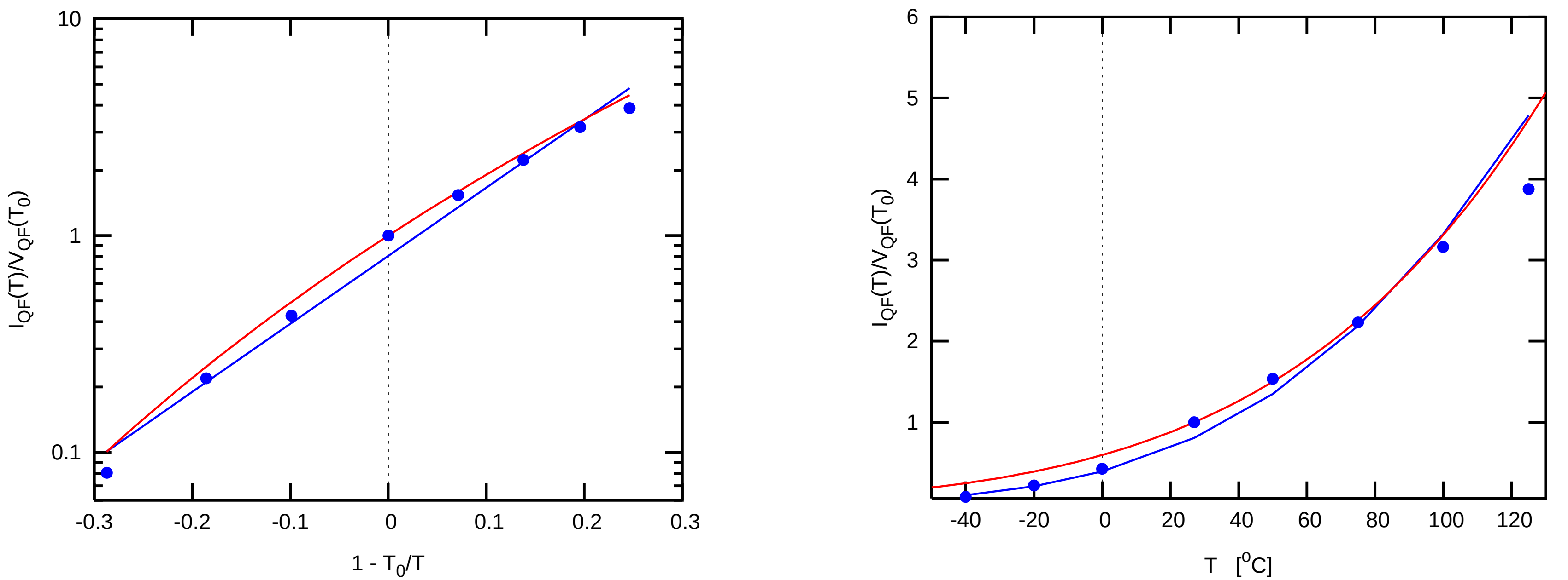


• Contrary to HICUM/L2 v2.24 (red), the important temperature variation of $\mathbf{H_{JEI}}$ is well described in HICUM/L2 v2.24G (blue)

Knee current

- 0.13 µm advanced HBT process f_T 250 GHz [8]

HICUM/L0

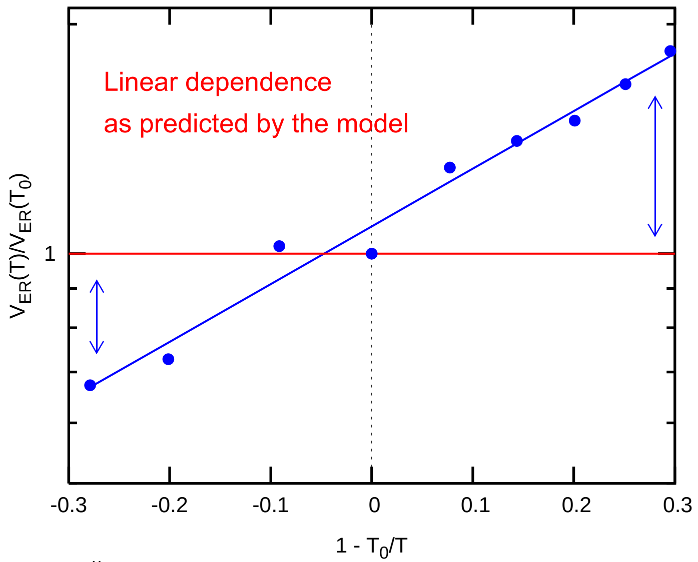


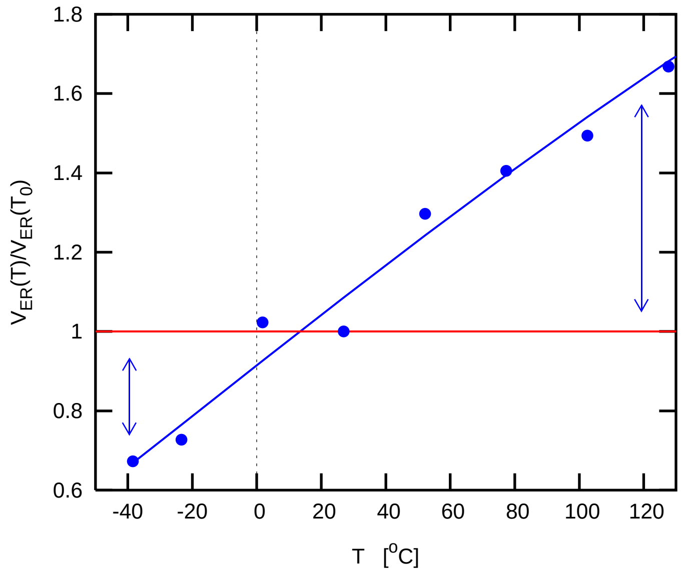
• Similar accuracy between HICUM/L0 v1.2 (red) and HICUM/L0 v1.2G (blue)

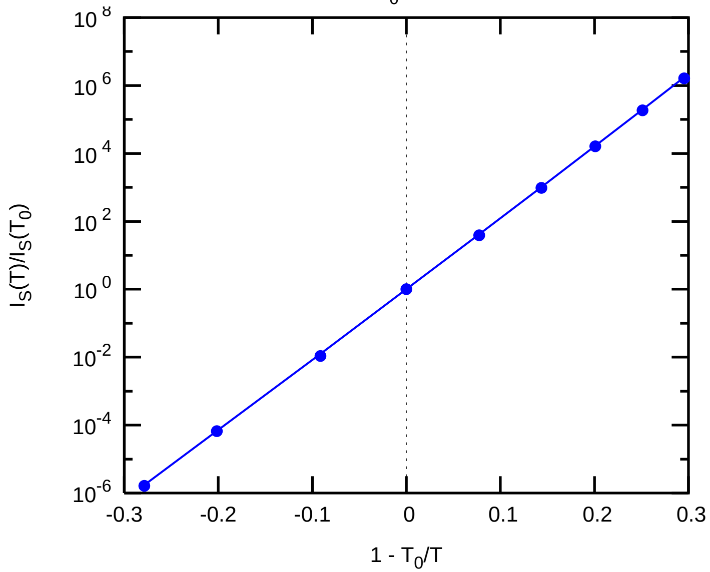
Saturation Curent and reverse Early effect (1/2)

- 0.18 µm power process [9]

HICUM/L0





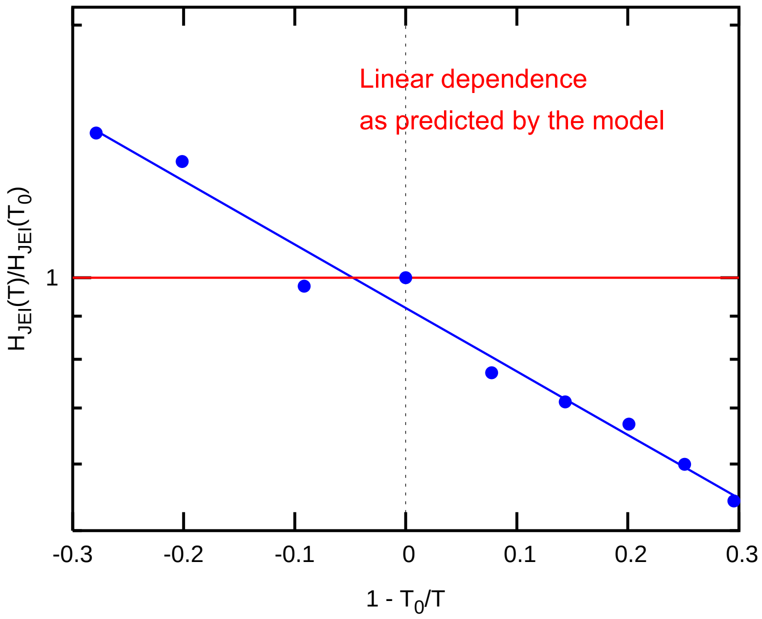


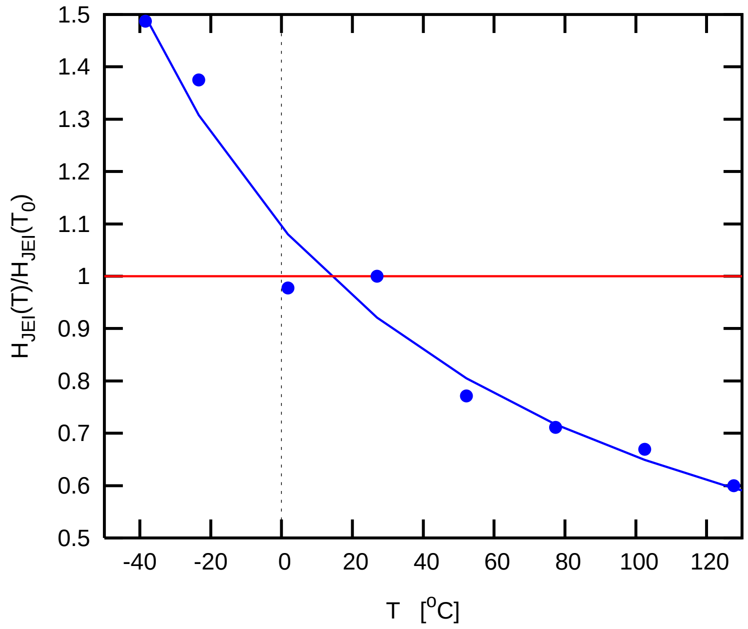
- Contrary to HICUM/L0 v1.2 (red), temperature variation of $\mathbf{V_{ER}}$ is well described in HICUM/L0 v1.2G (blue)
- We can remark that the temperature dependence is less important for this Si power transistor than for the advanced HBT device

Saturation Curent and reverse Early effect (2/2)

- 0.18 µm power process [9]

HICUM/L2



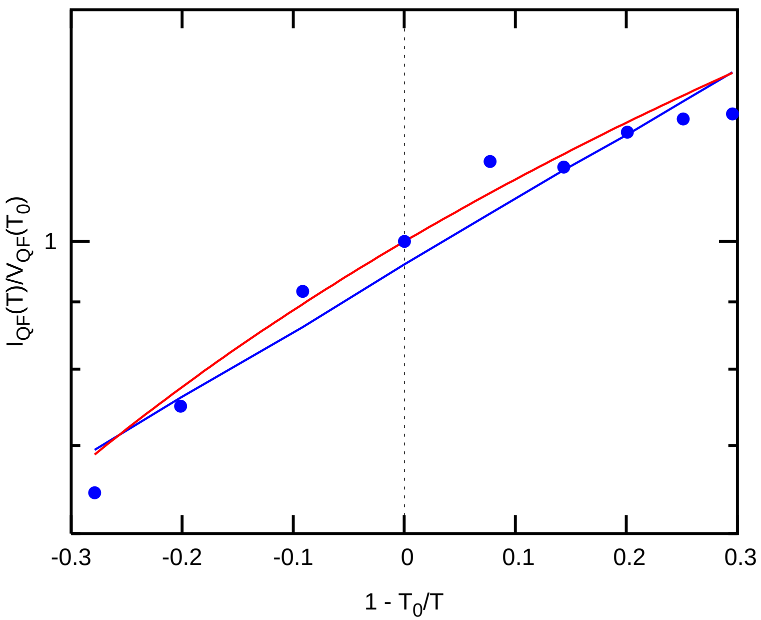


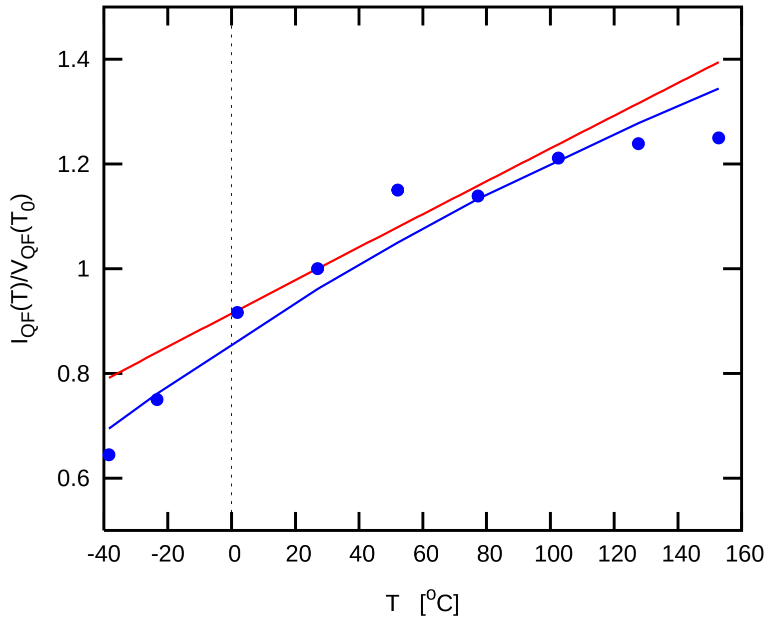
- Contrary to HICUM/L2 v2.24 (red), the temperature variation of $\mathbf{H_{JEI}}$ is well described in HICUM/L2 v2.24G (blue)
- We can remark that the temperature dependence of $\mathbf{H_{JEI}}$ is less important for this Si power transistor than for the advanced HBT device

Knee current

- 0.18 µm power process [9]

  HICUM/L0



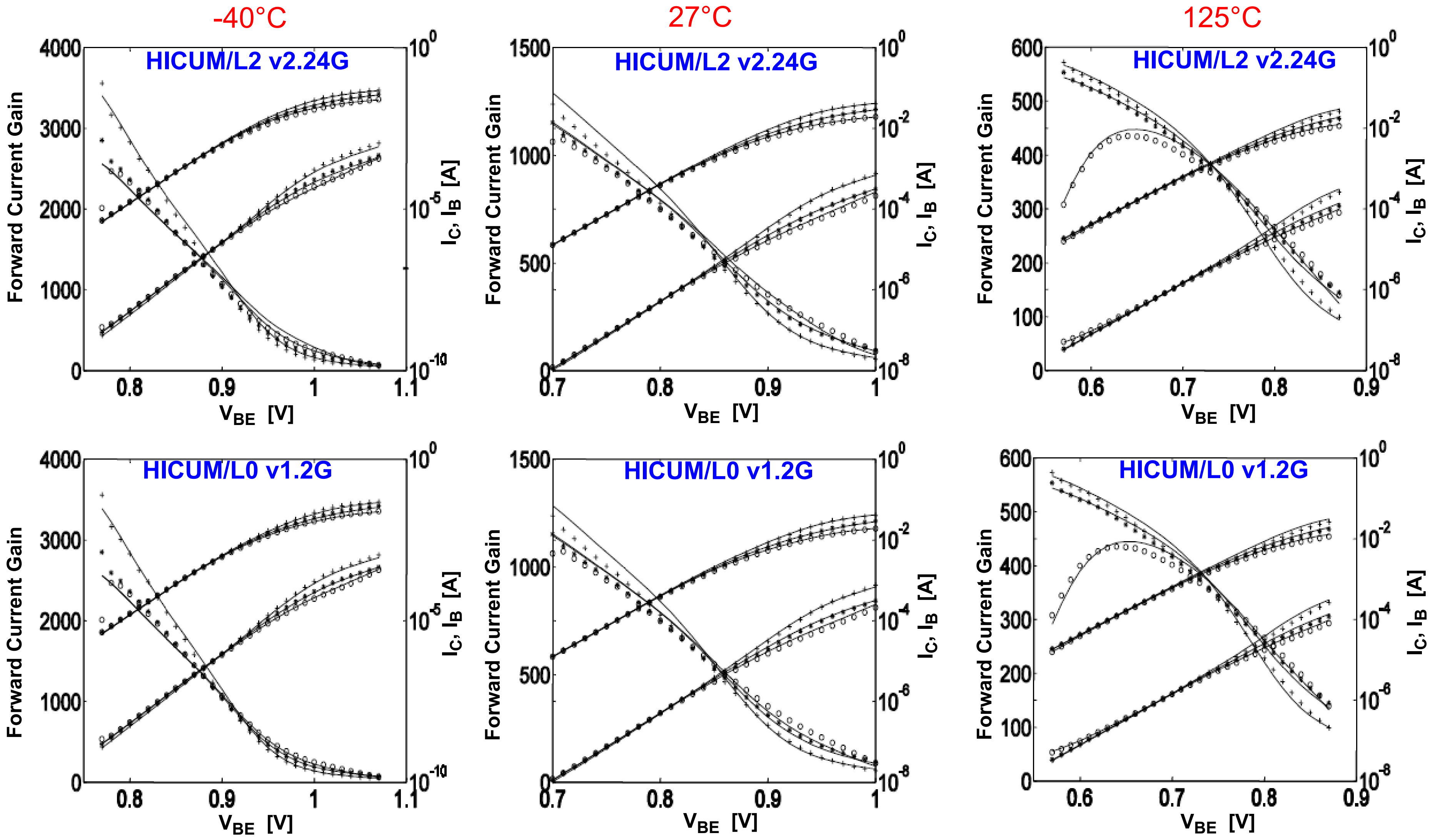


• Similar accuracy between HICUM/L0 v1.2 (red) and HICUM/L0 v1.2G (blue)

• We can remark that the temperature dependence of $\mathbf{I_{QF}}$ is less important for this Si power transistor than for the advanced HBT device

Forward Gummel plots and current gain

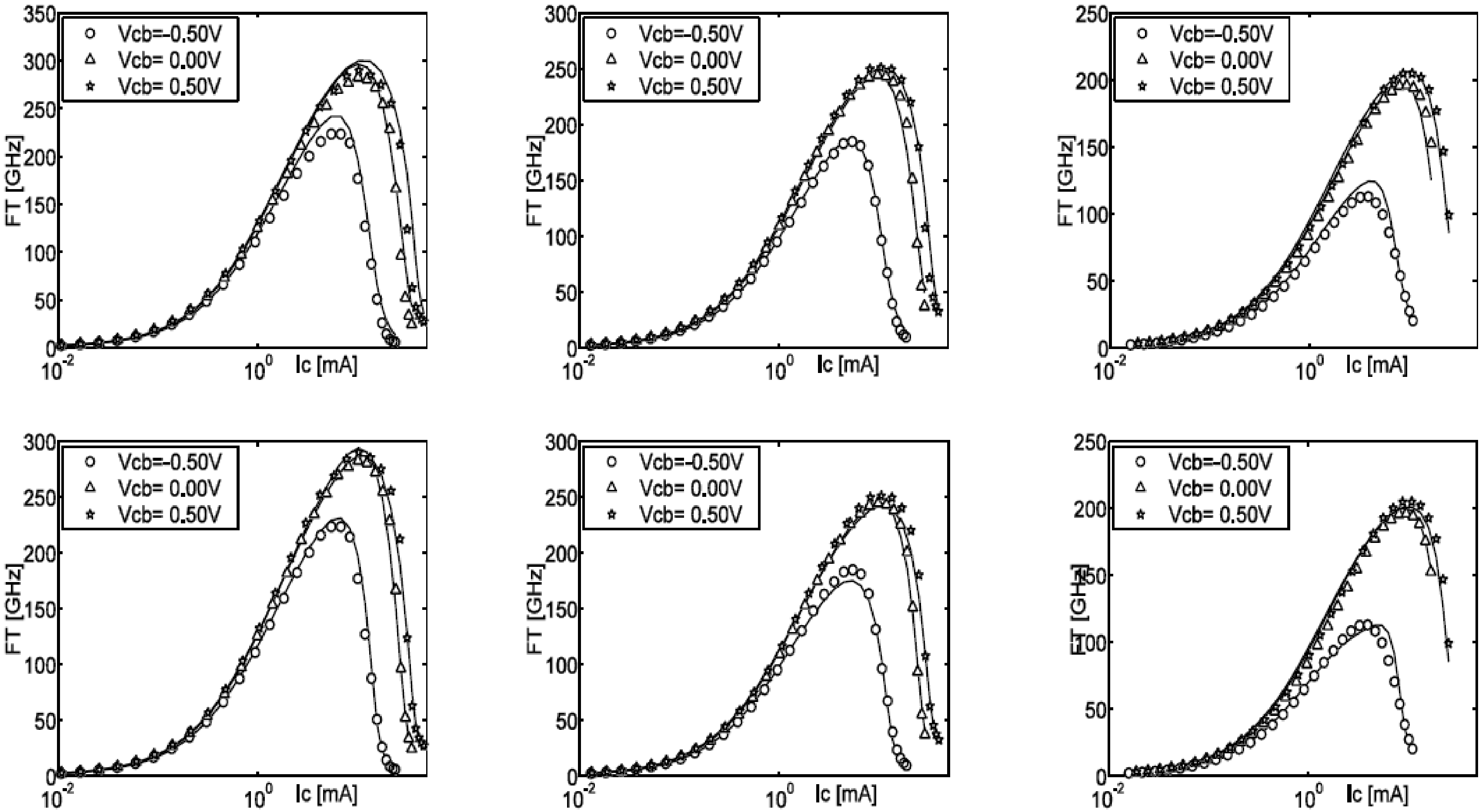
- 0.13 µm advanced HBT process f_T 250 GHz [8]
  - For both models, very good precision at medium and high current densities **(+ V_{BC} = - 0.5V, * V_{BC} = 0V ○ V_{BC} = 0.5V)**



f_T characteristics

- 0.13 µm advanced HBT process f_T 250 GHz [8]
  - The new low-bias charge concept applied both to HICUM/L2 and HICUM/L0 also gives very good results at high-current densities (DC + AC), in a wide range of temperatures

-40°C 27°C 125°C



HICUM/L2 V2.24G

HICUM/L0 V1.2G

Summary

- A novel low-bias charge concept valid for both BJT and HBTS models have been implemented in HICUM/L0 and HICUM/L2
  - Verilog-A code available
  - Validated with MATLAB and NGSPICE
- Extraction procedure described
  - Mainly direct extraction
  - Easier C_{10}, Q_{P0}, H_{JEI} extraction for HICUM/L2
- Validation on 2 different technologies (advanced HBT and power BJT)
  - At room temperature from low to high current densities
  - In DC and AC
  - In a wide range of temperatures [-40°C:125°C]
- Critical known limitations of HICUM/L0 and HICUM/L2 are solved
  - Modeling of the reverse Early effect
  - Temperature dependence
  - Parameter extraction

What else?

- HICUM/L0 v1.2G, HICUM/L2 v2.24G vs. HICUM/L2 v2.3

	HICUM/L0 v1.2G	HICUM/L2 v2.24G	HICUM/L2 v2.3
Physics based model	YES	YES	YES (?)
Release notes available	YES	YES	YES
Verilog-A code validated	YES vla code available and validated with Matlab, ELDO and NGSPICE	YES vla code available and validated with Matlab, ELDO and NGSPICE	YES vla code available Validation in progress at STM
Parameter extraction described	YES Easy parameter extraction described and implemented in Matlab	YES Easy parameter extraction described and implemented in Matlab	? Parameter extraction seems complex
Correlation between C_{10}, Q_{P0}, H_{jEI}, H_{jCi} solved	-	YES	NO
Tested on several technologies	YES Advanced HBTs from ST Power devices from AMS, in a wide range of temperature	YES Advanced HBTs from ST Power devices from AMS, in a wide range of temperature	? Advanced HBTs from DOTFIVE No test at negative temperatures
Unified approach between HL0 and HL2	YES	YES	NO

ST needs and plan (1/2)

- Today, important issues for the modeling of advanced HBTs
  - Convergence issues
  - Accuracy (bandgap applications)

- HICUM/L2 v2.23
  - Difficulty to reliably extract C_{10}, Q_{P0}, H_{JEI}, H_{JCI}.
  - Impossibility to accurately model the bias and the temperature dependence of g_m at low and medium currents densities (bias and temperature dependence of the *effective* reverse Early effect).
  - Still Implementation bugs in the VA code.

- HICUM/L0 v1.2
  - Less modeling issues at room temperature.
  - But same problems in temperature (low *effective* reverse Early effect temperature dependent).
  - Still Implementation bugs in the VA code.

- HICUM/L0 v1.2G and HICUM/L2 v2.24G
  - Solve all these critical issues.
  - What about HICUM/L2 v2.3 (under test at STMicroelectronics) and HICUM/L0 v1.3?

ST needs and plan (2/2)

- Based on these results, the next HL0 and HL2 revisions need to be defined in agreement with all HICUM users
  - Which modeling solutions for the next HICUM/L2 and HICUM/L0 revisions?
  - Criteria:
    - Physics based
    - Accurate model
    - Easy parameter extraction
    - Validated on several technologies (DC, AC, temperature)
  - VA code ready and validated needed for end of 2010
    - VA code given to beta users for validation in order to minimize *minor code bugs*
  - Implementation by CAD vendors in Q1 2011
  - PDKs with theses new features planned in Q2 2011

Acknowledgement

- Thanks to Laurent Lemaitre for the model implementation in NGSPICE using ADMS [12].

Appendix A: Relation between new and old Early models

- HICUM/L0 v1.2
  - Low current densities, reference temperature T_0

$$Q_P \approx Q_{P0} + Q_{JE} + Q_{JC} \Rightarrow \frac{Q_P}{Q_{P0}} \approx 1 + \frac{Q_{JE}}{Q_{P0}} + \frac{Q_{JC}}{Q_{P0}} \approx 1 + \frac{C_{JE0}(T_0)\cdot V_{TE}}{Q_{P0}} + \frac{C_{JC0}(T_0)\cdot V_{TC}}{Q_{P0}} \quad \Leftrightarrow$$

  - Introducing the nominal charge Q_{JNOM}

$Q_{Jnom} = C_{J0}(T_0)\cdot V_D(T_0)$ leads

$$\boxed{\begin{cases} \dfrac{Q_P}{Q_{P0}} \approx 1 + \dfrac{V_{TE}}{V_{ER}} + \dfrac{V_{TC}}{V_{EF}} \\ V_{ER} = \dfrac{Q_{P0}}{C_{JE0}(T_0)} = \dfrac{Q_{P0}}{Q_{JEnom}}\cdot V_{DE}(T_0) \\ V_{EF} = \dfrac{Q_{P0}}{C_{JC0}(T_0)} = \dfrac{Q_{P0}}{Q_{JCnom}}\cdot V_{DC}(T_0) \end{cases}} \qquad (10)$$

  - Comments: Q_{JE} is the MRG charge (DC capacitance)

Relation between new and old Early models

- HICUM/L0 v1.2G
  - Low current densities, reference temperature T_0

$$Q_P \approx Q_{P0} + Q_{JEnom} \cdot \Gamma_E + Q_{JCnom} \cdot \Gamma_C \quad \Rightarrow$$

$$\frac{Q_P}{Q_{P0}} \approx 1 + \frac{Q_{JEnom} \cdot \Gamma_E}{Q_{P0}} + \frac{Q_{JCnom} \cdot \Gamma_C}{Q_{P0}}$$

$$\boxed{\begin{cases} \dfrac{Q_P}{Q_{P0}} \approx 1 + \dfrac{\Gamma_E}{V_{ER\_new}} + \dfrac{\Gamma_C}{V_{EF\_new}} \\ V_{ER\_new} = \dfrac{Q_{P0}}{Q_{JEnom}} \\ V_{EF\_new} = \dfrac{Q_{P0}}{Q_{JCnom}} \end{cases}} \qquad (11)$$

- From (10) and (11) we can deduce

$$\boxed{\begin{cases} V_{ER\_new} = \dfrac{V_{ER}}{V_{DE}(T_0)} \\ V_{EF\_new} = \dfrac{V_{EF}}{V_{DC}(T_0)} \end{cases}}$$

Appendix B: I_S, C_{10}, Q_{P0}, H_{JEI} extraction

- Extraction at low current densities, V_{BC} = 0V and at the reference temperature T_0
  - The collector current is given by (3)

$$I_C = \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 + \mathbf{H_{JEI}} \cdot \Phi_E(T_0)}$$ which can be rearranged as for HICUM/L0

$$\boxed{\frac{e^{\frac{V_{BE}}{V_T}}}{I_C} = \frac{1}{\mathbf{I_S}} - \frac{\mathbf{H_{JEI}}}{\mathbf{I_S}} \cdot \ln\left(1 - \frac{V_{BE}}{\mathbf{V_{DEDC}}}\right)}$$

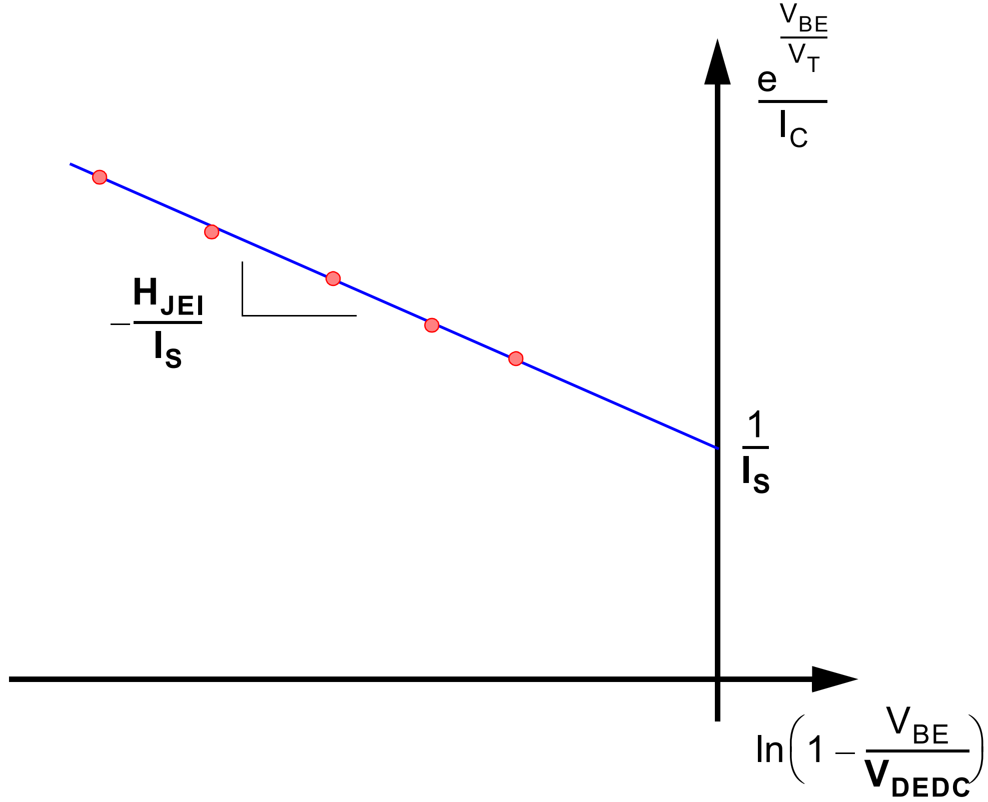
  - Same procedure then for HICUM/L0 v1.2G.
    Direct extraction using linear regression.

  - $\mathbf{Q_{P0}}$ can be estimated from HICUM/L0 parameter, or by optimizing the collector current at medium current densities knowing $\mathbf{T_0}$ (transit time)

$$\boxed{\mathbf{Q_{P0}} = \mathbf{I_{QF}} \cdot \mathbf{T_0}}$$

  - $\mathbf{C_{10}}$ is computed internaly from I_S and Q_{P0}

$$\boxed{\mathbf{C_{10}} = \mathbf{I_S} \cdot \mathbf{Q_{P0}}}$$



Appendix C: V_{EF} extraction

- Extraction from I_{C_cor} vs. V_{BC} at constant V_{BE} (0.7V) and at the reference temperature T_0

$$I_{C\_cor} = I_{C*} = I_C - I_{AVL} = \frac{\mathbf{I_S} \cdot \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right)}{1 + \frac{\Gamma_E(T_0)}{\mathbf{V_{ER}}} + \frac{\Gamma_C(T_0)}{\mathbf{V_{EF}}}} = \frac{\mathbf{I_S} \cdot e^{\frac{V_{BE}}{V_T}}}{1 + \frac{\Phi_E(T_0)}{\mathbf{V_{ER}}} + \frac{\Phi_C(T_0)}{\mathbf{V_{EF}}}} \Leftrightarrow$$

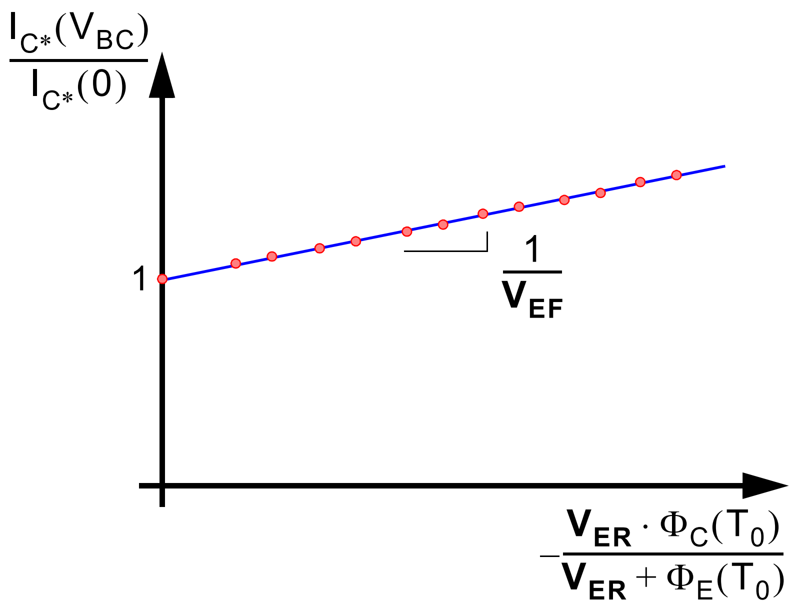
$$\frac{I_{C*}(V_{BC})}{I_{C*}(0)} = \frac{1 + \frac{\Phi_E(T_0)}{\mathbf{V_{ER}}}}{1 + \frac{\Phi_E(T_0)}{\mathbf{V_{ER}}} + \frac{\Phi_C(T_0)}{\mathbf{V_{EF}}}} = \frac{1}{1 + \frac{\Phi_C(T_0)}{\mathbf{V_{EF}}} \cdot \left\{ \frac{1}{1 + \frac{\Phi_E(T_0)}{\mathbf{V_{ER}}}} \right\}}$$

- For HBTs, V_{EF} >> 1 therefore

$$\boxed{\frac{I_{C*}(V_{BC})}{I_{C*}(0)} \approx 1 - \frac{1}{\mathbf{V_{EF}}} \cdot \frac{\mathbf{V_{ER}} \cdot \Phi_C(T_0)}{\mathbf{V_{ER}} + \Phi_E(T_0)}}$$

- V_{ER}, $\Phi_E(T_0)$ and $\Phi_C(T_0)$ are known
- Direct extraction from the slope of the characteristic

$$\frac{I_{C*}(V_{BC})}{I_{C*}(0)} \text{ vs. } \frac{\mathbf{V_{ER}} \cdot \Phi_C(T_0)}{\mathbf{V_{ER}} + \Phi_E(T_0)}$$



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