About h_{JEi} Parameter Extraction...

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Bipolar Arbeitskreis

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- Summary

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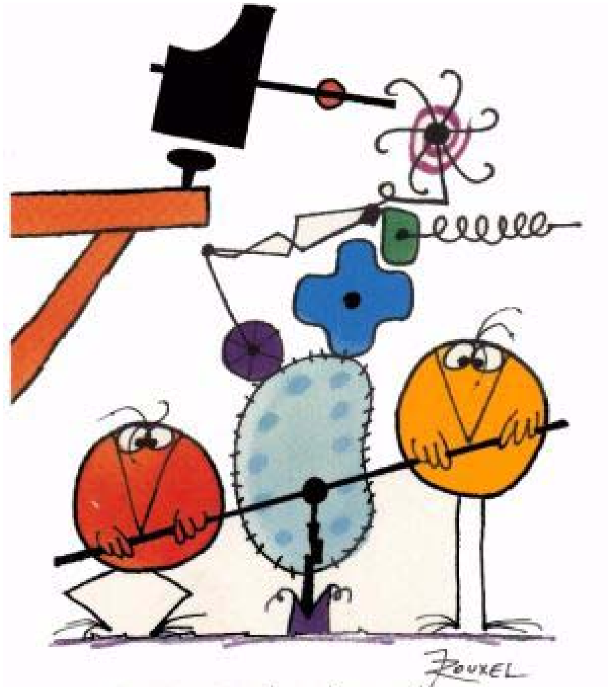

Image: http://zesonic.free.fr/devises.htm

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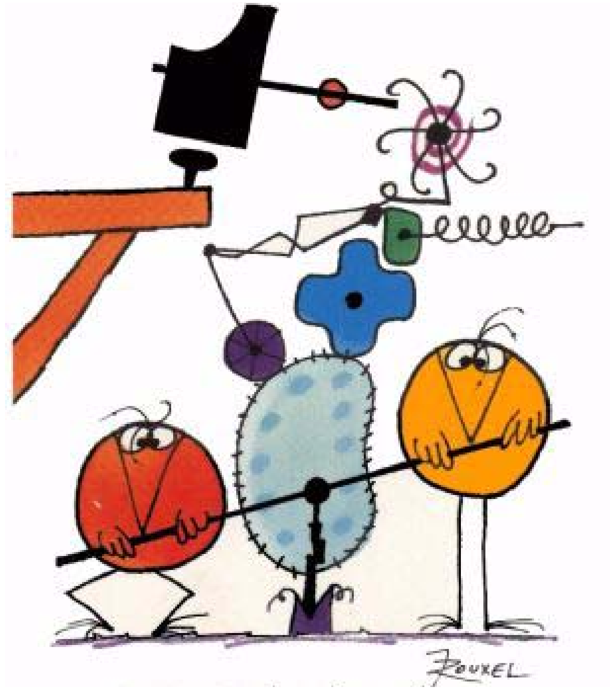
    - A very good knowledge of the model (capabilities and limits) is mandatory for developing reliable (both accurate and physical paremeters) extraction procedures.



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    - How to obtain both precise and physical model parameters? (i) from measurements more or less accurate, (ii) from model more or less difficult to understand, with sometime not enough degrees of freedom for decoupling DC and AC characteristics.

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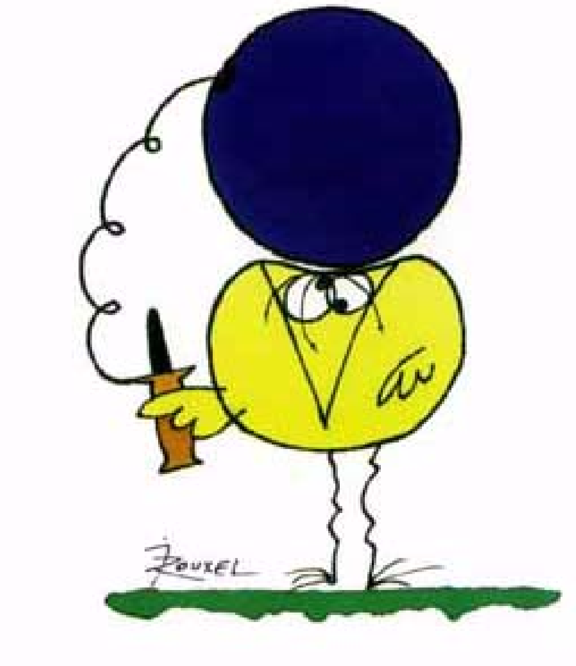
Thus: the more that fails, the more we have chances that works!.



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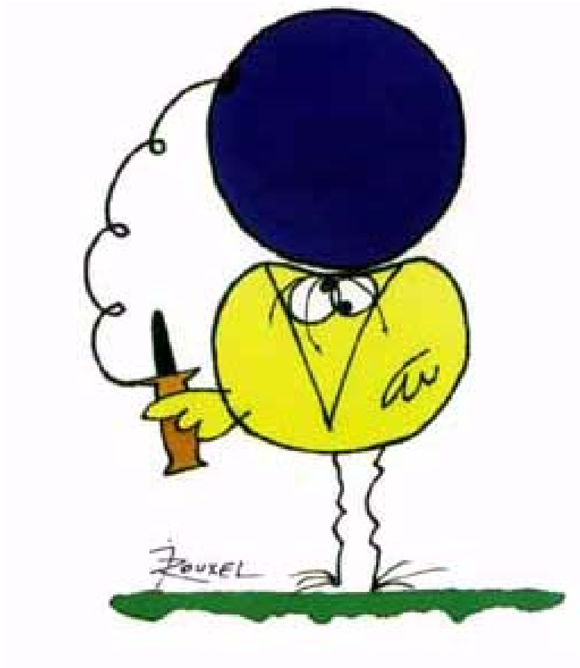

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  "a good compact model is useless without a good parameter extraction strategy, and even more, a bad model with a suitable parameter extraction methodology can be better"

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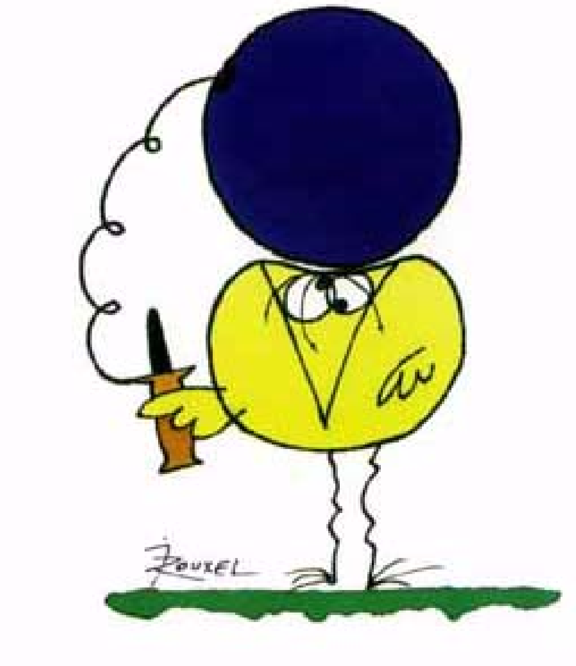

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- Application to the extraction of h_{jEi}

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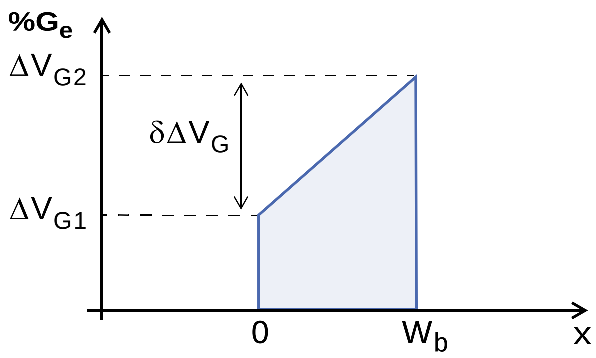
What is h_{jEi}?

Definition and typical values

- h_{jEi} is the BE depletion charge weighting factor in S_iG_e bipolar transistors (HBTs).

  S_i BJTs ➔ Q_{jEi}

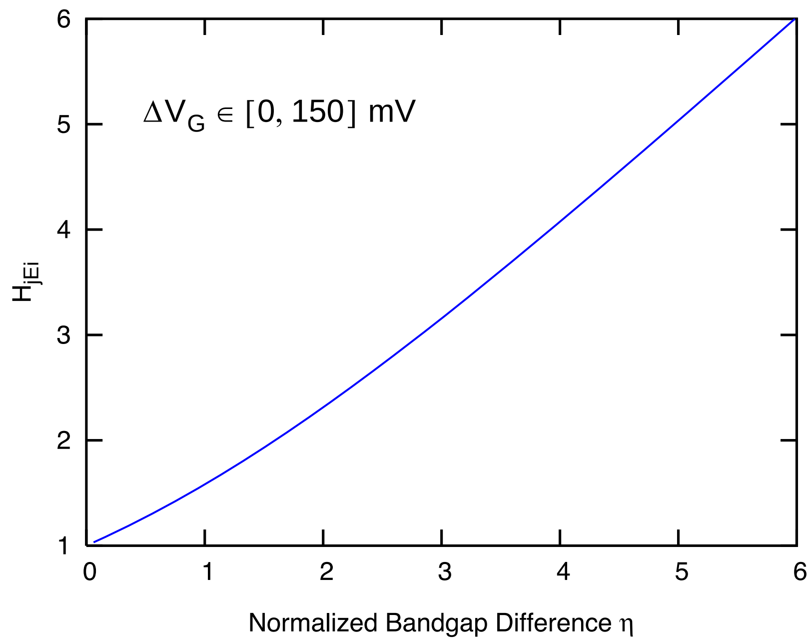
  S_iG_e HBTs ➔ $h_{jEi}.Q_{jEi}$



- h_{jEi} can be calculated, at low current densities, from [1]

  $$h_{jEi} \approx \frac{\eta \cdot e^{\eta}}{e^{\eta} - 1} \quad \text{with} \quad \eta = \frac{\delta \Delta V_G}{V_T}$$ as the normalized band-gap difference between beginning and end of the base region.

- Dependence of h_{jEi} as function of η for a relevant range of application ➔
- For S_i BJTs or S_iG_e HBTs with a G_e box profile h_{jEi} is equal to **1**.
- For S_iG_e HBTs with graded G_e profile h_{jEi} is normally greater than **1**.



h_{jEi} Extraction and Issue: Part I Low Currents

Expression of the collector current at low current densities

- HICUM/L2
- Low injection, voltage drop in series resistances negligible and V_{BC} = 0V

$$I_C \approx I_{CF} \approx \frac{C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}}{Q_{p0} + h_{jEi} \cdot Q_{jEi}} \qquad \text{non-ideality factor } M_{CF} \text{ assumed equal to 1} \qquad (1)$$

Extraction strategy

- From (1) we can write

$$Q_{p0} + h_{jEi} \cdot Q_{jEi} = \frac{C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}}{I_C} \quad \text{and finally} \quad \boxed{Q_{jEi} = \frac{C_{10}}{h_{jEi}} \cdot \frac{e^{\frac{V_{BEi}}{V_T}}}{I_C} - \frac{Q_{p0}}{h_{jEi}}} \qquad (2)$$

- At low current densities, the internal BE depletion charge Q_{jEi} vs. the normalized collector current

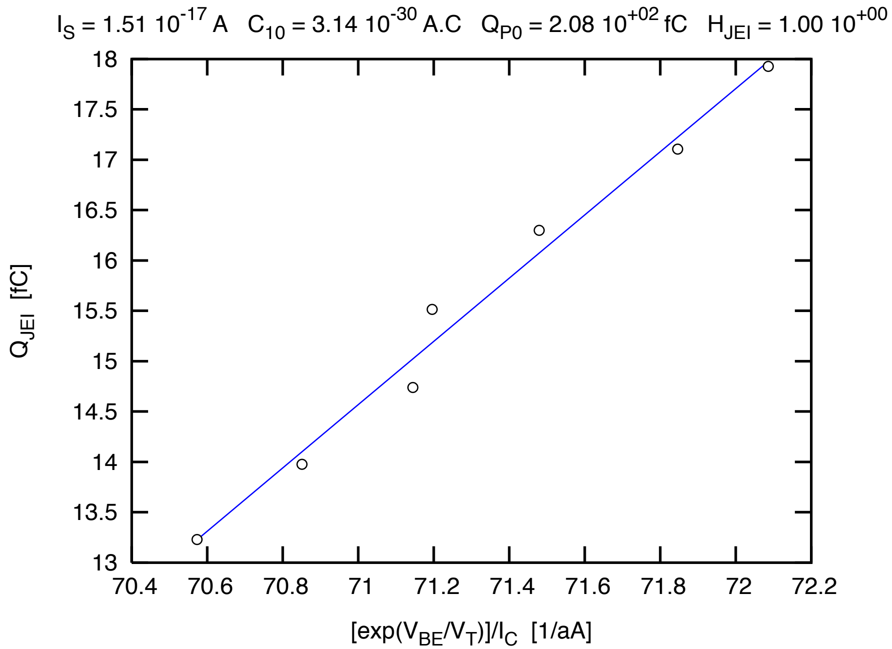
$$I_{CN} = I_C / e^{\frac{V_{BEi}}{V_T}} \text{ is linear, with a slope } s = \frac{C_{10}}{h_{jEi}} \text{ and an intercept } i = -\frac{Q_{p0}}{h_{jEi}}$$

Extraction issues

- From (2), a linear regression allows to directly obtain only the ratios C_{10*} and Q_{P0*}

$$C_{10*} = \mathbf{s} = \frac{C_{10}}{h_{jEi}} \quad \text{and} \quad Q_{P0*} = -\mathbf{i} = \frac{Q_{p0}}{h_{jEi}}$$

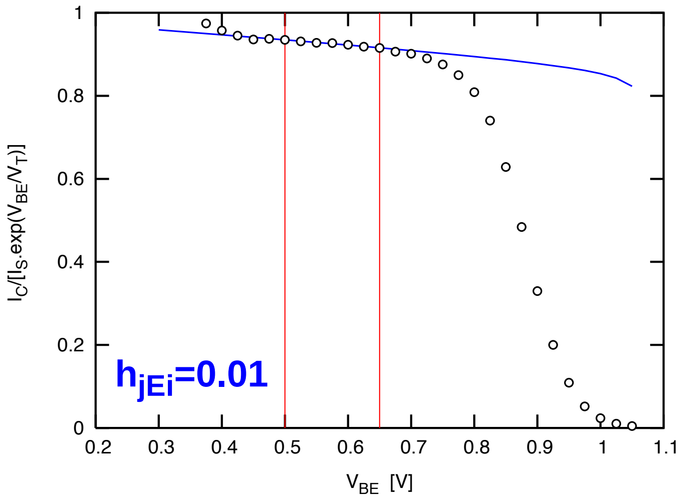
- With this methodology, because of the HICUM hole charge formulation, it is impossible to distinguish C_{10} from h_{jEi}, and Q_{P0} from h_{jEi}. There are as many C_{10} and Q_{P0} parameters there are values of h_{jEi} which give exactly the same accuracy on I_C at low and medium current densities.

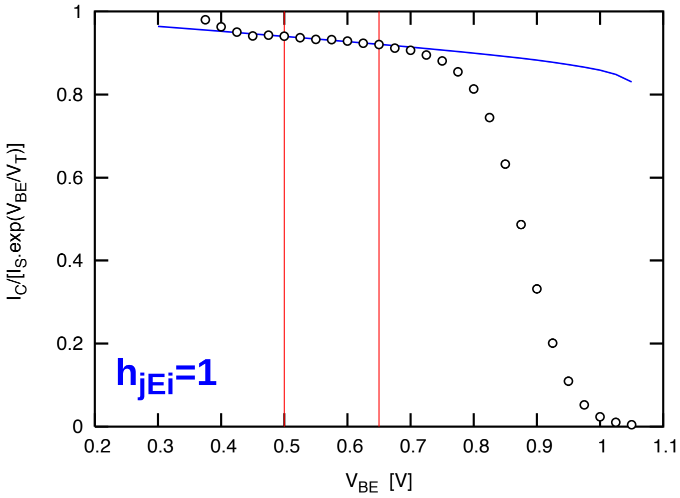


- In addition to this problem, the internal BE depletion charge must be accurately known (from the intrinsic BE junction capacitance).
  - C_{10} and Q_{P0} are directly correlated to the values of C_{JEI}, V_{DEI} and Z_{EI}.
  - Therefore, reliable (physics-based and accurate) parameter extraction is difficult on single-geometry transistor approach.
- The parameters are also strongly dependent on the temperature (but not specific to the HICUM model). A solution has been proposed by Z. Huszka [2] in order to obtain the temperature value directly from the measurements. To be tested.

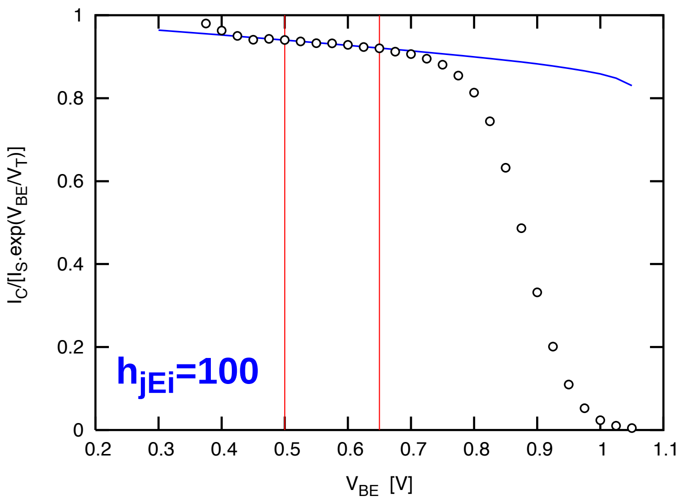
Effect of h_{jEi} on C_{10} and Q_{P0} Parameter Extraction

- Several trials: h_{jEi} = 1, 0.01, 100





- Normalized collector current at V_{BC} = 0V and T = 27°C.
- High current parameters and series resistances not yet extracted.



Parameter	h_{jEi} = 1	h_{jEi} = 0.01	h_{jEi} = 100
$C_{10} = C_{10*}.h_{jEi}$ (A.C)	$2.65\ 10^{-30}$	$2.73\ 10^{-32}$	$2.64\ 10^{-28}$
$Q_{P0} = Q_{P0*}.h_{jEi}$ (fC)	$1.76\ 10^{2}$	$1.82\ 10^{0}$	$1.76\ 10^{4}$
$I_S = C_{10}/Q_{P0}$ (A)	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$

- Same fit but with different values of C_{10}, Q_{P0} correlated to h_{jEi}.
- In all cases, same I_S.

Conclusion Part I: Low Current Study

- It is not possible to distinguish C_{10}, Q_{P0}, h_{jEi} (one of these three parameters must be known in order to determine the two others) from extraction on DC characteristics at low currents densities
  - Perhaps other extraction methods could be used?
  - All suggestions and proposals are welcome...
- Moreover, (i) the temperature must be accurately known (as many sets of model parameter than input temperature), (ii) the non-ideality factor of the forward transfer current M_{CF} must be set to 1, and (iii) the internal BE depletion charge has to be known as accurate as possible.
- A suggestion is to determine Q_{P0} from *tetrode* measurements [3], and than to optimize C_{10} and h_{jEi} from the normalized collector current.

Determination of Q_{P0} from Tetrode Measurements

- *Tetrode* measurements performed at different V_{BE} allow to determine $\overline{Q_{P0}}$ from the bias dependence of the internal base sheet resistance R_{SBi}

$$R_{SBi} \approx \frac{R_{SBi0}}{\overline{Q_{P0}} + Q_{jEi} + Q_{jCi}} \qquad (3)$$

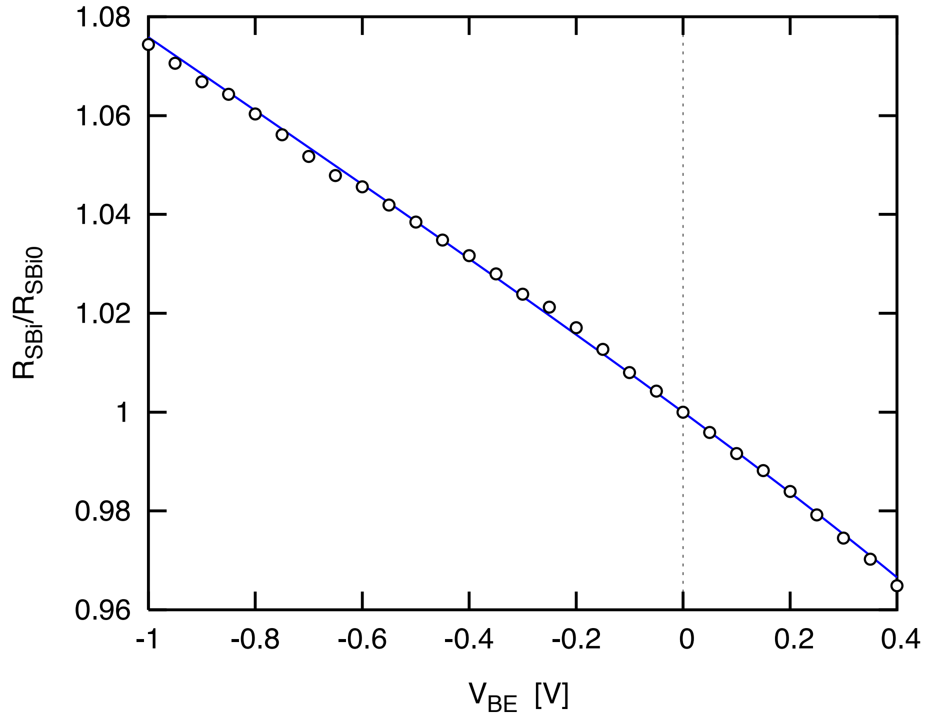
- Rearranging this equation leads

$$\frac{1}{R_{SBi}} \approx \frac{\overline{Q_{P0}}}{R_{SBi0}} + \frac{Q_{jEi} + Q_{jCi}}{R_{SBi0}} \qquad (4)$$

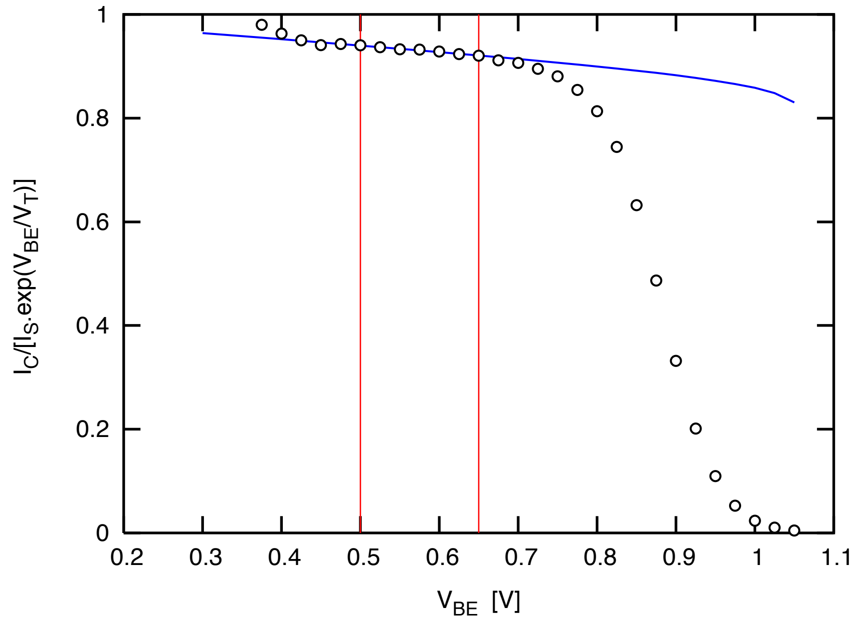
A linear regression of $1/R_{SBI}$ vs. $Q_{jEi}+Q_{jCi}$ gives $\overline{Q_{P0}}$ and R_{SBi0}

$$\begin{cases} \text{slope} = s = \dfrac{1}{R_{SBi0}} & \Rightarrow R_{SBi0} = \dfrac{1}{s} \\ \text{inter} = i = \dfrac{\overline{Q_{P0}}}{R_{SBi0}} & \Rightarrow \overline{Q_{P0}} = \dfrac{i}{s} \end{cases}$$

R_{SBi} = 1430 Ω/sq. $\overline{Q_{P0}}$ = 75 fC/µm²



C_{10} and h_{JEi} extraction knowing Q_{P0}



- $Q_{P0} = \overline{Q_{P0}} \cdot A_{Eeff} = 237 fC$

Parameter	$h_{jEi} = 1.35$	$h_{jEi} = 1$	$h_{jEi} = 0.01$	$h_{jEi} = 100$
$C_{10} = C_{10^*}.h_{jEi}$ (A.C)	$3.57\ 10^{-30}$	$2.65\ 10^{-30}$	$2.73\ 10^{-32}$	$2.64\ 10^{-28}$
$Q_{P0} = Q_{P0^*}.h_{jEi}$ (fC)	$2.37\ 10^{2}$	$1.76\ 10^{2}$	$1.82\ 10^{0}$	$1.76\ 10^{4}$
$I_S = C_{10}/Q_{P0}$ (A)	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$

- Same fit, same I_S, but with different values of C_{10}, Q_{P0} correlated to h_{jEi}

h_{jEi} Extraction and Issue: Part II Medium Currents

- Expression of the collector current at medium current densities
  - Medium current densities means *before the f_T peak and at the beginning of the DC current gain fall-off*.
  - V_{BC} = 0V and non-ideality factor M_{CF} assumed equal to 1

$$I_C \approx I_{TF} \approx \frac{C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}}{Q_{pT}}$$ with Q_{pT}, the transfer hole charge at V_{BC} = 0V given by (5)

$$Q_{pT} = \underbrace{Q_{p0} + h_{jEi} \cdot Q_{jEi}}_{Q_{pLow}} + Q_F = Q_{pLow} + Q_F \qquad (6)$$

  - At medium current densities the forward diffusion charge Q_F can be written

$$Q_F \approx Q_{F0} = \int_0^{I_{TF}} T_F di = T_{F0} \cdot I_{TF} \qquad (7)$$

T_{F0} is the forward transit time at low and medium currents and V_{BC}=0V, assumed to be constant in this range of operation.

From (5) we can finally write

$$Q_{F0} = T_{F0} \cdot I_{TF} = T_{F0} \cdot \frac{C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}}{Q_{pT}} \qquad (8)$$

From (6) and (8) leads

$$Q_{pT} = Q_{pLow} + Q_{F0} = Q_{pLow} + T_{F0} \cdot \frac{C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}}{Q_{pT}} \Leftrightarrow Q_{pT}^2 + Q_{pLow} \cdot Q_{pT} - T_{F0} \cdot C_{10} \cdot e^{\frac{V_{BEi}}{V_T}} = 0 \quad (9)$$

Solving this quadratic equation gives (negative solution ignored because Q_{pT} is greater than 0)

$$Q_{pT} = \frac{Q_{pLow}}{2} + \sqrt{\left(\frac{Q_{pLow}}{2}\right)^2 + T_{F0} \cdot C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}} = \frac{Q_{p0} + h_{jEi} \cdot Q_{jEi}}{2} + \sqrt{\left\{\frac{Q_{p0} + h_{jEi} \cdot Q_{jEi}}{2}\right\}^2 + T_{F0} \cdot C_{10} \cdot e^{\frac{V_{BEi}}{V_T}}} \quad (10)$$

or by putting Q_{P0} in factor

$$Q_{pT} = Q_{p0} \cdot \left\{ \frac{1 + h_{jEi} \cdot q_{jEi}}{2} + \sqrt{\left\{\frac{Q_{p0} + h_{jEi} \cdot q_{jEi}}{2}\right\}^2 + \underbrace{\frac{T_{F0}}{Q_{p0}}}_{1/I_{KF}} \cdot \underbrace{\frac{C_{10}}{Q_{p0}}}_{I_S} \cdot e^{\frac{V_{BEi}}{V_T}}} \right\} \quad (11)$$

- We obtain finally the expression of the collector current at medium current densities by reinserting (11) in (5)

$$I_C = \frac{I_S \cdot e^{\frac{V_{BEi}}{V_T}}}{\frac{1 + h_{jEi} \cdot q_{jEi}}{2} + \sqrt{\left\{\frac{1 + h_{jEi} \cdot q_{jEi}}{2}\right\}^2 + \frac{I_S}{I_{KF}} \cdot e^{\frac{V_{BEi}}{V_T}}}} \quad \text{with} \quad \begin{cases} I_S = C_{10}/Q_{p0} \\ I_{KF} = Q_{p0}/T_{F0} \\ q_{jEi} = Q_{jEi}/Q_{p0} \end{cases} \quad (12)$$

Comments

- Expression (12) is similar to the one of SGP model formulation, excepted that the forward knee current I_{KF}, which is a model parameter in SGP model, is defined as the ratio of the zero bias hole charge Q_{P0} to the low current forward transit time T_{F0}.

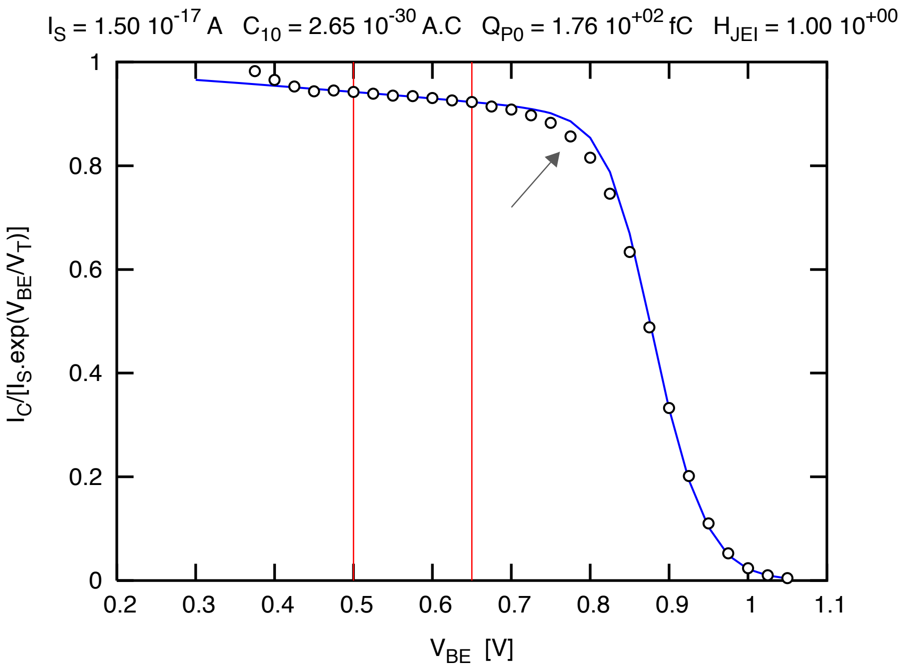
- This formulation is more physics, but a wrong combination of Q_{P0} and T_{F0} leads a bad fit of DC characteristics at high current densities.

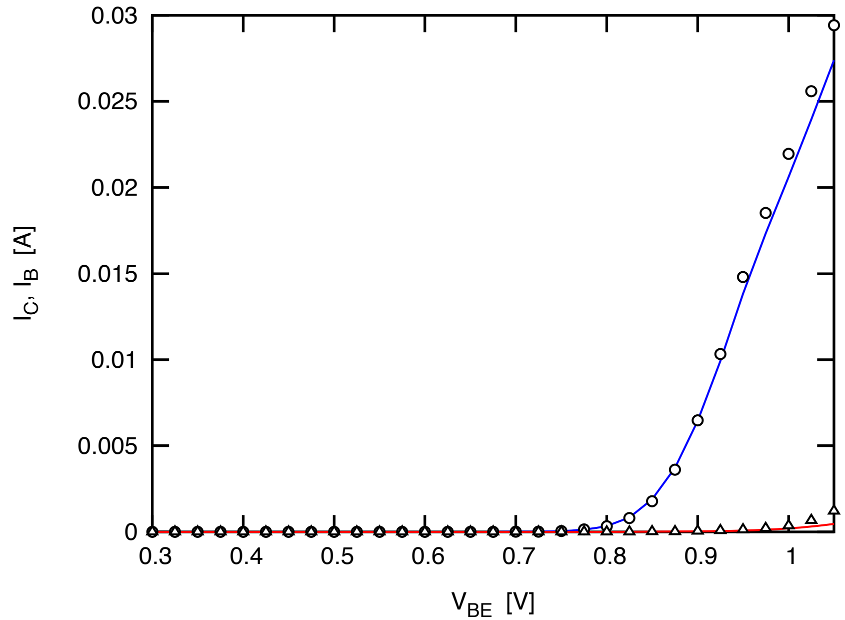
- Therefore, the difficulty (or even the impossibility), to decouple C_{10}, Q_{P0} and h_{jEi} from DC characteristics at low currents must have a strong impact a medium and high current densities.

- Verification ➔

Effect of h_{jEi}, C_{10} and Q_{P0} on DC Characteristics at Medium and High Current Densities

- h_{jEi} = 1

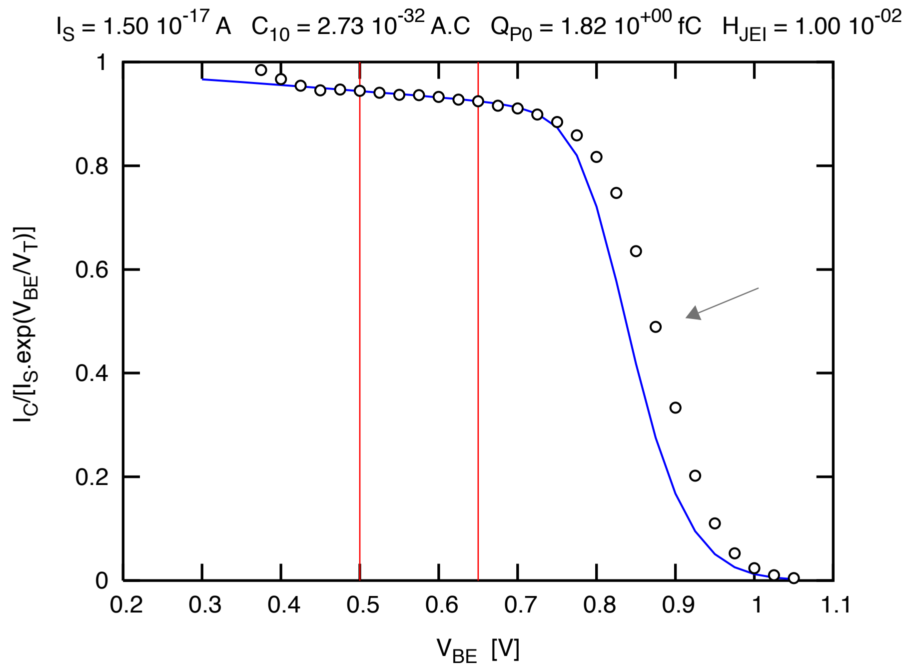


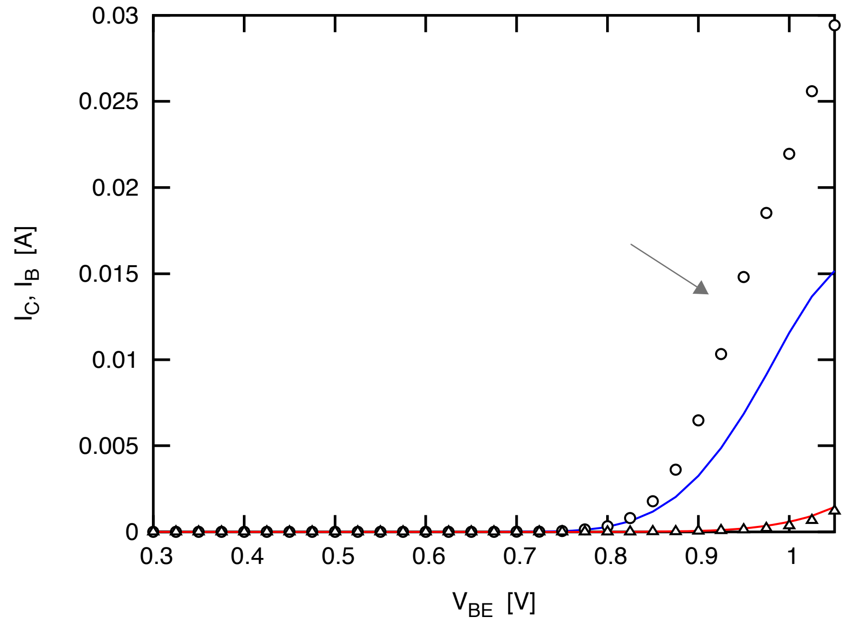


- With h_{jEi} = 1, after the high current parameter extraction (transit time, series resistances...), the fit on DC characteristics is satisfactory, with a little loss of accuracy around V_{BE} = 0.8 V.

Effect of h_{jEi}, C_{10} and Q_{P0} on DC Characteristics at Medium and High Current Densities

- h_{jEi} = 0.01

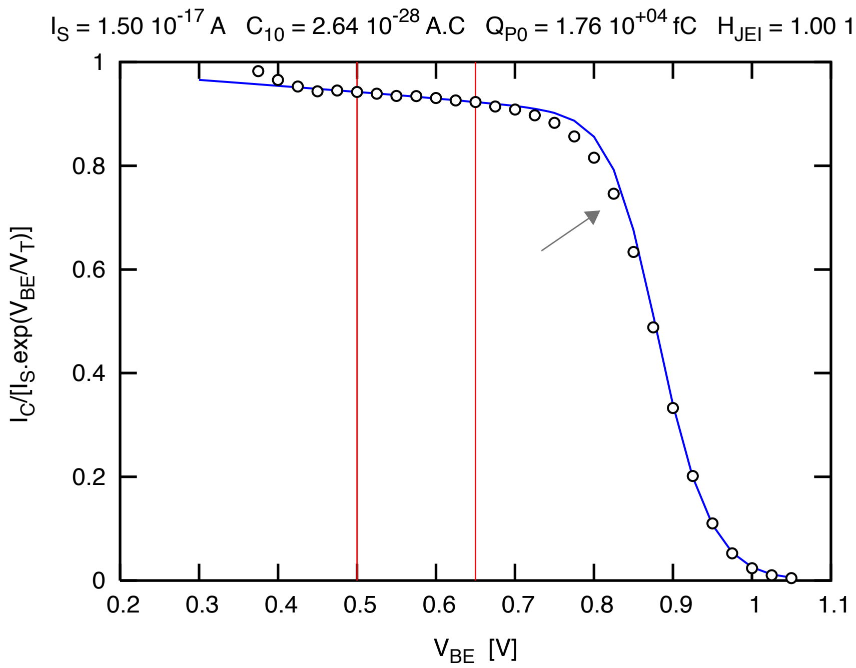


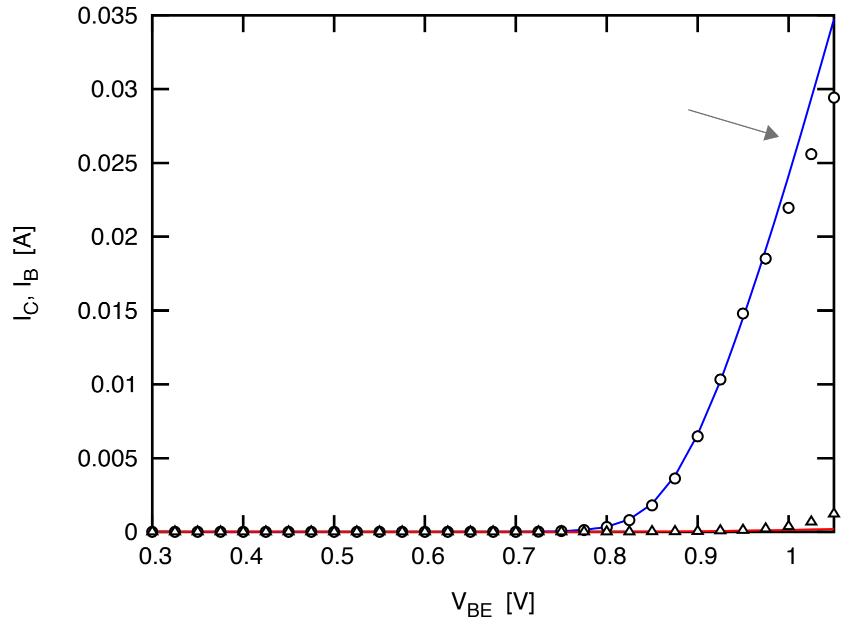


- With h_{jEi} = **0.01**, both C_{10} and Q_{P0} are underestimated by approximately a factor of **0.01**. There is no impact on DC characteristics at low currents ($I_S = C_{10}/Q_{P0}$), but as expected, there is a strong effect at high currents due to an underestimation of the forward knee ($I_{KF} = Q_{P0}/T_{F0}$) current by approximately a factor of **0.01**.

Effect of h_{jEi}, C_{10} and Q_{P0} on DC Characteristics at Medium and High Current Densities

- h_{jEi} = 100

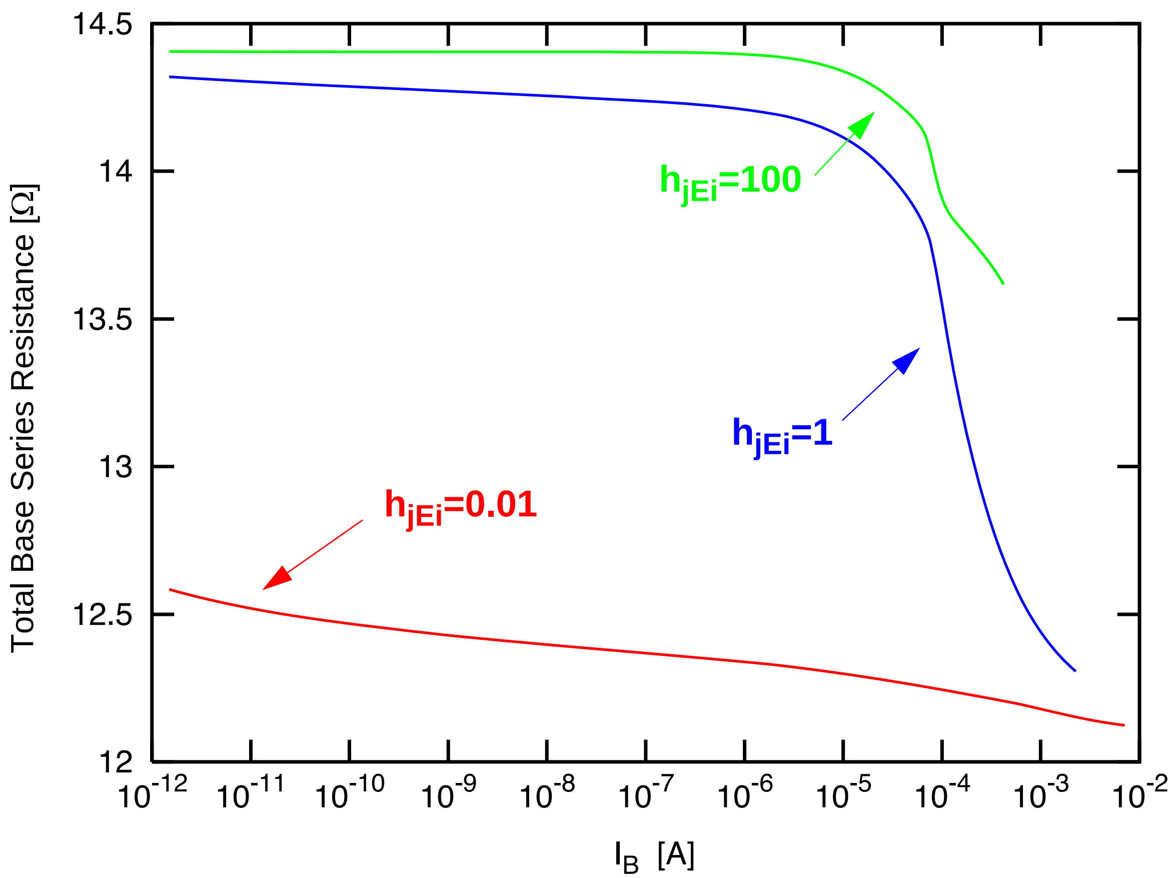




- With h_{jEi} = **100**, both C_{10} and Q_{P0} are overestimated by approximately a factor of **100**. There is no impact on DC characteristics at low currents ($I_S = C_{10}/Q_{P0}$), but as expected, there is an effect at high currents due to an overestimation of the forward knee current ($I_{KF} = Q_{P0}/T_{F0}$) by approximately a factor of **100**. This effect is less visible than for h_{jEi} = **0.01**, because in this case, at high currents the DC characteristics are no more controlled by the too high forward knee current, but rather by the voltage drop in resistances (R_E, $r_{bb'}$).

Impact on Base Series Resistance

- Despite h_{jEi} as no effect on the collector current at low current densities, it strongly affects the internal base resistance which is very sensitive to the value of Q_{P0}. Any value of h_{jEi} cannot be used.



Conclusion Part II: Medium Current Study

- As predicted, if the value of T_{F0}, determined from f_T characteristics at low and medium current densities, is assumed to be *exact*, we cannot used any value for Q_{P0}.
- The value of h_{jEi} does not affect the collector current at low and medium current densities, because the saturation current I_S defined as C_{10} over Q_{P0}, is independent on h_{jEi} (C_{10} and Q_{P0} are both proportional to h_{jEi}).
- In the opposite, the fall-off of the DC current gain at medium current densities, which depends on the knee current defined as Q_{P0} over T_{F0}, is now strongly dependent on h_{jEi} which only affects the value of Q_{P0}.

Parameter	$h_{jEi} = 1$	$h_{jEi} = 0.01$	$h_{jEi} = 100$
$C_{10} = C_{10*}.h_{jEi}$ (A.C)	$2.65\ 10^{-30}$	$2.73\ 10^{-32}$	$2.64\ 10^{-28}$
$Q_{P0} = Q_{P0*}.h_{jEi}$ (fC)	$1.76\ 10^{2}$	$1.82\ 10^{0}$	$1.76\ 10^{4}$
$I_S = C_{10}/Q_{P0}$ (A)	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$	$1.50\ 10^{-17}$
$I_{KF} = Q_{P0}/T_{F0}$ (A)	$128\ 10^{-3}$	$1.33\ 10^{-3}$	$12.8\ 10^{0}$

An Other Alternative to the Determination of h_{jEi}?

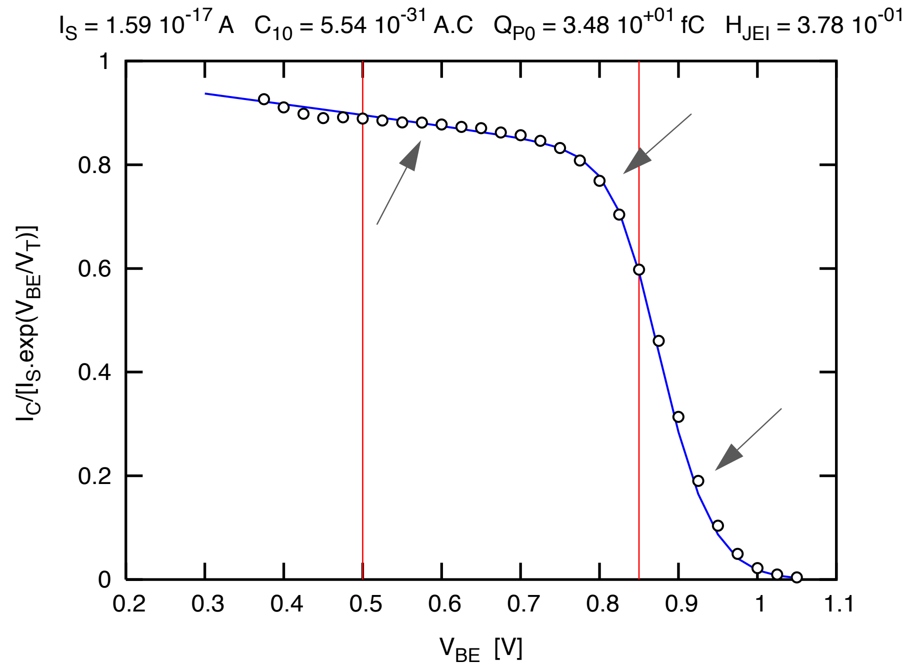
- From these analysis, the following proposal was suggested in [4]
  - Knowing T_{F0}, optimization of Q_{P0} in order to have the right fall-off of the forward DC current gain at medium current densities.
  - Now, knowing Q_{P0}, C_{10} and h_{jEi} can be determined, without ambiguity, from the normalized collector current at low current densities, as explained in part I.

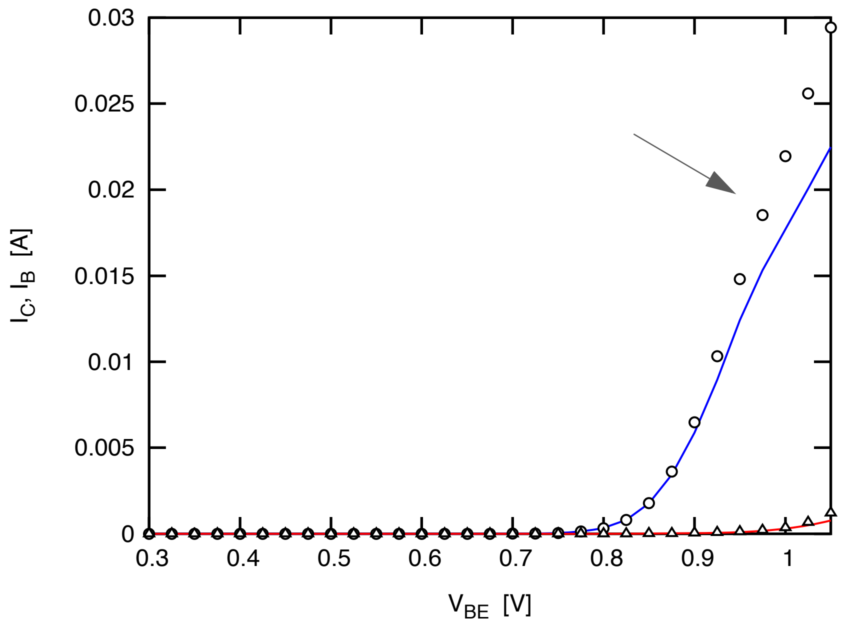
- The idea is interesting, but is it the *ultimate* method to accurately *decouple* C_{10}, Q_{P0} and h_{jEi}?
  - Not possible to be accurate both at medium and low current densities.
  - h_{jEi} value perhaps unrealistic?.
  - Is it a model (is h_{jEi} bias dependent?) or an extraction issue?

- The boundaries used for the optimization of Q_{P0} at high current must be carefully chosen, (i) not to low in order to have an impact of the knee current, (ii) not too high in order to be not affected by other high-current secondary effects (self-heating...).

Results

- Optimization between V_{BE} = 0.5 to 0.85 V

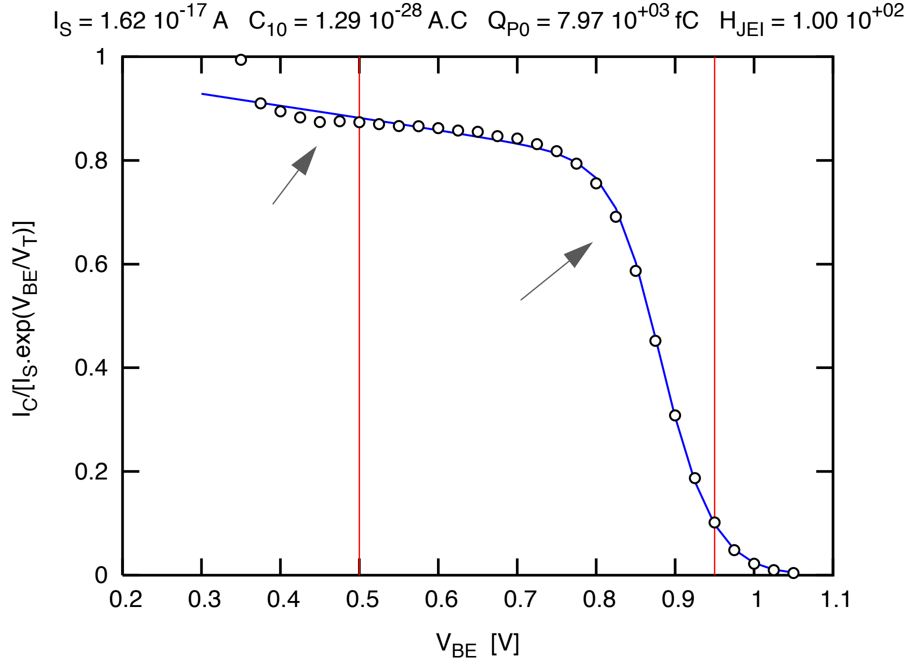


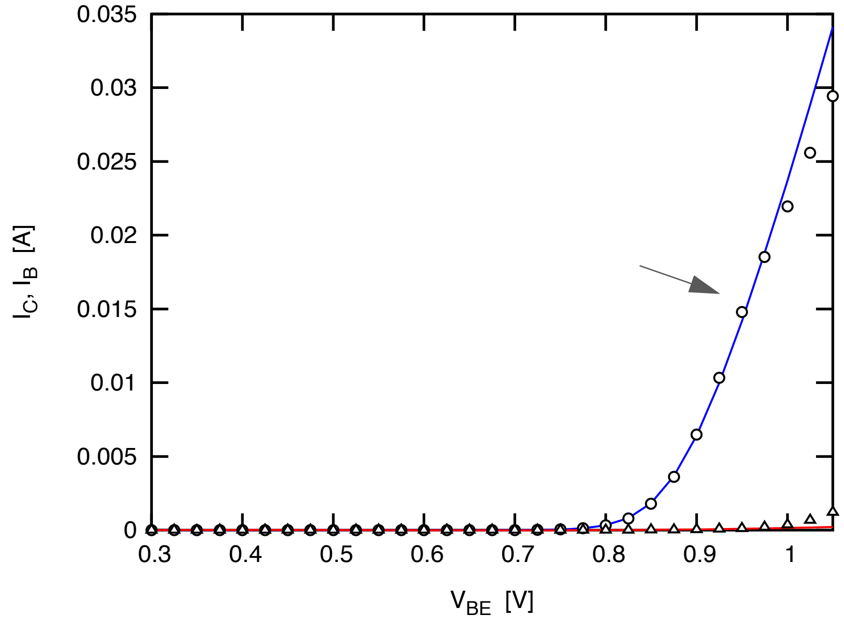


- Better fit around V_{BE} = 0.80 V
- But h_{jEi} less than 1 (non-physical?). Consequently, underestimation of C_{10} and Q_{P0}.
- Slope of the normalized collector current is too high at low current (I_S=1.59 10^{-17} instead 1.5010^{-17}A).
- High injection parameter need to be re-optimized in order to improve the accuracy at very high current densities.

Results

- Optimization between V_{BE} = 0.5 to 0.95 V





- Better fit around and after V_{BE} = 0.80 V
- But unrealistic parameters: **h_{jEi}** is too high, stuck to its maximum value (100). Consequently, overestimation of **C_{10}** and **Q_{P0}**.
- Slope of the normalized collector current is too high at low current (**I_S**=1.62 10^{-17} instead 1.5010^{-17}A).

Summary and Comments

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- Several ways were investigated to attempt to decouple these 3 parameters. But unfortunately there is no *miracle* and certainly, the *ultimate* method has always to be found.
- Any suggestions, ideas, proposals are welcome!...
- In the meantime, some advice
  - Either set **h_{jEi}** to **1,** it is better than to use a non-physical value, especially after for determining **C_{10}** and **Q_{P0}**.
  - Or, to determine **Q_{P0}** from tetrode measurements or TCAD simulations and than to optimize **C_{10}** and **h_{jEi}** from the normalized collector current $I_{CN} = I_C / e^{\frac{V_{BE}}{V_T}}$ in the low current region.
  - Avoid to fit **h_{jEi}** at medium current densities, that improve a little bit the accuracy in this region to the detriment of the physics, this parameter being in this case often underestimated.

And to Conclude...

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→ *If there is no solution it is perhaps because there is no problem…*

Image: **http://zesonic.free.fr/devises.htm**

References

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