A *Novel* FoM for Determining the Base Resistance of Bipolar Transistor

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Outline (1/2)

- Introduction
- HICUM/L2 base resistance model overview
- Impact of the model parameters on the bias dependence of the base resistance
- R_{BCE} FoM for base resistance determination
  - Impact of R_E and R_{CX}
  - Frequency range for R_{BCE} computation
- Validation using *synthetic* data (sensitivity analysis)
  - Effect of R_{BI0}, R_{BX}, F_{GEO}, F_{DQR0}, F_{QI}
- Impact of the complexity of the small-signal equivalent circuit
  - Effect of R_E, R_{CX}, R_{BI0}, R_{BX}
  - Effect of the capacitance partitioning (BE and BC) along the base resistances
    - F_{BEPAR}, split of C_{JE}
    - F_{BCPAR}, split of C_{JC}
  - Effect of the substrate network

Outline (2/2)

- Experimental results
  - R_{BCE} versus emitter width
  - Extraction of base resistance model parameters from R_{BCE} and f_{max}
- Conclusion and outlook...

Introduction (1/2)

- The base series resistances (intrinsic and extrinsic) are very important parameters for bipolar junction transistors (BJTs) or heterojunction bipolar transistors (HBTs)
- The base series resistances impact strongly the speed and the RF performances of bipolar transistors
  - Propagation delay time
  - Maximum oscillation frequency (f_{max})
  - Noise figure
- The accurate determination of the base series resistances is crucial
  - For the development and the optimization of new bipolar devices
  - For realistic simulations of RF integrated circuits
- Since many years, in literature, several methods have been proposed for the determination of the base series resistance
- Unfortunately, as well reported in [1], by A. Pawlak *et al.,* the determination of the base resistance on single transistor is either impossible or very inaccurate

Single Transistor-Based Methods for Determining the Base Resistance in SiGe HBTs: Review and Evaluation Across Different Technologies

Andreas Pawlak, Julia Krause, Holger Wittkopf, and Michael Schröter, *Senior Member, IEEE*

Introduction (2/2)

- In these slides we will review and evaluate the Figure of Merit (FoM)
  - R_{BCE} function

  proposed in [2] by Z. Huszka *et al.* for the determination of the base resistance

An Extended Two-Port Method for the Determination of the Base and Emitter Resistance

Z. Huszka, E. Seebacher and W. Pflanzl
austriamicrosystems AG, Schloss Premstätten A8141 Unterpremstätten, Austria
e_mail: zoltan.huszka@austriamicrosystems.com

- In fact, this FoM is not new, already published in [2], what is new is its use in evaluating and determining the base series resistances of BJTs or HBTs.
  - Not reviewed in [1]

Base resistance model (1/2)

- In HICUM/L2 the equation describing the bias dependence of the base series resistances is quite sophisticated compared with the SGP model

- Both conductivity modulation, emitter current crowding and impact of peripheral charges are taken into account

$$R_{Total} = \mathbf{R_{BI0}} \cdot \underbrace{\frac{Q_0}{Q_0 + \Delta Q_p}}_{\text{Conductivity modulation}} \cdot \underbrace{\frac{\ln(1+\eta)}{\eta}}_{\text{Emitter current crowding}} \cdot \underbrace{\frac{Q_{JEi} + Q_f \cdot \mathbf{F_{QI}}}{Q_{JEi} + Q_f}}_{\text{Peripheral charge}} + \mathbf{R_{BX}}$$

with

$$Q_0 = Q_{P0} \cdot (1 + \mathbf{F_{DQR0}})$$

$$\Delta Q_p \approx Q_{JEi} + Q_{JCi} + Q_f$$

$$\eta = \frac{R_i \cdot I_{BEi}}{V_T} \cdot \mathbf{F_{GEO}} \quad \text{where} \quad R_i = \mathbf{R_{BI0}} \cdot \frac{Q_0}{Q_0 + \Delta Q_p}$$

- If η is small ($< 10^{-6}$), $\frac{\ln(1+\eta)}{\eta}$ is approximated by $\frac{\ln(1+\eta)}{\eta} \approx 1 - \frac{\eta}{2}$

Base resistance model (2/2)

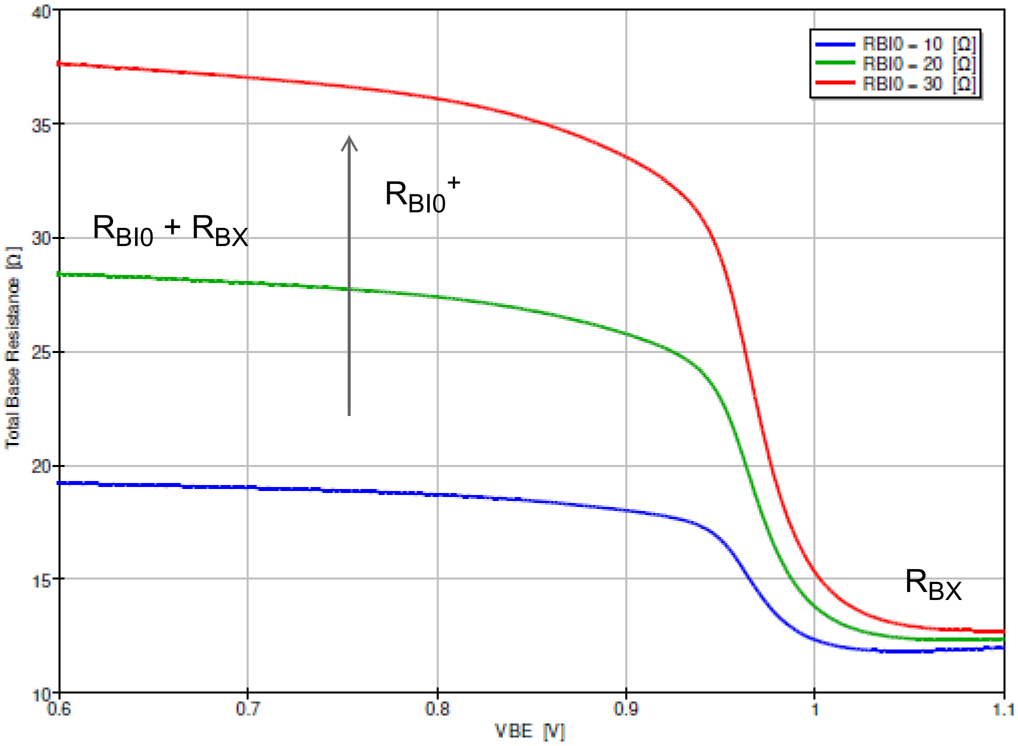
- HICUM/L2 parameter list describing the bias dependence of the total base resistance

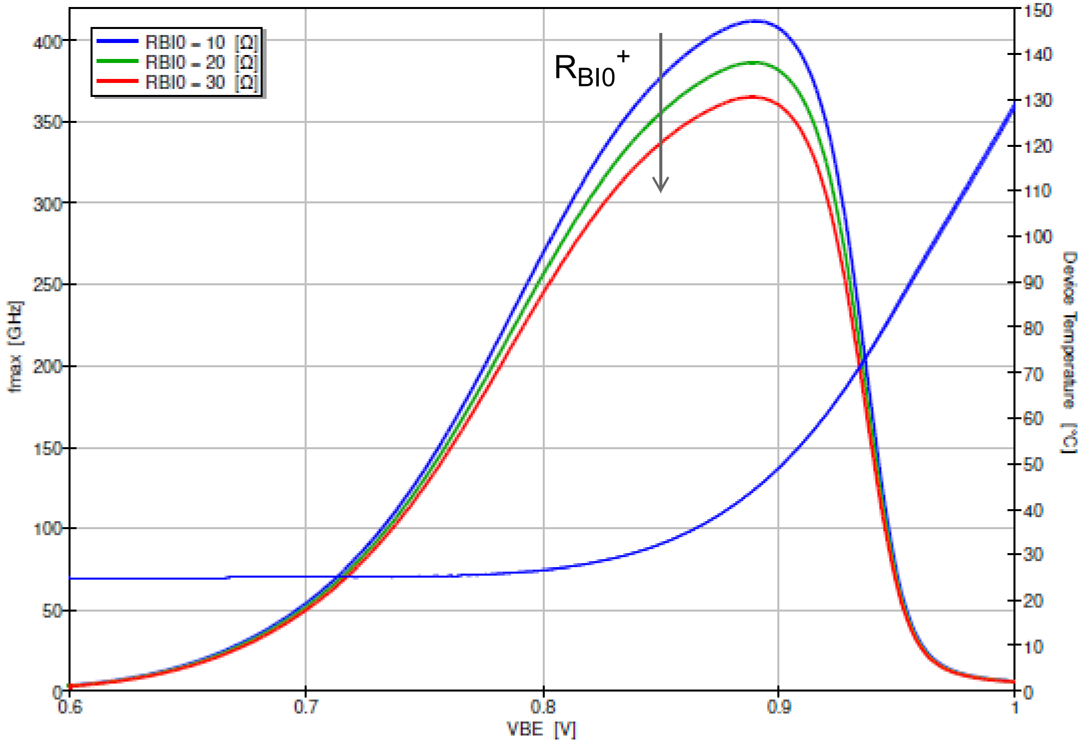
Parameter	Signification	Unit	Default	Min	MAX
R_{BI0}	Zero-bias intrinsic resistance	Ω	0	0	∞
R_{BX}	Extrinsic base resistance	Ω	0	0	∞
F_{GEO}	Factor for geometry dependence of emitter current crowding		0.6557	0	∞
F_{DQR0}	Correction factor for modulation by BE and BC space charge layer		0	-0.5	100
F_{QI}	Ratio of internal to total minority charge		1	0	1

- In order to better understand the relations between the model and the electrical characteristics, the total base resistance (intrinsic + extrinsic) is plotted versus V_{BE} at V_{BC} = 0 V, for different values of the model parameters (above table)

Effect of R_{BI0}

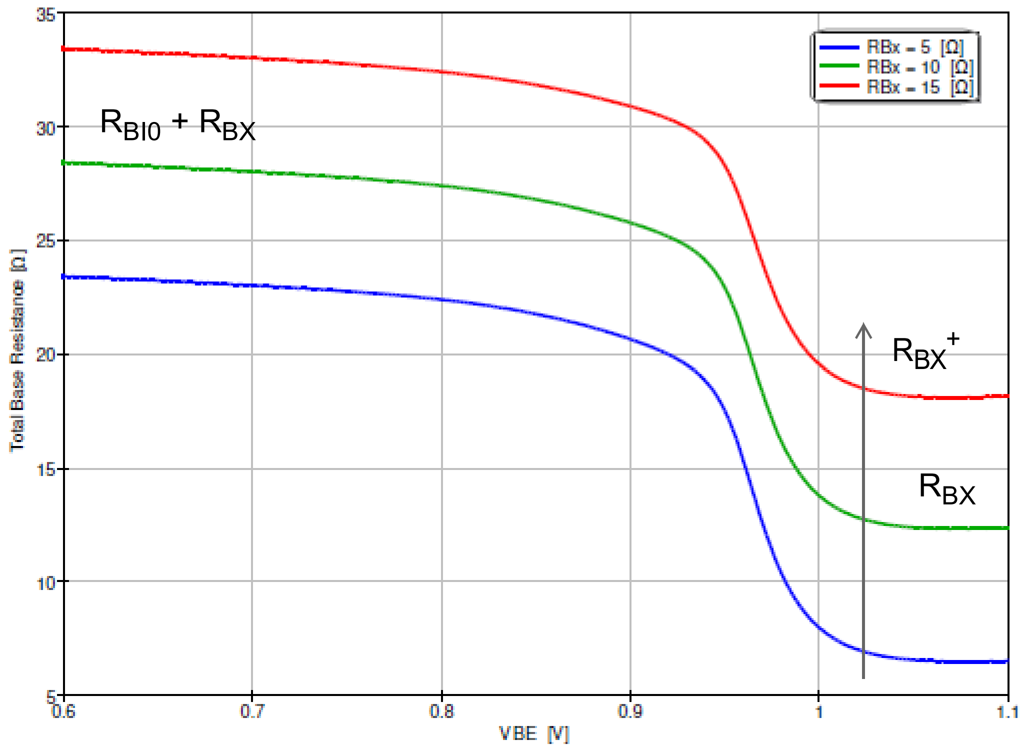
- Impact of R_{BI0} on both the base resistance and f_{max} characteristics at V_{BC} = 0 V
  - As expected, the zero-bias intrinsic resistance affects mainly the base resistance at low V_{BE}.
  - If R_{BI0} increases the peak f_{max} decreases.

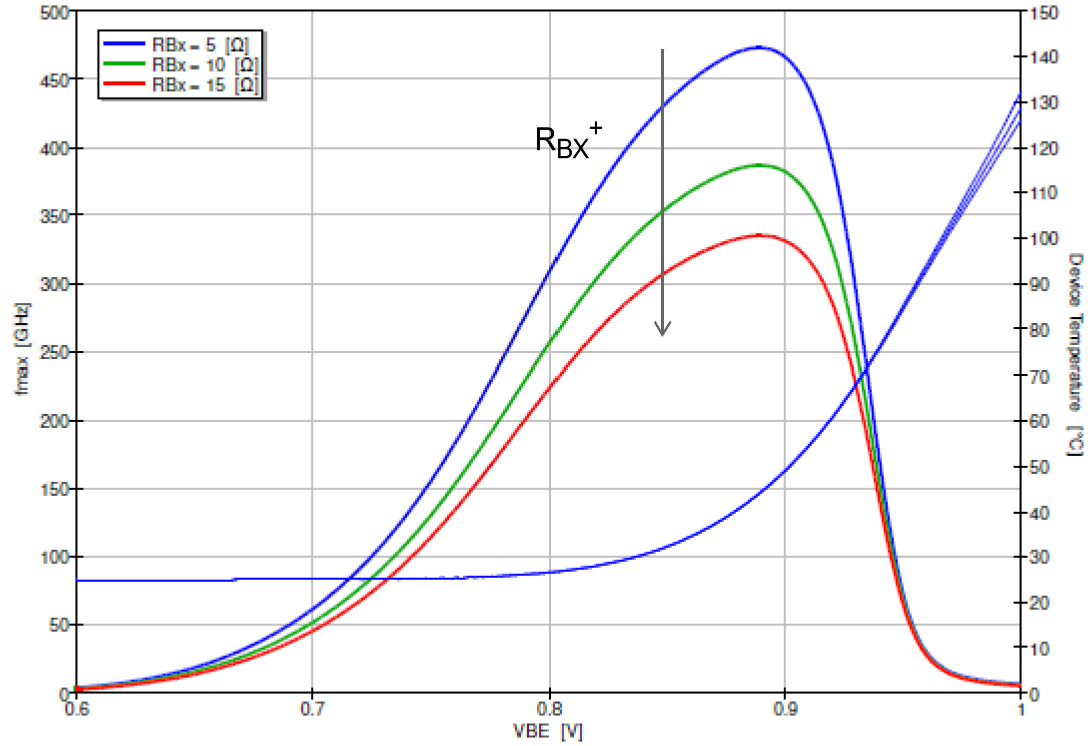




Effect of R_{BX}

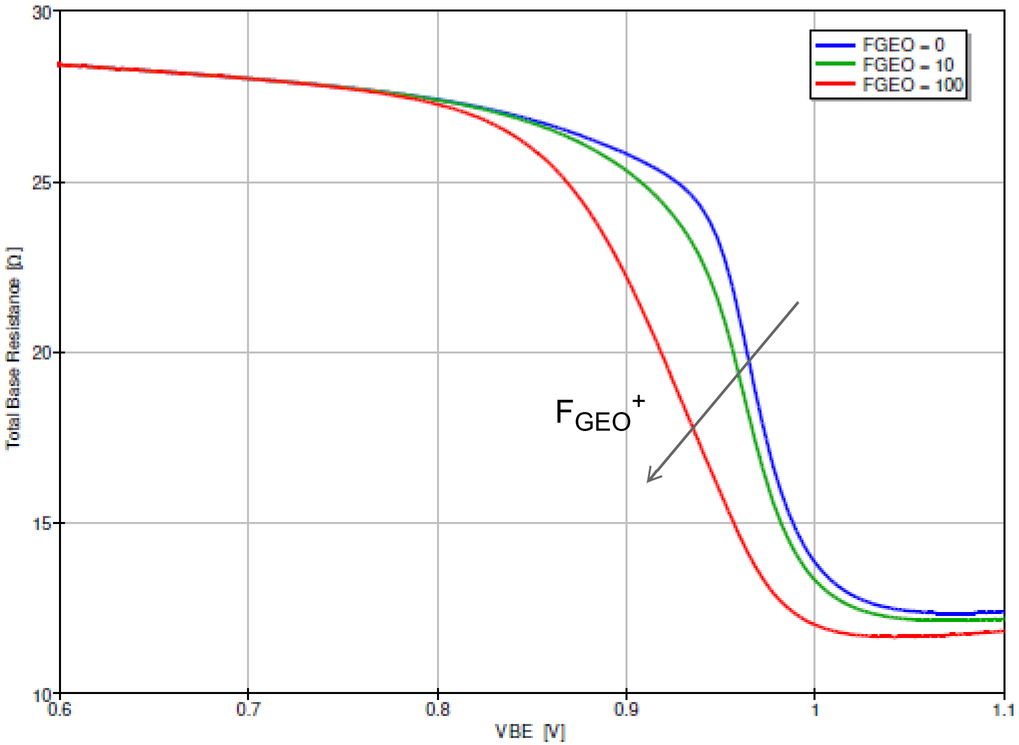
- Impact of R_{BX} on both the base resistance and f_{max} characteristics at V_{BC} = 0 V
  - The extrinsic base resistance R_{BX} has a greater impact on f_{max} than the intrinsic base resistance R_{BI0}

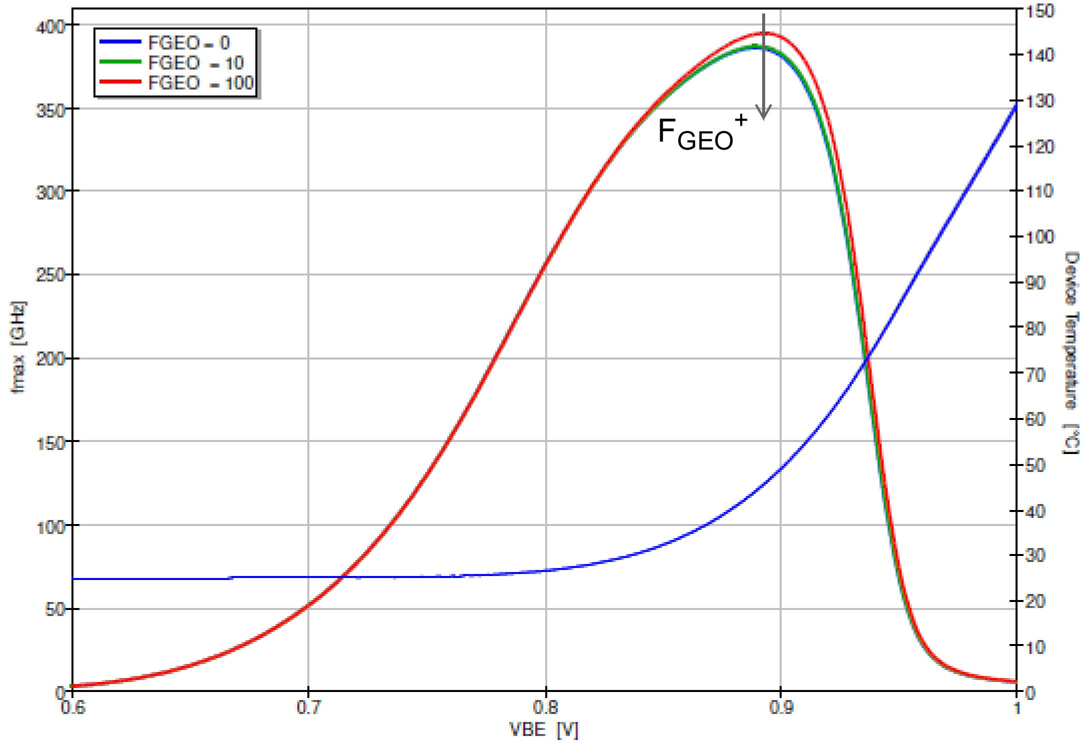




Effect of F_{GEO}

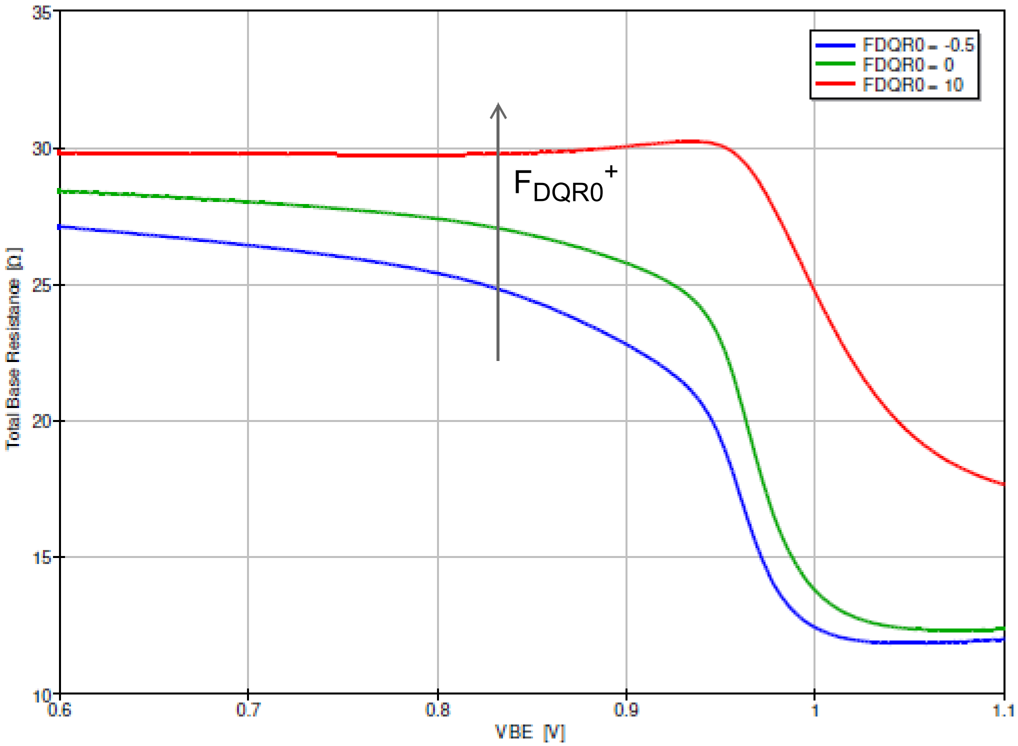
- Impact of F_{GEO} on both the base resistance and f_{max} characteristics at V_{BC} = 0 V
  - The F_{GEO} factor is used to adjust the bias dependence of R_{BIO} at high currents
  - If F_{GEO} increases, R_{BI0} decreases at a lower current density
  - Only a **very high** value of F_{GEO} has an impact on fmax

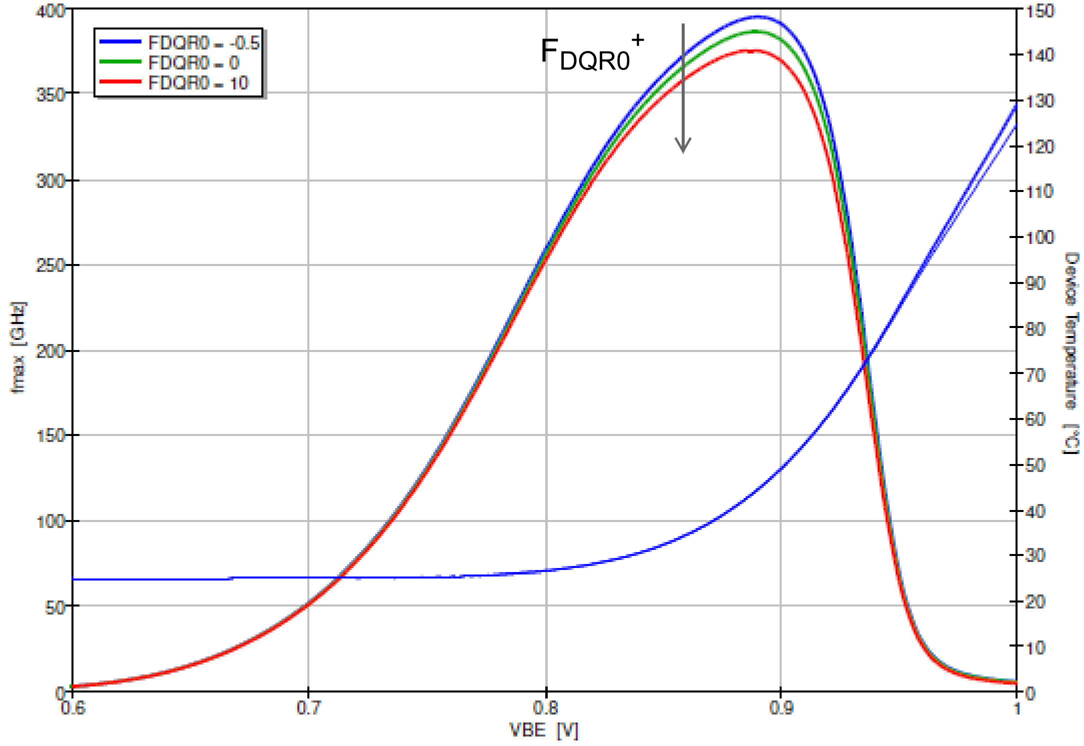




Effect of F_{DQR0}

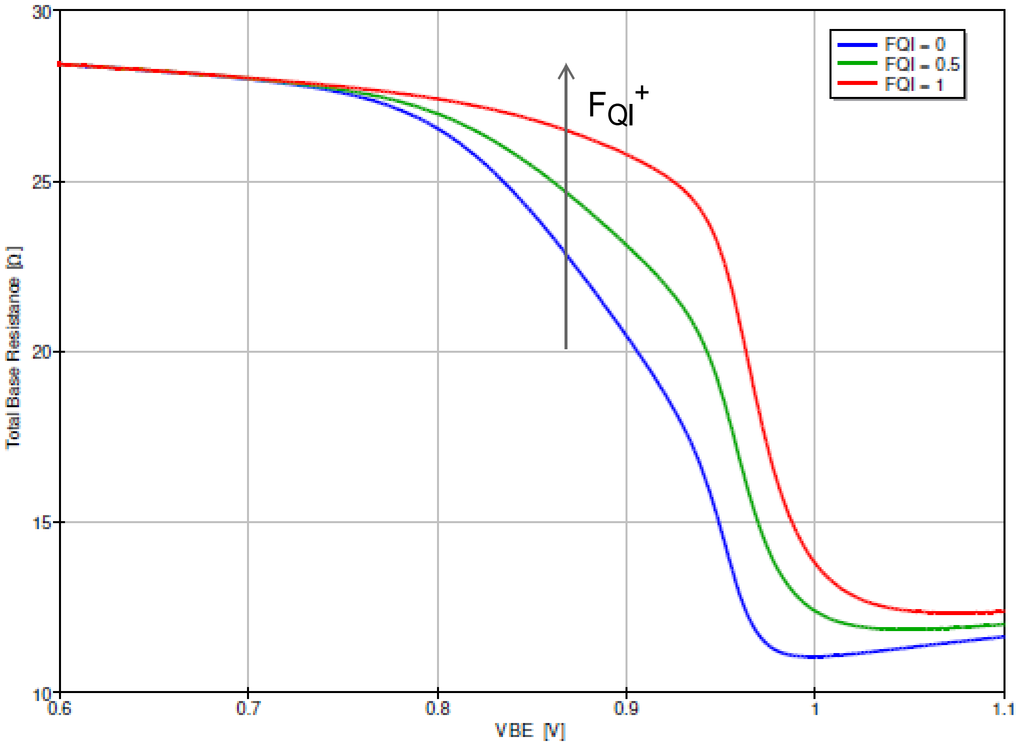
- Impact of F_{DQR0} on both base resistance and f_{max} characteristics at V_{BC} = 0 V
  - Used to adjust the value of the intrinsic base resistance R_{BI}. R_{BI} increases with F_{DQR0}
  - Has also an impact at high currents
  - Peak f_{max} decreases if F_{DQR0} increases

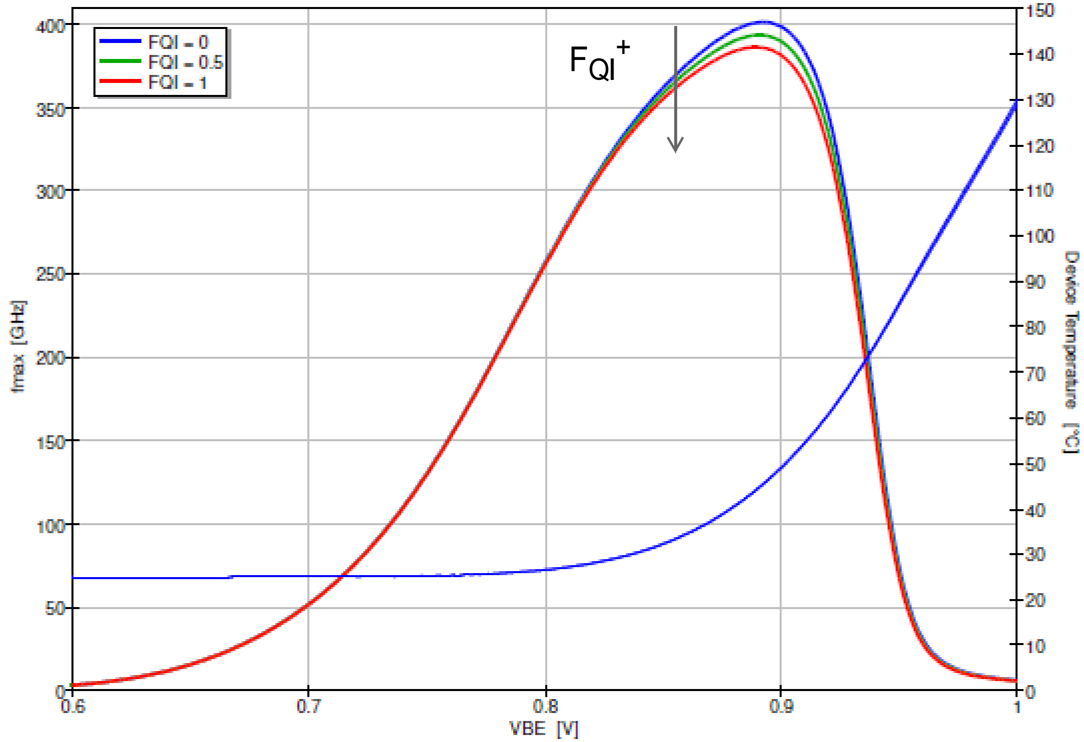




Effect of F_{QI}

- Impact of F_{QI} on both the base resistance and f_{max} characteristics at V_{BC} = 0 V
  - Like F_{GEO}, this parameter adjusts the intrinsic base resistance drop at high currents (**default value is 1**).
  - Has a little impact on the peak f_{max}
    - f_{max} decreases if F_{QI} increases.





FoM for Base resistance determination (1/3)

- The FoM used for the base resistance estimation is derived from the R_{BCE} function introduced in [2]

- Prerequisites and assumption
  - The small-signal measurements are de-embedded from R_{CX} (see Appendix A)
    - R_{CX} is evaluated from the measurement of sheet resistances of the extrinsic collector and from the layout of the transistor as described in [3] and [4]
  - For simplicity, the correcting factor ***cf*** (equation (16) in [2]) **is neglected**
  - The emitter resistance is determined using the method described in [5]
    - A QucsStudio worksheet in given in Appendix B

- The R_{BCE} FoM
  - In order to remove the transfer components between the input and the output, modified y-parameters are used

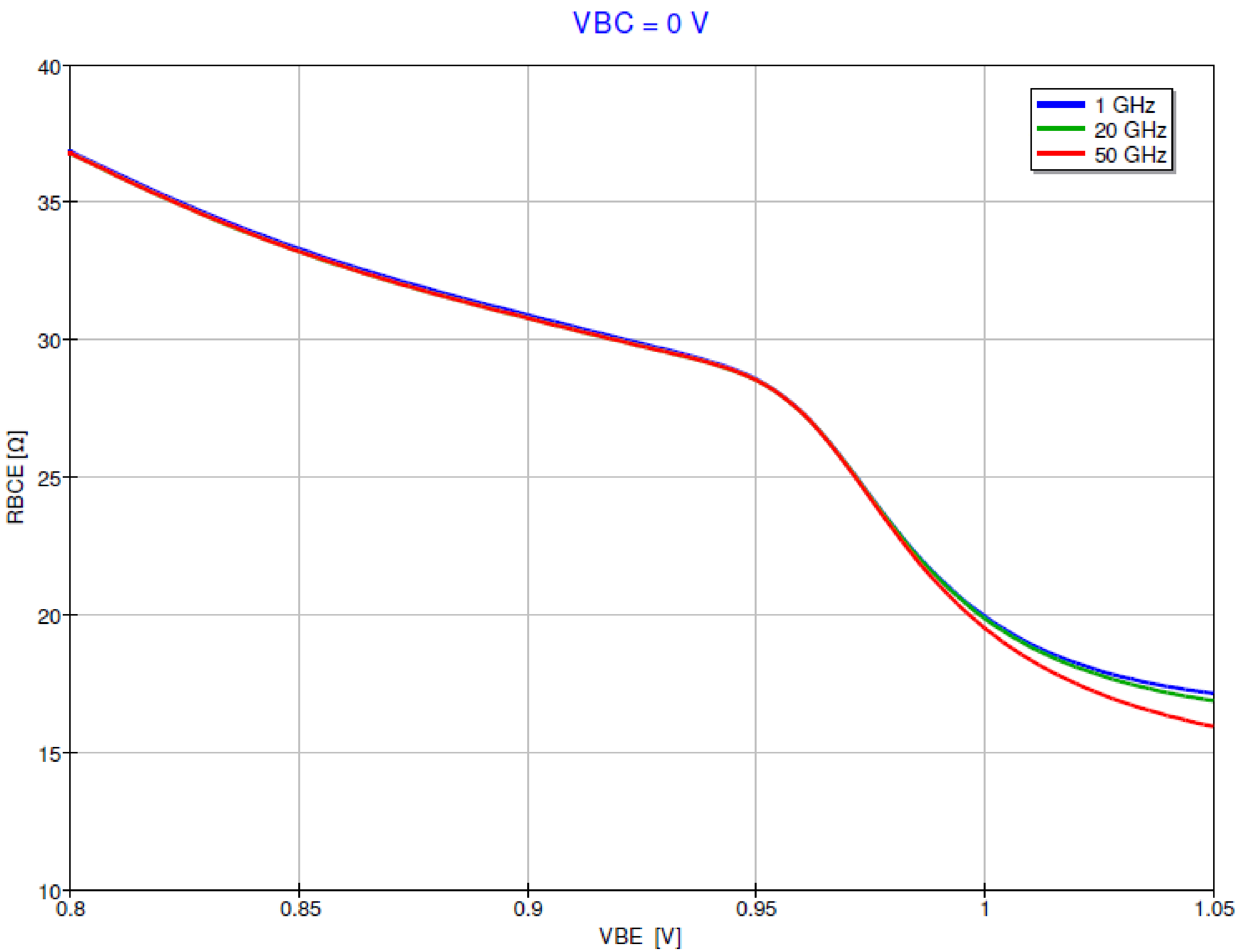
$$\begin{cases} \tilde{y}_{11e} = y_{11e} + y_{12e} \\ \tilde{y}_{21e} = y_{21e} - y_{12e} \end{cases} \text{ and } \begin{cases} \tilde{h}_{11e} = \dfrac{1}{\tilde{y}_{11e}} \\ \tilde{h}_{21e} = \dfrac{\tilde{y}_{21e}}{\tilde{y}_{11e}} \end{cases} \text{ then } R_{BCE} \text{ is computed [6], at a spot frequency, from } \boxed{R_{BCE} = \frac{\Im(\tilde{h}_{11e} \cdot \mathrm{conj}(\tilde{h}_{21e}))}{-\Im(\tilde{h}_{21e})}} \quad (1)$$

  - In first approximation we can demonstrate [2]
    $R_{BCE} \approx R_{Bi} + R_{Bx} + R_E$

  - To remove the impact of R_E, the measured R_E [5], [6] (see also Appendix B) is subtracted from R_{BCE}

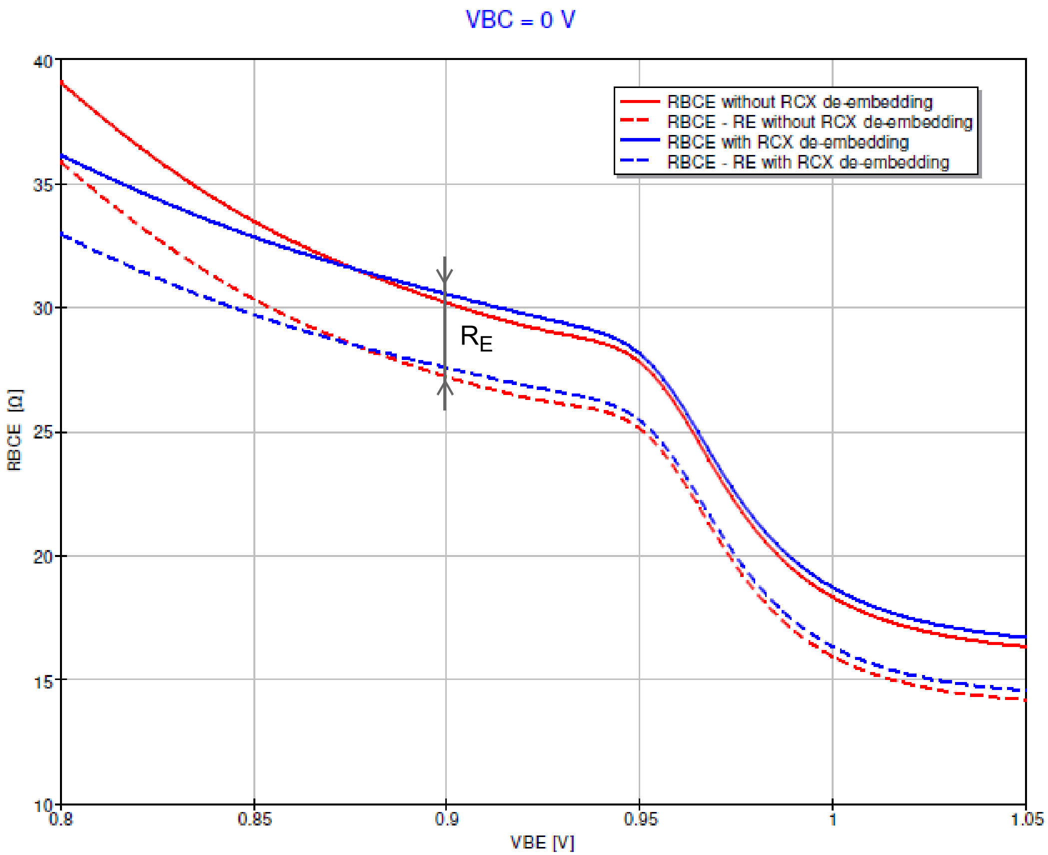
FoM for Base resistance determination (2/3)

- Contrary to the semi-circle method [7], [8], [9], the determination of R_{BCE} from (1) is virtually independent on the spot frequency used
  - Recommended values between 10 and 20 GHz



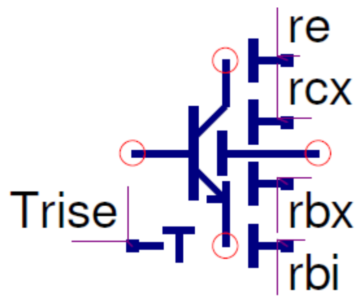
FoM for Base resistance determination (3/3)

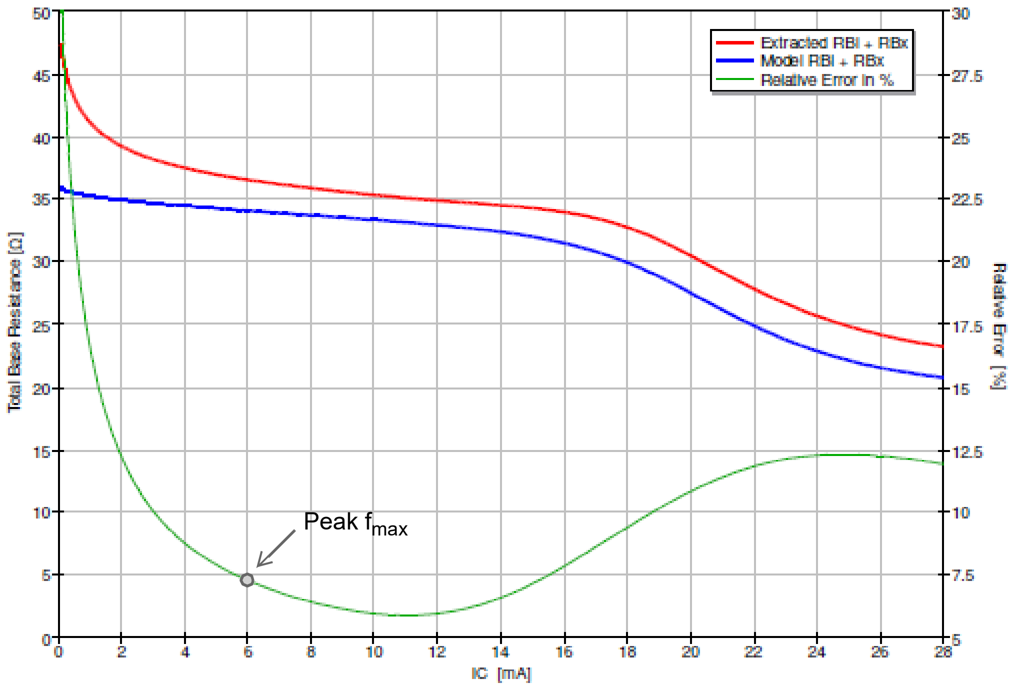
- Impact of R_{CX} de-embedding
  - In high-speed advanced HBTs, the external collector resistance R_{CX} is relatively small, so the impact of R_{CX} is only visible at low V_{BE} (i.e. low current), before the peak f_{max}.
  - Red curves without R_{CX} de-embedding
  - Blue curves with RCX de-embedding
  - Dashed lines R_E removed

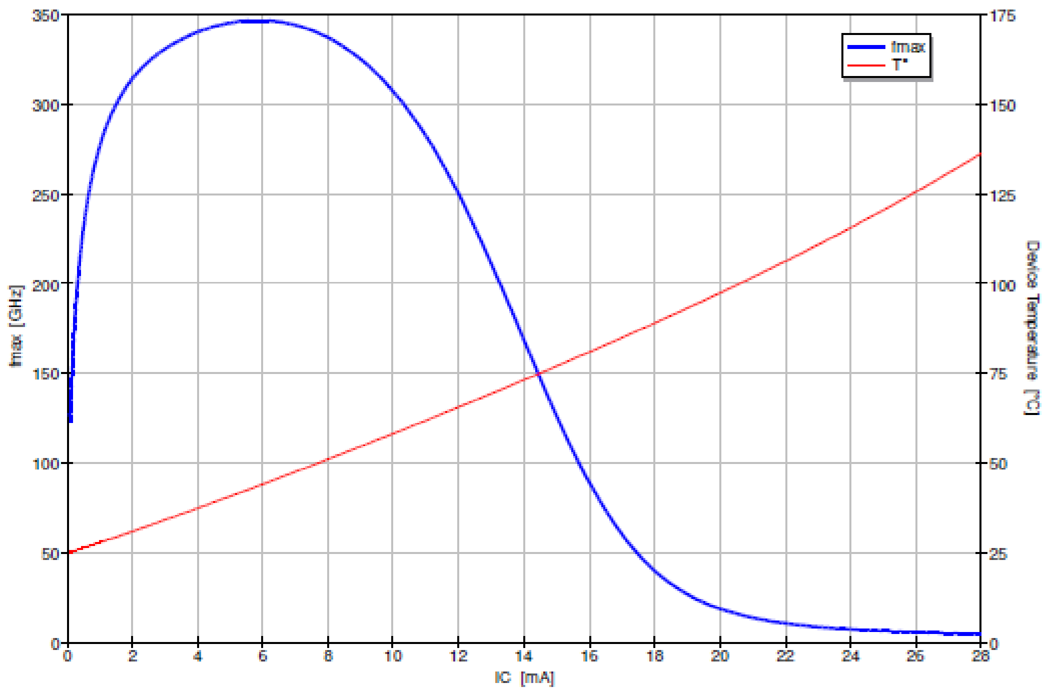


Validation based on *synthetic* data

- From a *realistic* model card $R_{Bi} + R_{Bx}$ is computed (V_{BC} = 0V) from $R_{BCE} - R_E$ (red curve) and compared, with QucsStudio [10], to the true value of $R_{Bi} + R_{Bx}$ (blue curve) coming from the model using a *strobe* transistor [11] as described in Appendix C
  - Over a wide range of I_C, before and after the f_{max} peak, the shape of the two curves is similar.
  - The difference between the 2 curves is between 5 and 12.5%, which is more than acceptable.
    - Is there another method that can determine the bias dependence of the base resistance, from *synthetic* data, with an accuracy better than 10 %?







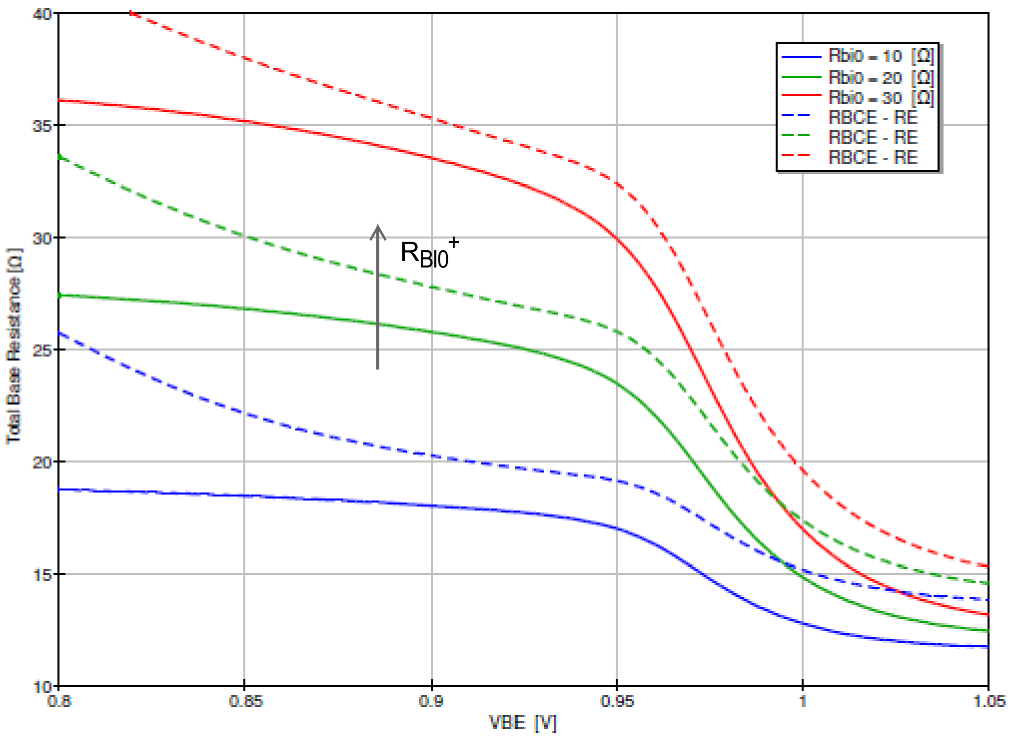
Sensitivity analysis

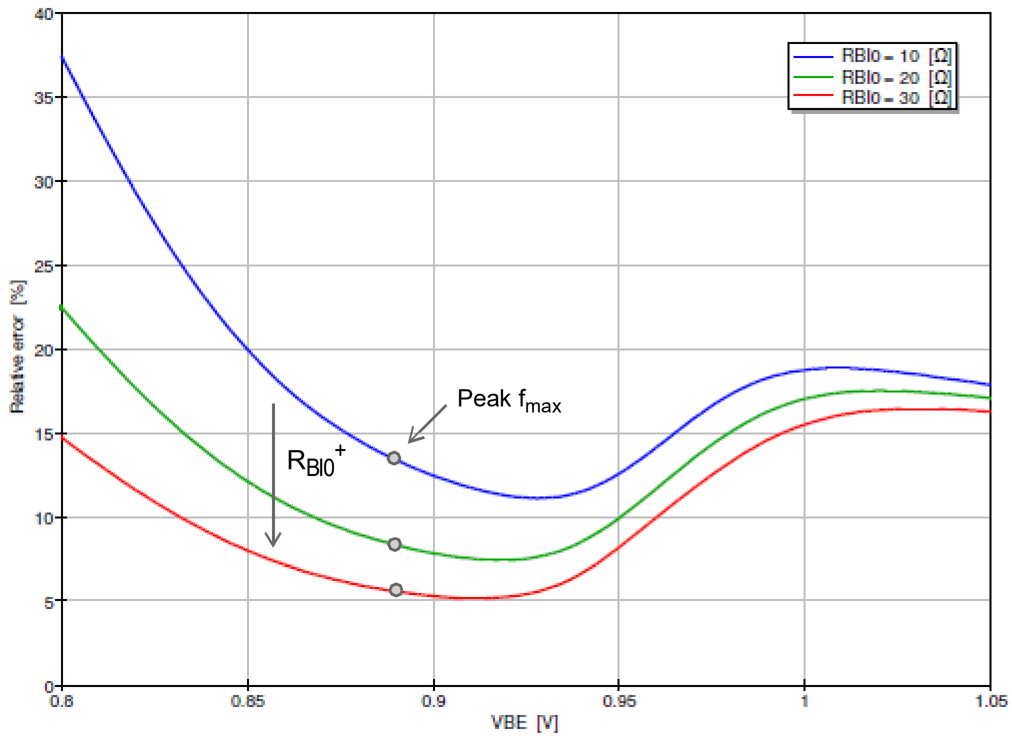
- To further validate this R_{BCE} FoM, we will compare the impact of the parameters (describing the dependence of the bias on the total resistance of the base)
  - R_{BI0}, R_{BX}, F_{GEO}, F_{DQR0}, F_{QI}

  on the base resistance model and on R_{BCE} - R_E

Effect of R_{BI0}

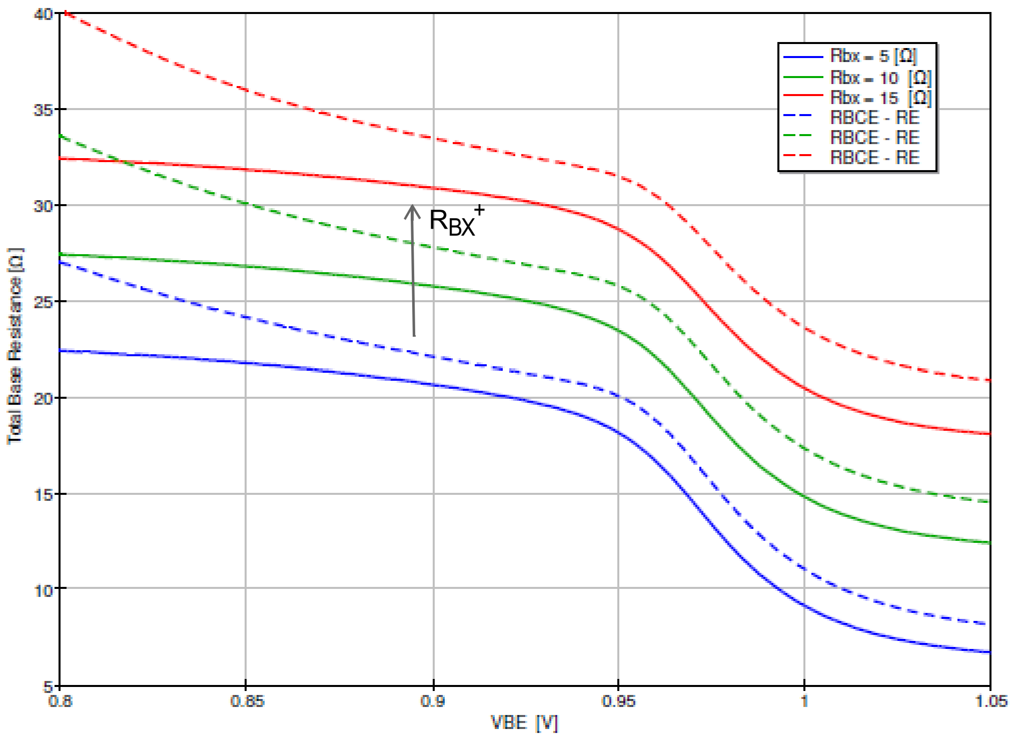
- Similar shape between the model (solid line) and the R_{BCE} - R_E FoM (dashed line), whatever the value of R_{BI0} (from 10 to 30 Ω)
- Difference between model and R_{BCE} - R_E FoM less than 15% around the peak f_{max} (V_{BE} = 0.89 V) where the impact of R_{BI0} is greatest

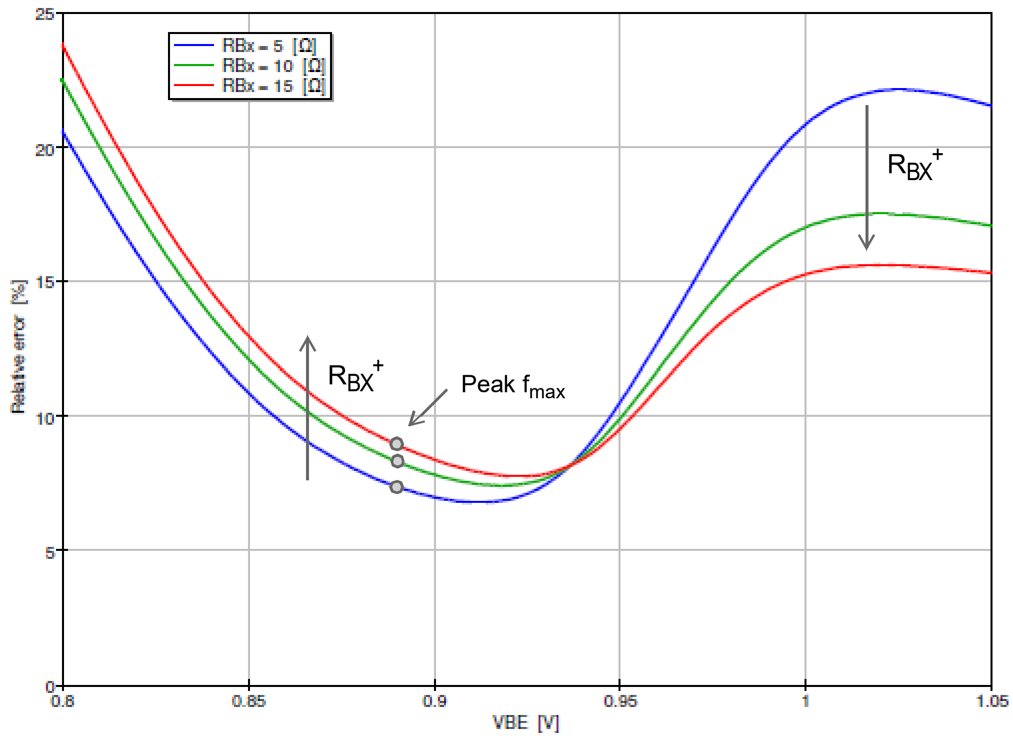




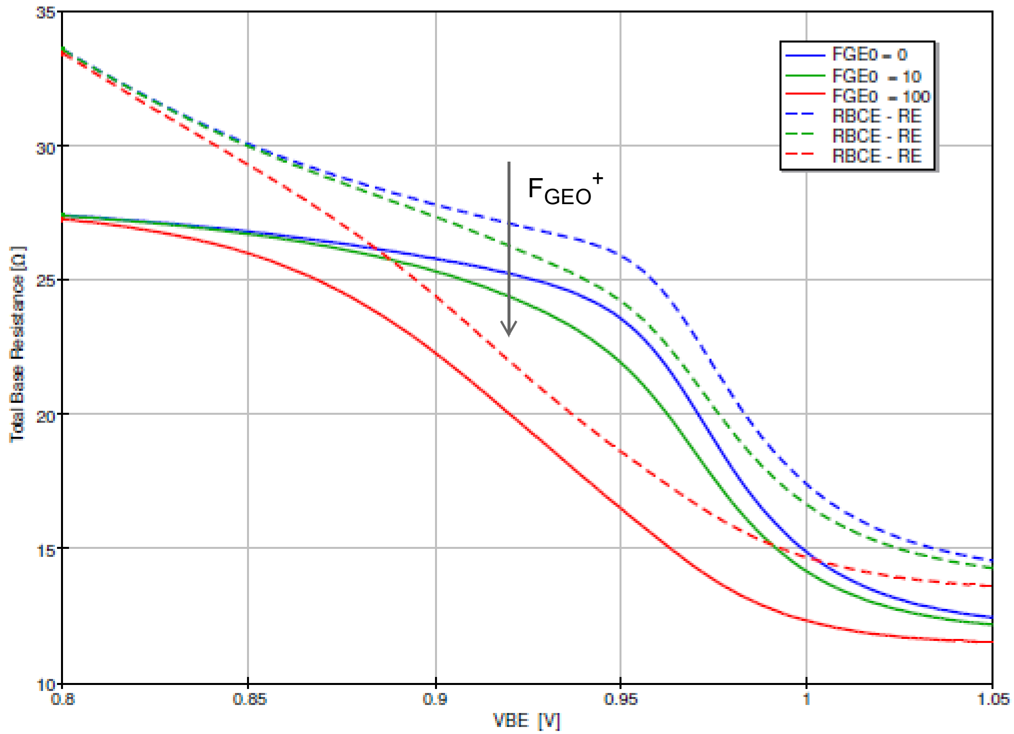
Effect of R_{BX}

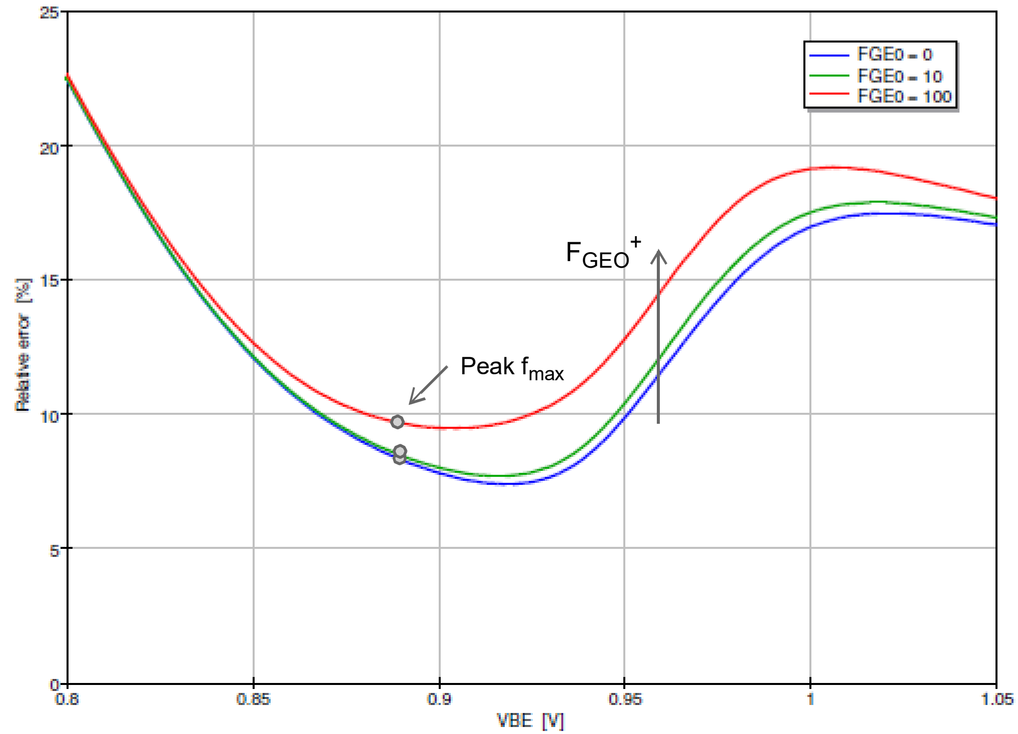
- Similar shape between the model (solid line) and the R_{BCE} - R_E FoM (dashed line), whatever the value of R_{BX} (from 5 to 15 Ω)
- Difference between model and R_{BCE} - R_E FoM less than 10% around the peak f_{max} (V_{BE} = 0.89 V) where the impact of R_{BX} is greatest





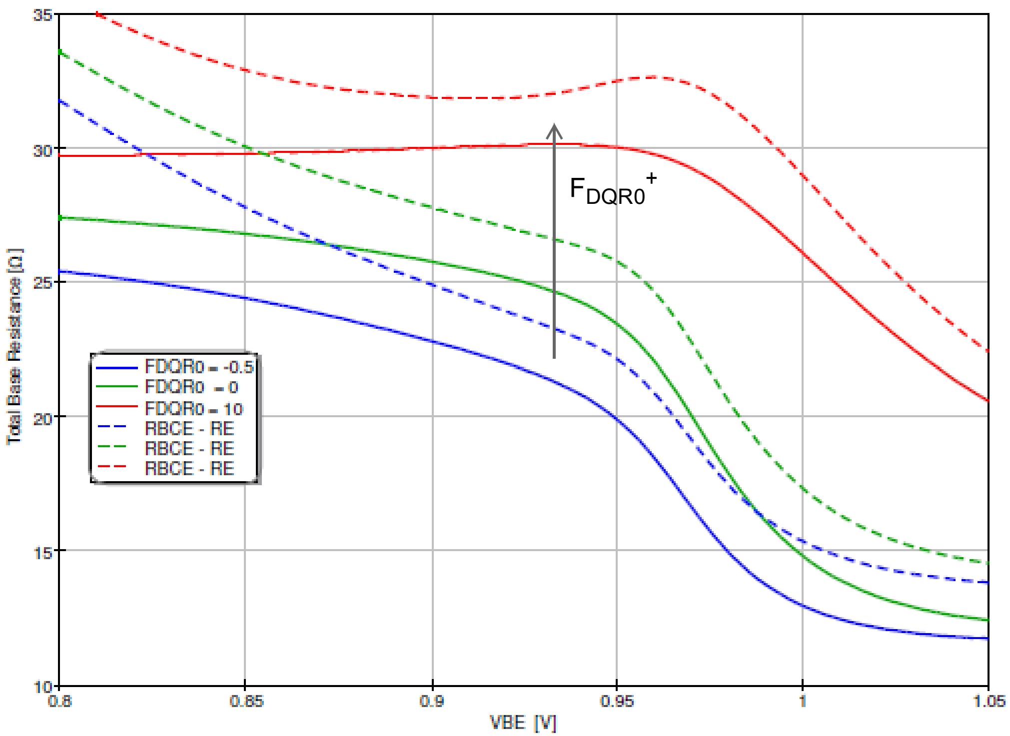
- Similar shape between the model (solid line) and the R_{BCE} - R_E FoM (dashed line), whatever the value of F_{GEO} (from 0 to 100, default value 0.66)
- Difference between model and R_{BCE} - R_E FoM less than 10% around the peak f_{max} (V_{BE} = 0.89 V) where the impact of F_{GEO} is greatest

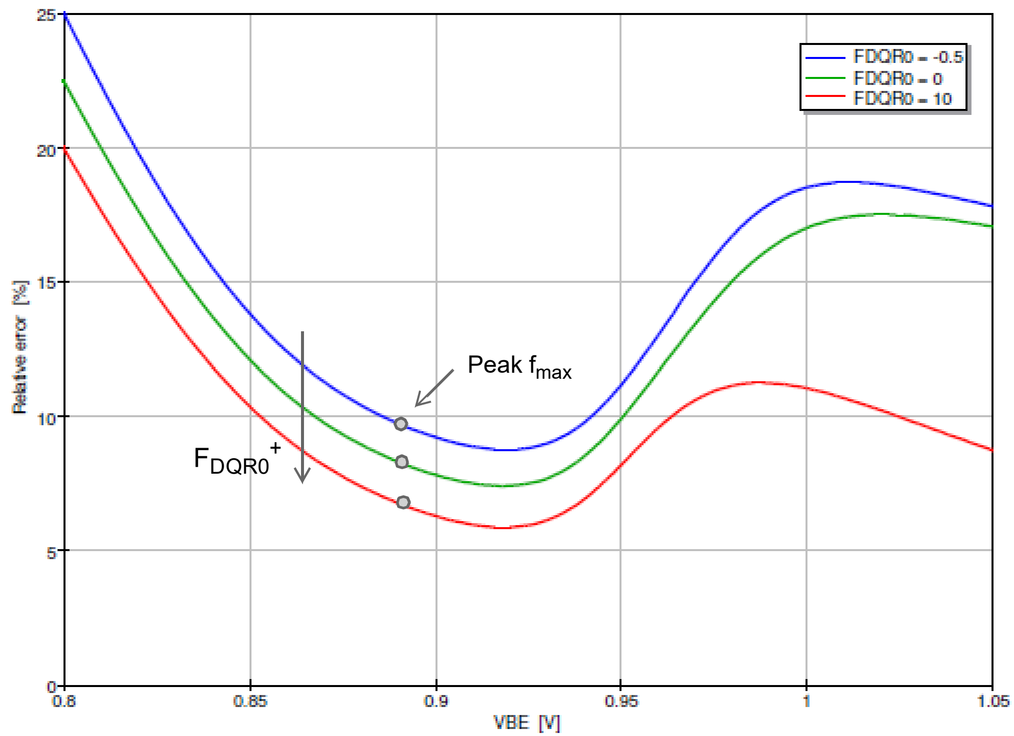




Effect of F_{DQR0}

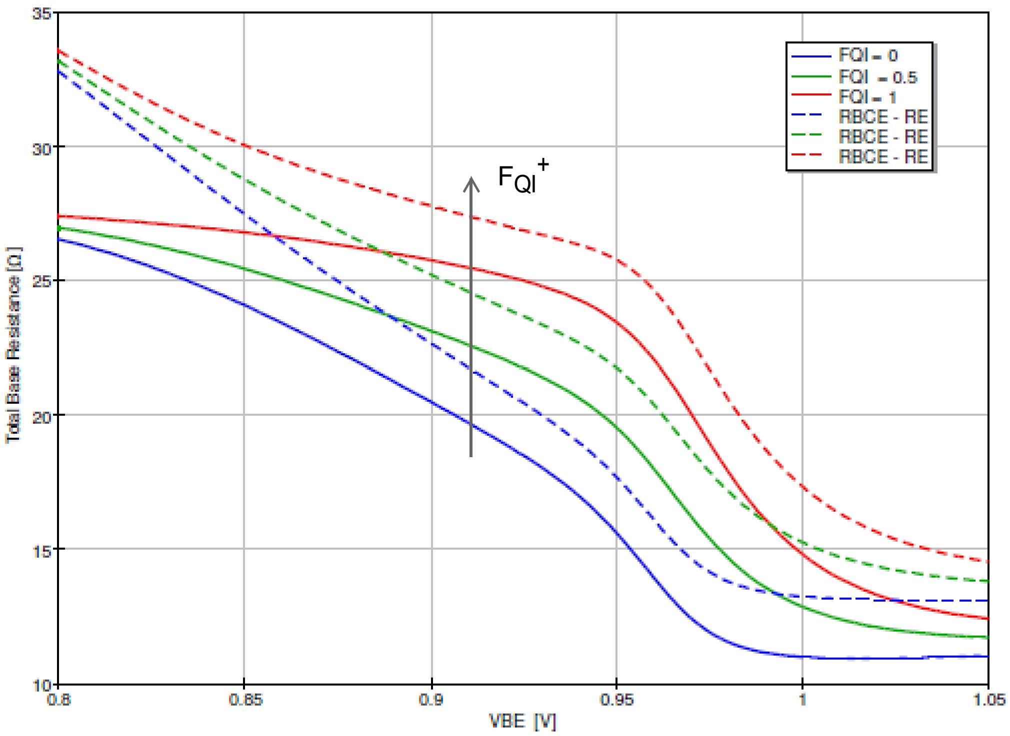
- Similar shape between the model (solid line) and the R_{BCE} - R_E FoM (dashed line), whatever the value of F_{DQR0} (from -0.5 to 10, default value 0)
- Difference between model and R_{BCE} - R_E FoM less than 10% around the peak f_{max} (V_{BE} = 0.89 V) where the impact of F_{DQR0} is greatest

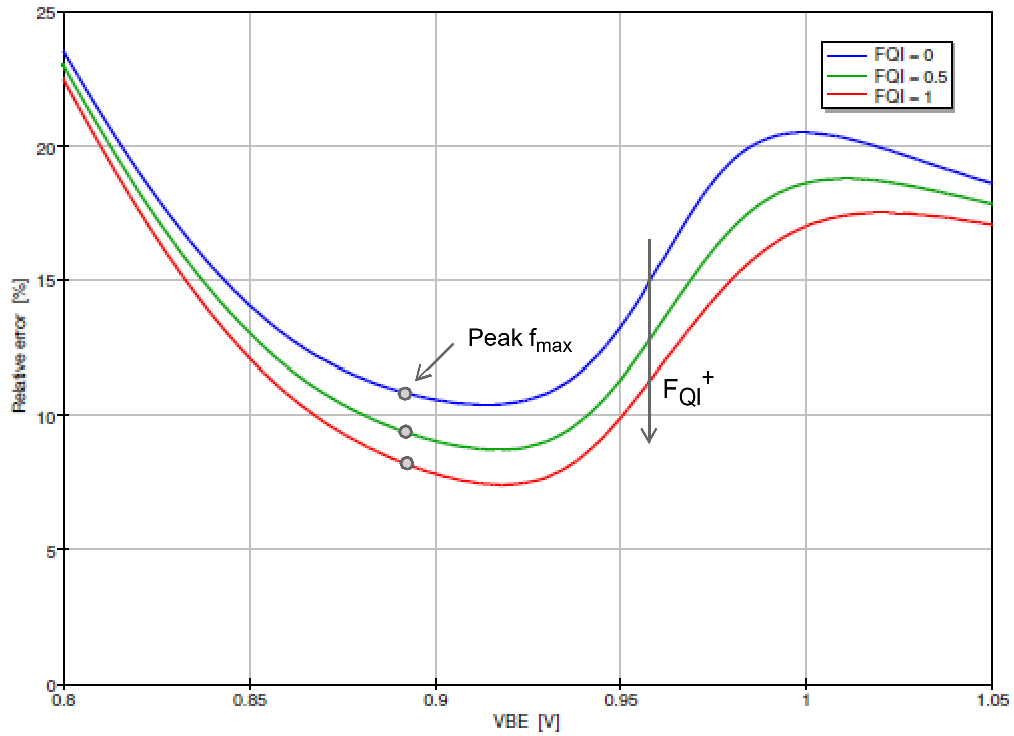




Effect of F_{QI}

- Similar shape between the model (solid line) and the R_{BCE} - R_E FoM (dashed line), whatever the value of F_{QI} (from 0 to 1, default value 1)
- Difference between model and R_{BCE} - R_E FoM less than 12% around the peak f_{max} (V_{BE} = 0.89 V) where the impact of F_{QI} is greatest





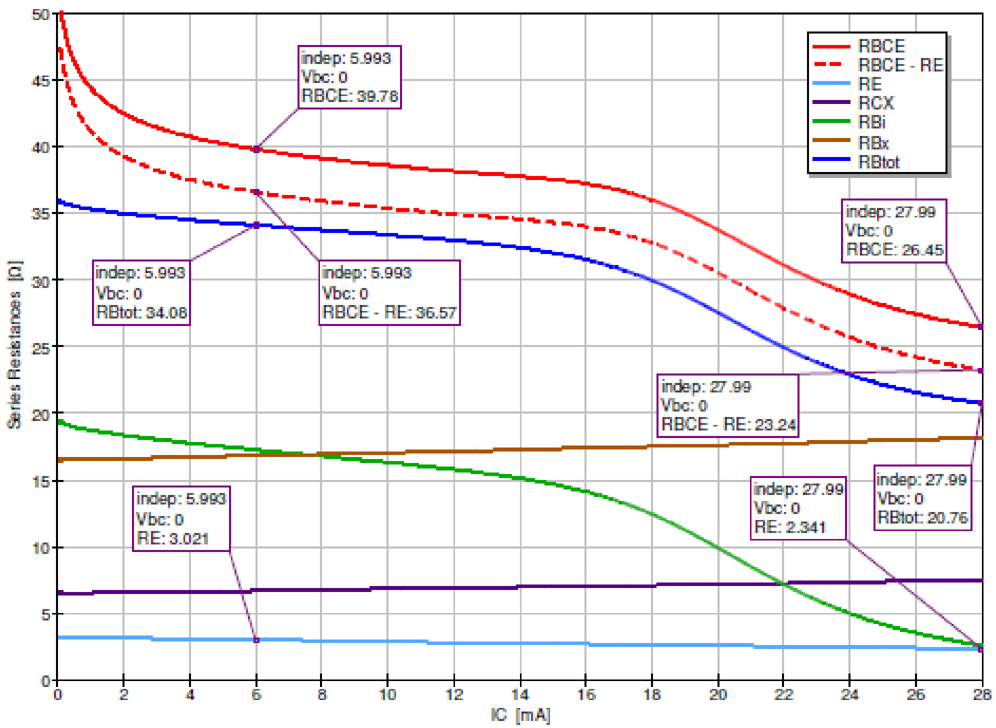
Impact of the topology of the small signal EC

- Equation (1) has been derived in [5], [6], assumed a simplified small signal equivalent circuit (EC) in comparison with the full small signal EC of HICUM/L2

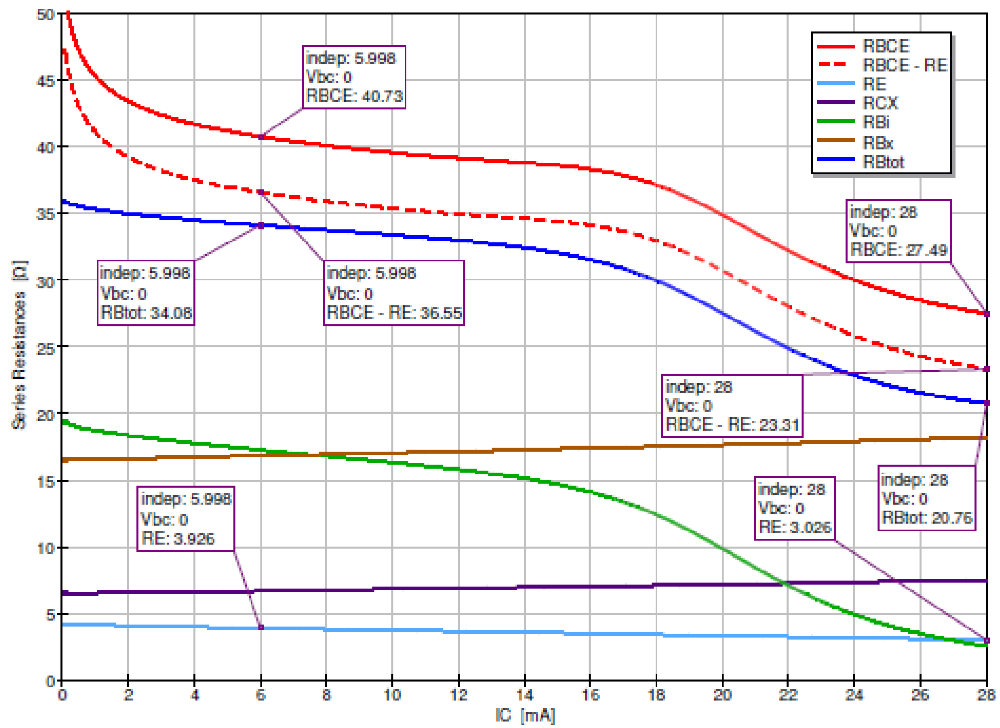
- In the following slides, we will look at the impact on the R_{BCE} FoM of some elements and of the topology of the EC
  - Emitter resistance
  - Collector resistance
  - Intrinsic base resistance
  - Extrinsic base resistance
  - Split of C_{BEPAR}
  - Split of C_{JBE}
  - Split of C_{BCX}
  - Split of C_{JBC}
  - Substrate network

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
R_E [Ω]	3.215	36.57	23.24	34.08	20.76	346.7	4.807
	4.180	36.55	23.31			344.4	4.611
Deviation	30 %	0.055 %	0.301 %			0.663 %	4.077 %

R_E = 3.215 Ω



R_E = 4.180 Ω



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Impact of R_E (2/2)

- We vary R_E by 30% of its nominal value

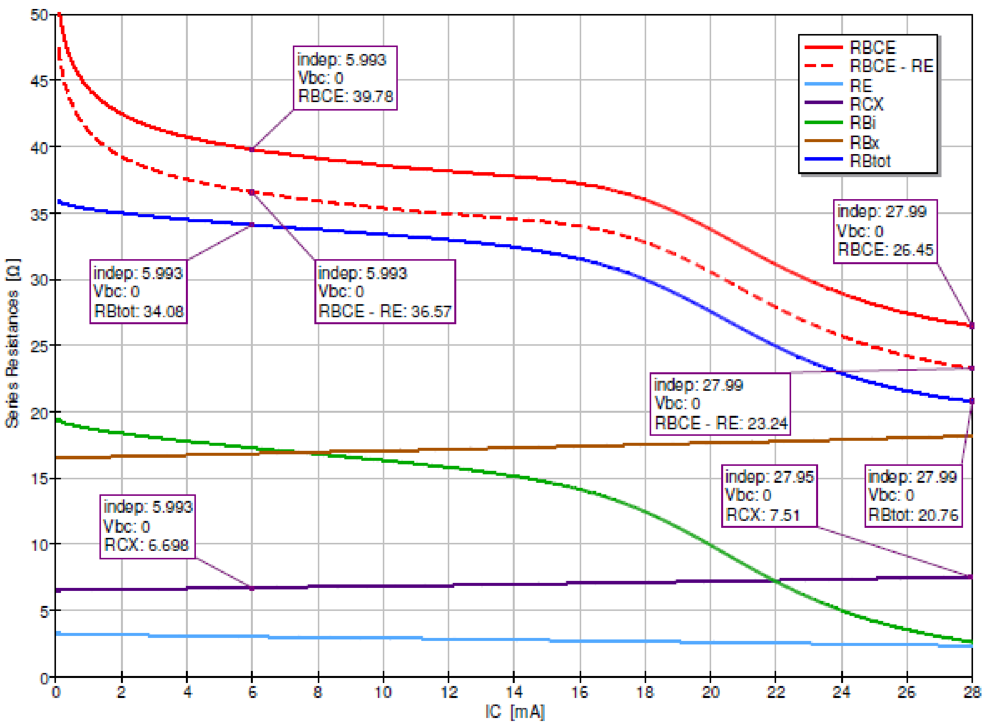
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents

- **Comments**
  - Despite a 30% variation in R_E, no impact on R_{BCE} - R_E
    - This means that the impact of R_E on R_{BCE} is not affected by other elements of the EC.
    - In other words, R_{BCE} is only influenced by the accuracy of R_E estimate.
    - Fortunately, R_E (and its uncertainty) is lower than R_{BCE}
  - Negligible impact on f_{max}

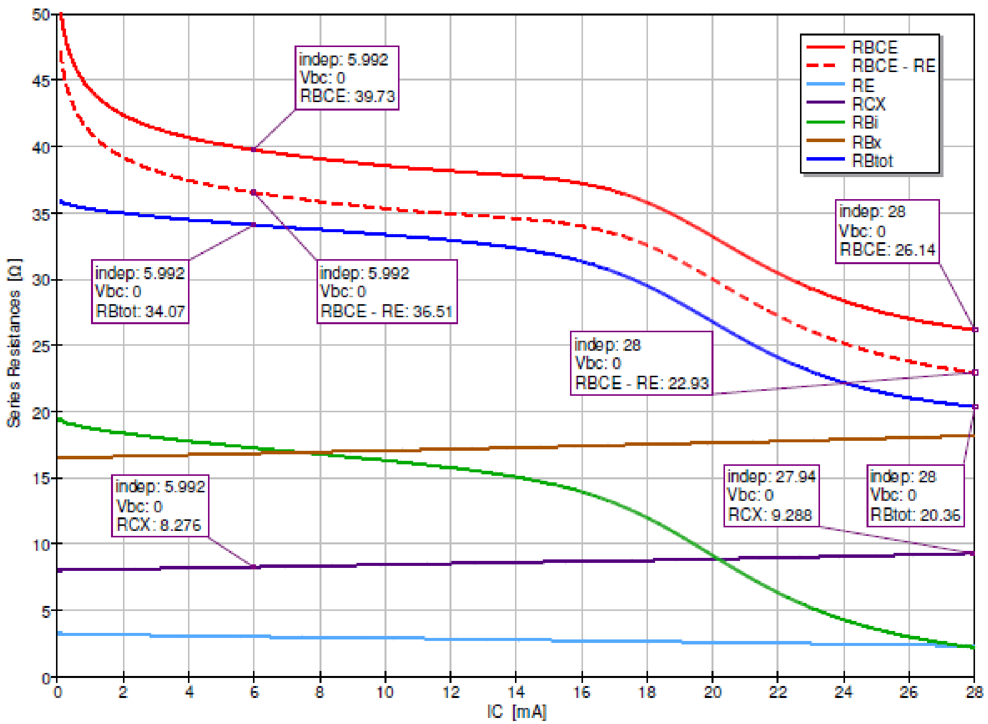
Impact of R_{CX} (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
R_{CX} [Ω]	6.515	36.57	23.24	34.08	20.76	346.7	4.807
	8.047	36.51	22.93	34.07	20.36	345.7	4.133
Deviation	30 %	0.164 %	1.334 %	0.029 %	1.927 %	0.288 %	14.02 %

R_{CX} = 6.515 Ω



R_{CX} = 8.047 Ω



Impact of R_{CX} (2/2)

- We vary R_{CX} by 30% of its nominal value

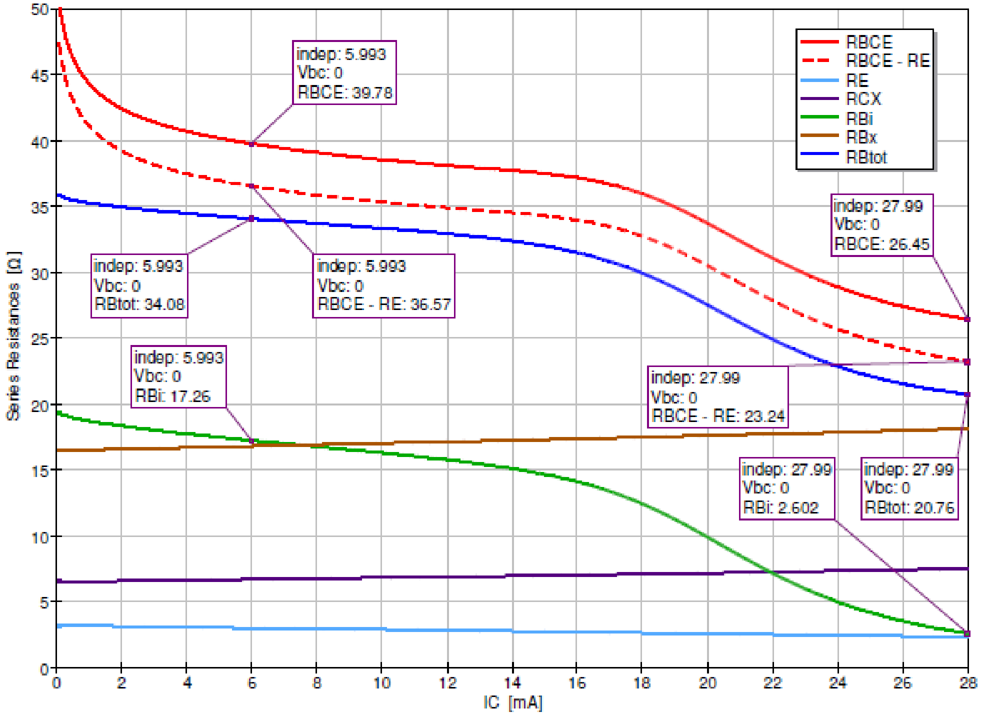
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents

- **Comments**
  - Despite a 30% variation in R_{CX}, no significant impact on R_{BCE} - R_E
    - This means the impact of R_{CX} on R_{BCE} is well de-embedded (see Appendix A)
  - Negligible impact on f_{max} at its peak, but more important effect at very high current
  - The small variation of the simulated base resistance R_{Btot} is due to the fact that the internal V_{BC} is not constant as the result of the variation in R_{CX}

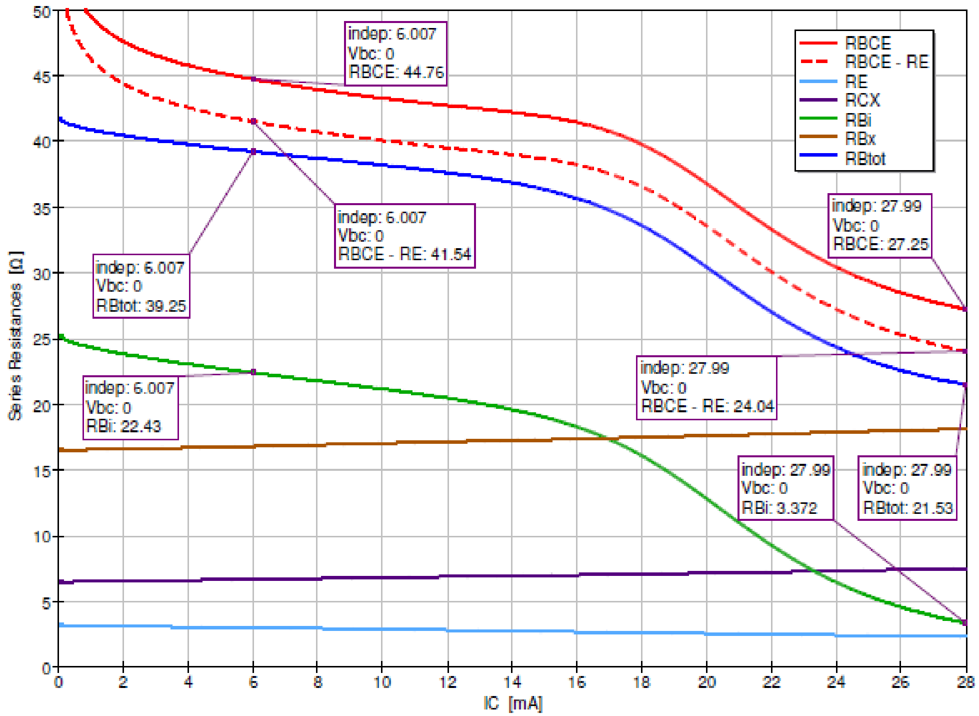
Impact of R_{BI0} (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
R_{BI0} [Ω]	21.79	36.57	23.24	34.08	20.76	346.7	4.807
	28.33	41.54	24.04	39.25	21.53	337.1	4.723
Deviation	30 %	13.59 %	3.44 %	15.17 %	3.71 %	2.77 %	1.75 %

R_{BI0} = 21.79 Ω



R_{BI0} = 28.33 Ω



Impact of R_{BI0} (2/2)

- We vary R_{BI0} by 30% of its nominal value

- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents

- **Comments**
  - Changes in R_{BI0} have a significant impact on R_{BCE} - R_E
  - It is also interesting to note is that the impact of R_{BI0} on R_{BCE} - R_E is similar to the impact on the simulated base resistance R_{Btot}
    - This confirms once again that R_{BCE} - R_E is strongly correlated with R_{Btot}
  - Changes in R_{BI0} of 30% has a small impact on f_{max}

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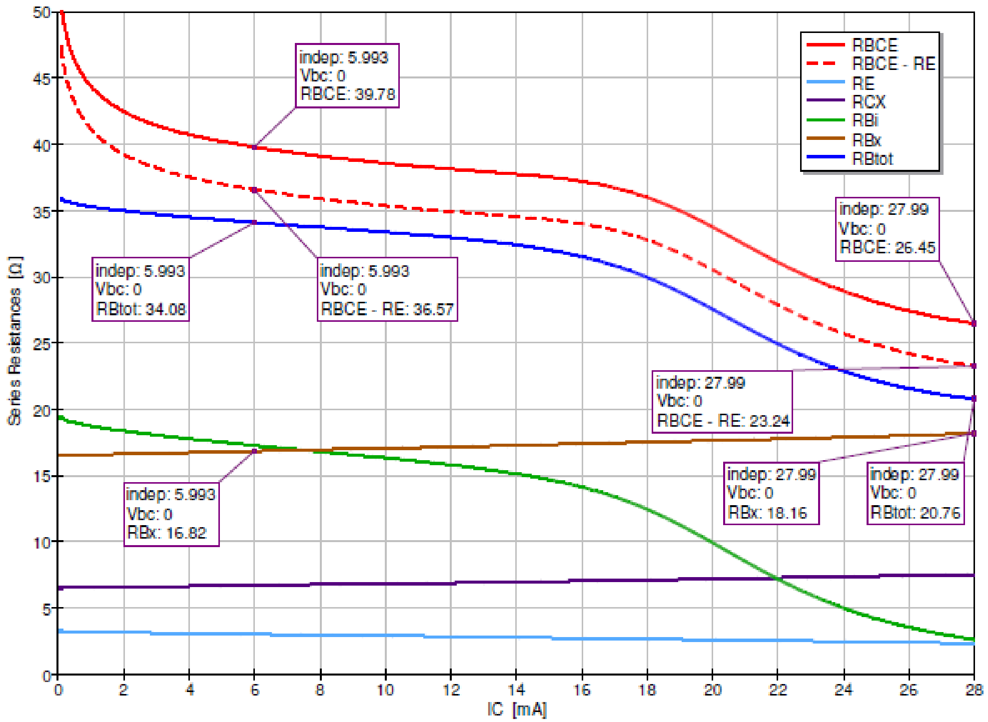
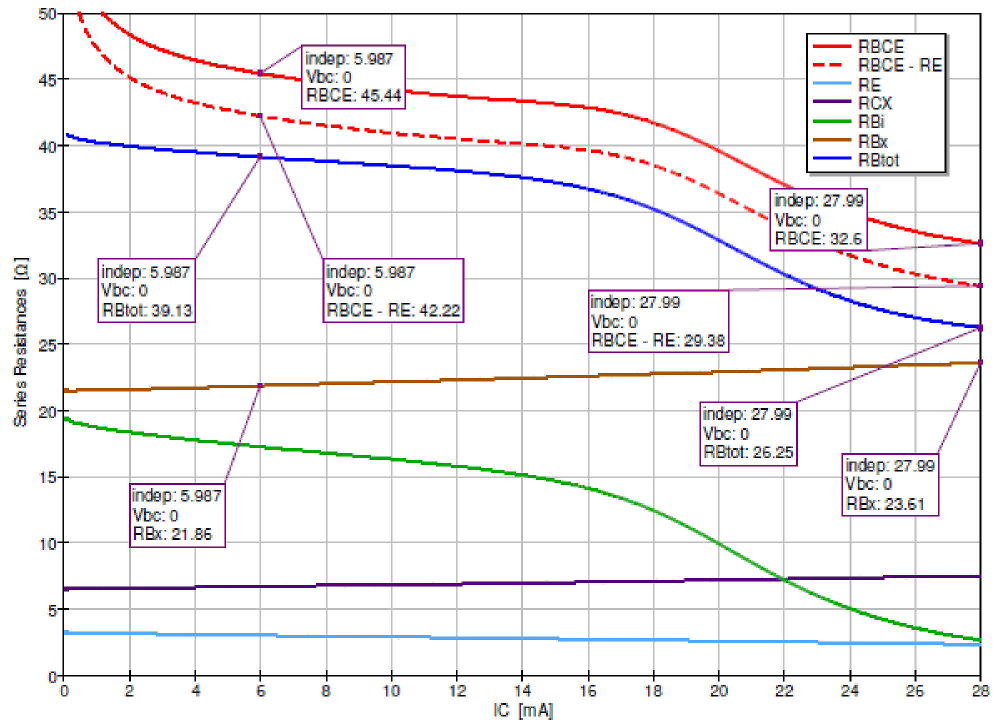
Impact of R_{BX} (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
R_{BX} [Ω]	16.51	36.57	23.24	34.08	20.76	346.7	4.807
	21.46	42.25	29.38	39.13	26.25	311.0	4.388
Deviation	30 %	15.53 %	26.42 %	14.82 %	26.45 %	10.30 %	8.72 %

R_{BX} = 16.51 Ω



R_{BX} = 21.46 Ω



Impact of R_{BX} (2/2)

- We vary R_{BX} by 30% of its nominal value

- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents

- **Comments**
  - Changes in R_{BX} have a significant impact on R_{BCE} - R_E
  - It is also interesting to note is that the impact of R_{BX} on R_{BCE} - R_E is similar to the impact on the simulated base resistance R_{Btot}
    - This confirms once again that R_{BCE} - R_E is strongly correlated with R_{Btot}
  - Contrary to RBI0, changes in R_{BX} of 30% has a significant impact on f_{max}

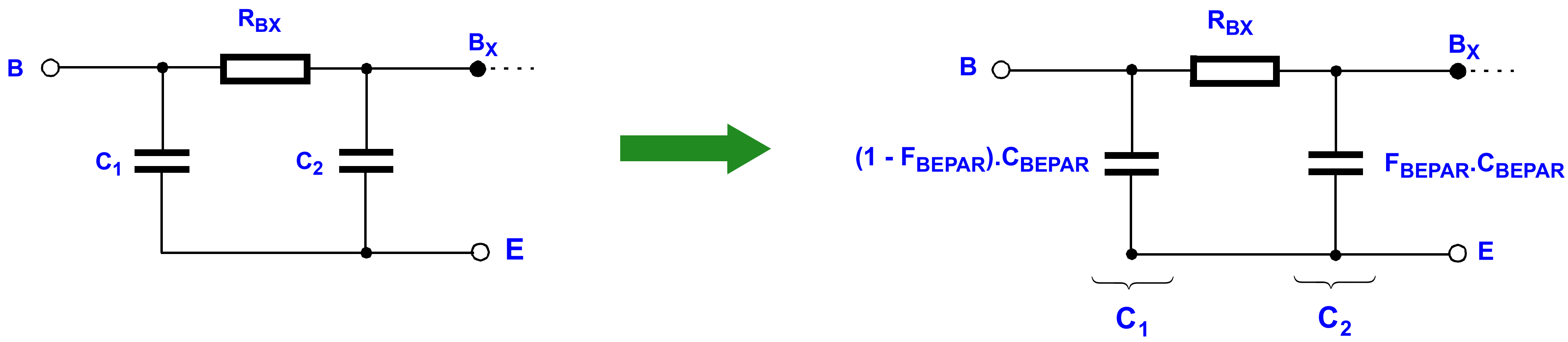
Conclusion

- This first analysis demonstrates
  - That the R_{BCE} - R_E FoM is not sensitive to the emitter and collector series resistances
    - R_{BCE} is de-embedded from R_{CX}
  - In the opposite R_{BCE} - R_E is very sensitive to the intrinsic and extrinsic base series resistances

- The question now is whether the topology of the small signal equivalent circuit has an impact on the R_{BCE} - R_E
  - Split of oxide and BE junction capacitance along the base resistance
  - Split of oxide and BC junction capacitance along the base resistance
  - Substrate network

Impact of F_{BEPAR} (1/3)

- The parasitic BE oxide capacitances is distributed along the base resistance
- For a compact model, a lumped representation is required. In HICUM/L2 two parasitics capacitances C_1 and C_2 are included in the equivalent circuit, respectively connected to the terminal base node B and to the external base node B_x

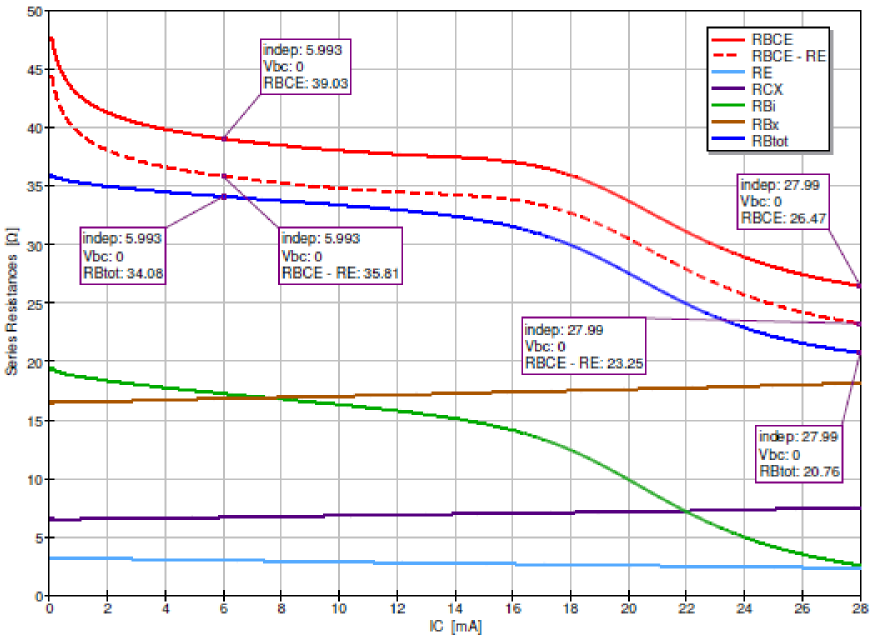


$$\begin{cases} C_1 = (1 - F_{BEPAR}) \cdot C_{BEPAR} \\ C_2 = F_{BEPAR} \cdot C_{BEPAR} \end{cases}$$

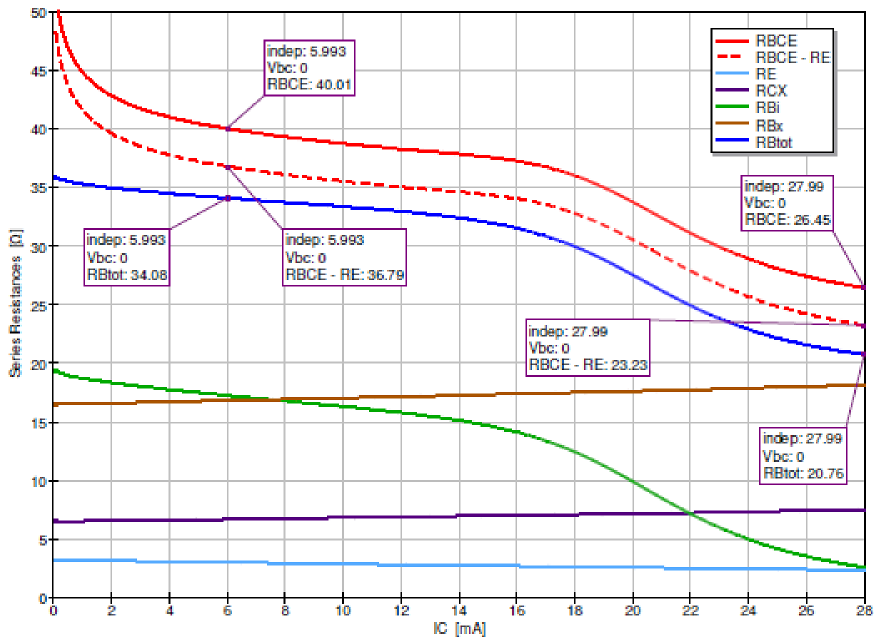
Impact of F_{BEPAR} (2/3)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
F_{BEPAR}	0.77 (reference value)	36.57	23.24	34.08	20.76	346.7	4.807
	0	35.81	23.25			352.4	4.808
	1	36.79	23.23			345.0	4.806
Deviation between 0 and 1		2.73 %	0.086 %			2.10 %	0.042 %

$F_{BEPAR} = 0$



$F_{BEPAR} = 1$



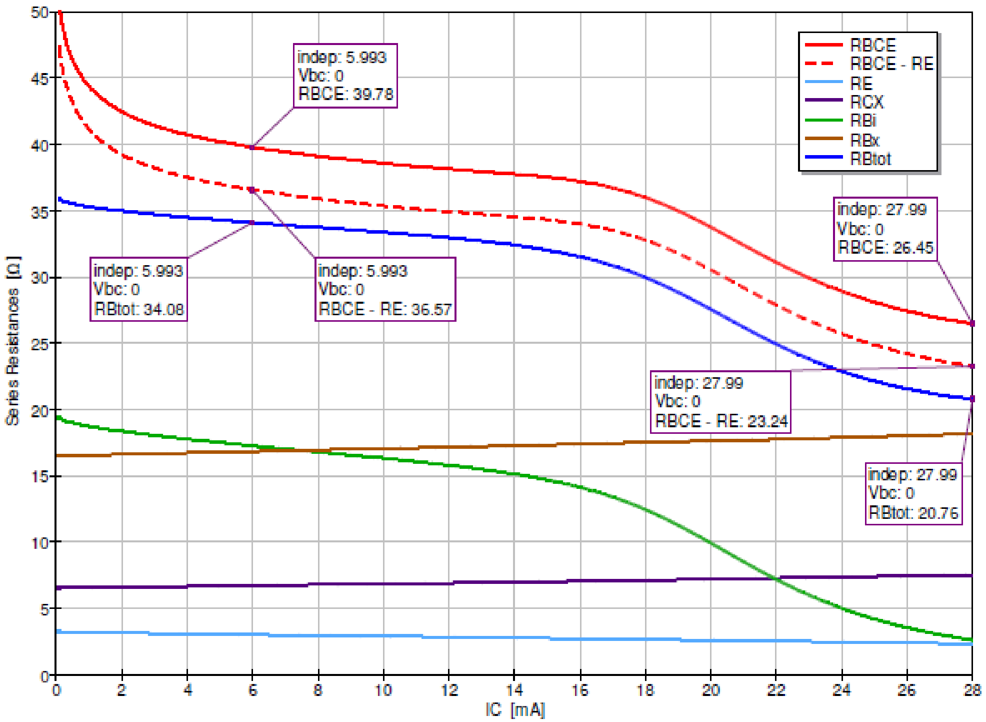
Impact of F_{BEPAR} (3/3)

- We set F_{BEPAR} to 0 and 1
  - For F_{BEPAR} = 0 the parasitic BE capacitance is connected to the terminal base node
  - For F_{BEPAR} = 1 the parasitic BE capacitance is connected to the extrinsic base node (between the extrinsic and the intrinsic base resistance)
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents
- **Comments**
  - F_{BEPAR} has a negligible impact on both R_{BCE} - R_E and f_{max}

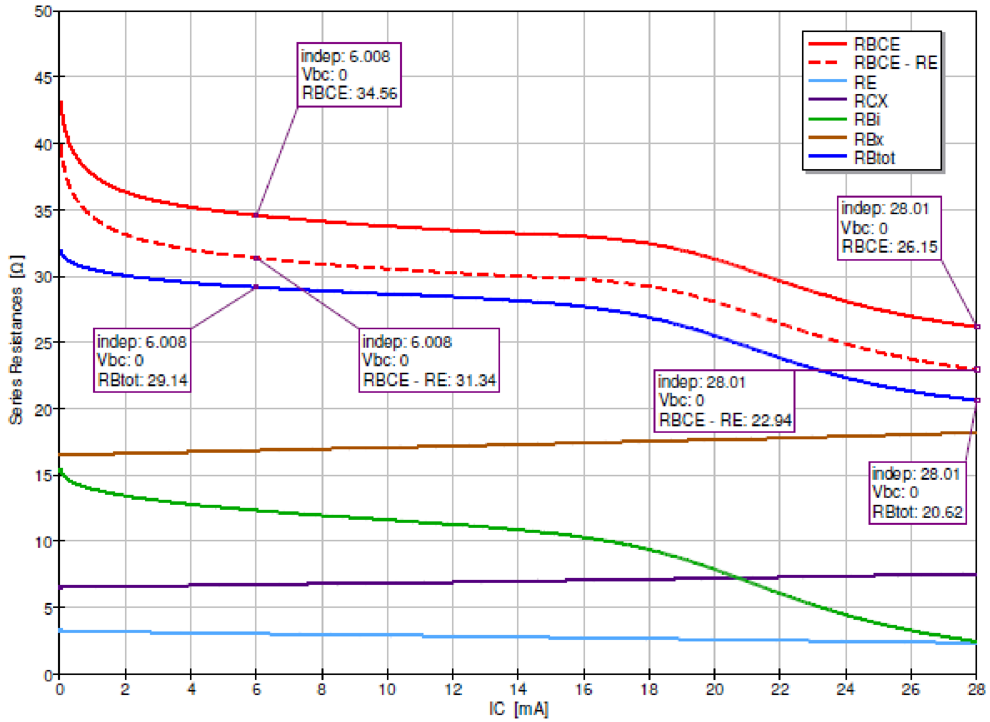
Effect of C_{JBE} Split (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
Split C_{JBE}	YES	36.57	23.24	34.08	20.76	346.7	4.807
	NO	31.34	22.94	29.14	20.62	290.5	4.860
Deviation		14.30 %	1.27 %	14.50 %	0.674 %	16.21 %	1.10 %

Split C_{JBE} YES



Split C_{JBE} NO

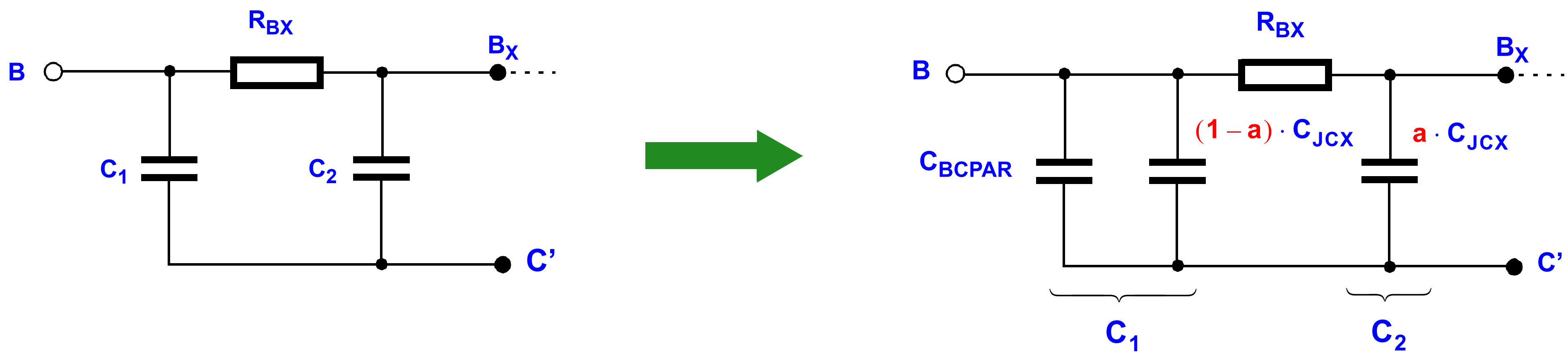


Effect of C_{JBE} Split (2/2)

- The BE depletion capacitance C_{JBE} can be divided on either side of the intrinsic base resistance
- Two cases are simulated
  - No split of the BE depletion capacitance
    - All the capacitance is connected to the internal base node
  - Split of BE depletion capacitance along the intrinsic base resistance as a function of its area and peripheral component
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents
- **Comments**
  - The split of C_{JBE} has a strong impact on the R_{BCE} - R_E FoM, on the simulated base resistance R_{Btot} (which is a function of Q_{JEI}) and f_{max}
    - A good partitioning of the BE depletion capacitance (area and peripheral part) is needed to accurately fit both f_{max} and the base resistance
  - Here again, It is interesting to note is that the impact of the split of C_{JBE} on R_{BCE} - R_E is similar to the impact on the simulated base resistance R_{Btot}
    - This confirms once again that R_{BCE} - R_E is strongly correlated with R_{Btot}

Effect of F_{BCPAR} (1/4)

- As for the BE capacitance, the extrinsic BC depletion capacitance is distributed a long the base resistance
- For a compact model, a lumped representation is required.
- In HICUM/L2 two parasitics capacitances C_1 and C_2 are included in the equivalent circuit, respectively connected to the terminal base node B and to the external base node B_x.



- The extrinsic BC depletion capacitance C_{JCX} is distributed in both sides of the extrinsic base resistance R_{BX} according to a partitioning factor **a.** In HICUM/L2 we have

$$\begin{cases} C_1 = C_{BCPAR} + (1-\mathbf{a}) \cdot C_{JCX} = (1-F_{BCPAR}) \cdot (C_{BCPAR} + C_{JCX}) \\ C_2 = \mathbf{a} \cdot C_{JCX} = F_{BCPAR} \cdot (C_{BCPAR} + C_{JCX}) \end{cases} \quad \text{with } a \in [0:1] \qquad (2)$$

Effect of F_{BCPAR} (2/4)

- From equation (2) F_{BCPAR} can be calculated from C_{BCPAR} and from C_{JCX0} knowing the partition factor **a**

$$F_{BCPAR} = \frac{\mathbf{a} \cdot C_{JCX0}}{C_{BCPAR} + C_{JCX0}} \qquad (3)$$

- In order to reduce arithmetic computation, F_{BCPAR} is calculated from the zero-bias extrinsic BC depletion capacitance C_{JCX0} rather than the voltage dependent value C_{JCX}

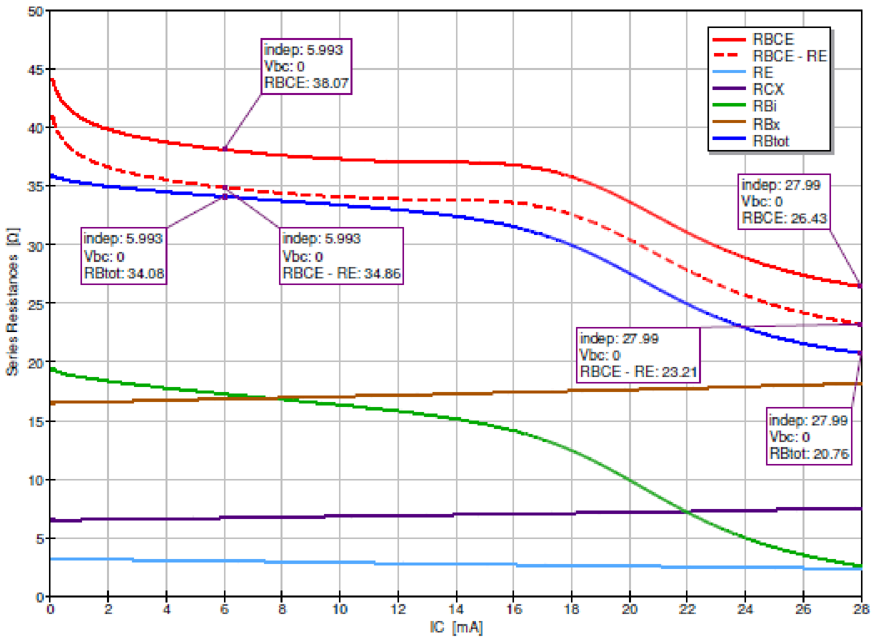
Warning

- Do not confuse the partitioning factor **a** which is used to split C_{JCX} along R_{BX} and the partitioning factor F_{BCPAR}, determined knowing **a**, which is used to calculate C_1 and C_2.

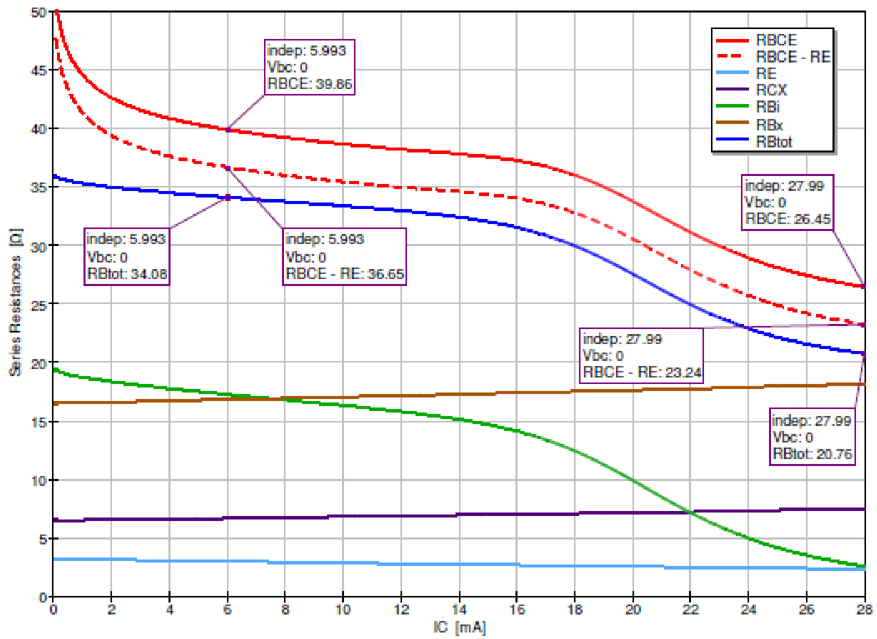
Effect of F_{BCPAR} (3/4)

Parameter		$R_{BCE} - R_E$ [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
F_{BCPAR}	0.82	36.57	23.24	34.08	20.76	346.7	4.807
	0 (C_{JCX} external)	34.86	23.21			557.6	4.825
	0.8598 (C_{JCX} internal)	36.65	23.24			341.2	4.806
Deviation between 0 and 0.8598		5.13 %	0.129 %			38.81 %	0.394 %

$F_{BCPAR} = 0$



$F_{BCPAR} = 0.8598$



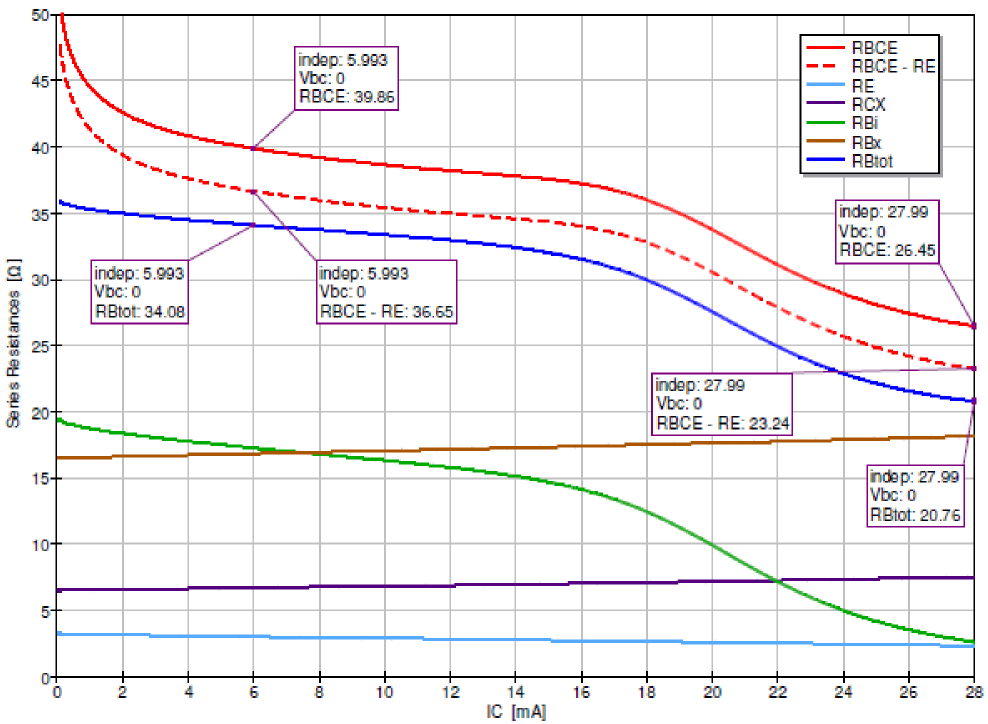
Effect of F_{BCPAR} (4/4)

- We set F_{BCPAR} to 0 and 0.8598
  - For F_{BCPAR} = 0 the extrinsic BC capacitance C_{JCX} is connected to the terminal base node
  - For F_{BCPAR} = 0.8598 the extrinsic BC capacitance C_{JCX} is connected to the extrinsic base node (between the extrinsic and the intrinsic base resistance)
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents
- **Comments**
  - At collector current close to the peak f_{max}, F_{BCPAR} has a significant impact on R_{BCE} - R_E but above all a strong impact on f_{max}
    - Correct determination of F_{BCPAR} is very important for accurate adjustment of peak f_{max}
  - At higher collector current the impact of F_{BCPAR} on both R_{BCE} - R_E and f_{max} is negligible

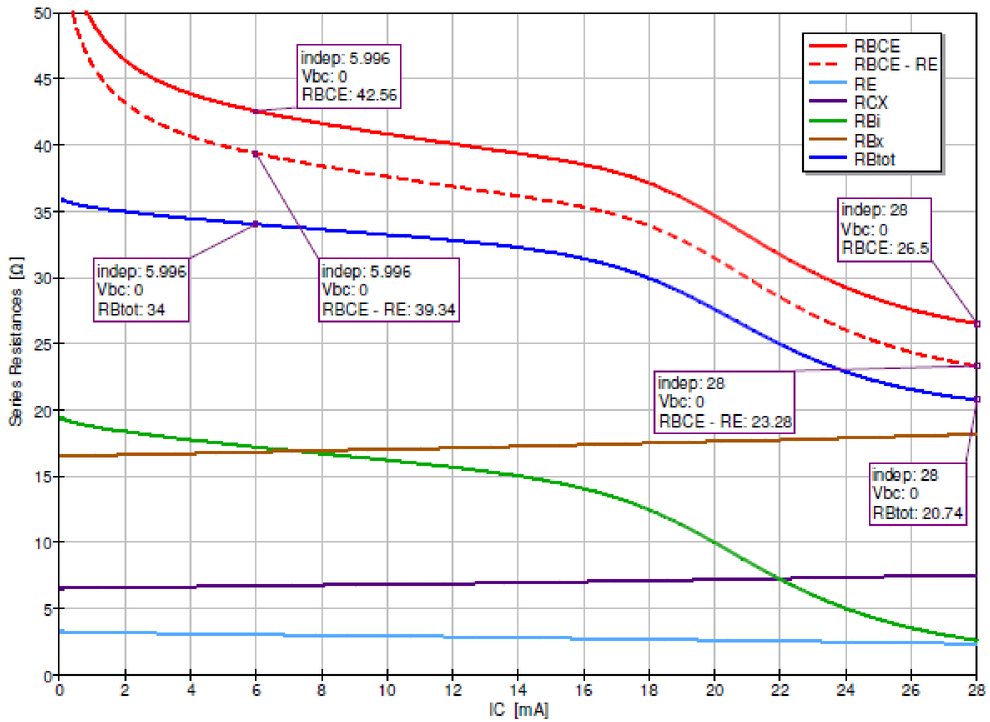
Effect of C_{JBC} split (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
Split C_{JBC}	YES	36.65	23.24	34.08	20.76	341.2	4.806
	NO	39.34	23.28	34.00	20.74	54.27	4.726
Deviation		7.34 %	0.172 %	0.235 %	0.096 %	530 %	1.66 %

Split C_{JBC} YES



Split C_{JBC} NO



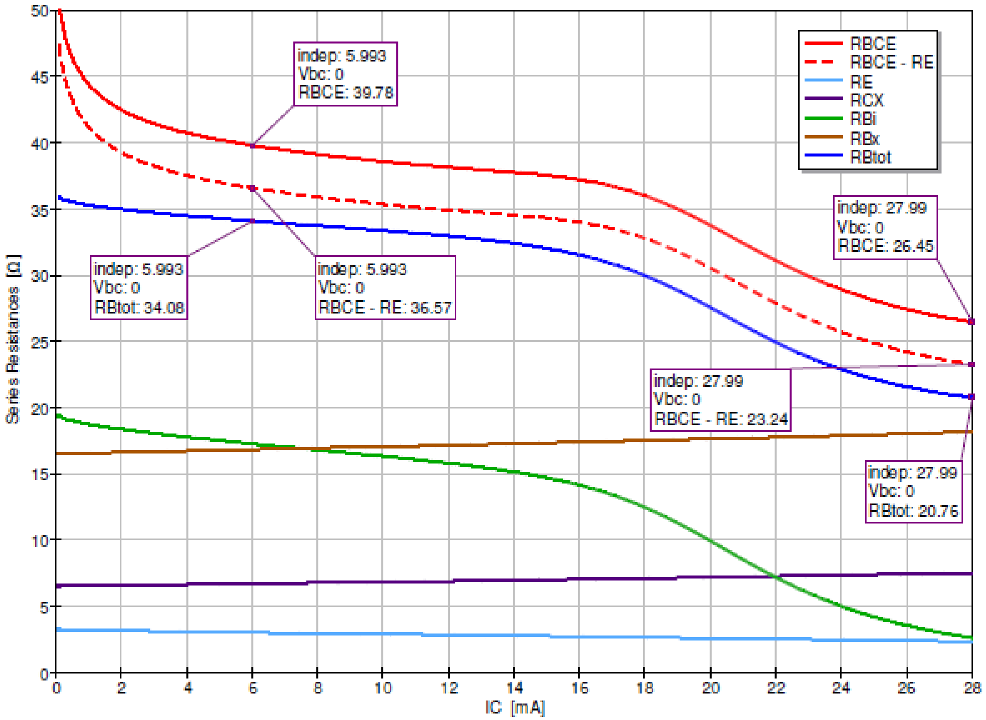
Effect of C_{BC} split (2/2)

- The BC depletion capacitance C_{JBC} can be divided on either side of the intrinsic base resistance
- Two cases are simulated
  - No split of the BC depletion capacitance
    - All the BC depletion capacitance is connected to the internal base node
  - Split of BC depletion capacitance along the intrinsic base resistance as a function of its area and peripheral component
- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents
- **Comments**
  - At collector current close to the peak f_{max}, the split of C_{JBC} has a significant impact on R_{BCE} - R_E but above all a strong impact on f_{max}
    - Correct partitioning of C_{JBC} is very important for accurate adjustment of peak f_{max}
    - At higher collector current the impact of the split of C_{JBC} on both R_{BCE} - R_E and f_{max} is negligible

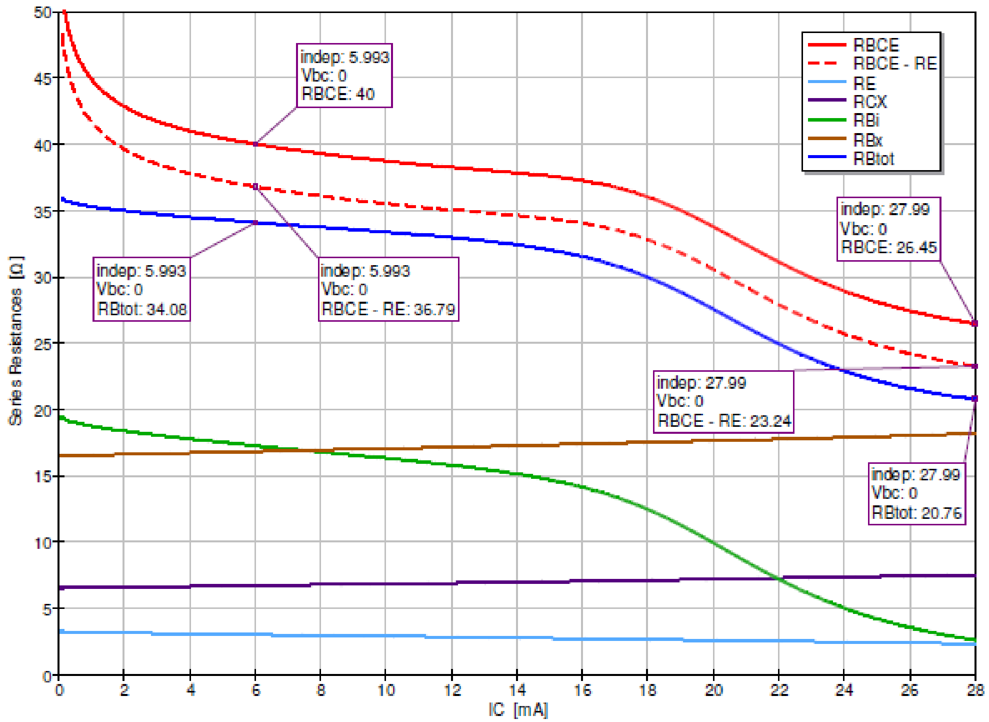
Effect of substrate network (1/2)

Parameter		R_{BCE} - R_E [Ω]		R_{Btot} model [Ω]		f_{max} [GHz]	
		6 mA	28 mA	6 mA	28 mA	6 mA	28 mA
Substrate network	YES	36.57	23.24	34.08	20.76	346.7	4.807
	NO	36.79	23.24			347.7	4.815
Deviation		0.602 %	0 %			0.288 %	0.197 %

Substrate network YES



Substrate network NO



Effect of substrate network (2/2)

- Simulation with and without substrate network

- We are looking at the impact on
  - the FoM R_{BCE} - R_E at 2 collector currents
    - Near the peak f_{max} 6 mA
    - Far from the peak f_{max} 28 mA
  - and f_{max} at the 2 collector currents

- **Comments**
  - The substrate network has a negligible impact on both R_{BCE} - R_E and f_{max}

Evaluation of R_{BCE} from measurements (1/2)

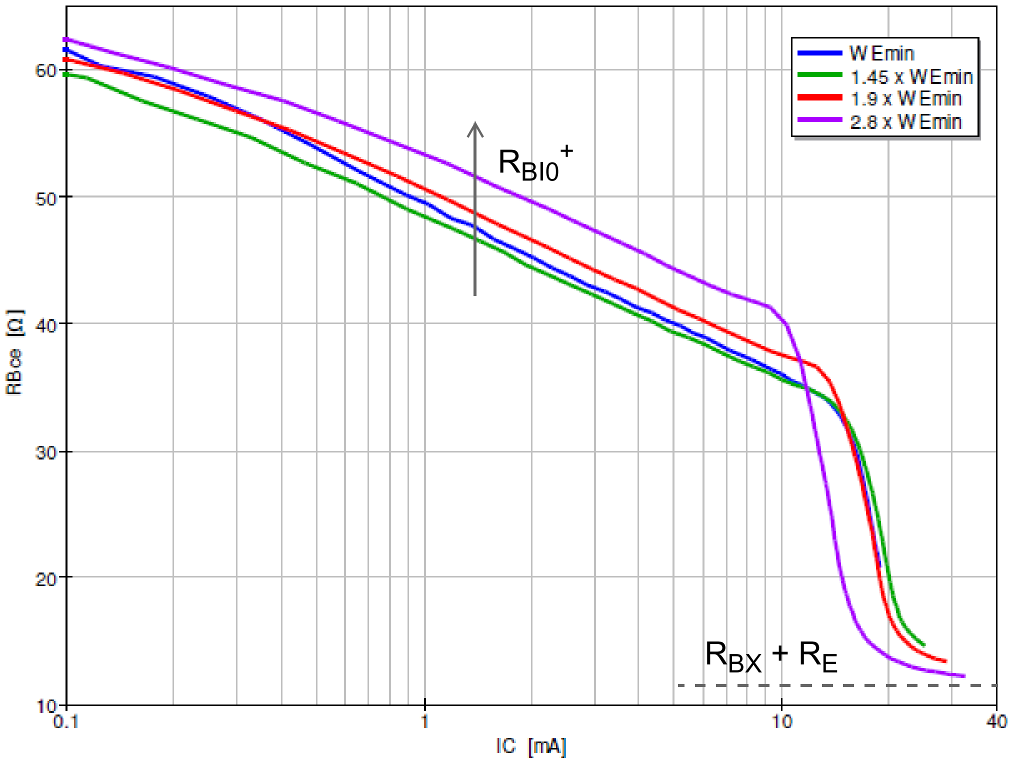
- To validate a new extraction method from *synthetic* data **is necessary**, but it **is not sufficient**
- Test on measured data is then **mandatory**
- Direct determination of R_{BCE} from (1), without R_{CX} and R_E de-embedding
- Example of results from 2D HBTs with variable emitter width (W_E) and constant emitter length

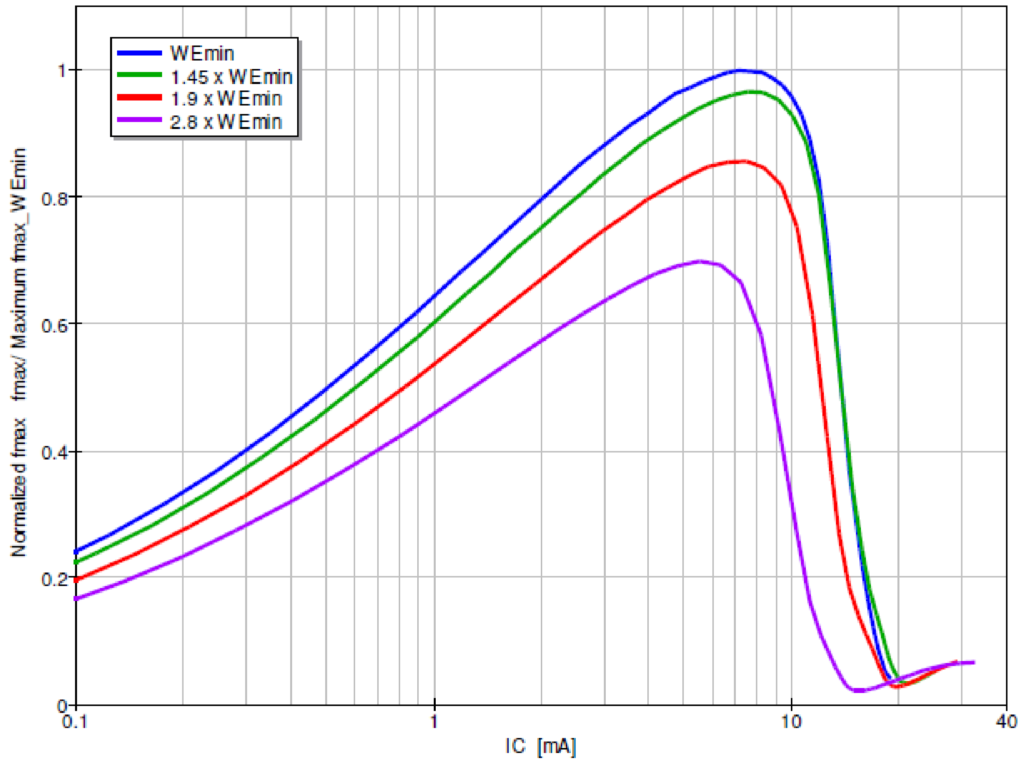
W_E	**W_{Emin}**	**1.45 x W_{Emin}**	**1.9 x W_{Emin}**	**2.8 x W_{Emin}**

- **Comments**
  - Results on the narrow transistor needs more investigations
    - Possible non-linear geometry scaling law?
    - R_{CX} and R_E de-embedding needed for more *reliable* results?
  - The results for the other transistor widths are consistent with the physics and f_{max} characteristics
    - At low currents R_{BCE} increases with the width of the emitter (R_{BI0} increasing)
    - At high currents the asymptotic values of R_{BCE} are similar (same R_{BX}, small R_{BI} high injection, emitter current-crowding)

Evaluation of R_{BCE} from measurements (2/2)

- R_{BCE} and normalized f_{max} (with respect to the maximum value of f_{max} at W_{Emin}), versus I_C, at V_{BC}=0V





Base resistance parameter optimization (1/3)

Prerequisite

- All HICUM/L2 model parameters have to be extracted excepted the parameter of the base resistance and the partitioning factor F_{BEPAR} and F_{BCPAR}
- Warning
  - The split of the depletion capacitances C_{JBE} and C_{JBC} along the base resistance must be accurately determined, other-wise an accurate optimization of f_{max} is not possible

Principle

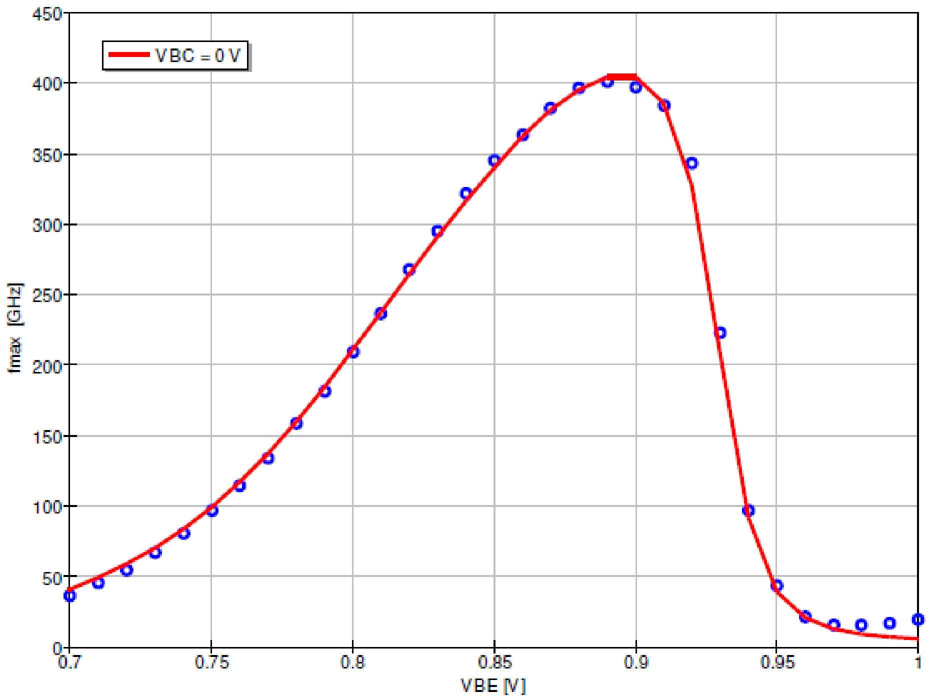
- Extraction of the following parameters on both f_{max} and R_{BCE} characteristics at V_{BC} = 0 V

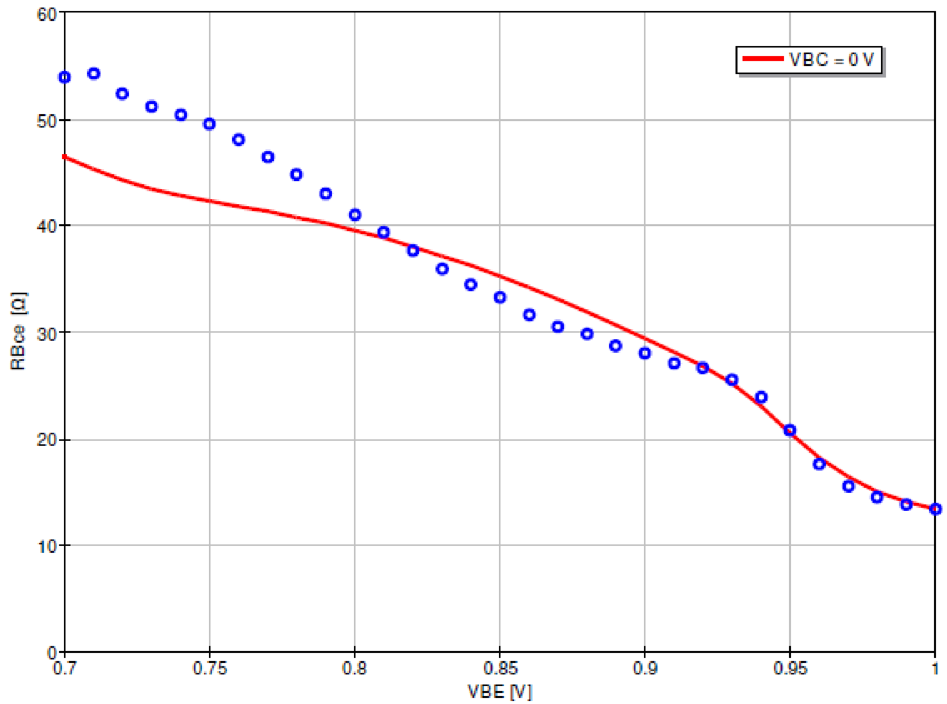
Parameter	Definition	Initial	Min	Max
R_{BI0}	Zero-bias intrinsic base resistance	**10**	0	∞
R_{BX}	Extrinsic base resistance	**10**	0	∞
F_{DQR0}	Correction factor for modulation by BE and BC space charge layer	**0**	-0.5	100
F_{QI}	Ratio of internal to total minority charge	**1**	0	1
F_{GEO}	Factor for geometry dependence of emitter current croding	**0.66**	0	1
F_{BEPAR}	Partioning factor of parasitic BE capacitance	**0.5**	0	1
F_{BCPAR}	Partioning factor of parasitic BC and extrinsic BC deletion capacitance	**0.5**	0	1

- In this first test, F_{QI} and F_{GEO} are not optimized and are set to their default values

Base resistance parameter optimization (2/3)

- Result at V_{BC} = 0 V

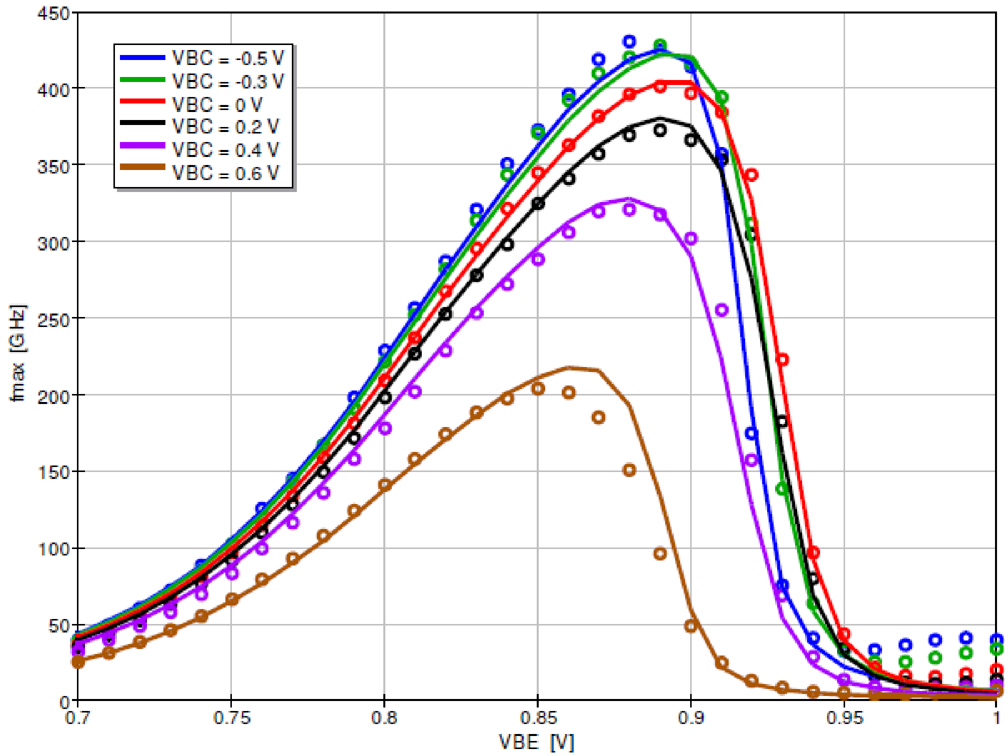


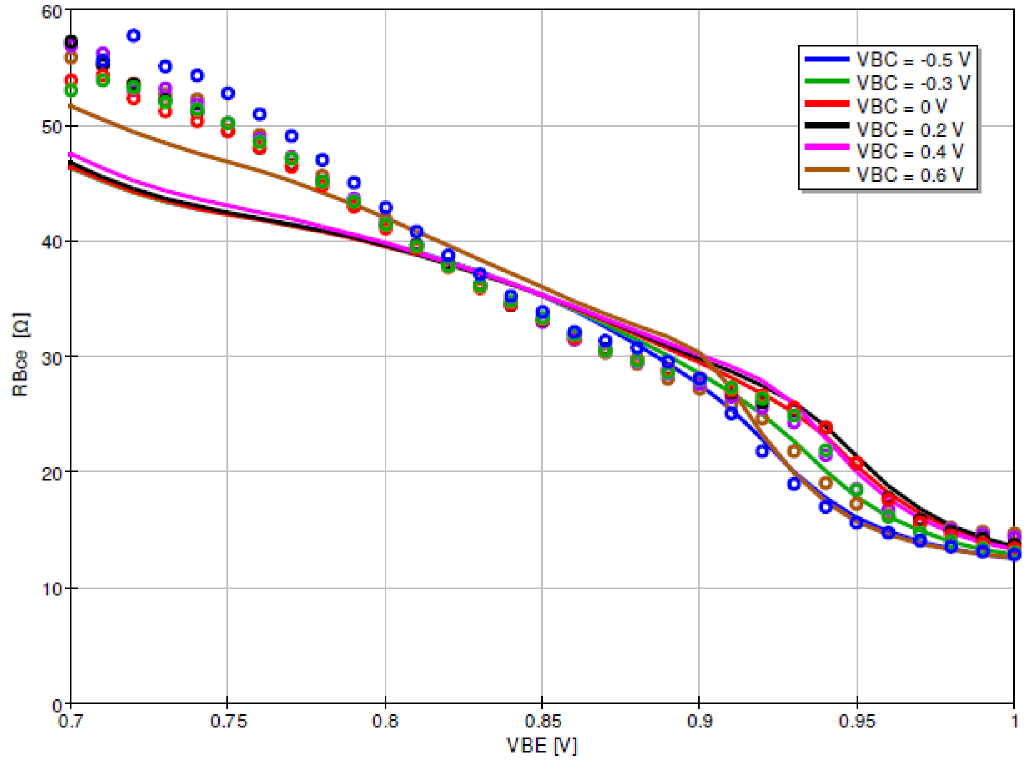


- To our knowledge, it is the first time that we can see a MHC on a parameter (R_{BCE}) which is close to the total base resistance + the emitter resistance, versus the bias (V_{BE} or I_C at constant V_{BC} or V_{CE})

Base resistance parameter optimization (3/3)

- Result for different V_{BC}





- Promising **first trial**, on a single transistor, of joint optimization of R_{BCE} and f_{max}, for the determination of the base resistance parameters and partitioning factors of capacitances

Summary and outlook (1/2)

- In this presentation, the R_{BEC} FoM (1), introduced in [2], has been studied in depth.
- From *synthetic* data, without any correction, this FoM allows to determine the dependence of the base resistance of bipolar transistor, in a wide range of current (before and after the f_{max} peak), with an accuracy around 20%.
- This accuracy can be improved knowing the emitter and collector series resistances, R_E and R_{CX}
- In this case the accuracy on the base resistance varies between 15 and 5%, depending on the operating point
- No other direct measurement method [1] provides this level of precision
- As for f_{max}, this FoM is very sensitive to the partition of the BE and BC depletion capacitance along the base resistance

Summary and outlook (2/2)

- We suggest to add this FoM to f_{max} optimization to better separated the effect of the split of the depletion capacitances from the effect of the base resistance
  - Split of C_{JBE} and C_{JBC}, split of C_{BEPAR} and C_{BCPAR} optimized on f_{max} characteristics
  - Parameters of the base resistance optimized on R_{BCE}
- Despite these positive and interesting initial results, the story is not over
- Future works
  - More tests and results are needed
  - Check the consistency of the results with transistors, coming from different technologies, with different structures and geometries
    - 1 and 2 base fingers
    - Interdigitated transistors
    - Sensitivity to the process splits
  - Add this FoM R_{BCE} to the f_{max} optimization and see if the f_{max} characteristics and the distribution of the BE and BC capacities along the base resistance can be better adjusted.
  - Not an easy task, which requires resources and time
    - All volunteers interested in continuing this evaluation are welcome...
    - If needed → *didier.celi@st.com*

Acknowledgments

- This entire study was carried out using QucsStudio [10]
  - Simulation
  - Plots
  - Parameter extraction
- This is not only a free and powerful circuit simulator but thanks to its interface with OCTAVE and to the routines developed by Zoltan Huszka, QucsStudio is a fantastic and unique tool for modeling purpose
  - Plot electrical characteristic or FoM of electronic devices
  - Model to Hardware Correlation (MHC)
  - Validation of new model features
  - Rapid study and development of extraction routines
  - Short learning curve thanks to a powerful GUI
  - No new programming language to learn
  - Can be used by beginners
  - Not open source but free
  - Developed for Windows but runs on Linux using Wine (not tested)

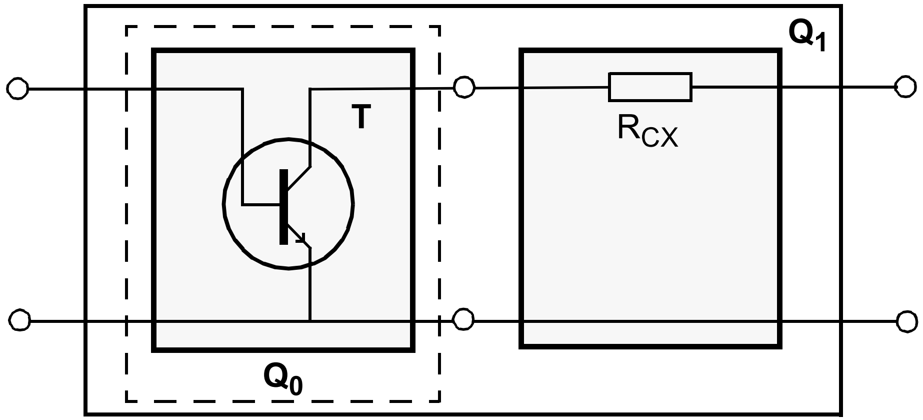
Appendix A: R_{CX} de-embedding

- How to remove the series resistance R_{CX} from the transistor?

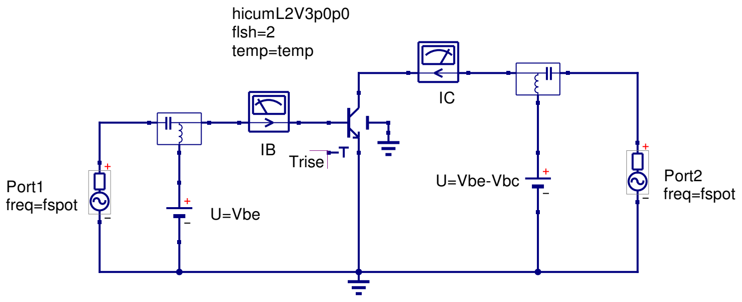
  - R_{CX} is assumed to be in cascade with the other parts of the transistor.
  - Removing R_{CX} from the quadrupole Q_1 is equivalent to multiply the chain matrix of the quadrupole by the inverse of the chain matrix of R_{CX}

$$[A_{Q_1}] = [A_{Q_0}] \cdot [A_{R_{CX}}] \Leftrightarrow [A_{Q_0}] = [A_{Q_1}] \cdot [A_{R_{CX}}]^{-1} \qquad (4)$$

  - $[A_{R_{CX}}] = \begin{bmatrix} 1 & R_{CX} \\ 0 & 1 \end{bmatrix} \Rightarrow [A_{R_{CX}}]^{-1} = \begin{bmatrix} 1 & -R_{CX} \\ 0 & 1 \end{bmatrix}$
  - The S-parameters matrix of Q_1 is converted in ABCD matrix.
  - Then the ABCD matrix of Q_0 is computed from (4)
  - In finally the ABCD matrix of Q_0 is converted in y-parameters matrix



Appendix B: RE extraction - QucsStudio worksheet



s-parameter simulation
SP1
Type=list
Points=1e9
output=dc

parameter sweep
SW1
Sim=SP1
Param=Vbe
Type=list

parameter sweep
SW2
Sim=SW1
Param=Vbc
Type=list
Points=0

RE_AC extraction
QucsStudio 3.3.2
Revision 1.01
23/08/2023

equation
track_card

equation
VBE_Range
vbe_lo=0.88
vbe_hi=0.93

equation
Regression_in
a1=xsel
a2=1-Vbesel+Vbesel
a3=0
a=ysel
w=1/a
Export=yes

equation
Regression_out
NFeff=x1
RE_regr=x2
Export=yes

Linear Regression

equation
3varRegression
b1=w*a1
b2=w*a2
b3=w*a3
b=w*a
Export=yes

equation
Y_Parameters_Meas
fspot=1e9
y11m=rY11m+j*iY11m
y12m=rY12m+j*iY12m
y21m=rY21m+j*iY21m
y22m=rY22m+j*iY22m

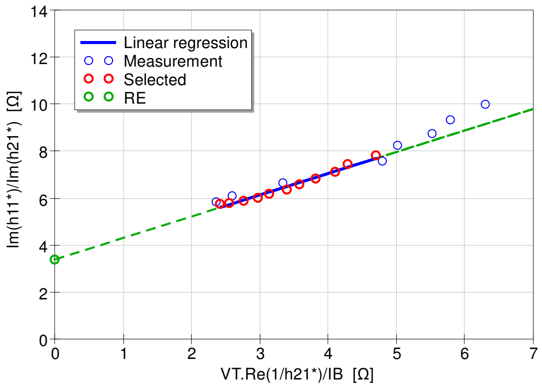
equation
Data_Selection
Vbesel=range(Vbe,vbe_lo,vbe_hi)
Usel=1-Vbesel+Vbesel
xsel=range(xm,vbe_lo,vbe_hi)
ysel=range(ym,vbe_lo,vbe_hi)

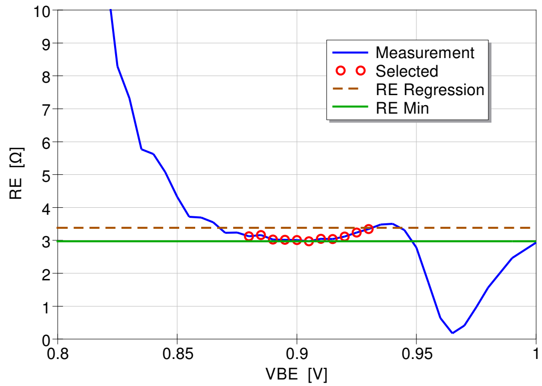
equation
RE_ZH
U=1+IC.I-IC.I
h11m=1/(y11m+y12m)
h21m=(y21m-y12m)/(y11m+y12m)
x=real(1/h21m)*VT/IBm
y=imag(h11m)/imag(h21m)
xm=U*real(1/h21m)*VT/IBm
ym=U*imag(h11m)/imag(h21m)
Rem=ym-xm
Resel=ysel-xsel
Re_min=min(Resel)

equation
Dummy
err_opt=0

equation
filtP_R12

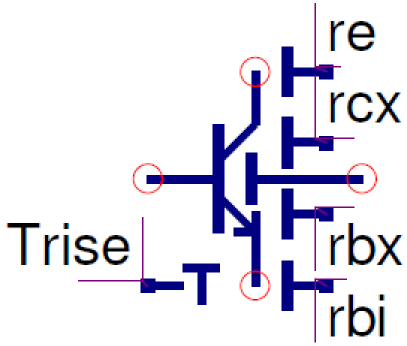
equation
Boltzmann
temp=TAMBm[1]
Tk=temp-T0K
VT=kB*Tk/qelectron
Rmin=1e-4





frequency	NF_eff	RE Min	RE regression
1e+09	0.9156	2.971	3.385

Appendix C: *Strobe* transistor with QucsStudio [11], [10]



What is a *strobe* transistor?

- Allows to export internal variables of the VA code
- Example for exporting R_{BI}, R_{BX}, R_{CX} and R_E

How to create a *strobe* transistor using QucsStudio?

- Additional nodes must be created

```
module hicumL2V3p0p0 (c,b,e,s,tnode,sn1,sn2,sn3,sn4);
```

- The module definition is extended by the terminal nodes `sn1,sn2,sn3,sn4`
  - The new terminal will appear on the transistor symbol
- The signal nodes are of voltage type as specified in the node definitions

```
//Node definitions
inout           c,b,e,s,tnode,sn1,sn2,sn3,sn4;
electrical      c,b,e,s;
voltage         sn1,sn2,sn3,sn4;
```

- Variable assignment to the new terminal nodes
  - Go to the end of the VA file and assign the output data at each signal node

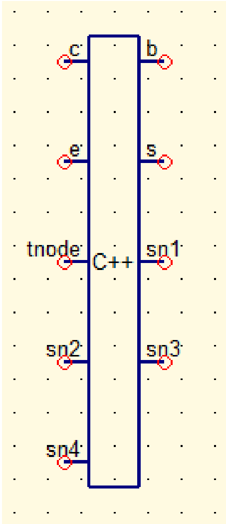
```
      V(sn1) <+ rbi;
      V(sn2) <+ rbx_t;
      V(sn3) <+ rcx_t;
      V(sn4) <+ re_t;
    end //analog
  endmodule
```

- Save the VA file and open it on the QucsStudio workspace. Compile the code using the run button 
- The file **hicumL2V3p0p0.VA.cpp** is generated

```
/*
 * hicumL2V3p0p0.va.cpp - device implementations for hicumL2V3p0p0 module
 * dynamically linked library for QucsStudio
 * created from VerilogAMS file by ADMS
 */
```

Use with default symbol

- Drag **hicumL2V3p0p0.VA.cpp** to the schematic



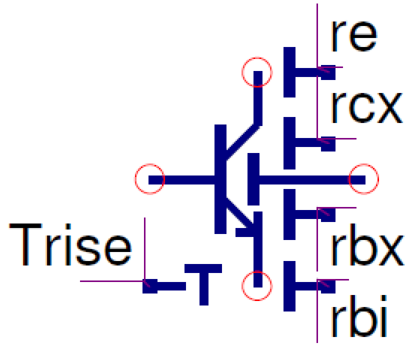
Use with transistor symbol

- It is also possible to associate a transistor symbol by adding it at the end of the `.cpp` file (not described here)

The device is ready to use in simulation

- The signals on the strobe nodes can be then used in equations or diagrams
  - They are referenced by `rbi.V`, `rbx.V`, `rcx.V` and `re.V`

rbx.V	Vbe Vbc
rcx.V	Vbe Vbc
re.V	Vbe Vbc
rbi.V	Vbe Vbc



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