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“Extraction of RE and its temperature dependence from RF measurements”

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a leap ahead

in Device Characterization and Modeling

Outline

- requirements against RE extraction
- the *gmx* method and its refinement
- derivation of the novel *RF* method
- extraction plots comparing the two approaches
- temperature dependence
- scaling between two emitter lengths
- summary

Preferences

- lack of additional measurement effort
- a transparent extraction theory
- justifiable neglections resulting in a reasonable extraction equation
- proven regression type extraction technique
- usage of unified RF test structures for saving modeling costs

An often used scheme meeting these requirements is the gmx method: extraction from the DC Gummel plot

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RE extraction from DC Gummel measurements

In forward active mode

$$I_c = \frac{c_{10}}{Q_{p,T}} \cdot \exp\left(\frac{V_{biei}}{V_T}\right) \quad V_{biei} = V_{be} - (rb + re) \cdot I_b - re \cdot I_c \approx V_{be} - re \cdot I_c$$

$$\frac{\partial \ln(I_c)}{\partial vbe} = \frac{gmx}{I_c} = -\frac{\partial \ln(Q_{p,T})}{\partial vbe} + \frac{1}{V_T} - \frac{re}{V_T} \cdot gmx$$

The variation of the weighted charge logarithm is relatively small providing the linear regression [1]

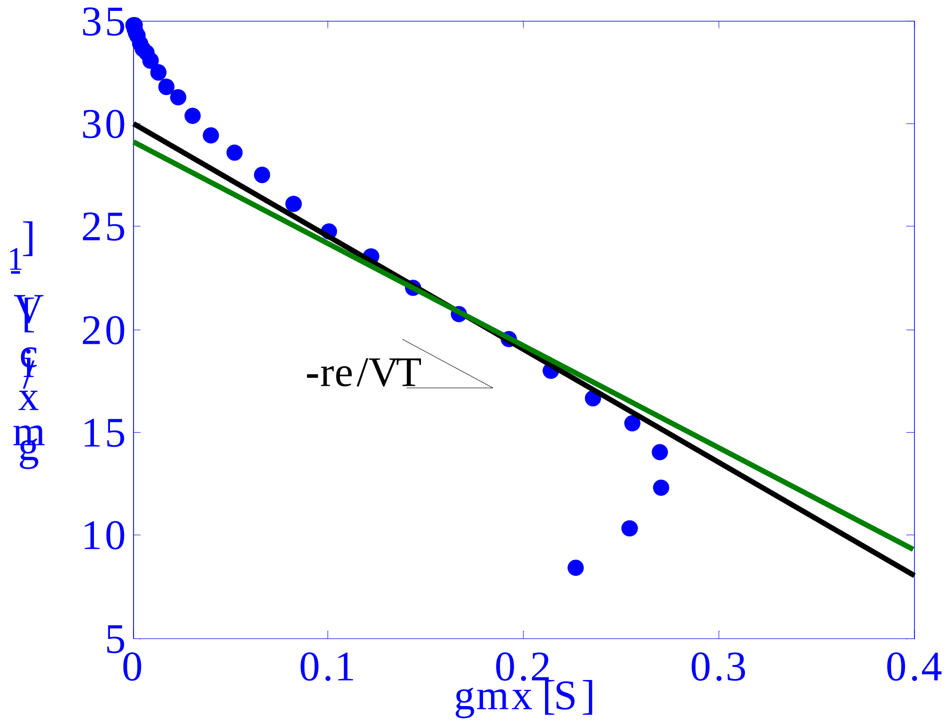
$$\frac{gmx}{I_c} \approx \frac{1}{V_T} - \frac{re}{V_T} \cdot gmx$$

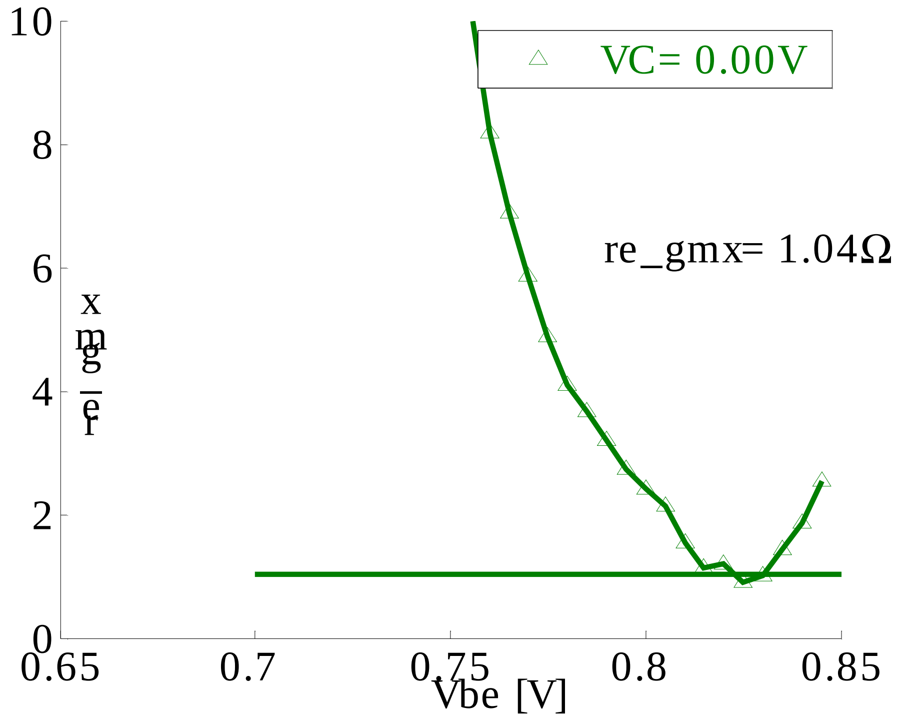
It is difficult to select the regression interval. Rearranged form

$$re \approx \frac{1}{gmx} - \frac{V_T}{I_c}$$

This should be constant: best satisfied around the extremum

Comparison of the two evaluations





selection of the regression interval is subjective

minimum location is unique and easy to determine

RE extraction from RF measurements, I.

An expression for the inverse intrinsic transconductance was derived in [2]

$$\frac{1}{gm} + re = \frac{\Im(\tilde{h}_{11e})}{\Im(\tilde{h}_{21e})} \qquad (1)$$

Tilde ~ denotes unilateralized (UL) parameters [3]

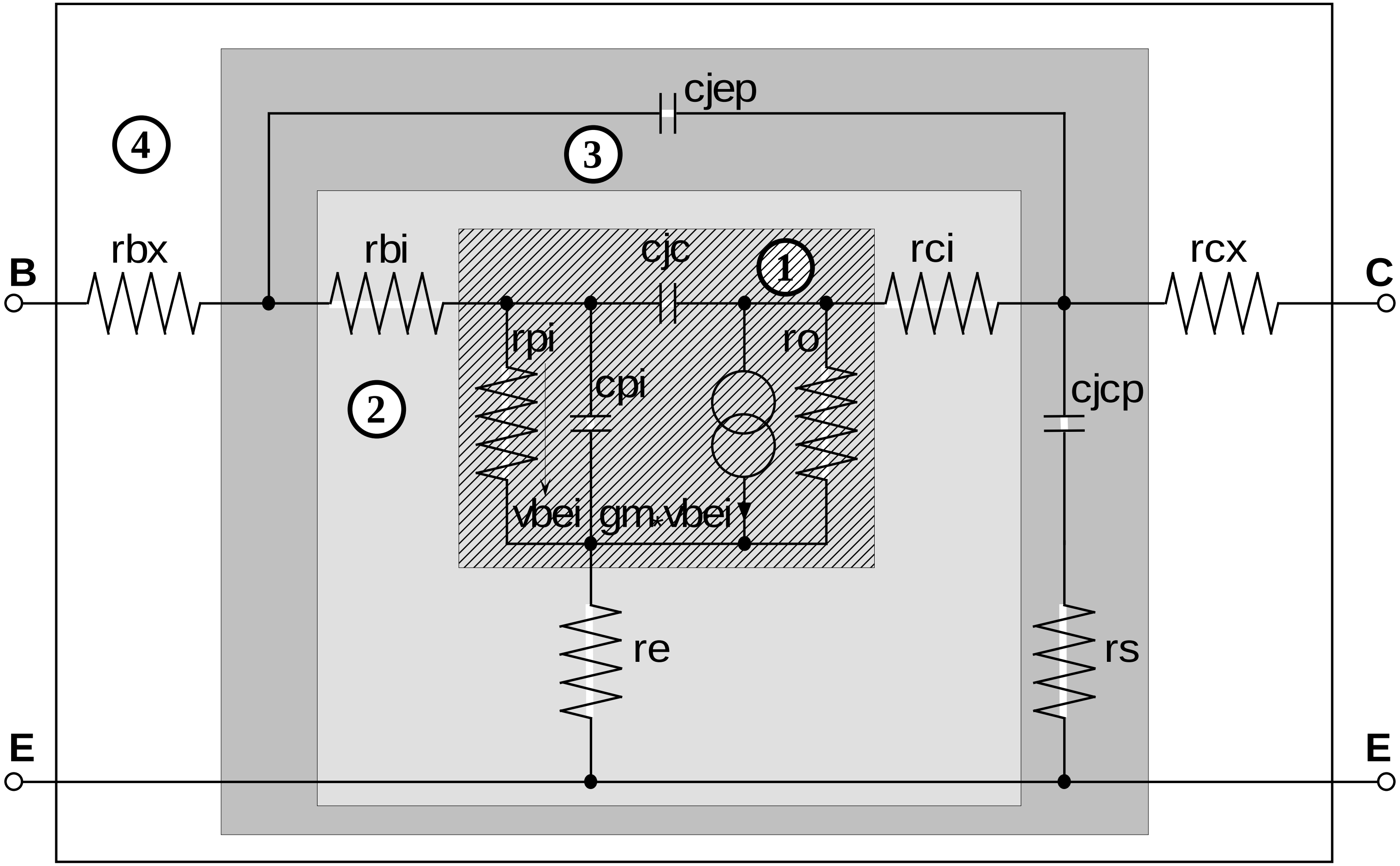
$$\tilde{y}_{ii} = y_{ii} + y_{12} \quad \tilde{y}_{21} = y_{21} - y_{12} \quad \tilde{z}_{ii} = z_{ii} - z_{12} \quad \tilde{z}_{21} = z_{21} - z_{12}$$

$$\tilde{h}_{11} = \frac{1}{\tilde{y}_{11}} \quad \tilde{h}_{21} = \frac{\tilde{y}_{21}}{\tilde{y}_{11}} = -\frac{\tilde{z}_{21}}{\tilde{z}_{22}} \qquad i = 1,2$$

In UL parameters the transfer branch elements (e.g. parallel capacitances (**Y**) and series vertical terms like RE (**Z**) cancel

An alternative method will be deduced for *gm* making it possible to determine RE from (1)

RE extraction from RF measurements, II.



Simplified equivalent circuit for all present HBT/BJT models

RE extraction from RF measurements, III.

Block#1 parameters

$$y_{11e}^{(1)} = gpi + s \cdot (cpi + cjc)$$
$$y_{12e}^{(1)} = -s \cdot cjc$$
$$y_{21e}^{(1)} = gm - s \cdot cjc$$
$$y_{22}^{(1)} = go + s \cdot cjc$$

⇒

$$\tilde{y}_{11e}^{(1)} = gpi + s \cdot cpi$$
$$y_{12e}^{(1)} = -s \cdot cjc$$
$$\tilde{y}_{21e}^{(1)} = gm$$
$$\tilde{y}_{22e}^{(1)} = go$$

$$\tilde{y}_{11e}^{(1)} = \frac{I_{bei}}{V_T} + j\omega \cdot (cjei + cd)$$

Block#2 parameters

$$y_{11e}^{(2)} = \frac{y_{11e}^{(1)} + (re + rci)\Delta \mathbf{Y}^{(1)}}{\varepsilon^{(2)}}$$

$$y_{12e}^{(2)} = \frac{y_{12e}^{(1)} - re \cdot \Delta \mathbf{Y}^{(1)}}{\varepsilon^{(2)}}$$

$$y_{21e}^{(2)} = \frac{y_{21e}^{(1)} - re \cdot \Delta \mathbf{Y}^{(1)}}{\varepsilon^{(2)}}$$

$$y_{22}^{(2)} = \frac{y_{22}^{(1)} + (re + rbi)\Delta \mathbf{Y}^{(1)}}{\varepsilon^{(2)}}$$

$$\tilde{y}_{11e}^{(2)} = \frac{\tilde{y}_{11e}^{(1)} + rci\Delta \mathbf{Y}^{(1)}}{\varepsilon^{(2)}}$$

$$\tilde{y}_{21e}^{(2)} = \frac{\tilde{y}_{21e}^{(1)}}{\varepsilon^{(2)}} = \frac{gm}{\varepsilon^{(2)}}$$

$$\varepsilon^{(2)} = \Delta \mathbf{Z}^{(2)} \cdot \Delta \mathbf{Y}^{(1)} = 1 + re \cdot y_{11b}^{(1)} + rbi \cdot y_{11e}^{(1)} + rci \cdot y_{22}^{(1)} + \Delta r \cdot \Delta \mathbf{Y}^{(1)}$$
$$\Delta r = re \cdot rbi + re \cdot rci + rci \cdot rbi$$

RE extraction from RF measurements, IV.

Block#3 parameters

$$\tilde{y}_{11e}^{(3)} = \tilde{y}_{11e}^{(2)}$$

$$\tilde{y}_{21e}^{(3)} = \tilde{y}_{21e}^{(2)}$$

Block#4 parameters

$$\varepsilon^{(4)} = \Delta\mathbf{Z}^{(4)} \cdot \Delta\mathbf{Y}^{(3)} = 1 + rbx \cdot y_{11e}^{(3)} + rcx \cdot y_{22e}^{(3)} + rcx \cdot rbx \cdot \Delta\mathbf{Y}^{(3)}$$

$$\tilde{y}_{11e}^{(4)} = \frac{\tilde{y}_{11e}^{(3)} + rcx \cdot \Delta\mathbf{Y}^{(3)}}{\varepsilon^{(4)}} \qquad \tilde{y}_{21e}^{(4)} = \frac{\tilde{y}_{21e}^{(3)}}{\varepsilon^{(4)}}$$

$$\Rightarrow$$

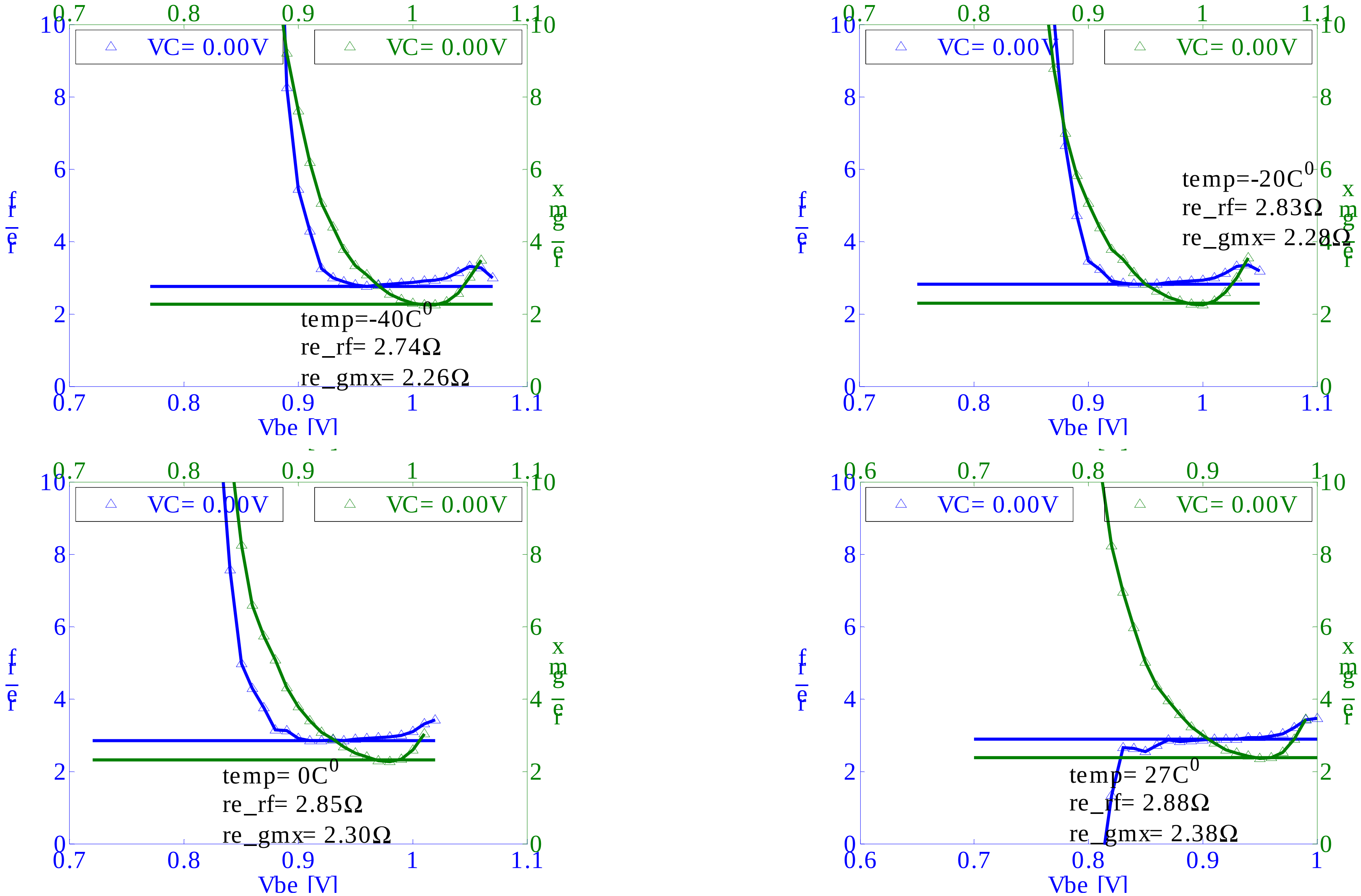
$$\tilde{y}_{11e}^{(4)} = \frac{\tilde{y}_{11e}^{(3)} + rcx \cdot \Delta\mathbf{Y}^{(3)}}{\varepsilon^{(4)}} = \frac{\tilde{y}_{11e}^{(2)}}{\varepsilon^{(4)}} + \frac{rcx}{\Delta\mathbf{Z}^{(4)}} = \frac{\tilde{y}_{11e}^{(1)} + rci \cdot \Delta\mathbf{Y}^{(1)}}{\varepsilon^{(4)} \cdot \varepsilon^{(2)}} + rcx \cdot \Delta\mathbf{Y}^{(4)}$$

$$\tilde{y}_{21e}^{(4)} = \frac{\tilde{y}_{21e}^{(3)}}{\varepsilon^{(4)}} = \frac{\tilde{y}_{21e}^{(2)}}{\varepsilon^{(4)}} = \frac{gm}{\varepsilon^{(2)} \cdot \varepsilon^{(4)}}$$

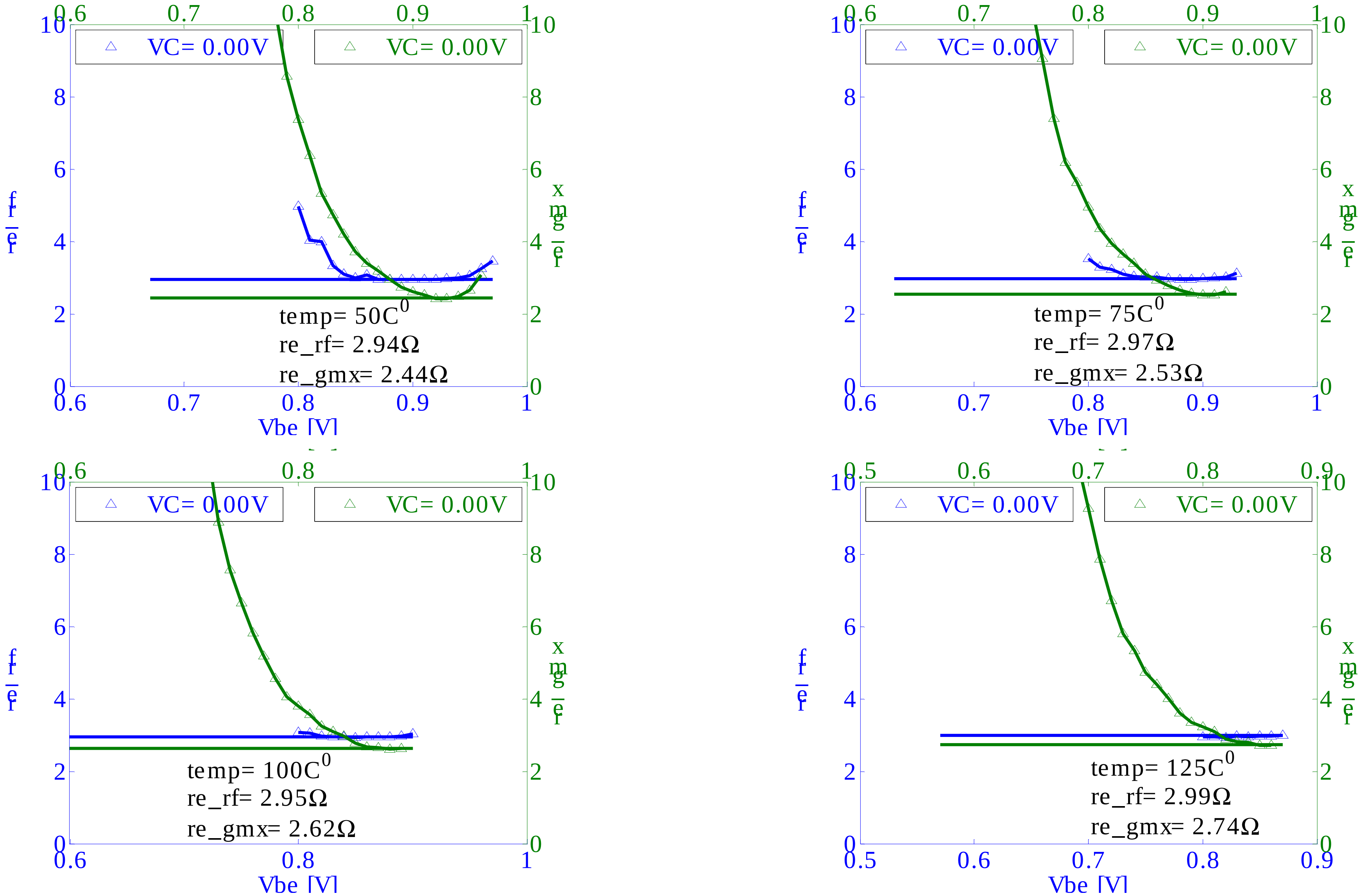
$$\frac{1}{gm} = \frac{1}{\tilde{h}_{21e}^{(4)}} \cdot \frac{1}{\tilde{y}_{11e}^{(1)}} \cdot \frac{1 - rcx \cdot \tilde{h}_{11e}^{(4)} \cdot \Delta\mathbf{Y}^{(4)}}{1 + rci \cdot \tilde{h}_{11e}^{(1)} \cdot \Delta\mathbf{Y}^{(1)}} \approx \frac{1}{\tilde{h}_{21e}^{(4)}} \cdot \frac{1}{\tilde{y}_{11e}^{(1)}} \approx \Re\left(\frac{1}{\tilde{h}_{21e}^{(4)}}\right) \cdot \Re\left(\frac{1}{\tilde{y}_{11e}^{(1)}}\right) = \Re\left(\frac{1}{\tilde{h}_{21e}^{(4)}}\right) \cdot \frac{V_T}{I_{bei}}$$

Putting in (1): $re = \frac{\Im(\tilde{h}_{11e})}{\Im(\tilde{h}_{21e})} - \Re\left(\frac{1}{\tilde{h}_{21e}}\right) \cdot \frac{V_T}{I_b}$ same *h* parameters as for Tf

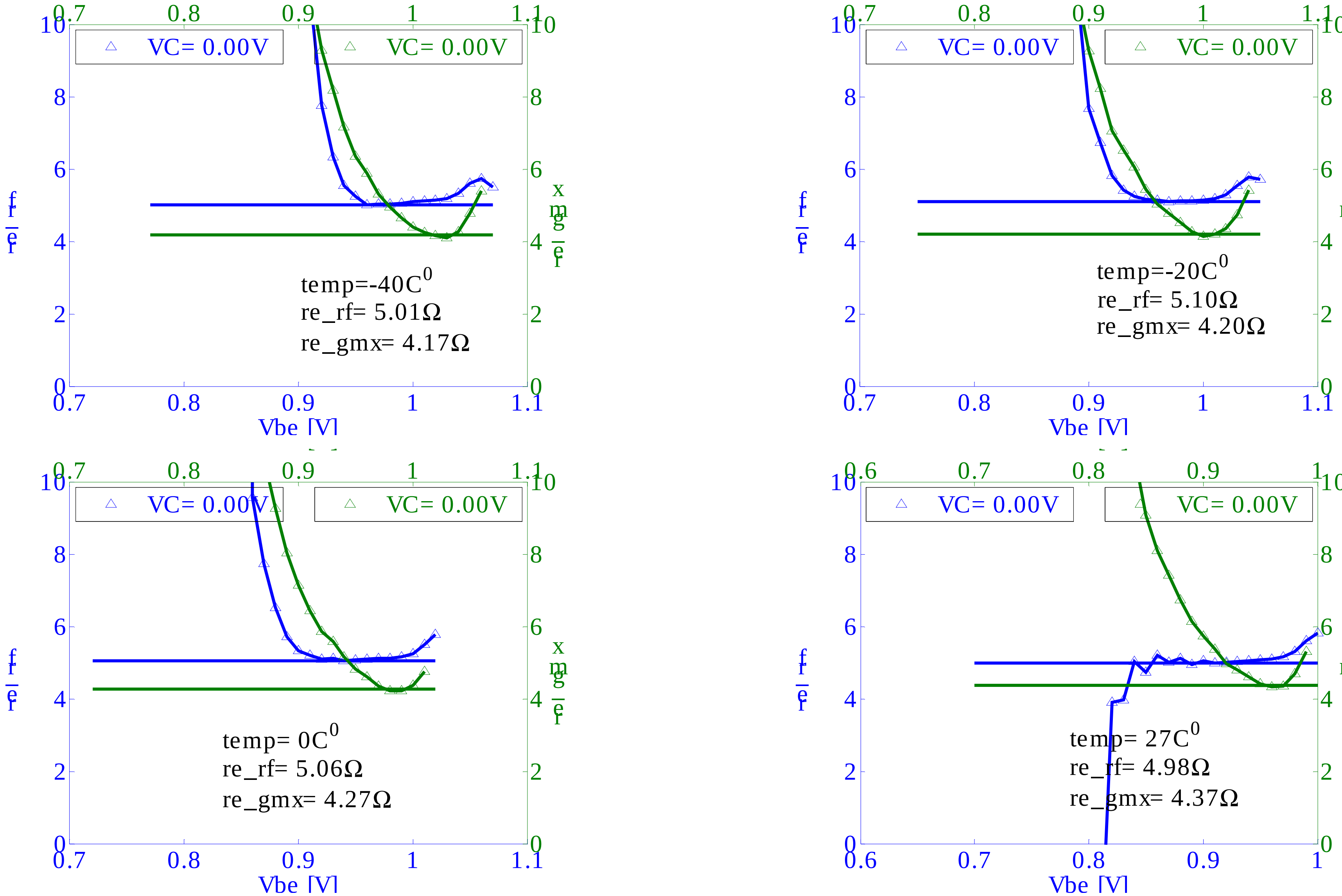
Le=5um, We=0.27um, Tamb=-40 … 27C^0



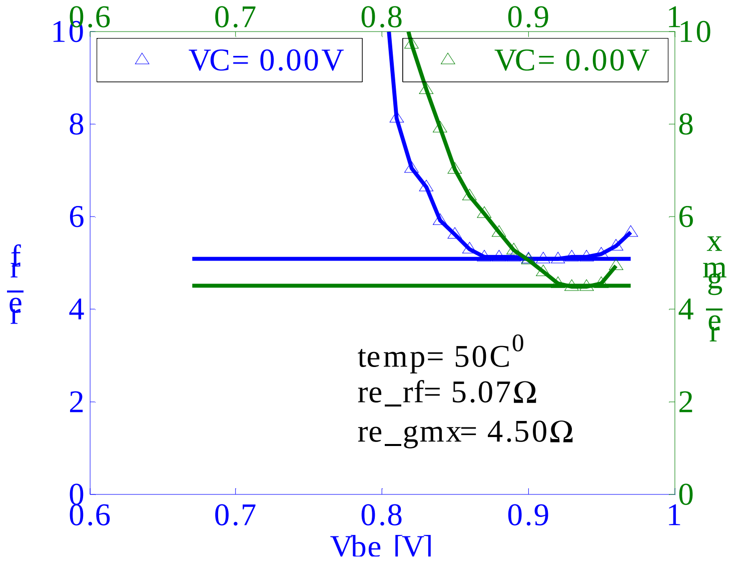
Le=5um, We=0.27um, Tamb=50 … 125C^0

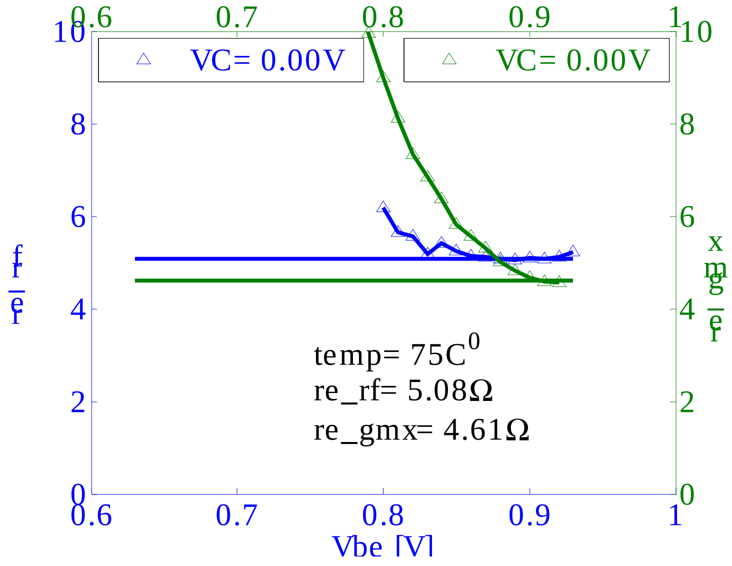


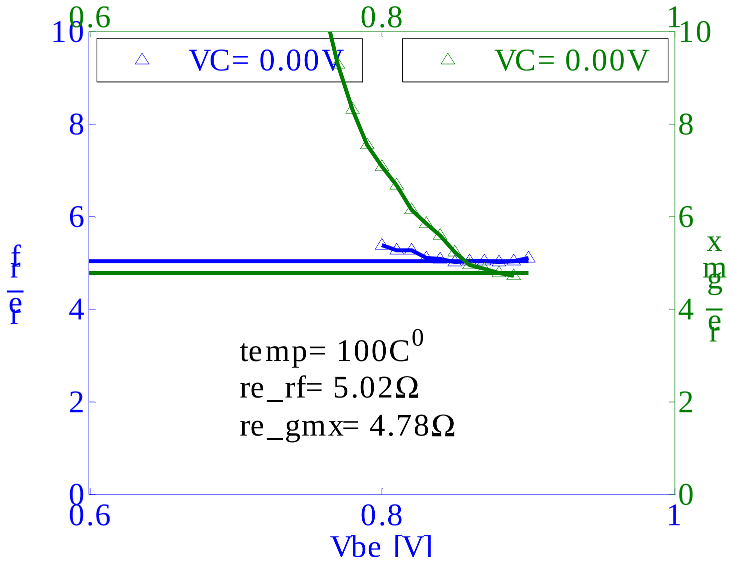
Le=3um, We=0.27um, Tamb=-40 … 27C⁰

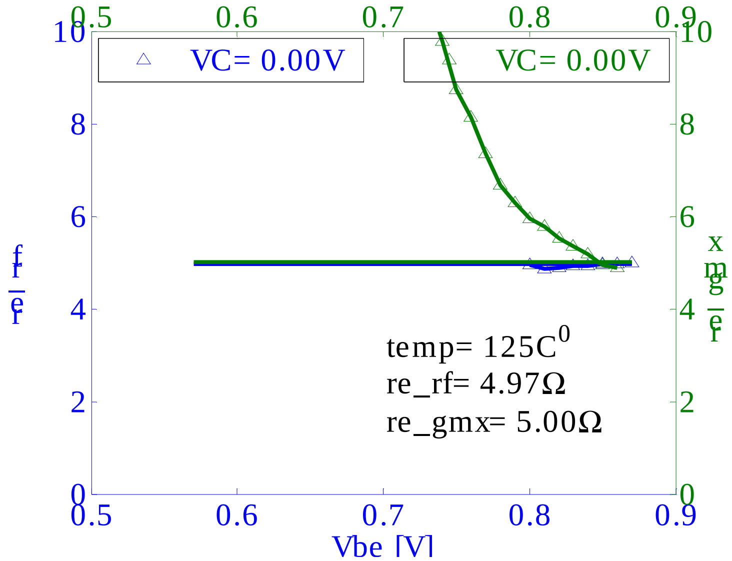


Le=3um, We=0.27um, Tamb=50 … 125C⁰

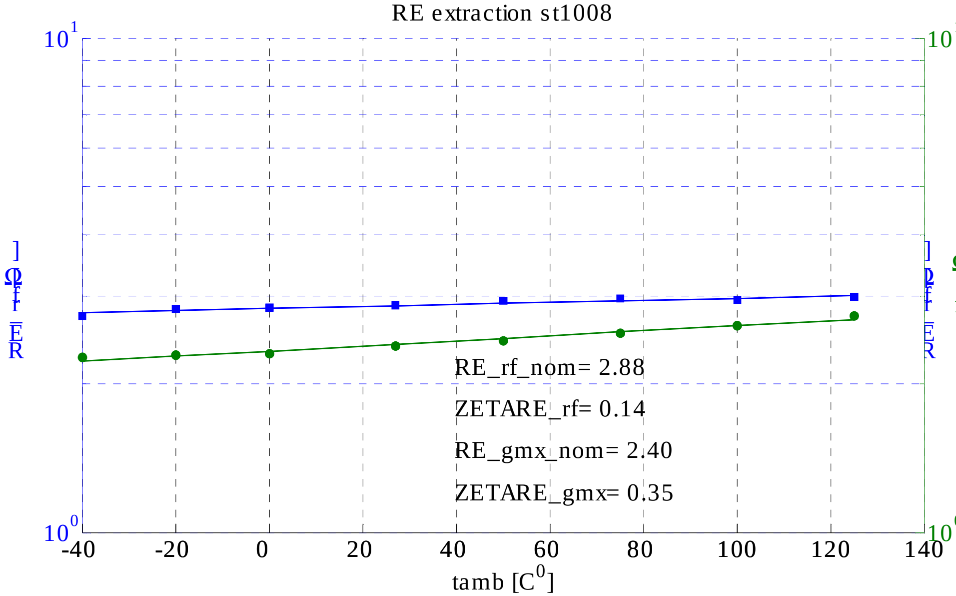


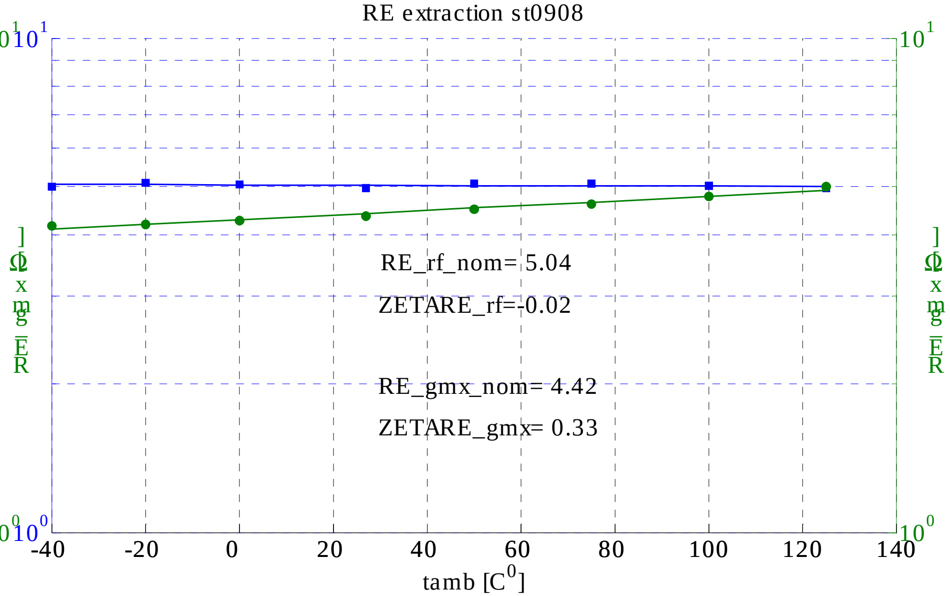






Temperature dependence and scaling





Le=5um, We=0.27um

re_rf_scaled =2.88*5=**14.40 Ω*um**

re_gmx_scaled =2.40*5=**12.00 Ω*um**

Le=3um, We=0.27um

re_rf_scaled =5.04*3=**15.12 Ω*um**

re_gmx_scaled =4.42*3=**13.26 Ω*um**

The gmx method results in smaller RE and a larger temperature dependence.

Summary

- an improvement of the gmx method has been suggested
- the proposed novel RF method is practically free of neglections
- the same RF data is shared what is necessary anyway for the extraction the transit time parameters
- temperature measurements showed slightly positive temperature coefficients
- the gmx method provides consistently smaller RE values

Acknowledgements

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References

[1] D. Berger, “Etude et validation d’un modele de transistor bipolare dedie aux applications haute frequences,” *PhD Theses,* 14 June 2004, L’Universite Bordeaux I, France

[2] Z. Huszka, E. Seebacher and W. Pflanzl, “An Extended Two-Port Method for the Determination of the Base and Emitter Resistance,” IEEE BCTM2005, 11.3

[3] Z. Huszka, E. Seebacher and W. Pflanzl, „Joint Extraction of the Base and Collector Resistances with the Base-Collector Capacitance Split of HBT/BJT Transistors,“ IEEE BCTM2006, 5.4