7th HICUM Workshop 2007

A new transit time extraction algorithm based on matrix deembedding techniques

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Introduction

- **T_F importance:**
  - T_F physical information from S parameters
  - T_F necessary to extract all high injection model parameters
  - T_F more convenient than using F_T (Effects of transit time and capacitances decoupled)
  - Less computational effort for extraction / optimization

- **Brief review of a few existing methods:**
  - Conventional method based on $1/(2.\pi.F_T)$
  - Methods based on de-embedding techniques

- **Objective:**
  - Accurate transit time extraction including the saturation at high injection
  - Focus on the deep saturation region especially for advanced BiCMOS technologies
  - Figures of merit to help improve extraction strategy (e.g. T_{BVL} & D_{T0H} extraction, capacitance behavior in the forward region)

Outline

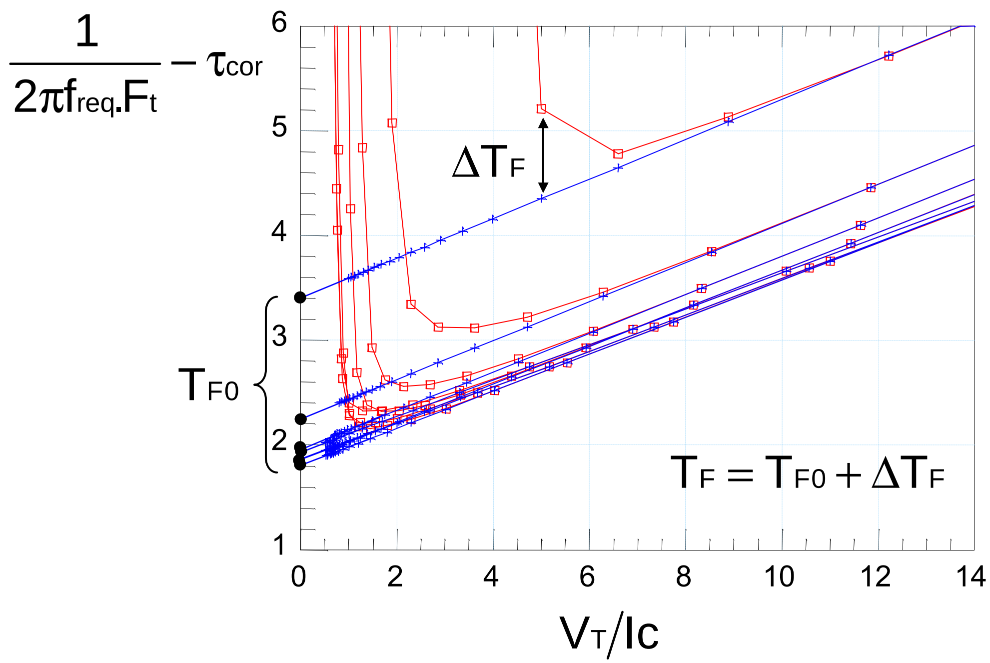
- I – State of art
- II – Improved Transit time extraction method
- III – Extraction Results
- IV - Conclusion

I – State of art

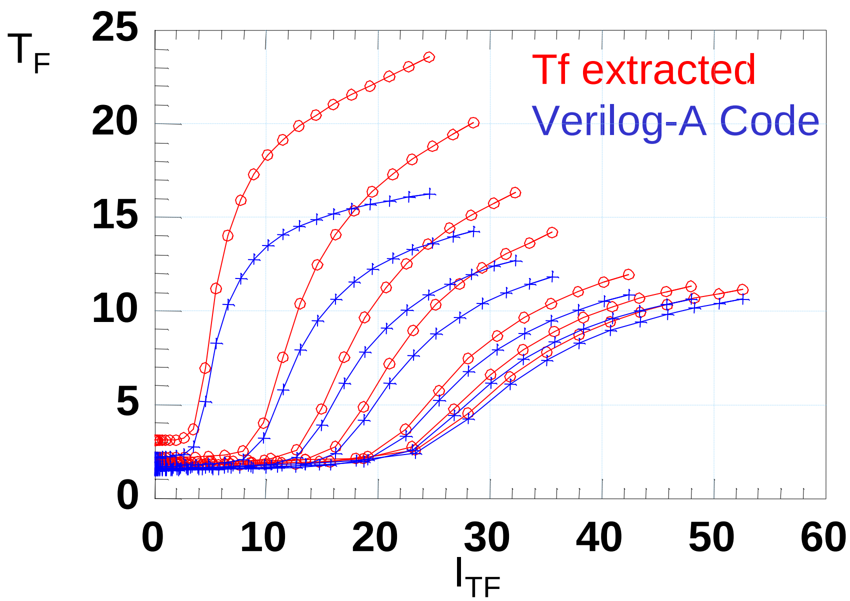
Conventional method: tangent method

$$\frac{1}{2\pi f_{req}.F_t} - \tau_{cor} = T_F + \left(C_{BC}.\left(1+1/\beta_0\right) + C_{BE}\right).\frac{1}{g_m} \quad \text{with} \quad g_m \approx \frac{Ic}{m_C.V_T}$$

$$\tau_{cor} = \left(r_E + r_{CX}\right).C_{BC}.\left(1+1/\beta_0\right)$$



Conventional method: tangent method



Vbc=0.6V, 0.4V, 0.2V, 0V, -0.5V, -1V, -1.5V

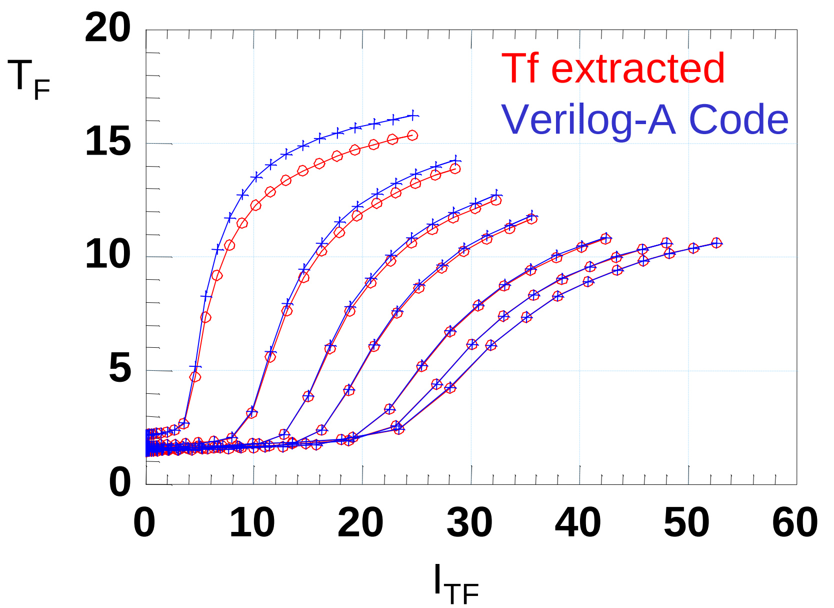
+ Robust at low injection, although it gives effective extracted parameters
- T_F extraction not accurate especially at high injection and in the saturation region
- Bad g_m approximation

M. Malorny, M. Schröter

“Analytical method for calculating elements of an arbitrary equivalent circuit”, MIXDES 2004, Poland, pp.79-84

Z. Huszka

“A Pragmatic Yet Accurate Transit Time Extraction Method for HICUM”, Private communication



Vbc=0.6V, 0.4V, 0.2V, 0V, -0.5V, -1V, -1.5V

2 Methods based on de-embedding techniques

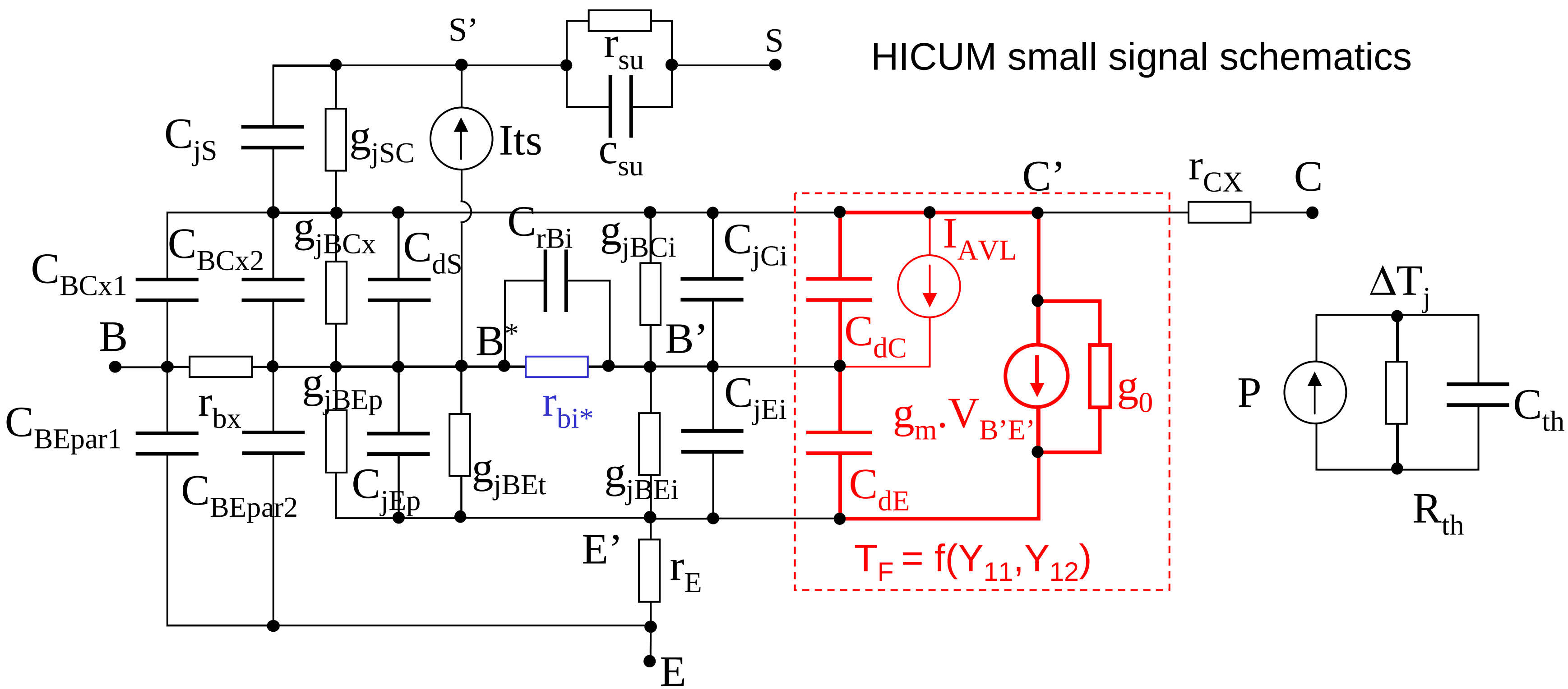
+ Good determination of g_m and g_0
+ Accurate T_F extraction

- The saturation involves a small error for the high injection region.
- Requires a very good accuracy of the capacitances C_{BE} and C_{BC}

The new suggested method is an improvement of this approach

II – Improved transit time extraction method

Strategy: Access to the T_F dependent main circuit



Access to the T_F dependent circuit by deembedding techniques requires to determine:

- The temperature
- The internal nodes
- Calculate all bias dependant components of the small signal circuit

II – Improved transit time extraction method

Approximation of the internal temperature

Approximation of the internal nodes B', B*, E', C', E', S'

Component calculation of the equivalent small signal circuit

↓

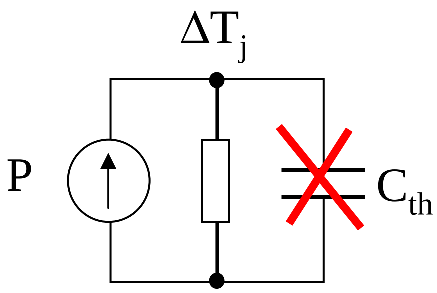
Full deembedding by matrix calculation

↓

Transit time extraction

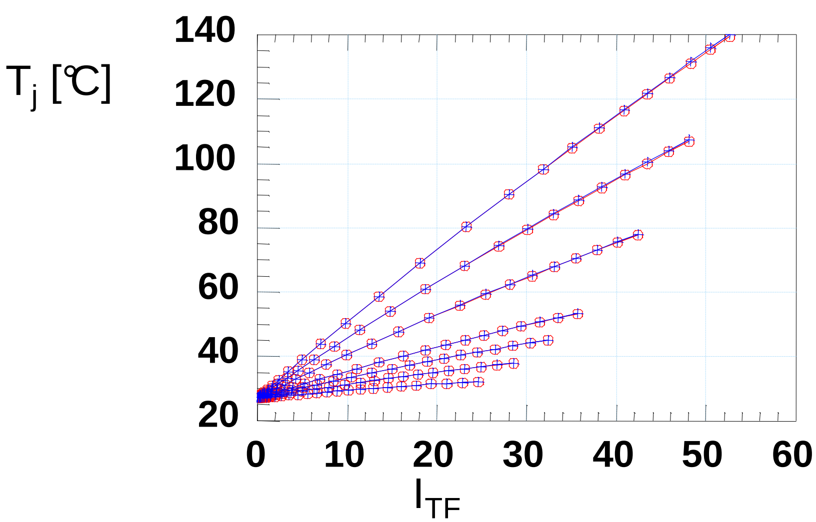
Temperature

Extraction from S-parameters measurement => Small signal => C_{th} could be neglected



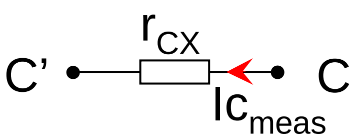
$T_j = T_{ambient} + P.R_{th}$

$F_{LSH}=0$	$P = Ic_{meas.}$
$F_{LSH}=1$	$P \approx Ic_{meas}.(V_{CE} - R_E.(Ic_{meas}+Ib_{meas}) - R_{CX}.Ic_{meas})$
$F_{LSH}=2$	$P_1 = Ib_{meas}.(V_{BE} - R_E.(Ic_{meas}+Ib_{meas}))$ $P_2 = Ic_{meas}.(V_{CE} - R_E.(Ic_{meas}+Ib_{meas}) - R_{CX}.Ic_{meas})$ $P_3 = R_E.(Ic_{meas}+Ib_{meas})^2$ $P \approx P_1 + P_2 + P_3$

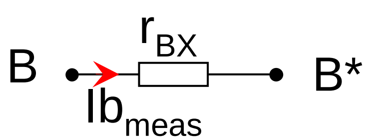


Temperature approximation
Verilog-A Code

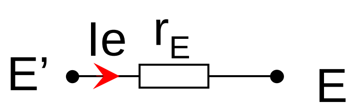
Approximation of the internal nodes



$V_{C'}=V_C-r_{CX}(T_j).Ic_{meas}$

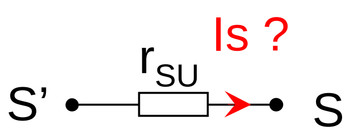


$V_B{*}=V_B-r_{BX}(T_j).Ib_{meas}$



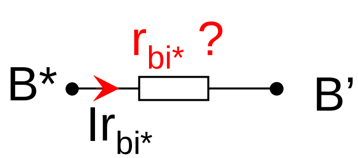
Ie≈ $Ib_{meas}+Ic_{meas}$ (Structure RF common emitter => Ie is not measured)

$V_{E'}=V_E+r_E(Tj).(Ib_{meas}+Ic_{meas})$



For V_{BC}<0.5V the substrate current (Is is not measured) is low ($V_{SS'}$ ≈0V).

$V_{S'}$ is assumed equal to V_S (involving an error on the calculation of $V_{S'C'}$ and $V_{S'B*}$)



$Ir_{bi*}=Ib_{meas}-I_{jBCx}-I_{jBEp}-I_{ts}-T_{UNODE}.I_{BEtp}$

$V_{B'}=V_{B*}-I_{rbi*}.r_{bi*}$

r_{bi*} calculated for a self-consistent algorithm

II – Improved transit time extraction method

Approximation of the internal temperature

Approximation of the internal nodes B’, B*, E’, C’, E’, S’

Component calculation of the equivalent small signal circuit

↓

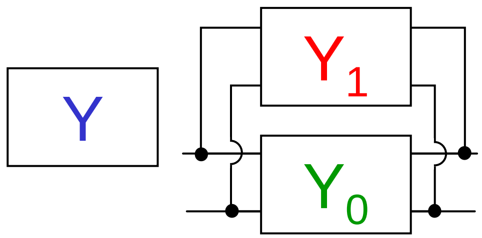
Full deembedding by matrix calculation

↓

Transit time extraction

Deembbedding

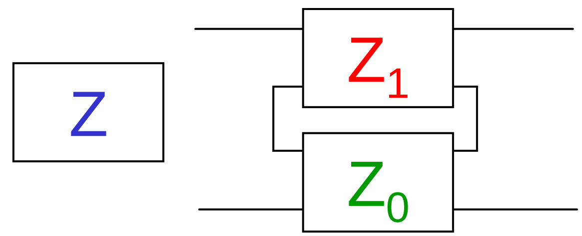
Y Matrix



$$[Y] = [Y_0] + [Y_1]$$

$$[Y_0] = [Y] - [Y_1]$$

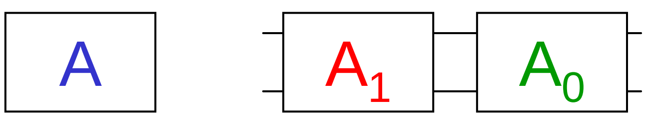
Z Matrix



$$[Z] = [Z_0] + [Z_1]$$

$$[Z_0] = [Z] - [Z_1]$$

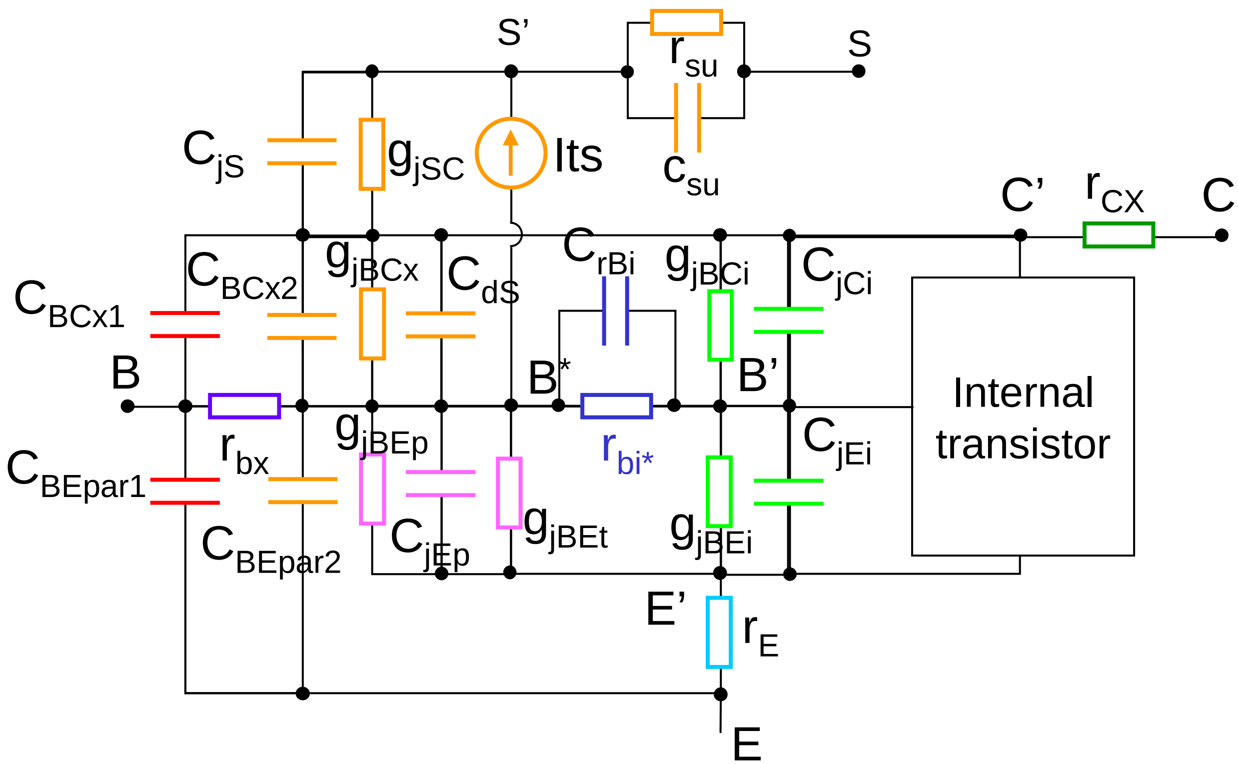
A Matrix



$$[A] = [A_1] \, . \, [A_0]$$

$$[A_0] = [A_1]^{-1} . [A]$$

Full deembedding



A Step1

Y Step2

A Step3

Y Step4

Z Step5

Y Step6

A Step7 **(*)**

Y Step8

(*) r_{bi*} is deembeded as a passive resistance (r_{bi*} is bias dependent)
Different approaches available to compute r_{bi*}: calculation, extraction, …

II – Improved transit time extraction method

Approximation of the internal temperature

Approximation of the internal nodes B’, B*, E’, C’, E’, S’

Component calculation of the equivalent small signal circuit

↓

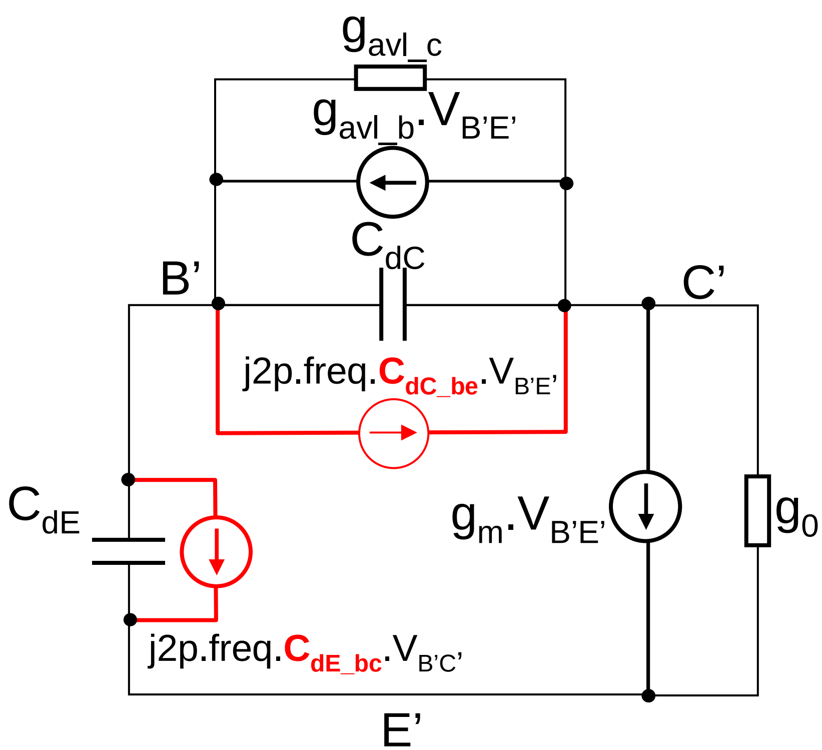
Full deembedding by matrix calculation

↓

Transit time extraction

Y matrix (from HICUM Verilog-A code)

$$\begin{bmatrix} g_{avl\_c} + g_{avl\_b} + 2\pi.f_{req}.\left(C_{dE} + C_{dE\_bc} + C_{dC\_be} + C_{dC}\right) & -g_{avl\_c} - j.2.\pi.f_{req}.\left(C_{dE\_bc} + C_{dC}\right) \\ g_m - g_{avl\_c} - g_{avl\_b} - j.2.\pi.f_{req}.\left(C_{dC} + C_{dC\_be}\right) & g_0 + g_{avl\_c} + j.2.\pi.f_{req}.C_{dC} \end{bmatrix}$$



$$\partial Q_f = C_{dE}.\partial V_{B'E'} + C_{dE\_bc}.\partial V_{B'C'}$$

$$\partial Q_r = C_{dC}.\partial V_{B'C'} + C_{dC\_be}.\partial V_{B'E'}$$

$$C_{dE} = \left.\frac{\partial Q_f}{\partial V_{B'E'}}\right|_{V_{B'C'}=cte} \qquad C_{dE\_bc} = \left.\frac{\partial Q_f}{\partial V_{B'C'}}\right|_{V_{B'E'}=cte}$$

$$C_{dC} = \left.\frac{\partial Q_r}{\partial V_{B'C'}}\right|_{V_{B'E'}=cte} \qquad C_{dC\_be} = \left.\frac{\partial Q_r}{\partial V_{B'E'}}\right|_{V_{B'C'}=cte}$$

g_m & g_0 determination

$$\begin{bmatrix} g_{avl\_c} + g_{avl\_b} + 2\pi.f_{req}.\left(C_{dE} + C_{dE\_bc} + C_{dC\_be} + C_{dC}\right) & -g_{avl\_c} - j.2.\pi.f_{req}.\left(C_{dE\_bc} + C_{dC}\right) \\ g_m - g_{avl\_c} - g_{avl\_b} - j.2.\pi.f_{req}.\left(C_{dC} + C_{dC\_be}\right) & g_0 + g_{avl\_c} + j.2.\pi.f_{req}.C_{dC} \end{bmatrix}$$

$$g_m = R\left(Y_{21}\right) + R\left(Y_{11}\right)$$
$$g_0 = R\left(Y_{22}\right) + R\left(Y_{12}\right)$$

$R(Y_{11})$ and $R(Y_{12})$ are too noisy and sensitive to the deembedding and the measurement accuracy. In general $|g_m| >> |g_{avl\_b} + g_{avl\_c}|$ and $|g_0| >> |g_{avl\_c}|$ then g_{avl_b} and g_{avl_c} could be neglected:

$$g_m \approx R\left(Y_{21}\right)$$
$$g_0 \approx R\left(Y_{22}\right)$$

N.B.: Another solution is to determine a self-consistent expression for g_0 and g_m using:

$$g_{avl\_b} = -K_{avl}.\left(g_m + g_0\right)$$
$$g_{avl\_c} = -K_{avl}.g_0 + g_a$$

C_{dC_be} negligible

$$\frac{imag(Y_{11})}{j.2.\pi.f_{req}} = C_{dE} + C_{dE\_bc} + C_{dC} + C_{dC\_be}$$

Rigorously $C_{dC\_be} = imag(Y_{21})/(j.2.\pi.f_{req}) - imag(Y_{22})/(j.2.\pi.f_{req})$

However imag(Y_{22}) is too sensitive to the substrate network, moreover C_{dC_be} is low for V_{BC}<0.7V, then practically C_{dC_be} is negligible.

$$\frac{imag(Y_{11})}{j.2.\pi.f_{req}} \approx C_{dE} + C_{dE\_bc} + C_{dC}$$

T_F from Imag(Y_{11})

$$\frac{imag(Y_{11})}{j.2.\pi.f_{req}} \approx C_{dE} + C_{dE\_bc} + C_{dC}$$

$$\begin{cases} C_{dE} = \left.\frac{\partial Q_F}{\partial V_{B'E'}}\right|_{V_{B'C'}, I_{TF}} + \left.\frac{\partial I_{TF}}{\partial V_{B'E'}}\right|_{V_{B'C'}} . \left.\frac{\partial Q_F}{\partial I_{TF}}\right|_{V_{B'C'}} = \left.\frac{\partial Q_{FF}}{\partial V_{B'E'}}\right|_{V_{B'C'}, I_{TF}} + (g_m + g_0).T_F \\ C_{dE\_bc} = \left.\frac{\partial Q_F}{\partial V_{B'C'}}\right|_{V_{B'E'}, I_{TF}} + \left.\frac{\partial I_{TF}}{\partial V_{B'C'}}\right|_{V_{B'E'}} . \left.\frac{\partial Q_f}{\partial I_{Tf}}\right|_{V_{B'E'}} = \left(I_{TF}.\frac{dT_{f0}}{dV_{B'C'}} + \left.\frac{\partial Q_{FF}}{\partial V_{B'C'}}\right|_{V_{B'E'}, I_{TF}} \right) - g_0.T_F \end{cases}$$

$$\left.\frac{\partial Q_{FF}}{\partial V_{B'E'}}\right|_{V_{B'C'}, I_{TF}} = -\left.\frac{\partial Q_{FF}}{\partial V_{B'C'}}\right|_{V_{B'E'}, I_{TF}} \Rightarrow \frac{imag(Y_{11})}{j.2.\pi.f_{req}} \approx g_m.T_F + I_{TF}.\frac{dT_{F0}}{dV_{B'C'}} + C_{dC}$$

$$T_f \approx \frac{1}{g_m}.\left(\frac{imag(Y_{11})}{j.2.\pi.f_{req}} - C_0 \right)$$

$$C_0 = I_{TF}.\frac{dT_{f0}}{dV_{B'C'}} + C_{dC}$$

Determination of C_0 from Imag(Y_{12}) at low injection

$$-\frac{\mathrm{imag}(Y_{12})}{j.2.\pi.f_{req}} = C_{dE\_bc} + C_{dC} = \left(I_{TF}.\frac{dT_{f0}}{dv_{B'C'}} + \left.\frac{dQ_{FF}}{dv_{B'C'}}\right|_{\substack{V_{B'E'} \\ I_{TF}}} \right) - g_0.T_F + C_{dC}$$

For the **low injection** region:

$$\left.\frac{\partial Q_{FF}}{\partial v_{B'C'}}\right|_{\substack{V_{B'E'} \\ i_{TF}}} \approx 0 \qquad \text{and} \qquad g_0.T_F \approx 0$$

Therefore:

$$-\frac{\mathrm{imag}(Y_{12})}{j.2.\pi.f_{req}} = C_{dE\_bc} + C_{dC} \approx I_{TF}.\frac{dT_{f0}}{dv_{B'C'}} + C_{dC} = C_0$$

At **low injection** region (before the Ft peak):

$$C_0 \approx -\frac{imag(Y_{12})}{j.2.\pi.f_{req}}$$

Determination of C_0 from Imag(Y_{12}) at high injection

At **low injection** and **V_{BC}<0.4V** $C_{dc}\approx 0$, then:

$$-\frac{\text{imag}(Y_{12})}{j.2.\pi.f_{req}} \approx I_{TF}.\frac{dT_{f0}}{dv_{B'C'}} + C_{dC} \approx I_{TF}.\frac{dT_{f0}}{dv_{B'C'}}$$

$$-\frac{\text{imag}(Y_{12})}{j.2.\pi.f_{req}.I_{TF}} \approx \frac{dT_{f0}}{dv_{B'C'}} = D_{T0H}.\frac{dc}{dv_{B'C'}} + T_{BVL}.\frac{1}{C_{jci0}(T_j)}.\frac{d(C_{jci}(T_j))}{dv_{B'C'}}$$

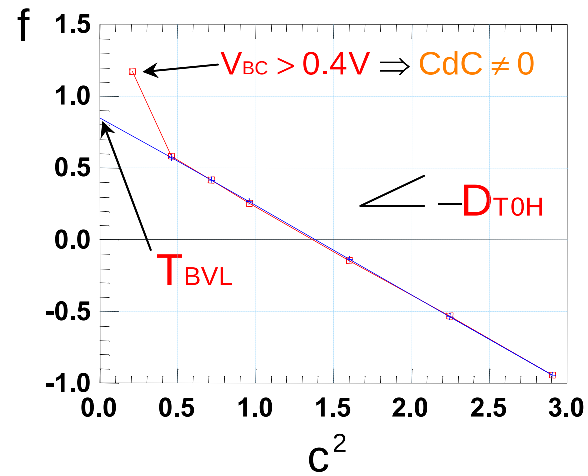
$$c = C_{jci0}(T_j)/C_{jci}(T_j)$$

$$T_{f0} = T_0 + D_{T0H}.(c-1) + T_{BVL}.\left(\frac{1}{c}-1\right)$$

$$\frac{dc}{dv_{B'C'}} = -\frac{c^2}{Cjci0(Tj)}.\frac{d(C_{jci}(T_j))}{dv_{B'C'}}$$

T_{BVL} and D_{T0H} are extracted from a linear regression:

$$f = \left(-\frac{\text{imag}(Y_{12})}{j.2.\pi.f_{req}.I_{TF}}\right).\frac{C_{jci0}(T_j)}{\frac{d(C_{jci}(T_j))}{dv_{B'C'}}} = T_{BVL} - c^2.D_{T0H}$$

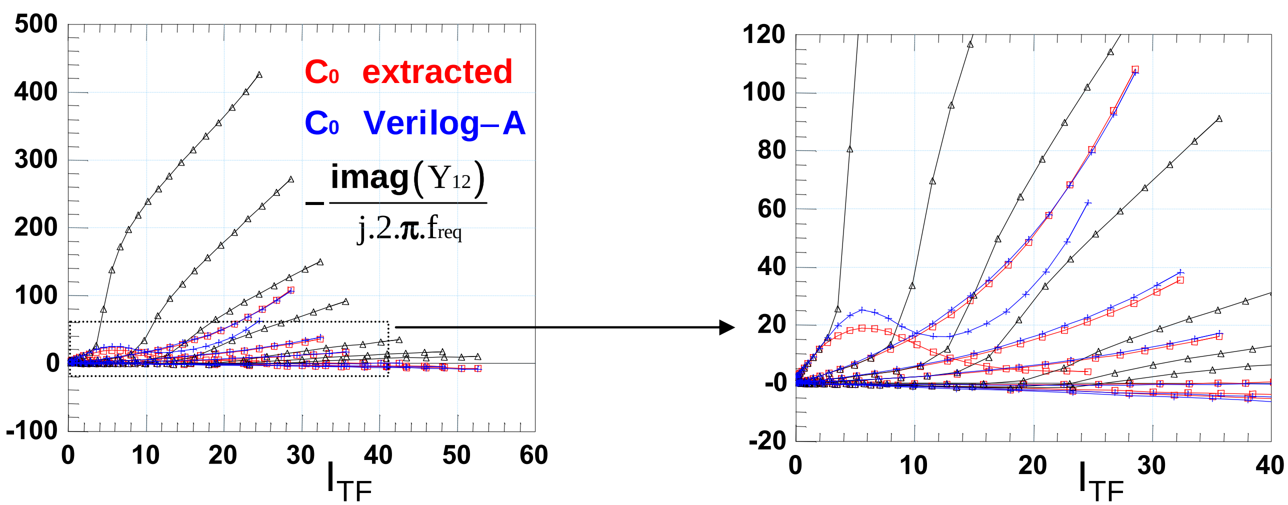


Determination of C_0 from Imag(Y_{12}) at high injection

For the high injection region (after the Ft peak):

$$C_0 = I_{TF}.\left(D_{T0H}.\frac{dc}{dv_{B'C'}} + T_{BVL}.\frac{1}{C_{jci0}(T_j)}.\frac{d\left(C_{jci}(T_j)\right)}{dv_{B'C'}}\right)\Bigg|_{calc} + C_{dC}^*$$

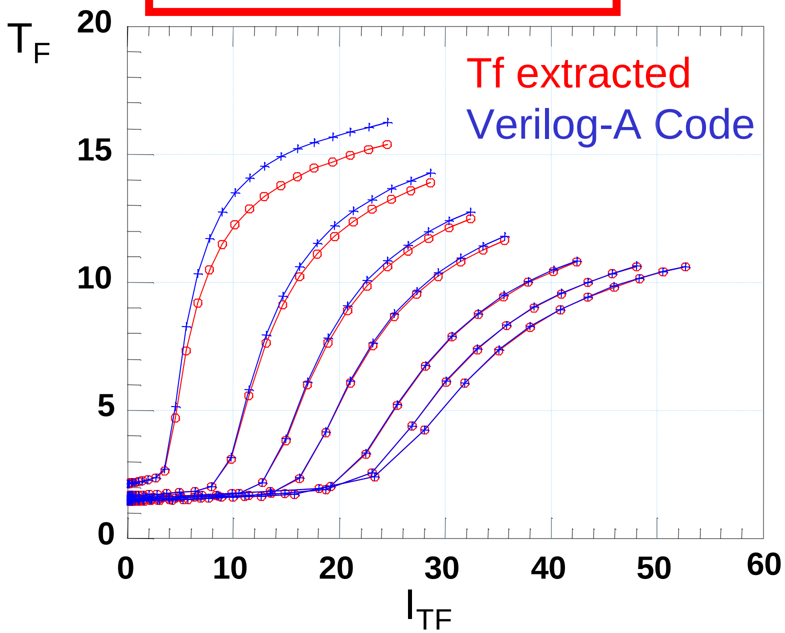
$$C_{dC}^* = -\frac{imag(Y_{12})}{j.2.\pi.f_{req}}\Bigg|_{peak\,Ft} - \left(I_{TF}.\left(D_{T0H}.\frac{dc}{dv_{B'C'}} + T_{BVL}.\frac{1}{C_{jci0}(T_j)}.\frac{d\left(C_{jci}(T_j)\right)}{dv_{B'C'}}\right)\Bigg|_{calc}\right)\Bigg|_{peak\,Ft}$$

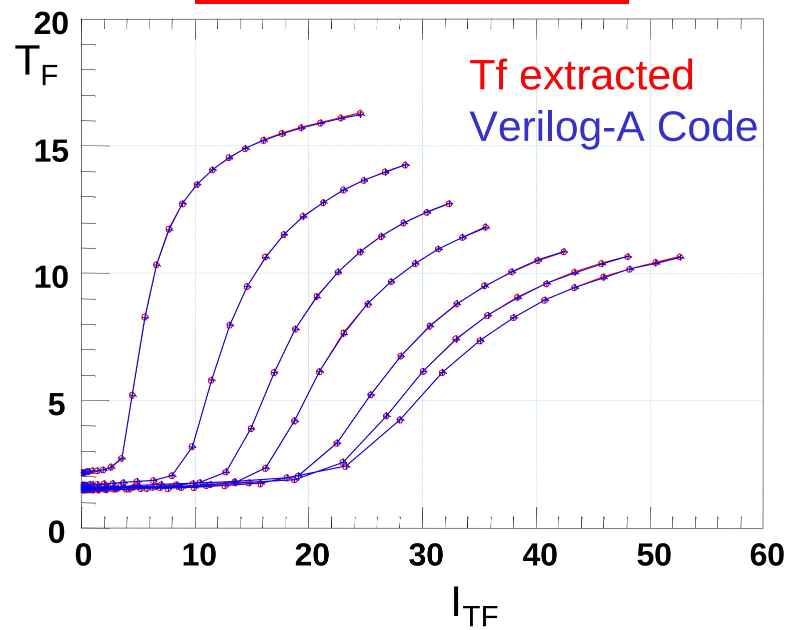


Real improvement

$$T_f \approx \frac{imag(Y_{11}+Y_{12})}{j.2.\pi.f_{req}.g_m}$$

$$T_f \approx \frac{imag(Y_{11})}{j.2.\pi.f_{req}.g_m} - \frac{C_0}{g_m}$$





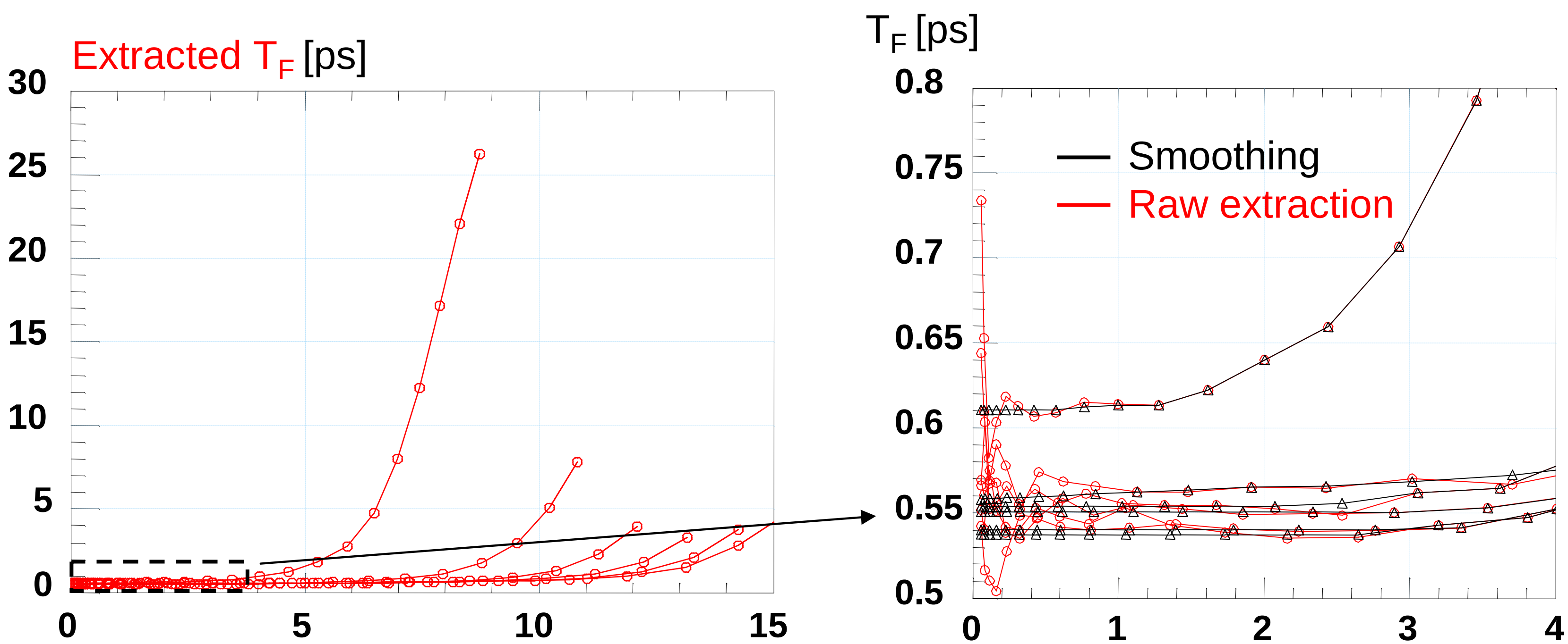
- Without C_0 the result is the same as the Malorny/Shröter and Huszka methods
- Full matrix deembedding convenient but actually not necessary
- Real improvement: T_{BVL} & D_{T0H} extraction and dT_{F0} calculation (C_0).

II – Extraction Results

Application on measurement

BICMOS9 W_E=0.3µm, L_E=3.70µm

Final transit time extraction

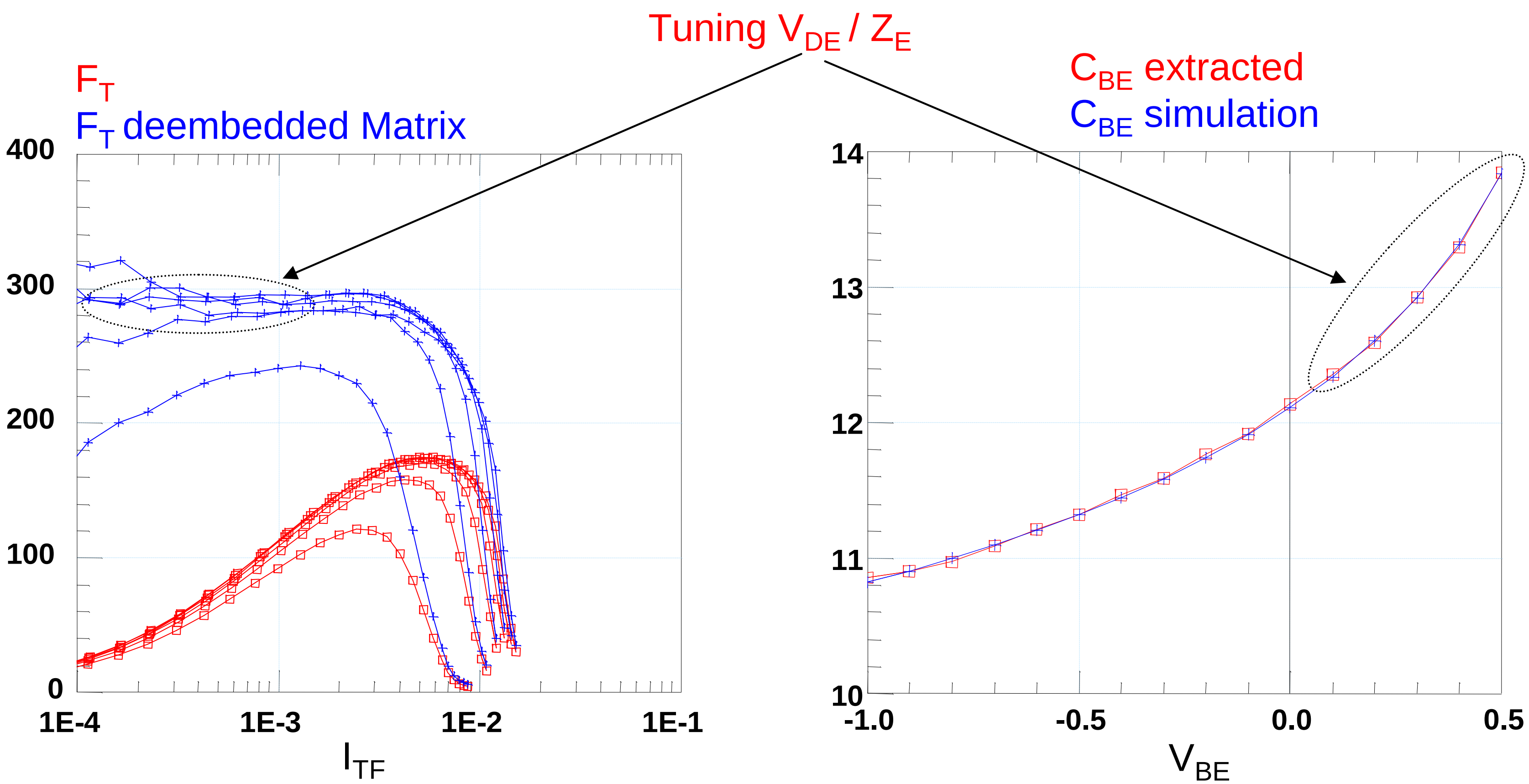


ST-BICMOS9 technology (0.13µm) : F_T = 160 GHz, F_{max} = 160 GHz

Application on measurement

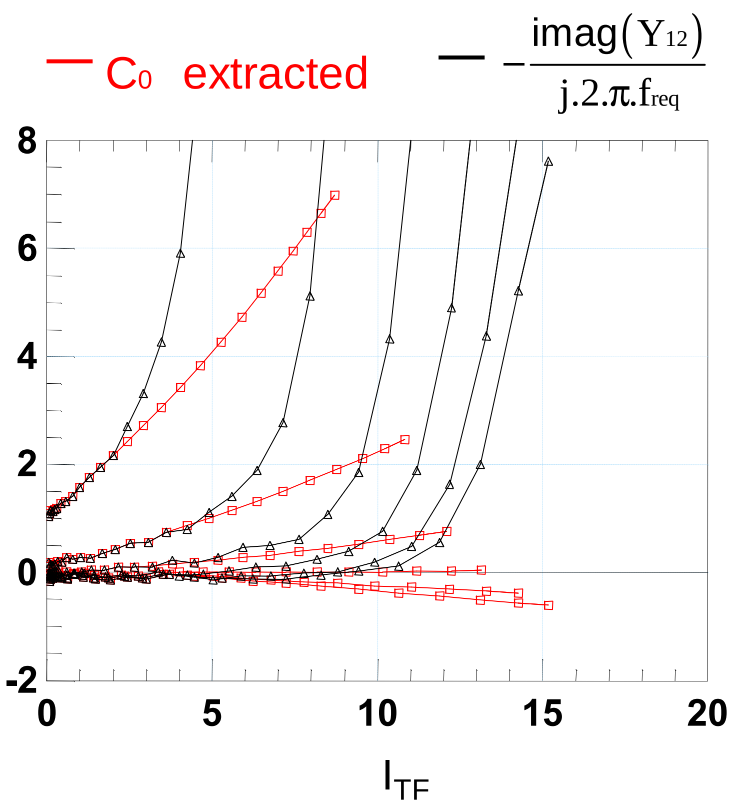
BICMOS9 W_E=0.3µm, L_E=3.70µm

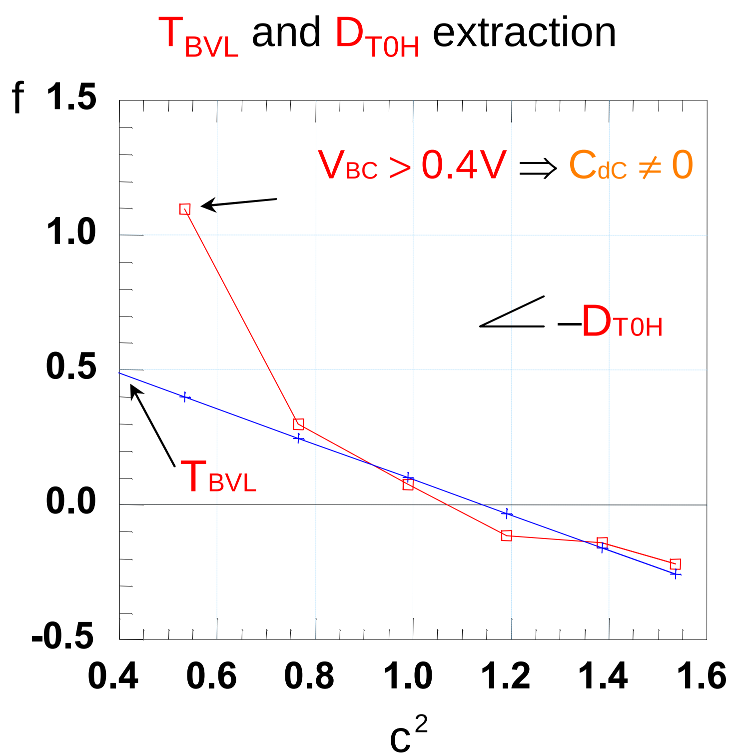
Base-emitter capacitance correction



Application on measurement

BICMOS9 W_E=0.3µm, L_E=3.70µm



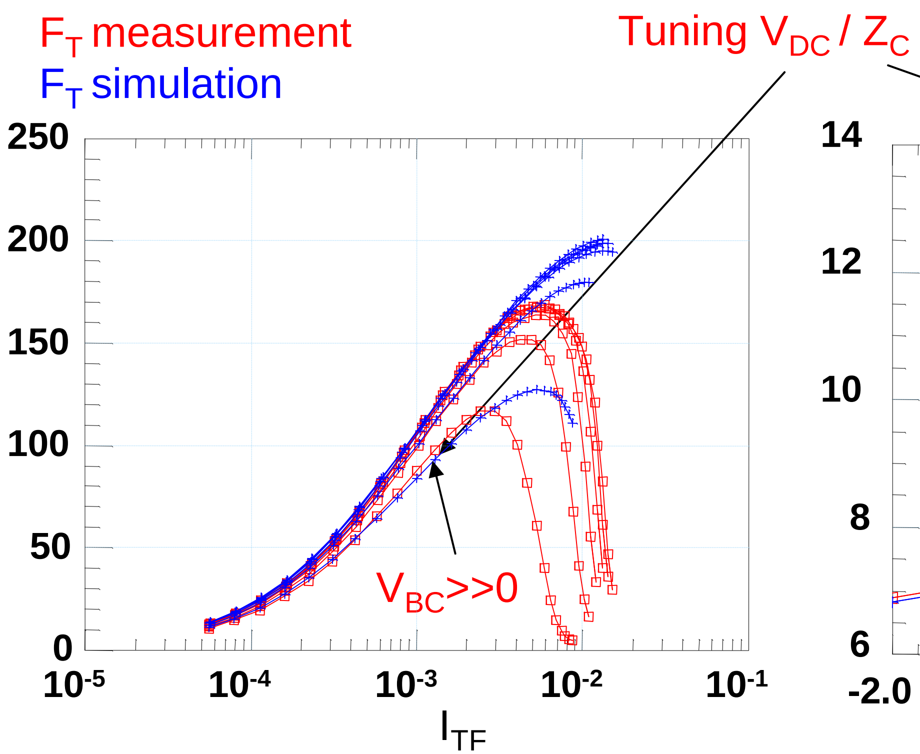


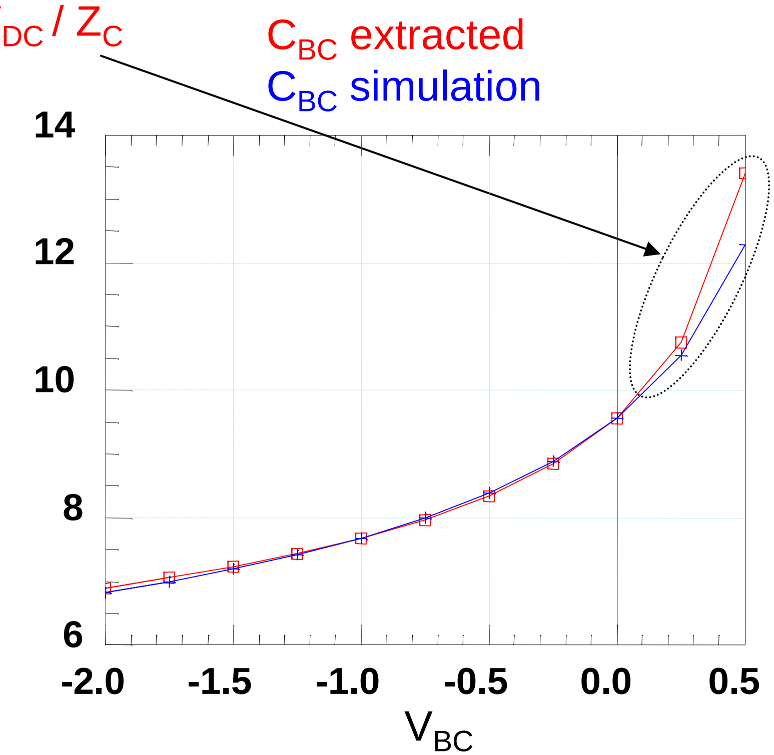
Application on measurement

BICMOS9 W_E=0.3µm, L_E=3.70µm

Base-Collector capacitance correction

C_{BC} parameters **not** enough accurate for V_{BC}>0





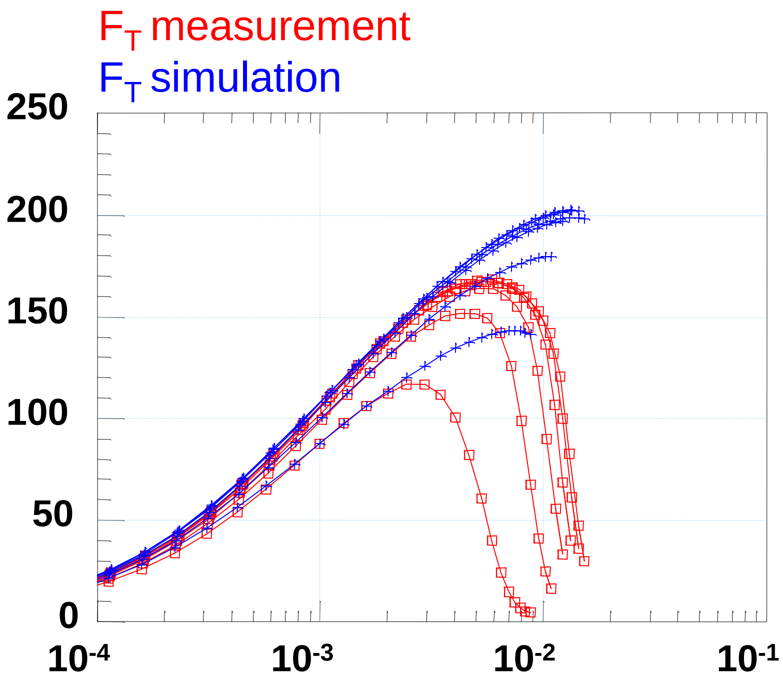
After direct T_{BVL} & D_{T0H} extraction

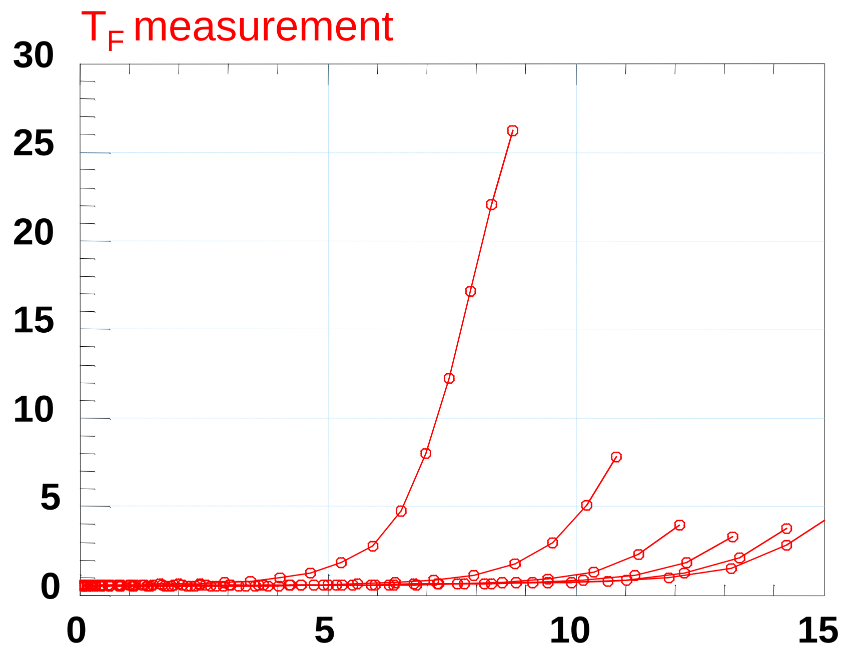
State of art | Method | Result

Application on measurement

BICMOS9 W_E=0.3µm, L_E=3.70µm

Final transit time extraction





IV – Conclusion

Conclusion

- **Highly accurate T_F extraction method including the saturation region**
  - Better approximation of T_F (better than $C_{dE} = g_m.T_F$)
  - Full matrix deembedding convenient but not necessary

- **T_{BVL} & D_{T0H} extraction from Y_{12}**
  - Extraction using a linear regression
  - Method mainly sensitive to the well known C_{BC} capacitance only

- **Capacitance parameters optimization in forward mode**
  - FOM: deembeded F_T after matrix deembedding
  - Capacitance optimization without modifying the capacitance in reverse mode

- **New approach for r_{bi*} extraction (Not presented):**
  - rbi* extraction less sensitive to the avalanche phenomenon