Normalized HICUML2 and new Advancements in TF Extraction

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Overviwev

I. Normalized Parameters

- MATLAB environment allows to use characterization friendly parameter alternatives
- Unofficial yet but preserves 100% model compatibility

II. TF: the Ultimate Cornerstone of HICUM Modeling

- Overwiev of the present TF determination methods
- An exact and robust novel TF extraction scheme
- The „in-situ“ determination of the *CJE* parameters
- A new automated extraction method for I_{ck}

Overdetermination at Low Currents

$$I_T = \frac{C_{10} \cdot \left[\exp\left(\frac{V_{b'e'}}{V_T}\right) - \exp\left(\frac{V_{b'c'}}{V_T}\right)\right]}{Q_{p0} + h_{jei} \cdot Q_{jei} + h_{jci} \cdot Q_{jci} + Q_F} \quad \text{low bias} \Rightarrow \frac{C_{10} \cdot \exp\left(\frac{V_{b'e'}}{V_T}\right)}{Q_{p0} + h_{jei} \cdot Q_{jei} + h_{jci} \cdot Q_{jci}}$$

The redundancy is even more obvious from:

$$I_T \approx \frac{Q_{p0} \cdot \left(\frac{C_{10}}{Q_{p0}}\right)}{Q_{p0} \cdot \left(1 + \frac{h_{jei} \cdot Q_{jei}}{Q_{p0}} + \frac{h_{jci} \cdot Q_{jci}}{Q_{p0}}\right)} \exp\left(\frac{V_{b'e'}}{V_T}\right)$$

Q_{p0} unnecessarily links the high and low ranges making the direct extraction of *hjei* and *hjci* an iterative process

The *hjei, hjci, qp0* problem has been a permanently recurrent issue on HICUM and BIPAK WS-s [1,2,6]

Trick of Gummel&Poon: Normalization

$$I_T = \frac{IS \cdot \left[\exp\left(\frac{V_{b'e'}}{V_T}\right) - \exp\left(\frac{V_{b'c'}}{V_T}\right) \right]}{1 + \frac{q_{jei}}{VER} + \frac{q_{jci}}{VEF} + \frac{Q_F}{Q_{p0}}} \quad \text{low bias} \Rightarrow \frac{IS \cdot \left[\exp\left(\frac{V_{b'e'}}{V_T}\right) - \exp\left(\frac{V_{b'c'}}{V_T}\right) \right]}{1 + \frac{q_{jei}}{VER} + \frac{q_{jci}}{VEF}}$$

VBIC notations

$$is = \frac{c_{10}}{Q_{p0}} \quad \Leftrightarrow \quad c_{10} = is \cdot Q_{p0}$$

Available in L0 and L2

$$vef = \frac{Q_{p0}}{hjci \cdot C_{jci0}} \quad \Leftrightarrow \quad hjci = \frac{Q_{p0}}{vef \cdot C_{jci0}}$$

Available in L0

$$ver = \frac{Q_{p0}}{hjei \cdot C_{jei0}} \quad \Leftrightarrow \quad hjei = \frac{Q_{p0}}{ver \cdot C_{jei0}}$$

Neither L0 (why?) nor L2

Equivalent forms bearing the same „PHYSICALITY“

Extract *tf0* and *Cje* with the new method first to get rid of the unwanted influence of an incorrect *ajei* !

Avalanche

$$I_{AVL} = I_{Tf} \cdot f_{AVL} \cdot V_{DCi} \cdot c^{1/zci} \cdot \exp\left(\frac{q_{AVL}}{C_{jci0} \cdot V_{DCi} \cdot c^{1/zci}} \right)$$

Normalized MATLAB parameters:

$$\left.\begin{aligned} \text{favln} &= f_{AVL} \cdot V_{DCi} \\ \text{qavln} &= \frac{q_{AVL}}{C_{jci0} \cdot V_{DCi}} \end{aligned}\right\}$$

Available in L0 as k_{AVL}, e_{AVL}

(rename *favln, qavln* later)

Normalization has been fully adapted in L0, partially in L2 (*IS*). Full official L2 adaptation could make low-medium DC modeling as easy as in SGP or VBIC

Conveniency Option for Peripheral EB

There are 8 *front* IBE parameters in L2:

ibeis, mbei, ireis, mrei, cjei0, vdei, zei, ajei

plus 8 for emitter *periphery* DIODE (no transistor action).

16 parameters is absolutely redundant

In practice many of them are inactive or estimated.

MATLAB option: 8 front and one ratio parameter

$$cjep0 = \mathrm{kperi} \cdot (cjei0 + cjep0); \quad 1 \geq \mathrm{kperi} \geq 0$$

$$ibeps = ireps = 0; \quad [vdep, zep, ajep] = [vdei, zei, ajei]$$

kperi<0 defaults to original model

Fine tuning parameter leaving *CJETOT* unchanged

Report: Low-Medium Bias Optimization

```
07-May-2007
D1DB12
extract low-medium bias parameters, startup skeleton card: hicumL2V2p23_c
Residual rms error: rms=[   2.48462   1.70301   1.33014  36.16915] %
Run time: 8.800940e+002 sec

DCM1D@fgs (dchsim.m over Custom_4)
ibeis; mbei; ireis; is; ver; vef;
DCAVL@fgs (dchsim.m over Custom_5)
favln; qavln;
DCM2D@fgs (dchsim.m over Custom_6)
ibeis; mbei; ireis; is; ver; vef; favln; qavln;
DCEXT@fgs (dchsim.m over full)
dummy;
%-------------------------Modified settings to (default)-------------------------
 addGmin=0;
(addGmin=1;  %adds Gmin to branches (bi,ei) and (bi,ci))
%-------------------------End of modified settings----------------------
```

L-M Bias Optimization: Result File Detail

NPN121_12

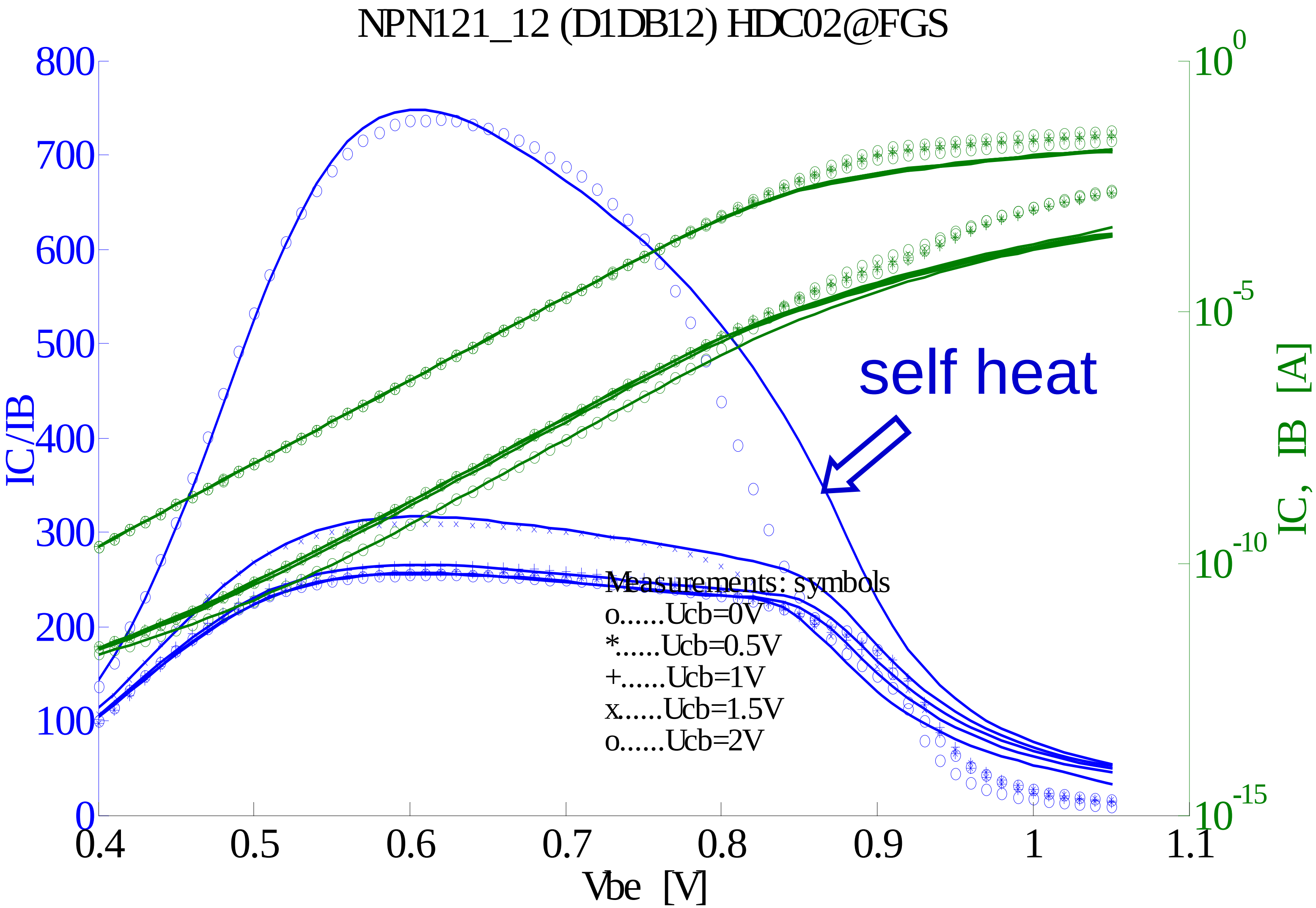
C10	3.152e-31	TSF	1.000e-11	ALQF	2.250e-01
HJEI	6.309e+00	RSU	1.000e+01	ALIT	4.500e-01
HJCI	1.038e+00	CSU	0.000e+00	FLNQS	0.000e+00
QP0	2.780e-14	CJEI0	2.966e-15	KF	1.430e-08
ICH	2.090e-02	VDEI	1.000e+00	AF	2.000e+00
HFE	1.000e+00	ZEI	4.000e-01	CFBE	-2.000e+00
HFC	1.000e+00	AJEI	2.800e+00	LATB	0.000e+00
:::::::::	:::::::::	:::::::::	:::::::::	:::::::::	:::::::::
FAVL	6.022e+00	VPTS	1.000e+02	ZETACT	3.500e+00
QAVL	1.604e-15	T0	1.500e-13	ZETABET	4.000e+00
:::::::::	:::::::::	:::::::::	:::::::::	:::::::::	:::::::::
FQI	1.000e+00	RCI0	8.000e+02	VERSION	2.230e+00
RE	3.317e+01	VLIM	7.000e-01	IS	1.134e-17
RCX	2.437e+02	VCES	1.000e-01	VER	1.486e+00
ITSS	8.694e-19	VPT	5.000e+00	VEF	2.677e+02
MSF	1.014e+00	TR	0.000e+00	FAVLN	5.420e+00
ISCS	1.000e-18	CBEPAR	1.000e-16	QAVLN	1.782e+01
MSC	1.000e+00	CBCPAR	2.000e-16		

May change during next extraction steps

QP0 is arbitrary (default) this phase

Stay invariant during next extraction steps

L-M Bias Optimization: Fit



VEF and AVL are correlated: a safe alternative to „physical“ extraction is OPTIMIZATION (1/4hrs here)

Overview of TF Extraction Methods, I.

$$\frac{1}{2\pi \cdot f_T} = \tau_f + \frac{C_{BC}\left(1+1/\beta_0\right)+C_{BE}}{gm} + (re+rcx)\cdot C_{BC}\cdot\left(1+1/\beta_0\right)$$

[4,5] are using equations from MAPLE analysis with **25** pre-determined parameters needed:

cjcx0, vdcx, zcx,vptcx, fbcpar, cbcpar, cbepar, fbepar, cjei0, vdei, zei, ajei, cjep0, vdep, zep, ajep, ajep, cjci0, vdci, zci, vptci, re, rcx, rbx, bias-dependent rbi,

- HICUM equations **FORCE** model to physical reality
- error propagation, remodeling at parameter change
- extremely complicated, starting formula is inaccurate

Overview of TF Extraction Methods, II.

$$\frac{1}{2\pi \cdot f_T} = \underbrace{\tau_f + (re + rcx) \cdot C_{BC}}_{t_1} + t_2 \cdot \frac{1}{I_C} + + t_3 \cdot \frac{1}{I_C} \cdot \ln\left(\frac{1}{I_C}\right)$$

[3] presents an analysis of the *TF* extraction problems. [8] is using the simplified equation above with the following 12 pre-determined parameters needed:

cjcx0, vdcx, zcx,vptcx, fbcpar, cbcpar, cjci0, vdci, zci, vptci, re, rcx

- effect of using 1/Ic instead of C/gm not analyzed
- optimal extraction range not advised
- details of extrapolation to zero undisclosed

It is a remarkable feature that the extraction problem has been reduced to a 3-variable regression

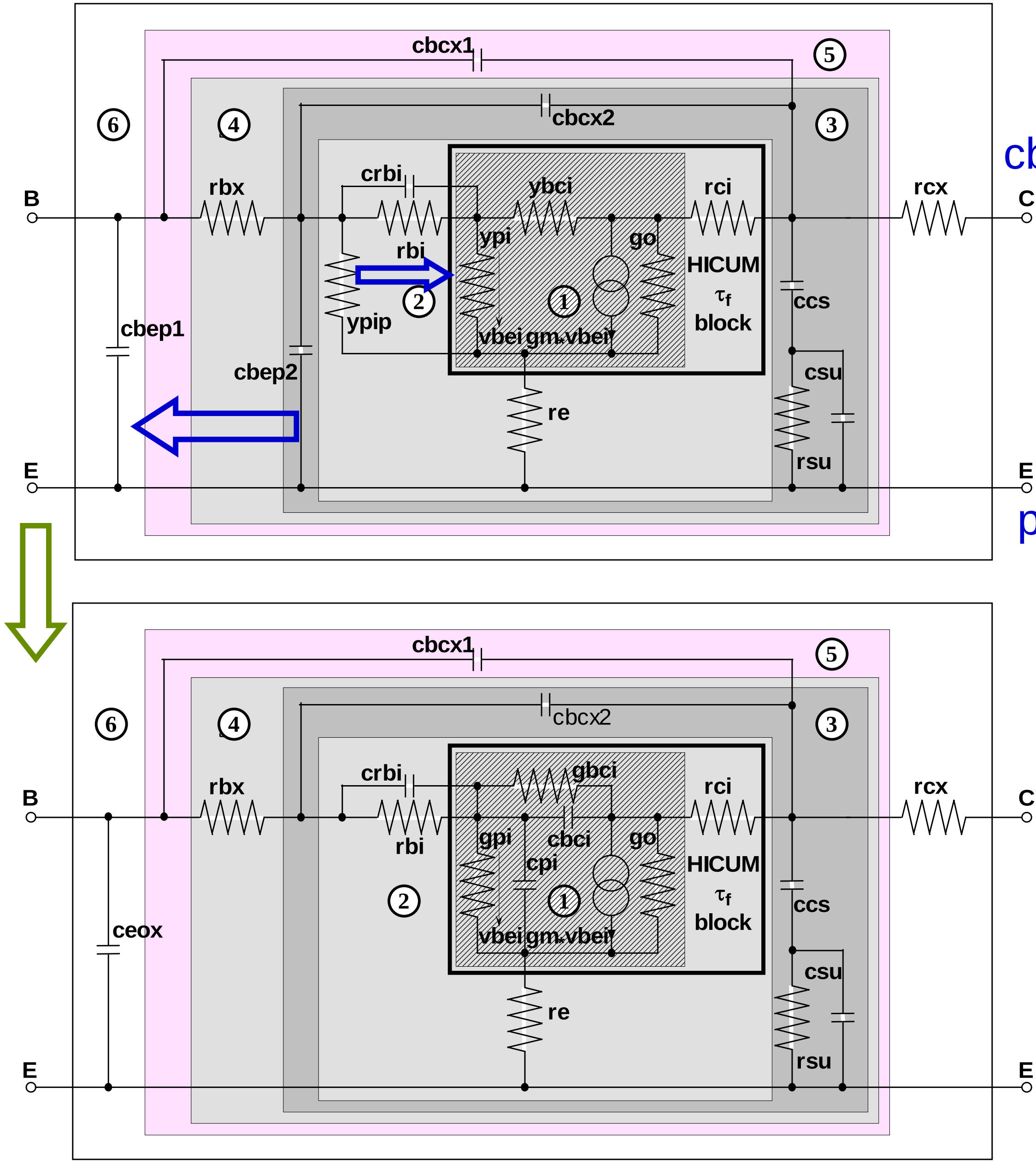
MOTTO

„Whenever you have to do with a structure-endowed entity Σ try to determine its group of automorphisms, the group of element-wise transformations which leave all structural relations undisturbed. You can expect to gain a deep insight into the constitution of Σ this way“

S. J. Mason, *„Power Gain in Feedback Amplifier,“* Transactions of the I. R. E., pp. 20-25, June 1954

The use of two such invariants ($\Im 1$, $\Im 2$) will be introduced and veryfied in this paper

New TF Extraction: equivalent circuit



simplification #1

cbep2 shited into cbep1 (fbepar=0)

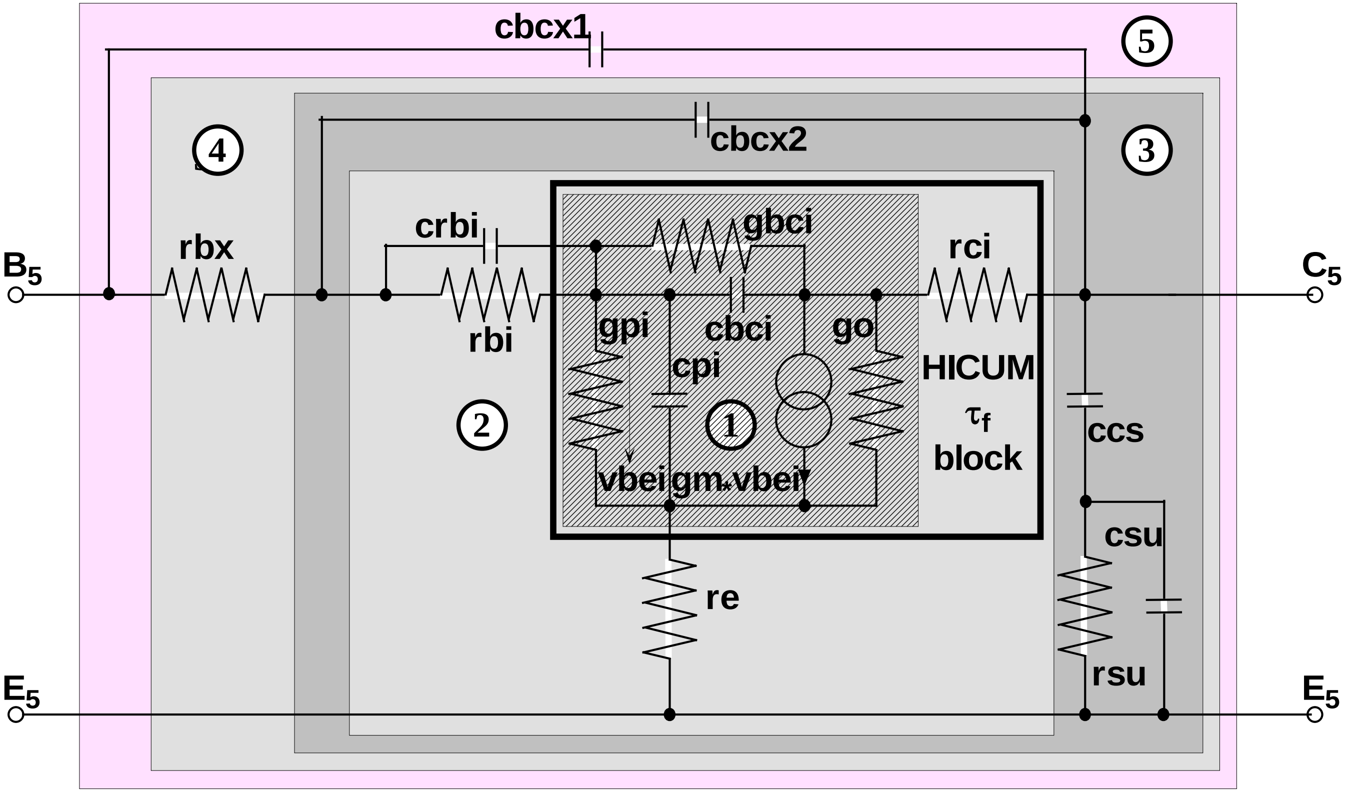
simplification #2

peripheral emitter shifted into front

Both moves are justified by the large impedance of *ceox* to *rbx* and *yp* to *rbi* at the extraction frequency of less than $f_T/10$

New TF Extraction: deembedding [11]

$$\mathbf{Z}_e^{(5a)} = \begin{bmatrix} z_{11e}^{(6)} & z_{12e}^{(6)} \\ z_{21e}^{(6)} & z_{22e}^{(6)} - rcx \end{bmatrix} \quad \mathbf{Y}_e^{(5a)} = inv(\mathbf{Z}_e^{(5a)}) \quad \mathbf{Y}_e^{(5)} = \begin{bmatrix} y_{11e}^{(5a)} - j\omega \cdot ceox & y_{12e}^{(5a)} \\ y_{21e}^{(5a)} & y_{22e}^{(5a)} \end{bmatrix}$$



UL parameters [9]

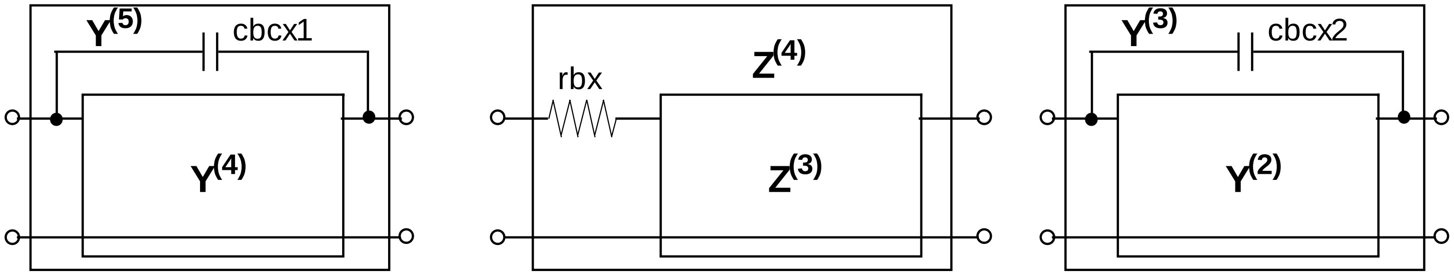
$$\tilde{y}_{ii} = y_{ii} + y_{12}; \quad \tilde{y}_{21} = y_{21} - y_{12}; \quad \tilde{h}_{11} = 1/\tilde{y}_{11}$$

$$\tilde{z}_{ii} = z_{ii} - z_{12}; \quad \tilde{z}_{21} = z_{21} - z_{12}; \quad \tilde{h}_{21} = \tilde{y}_{21}/\tilde{y}_{11}$$

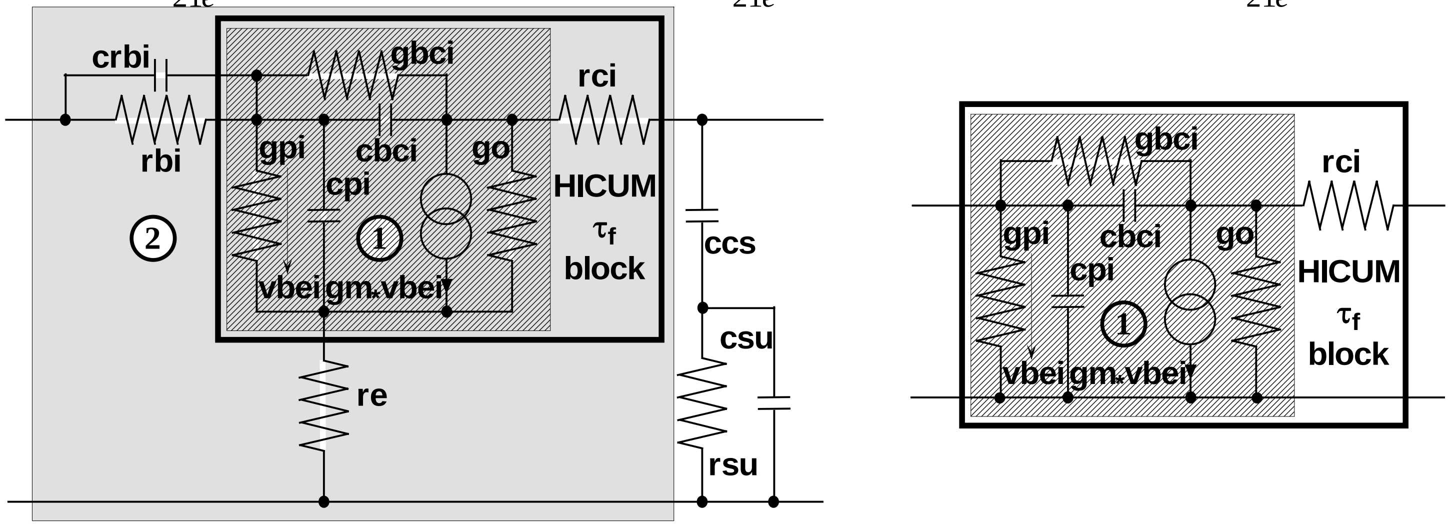
UL gain of deembedded block

$$\frac{1}{\tilde{h}_{21e}^{(5)}} = \frac{\tilde{y}_{11e}^{(5)}}{\tilde{y}_{21e}^{(5)}} = \frac{1}{\tilde{h}_{21e}^{(6)}} + \frac{rcx}{\tilde{z}_{21e}^{(6)}} - \frac{j\omega \cdot ceox}{\tilde{y}_{21e}^{(6)}}(1 - rcx \cdot \tilde{y}_{22e}^{(6)})$$

New TF Extraction: propagation of $1/\tilde{h}_{21e}$



$$\mathfrak{I}1: \quad \frac{1}{\tilde{h}_{21e}^{(5)}} \equiv \frac{1}{\tilde{h}_{21e}^{(4)}} \equiv \frac{1}{\tilde{h}_{21e}^{(3)}}$$



$$\frac{1}{\tilde{h}_{21e}^{(5)}} = \frac{1}{\tilde{h}_{21e}^{(2)}} = -\frac{\tilde{z}_{22e}^{(2)}}{\tilde{z}_{21e}^{(2)}} = -\frac{\tilde{z}_{22e}^{(1)} + rci}{\tilde{z}_{21e}^{(1)}} = \frac{1}{\tilde{h}_{21e}^{(1)}} + \frac{rci \cdot \Delta\mathbf{Y}^{(1)}}{\tilde{y}_{21e}^{(1)}}$$

New TF Extraction: final equation

$$\mathbf{Y}_e^{(1)} = \begin{bmatrix} gpi + s\cdot cpi + ybci & -ybci \\ gm - ybci & go + ybci \end{bmatrix} \qquad \mathbf{Y}_b^{(1)} = \begin{bmatrix} gm + go + gpi + s\cdot cpi & -go \\ -gm - go & go + ybci \end{bmatrix}$$

$$\frac{\Delta\mathbf{Y}^{(1)}}{\tilde{y}_{21e}^{(1)}} = -\frac{\Delta\mathbf{Y}^{(1)}}{\tilde{y}_{21b}^{(1)}} = -\frac{1}{\tilde{h}_{21b}^{(1)}}\frac{\Delta\mathbf{Y}^{(1)}}{\tilde{y}_{11b}^{(1)}} = -\frac{1}{\tilde{h}_{21b}^{(1)}}\cdot\frac{y_{11b}^{(1)}}{\tilde{y}_{11b}^{(1)}}\cdot\frac{\Delta\mathbf{Y}^{(1)}}{y_{11b}^{(1)}} = -\frac{1}{\tilde{h}_{21b}^{(1)}}\cdot\left(1+\frac{go}{\tilde{y}_{11b}^{(1)}}\right)\cdot\left(y_{22b}^{(1)} - go\cdot h_{21b}^{(1)}\right) \approx j\omega\cdot cbci\cdot\left(1+\frac{1}{\tilde{h}_{21e}^{(1)}}\right)$$

$$\frac{1}{\tilde{h}_{21e}^{(5)}} = \frac{1}{\tilde{h}_{21e}^{(1)}} + j\omega\cdot rci\cdot cbci\cdot\left(1+\frac{1}{\tilde{h}_{21e}^{(1)}}\right)$$

$$\boxed{t_T = \frac{1}{\omega}\cdot\Im\left(\frac{1}{\tilde{h}_{21e}^{(5)}}\right)}$$

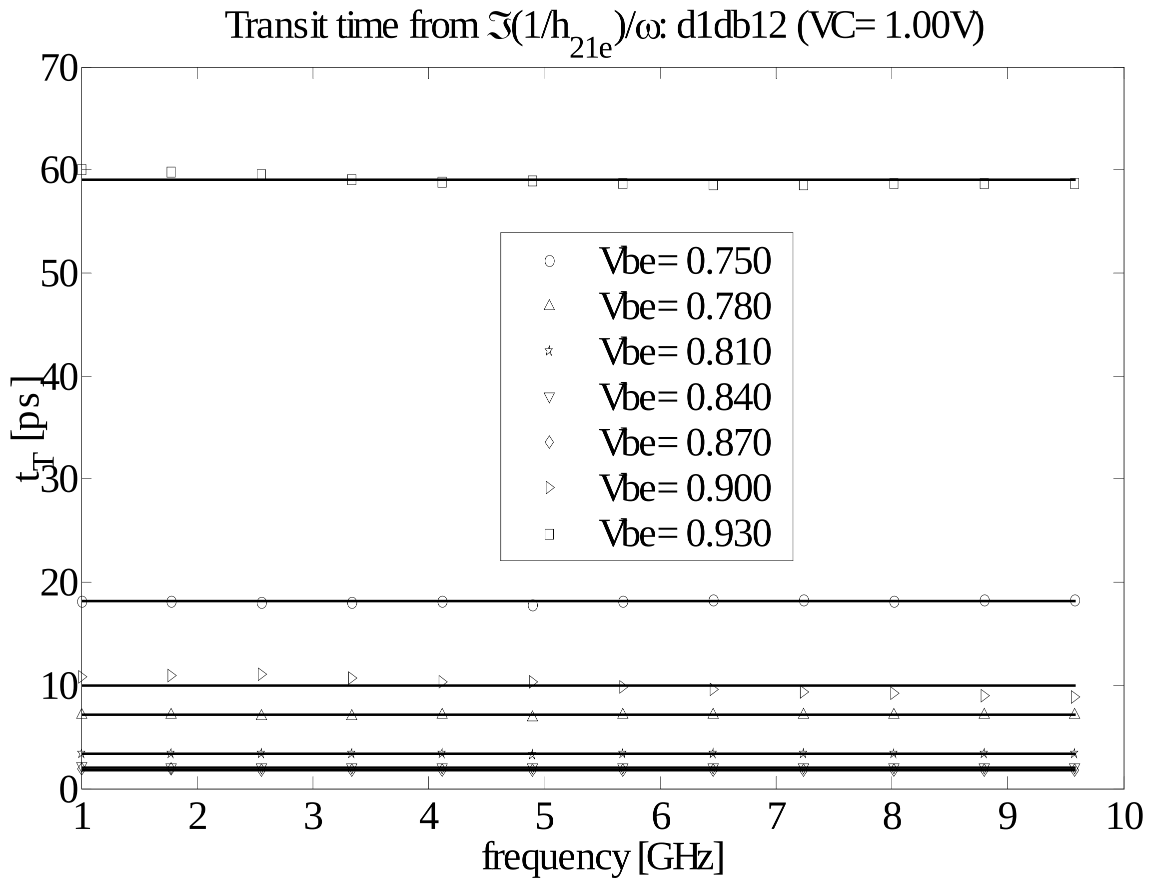
$$t_T = \underbrace{t_f^{(1)} + tci}_{t_{f\_HICUM}} + \frac{C_{jE}}{gm}$$

$$\boxed{t_T = t_f + \frac{C_{jE}}{gm} = tf0 + \Delta t + \frac{C_{jE}}{gm}}$$

An absolutely correct equation with t_T extractable at the cost of only two CONSTANT parameters: *rcx, ceox*

NO MODEL FORCE TO REALITY!

New TF Extraction: transit time



Theoretically the formula is valid at all frequencies. In practice average min. 5 points within 1...10GHz

Spot frequency $t_T = \left(\omega \cdot \left|h_{21e}\right|\right)^{-1}$ **is unadvised!**

New TF Extraction: *gm* and *rb*

$$t_T = tf0 + \Delta t + \frac{C_{jE}}{gm}$$

The following formulas have been deduced in [7] for the intrinsic transconductance and the bias-dependent total base resistance. Both can be computed from the same data and frequency range as t_T.

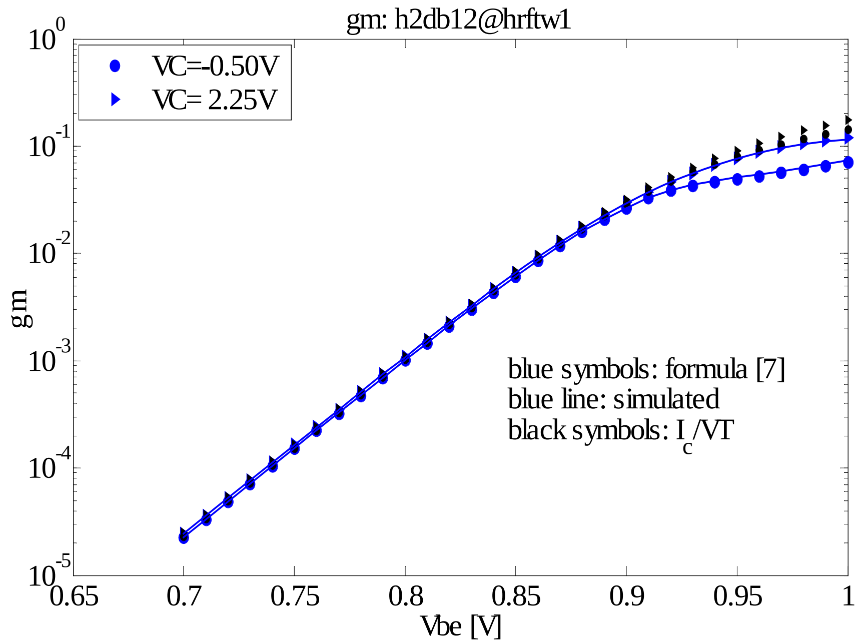
$$\frac{1}{gm} = \frac{\Im(\tilde{h}_{11e}^{(5)})}{\Im(\tilde{h}_{21e}^{(5)})} - re$$

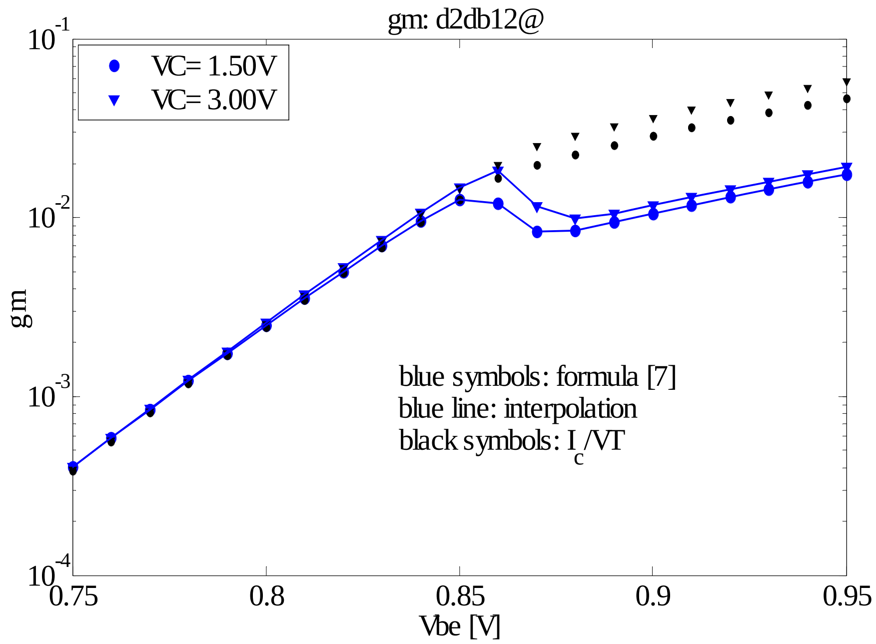
$$rbce = rbx + rbi + re = \frac{\Im(\tilde{h}_{11e}^{(5)} conj(\tilde{h}_{21e}^{(5)}))}{-\Im(\tilde{h}_{21e}^{(5)})}$$

The intrinsic BE bias results as $V_{biei} = V_{be} - rbce \cdot I_b - re \cdot I_c$

THREE parameters needed so far: *re, rcx, ceox*

New TF Extraction: verification of *gm* [7]





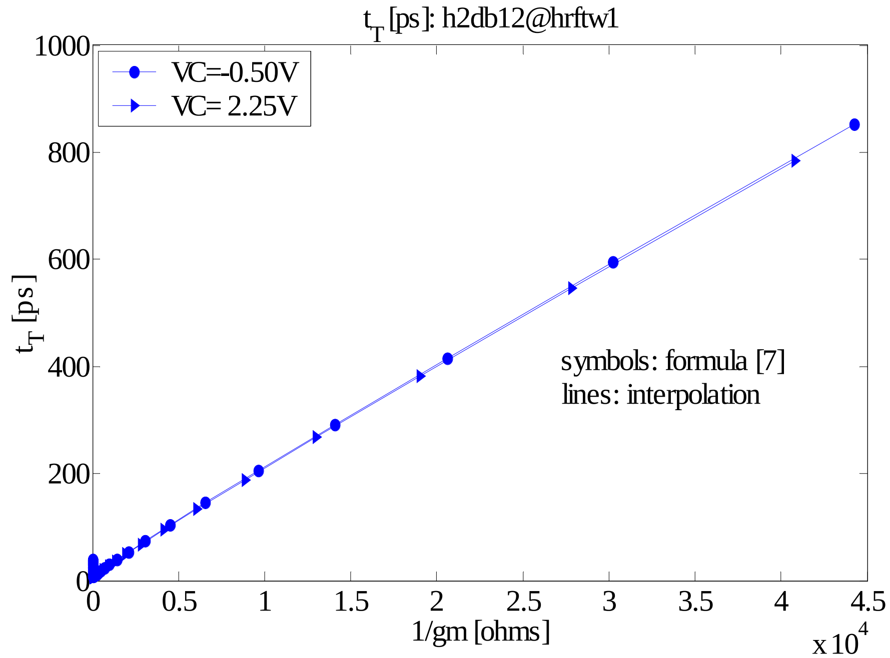
synthetic data with card *hicumL2V2p23_c*

typical HBT of 50GHz/3V

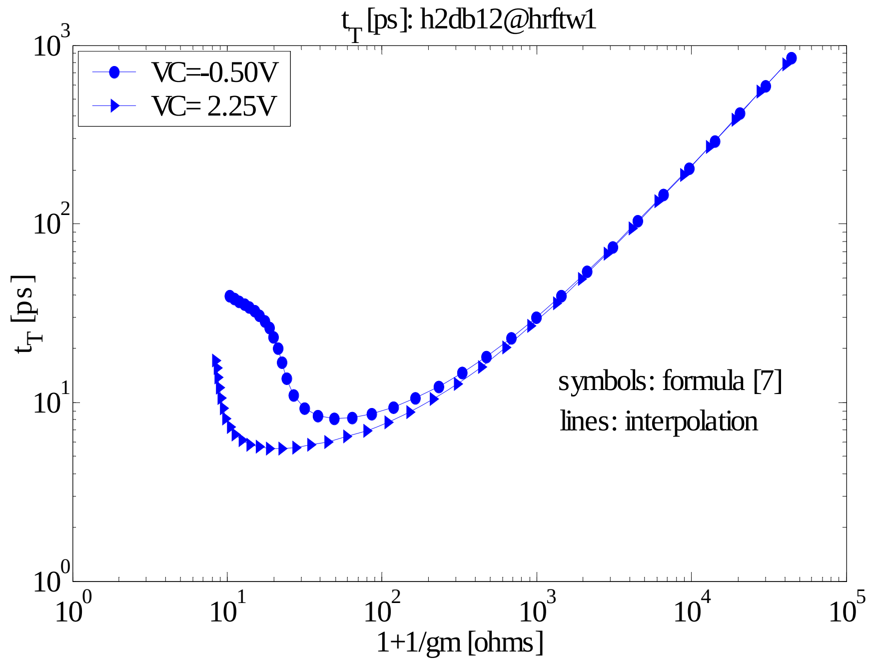
Electron barrier related kink [10] was not possible to reproduce in synthetic data by parameter variation

MODEL FORCE TO REALITY MUST BE AVOIDED!

New TF Extraction: visualization



conventional style

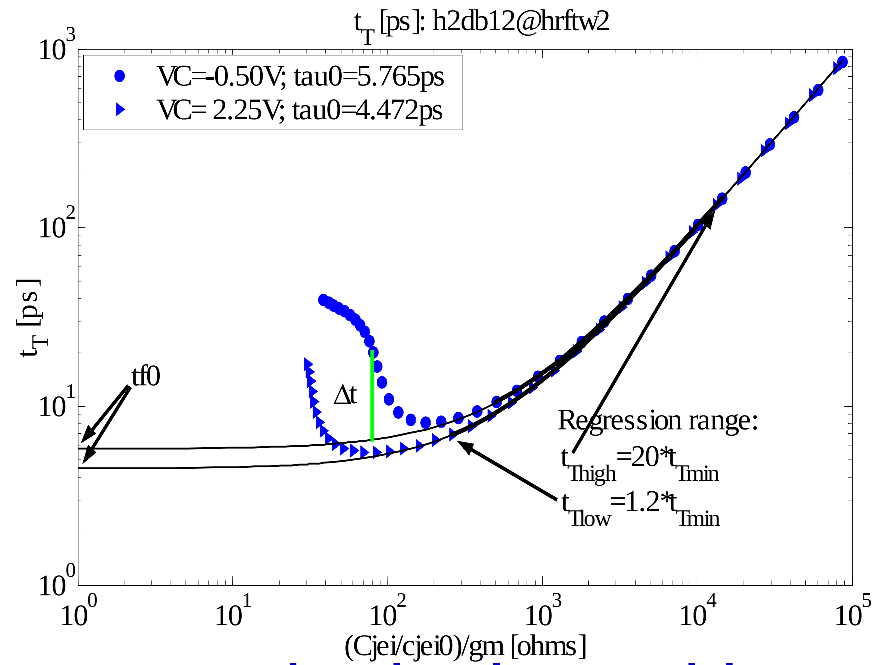


proposed style

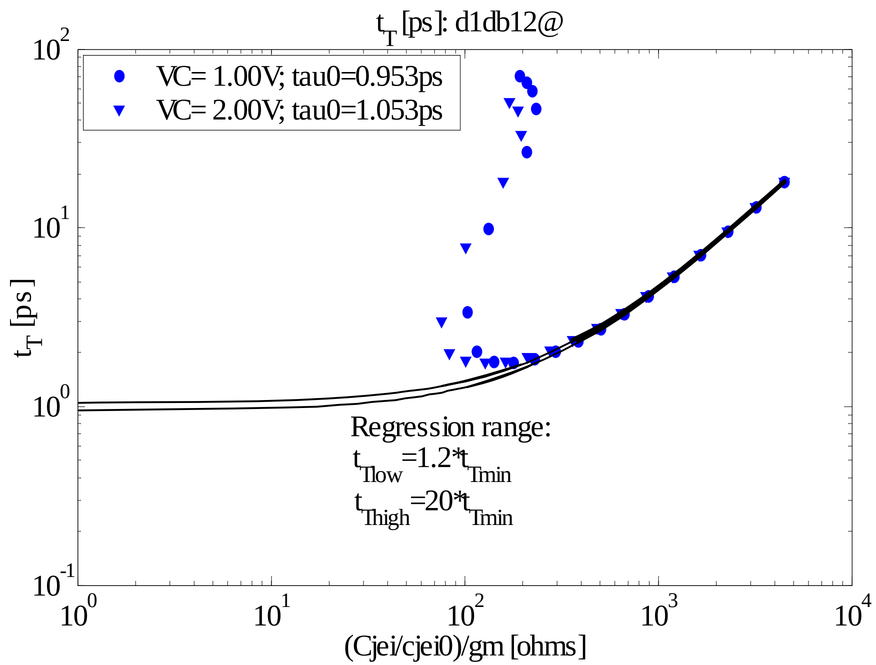
- loglog plot with 1+xdata e.g. : 1+1/gm on xaxis
- *tf0* will appear as the intercept with the x=1 line

The linear t_T vs. *VT/Ic* convention is invalid anyway

New TF Extraction: *tf0,Δt* regression



synthetic data with card *hicumL2V2p23_c*



typical HBT of 70GHz/2V

$\text{xvar} = Cjei / cjei0 / gm$ function from [8]: $t_T = x_1 + x_2 \cdot \text{xvar} + x_3 \cdot \text{xvar} \cdot \ln(\text{xvar})$

Regression range limits related to t_{Tmin}: [1.2;20] widely applicable

Flapback (gm): present C_{jE} model saturates at *aje* i/o declining as theory suggests [12]. But tf(Ic) is O.K.!

New TF Extraction: regression math.

Vectors: $\mathbf{a}_1(j)=1,\ \mathbf{a}_2(j)=\mathrm{xvar}(j),\ \mathbf{a}_3(j)=\mathrm{xvar}(j)\cdot\ln(\mathrm{xvar}(j)),\ \mathbf{b}(j)=\mathrm{t}_T(j)$

Matrix: $\mathbf{A}=[\mathbf{a}_1\ \mathbf{a}_2\ \mathbf{a}_3]$ Vector of unknowns: $\mathbf{x}=[x_1\ x_2\ x_3]^T$

Solution with MATLAB's backslash operator: $\mathbf{x}=\mathbf{A}\backslash\mathbf{b};\quad tf0=\mathbf{x}(1)$

Reference and incremental transit times: $\mathbf{t}_{Tref}=\mathbf{A}_{all}\cdot\mathbf{x};\quad \Delta\mathbf{t}=\mathbf{t}_T-\mathbf{t}_{Tref}$

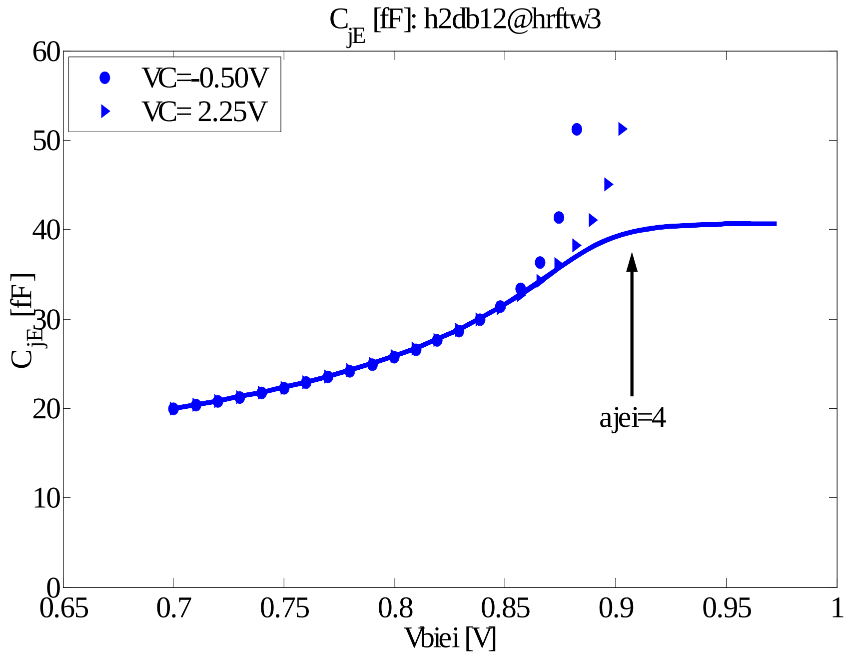
Effect of *xvar* selection on *tf0* [ps]

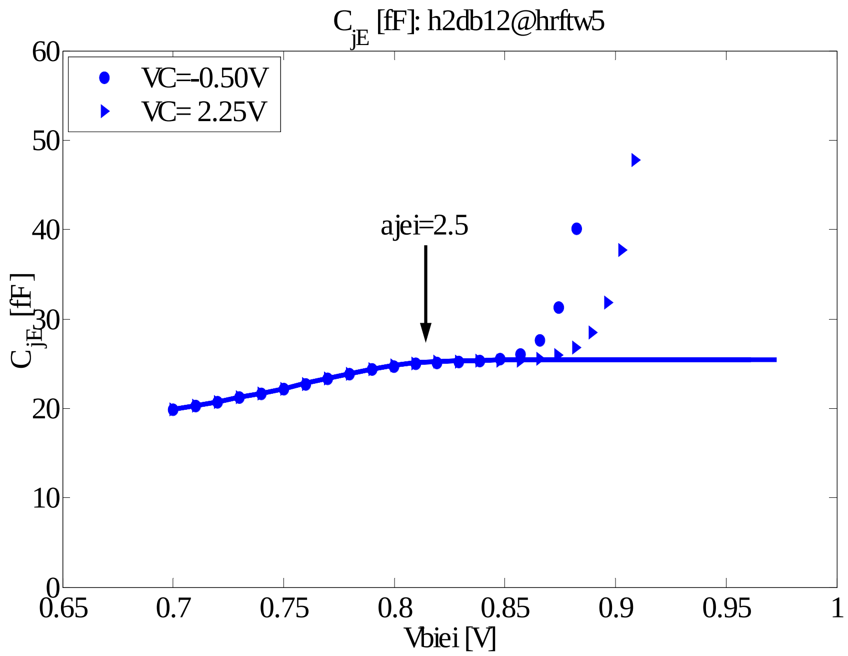
XVAR	*SIMULATED*	*CJEI/CJEI0/GM*	*1/GM*	*VT/IC*
SYNTHETIC	**5.720** **4.491**	5.765 4.472	6.384 4.897	6.457 4.952
HBT 70GHz/2V	**N.A.** **N.A.**	0.953 1.053	1.154 1.237	1.185 1.288

Theoretical *xvar* is the best: *vjei, zei, ajei* are needed

New TF Extraction: C_{jE} parameters

$C_{jE} = gm \cdot (t_T - tf0 - \Delta t)$ low bias $\Rightarrow C_{jE} \approx gm \cdot (t_T - tf0)$; $V_{biei} = V_{be} - rbce \cdot I_b - re \cdot I_c$



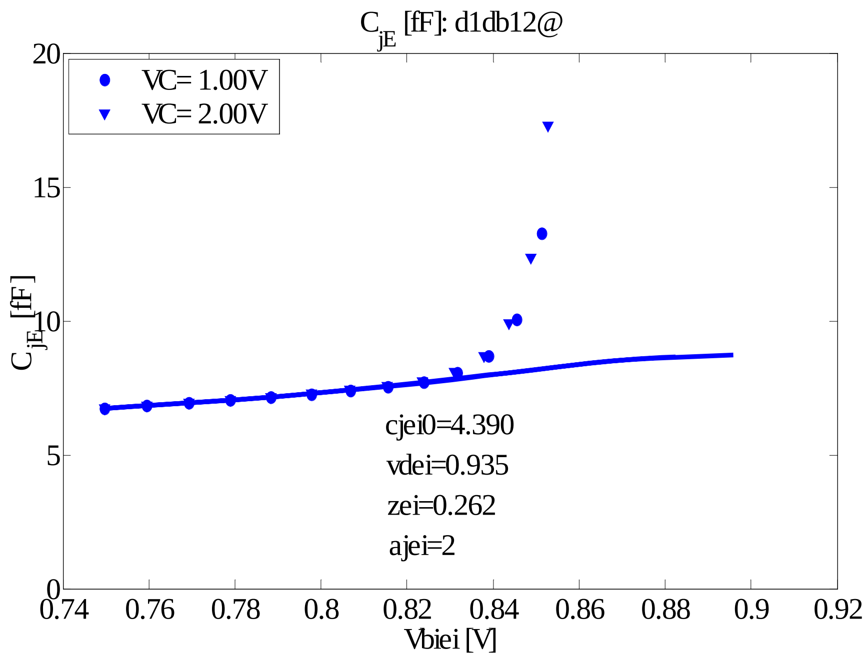


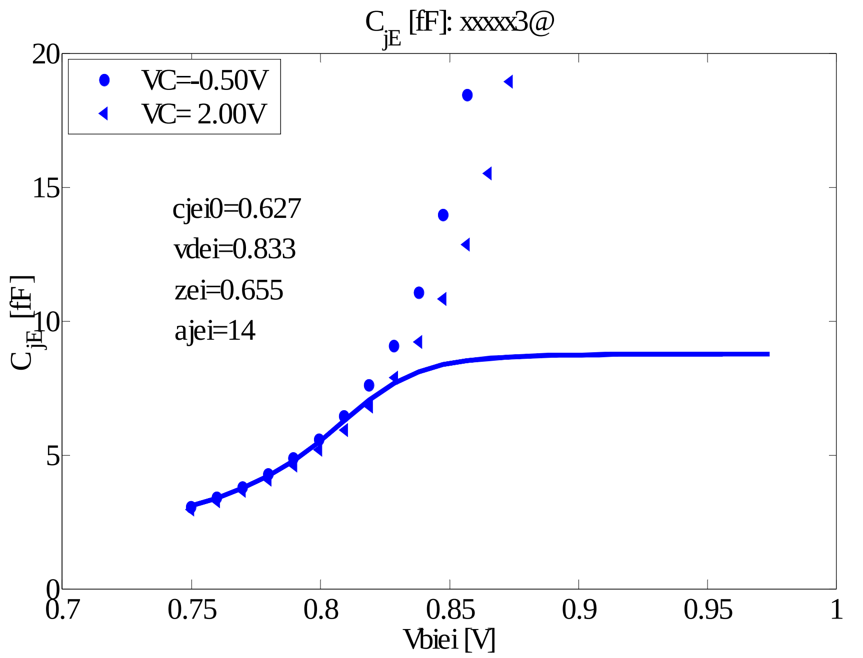
synthetic data with *ajep=ajei* varied, *cjei0+cjep0* kept constant (*kperi* concept), *zep=zei, vdep=vdei*

Extract C_{jE} parameters from t_T (omit CAP structures and cold) set *ajei* corner in rising part, use *kperi*

New TF Extraction: C_{jE} parameters

Practical Examples





HBT of 70GHz/2V

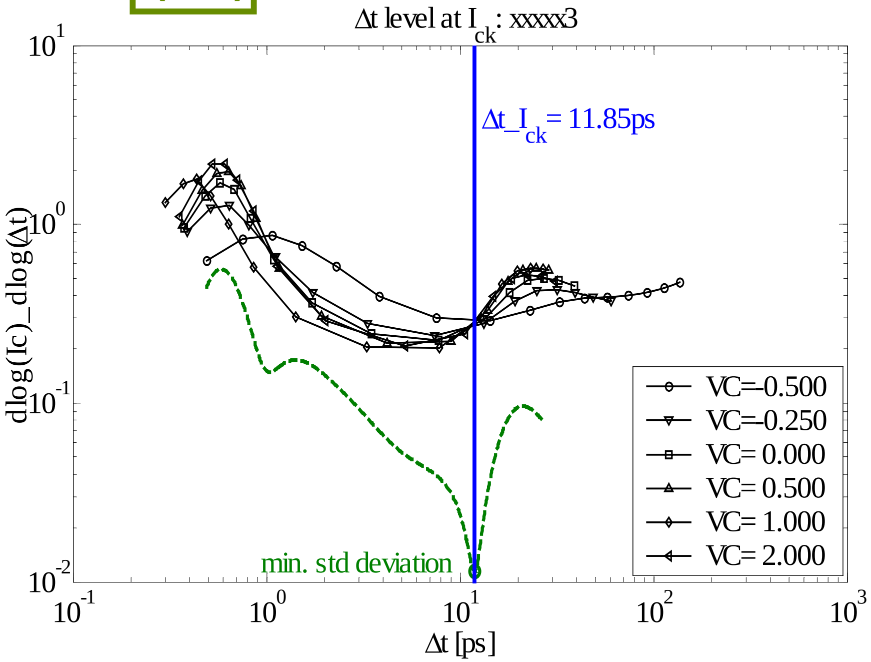
HBT of 45GHz/?V

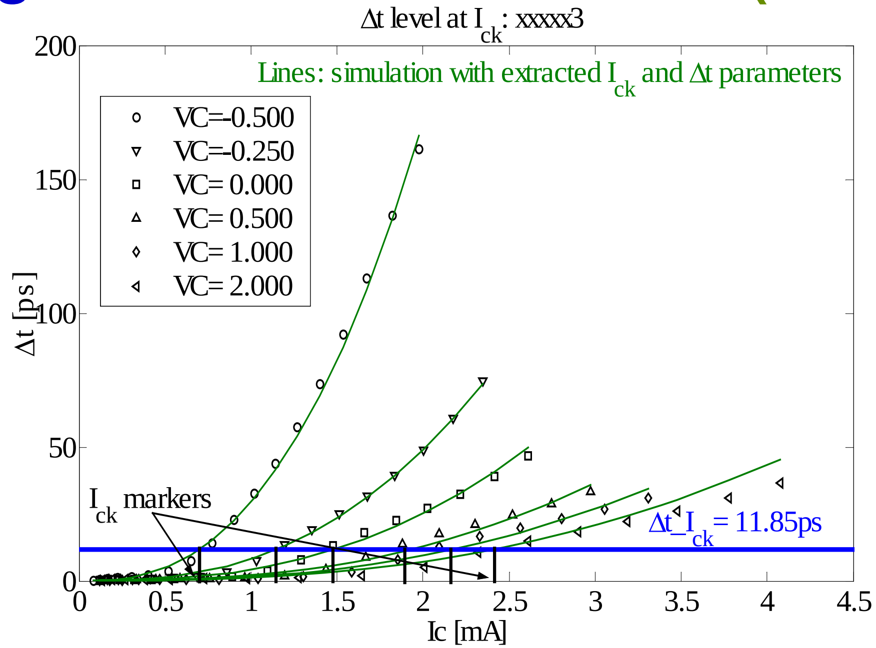
Measure from Vbe=0.70V for increased accuracy

Extract C_{jE} parameters and *tf0* together (iteratively) to account for parameter interaction

New TF Extraction: deterministic I_{ck}

FD derivatives $g(\Delta t, Vc) = \dfrac{d(\log(Ic))}{d(\log(\Delta t))}$ cross a common intercept point $\boxed{(\mathfrak{I}2)}$ at *Δt_Ick* constituting the masterline for *Ick(Vce)*

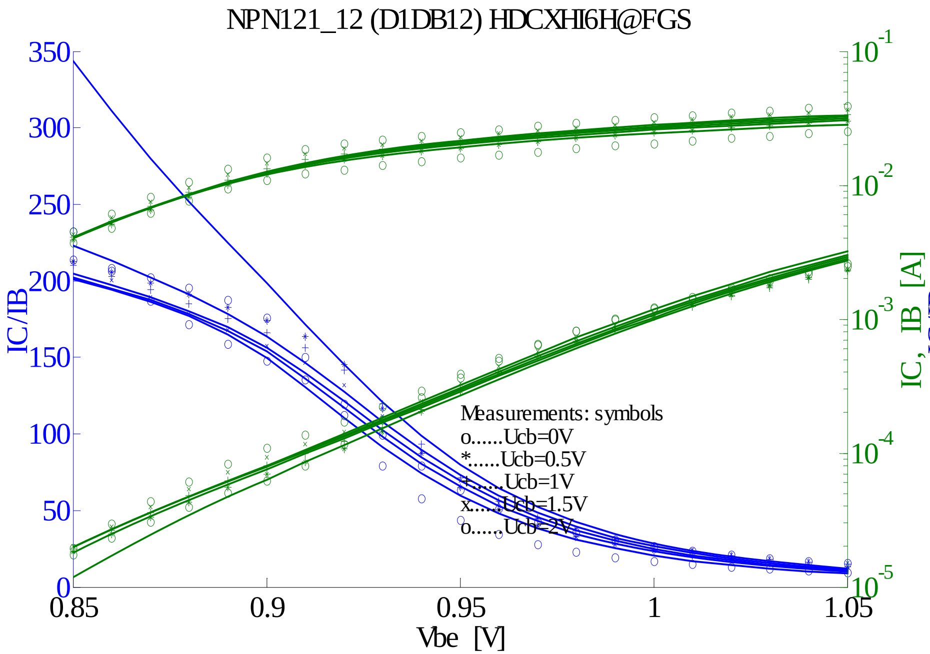


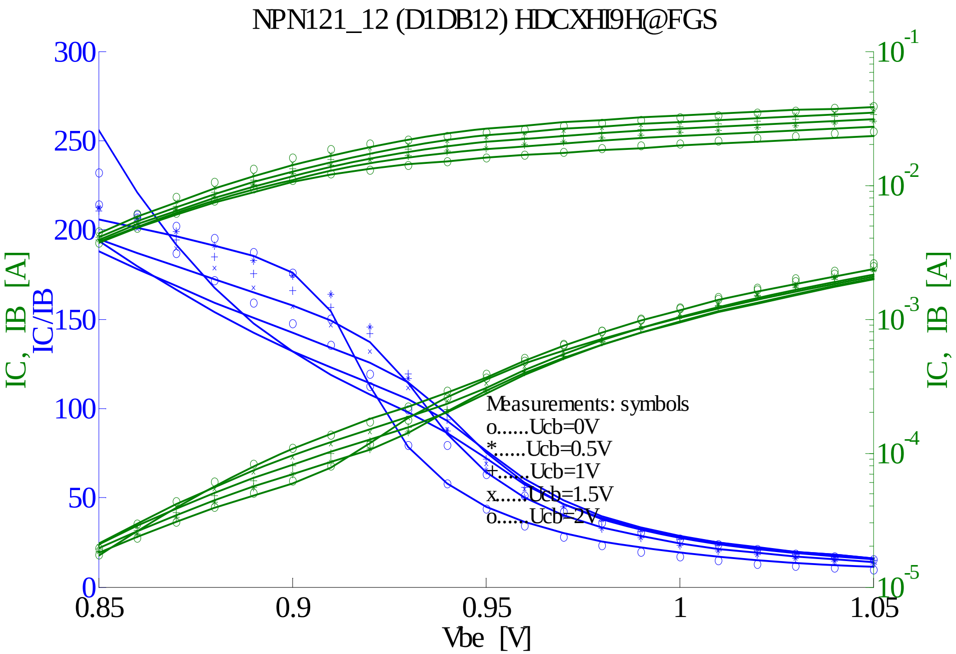


The direct automatic method upgrades former heuristic alternatives. MATLAB is ideally suited to the computation intensive FD, spline & statistical operations

New TF Extraction: self heating

HBT of 70GHz/2V





Extracted parameters

Optimized w/ self heating

Final optimization w/ self heating justifies HICUML2 excellence and the robustness of the MATLAB tool

Summary

- a normalized HicumL2v2.23 has been implemented in a MATLAB extraction environment
- normalization reveales equivalence of Hicum to other HBT/BJT models in the low-medium range allowing the inheriatage of well refined conventional techniques
- a completely new concept has been suggested for *TF* extraction
- import of only *re, rbx* and *ceox* is needed for providing *tf0* and Δt plus 4 „in-situ" extracted C_{jE} parameters
- a novel invariance principle has ben adapted to the last critical stage of transit time related extraction enabling the fully automated determination of I_{ck}

References

1. D. Berger and D. Celi, "A Novel Method for Transit time Parameter Extraction Taking into Account the Coupling Between DC and AC Characteristics," HICUM Workshop, 30. Sep. 2001, Minneapolis, MN
2. J. Berkner, "Contributions to HICUM Parameter Extraction," HICUM Workshop, 30. Sep. 2001, Minneapolis, MN
3. B. Ardouin, T. Zimmer, **„**Accurate Transit Time Parameter Extraction,**"** Hicum Workshop, Dresden, June 2003.
4. Markus Malorny, "Improved Tf and fT Determination," Hicum Workshop, Dresden, June 2002.
5. M. Malorny, M. Schröter, D. Celi, D. Berger, **"**An improved method for determining the transit time of Si/SiGe bipolar transistors,**"** Proc. BCTM, pp. 229-232, 2003
6. D. Celi, "About hjei Parameter Extraction," BipAK, Erfurt, Oct. 2006
7. 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
8. S. Fregonese, S. Lehmann, T. Zimmer, M. Schroter, D. Celi, B. Ardouin, H. Beckrich, P. Brenner and W. Kraus, „A Computationally Efficient Physics-Based Compact bipolar transistor Model for Circuit Design—Part II: Parameter Extraction and Experimental Results," IEEE Transactions on Electron Devices, Vol.53, No.2, February 2006, pp287-294
9. 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
10. K. Lee, D.-H. Cho, K.-W. Park and B. Kim, „Improved VBIC Model for SiGe HBTs with an Unified Model of Heterojunction Barrier Effects," IEEE Transactions on Electron Devices, Vol.53, No.4, April 2006, pp743-752
11. Z. Huszka, "A Self Consistent Joint Extraction of t0 and RCX for HICUM," 6th Hicum Workshop, Heilbronn, June 2006
12. http://www.iee.et.tu-dresden.de/~schroter/Hicum_PD/Hicum22/HICUM-L2V2p2.pdf