(Update of XMOD activities)

Practical Scalable and Statistical Modeling of SiGe HBT's

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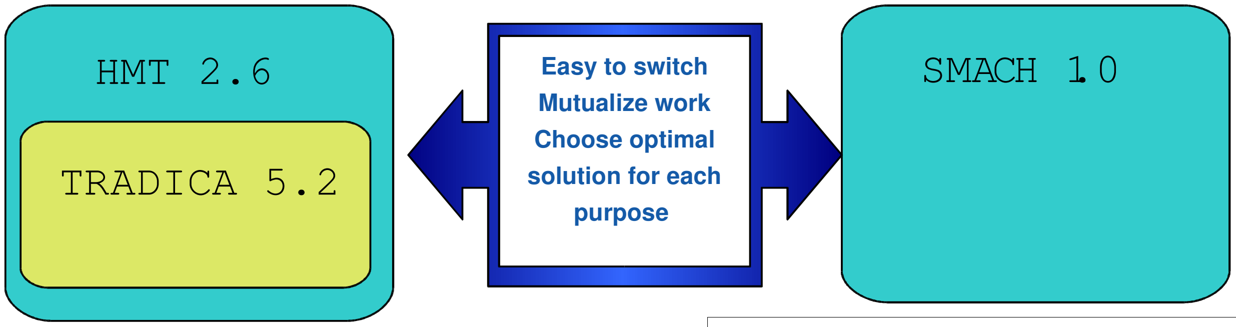
OUTLINE

- ✓Introduction
- ✓Scalable Model
- ✓Statistical modeling
  - PCM based methods
  - Results
- ✓Conclusion

Extraction Tools

TRADICA BASED SOLUTION

SIMULATOR MACRO LANGUAGE SOLUTION



- Fully physics based solution
- Hierarchy of models (level0, level2, level 4, sgp)
- Accurate scaling equations for wide range of process and geometries
- Statistical tool (incl. predictive)
- Complex behaviors can be handled
- reliable

- Simplified but physics based solution (no proprietary scaling equations)
- Allows fast scalable model
- Allows optimization
- mimic Bsim like behavior with physics based equation
- fast full statistical modeling (corners, Monte Carlo & Mismatch)
- potentially restricted (less geometries)

SMACH is a request from customers → smooth transition to TRADICA

SCLABLE & STATISTICAL MODEL

```
define            SMACH     (C B E S )
parameters        DRAWN_BE0=0.42 DRAWN_LE0=0.84 NE=1 MULT=1  \
\
A_BE0=0.01 A_EG0=0.01  R_EGG=0.01  R_WB=0.01  R_NAB=0.01   R_NDC=0.01  R_WC=0.01  R_NCX=0.01 R_WE=0.01  \
R_NDE=0.01   R_GAIB=0.05  FAC_T0=0.6 FAC_SIC=1.5 \
\
SIG_BE0=0 SIG_EG0=0 SIG_EGG=0 SIG_WB=0 SIG_NAB=0 SIG_NDC=0 SIG_WC=0 \
SIG_NCX=0 SIG_WE=0 SIG_NDE=0 SIG_GAIB=0

;-----------  PROCESS GEOMETRY   --------------
 b_ov=0.12
w_s=0.1
b_pm=0.1
l_pm=0.1
...
;-----------  ELECTRICAL specific parameters              --------
 C_JEI0=4.3
C_JCI0=4.2
C_JEP0=0.85
C_JCB0=0.1274
...
C_10=3.467E-014
Q_P0=1.5
 ...
;----------- Internal Calculations --------
 PBC=(MULT*NE*2*(BBC+LBC))
ASIC=(MULT*NE*(BE0+2*b_sic)*(LE0+2*b_sic))
PSIC=(2*MULT*NE*((BE0+2*b_sic)+(LE0+2*b_sic)))
...

model MAIN HICUM Tnom= 27   \
C10 = (C_10*AE*AE*1e-18*r_AE0*r_AE0* (1+R_EGG*SIG_EGG)*(exp(A_EG0*SIG_EG0)) )   \
Qp0 = (Q_P0*AE*1e-15*r_AE0*(1+R_WB*SIG_WB)*(1+R_NAB*SIG_NAB))   \
...
Rci0 = ((R_CI0/(AE*fcs))*(1+R_WC*SIG_WC)/((1+R_NDC*SIG_NDC)))   \
...
end SMACH
```

Instance Parameters

1 σ TP variations

(% from nominal) R_x's

deviation from nominal

(number of σ) SIG_x's

geometrical information

geometry independent

parameters

Intermediate calculations

Satistical equation

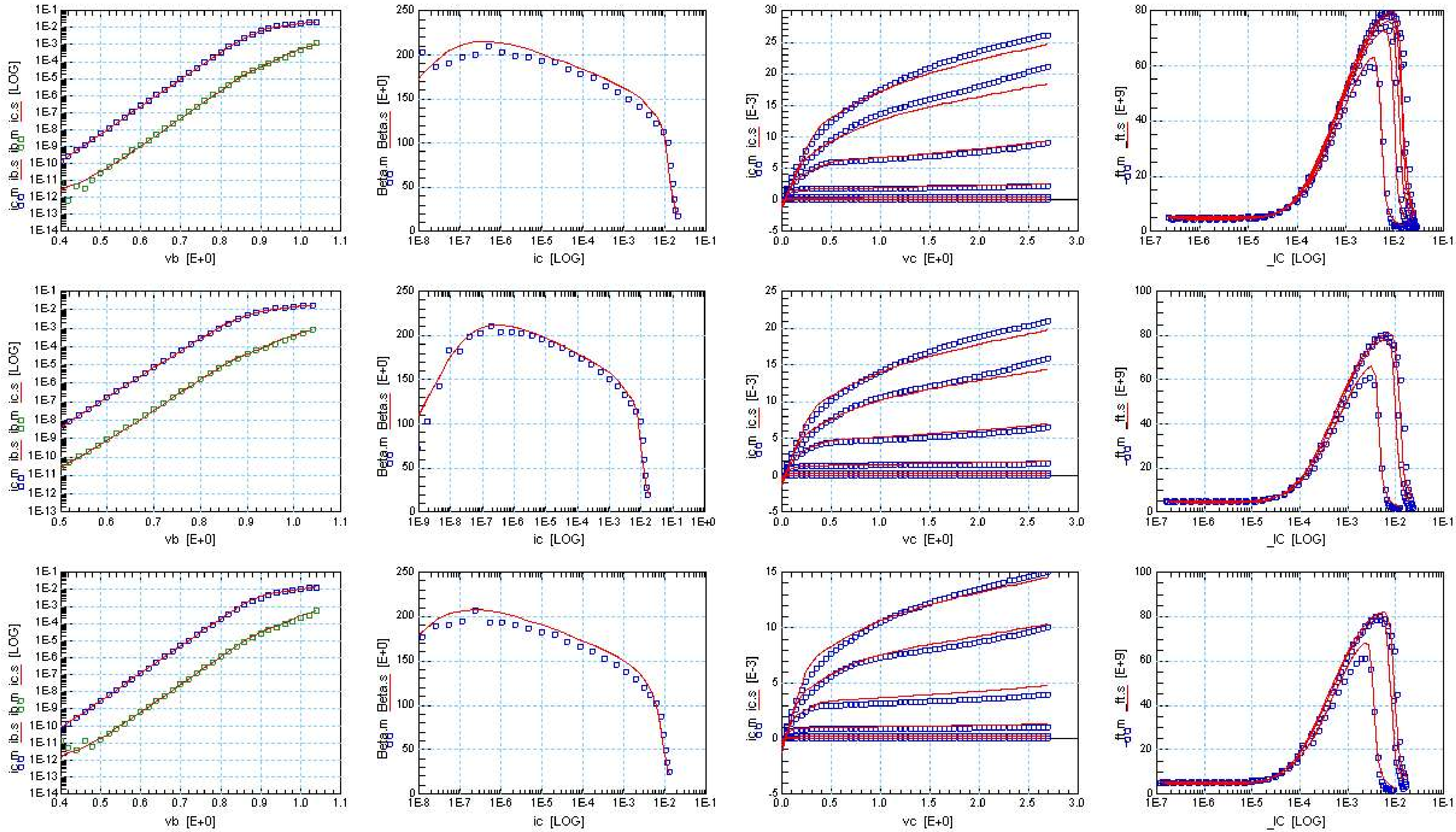
Scaling equation

SCLABLE & STATISTICAL MODEL

- Fast and easy connection with ICCAP toolkit
- Allows optimization of multi-geometry targets
- Important extraction schemes still hold (eg, transit time, etc.)
- Maximize use of ICCAP productivity features (plot optimizer and multiplot display coupled with GUI)

Quick scalable model can be produced in a single day
More accurate and/or general model realized very quickly

SCLABLE & STATISTICAL MODEL



IHP 80 Ghz SiGe Low cost Process: 3 Low Voltage HBT (see reference reference [2])

SCLABLE & STATISTICAL MODEL

- PCA based methods: measure & model n dies (n large) → run statistical analysis (eg, PCA) on parameter database → reconstruct variance (obtain correlation in model parameters)
- Monte Carlo: apply statistical variations to model parameters for large samples → no correlation is usually taken into account
- PCM based methods: usually a weird combination of empirical and experience based methods trying to use the statistical information contained in PCM data as input for model parameter variation (WC models)

SMACH uses a new PCM based method

- Theory based on a simplification of the work realized by M. Schroter’s et al [1]
- Practical implementation is very efficient and powerful

SCLABLE & STATISTICAL MODEL

Available PCM data

Inline measurements

IC standard transistor	*Vbe=0.7 V*
IB standard transistor	*Vbe=0.7 V*
Cje transistor array !!	*Vbe=0 V*
Cjc transistor array !!	*Vbc=0 V*
RSBI tetrodes	*Single Vbe & Vbc*
RE standard transistor	*simple Flyback method*

Limited number of HF measurements (2 Lots, limited number of dies)

f_T Max standard transistor !!	*automated scheme for Vbe selection* *Spot frequency*

SCLABLE & STATISTICAL MODEL

- Statistical information is contained in PCM measurements, but PCM's are correlated
- difficult to link PCM's to model parameters
- TP's are uncorrelated but their statistical behavior is unknown
- HiCUM model parameter are physics based (can be linked to technology)

Link (via equations) important model parameters with technological parameters (TP's) eg, doping concentrations, junction widths, Germanium content

Fit (reproduce by simulation) the PCM measurements Statistical distributions and calculate standard deviations

This should require to run a very large number of random samples (with Gaussian distributions) --> not Feasible ?

The new methodology overcomes this issue!

SCLABLE & STATISTICAL MODEL

Dependence of PCMs on technological parameters (TP's)

TP / PCM	*ΔEg(0)*	*ΔEg(grade)*	*WB*	*NAB*	*NDC*	*WC*	*NCX*	*WE*	*NDE*	*γIB*	*ΔL*
IC	X	X	X	X							X
IB								X	X	X	X
Beta	X	X	X	X				X	X	X	
CJE				X							(X)
CJC					X						(X)
CJCB							X				(x)
f_T		X	X	X	X		(x)				(x)
RSBI			X	X							
CJCI (PT)						X					
RE								X	X		X

Instead of trying to find a link between PCM's and TP's, derive the link between model parameters and TP's then resimulate PCM's (Optimize) until we get the target PCM distributions

SCLABLE & STATISTICAL MODEL

Example of equation:

$$C=\frac{\varepsilon_0\varepsilon_r}{\sqrt{2\frac{\varepsilon_0\varepsilon_r}{qN}Vd}}$$

abrupt junction

$$C=\frac{\sqrt{\varepsilon_0\varepsilon_r}A}{\left(2\frac{Vd}{qN}\right)^Z}$$

General case

$$\frac{C^*}{\overline{C}}=\left(\frac{\overline{Vd}}{Vd^*}\frac{N^*}{\overline{N}}\right)^Z$$

Capacitance relative deviation from nominal

Vd can't be determined analytically, but its variation is small: $Vd=V_T\ln\left(\frac{N_AN_D}{n_i^2}\right)$

Typically 2% for 20% of variation for doping

Finally we get: $\frac{C^*}{\overline{C}}\approx\left(\frac{N^*}{\overline{N}}\right)^Z$

And so on for every important model parameter...

- **HiCUM physics based parameters: T0, RCI0, VLIM, C10,Qp0, etc .**
- **Note Physical parameters for junction capacitance are very important ! (error on Zx means error on N)**

SCLABLE & STATISTICAL MODEL

Fitting PCM statistical variation with re-simulated PCM:

```
define          SMACH     (C B E S )
parameters      DRAWN_BE0=0.42 DRAWN_LE0=0.84 NE=1 MULT=1  \
\
A_BE0=0.01 A_EG0=0.01  R_EGG=0.01  R_WB=0.01  R_NAB=0.01   R_NDC=0.01  R_WC=0.01  R_NCX=0.01 R_WE=0.01  \
R_NDE=0.01   R_GAIB=0.05  FAC_T0=0.6 FAC_SIC=1.5 \
\
SIG_BE0=0 SIG_EG0=0 SIG_EGG=0 SIG_WB=0 SIG_NAB=0 SIG_NDC=0 SIG_WC=0 \
SIG_NCX=0 SIG_WE=0 SIG_NDE=0 SIG_GAIB=0
...
...
```

Parameters to be optimized

Parameters to be randomly switched between -3σ and +3σ

- Use the scalable model netlist with single bias point
- Target is the PCM distribution standard deviation. Simulation (must) produce a Gaussian distribution
- Replace random values by linear sweep (produce empirically standard deviations of 1)

Each PCM standard deviation can be computed with a single simulation (~a few seconds), allowing standard non linear optimization algorithm to be used

- No need for Surface Response Methods (difficult to implement in ICCAP)

SCLABLE & STATISTICAL MODEL

Optimization procedure:

Each step needs only a few parameters to be optimized (limited number of sweeps)

CJE --> NAB

CJC --> NDC

RSBI -->WB + (NAB)

RE –-> WE + NDE

IB --> γIB (WE, NDE) ,Δ L

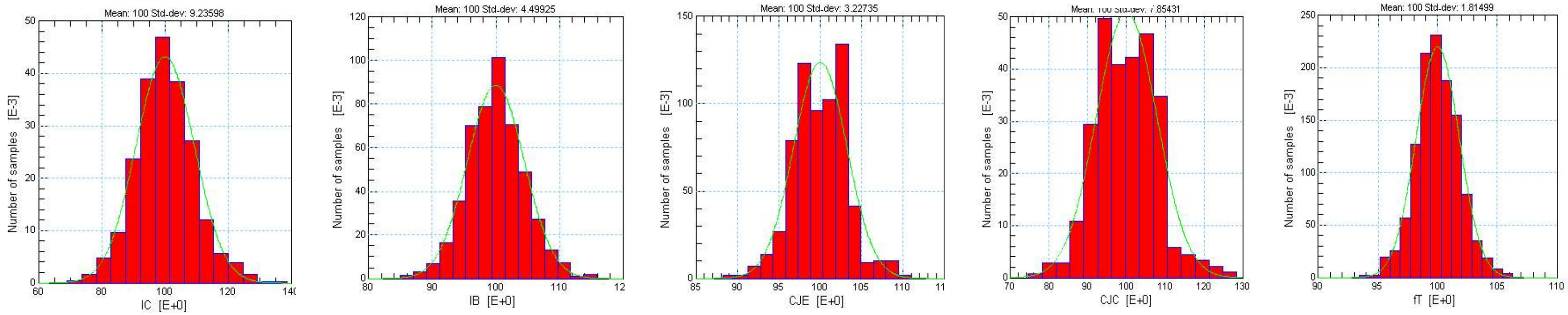
FT --> ΔEg (grade)

IC --> ΔL, ΔEg(0)

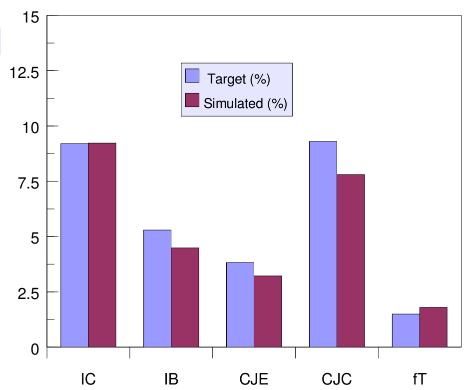
SCLABLE & STATISTICAL MODEL

Verification: run 1000 random samples, plot distributions, calculate standard deviations, compare to target PCM's

IC IB CJE CJC f_T



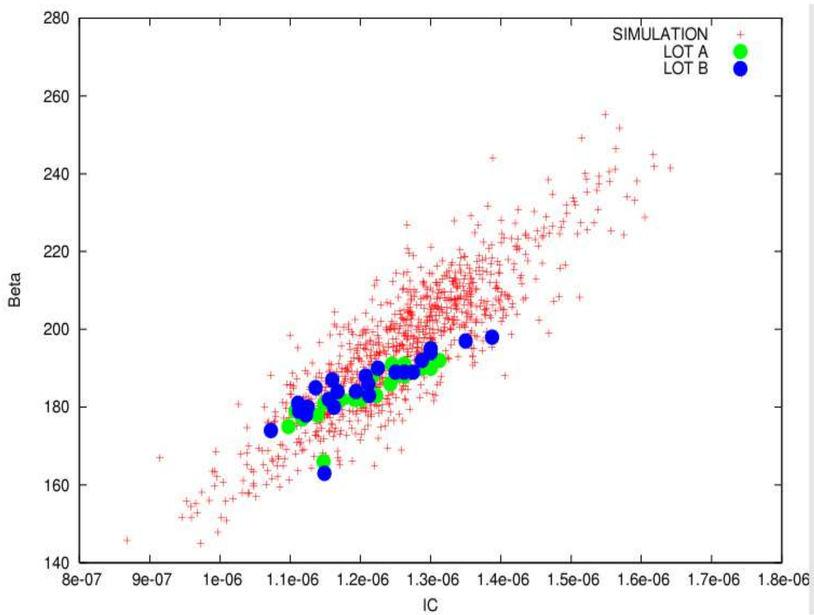
PCM standard deviation

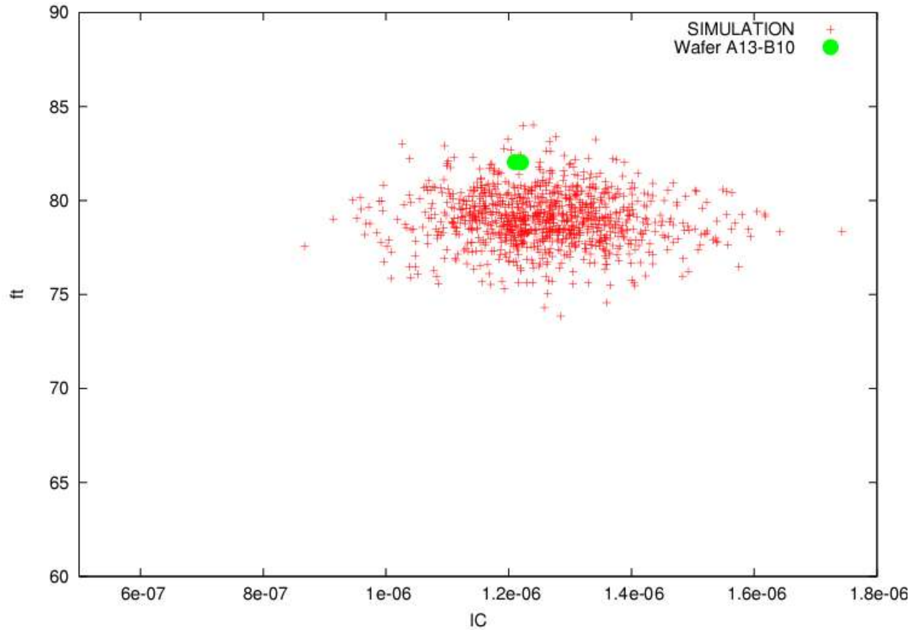


SCLABLE & STATISTICAL MODEL

Verification: Scatter plot of Beta vs IC and fT vs IC

1000 Monte Carlo samples vs measurements (2 LOTS)

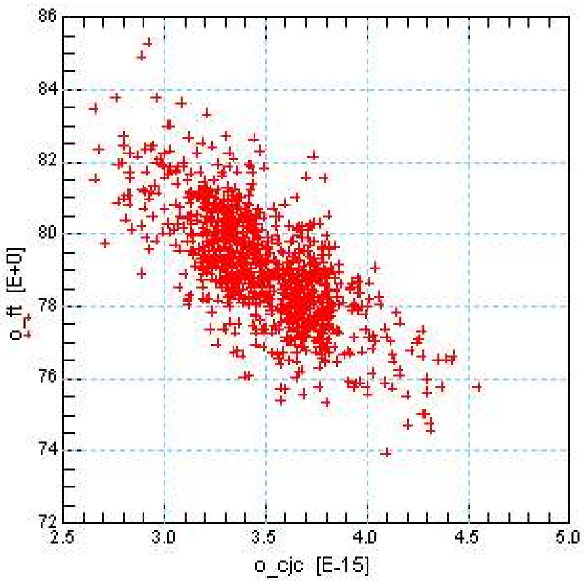




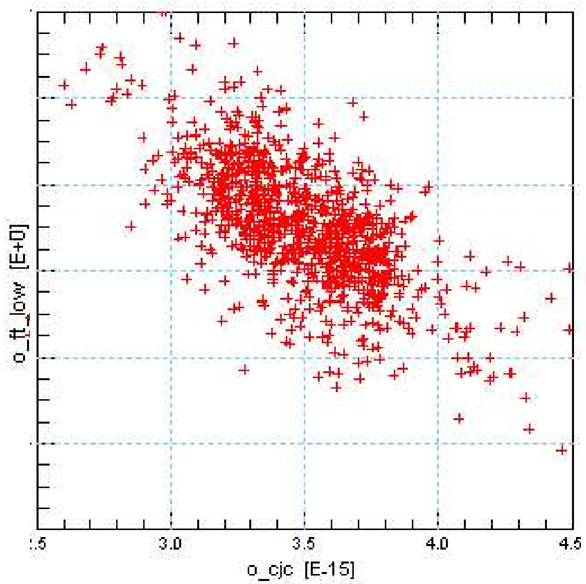
SCLABLE & STATISTICAL MODEL

PCM design and choice of measurement scheme of utmost importance:

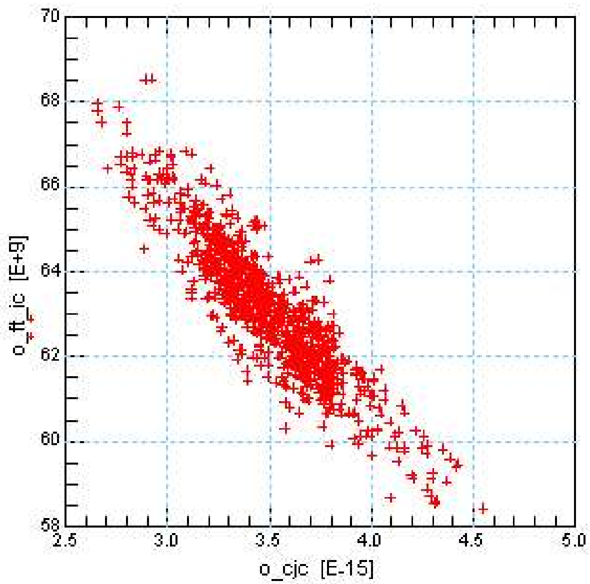
Peak f_T vs CJC



f_T (VBE=0.7) vs CJC



f_T (IC=250 µA) vs CJC



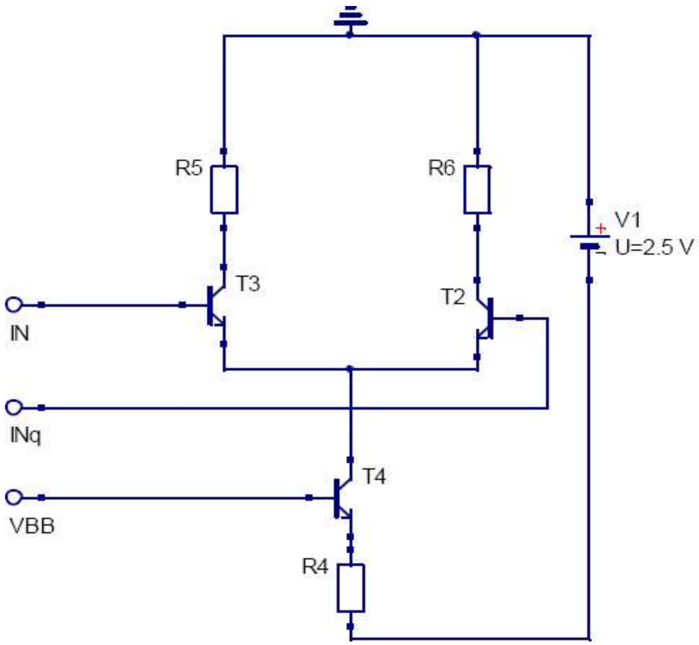
Correlation is fundamentally different !

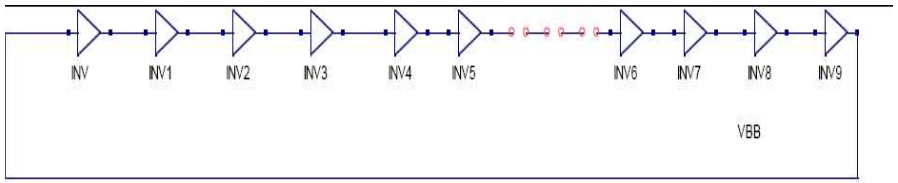
Pay attention also to large area diodes for CV measurements (avoid size variation)etc...

SCLABLE & STATISTICAL MODEL

Verification: **Circuit verification Ring Oscillator (53 CML inverters)**

Run 50 Monte Carlo Samples (11 stages only) and compare with measurements



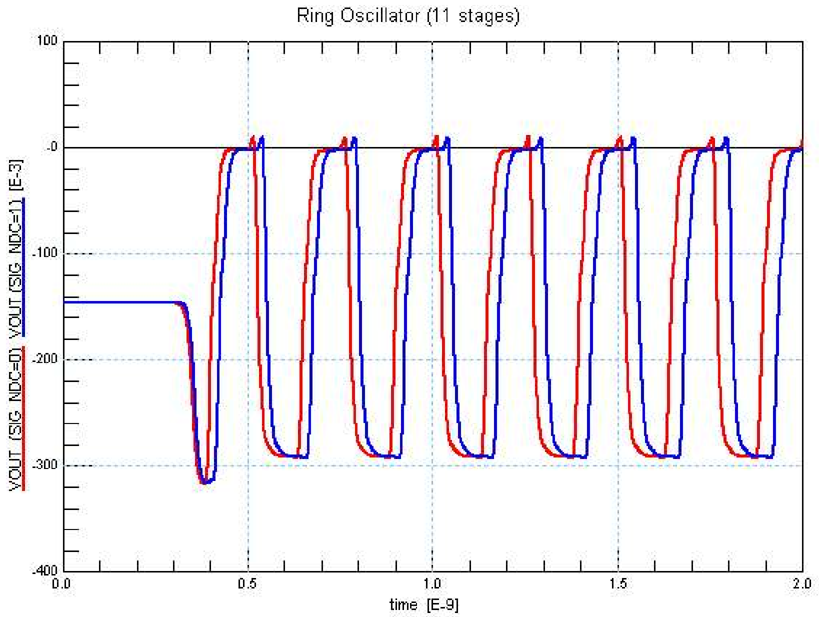


Note that no convergence issues have been observed !

SCLABLE & STATISTICAL MODEL

The statistical scalable model allows sensitivity investigation:

here 2 simulations with nominal (blue) and +1σ deviation of the Technological Parameter NDC (red) --> interesting feedback to technologists!

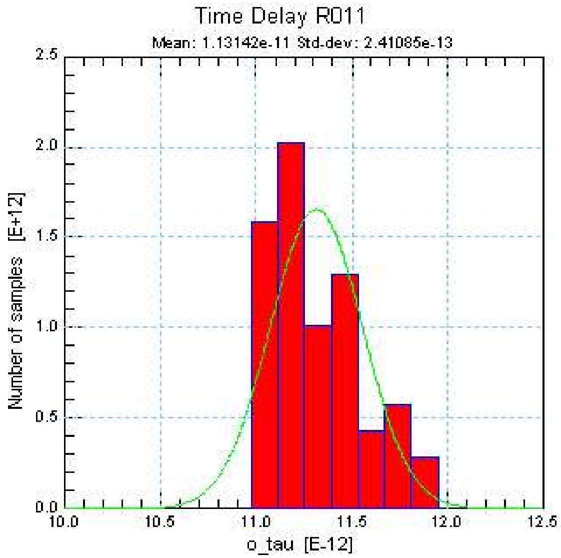


SCLABLE & STATISTICAL MODEL

Preliminary results: **50 Monte Carlo simulations of RO vs measure (18 samples)**

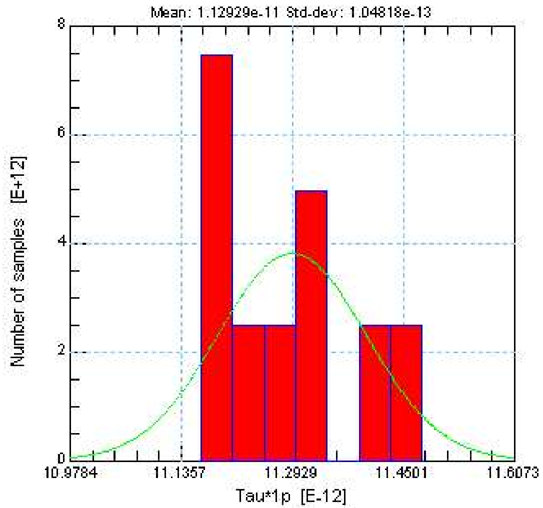
σsim 2.12%

mean sim 11.31ps



σmeas 0.9%

mean meas 11.29ps



- **Diffused resistor model needs refinement (and statistics)**
- **Simulate extracted view for additionnal parasitics ?**
- **Need more measurements in order to have a fair comparison**
- **Investigate correlation in circuit FoM (eg, oscillator frequency vs consumption)**
- **Recenter model parameter (skew) to prevent "golden die" not centered**

SCLABLE & STATISTICAL MODEL

XMOD toolkits

Toolkit name	Strategy	Model	Availability
Hicum Aperitif Toolkit	Single transistor	HICUM (level2)	Available
SMACH	Scalable methodology	HiCUM level 2	October 2006
Hicum Master Toolkit (HMT)	Scalable methodology	HICUM (level2)	Available
TRADICA Standalone (GUI version)	Scalable methodology	HICUM (level2 & level 0)	Available
Xmod SGP Toolkit	Single transistor	SGP	Under development
Xmod VBIC Toolkit	Single transistor	VBIC	Available

SCLABLE & STATISTICAL MODEL

Thanks to IHP for that collaboration and for providing the data

Special thanks to R. Scholz and G. Fischer

References

[1] M. Schroter et al, “Statistical modelling of high-frequency bipolar transistors”, IEEE BCTM, 2005

[2] D. Knoll et al, “A flexible, Low Cost, High Performance SiGe:C BiCMOS Process with a One-Mask HBT Module”, IEDM 2002

[3] M. Schroter et al, “High Frequency circuit Design Oriented Compact Bipolar Transistor Modeling with HiCUM”, IEICE transactions on electronics, VOL E88-C, No6, June 2005