Scalable parameter extraction methodologies using TRADICA and HMT for HiCUM level 2.1
Tricks and techniques

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HICUM Workshop – Crolles – June 2005

XMod Technologies
Advanced Bipolar/BiCMOS modeling and parameter extraction solutions

OUTLINE

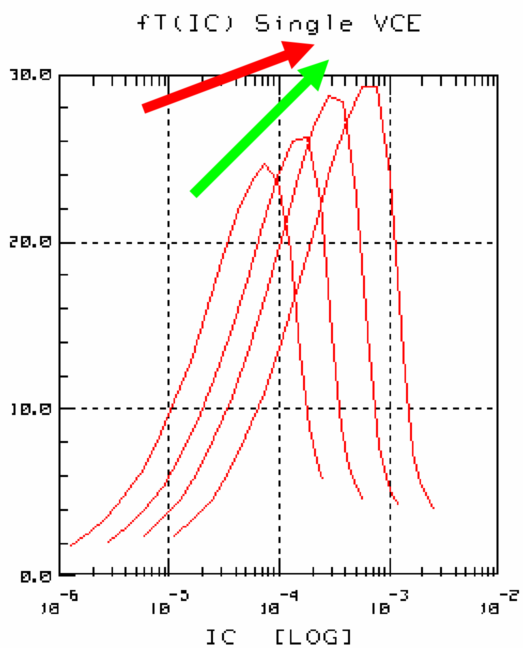
- ✓ **Introduction**
  - Technological context
  - What is scaling?
- ✓ **Measurements**
  - new constraints
- ✓ **The myth of “fitting results”**
  - What is a good model?
  - Scaling versus single fit
- ✓ **Scalable extraction methodology**
  - Procedure description
- ✓ **Solutions**
  - Tools usability
- ✓ **Conclusion**

INTRODUCTION

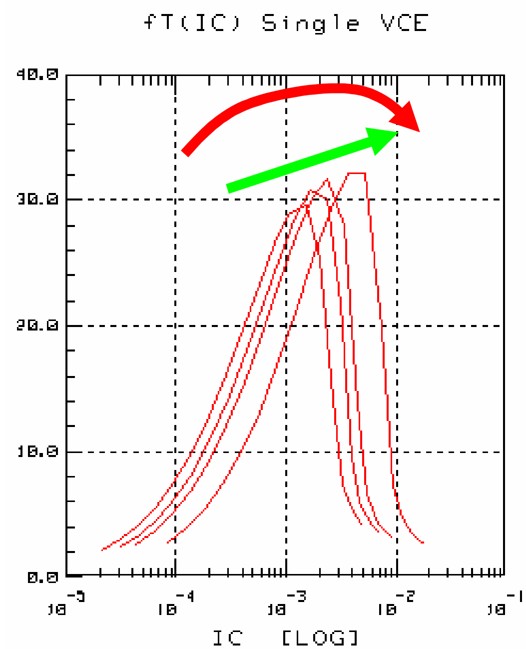
Physical effects becoming increasingly critical

Transit frequency geometry dependence: & combined with self-heating

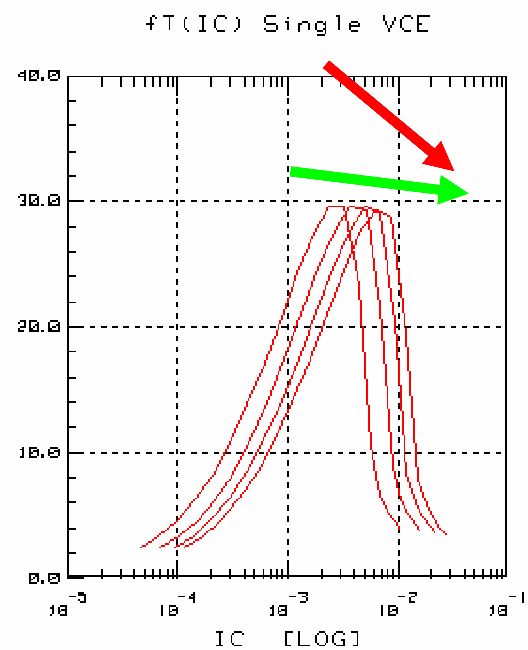
Length dependence
Width =0.4



Width dependence
Long stripe



Emitter finger dependence nE=2~5



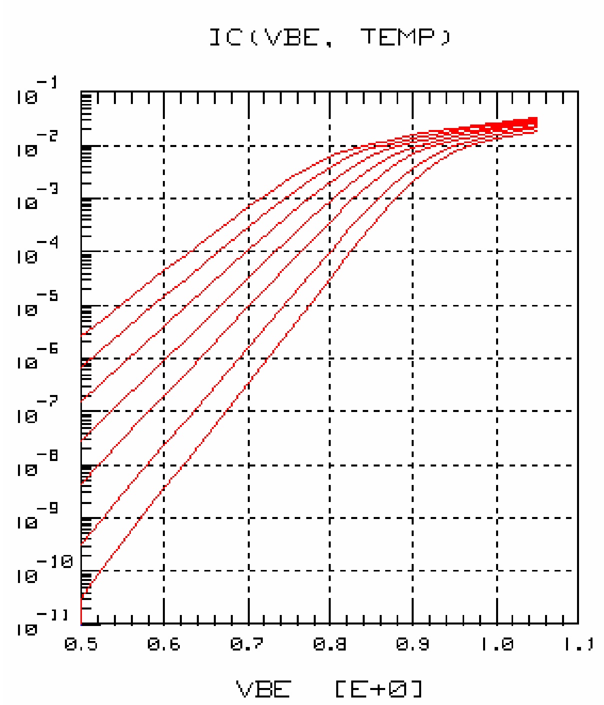
Typical behavior
Strong self Heating

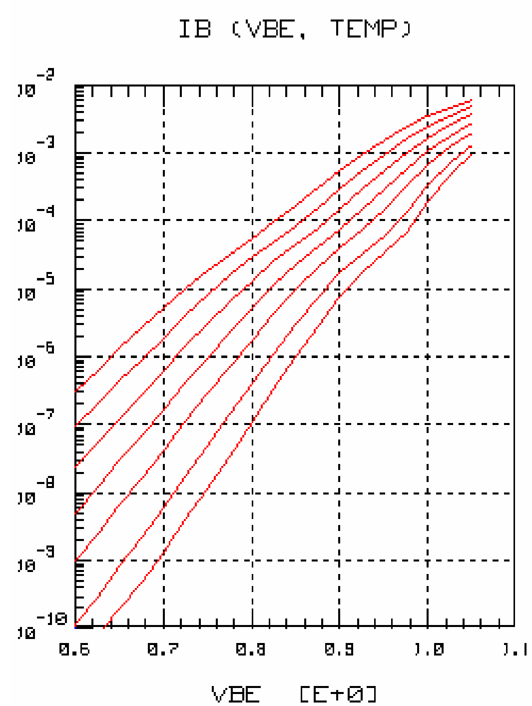
INTRODUCTION

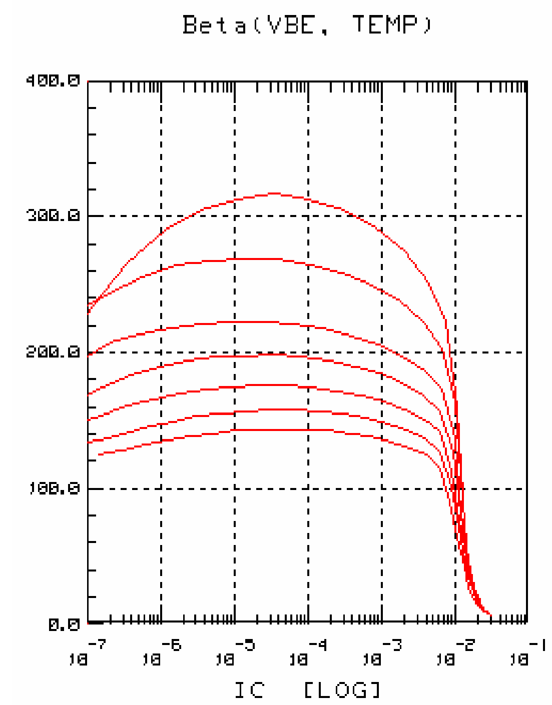
Physical effects becoming increasingly critical

TEMP= -20, 0, 27, 50, 75, 100 and 125°C

Heteroiunction barrier effect:







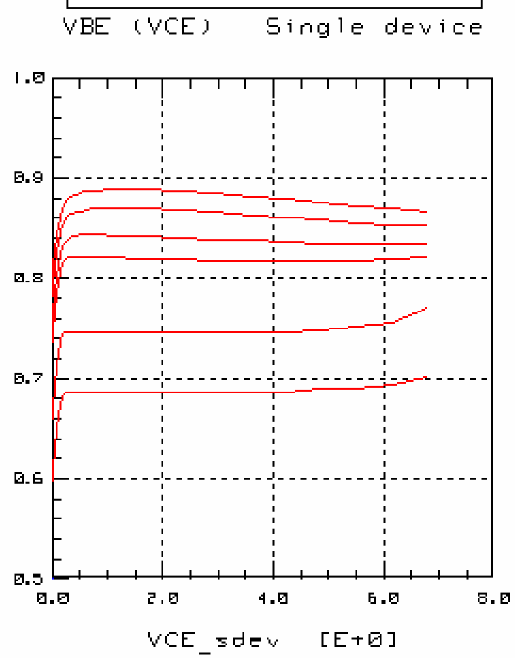
Base current increase at high bias → Beta abrupt fall off drop
Has an effect on IC → mistakenly taken into account through RE or RC
Thermally activated → more pronounced at low temperature

INTRODUCTION

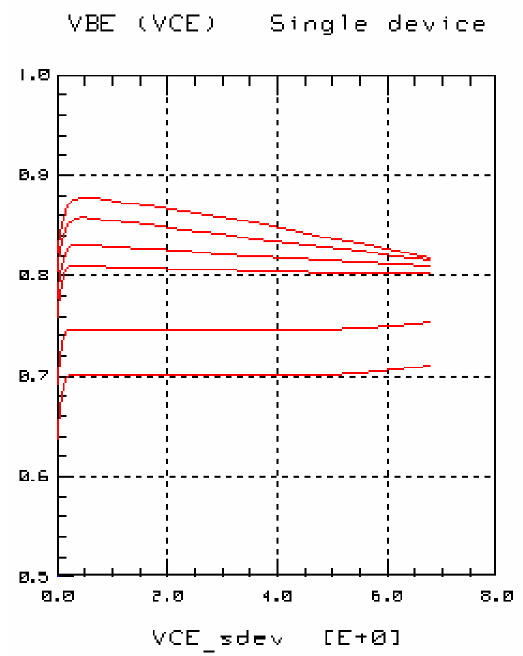
Physical effects becoming increasingly critical

Self Heating: Strongly geometry dependant
VBE (VCE, IB)

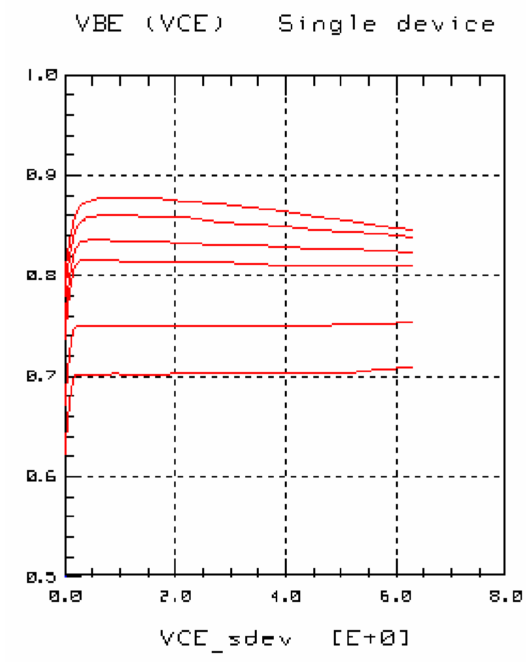
Emitter width 0.4
1E2B2C



Emitter width 1.6
1E2B2C



Emitter width 0.4
2E4B2C

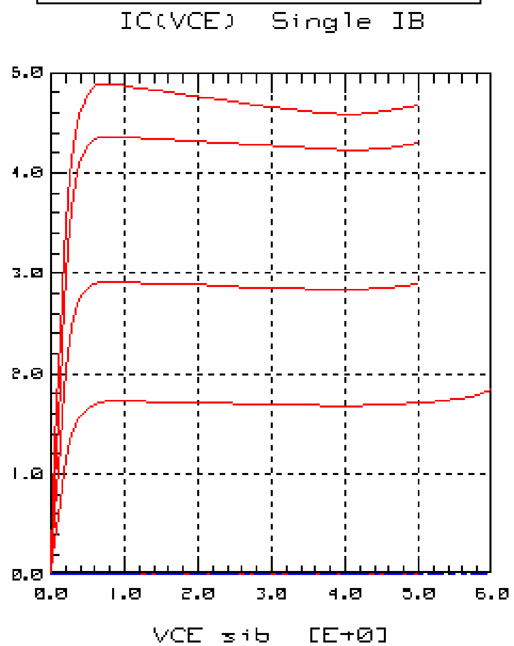


INTRODUCTION

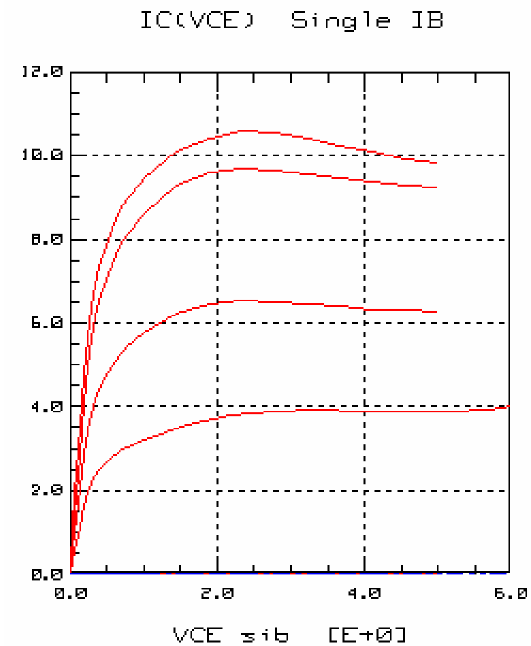
Physical effects becoming increasingly critical

Self Heating: **coupled with high current effects**

Moderate current density



High current density



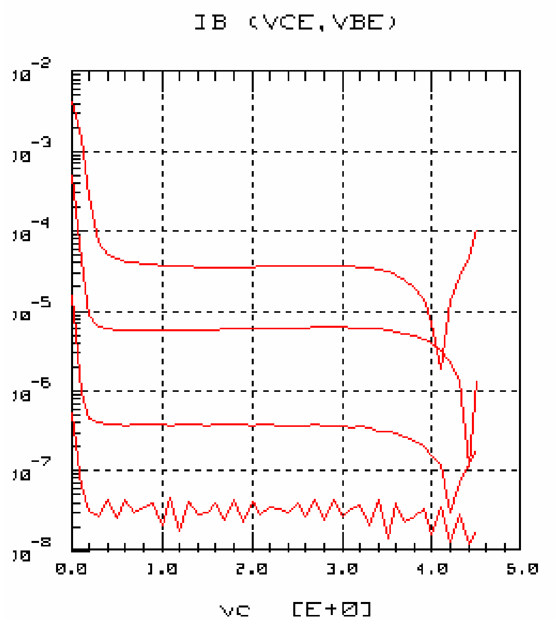
IC (VCE, IB)
Width =0.4, 1E2B2C, 2E3B2C, 4E5B2C
Width= 1.6, 1E2B2C

INTRODUCTION

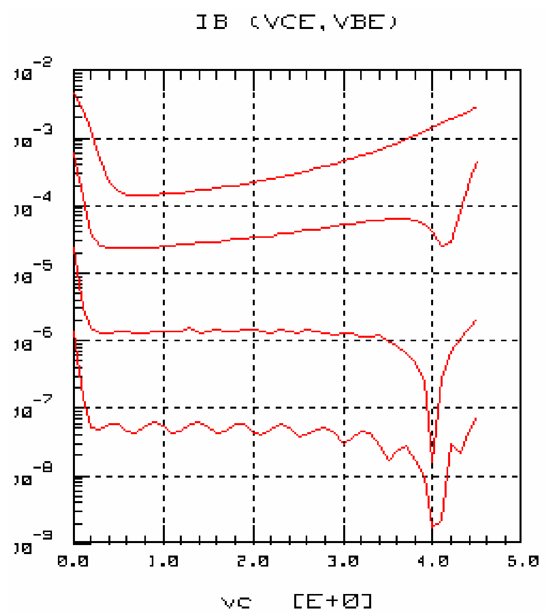
Physical effects becoming increasingly critical

Avalanche: coupled with self heating

Width = 0.4



Width = 1.6



Self-heating → temperature increase → avalanche temperature dependence → need for avalanche temperature coefficients

INTRODUCTION

All these effects have clear geometry dependence

Scaling not only helps to:

- **reduce parameter extraction time and effort**
- **Produce more devices (flexibility to designers)**

Scaling also helps to understand and capture physical effects and their geometry dependence which could simply not de done with single transistor approach

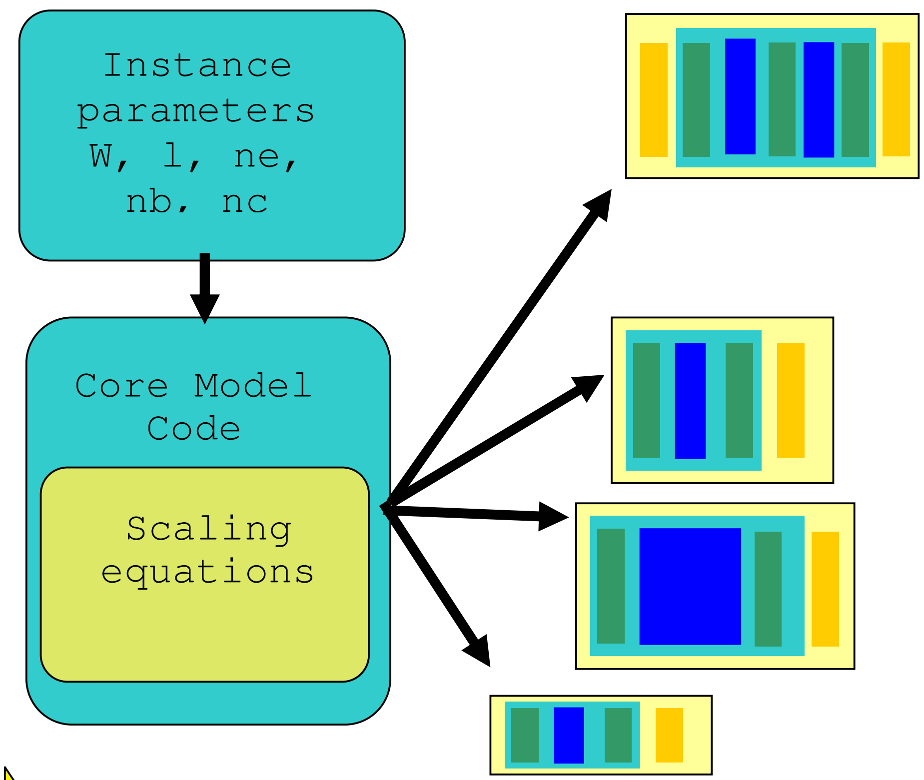
Need for Physics based models (HiCUM), good measurements, accurate and physics based scaling rules and good extraction tools

Method #1 : MOS like, eg bsim3v3

INTRODUCTION

Different scaling approaches:

Scaling equation included in model code



Not suitable

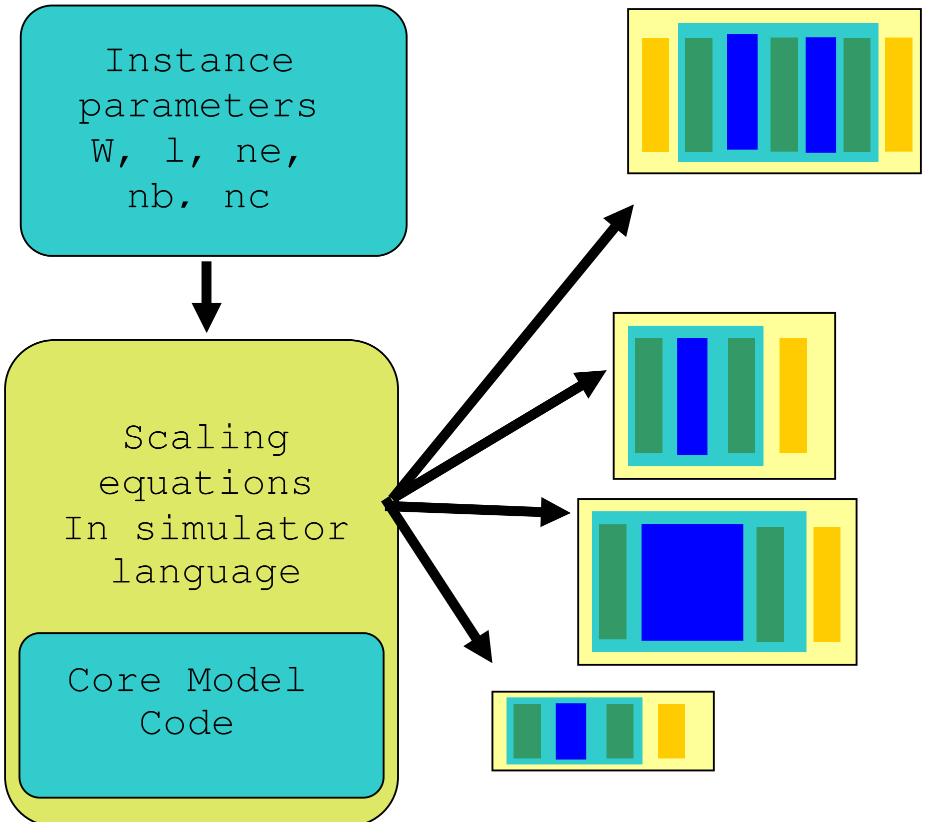
- In Bipolar scaling equations are complex
- Need new model every year
- Model need to apply to a wide variety of processes

→ model code never stable for most advanced technologies
→ Burden for model developers, less support, less research
→ Pressure → quick fix of deficiencies with fitting parameters = bad model for a long time

INTRODUCTION

Different scaling approaches:

Scaling equation included in macro model



Support difficult on the long run

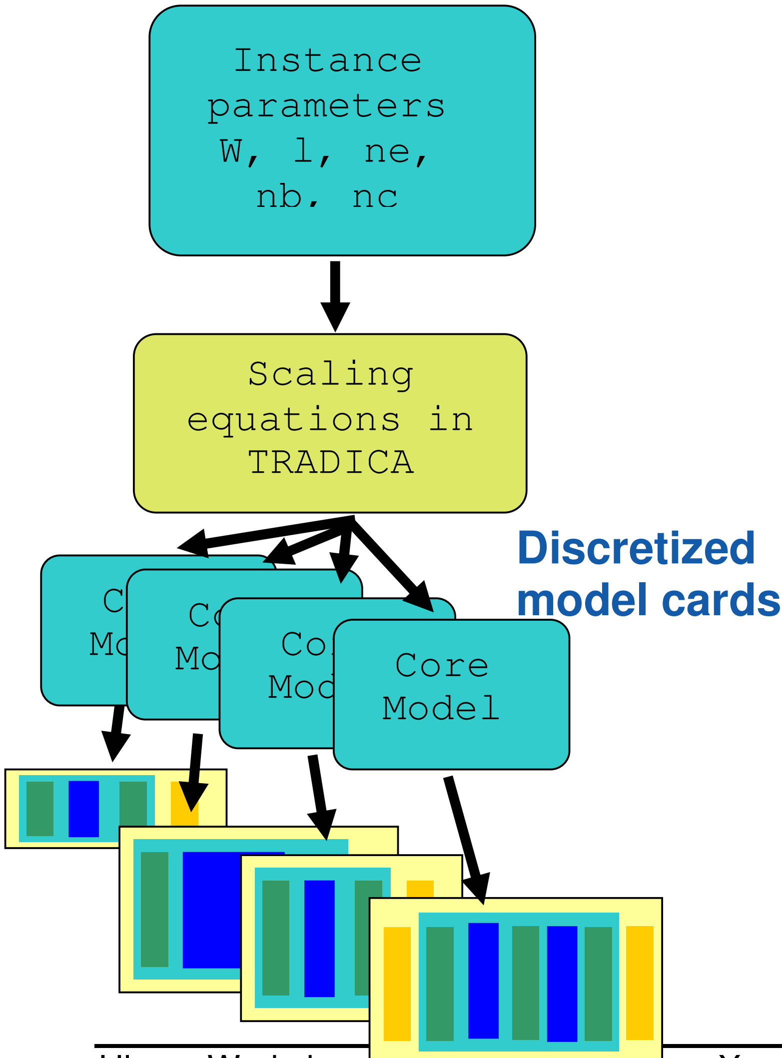
Method #2 : Macro model

- Complex equations difficult to handle with simulator macro language
- Simulator compatibility issues
- In house solutions = different for every company → the MOS nightmare!
- Burden at the foundry level
- High support cost for each company
- Version handling x number of simulator supported x processes, …
- …

INTRODUCTION

Different scaling approaches:

Scaling equation in an external program



Method #3 : TRADICA & HMT

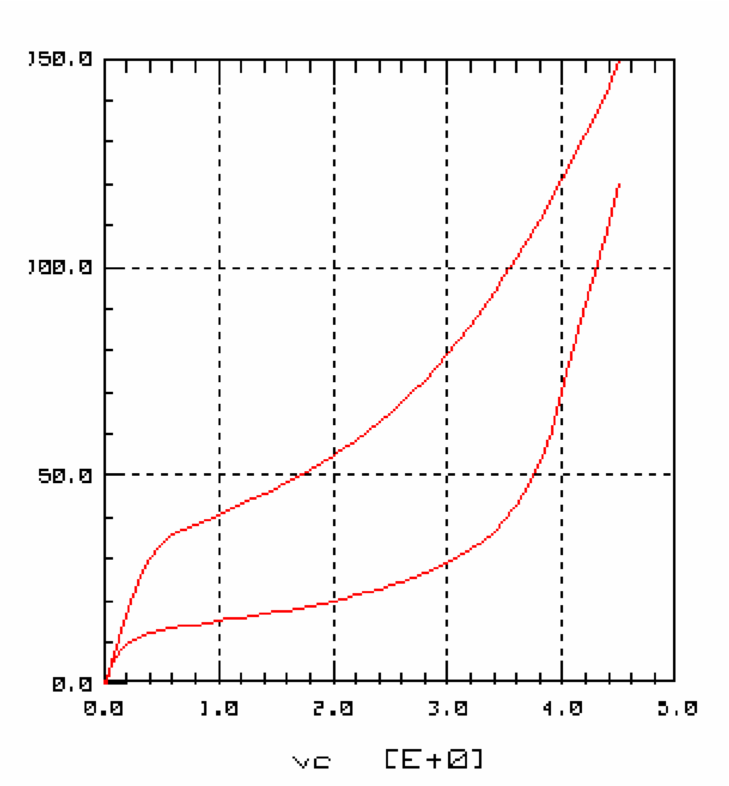
- Advanced scaling equations can be used (suitable for a wide variety of technologies)
- Efficient handling of corner/statistical models
- Model library has very simple syntax (simulator support)
- Scaling equations and model core decoupled
- Cost and support shared among several companies
- …

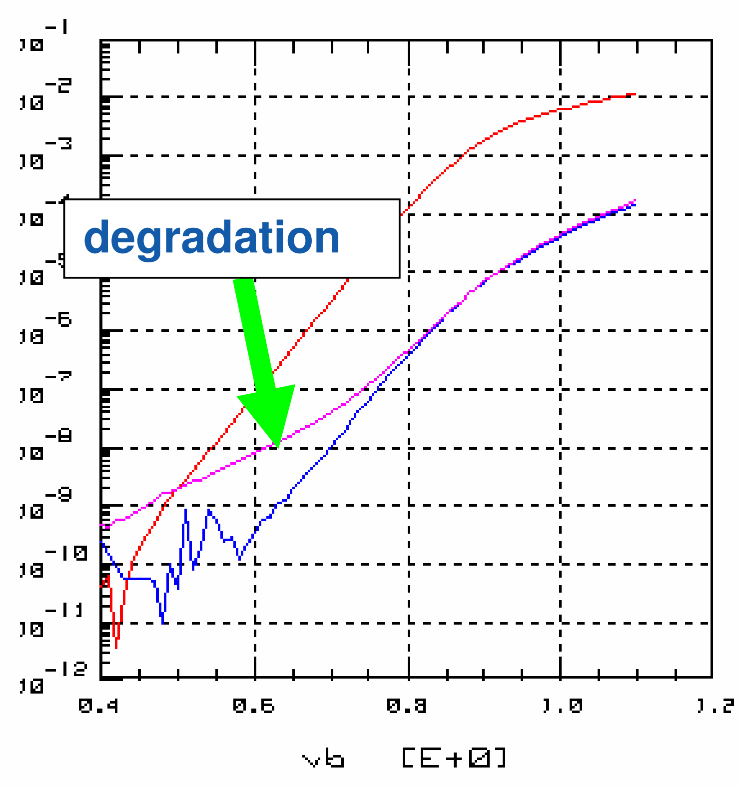
MEASUREMENTS

HIGH CONSTRAINTS:

Choosing bias conditions:

Need to measure high bias and high voltage to obtain fT peak and avalanche → may result in device degradation or destruction

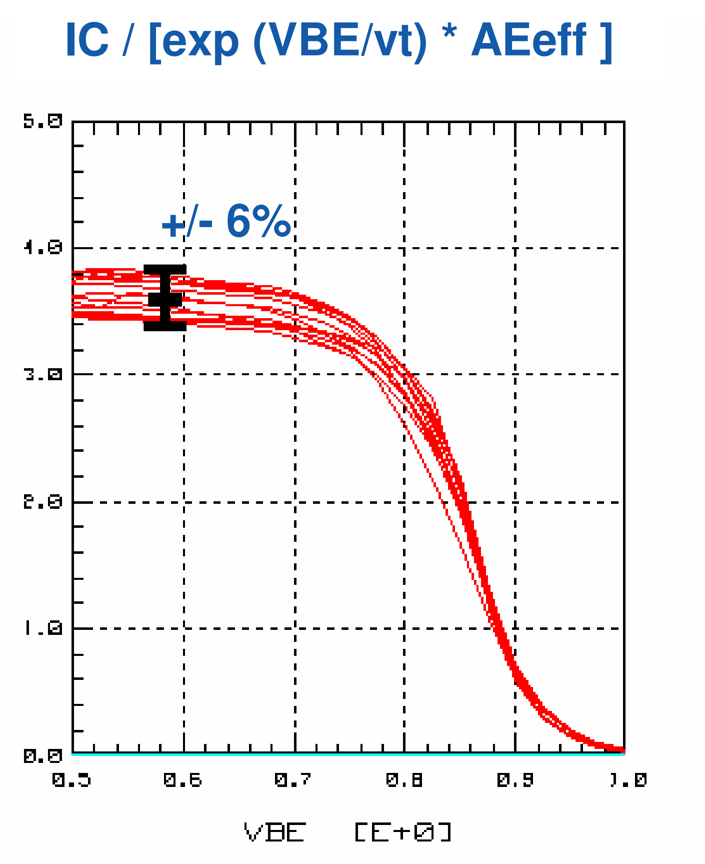




MEASUREMENTS

HIGH CONSTRAINTS:

Example: 10 different devices with different emitter dimensions



Advantages:
- Information about process scalability
- Statistical variation within the same die
- Remove outliers for extraction
- Do not spend effort to fit irrelevant data
- Detect inconsistencies

Disadvantage:
- Higher constraints
- Difficult to measure a suitable data set
- Can't achieve "perfect fit"
- …

MEASUREMENTS

Measurements for scalable extraction:

VERY HIGH CONSTRAINTS:

ALL measurements have to be consistent
+ Large number of measurements required (geometry, frequency, bias and temperature range)
+ Measure on the same die
+ High currents & high voltage bias
+ time constraints
+ de-embeding dummies (chip space/accuracy)

Measurement inconsistency "AVALANCHE" phenomenon
→ one single mistake can degrade all measurements

Measurement errors are unavoidable → need for careful data consistency checks (with respect to geometry)

THE "MYTH" OF GOOD FIT

What is a good model?:

Single transistor models look NICE:

- **The RMS error can be very low**
- **Model parameters are optimized in that way**

But

- **Optimization "noise" in model parameters**
- **Overlapping contradictory physical effects are invisible → not captured by models**
- **Statistical variation "noise" in model parameters**
- **Parameter geometry consistency is not granted**
- **Limited measurement consistency check (w.r.t. geometry)**
- **The measured die will never be seen again → false feeling of safety!**

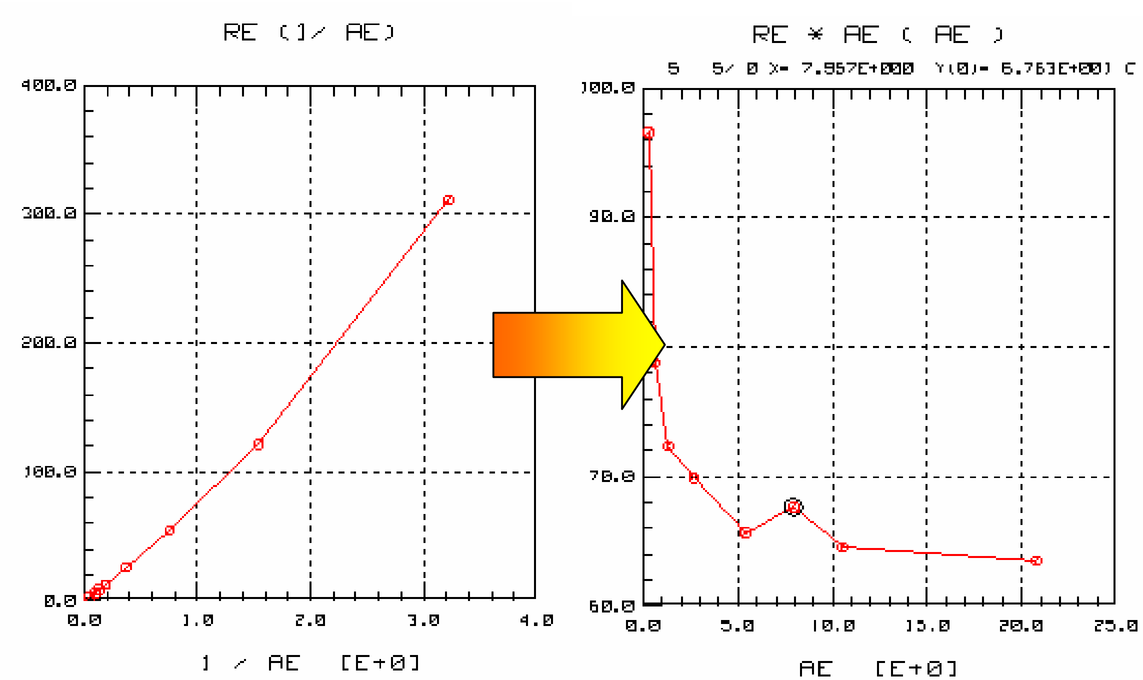
THE “MYTH” OF GOOD FIT

Example:

RE extraction from the gm method:

With the single transistor method each extracted value is used as is.

On the plot below it looks good, but the area specific parameter r_KE is **not flat!**



- For the devices with large widths, the self heating effect is strong → IC increases → gm increases → apparent RE is lower
- Small devices are subject to emitter size variations
- Large sizes affected by contact resistances

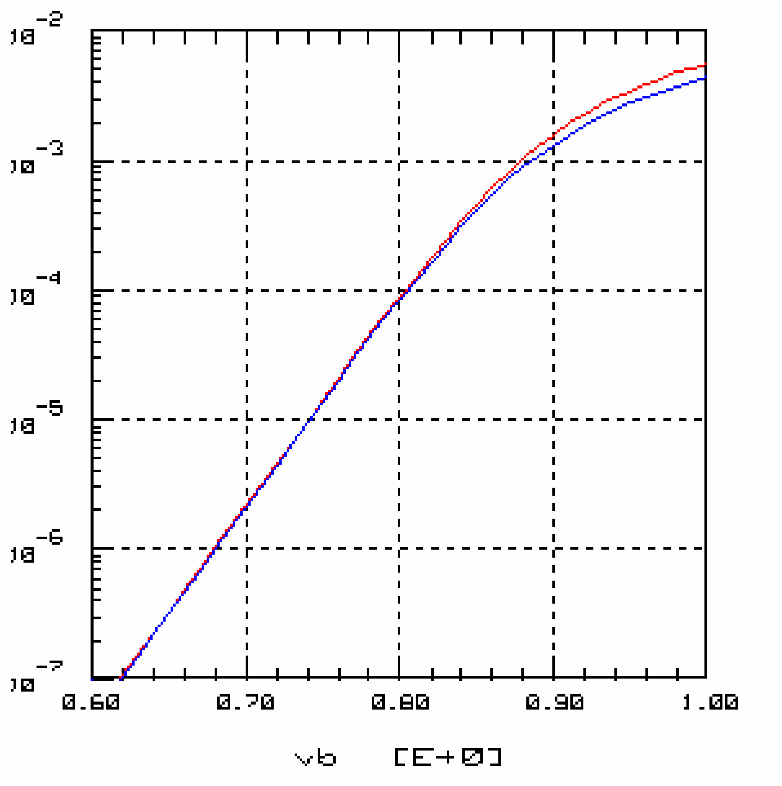
→ Only a few devices are relevant for a given extraction → geometrical calculation is necessary

THE "MYTH" OF GOOD FIT

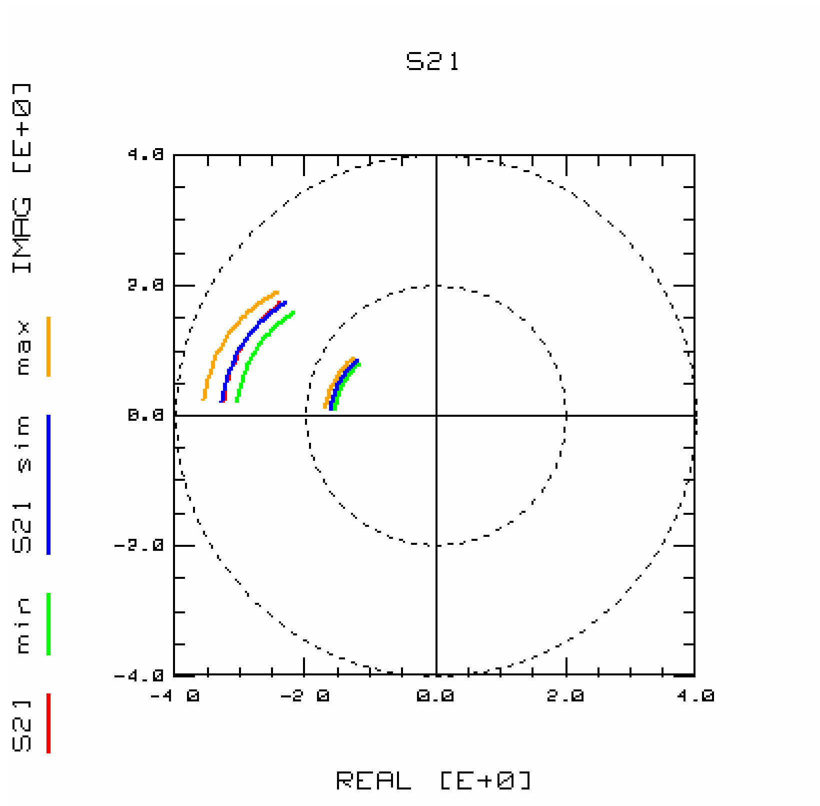
IMPLICATIONS

Contact and setup parasitic resistances or extraction error:

→ dramatic effect on S-parameter fitting



S21 simulation with RE +/- 10%



THE "MYTH" OF GOOD FIT

What is a good model? **(I don't have the answer!)**

Some useful elements:

- **A scalable model ensures consistency of the model parameters**
- **A scalable model requires consistent measurements by definition**
- **A scalable model with a RMS error within intra die statistical deviation is a good starting point** (easy to evaluate for DC, but for S parameters?)
- **A scalable model should capture the physical effects and trends (fT peak vs geometry, high current effects vs geometry, self-heating vs geometry, …)**

➡ **Scalable models realize a trade off: any discrepancy between measurement and simulation has to be evaluated carefully with respect to process variations**

Model the process not a measured die

SCALABLE METHOD

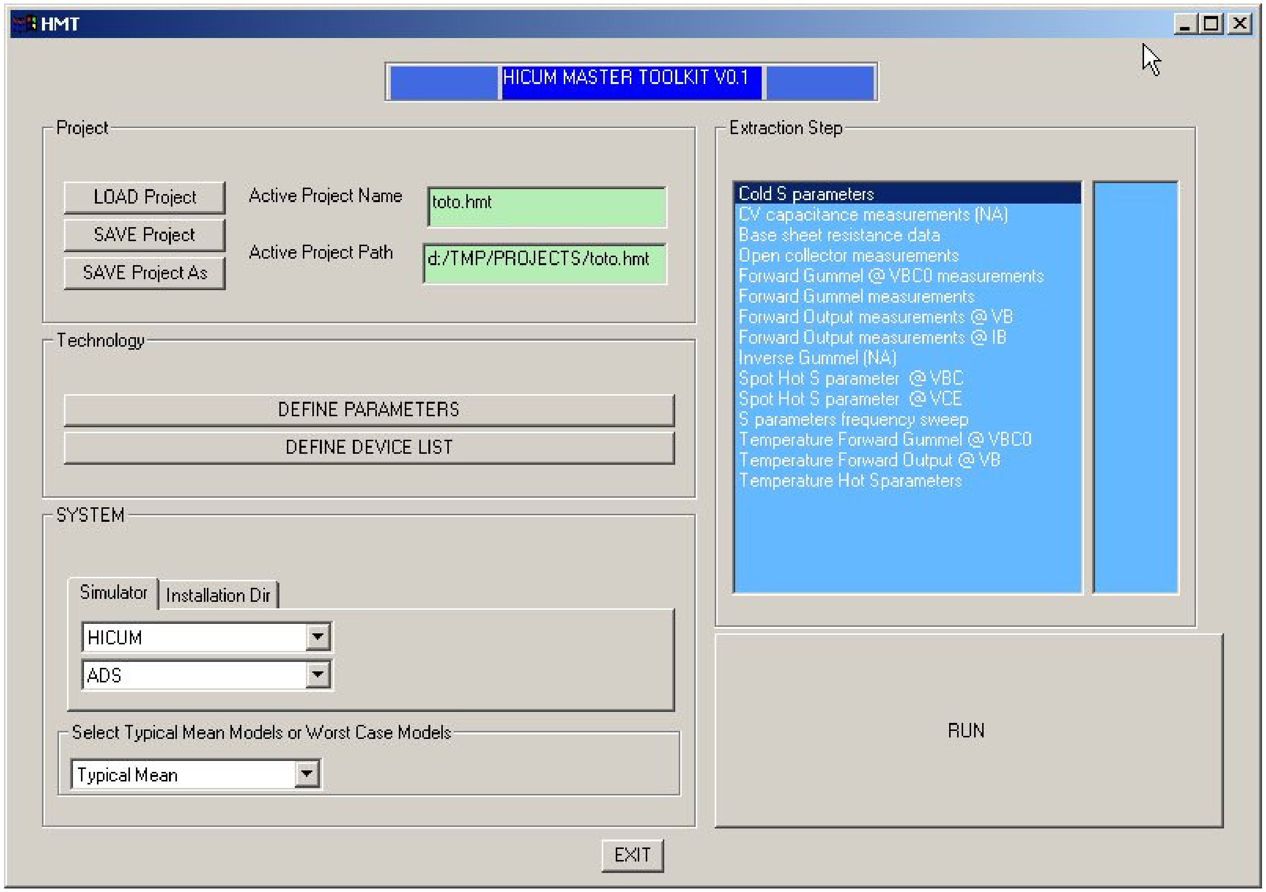
Physics based extraction

Methodology based on:

- **TRADICA (batch version) from M. SChroter**
- **HMT - HiCUM Master Toolkit (ICCAP scalable extraction tool) from XMOD**

HMT Main window

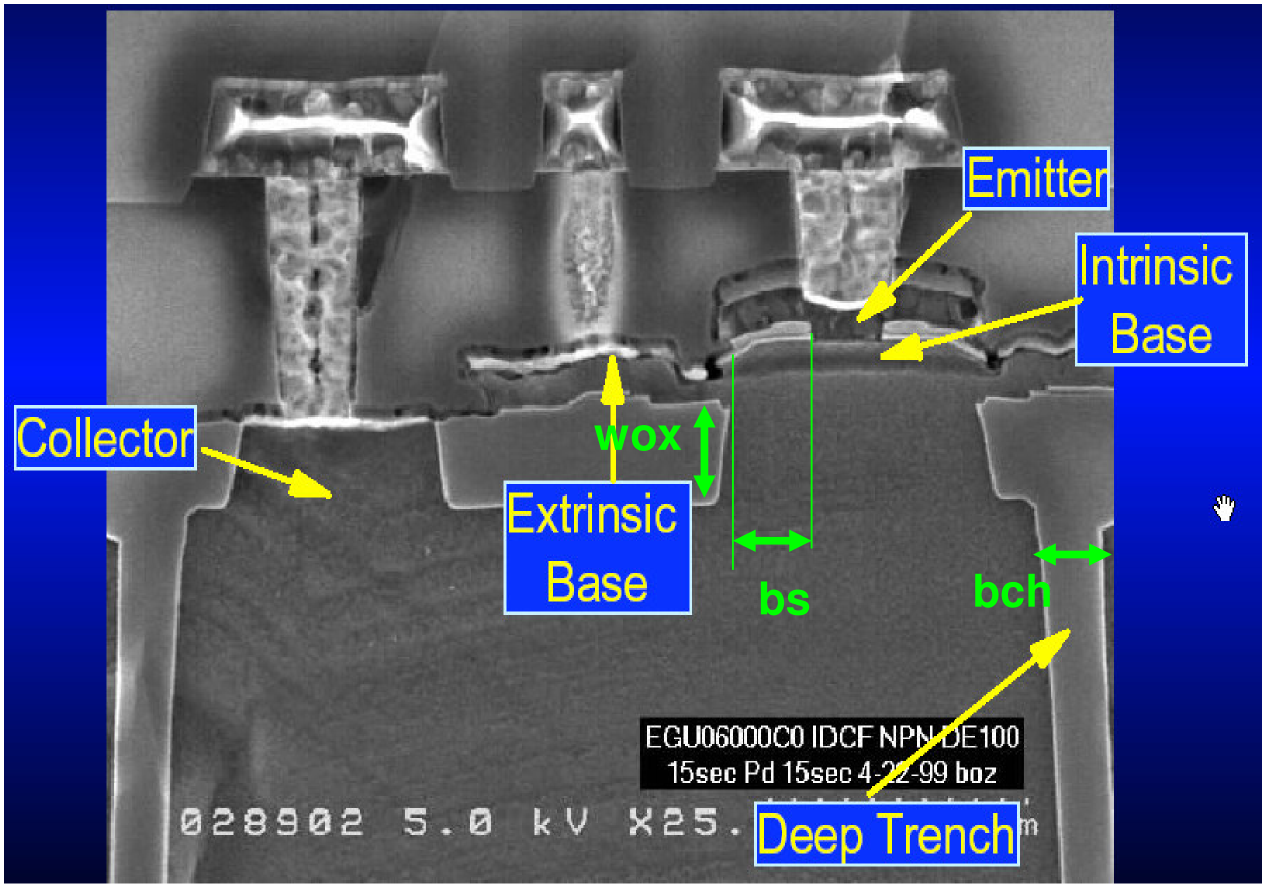
- **Extract model parameters**
- **Link to TRADICA**
- **Generate model library**



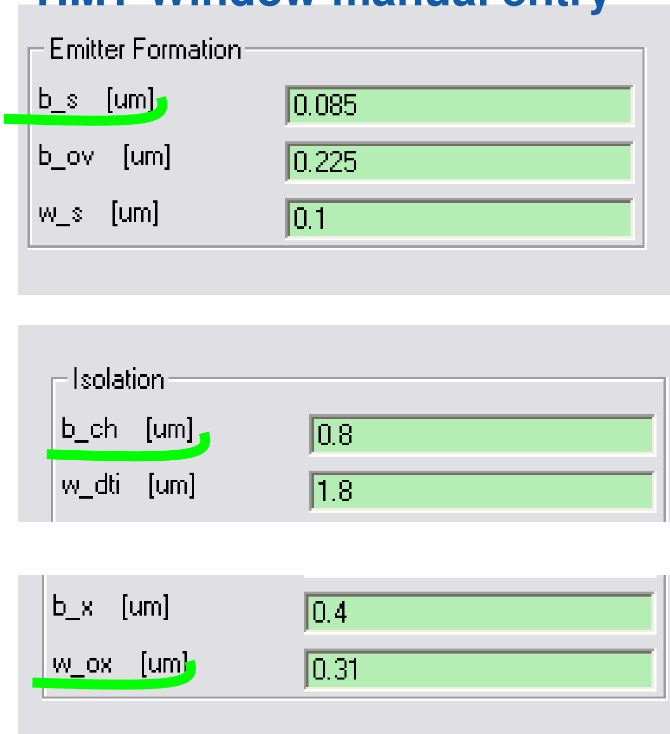
SCALABLE METHOD

Process and geometry data collection:

1st step: determine geometry parameters from SEM cross section



HMT Window manual entry



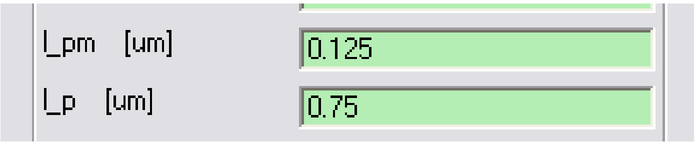
And so on …

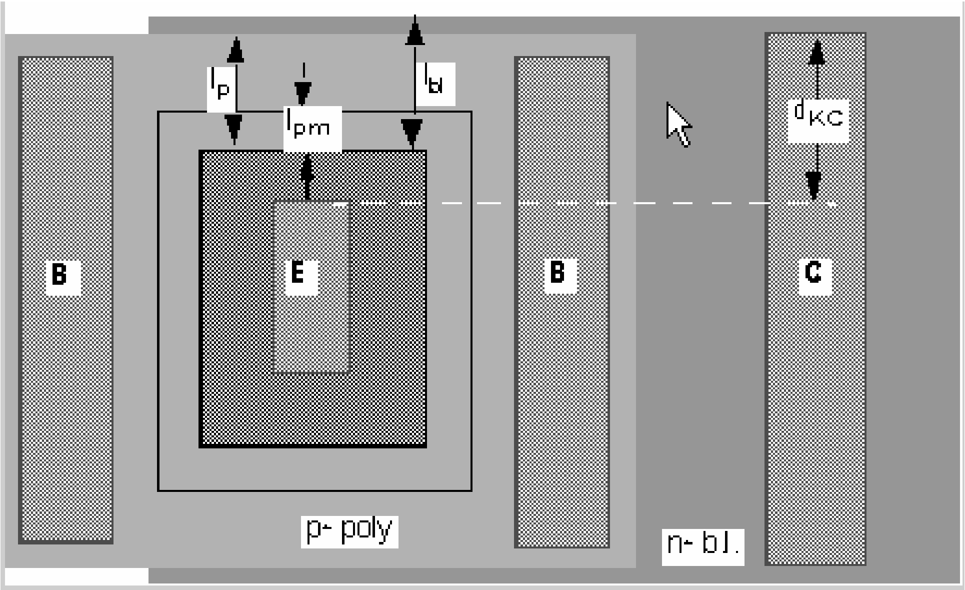
SCALABLE METHOD

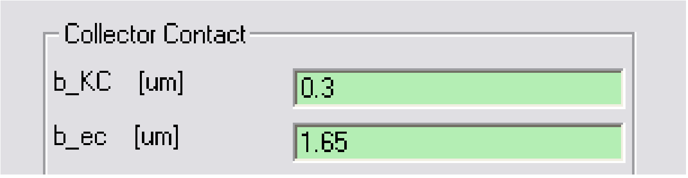
Process and geometry data collection:

2nd step: determine geometry parameters (top view) from layout rules or/and top view SEM

HMT Window manual entry







And so on …

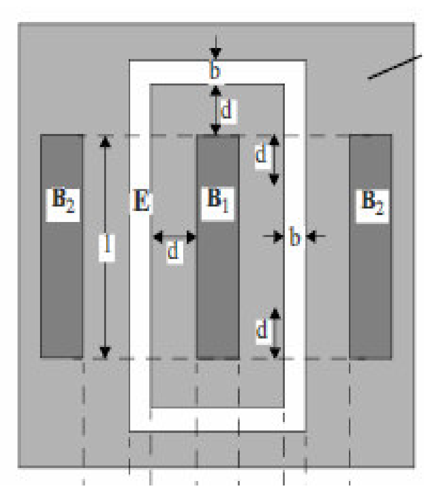
SCALABLE METHOD

Process data extraction:

3^{rd} step: determine sheet & contact resistances from test structures with HMT

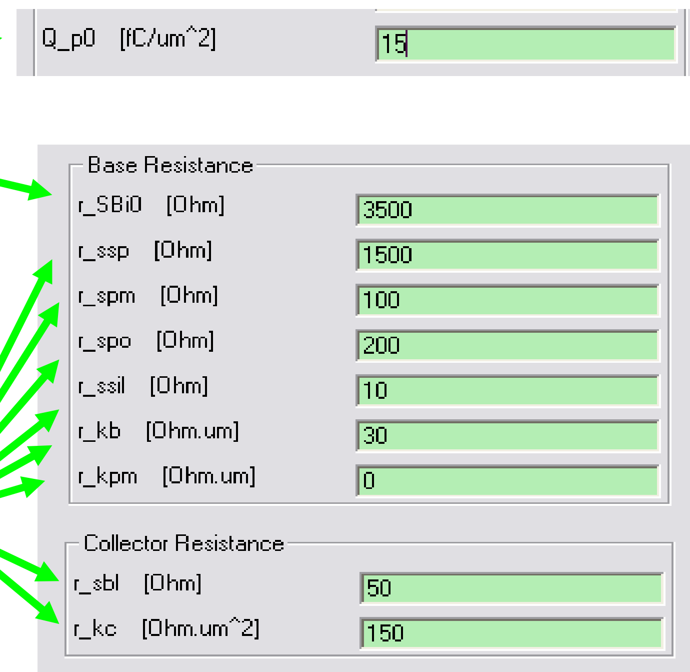
- **Measure test structure and import data in HMT (ICCAP Tool)**
- **Run HMT extraction routines**

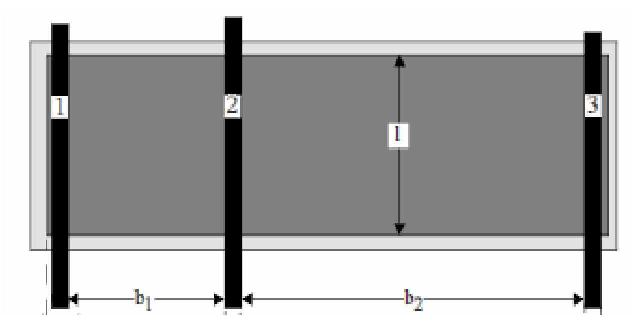
HMT Window automatic extraction



Tetrode transistors = ring emitter

different widths and lengths





3 or 4 contact sheet resistance test structures: For buried layer, Poly, silicide, …

Manual entry can still be used if test structures are not available

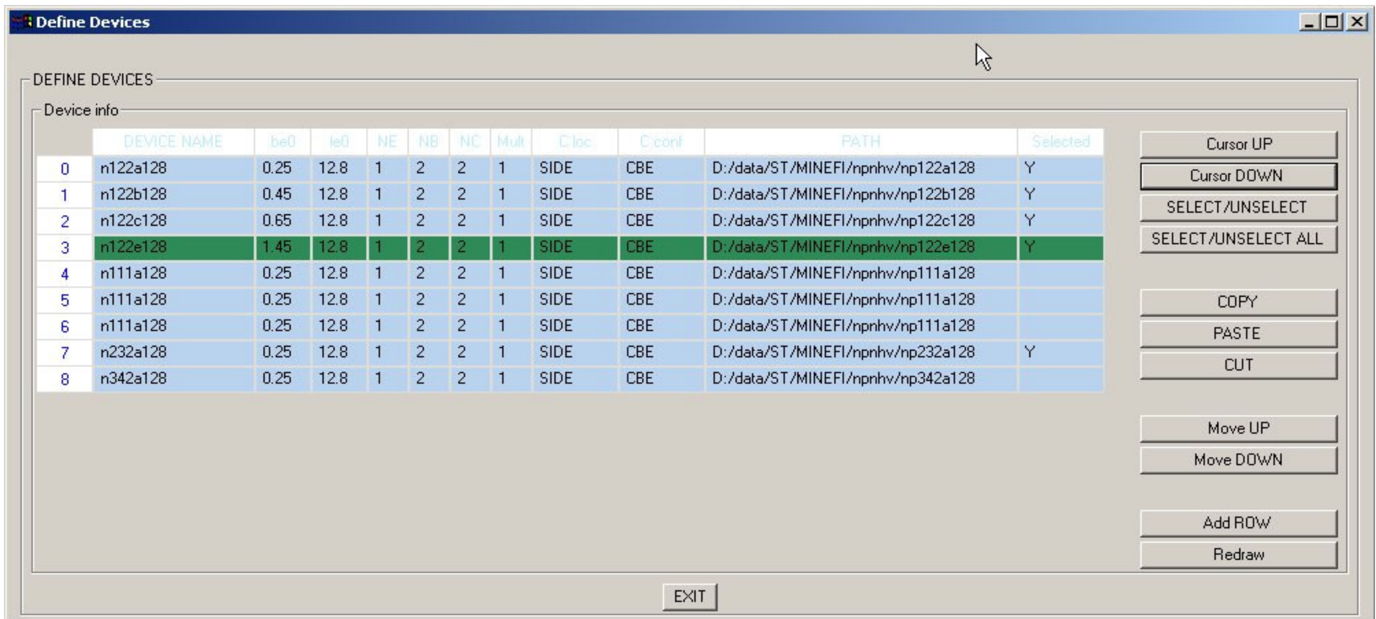
SCALABLE METHOD

Process specific parameters extraction:

4th step: extract process specific (geometry independent) parameters from DC and RF measurements

- **Select devices in HMT**
- **Import data (automatic procedure)**
- **Navigate through data if necessary**
- **Run extraction**
- **Go to the next extraction step**

HMT transistor and test structure selection window → easy to define link to data file and activate/de-activate devices



	DEVICE NAME	be0	le0	NE	NB	NC	Mult	C loc	C conf	PATH	Selected
0	n122a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np122a128	Y
1	n122b128	0.45	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np122b128	Y
2	n122c128	0.65	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np122c128	Y
3	n122e128	1.45	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np122e128	Y
4	n111a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np111a128	
5	n111a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np111a128	
6	n111a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np111a128	
7	n232a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np232a128	Y
8	n342a128	0.25	12.8	1	2	2	1	SIDE	CBE	D:/data/ST/MINEFI/npnhv/np342a128	

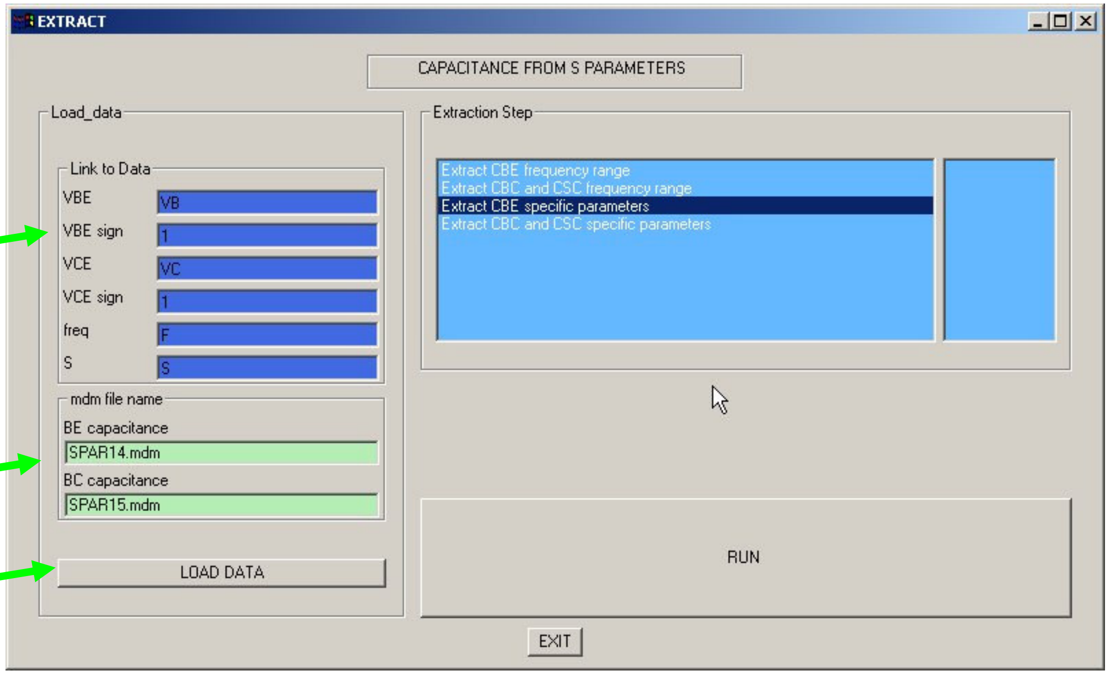
SCALABLE METHOD

- Select devices in HMT
- Import data (automatic procedure)
- Navigate through data if necessary
- Run extraction
- Go to the next extraction step
-

Naming conventions

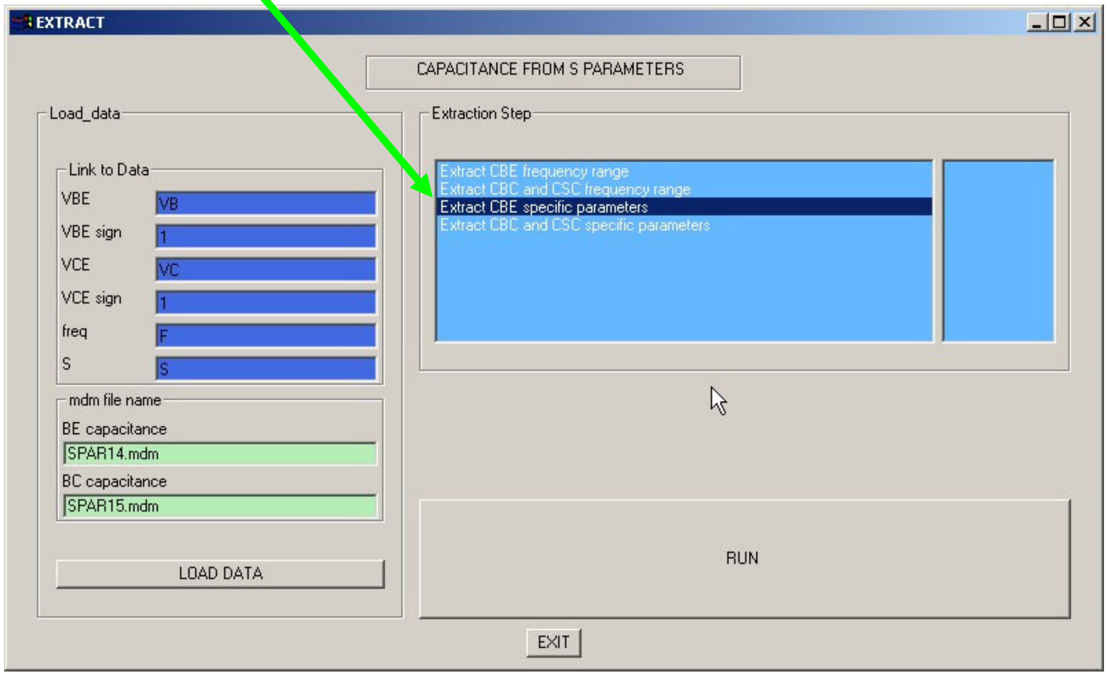
Data file name

Hit load button



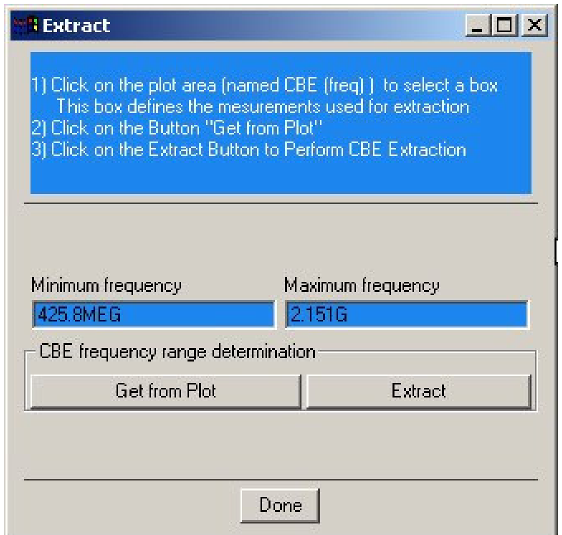
SCALABLE METHOD

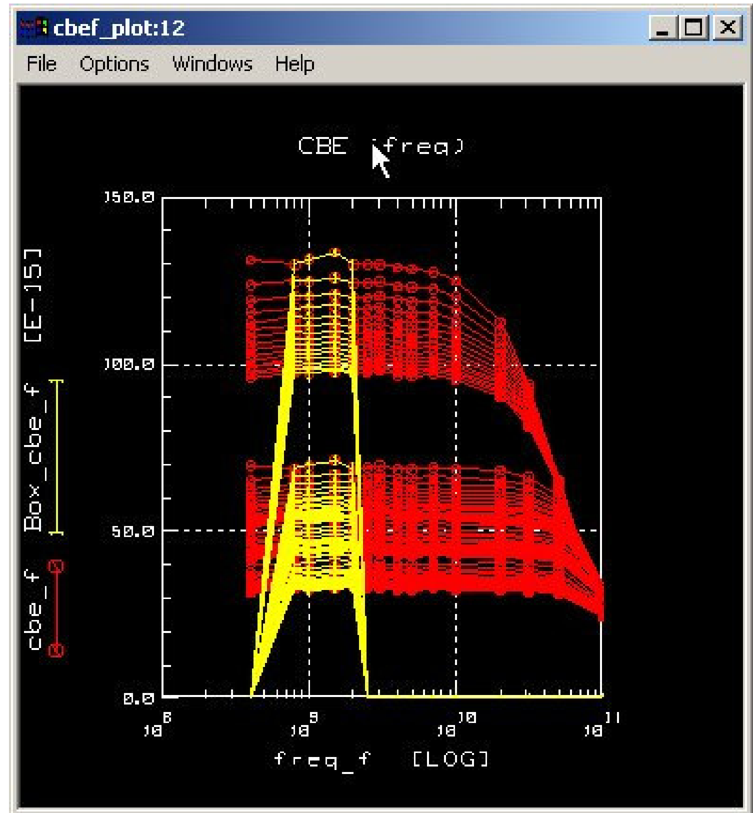
- Select devices in HMT
- Import data (automatic procedure)
- Navigate through data if necessary
- Run extraction
- Go to the next extraction step



SCALABLE METHOD

Example: procedure to extract CJE from cold S-parameter measurements

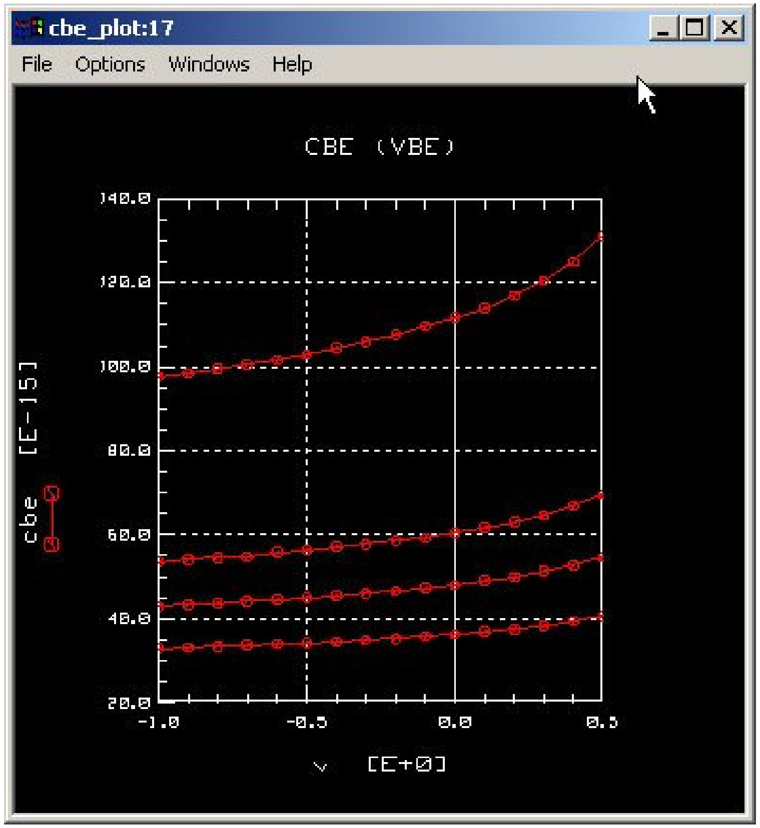




Select frequency range from which the parameters have to be extracted
(yellow curves underline selected data)

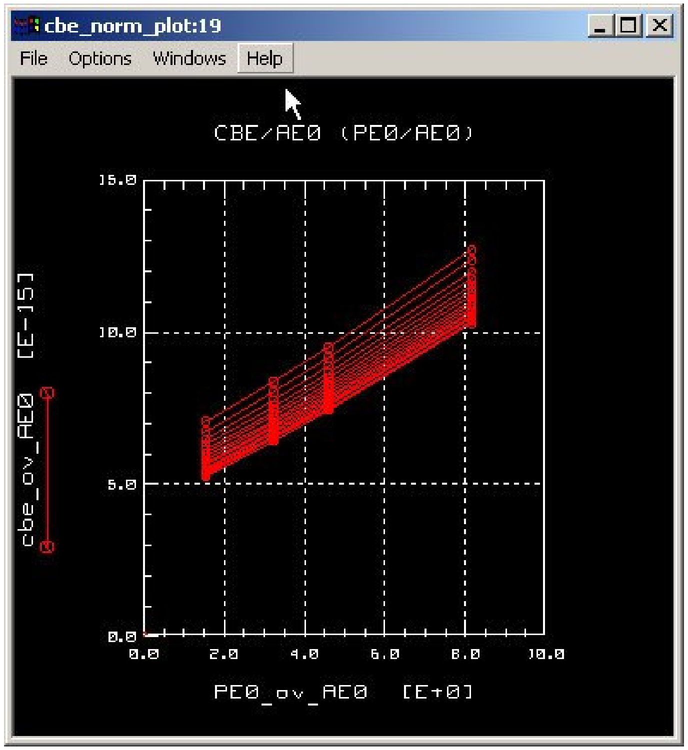
SCALABLE METHOD

CJE versus voltage



Capacitance versus bias is computed for the selected transistors

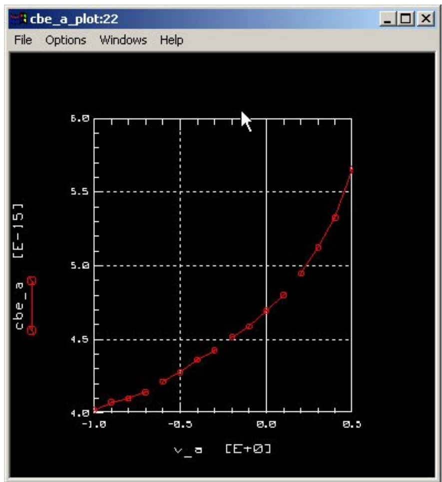
CJE versus geometry



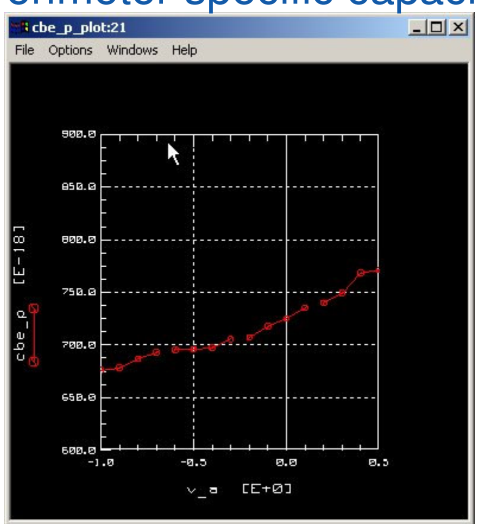
Capacitance versus Geometry automatically displayed: from slope and intercept area and perimeter component are calculated

SCALABLE METHOD

Area specific capacitance



Perimeter specific capacitance

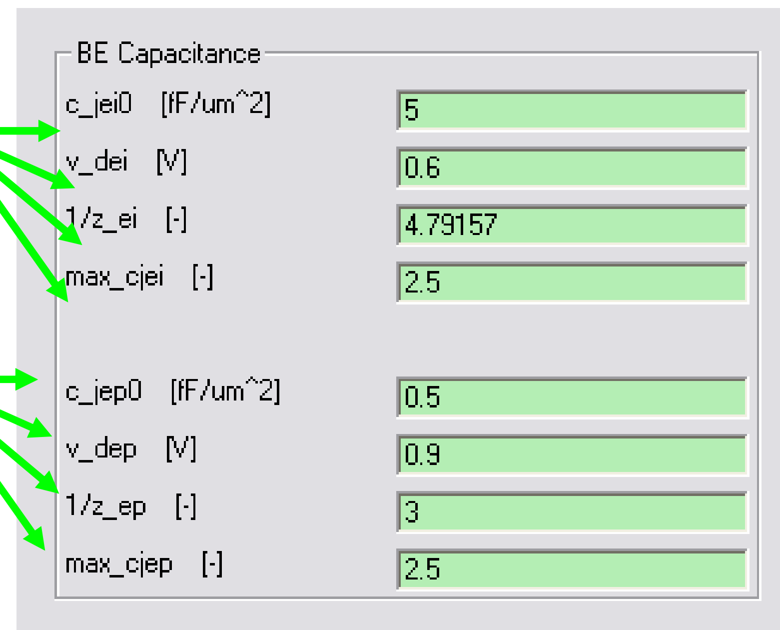


Capacitance specific parameters are extracted from area and perimeter capacitance components

The whole sequence takes 2 minutes

Extraction routines

Extraction routines



And so on for all the specific model parameters …

SCALABLE METHOD

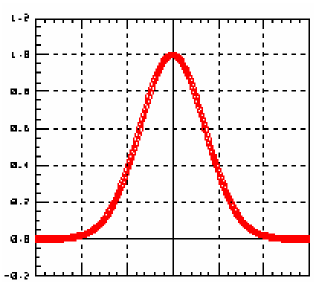
Verify model accuracy:

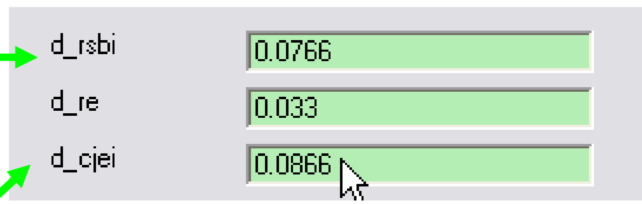
6th step: navigate through data (Gummel, IC(VCE), S parameters, ...) select/unselect transistor geometries and run Measurement/Simulation comparisons

Determine PCM data deviation:

7th step: Determine PCM deviations from mean value

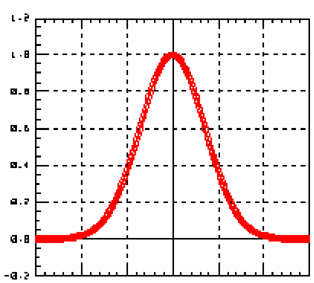
d_rsbi





And so on …

d_cjei



SCALABLE METHOD

Determine PCM data deviation:

8^{th} step: Determine PCM combination producing the +/-3 σ FoM deviation (eg, f_T)

- **Through TRADICA statistical analysis (Design of Experiment & surface response method)**
- **Through simulations within HMT (eg, manual DoE)**

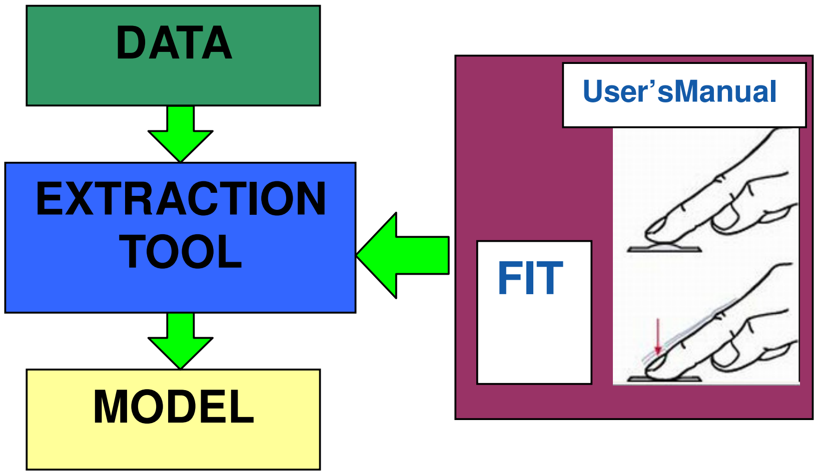
Generate typical parameters and corner models:

9^{th} step: Run model generation (choose model, device list, simulator syntax, corner fast/slow)

TOOLS USABILITY

The dream of modeling engineers? Maybe a nightmare …

This tool (probably) does not exist



In real life modeling:

- **At each step users have to interact**
- **Users need to keep the control**

TOOLS USABILITY

Advanced bipolar modeling requires a lot of HUMAN interaction:

the extraction tools have to facilitate this interaction eg, automate only time consuming and repetitive part of the work

- **Data manipulation (select/unselect devices – import data)**
- **Perform automatic calculations**
- **Iterate through the extraction and verification steps**
- **Generate automatic documentation (report ready plots)**

This is not a gadget!

- **Engineers can focus on device physics instead of loosing time**
- **Navigate through 200 to 400 plots and get a broad view of the process behaviour requires very efficient tools**

CONCLUSION

XMOD toolkits

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

CONCLUSION

- We have presented the coming challenges of successful scalable methods
- Doing measurements suitable for scalable extraction methodologies is very difficult
- Scalable methodology is a powerful tool for measurement consistency checking
- A critical review of model quality criteria has been presented
- The scalable extraction methodology used within XMOD has been detailed
- Considerations related to parameter extraction tools have been presented

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