PCM- and Physics-Based Statistical BJT Modeling Using HICUM and TRADICA

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Introduction

Parameter types

Statistics

Parameter mapping

Evaluation Methods

Results

Conclusions

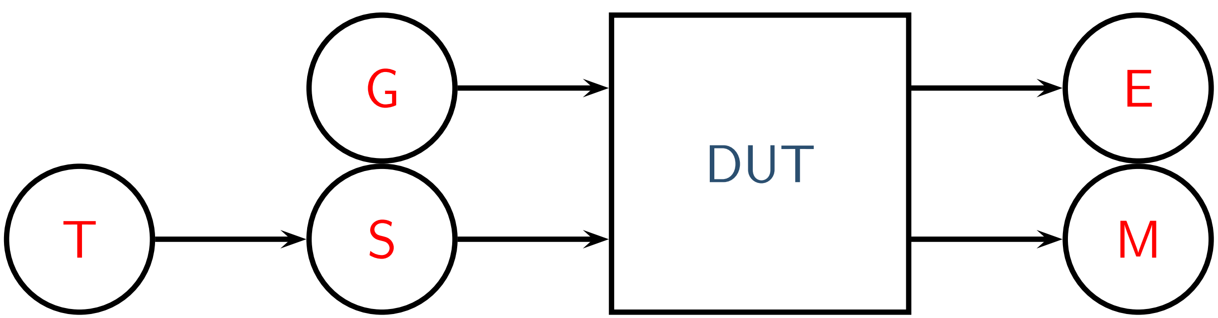
References

- roots in digital design
  - often similar topology
  - 2 highly correlated figures of merit : speed & power
  - simplified : $\frac{\partial V}{\partial t} = \frac{I}{C}$
  - leads to fast & slow corner models
- possibly good enough for slew rate
- but what about
  - hysteresis of Schmidt trigger
  - phase margin
  - offset voltage
  - headroom of an amplifier
- depends on design $\Rightarrow$ analog design knowhow

- something more flexible is needed
- but on solid physical base
- proposed approach allows
  - wcs/bcs simulation, definable by designer
  - on top of that simulation of local (mismatch) variation for selected devices
  - simulation of global (process) variation
  - sweep of process parameter

Parameter types

- T : Technology parameters
  (doping, layer thickness, ...)
- S : Specific electrical parameters
  (sheet res., cap. per area, ...)
- G : Geometric parameters (design & TDR)
- E : Electrically measurable data (E-test, PCM)
- M : Model parameters



- why statistics on P={T,S}?
  - (P,G) only rational basis for process variations and mismatch
  - no need to specify correlations
  - during life cycle of technology changes occur in process flow (⇒ P) and layout rules (⇒ G)
  - makes retargeting easier
- $P = P_{nom} + \Delta P_G + \Delta P_L(w, l)$
  - ΔP_G set external to models
    common to all instances
    deterministic (corners) or random (process variation)
  - ΔP_L random (mismatch, local variation)
    evaluated per instance

- To get familiar with the idea, consider simplest case:
- low ohmic poly resistor

$$R = 2 * \frac{RCS}{W} + RSH * \frac{L}{W+DW}$$

- G : W, L
- P : RSH, RCS, DW
- E : R

- For the variance of the poly resistor we have :

$$\sigma_R^2 = \left(\frac{\partial R}{\partial RSH}\right)^2 \sigma_{RSH}^2 + \left(\frac{\partial R}{\partial DW}\right)^2 \sigma_{DW}^2 + \left(\frac{\partial R}{\partial RCS}\right)^2 \sigma_{RCS}^2$$

- two ways to use :
- POV : calculate σ_R^2 from known variances of RSH, RCS, DW
- BPOV :
  - observe σ_R^2
  - calculate sensitivities
  - solve for variances of RSH, RCS, DW s.t. nonnegativity constraint ([5])
  - same approach for mismatch and process variation

- Use physics based nominal model at start
- We use TRADICA for model generation
- Shift nominal model to center if neccessary
- Enhanced version of TRADICA generates models incl. mapping equations
- For examples of mapping relations see ([3], [4])
- Uses Taylor-series expansion of mapping relations
- Up to now sufficiently accurate

Part of HICUM model for SPECTRE :

```
subckt N00705B110H c b e s
parameters
+ b_e0 =0.500E-06 l_e0 =0.700E-06

+ r_nbei_l = r_nbei_rm_nsic*r_nbei_sm_nsic/sqrt(b_e0*l_e0)
+ r_nbei = r_nbei_g_nsic+r_nbei_l

+ a_be0_l = a_be0_rm_nsic*a_be0_sm_nsic/sqrt(l_e0)
+ a_be0 = a_be0_g_nsic+a_be0_l

Q c b e s MOD

model MOD bht type=npn tnom=27 updatelevel=1
+ c10 = 2.364E-33 - 7.680E-34* r_nbei + 6.674E-27* a_be0
+ ich = 8.956E-04 + 1.277E+03* a_be0
+ cjei0 = 2.023E-15 + 9.636E-16* r_nbei + 2.900E-09* a_be0
```

Process Parameters	SGPM Parameters	HICUM Parameters
int. base doping (r_nbei)[1]	Ic, BF Cje, Rb	$c10, qp0, cjei0, rbi0$ $cjep0$
int. base width (r_wb)	Ic, BF Rb	$qp0, tbvl, thcs$
int. collector doping (r_nci)	Cjc, tf IKF, ITF	$cjci0, tbvl, thcs$ $vptci, t0$
base current (r_jbei)	Ib, BF	$ibeis, ireis$
emitter size (a_be0)[2]	Ic, Ib, Cje tf	$c10, qp0, ich$ $cjei0, cjci0, t0$
int. collector width (a_wc)	IKF, ITF	$vptci, thcs, rci0$ $latb, latl$

[1] r_ : relative variation
[2] a_ : absolute variation

Process Parameters	SGPM Parameters	HICUM Parameters
ext. collector doping (r_ncx)	Cjc	$cjcx0$
buried layer doping (r_nbl)	Rc	rcx
substrate doping (r_nsu)	Cjs	$cjs0, iscs$

Observations :

- external BJT parameters (mostly) uncorrelated
- at least 8 correlated internal BJT parameters (single device)
- now imagine you've 10 or 100 BJT models ...
- $\Rightarrow$ physics-based approach much more efficient

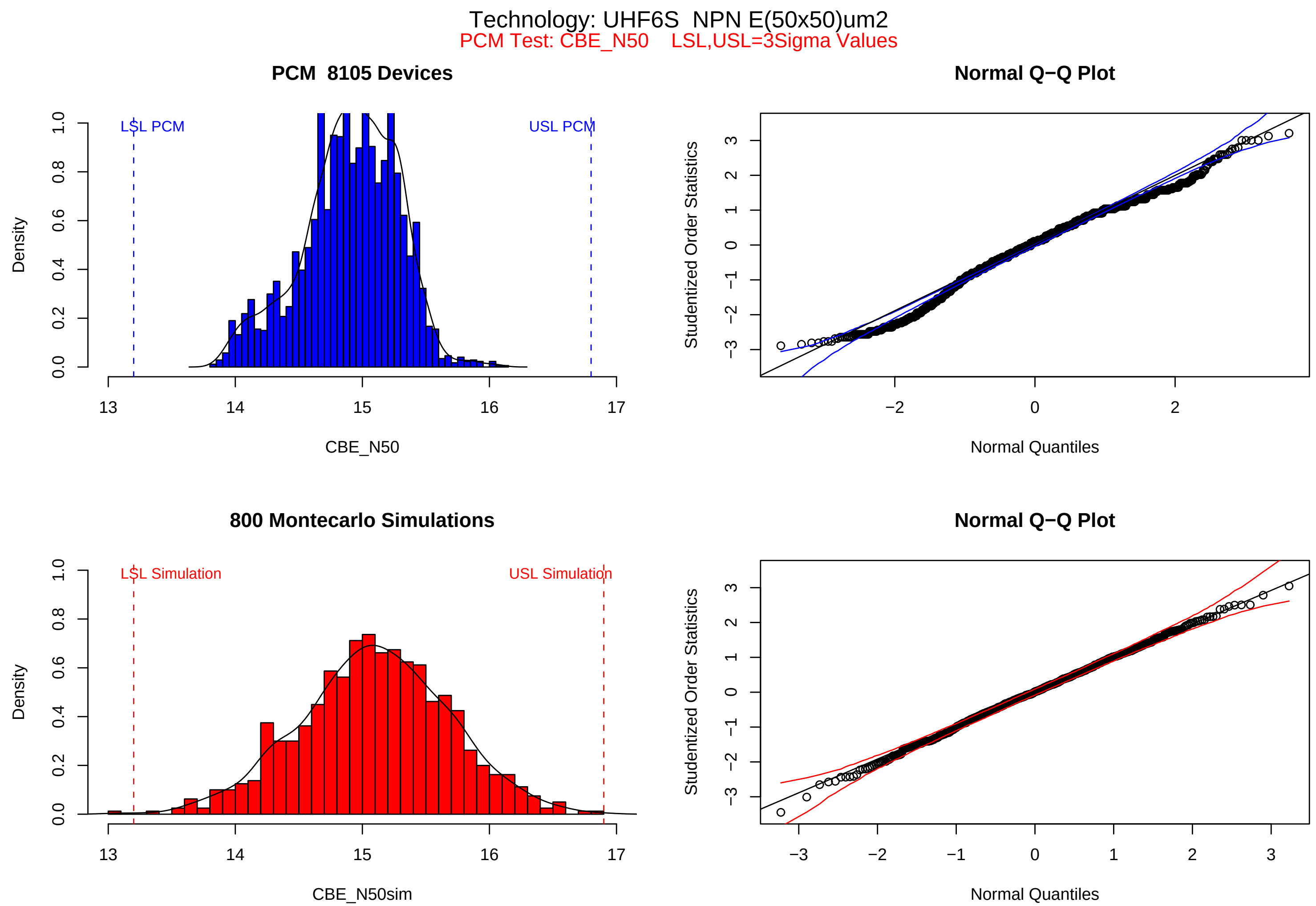
- refers to direct model parameter extraction from PCM data
- usual candidates : $VTH, DL, DW, BF, VAF, \ldots$
- no guarantee your simulations are o.K. when the model contains published values from EDR
- reasons :
  - many methods to extract "physical" parameters exist, giving different results
  - different models for same device may need different parameters
  - relation between electrical observables and model parameters is approximate
  - goal of modeling : as good as possible representation of electrical behavior, not of "physical" parameters

- refers to indirect or closed-loop procedure ([1])
- mimick PCM conditions as close as possible
  - same device geometry
  - same bias
  - same data reduction
- simulate PCM test
- compare distributions from PCM test and simulation
- repeat cycle regularly, even for mature technology

The following slides show selected results.
All simulations have been done using HICUM/L2 with SPECTRE.

- Large area BE-Capacitance of VNPN
- V_{BE}-mismatch of VNPN-pair
- measured correlations of VPNP
- simulated correlations of VPNP

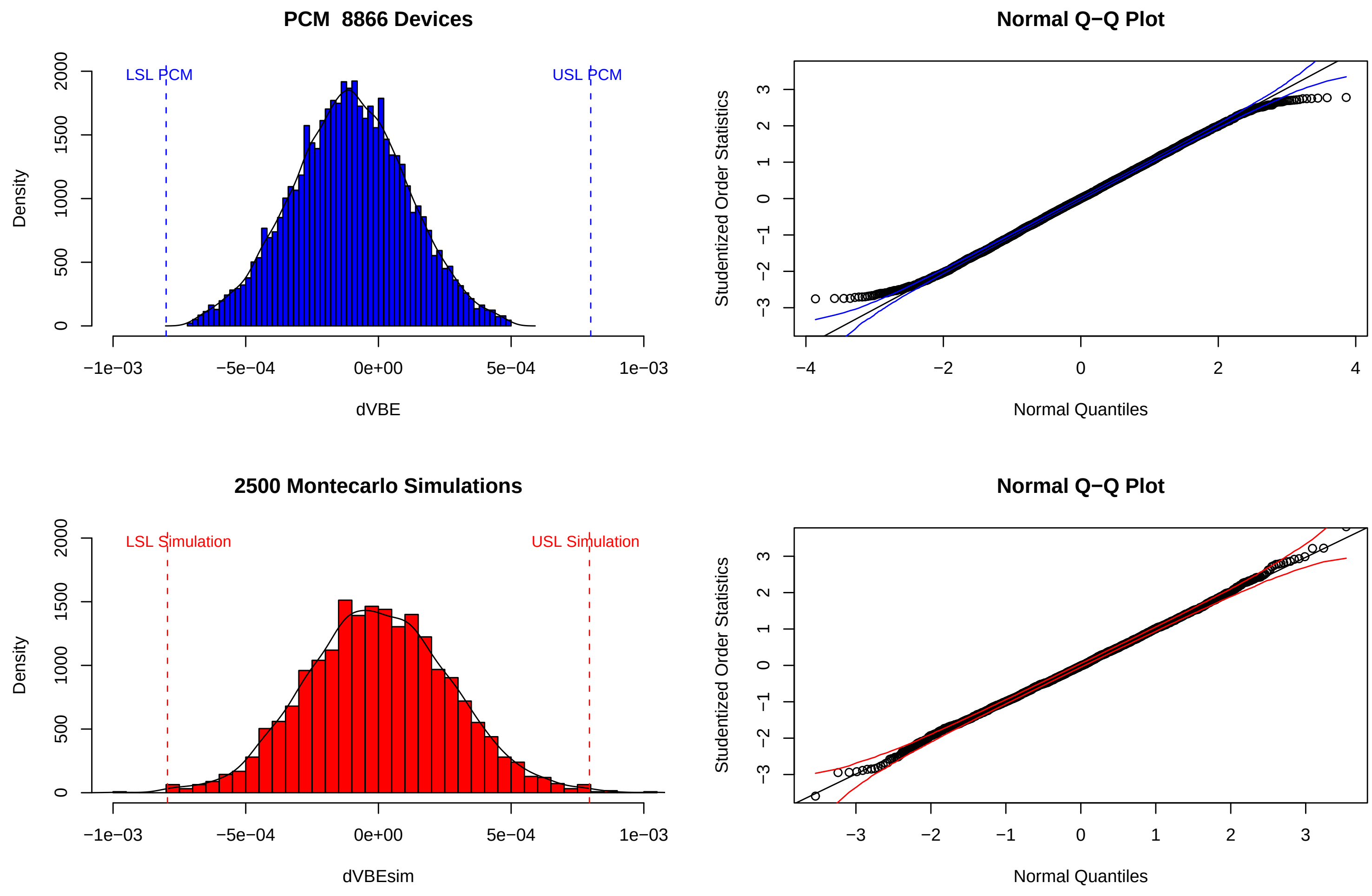
Results



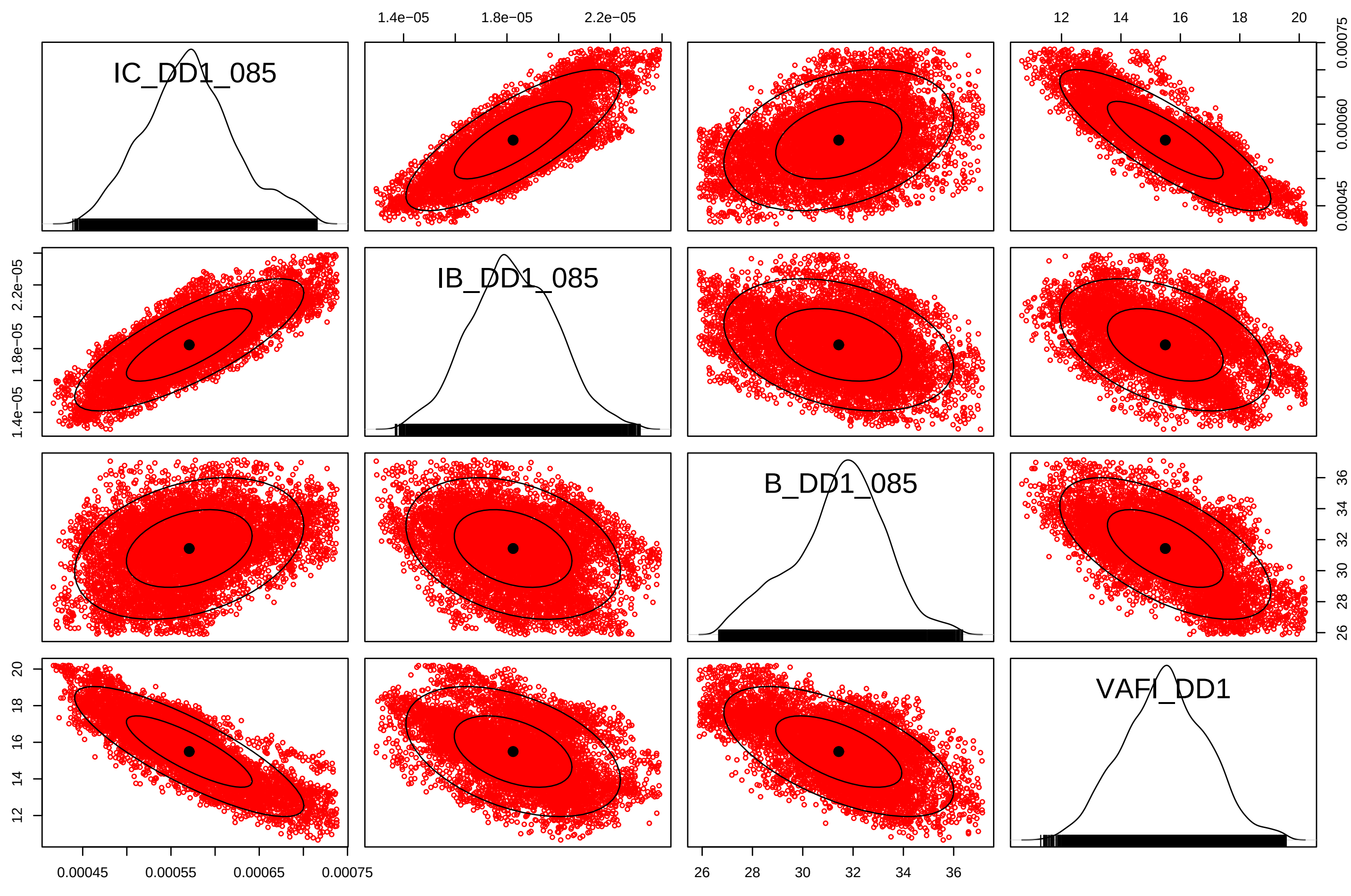
Technology: UHF6S NPN E(50x50)um2
PCM Test: CBE_N50 LSL,USL=3Sigma Values
PCM 8105 Devices
LSL PCM
USL PCM
Density
CBE_N50
Normal Q−Q Plot
Studentized Order Statistics
Normal Quantiles
800 Montecarlo Simulations
LSL Simulation
USL Simulation
Density
CBE_N50sim
Normal Q−Q Plot
Studentized Order Statistics
Normal Quantiles

Technology: UHF6S NPN E(0.5x9.7)um2

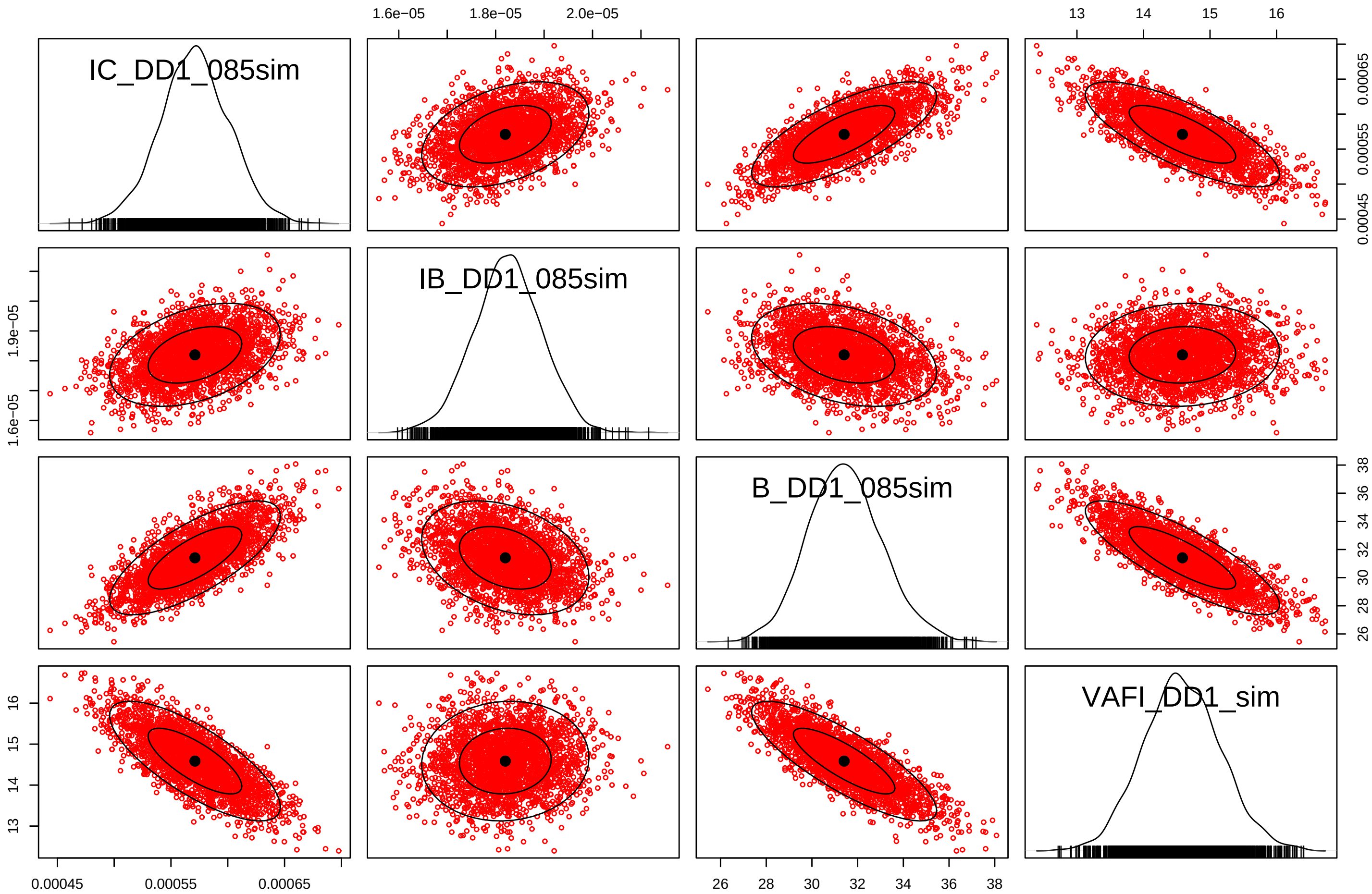
PCM Test: DVBE_NN1_085 LSL,USL=3Sigma Values



Technology: UHF6S VPNP4 PCM_Measurements:DD1 E(0.5x9.7)um2 CBEB



Technology: UHF6S VPNP4 Process Simulations:DD1 E(0.5x9.7)um2 CBEB



- discussed statistical BJT models using HICUM (& SGPM)
- based on physics and fundamental process parameters
- no overhead for correlations
- VNPN & VPNP covered incl. mismatch
- limitations of corner models discussed
- Loop closure discussed
- to do
  - extend statistics to s-parameters
  - additional mismatch teststructures needed

[1] C.C. McAndrew,"Compact Device Modeling for Circuit Simulation," CICC 1997, pp. 151-158

[2] C.C. McAndrew,"Statistical Modeling for Circuit Simulation," Interntl. Symp. on Quality Electronic Design, ISQED'03

[3] P.G. Drennan and C.C. McAndrew,"A Comprehensive MOSFET Mismatch Model," IEDM 1999, pp. 167-170

[4] M. Schroter, H. Wittkopf, and W. Kraus, "Statistical Modeling of High-Frequency Bipolar Transistors," invited paper, BCTM'05

[5] Lawson, Hanson,"Solving Least Squares Problems,"Prentice Hall, 1974

[6] O'Riordan,"Recommended Spectre Monte Carlo Modeling Methodology,", www.designers-guide.org