

BPV method as a tool for statistical compact modeling of SOI CMOS technology



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1. Motivation

Incorporation of process/device variability in the design is of growing importance. Many efforts in this field have been undertaken by the compact modeling community. Development of the statistical models of multi-gate MOSFETs is one of the goals of FP7 Marie-Curie project "Compact Modeling Network" (COMON) [1]. Development of the statistical modeling methodology for use locally in ITE is also the goal of the work.

The results of our work were reported for the first time at the MIXDES'2010 conference [2]. However that work was based on numerically generated pseudo-measurement data. The chosen methodology proved its efficiency. Namely, electrical parameter distributions estimated using the methodology fitted very well the distributions used to obtain the pseudo-measurement data.

A progress of our work on statistical modeling concept (data analysis, implementation) is reported. The methodology has been tested via the real measurement data.

2. Description of method

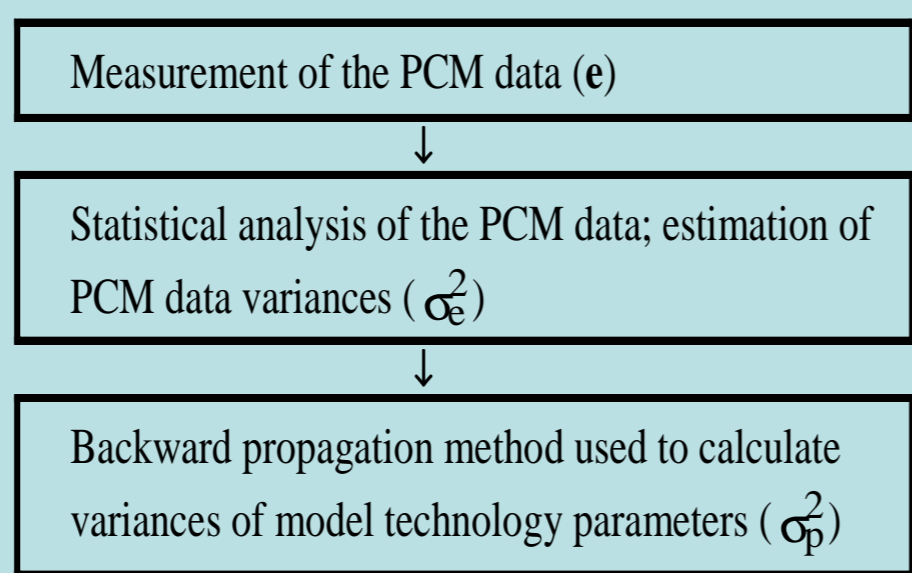
Statistical simulation of ICs

- Worst Case (WC), Corner analysis
 - + Fast design space exploration in terms of PVT variations
 - Lack of correlation between model parameters
- Monte Carlo (MC) analysis
 - + Precisely evaluation of safe area of IC design
 - Time-consuming

Statistical model extraction

- Principal Component Analysis (PCA)
 - + Statistically independent principal components
 - Meaningless of principal components
- Forward Propagation of Variance (FPV) method
 - + Direct connection with measured data
 - Does not guarantee the accurate modeling of electrical performances
- **Backward Propagation of Variance (BPV)** method [3]
 - + Physically based statistical modeling
 - + High accuracy and ability to include variances of different block performances
- FPV+BPV

$$\begin{bmatrix} \sigma_{V_{th}(P)}^2 \\ \sigma_{I_{dsat}(P)}^2 \\ \sigma_{g_m(P)}^2 \\ \sigma_{r_{ds}(P)}^2 \\ K \\ \sigma_{V_{th}(N)}^2 \\ \sigma_{I_{dsat}(N)}^2 \\ \sigma_{g_m(N)}^2 \\ \sigma_{r_{ds}(N)}^2 \\ K \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & K \\ S_{21} & S_{22} & K \\ K & K & O \end{bmatrix} \cdot \begin{bmatrix} \sigma_{TOX}^2 \\ \sigma_{lnNSUB(P)}^2 \\ \sigma_{U_{OQ}(P)}^2 \\ \sigma_{DL(P)}^2 \\ \sigma_{DW(P)}^2 \\ \sigma_{lnNSUB(N)}^2 \\ K \end{bmatrix}$$



Sensitivities of Process Control Monitors (PCMs) to process parameters are given by:

$$S_{11} = \left\{ \frac{\partial V_{th}(P)}{\partial TOX} \right\}^2 \quad S_{12} = \left\{ \frac{\partial V_{th}(P)}{\partial lnNSUB(P)} \right\}^2 \quad \text{etc.}$$

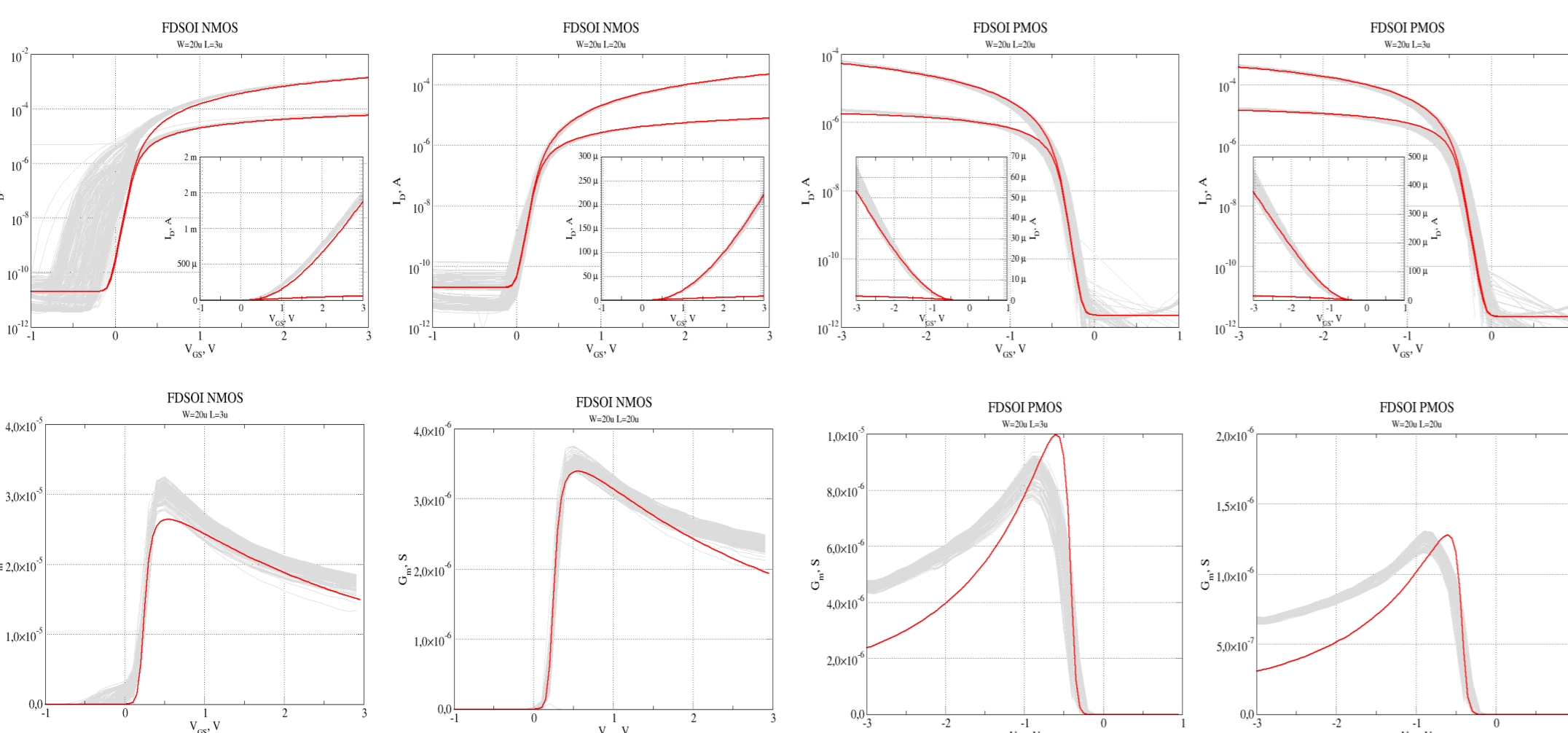
The equations solved using a **Sequential Quadratic Programming (SQP)** method [6]. In this work implementation of SQP in GNU Octave was used. The advantage of SQP against Ordinary Least Square (OLS) [3] is the ability to take into account constraints, like positivity of squared variances.

3. Experimental data

Hundreds of n-channel inversion-mode and p-channel accumulation-mode FD SOI MOSFETs of series of sizes (widths 20..3 μm, lengths 20..1.5 μm) have been measured. The devices have been manufactured in ITE clean-room based on the FD SOI CMOS technology transferred from UCL to ITE within the FP7 project TRIADE [7].

According to requirements of the BPV method the PCM data have been measured/calculated based on the three electrical I(V) characteristics of the MOSFETs: $I_D(V_{GS})@V_{DS}=0.05V$, $I_D(V_{GS})@V_{DS}=3.0V$, $I_D(V_{DS})@V_{GS}=3.0V$. On the charts below clouds of the experimental $I_D(V_{GS})$ and calculated $g_m(V_{GS})$ curves are shown for two geometries of n- and p-channel MOSFETs. Additionally the corresponding EKV model curves are shown.

Weak subthreshold characteristics of the "shorter" n-channel MOSFETs and non-ideal transconductance curves of the p-channel MOSFETs are visible.

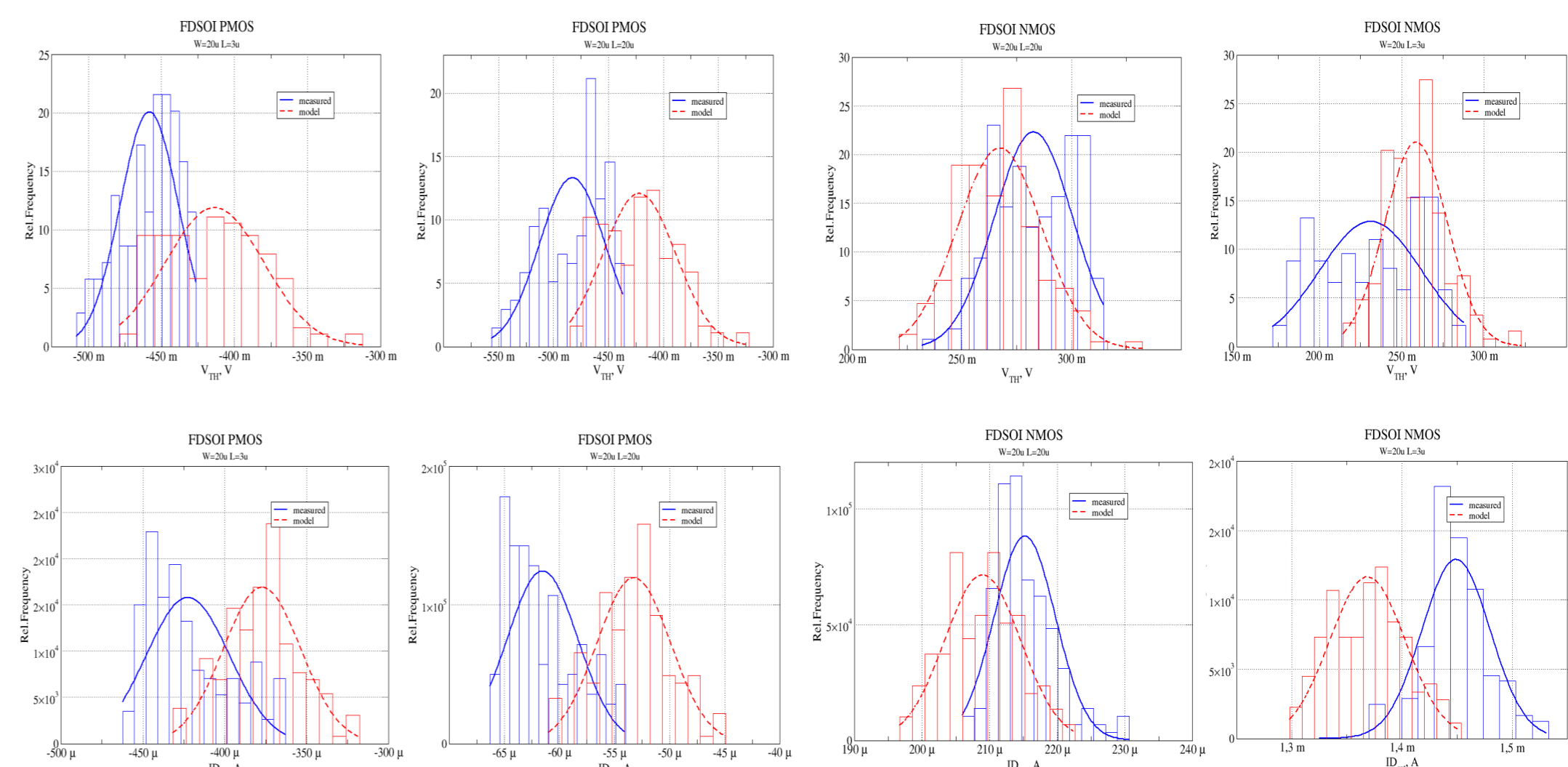


4. Statistical modeling results

Par.name	Variances extraction results using BPV		
	mean	σ_{model}	units
TOX	31.0	0.58	nm
PMOS			
Log(NSUB)	52.51	0.39	unitless
UO	416.1	21	cm ² /(V·s)
NMOS			
Log(NSUB)	46.66	0.25	unitless
UO	581.3	12	cm ² /(V·s)

Geometry, WxL [μm x μm]	PCM Variances Extraction Results via BPV			
	Name	$\sigma_{meas.}$	σ_{model}	Units
pMOS				
20x20	V_{th}	30.0	33.0	mV
	I_{dsat}	3.21	3.34	uA
	G_m	0.04	0.08	uS
20x10	V_{th}	30.5	33.1	mV
	I_{dsat}	6.63	6.74	uA
	G_m	0.09	0.17	uS
20x5	V_{th}	32.9	33.3	mV
	I_{dsat}	14.3	13.74	uA
	G_m	0.20	0.35	uS
20x3	V_{th}	19.9	33.6	mV
	I_{dsat}	25.3	23.61	uA
	G_m	0.39	0.64	uS
nMOS				
20x20	V_{th}	17.8	19.3	mV
	I_{dsat}	4.53	5.59	uA
	G_m	0.07	0.08	uS
20x10	V_{th}	18.0	19.2	mV
	I_{dsat}	9.18	11.0	uA
	G_m	0.16	0.16	uS
20x5	V_{th}	21.7	19.1	mV
	I_{dsat}	18.4	21.3	uA
	G_m	0.39	0.34	uS
20x3	V_{th}	31.0	18.9	mV
	I_{dsat}	30.0	34.3	uA
	G_m	1.1	0.61	uS

The accuracy of the extracted variances of PCMs depends on the number of samples. From the table V in [2] the expected accuracy is around 50%. Also the accuracy of the method depends on fitting of nominal values of PCMs. In case of minimum gate lengths the modeled distributions of V_{th} and I_{dsat} are shifted against measured ones, as it is shown on histograms below.



Conclusions

BPV method is stable and self-consistent method for Statistical MOSFET Modeling.

PCMs measurements are enough to estimate with predictable accuracy the distribution of technological parameters of EKV MOSFET model

The proposed implementation is used for statistical modeling of CMOS SOI technologies at ITE

This method will be applied to statistical modeling of multi-gate FinFET MOSFET technologies

The next development of extended BPV is the QPV [4, 5] to take into account for nonlinearities in PCMs and correlations between process parameters.

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