Capturing Intrinsic Parameter Fluctuations using the PSP Compact Model

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Abstract— Statistical variability (SV) presents increasing challenges to CMOS scaling and integration at nanometer scales. It is essential that SV information is accurately captured by compact models in order to facilitate reliable variability aware design. Using statistical compact model parameter extraction for the new industry standard compact model PSP, we investigate the accuracy of standard statistical parameter generation strategies in statistical circuit simulations. Results indicate that the typical use of uncorrelated normal distribution of the statistical compact model parameters may introduce considerable errors in the statistical circuit simulations.

Keywords- Statistical variability; mismatch; statistical compact modelling; MOSFETs;

I. INTRODUCTION

Compact model [1] are at the interface between IC designers and semiconductor foundries. They facilitate the operation of the fabless design industry, with an annual revenue close to $50 billion in 2008. On the other hand, Statistical variability (SV), which arises from discreteness of charge and granularity of matter, is one of the fundamentally limiting factors of CMOS scaling and integration in the nanometer regime [2]. Due to its purely statistical nature SV introduces increasing challenge for accurate compact modeling and statistical circuit simulation [3] [4] [5]. In order to achieve reasonable performance and yield in contemporary CMOS design, the SV has to be accurately represented by industry standard compact models. In this paper, we benchmark commonly used statistical compact model (SCM) parameter generation strategies for PSP and compare with a direct statistical parameter extraction approach providing critical information regarding the accuracy of the different SCM strategies. Section II presents the physical simulation of the SV in a 35 nm gate-length test device used in this study. In section III, the direct parameter extraction approach used to benchmark the other statistical parameter generation strategies is discussed in detail, and the impact of statistical parameter set size on its accuracy is presented. Section IV compares the accuracy of the commonly used SCM approaches with a direct extraction strategy at device and circuit level. The final conclusions are presented in section V.

II. SV IN 35NM GATE LENGTH DEVICE

The Glasgow ‘atomistic’ 3D drift-diffusion simulator was used for the physical SV simulations in this study, employing density gradient quantum corrections for electrons and holes to prevent artificial charge trapping at discrete dopants [7]. A 35 nm poly-gate nMOSFET, which has been carefully designed to match the performance of state-of-the art 45nm technology devices [8], [9] is used as a test device. The continuous doping profile of this device, simulated using Sentaurus Process, is shown in Fig.1a. The combined impacts of random discrete dopants (RDD), line edge roughness (LER) and poly gate granularity (PGG) have been simulated simultaneously. Devices with W/L of 1 have been simulated to reduce CPU time. Discrete dopants are generated based on the continuous doping profile, by placing dopant atoms on silicon lattice sites with the probability determined by the local ratio between dopant and silicon atom concentration [7]. LER is introduced using a 1-D Fourier synthesis technique with a Gaussian correlated power spectrum with a correlation length of 30nm and RMS amplitude of 1.3nm [10]. PGG is introduced by randomly selecting regions of a large polycrystalline silicon grain image. Along the grain boundaries, the Fermi level is pinned in the silicon bandgap at a 0.3 eV below the conduction band edge [11]. Fig. 1b shows a typical potential distribution in the simulated transistor under the influence of the combined SV sources. The poly grain boundaries can be clearly identified in the gate region.

Figure 1. (a) 2D doping profile of template 35nm physical gate length nMOSFET. (b) Typical potential profile with RDD, LER and PGG effects on
The simulated Id-Vg characteristics of 200 microscopically different devices are shown in Fig.2. The distribution of leakage current spans approximately 3 orders of magnitude, indicating that SV has strong impact on the electro-statically dominated sub-threshold behaviour. It is well known that the DD simulations can underestimate the variability of $I_{on}$ [12]. However, the observed deviation from the mean value of $I_{on}$ is still ~45%. It is important to mention that device figures of merit, such as threshold voltage, do not always follow a Gaussian distribution under the influence of SV [13]. Although multi-width devices are commonly used in digital design, the observed degree of variability will still have a significant impact on yield and performance of circuits and systems, despite the SV reduction with the increase of the gate area. Compact models extracted for the simulated square devices can be used in circuit simulations involving larger channel width devices by using the methodology described in [14].

III. DIRECT STATISTICAL PARAMETER EXTRACTION STRATEGY

A two-stage direct SCM extraction procedure [14] is applied without any pre-assumption of parameter distribution, correlation or sensitivity. As a result within the accuracy of the CM fitting this approach will provide the most accurate representation of the current voltage characteristics obtained from physical 3D simulation or from measurement. This direct extraction approach, therefore, serves as reference in our comparison of different SCM strategies. In the first stage of the extraction process, a local level parameter extraction strategy is applied to obtain complete set of PSP parameters for a uniformly doped device with no sources of variability. In the second stage, based on the physical analysis of the impact of intrinsic SV on device operation, 7 possible fitting parameters are identified for PSP. NSUBO is the basic substrate doping parameter, which physically determines the threshold voltage of device, and is chosen to account for threshold voltage variation. Both CFL and ALPIL1 are short channel effects parameters, and are selected to account for short channel effects variation. UO and CSO are mobility parameters, and are selected to account for transport variation introduced by SV. CTO is an interface state parameter, and together with NSUBO, can be used to mimic the sub-threshold behavior variation introduced by SV. RSW1 is a source/drain series resistance parameter, and is selected to account for the influence of SV within the Source and Drain regions.

The accuracy of a SCM is determined by the choice of model parameters, and the size of the parameter set. Provided that the parameter set contains both low field and high field parameters, a two sub-steps are applied during the second stage statistical parameter extraction: IdVg characteristics at low drain bias condition are selected to extract basic variation parameters in the first sub-step and high-field variation is extracted during second sub-step. Due to the increasing importance of standby power dissipation in low power IC design, we treat $I_{off}$ and $I_{on}$ equally during statistical extraction and the RMS errors used in both the sub-threshold and on current regimes are calculated on a linear scale. The impacts of the number of statistical parameters on the accuracy of SCM are presented in Fig.3, the mean RMS error is ~16% when using 1-parameter set, and is reduced to 1.32% when using a full 7-parameter set. Fig.4 further illustrates the device figures of merit obtained from a 7-parameter SCM when compared to
physical simulation (please note: in the rest of paper, the full 7-parameter set is used as the baseline for comparison). As the inset in Fig.4 clearly demonstrates, strong correlation between compact model parameters and physical properties of the device are maintained during statistical extraction. Such correlation can provide guideline for the different techniques to generate SCM sets based on the distributions of the figure of merits of device characteristics.

IV. BENCHMARKING OF ACCURACY ON STATISTICAL PARAMETER GENERATION STRATEGIES

Using the ensemble of models generated by direct statistical parameter extraction, a statistical CM library can be constructed and devices in circuits can be randomly selected from the library during statistical circuit simulation. Although this is the most rigorous method of performing statistical circuit simulation, the available statistical sample size is pre-determined by size of the CM library. Common practice in Monte Carlo circuit simulation is to generate statistical parameter values on the fly. Here, two statistical parameter generation approaches are investigated and compared to the results of direct parameter extraction. The first approach is to generate ensemble CM parameters assuming independent normal distributions for each extracted parameter, which is the standard approach in most SPICE-like circuit simulators. This method will be referred to as the “naïve approach” for the remainder of this paper. The second approach is based on Principal Component Analysis (PCA) [15] which allows correlations between extracted parameters to be maintained. This method will be referred to as the “PCA approach” in this paper. Although PCA itself does not require that the original multi-dimension data follow a particular distribution. However, in order to reconstruct the original data from statistical independent principal components, it is simple to execute under the assumption that the original data closely approximate normal distributions. Therefore in the PCA approach, we assume that parameters follow normal distribution.

A comparison of parameters generated by both the naïve and the PCA techniques, and the direct parameters extraction is illustrated in Fig.5. The correlations between statistical parameters are well preserved by the PCA method but are lost by the naïve approach, which is clearly demonstrated by the scatter plot Nsub0 – CT0. As expected the mean values of parameters generated by both analytical approaches are close to the expected values from direct extractions. However, there are considerable errors in the tail of the distributions due to the normal distribution approximation in both parameter generation approaches while actual parameter distributions are typically not normal, as demonstrated in Fig.6 where the straight line represents the ideal normal distribution case.

![Figure 5. Scatter plots between PSP statistical parameters. Down left: Comparison between direct extraction and PCA approaches. Black square: direct extraction; Red circle: PCA approach. Up right: Comparison between direct extraction and naïve approach. Black square: direct extraction; Red circle: naïve approach.](image)

![Figure 6. Probability plot of typical PSP statistical parameter from direct extraction.](image)

![Figure 7. Probability plot of Vth generated by different statistical approaches](image)

The ability of the naïve and the PCA approaches to reproduce device figures of merit is of primary importance when determining their usefulness in statistical circuit simulation. This is illustrated in Fig.7-8. Both approaches generally preserve the threshold voltage distribution with errors in the calculated standard deviation (σ) of less than 10% when compared to direct extraction. However, only the PCA approach satisfactorily reproduces the distribution of $I_{on}$ with an error in σ of 3%. In contrast the naïve approach produces an
error of 30% in $\sigma$ of $I_{on}$, indicating that the naïve approach will introduce considerable errors in circuit timing simulations where $I_{on}$ is important.

Using compact model ensembles generated using the direct extraction, naïve and PCA approaches, Monte Carlo circuit simulations were carried out on a three stage CMOS ring oscillator, in order to assess the impact of statistical compact model extraction strategies on the accuracy of statistical circuit simulation. Since the direct extraction approach very closely reproduces the ‘atomistic’ physical device simulation results, the circuit simulations using models extracted with this approach are our gold standard. Hence, we benchmark results from two other approaches against the gold standard simulations. The results of Monte-Carlo circuit simulations can be seen in Fig.8. Although the mean period of the ring oscillator obtained from all three statistical CM approaches are very close, at ~27ps, significant deviations in the distribution of the oscillator period are observed when using the naïve approach. For this particular circuit, comparing the naïve approach to direct extraction simulations gives ~44% error in the standard deviation of the oscillator period, while the error is reduced to ~16% by the PCA approach.

Figure 8. Probability plot of $I_{on}$ generated by different statistical approaches

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Figure 9. Probability plot of oscillation period from different statistical approaches

V. CONCLUSIONS

Based on physically simulated SV in a state-of-the-art 35nm gate length MOSFETs, a benchmarking of SCM strategies for PSP has been carried out. Results indicate that a naïve approach, which generates SCM parameters assuming independent normal distribution for each extracted parameter, introduces considerable error in statistical circuit simulation. The used of a PCA approach, which preserves in bulk the inter-parameter correlations, provides significantly more accurate results in both device and circuit simulations.

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