Evaluation of threshold voltage dispersion in 45 nm CMOS technology with TCAD-based sensitivity analysis.

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Abstract—We propose an approach based on sensitivity analysis to evaluate threshold voltage variability of nanoscale MOSFETs due to line edge roughness (LER) and to random discrete dopants (RDD). It requires a very limited number of TCAD simulations, corresponding to computational load much smaller than that required for statistical simulations. We apply our approach to 45 nm CMOS technology, and show that with only a few tens of device simulations one can obtain results comparable to those of statistical simulations, with an improved understanding of the impact of physical parameters on the variability of electrical characteristics.

(Keywords: mismatch, parameter fluctuations, variability, MOSFET)

I. INTRODUCTION

Managing the statistical dispersion of transistor characteristics is one of the main requirements in the development of current and next CMOS technology nodes. To this purpose, one needs i) full understanding of variability sources and ii) tools and methods for a quantitative evaluation of parameter fluctuations at the device design and manufacturing stage.

Regarding the latter issue, statistical simulations are now the preferred approach [1,2]. As far as threshold voltage is concerned, the main sources of variability have been clearly identified and understood: random dopant distribution (RDD), line-edge roughness (LER), oxide-thickness variations [3], and polysilicon or metal-gate random grain distribution (RGD) [4].

In the literature, some analytical models of threshold voltage dispersion due to RDD [5,6] and to LER [7] have been proposed. Typically, they can be used only in the case of idealized structures and/or very simple doping profiles. However, analytical and semianalytical models have two important advantages: they are very faster than statistical simulations, and can help to clearly identify and understand the role of key physical parameters on the variability electrical parameters.

Here, we propose an approach based on sensitivity analysis and a limited number of TCAD simulations that provides the advantages of speed and physical understanding that is typical of analytical models, and the possibility of considering realistic doping profiles and geometry provided by TCAD simulations.

We focus on threshold voltage variability due to LER and RDD, considering the case of 45 nm bulk CMOS nMOSFETs for which data from statistical simulations to be used as a comparison are available [4].

Limited to the effect of LER, we have already demonstrated - for a different device structure - that our methodology allows us to obtain quantitatively very similar results as a 3D statistical simulation, which requires much larger computational resources [8].

II. APPROACH

The approach we propose requires us, as a first step, to translate all variability sources (process and geometry) in terms of dispersion of a set of synthetic parameters. Then, we have to identify a set of independent variability sources and synthetic parameters. Finally, we have to evaluate through sensitivity analysis the contribution to the dispersion of electrical parameters (e.g. the threshold voltage $V_{th}$) of each independent source. The last step is based on the assumption that the effect of each source of variability is sufficiently small that linearization is applicable.

The considered device is a minimum size nMOSFET, with polysilicon gate length of 42 nm, oxide thickness 1.7 nm, width of 45 nm. Further data can be found in Ref. [4]. TCAD simulations and scripts have been performed with Sentaurus [9].

A. Effect of random dopant distribution

In the case of RDD, the source of threshold voltage dispersion is the fluctuation of the dopant distribution in the active area. What matters is not only the total number of dopants in the active area, but also their position. However, we do not need to know with atomic precision the effect of dopant distribution on threshold voltage.

First, we can acknowledge that the mechanism is mainly due to electrostatics, therefore impurity position along the width direction is not relevant. This allows us to simplify our analysis considering only 2D device structures. Then, we can assume that the effects of fluctuations of the number of dopants in different regions are small enough to add up linearly.

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For a given variation of dopant distribution $\Delta N_A(x, y, z)$ with respect to the nominal value we can write the following expression:

$$\Delta V_{th} = \int K(x,y) \Delta N_A(x, y, z) \, dx \, dy \, dz$$  \hspace{1cm} (1)

Where $\Delta V_{th}$ is the resulting variation of the threshold voltage, and $K(x,y)$ has the role of a propagator. The expression requires the linearity assumption to hold. The first assumption implies that $K$ does not depend on $z$.

To conveniently compute the propagator $K$, we can assume that $K$ is a smooth function of $x$ and $y$, and move from the continuum to a discrete space, partitioning the active area in small rectangular boxes, as shown in Fig. 1a. Now we can write:

$$\Delta V_{th} = \sum_i \Delta V_{th_i} = \sum_i K_i \Delta N_i$$  \hspace{1cm} (2)

The sum runs over all boxes, $\Delta N_i$ is the variation of the number of dopants in box $i$, and $\Delta V_{th_i}$ is the threshold voltage variation if only dopants in box $i$ are varied.

In practice, we multiply doping in box $i$ by a factor $(1+\omega)$ and compute $\Delta V_{th_i}$ with TCAD simulations. Therefore we have

$$\Delta N_i = \omega \Delta N_i \quad \Delta V_{th_i} = \alpha K_i \Delta N_i$$

so that (2) becomes,

$$\Delta V_{th} = \sum_i \left( \frac{\Delta V_{th_i}}{\alpha} \right) \frac{\Delta N_i}{N_i}$$  \hspace{1cm} (4)

We know need another reasonable assumption: doping variations in different boxes are non independent Poissonian processes. Therefore from (4) we can write

$$\sigma_{V_{th}}^2 = \sum_i \left( \frac{\Delta V_{th_i}}{\alpha} \right)^2 \frac{\sigma_{N_i}^2}{N_i^2}$$  \hspace{1cm} (5)

Since $N_i$ is a Poisson process is $N_i = \sigma_{N_i}$, we finally have

$$\sigma_{V_{th}}^2 = \sum_i \left( \frac{\Delta V_{th_i}}{\alpha} \right)^2 \frac{1}{N_i}$$

The threshold voltage dispersion due to RDD only requires a single TCAD simulation for each box, and an integral of the doping profile in each box. Box partitioning is shown in Fig. 1 and is smaller than the whole active area, because one can easily check that far from the channel the impact of doping fluctuations on $V_{th}$ rapidly goes to zero.

To evaluate what is the granularity of partition required to obtain reasonably accurate results we have used different partitions, shown in Fig. 2: 10x1 (a), 10x2 (b), 10x5 (c), 20x 10 (d), 40x20 (e). The table in Fig. 2 shows the standard deviation of the threshold voltage obtained at $V_{th} = 50 \text{ mV}$, and $V_d = 1.1 \text{ V}$. If the device is symmetric with respect to a source-drain swap, for low $V_{th}$ we can reduce to half the number of simulations required, since the propagator too is symmetric.

Results show that only few simulation (case 2b 20 for high $V_{th}$, or 10 for low $V_d$) are sufficient to obtain reasonably accurate results. Very accurate results can be obtained in case...
2d with a factor 10 more simulations. We have also checked that doping variations in the regions external to the partitions shown have no effect on the threshold voltage.

B. Effect of line-edge roughness

We can translate line edge roughness in term of the dispersion of the average position of both gate edges along the y axis (\(y = 0 + y_1\) and \(y = L + y_2\)) in Fig. 1b. This in turn translates into gate length dispersion. We assume that \(y_1\), \(y_2\) are only affected by LER and their fluctuations are governed by independent processes.

To evaluate the variance of \(y_i\) we assume a Gaussian autocorrelation function \(r(c)\) of correlation length \(A_L\) and mean square amplitude \(A_L^2\):

\[
r(d) = A_L e^{-\frac{d^2}{2A_L^2}}
\]

We find that:

\[
\sigma_{\Delta Vt}^2 = \sigma_{\Delta L}^2 = \frac{2\lambda_i^4 A_L}{W^2} \left[ \Lambda \left( \frac{W}{2\lambda_i} - 1 \right) + \frac{\sqrt{2}}{W} \text{erf} \left( \frac{W}{\sqrt{2}A} \right) \right]
\]

The variance of \(V_{th}\) due to line-edge roughness therefore is:

\[
\sigma_{V_{th}}^2 = \left( \frac{\partial V_{th}}{\partial y_1} \right)^2 \sigma_{\Delta y_1}^2 + \left( \frac{\partial V_{th}}{\partial y_2} \right)^2 \sigma_{\Delta y_2}^2 = 2 \left( \frac{\partial V_{th}}{\partial L} \right)^2 \sigma_{\Delta L}^2
\]

All required derivatives only require two 2D TCAD simulations, and are strictly dependent on device length, as shown in Fig. 3.

The total variance of the threshold voltage is computed by summing the variances due to all independent physical effects.

\[
\text{TABLE I. RESULTS OF THE PROPOSED METHOD FOR THE THRESHOLD VOLTAGE STANDARD DEVIATION OF A MINIMUM SIZE NMOSFET (L=W=45nm) AND COMPARISON WITH ASENOV RESULTS}
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<tr>
<td>V_{th} = 50mV</td>
<td>6 mV</td>
<td>22 mV</td>
<td>53 mV</td>
<td>59 mV</td>
</tr>
<tr>
<td>V_{th} = 1.1V</td>
<td>29 mV</td>
<td>53 mV</td>
<td>59 mV</td>
<td>61 mV</td>
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REFERENCES


