Compact Modeling of Parameter Variations of Nanoscale CMOS due to Random Dopant Fluctuation

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ABSTRACT

In nanoscale CMOS design, the compact modeling of random dopant fluctuation (RDF), which is the major variability source, is crucial important to bridge the variation aware design to the underlying physics. In this paper the variability modeling taking both threshold voltage (V_{th}) and mobility (μ) into account is presented. The difference between the proposed method and the traditional approach using only V_{th} variation for RDF is compared and discussed.

Keywords: random dopant fluctuation (RDF); statistical compact modeling; nanoscale CMOS circuit

1 INTRODUCTION

The CMOS scaling is advancing to 10nm regime [1]. Such aggressive scaling is accompanied with the increasing variability due to all kinds of random effects, posing a grand challenge to circuit design. Among all the variations in CMOS, random dopant fluctuation (RDF) has been considered as the most significant intrinsic variation source. RDF is originated from the random placement of the dopant atoms that follow a Poisson distribution in the channel region. As the device size scales down, the total number of channel dopants decreases [2], and such a decrease results in a dramatic increase doping density variation.

RDF mainly impacts on two parameters of a nanoscale CMOS device: threshold voltage (V_{th}) and mobility (μ) (Figure 1a). The dopant number variation will result in surface potential fluctuation along depth direction, thus leads to a V_{th} variation [3]. On the other hand, as shown in Figure 1a, the uncertainty of dopant numbers and position in the channel region will lead to significant ionized impurity scattering and transport variation [4], which is the mobility (μ) variation.

There have been many studies on the V_{th} variation induced by RDF. For example, an analytical model was derived using 3D drift-diffusion simulator [3]. An empirical model against 3D atomistic simulator was proposed and verified with sub 100nm nodes devices [5]. Based on [3], an analytical model was proposed to normalize the V_{th} variation from multiple fabs [6]. Meanwhile, the researches on the mobility variation due to RDF are quite few. Particularly, to the best knowledge of the authors, the variability compact modeling taking into accounts both threshold voltage and mobility has been reported.

In this work, a compact model considers both threshold voltage and mobility is proposed for statistical circuit simulation, and the comparison between the proposed modeling methodology and previous work which only consider V_{th} variation is discussed. The possible risk of simply using V_{th} to represent the impact of RDF in modeling and measurement is also discussed.

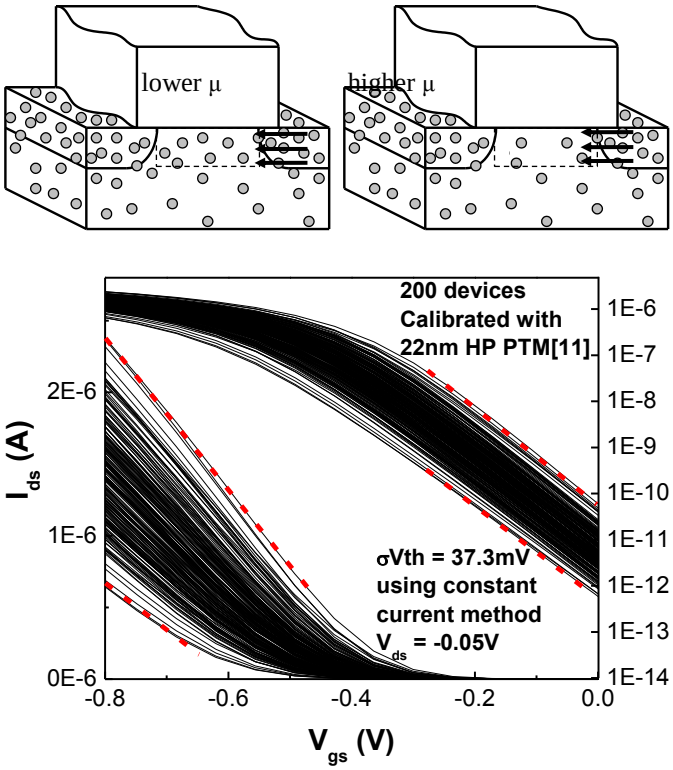


Figure 1: Two devices with different mobility due to RDF; TCAD simulated IV curves of 200 devices.

2 COMPACT MODELING

2.1 Simulation of RDF induced V_{th} and μ

To simulate the discrete Coulomb scattering due to RDF, the equivalent charge density model (equation 1) leveraging the long-range potential [7] is adopted.

$$\rho(r) = \frac{qk_c^{\,3}}{2\pi^2}\frac{\sin(k_c r)}{(k_c r)^3} \quad (1)$$

where q, k_c and r is the elementary charge, the inverse of screening length, and the distance to the center of the atom respectively. In the simulations, we treat k_c as a fitting parameter. The coefficient of the expression on the right side in (1) is normalized such that the integral of the doping density over the entire space becomes unity as suggested by [9] and [10]. Such a fitting keeps our method consistent with TCAD simulation under nominal continuous doping. By using the model the impact of each dopant is able to be incorporated in 3D commercial TCAD tool [10]. The nominal device used is 22nm PMOS calibrated with PTM 22nm HP [11]. 200 of devices with W=15nm are simulated under RDF.

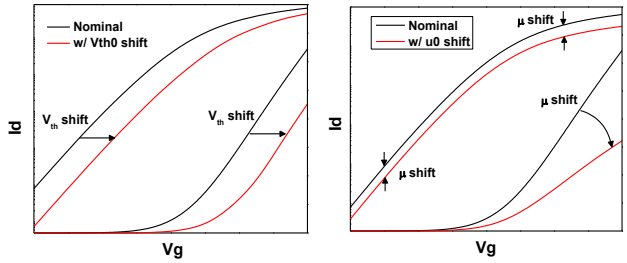
The simulation result is shown in Figure 1b. It is clearly observed that the impact due to RDF is almost a shift along Vg in sub-threshold region, while it is not only a shift but also slope change due to mobility variation in strong inversion region. The result indicates that there are both threshold voltage variation and mobility variation induced by RDF.

2.2 Compact modeling of RDF using both V_{th} and μ

To do the compact modeling of RDF, we first look into how the two parameters impact on the drain current. Take BSIM4 as an example, the effect of a vth0 (Long-channel threshold voltage at V_{bs}=0) shift is approximately a shift along V_g. The parameter u0 (low field mobility) is like a coefficient to drain current. So the shift of u0 will be a shift of log10(I_d) vs. V_g along y axis, thus in sub-threshold region it cannot be decoupled with vth0 shift, and in the strong inversion region it will result in not only the shift along V_g, but also the slope variation of the IV curves (Figure 2). So the vth0 is barely good enough to model RDF induced variation in sub-threshold region. To model the variation in all operating region, we should take both vth0 and u0 into account. For other compact models, the strategies are similar.

As we are going to model RDF using more than one parameter, the correlation between the parameters should not be ignored if they are not independent. From the device physics, we know that both the threshold voltage and mobility are associated with channel doping. A higher dopants number in channel region will usually lead to a higher absolute value of threshold voltage, and a lower mobility due to scattering. While even the dopant numbers are the same, the dopants are ununiformly distributed in the channel, so the two parameters should not be fully correlated (the correlation < 1).

There have been varous models for V_{th} variation induced by RDF [2][3][5][7]. In this paper, we use the equation derived from [3]. With a few more derivations, the V_{th} variation can be expressed as a function of effective channel width (W), effective channel length (L), oxide thickness (t_{ox}), and channel doping density (N_{ch}):



(a) (b)

Figure 2: The effect of BSIM model parameter (a) IV under V_{th0} shift; (b) IV under μ_0 shift devices.

$$\sigma V_{th(RDF)} = C_1 \frac{q}{\sqrt{3W_{eff}L_{eff}}}\frac{t_{oxe}}{\varepsilon_{ox}}\left(\frac{2\varepsilon_{Si}N_{ch}}{q}\right)^{\frac{1}{4}} \quad (2)$$

where C_1 is a fitting parameter accounting for surface potential and the correction term; t_{ox}, ε_{Si}, ε_{ox}, and q are the equivalent oxide thickness, permittivity of silicon, permittivity of the oxide layer, and the elementary charge, respectively.

The purpose of the model is for circuit simulation, so in this paper a first order model of low-filed mobility variation due to RDF is proposed to account for the Coulomb scattering induced mobility fluctuation in the channel region. There are three factors considered: the effective channel length, the effective channel width, and channel doping density. To the first order, μ is proportional to the ratio of the mean free time (τ_c) over the carrier effective mass (m*). The mean free time is inversely proportional to the doping density [12]:

$$\mu_{(\text{Coulombscattering})} \propto \frac{\tau_c}{m^*} \propto \frac{1}{N_{ch}} \quad (3)$$

The total dopant number in channel region follows a Poisson distribution [3], so the fluctuation of dopant number in channel region is:

$$\sigma N = \sqrt{N_{ch}W_{eff}L_{eff}W_{dep}} \quad (4)$$

where W_{dep} is the depletion width. By expanding W_{dep} term and ignoring other second order terms, the following dependency is obtained:

$$\sigma N \propto N_{ch}^{\,0.25} \quad (5)$$

Combining (3), (4), and (5), the dependency of the mean free time fluctuation due to Coulomb scattering is expressed as the following:

$$\sigma\tau_{c(\text{Coulombscattering})} \propto N_{ch}^{\,0.25} \quad (6)$$

Notice that the current density is not uniform along the depth direction, and the Coulomb scattering is not the only source associated to mobility. So the derivation only qualitatively gives a trend dependency on doping density. Taking into account of above, a better dependency is expressed as:

$$\sigma\mu_{(\text{Coulomb scattering})} \propto \frac{N_{ch}{}^{\alpha}}{m^*} \tag{7}$$

If we take the MOS as many pieces along the width direction, then the total current is a sum up of the current from all pieces. Thus, the total current variation due to mobility variation is inverse proportional to the square root of the effective channel width. Similarly, the mean free time along channel length direction is the average of τ_c in all pieces. So the mobility variation is inversely proportional to the square root of the effective channel length. In nano-scale devices, the doping concentration is typically high enough that Coulomb scattering will dominate the low field mobility. So combining with eq. (7), a simple model account for RDF induced mobility fluctuation is formulated as the following:

$$\sigma\mu_{(\text{Coulomb scattering})} = \frac{C_2}{m^*}\frac{N_{ch}{}^{\alpha}}{\sqrt{W_{eff}L_{eff}}} \tag{8}$$

where C_2 and α is fitting parameters. α should be a positive real number that smaller than 1.

Under high vertical field, the Si-oxide surface scattering dominates, so the dependency on doping and effective mass in eq. (8) may not be adquate in statistical compact modeling. While for the drift process, the dependency on geometry still holds.

$$\sigma\mu = \frac{C_3}{\sqrt{W_{eff}L_{eff}}} \tag{9}$$

Typically in circuit simulation, the design variables are limited, particularly for a device, the geometry is usually the only parameters that circuit designers work on. Both eq. (2) and (9) have the dependency on W/L, which is enough to cover the needs of circuit designers for a variation-aware design.

Besides eq. (2) and (9), the correlation between the two parameters is needed for a complete compact modeling solution. The correlation coefficient is usually an empirical value extracted from TCAD/Si data. For other models, the modeling flows are similar: 1) To use eq. (2) and (9) to model the parameters variation that account for threshold voltage/surface potential variation, and low-field mobility. 2) To extract correlation from TCAD/Si data or experience.

3 RESULT AND DISCUSSION

3.1 Modeling of TCAD data

By using the derived models of σV_{th} and $\sigma\mu_0$, the modeling flow is described as the following: 1) Get the variation IV data from TCAD/Si data. 2) Based on the calibrated nominal model of the TCAD/Si data, to optimize the two parameters that account for threshold voltage (or surface potential) and low field mobility for each IV data sample. 3) Extract the standard deviation of the two parameters and their correlation coefficient.

Take the TCAD data in Figure 1 as an example, the nominal device in TCAD simulation is well tempered with 22nm High Performance PTM model [11]. So 22nm HP PTM P-type model is used as the nominal model in parameter extraction. Then for each simulated IV, a convex optimization of the shifts of the two BSIM4 parameters, Δvth0 and Δu0, is performed to find the best fit of the TCAD result. After the Δvth0 and Δu0 of each device is obtained, the standard deviation and the correlation coefficient between Vth0 and u0 are extracted. The result is demonstrated in Figure 3. The correlation coefficient will be used as an empirical parameter in circuit simulations under a given process. From Figure 3, the negative correlation between |vth0| and u0 is observed, which is consistent with device physics.

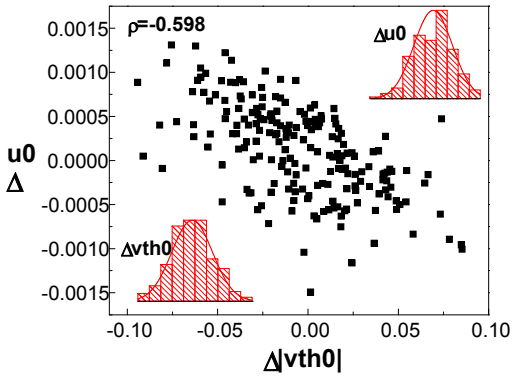


Figure 3: Extracted Δvth0 and Δu0 using BSIM4

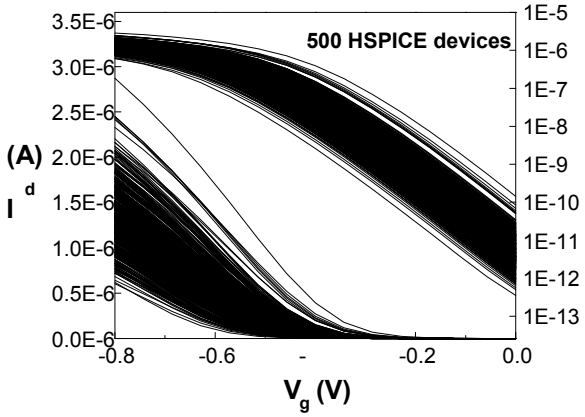


Figure 4: SPICE simulated IV of 500 devices

With the extracted standard deviation of the two parameters and the correlation coefficient, the Monte Carlo simulation with 500 devices is performed to verify the modeling flow. The simulated result is illustrated in Figure 4 and table I. It shows a good consistency with the variability from TCAD simulation.

	σI_{ds} @V_g=-0.8	$\sigma \log 10(I_{ds})$ @V_g=0
TCAD	3.54e-7 A	0.406
This work	3.47e-7 A	0.412
V_{th}-only	2.59e-7 A	0.425

Table 1: Comparison of TCAD, this work, and Vth-only method

3.2 Comparison with traditional "V_{th}-only" modeling

As mentioned in introduction, most previous researches focused on utilizing V_{th} shift to model the impact of RDF on MOSFET[3][5][6]. Many studies of circuit level variability simulation use only v_{th} variation to simulate the impact of RDF on circuits, such as [13][14]. While in digital circuit design, the current in strong inversion usually dominates the circuit performance. The variability in all operating region should be concerned in the simulation considering RDF, which cannot be achieved by using only V_{th} for RDF induced variations. Table I demonstrates the standard deviation of I_{ds} in strong inversion region and sub-threshold region. Results with proposed new modeling approach and traditional V_{th} only approach are compared. The result from TCAD data is also shown as the reference data. From the table we see that the variability from both the strong inversion region and sub-threshold region are well captured by using the proposed method, while the traditional method can only correct reproduced the variability in sub-threshold region. A 26.8% underestimation of the I_{ds} variation in the strong inversion region is observed. Such a huge underestimation may result in substantial deviation in circuit simulation, particularly variation aware digital design.

4 SUMMARY AND CONCLUSION

In this paper, a new modeling approach mapping both V_{th} and μ to RDF is proposed. The method is able to accurately reproduce the impact of RDF on IV curves in the whole operating region. The difference between the new methodology and traditional "V_{th}-only" modeling is compared. The probable risk ignoring mobility fluctuation in modeling is discussed. The whole novel modeling flow is verified with TCAD simulation result, helping circuit designers for a better and accurate variation aware design.

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