Investigation of Switching-Time Variations for Nanoscale MOSFETs Using the Effective-Drive-Current Approach

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***Abstract*—This letter investigates the impacts of random dopant fluctuation (RDF) and line edge roughness (LER) on the switching-time (ST) variation for nanoscale MOSFETs using the effective-drive-current (I_{eff}) approach that decouples the ST variation into transition-charge (ΔQ) and I_{eff} variations. Although the RDF has been recognized as the main variation source to the threshold-voltage variation, this letter indicates that the relative importance of LER increases as the ST variation is considered.**

***Index Terms*—Line edge roughness (LER), MOSFET, random dopant fluctuation (RDF), switching time (ST).**

I. Introduction

With MOSFET scaling, the impact of random dopant fluctuation (RDF) and line edge roughness (LER) on the threshold-voltage (V_{th}) variation of nanoscale transistors is growing and being extensively examined [1]–[3]. For example, Asenov *et al.* [2] has shown that, for a given LER variation, as gate dimensions are reduced, the V_{th} fluctuations increase and are comparable in magnitude to those caused by RDF. Roy *et al.* [3] has concluded that the V_{th} variation due to RDF would dominate the behavior of the bulk MOSFETs if the LER can meet the prescription of the International Technology Roadmap for Semiconductors.

For logic circuits, however, the variation of signal switching time (ST) due to RDF and LER is particularly important. Whether there is any gap between V_{th} and ST variations merits investigation. In this letter, we investigate the ST variation due to RDF and LER for bulk MOSFETs using the approach of effective drive current in CMOS inverters [4].

II. Methodology

We decouple the ST variation into transition-charge (ΔQ) and effective-drive-current (I_{eff}) variations. The ST can be defined as $\Delta Q/I_{\mathrm{eff}}$ [5], where ΔQ is the transition charge between logic "ON" and "OFF" states. The ΔQ for an NFET can be calculated by $Q_n(V_{\mathrm{GS}} = V_{\mathrm{DD}}, V_{\mathrm{DS}} = 0\ \mathrm{V}) - Q_n(V_{\mathrm{GS}} = 0\ \mathrm{V}, V_{\mathrm{DS}} = V_{\mathrm{DD}})$. The I_{eff} for an NFET can be approximated as $[I_{\mathrm{DS}}(V_{\mathrm{GS}} = V_{\mathrm{DD}}, V_{\mathrm{DS}} = 0.5V_{\mathrm{DD}}) + I_{\mathrm{DS}}(V_{\mathrm{GS}} = 0.5V_{\mathrm{DD}}, V_{\mathrm{DS}} = V_{\mathrm{DD}})]/2$ [4]. Therefore, in contrast to the time-consuming mixed-mode transient simulation, only dc simulation for a single device is needed to derive ΔQ and I_{eff}. More importantly, the effective-drive-current approach may provide physical insights in the assessment of ST variations.

The device parameters of bulk MOSFETs used in this letter are gate length (L_{gate}) = 25 nm, channel width (W) = 25 nm, oxide thickness (t_{ox}) = 0.8 nm, source/drain junction depth (x_j) = 12.5 nm, channel doping (N_{ch}) = $4.8 \times 10^{18}\ \mathrm{cm}^{-3}$, and supply voltage ($V_{\mathrm{DD}}$) = 0.8 V. To assess the RDF in bulk MOSFETs, we have carried out the atomistic device simulation using the Monte Carlo approach to generate the dopants in the channel [1]. To avoid the charge trapping in the sharp Coulomb potential well and, hence, the mesh size dependences of the simulation results, we have employed the density gradient method in our atomistic simulation [3]. The boundary condition at the Si/SiO_2 interface for the density gradient method is that the carrier density changes continuously across the interface, i.e., the continuity of the wavefunctions across the interface [6]. Fig. 1(a) shows one of the 150 samples in our atomistic simulation. To assess the LER, the line edge patterns were derived using the Fourier synthesis approach similar to the one in [2], and then, the Monte Carlo simulation was performed. The parameters used in the LER simulation are the rms amplitude $\Delta = 1$ nm [7] and the correlation length $\Lambda = 30$ nm. Fig. 1(b) shows one of the 150 samples in our simulation. In this letter, we use the drift-diffusion equation as the transport model. The velocity saturation model is used to assess the on-current under the high drain field.

III. Results and Discussion

Fig. 2(a) compares the saturation threshold-voltage ($V_{\mathrm{th,sat}}$) distributions due to RDF and LER for bulk MOSFETs. Fig. 2(b) compares the ST distributions due to the RDF and LER. It can be seen that the standard deviation of $V_{\mathrm{th,sat}}$ ($\sigma V_{\mathrm{th,sat}}$) due to RDF is larger than that due to LER. Nevertheless, Fig. 2(b) shows that the standard deviation of ST (σST) due to LER is comparable with that due to RDF. In other words, the relative importance of LER for ST variation increases as compared with

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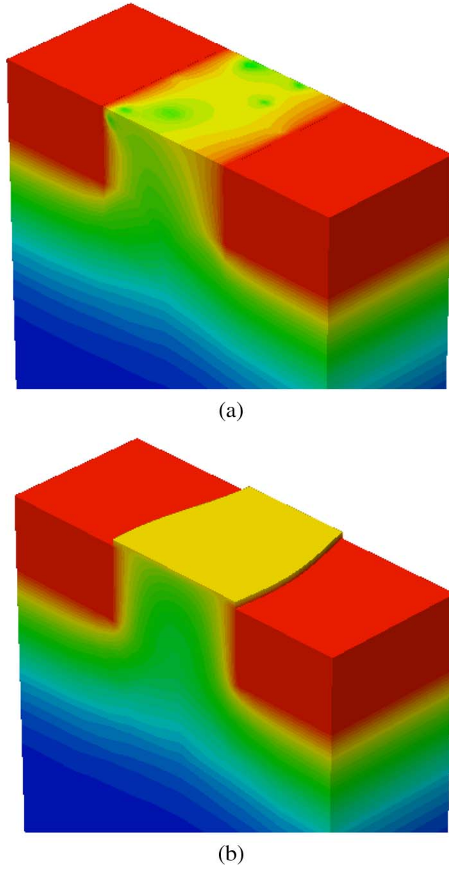

Fig. 1. Simulated bulk MOSFETs in this letter. (a) One of the samples with RDF and (b) one of the samples with LER.

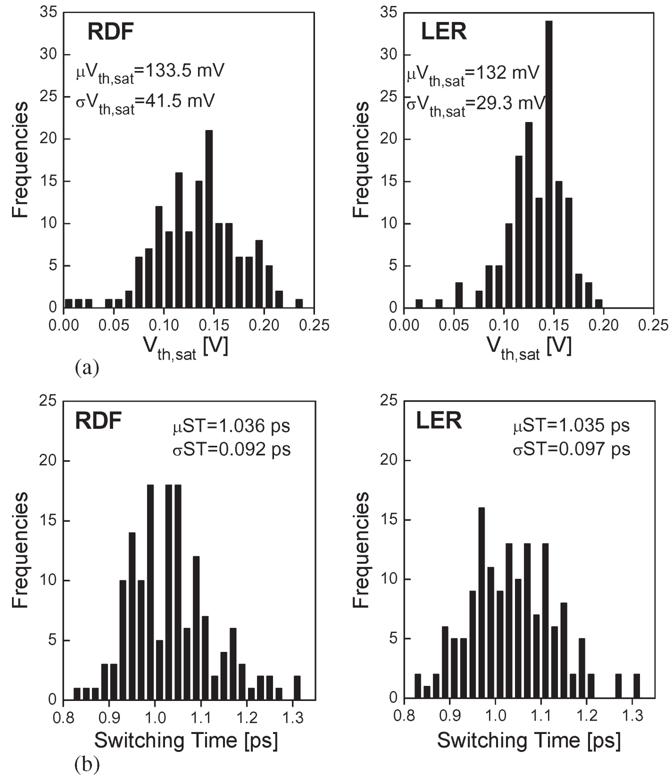

Fig. 2. (a) $V_{\mathrm{th,sat}}$ distribution of 150 samples due to RDF and LER. (b) ST distribution of 150 samples due to RDF and LER.

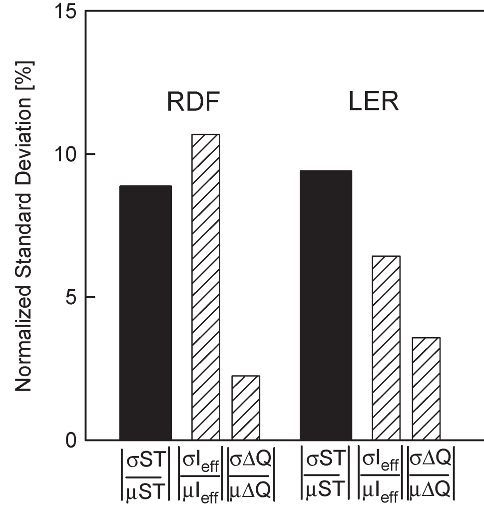

Fig. 3. Normalized standard deviations of ST, I_{eff}, and ΔQ due to RDF and LER.

that for $V_{\mathrm{th,sat}}$ variation. Since $\mathrm{ST} = \Delta Q / I_{\mathrm{eff}}$, the normalized standard deviation of ST ($\sigma\mathrm{ST}/\mu\mathrm{ST}$) can be approximated as $|\sigma\mathrm{ST}/\mu\mathrm{ST}| \approx |\sigma\Delta Q/\mu\Delta Q - \sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$, where $\mu\mathrm{ST}$, $\mu\Delta Q$, and μI_{eff} are the mean values of ST, ΔQ, and I_{eff}, respectively. In this letter, we consider the standard deviations $\sigma\mathrm{ST}$, $\sigma\Delta Q$, and σI_{eff} as signed numbers. Fig. 3 shows the $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$, $|\sigma\Delta Q/\mu\Delta Q|$, and $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$ (normalized standard deviation of ST, ΔQ, and I_{eff}, respectively) caused by RDF and LER. It can be seen that the $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ due to RDF is roughly equal to the difference of $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$ and $|\sigma\Delta Q/\mu\Delta Q|$ due to RDF. However, the $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ due to LER is roughly equal to the sum of $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$ and $|\sigma\Delta Q/\mu\Delta Q|$ due to LER. The results in Fig. 3 can be explained as follows. The impact of RDF on MOSFETs stems from the variation of the effective channel doping ($N_{\mathrm{ch,eff}}$). For devices with smaller $N_{\mathrm{ch,eff}}$ values, the V_{th} is smaller, and hence, I_{eff} and ΔQ are larger because they are roughly proportional to $(V_{\mathrm{GS}} - V_{\mathrm{th}})$. Thus, I_{eff} and ΔQ are positively correlated [Fig. 4(a)]. Therefore, $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ is roughly equal to the difference between $|\sigma\Delta Q/\mu\Delta Q|$ and $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$ because the quantities of $\sigma\Delta Q$ and σI_{eff} have the same sign. In other words, the impacts of RDF on ΔQ and I_{eff} are mutually canceled, and $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ is reduced.

The impact of LER on MOSFETs results from the variation of the effective channel length (L_{eff}). For devices with shorter L_{eff}'s, the V_{th} is smaller because of the short-channel effect, and hence, the I_{eff} is larger. As for ΔQ, devices with shorter L_{eff}'s possess smaller ΔQ's because ΔQ is proportional to the gate area ($W \times L_{\mathrm{eff}}$). Thus, I_{eff} and ΔQ are negatively correlated [Fig. 4(b)]. Therefore, $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ is roughly equal to the sum of $|\sigma\Delta Q/\mu\Delta Q|$ and $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$ because the quantities of $\sigma\Delta Q$ and σI_{eff} have the opposite sign. In other words, the $|\sigma\mathrm{ST}/\mu\mathrm{ST}|$ is larger than either $|\sigma\Delta Q/\mu\Delta Q|$ or $|\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}|$.

It should be noted that, for ultrascaled devices in which ballistic transport becomes significant, the I_{eff} will be underestimated if the drift-diffusion model is used. However, the normalized standard deviation of I_{eff} ($\sigma I_{\mathrm{eff}}/\mu I_{\mathrm{eff}}$) may not be

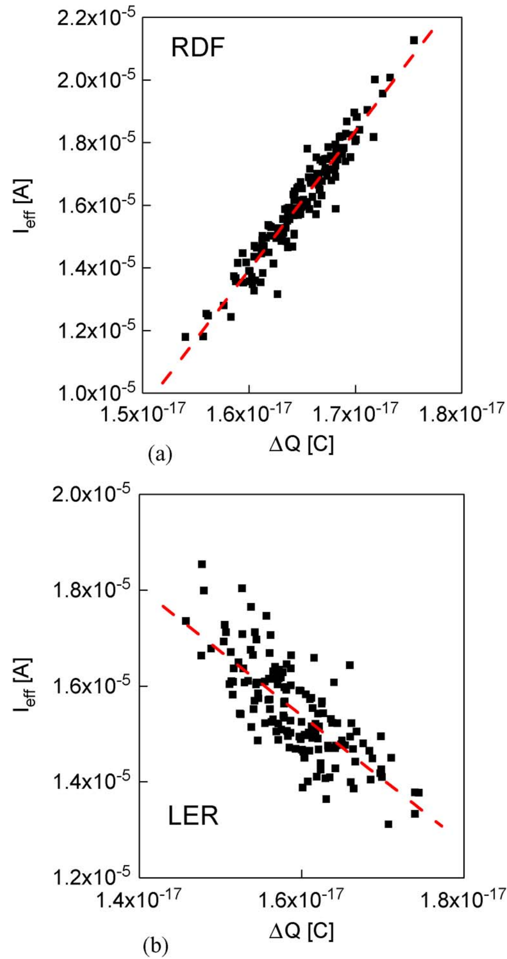

Fig. 4. Correlations of I_{eff} and ΔQ distributions for MOSFETs with (a) RDF and (b) LER.

as sensitive to the transport model as the I_{eff}. Aside from the electrostatic potential fluctuation, the discrete dopants will also cause the mobility fluctuation, which is not considered in this letter. Therefore, the σI_{eff} due to RDF may be larger than that in Fig. 3 because of the mobility fluctuation caused by discrete dopants.

IV. Conclusion

We have investigated the impacts of RDF and LER on the ST variation for nanoscale MOSFETs using the effective-drive-current approach that decouples the ST variation into ΔQ and I_{eff} variations. Our results indicate that the ST variation caused by LER may be larger than that caused by RDF. This is because I_{eff} and ΔQ variations due to RDF are mutually canceled and the ST variation caused by RDF is reduced, while I_{eff} and ΔQ variations due to LER increase the ST variation caused by LER. Although the RDF has been recognized as the main variation source to V_{th} variation, the relative importance of LER increases as the ST variation is considered. This letter may provide insights for device and circuit designs using advanced CMOS technology.

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