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A Device-level Characterization Approach to Quantify the Impacts of Different Random Variation Sources in FinFET Technology

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***Abstract*— A simple device-level characterization approach to quantitatively evaluate the impacts of different random variation sources in FinFETs is proposed. The variations of V_{th} induced by the two major categories of variation sources: metal gate granularity (MGG) and line-edge roughness (LER) are theoretically decomposed based on the distinction in physical mechanisms and their influences on different electrical characteristics. The effectiveness of the proposed method is confirmed through both TCAD simulations and experimental results. This work can provide helpful guidelines for variation-aware technology development.**

***Index Terms*— FinFET, Random Variation, Characterization, Line-edge Roughness (LER), Metal Gate Granularity (MGG).**

I. INTRODUCTION

WITH the continuous scaling of CMOS technology, random variations have caught lots of attentions [1-7]. The most challenging variation sources are random dopant fluctuation (RDF), metal gate granularity (MGG) and line-edge roughness (LER). For FinFET technology, RDF is suppressed owing to the lightly doped fin, but LER is deteriorated due to the complexity of the structure, resulting in fin-edge roughness (FER) and gate-edge roughness (GER). The three major variation sources are illustrated in Fig. 1.

Although the origins of these random variation sources are different, their impacts on the device electrical characteristics are difficult to be distinguished from each other. Most previous studies targeting on single random variation source were based on TCAD simulation without experimental evidence [8], and those experimental studies could only provide an investigation on the overall impacts of different variation sources [9].

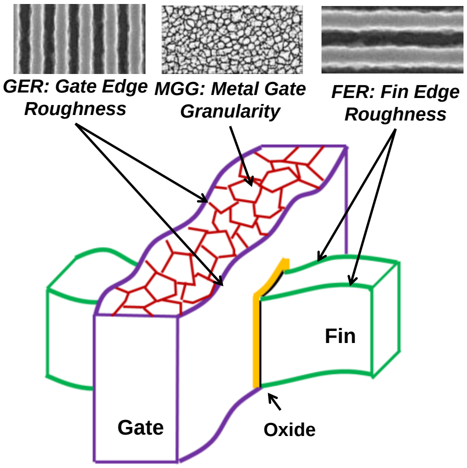

Fig. 1. Illustration of the major random variation sources in FinFETs: metal gate granularity (MGG), gate-edge roughness (GER) and fin-edge roughness (FER).

However, it is important to know experimentally how many impacts of each variation source bring exactly on device electrical characteristics. For technology development, it provides direct assessment on the relative importance of the random sources for different processes, thus giving guidelines for process optimization.

In this work, we found that these variation sources can be classified into two categories based on their unique physical mechanisms on device electrical characteristics. And a simple characterization approach is proposed for the decomposition of their impacts on V_{th}. This method is verified through both 'atomistic' TCAD simulations and experimental results.

II. METHODOLOGY

The major variation sources have very distinct physical mechanisms, displayed as divergence in the impacts on different electrical figures of merit. MGG affects the effective workfunction of the gate, leading to a direct shift of threshold voltage V_{th}. As for LER (FER and GER), the effective fin width and the effective gate length are influenced, resulting in the change of device electrostatic control. Therefore, both V_{th} and subthreshold swing (*SS*) are affected by LER (either FER or GER), but only V_{th} would be affected by MGG.

In order to confirm the above speculations, 'atomistic' TCAD simulations are carried out based on 14nm FinFET template designed in collaboration between IBM, Glasgow University and Gold Standard Simulations (GSS) [10], with the

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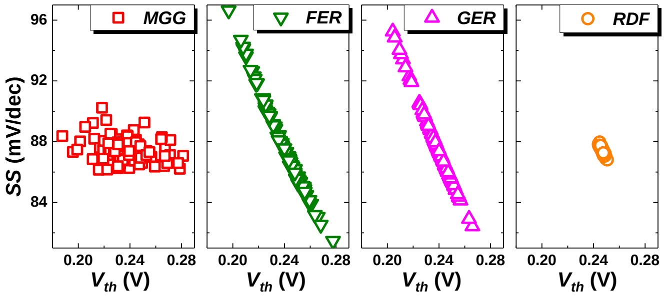

Fig. 2. The correlations between V_{th} and *SS* under each individual random variation sources. All MGG, FER and GER induce large variation into V_{th}, but only FER and GER contribute significantly to *SS* variation, which has strong linear correlation with V_{th} variation. As for RDF, the corresponding variations are small enough to be neglected, as expected for FinFETs with lightly doped fin.

GSS atomistic simulator GARAND [11].

As shown in Fig. 2, MGG induces V_{th} variation only, while LER contributes to both V_{th} and *SS* variation, as expected. Moreover, LER induced SS variations are found to have a strong linear correlation with the corresponding V_{th} variations. Accordingly, the following treatments can be made:

(1) *SS* variation (δSS) is induced totally by LER; while V_{th} variation (δV_{th}) is induced by both MGG (δV_{th}^{MGG}) and LER (δV_{th}^{LER}):

$$\delta V_{th} = \delta V_{th}^{MGG} + \delta V_{th}^{LER} \tag{1}$$

(2) *SS* variation (δSS) has linear dependence on V_{th} variation induced by LER (δV_{th}^{LER}):

$$\delta SS = k \cdot \delta V_{th}^{LER} \tag{2}$$

(3) MGG induced V_{th} variation (δV_{th}^{MGG}) is independent from LER induced V_{th} variation (δV_{th}^{LER}).

$$\operatorname{cov}\left(\delta V_{th}^{MGG}, \delta V_{th}^{LER}\right) = 0 \tag{3}$$

Then, the covariance matrix of δV_{th} and δSS can be written as:

$$\Sigma = \begin{bmatrix} \sigma^2\left(\delta V_{th}^{MGG}\right) + \sigma^2\left(\delta V_{th}^{LER}\right) & k \cdot \sigma^2\left(\delta V_{th}^{LER}\right) \\ k \cdot \sigma^2\left(\delta V_{th}^{LER}\right) & k^2 \cdot \sigma^2\left(\delta V_{th}^{LER}\right) \end{bmatrix} \tag{4}$$

Therefore, the only parameter *k* can be calculated from the covariance matrix as follow:

$$k = \frac{\Sigma_{22}}{\Sigma_{21}} \tag{5}$$

And the V_{th} variation induced by the two categories can be calculated, as follow:

LER induced:

$$\sigma^2\left(\delta V_{th}^{LER}\right) = \frac{\sigma^2(\delta SS)}{k^2} \tag{6}$$

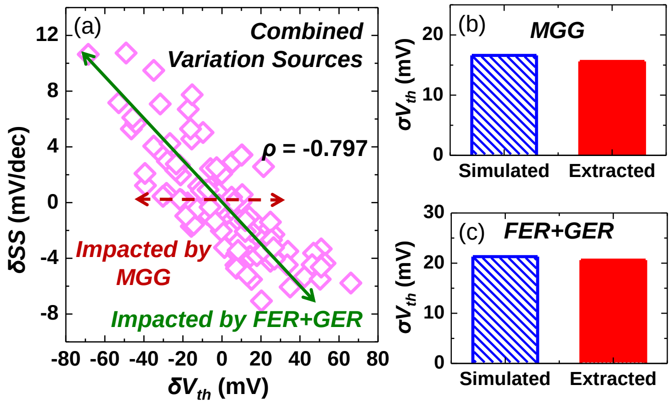

Fig. 3. (a) The correlation between δSS and δV_{th} under combined variation sources; (b) Comparison of MGG induced σV_{th} between extraction from Fig. 3 (a) and TCAD simulation considering only MGG; (c) Comparison of FER+GER induced σV_{th} between extraction from Fig. 3 (a) and TCAD simulation considering LER and GER.

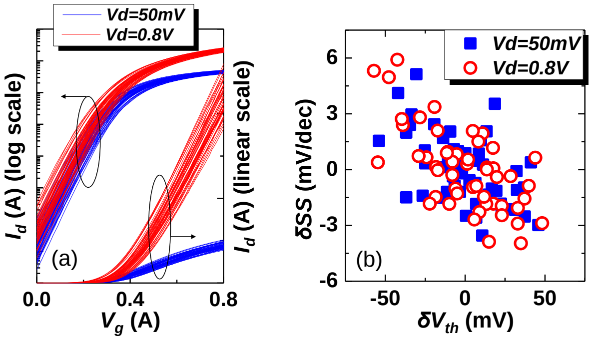

Fig. 4. (a) Measured transfer curves. (b) The corresponding δV_{th} and δSS, showing a clear linear correlation between δV_{th} and δSS.

and MGG induced:

$$\begin{aligned} \sigma^2\left(\delta V_{th}^{MGG}\right) &= \sigma^2\left(\delta V_{th}\right) - \sigma^2\left(\delta V_{th}^{LER}\right) \\ &= \sigma^2\left(\delta V_{th}\right) - \frac{\sigma^2(\delta SS)}{k^2} \end{aligned} \tag{7}$$

III. RESULTS AND DISCUSSION

A. Verification with TCAD Simulations

Fig. 3 (a) shows the TCAD simulated δSS and δV_{th} with combined random variation sources. A moderate linear correlation between δSS and δV_{th} can be observed, which would be the compromised impacts of MGG and LER. In order to verify the proposed method, the extraction results from the combined cases (i.e., extracted from Fig. 3 (a)) are compared against the simulation results with each individual random variation source, as shown in Fig. 3 (b) and (c). The good consistency confirms the accuracy of the proposed method.

B. Verification with Experimental Results

The devices measured in this work are fabricated based on 16nm FinFET technology, with different L_g and N_{Fin}=4. The typical transfer curves are plotted in Fig. 4 (a), from which V_{th} and *SS* are then extracted. As shown in Fig. 4 (b), there is a moderate linear correlation between *SS* and V_{th}, indicating the compromised impact of LER and MGG, from which $\sigma^2(V_{th}^{MGG})$ and $\sigma^2(V_{th}^{LER})$ can be extracted then.

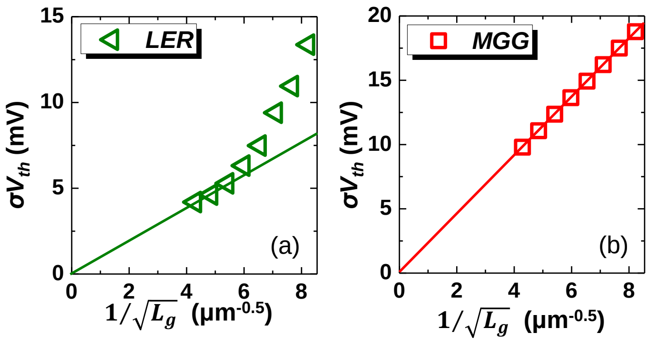

Fig. 5. σV_{th} caused by (a) LER and (b) MGG vs. reciprocal square root of L_g (N_{Fin}=1). In the long channel region, both variations are proportional to the reciprocal square root of L_g, while in the short channel region, LER induced σV_{th} starts to deviate from the previous trend and increase dramatically.

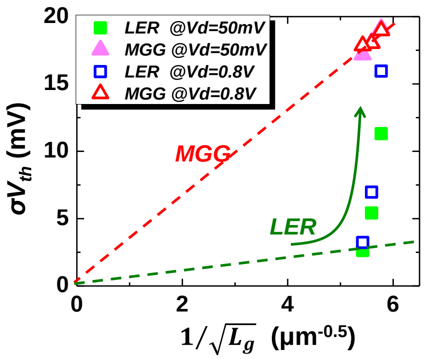

Fig. 6. Extraction results from experimental data. While σV_{th}^{MGG} is basically proportional to the reciprocal square root of L_g, σV_{th}^{LER} increases dramatically as L_g decreases.

In order to further verify the proposed method, the geometry dependence of σV_{th} is examined. The impacts of LER and MGG have different dependence on FinFET geometry, especially L_g, due to their distinct physical mechanisms. Generally, the standard deviation of random variation would be proportional to the reciprocal square root of gate area. For MGG, V_{th} variation is caused by the dispersion of the effective work function, which directly depends on the gate area. So σV_{th}^{MGG} would be proportional to the reciprocal square root of L_g. However, for LER, V_{th} variation would depends on the gate control, thus deteriorated with smaller L_g, as discussed in our previous study [12]. Therefore, as L_g gets smaller, σV_{th}^{LER} would increase much faster than reciprocal square root of L_g. This can be confirmed as in Fig. 5, which shows Monte Carlo simulation results based on our newly-developed predictive compact model of FinFET random variations [12]. In the case of long channel, both LER and MGG variation follow the proportional rule against square root of L_g, while in the case of short channel, LER variation dramatically increases and deviates from the previous trend. This is caused by the coupling effect between LER variation and short channel effects.

Accordingly, the L_g dependence of σV_{th}^{MGG} and σV_{th}^{LER} from experimental extractions are plotted in Fig. 6. σV_{th}^{MGG} is basically proportional to the reciprocal square root of L_g, as expected. As for σV_{th}^{LER}, the variation increases much faster. Although the transition as expected in the simulation result (Fig. 5 (a)) is not observed, the growth trend obviously exceeds the proportional one. In this case, the effectiveness of the proposed method is confirmed.

This quantitative evaluation of the impacts induced by MGG and LER can provide helpful information for technology development. It is worth noting that for short L_g, the variations induced by LER is comparable with those induced by MGG. And according to the growth trends, LER is likely to take over the dominating role of MGG very soon if LER is not optimized as L_g continues to scale down.

IV. CONCLUSION

A novel and simple method to decompose the impacts induced by different random variation sources in FinFETs on the variation of device electrical characteristics is proposed. The influence of two major categories of random variation sources: MGG and LER on σV_{th} are decomposed theoretically and verified by both TCAD simulations and experimental results. σV_{th}^{LER} increases dramatically when L_g shrinks, while σV_{th}^{MGG} is basically proportional to the reciprocal square root of L_g. The proposed method is helpful for variability-aware design-technology co-optimization, by providing a simple way to experimentally and quantitatively evaluate the impacts caused by different random variation sources from device level.

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