Investigations on the Correlation between Line-edge-roughness (LER) and Line-width-roughness (LWR) in Nanoscale CMOS Technology

Xiaobo Jiang[1], Meng Li[1], Runsheng Wang[1*], Jiang Chen[2] and Ru Huang[1*]

[1] Institute of Microelectronics, [2] Department of Electronics,
Peking University, Beijing 100871, China
*Email: ruhuang@pku.edu.cn; r.wang@pku.edu.cn

Abstract

In this paper, the correlation between line-edge-roughness (LER) and line-width-roughness (LWR) is studied for the first time. Based on the characterization methodology of auto-correlation functions (ACF), a new theoretical model of LWR is proposed, in which the ACF of LWR can be analytically obtained from the ACFs of LER in the two line-edges. An improved method of generating "practical" lines with correlated LER is also proposed for statistical simulations. The model indicates that the LWR ACF is composed of two parts: one involves LER information, the other involves the cross-correlation of LER in the two line-edges, which agrees well with simulation results. It is also found that the correlation length of LWR reduces with increasing the correlation coefficient of the two LER sequences with different correlation lengths. The results provide helpful guidelines for the characterization, modeling and the optimization of LER/LWR in nanoscale CMOS technology.

1. Introduction

As devices shrinking into nanometer region, random variations have become critical issues, in which the line-width-roughness (LWR) or line-edge-roughness (LER) (as schematically shown in Fig. 1) are reported to be non-negligible beyond 16nm node [1-3]. Besides the LER/LWR in gate lines, channel LER/LWR in multi-gate devices (e.g., in FinFETs [4-6] and gate-all-around nanowire FETs [7-10], is also paid more and more attentions. In previous studies, LER and LWR are often treated equally or independently. Most reports use LER and LWR synonymously, i.e., took either LWR or LER to study its properties and impacts. However, LWR and LER are actually different and related, and have different impacts on the device performance. For example, a line can have no LWR but does have LERs at two edges, and experiments have found that the LER in two edges of the line can have a nonzero correlation coefficient [4,10]. However, there has been no study on the inherent correlation between LER and LWR. Therefore, in this paper, a new theoretical model and an improved statistical simulation method are proposed for understanding, evaluating and characterizing the correlation between LER and LWR. Both the correlation and the characteristics in LER and LWR are studied in detail, which provides helpful information for the future design optimization of LER/LWR in nanoscale CMOS technology

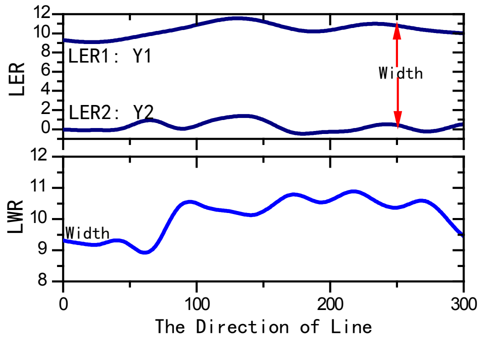

Fig. 1 Sketches of LER and LWR in a line.Y_1, Y_2 denote two LER sequences.

2. Theoretical Modeling

The model proposed in this paper is based on characterization methodology of auto-correlation function (ACF) [1,9,10]. LER/LWR can be detected from top-view SEM images, as is shown in Fig. 2(a-b) as an example [9], and then ACF of LER/LWR can be calculated. In most cases after lithography and dry etching, LER/LWR ACFs are found to be in consistency with the Gaussian function, as is shown in Fig. 2(c), where λ is defined as the correlation length reflecting the average distance between adjacent peaks in LER/LWR. And the rms (Δ) of LER/LWR reflects its variation amplitude.

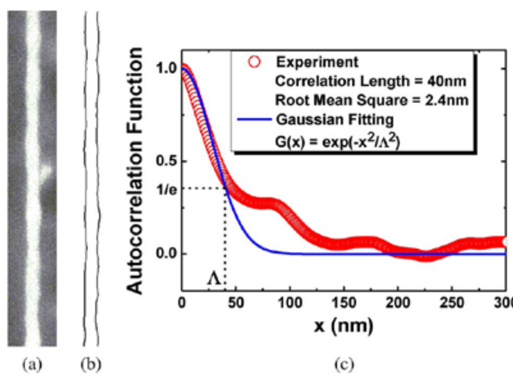

Fig. 2 (a) Top-view SEM image of a 40nm-wide Si nanowire channel with (b) edges detected. (c) ACF of the left edge with Gaussian fitting [9].

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2.1 General Theory

The correlation between LWR rms (Δ_W) and LER rms of both line-edges (Δ_1, Δ_2) is simple:

$$\Delta_W^2 = \Delta_1^2 + \Delta_2^2 - 2\rho\Delta_1\Delta_2$$

where ρ is the correlation coefficient of the two LER sequences.

However, LER/LWR has more information in addition to its rms: the spatial information which is described by its ACF, which should be accurately modeled.

ACFs of the two LERs are denoted as R_1 and R_2, and R_W is the LWR ACF. For convenience, we use y_1 = Y_1-avg(Y_1) and y_2 = Y_2-avg(Y_2). Y_1, Y_2 are defined in Fig. 1. Therefore, R_1, R_2, R_W can be written as:

$$R_1(x) = y_1(x) * y_1(-x)$$

$$R_2(x) = y_2(x) * y_2(-x)$$

$$R_W(x) = R_1(x) + R_2(x) - R_X(x)$$

where $R_X(x)$ is the cross-correlation function

$$R_X(x) = R_{12}(x) + R_{21}(x)$$

$$= y_1(x) * y_2(-x) + y_1(-x) * y_2(x)$$

Through Fourier transform, one can have:

$$R_X(x) = 2b_0 r(x) + b_1\left[r(x+\mu) + r(x-\mu)\right]$$

$$+ b_2\left[r(x+2\mu) + r(x-2\mu)\right] + \ldots$$

where $r(x) = F^{-1}\left[\sqrt{F(R_1)F(R_2)}\right]$.

The above results indicate that, the LWR ACF can be divided into two parts: ACFs of the two LERs and the cross-correlation of the two LERs. It should be noted that, there is a translation parameter μ which cannot be implied by the LER ACFs. The μ can be considered as the quantification of the translation of the two line-edges.

2.2 Application of the model

Specifically, when the two LER ACFs are Gaussian type, which is the typical observation in experiments, i.e.,

$$R_1(x) = \Delta_1^2 \exp\left(-x^2/\lambda_1^2\right),$$

$$R_2(x) = \Delta_2^2 \exp\left(-x^2/\lambda_2^2\right),$$

and μ=0, the LWR ACF is totally determined by LER ACFs:

$$R_W(x) = \Delta_1^2 \exp\left(-x^2/\lambda_1^2\right) + \Delta_2^2 \exp\left(-x^2/\lambda_2^2\right)$$

$$-2\Delta_1\Delta_2\sqrt{2\lambda_1\lambda_2/\left(\lambda_1^2+\lambda_2^2\right)}\exp\left[-x^2/\left(\lambda_1^2+\lambda_2^2\right)\right]$$

From this equation result, we can get three key messages: (1) $R_X(x)$ is also Gaussian type, thus we can define a cross-correlation length λ_X which is similar to the concept of correlation length. (2) λ_X is a function of the two LER correlation lengths and has no dependence on the ρ of the two edges. It can be written as: $\lambda_X = \sqrt{\lambda_1^2+\lambda_2^2/2}$. (3) when the two LERs has different correlation lengths ($\lambda_1 \neq \lambda_2$), the absolute value of ρ is smaller than 1. The maximum value of ρ is $\rho_{\max} = \sqrt{2\lambda_1\lambda_2/\lambda_1^2+\lambda_2^2}$.

3. Improved Statistical Simulation Method

In previous studies, Fourier synthesis method is adopted to generate random LER [1,9]. However, this method can only be used to generate one edge of LER or LWR. Because arbitrary two random LER generated by this method results in ρ=0 of them, which is not the case in most experimental results. Here, we propose an improved method to generate random LERs with a certain correlation coefficient for statistical simulations of "practical" lines with LER and LWR.

The original method uses white noise sequences to induce the randomness. Here we use linear transform to induce relativity into the two white noises used to generate LERs:

$$\begin{pmatrix} wn_1 \\ wn_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ a & b \end{pmatrix}\begin{pmatrix} wn_a \\ wn_b \end{pmatrix}$$

where wn_a, wn_b are two white noise sequences generated. Now wn_1 and wn_2 have a correlation coefficient a, which can be an arbitrary value within -1 to 1.

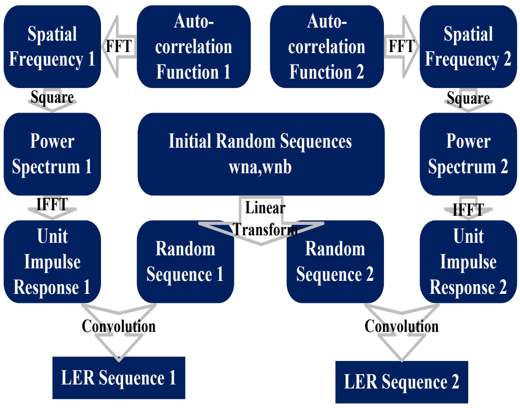

Fig. 3 Flow chart of the improved simulation method.

The proposed simulation flow is shown in Fig. 3. It is worth noting that, both the parameter a and LER ACFs have impacts on the ρ. During simulation, the LER ACFs are fixed, thus the corresponding relationship between a and ρ can be obtained.

4. Results and Discussion

Using the improved method mentioned above, statistical simulations are performed to investigate the correlation between LER and LWR. Both LER ACFs are Gaussian type. Since correlation in rms is simple, here we consider Δ_1=Δ_2=1. Then we choose different pair of λ_1 and λ_2. Once λ_1, λ_2 are fixed, the corresponding relationship between a and ρ can be obtained.

The range of ρ is divided into 21 non-overlapping intervals: [-1,-0.95], [-0.95,-0.85] … [0.95, 1]. 101 pairs of LERs with the certain ρ interval are generated. For each pair of LERs, LWR ACF $R_W(x)$ and the LER cross-correlation $R_X(x)$ are calculated. Then Gaussian function is used to fit $R_X(x)$, and the mean square error (MSE) is taken as the quantification of the degree of fitting.

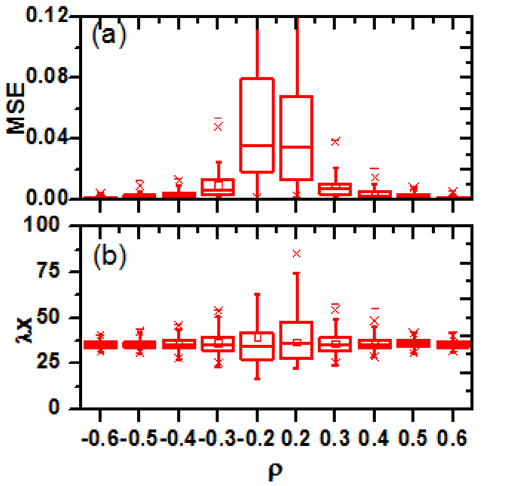

Fig. 4 (a) Box plot of MSE vs. ρ; (b) Box plot of λ_X vs. ρ, the median value keeps the same as ρ changes. The simulated λ_1=10 and λ_2=50 in this figure.

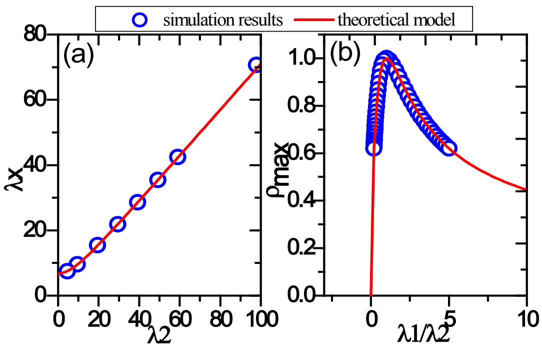

Fig. 5 (a) The median value of λ_X vs. λ_2 when λ_1=10; (b) ρ_{max} vs. λ_1/λ_2.

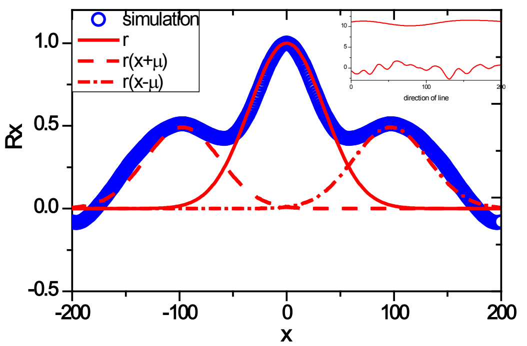

Fig. 6 Typical R_X that doesn't fit a Gaussian function. The inserted is the corresponding LER/LWR.

As shown in Fig. 4(a), MSEs are evidently smaller than 0.02, except for those ρ close to 0, which means $R_X(x)$ is in consistency with the Gaussian function. And the cross-correlation length λ_x does not depend on ρ [Fig. 4(b)]. The extracted λ_X and ρ_{max} from the simulation results are in great agreement with the theoretical model proposed in section 2.2, as shown in Fig. 5. As for the few cases in which λ_X are far away from its median value, we can find the typical $R_X(x)$ in Fig. 6. These cases have nonzero translation length (μ), as is expected in section 2.1.

However, in contrary to λ_X, the LWR correlation length λ_W decreases when ρ increases, if $\lambda_1 \neq \lambda_2$. The larger λ_1/λ_2 gets, the faster λ_W decreases, as shown in Fig. 7.

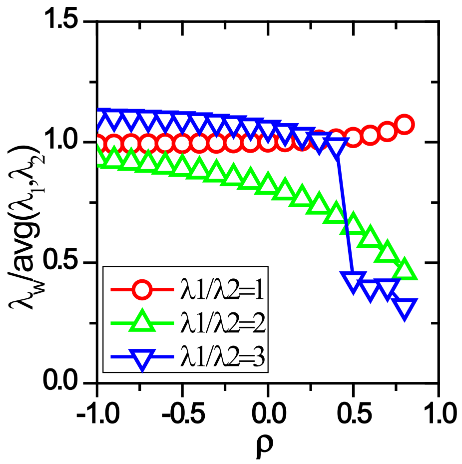

Fig. 7 $\lambda_w/avg(\lambda_1, \lambda_2)$ vs. ρ when λ_1=10 and λ_2=50.

5. Summary

In this paper, the correlation between LER and LWR are investigated for the first time. A new theoretical model is proposed to describe the correlation between LER ACFs and LWR ACF. LWR ACF depends on LER ACFs and the additional translation length μ of the two edges. The model agrees well with statistical simulation results, which is based on an improved Fourier synthesis method. The λ_X is independent of ρ but only related to λ_1 and λ_2. However the λ_W is found to decrease as ρ increases, if the two LERs has different correlation lengths ($\lambda_1 \neq \lambda_2$).

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References:

[1] A. Asenov, et al., *IEEE T-ED*, vol.50, p.1254, 2003. [2] *ITRS* 2011 (http://www.itrs.net). [3] Y. Ye, et al., *J Comput Electron*, vol.9, p.108, 2010. [4] A. Dixit, et al., *IEDM Tech. Dig.*, p.709, 2006. [5] E. Baravelli, et al., *IEEE T-ED*, vol.54, p.2466, 2007. [6] K. Patel, et al., *IEEE T-ED*, vol.54, p.3055, 2009. [7] Ru Huang, et al., *IEEE CICC*, 2-1, p.1, 2011. [8] R. Wang, et al., *IEEE T-ED*, vol.58, p.2317, 2011. [9] T. Yu, et al., *IEEE T-ED*, vol.57, p. 2864, 2010. [10] R. Wang, et al., *IEDM Tech. Dig.*, p.792, 2010.