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Oxide Variability Analysis Exploiting Greens Function Simulations

Ahsin Murtaza Bughio[1*], **Junaid Iqbal**[2], **Khalil Muhammad Zuhaib**[3], **Umair Ali Khan**[4], **Nasreen Nizamani**[1]

[1] *Department of Electronic Engineering, QUEST, Nawabshah, PAKISTAN.*
[2] *Department of Mechanical Engineering, QUEST, Larkana-Campus, PAKISTAN.*
[3] *Department of Electronic Engineering, QUEST, Larkana-Campus, PAKISTAN.*
[4] *Department of Computer Systems Engineering, QUEST, Nawabshah, PAKISTAN.*
**Corresponding Author (Email: ahsan.murtaza @ quest.edu.pk).*

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Abstract

Aggressive downscaling of MosFET devices has some limitation due to short channel effects. These short channel effects affect the electronic behavior of device adversely. FinFET was proposed to overcome this shortcoming of MosFETs. But like MosFETs, FinFET have a problem of variability, which becomes more and more effective with the scaling. Variability analysis was the main theme of this research. Oxide thickness variations were taken into account for this research. 5%, 10% and 25% of variations were applied to oxide thickness and results were obtained for drain current, leakage current and threshold voltage. Synopsys Sentaurus as well as in-house simulator (Green's function simulation) were used for variability analysis.

Disciplinary: Electronics Engineering and Tehnology, Physics.

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1 Introduction

With the ever-increasing appetite for technology, the miniaturization of electronic devices is inevitable. MosFETs are the most common electronic devices used in the semiconductor devices. But due to short channel effects, the MosFETs performance deteriorates significantly. FinFET offers many advantages over MOSFETs. But the main advantages that FinFET offers are

- They greatly reduce SCE, which leads to even shorter lengths of the channel as compared to their counterpart i.e., bulk MOSFET (Bughio et al., 2017)
- Provides steeper sub-threshold slope which offers a larger gate over-drive for the same voltage supply and at the same off-current (Raskin, 2015)
- Also, provides the option of reduced channel doping which affects the mobility and offers good carrier transport behavior (Seoane et al., 2013)

As everything has its own merits and demerits, the same is the case with FinFET. By virtue of scaling, the soi-disant transistors don't behave identically, though the transistors are fabricated keeping all aspects the same. Characterization of variability and analysis in evolving technologies are requisites for refined performance and process competence. The importance of process variations was stated in the 2011 International Technology Roadmap for Semiconductors (ITRS) (ITRS, 2013), "One of the key problems that designers face due to further shrinking of feature sizes is the increasing variability of design-related parameters, resulting either from variations of fabrication parameters or from the intrinsic atomistic nature which affects, e.g., channel doping." Thus, attention from scientists around the world was diverted to process variability and different aspects of variability came under research afterwards.

FinFET is the promising device for future but it is also susceptible to variability effects. In this paper, we will focus on the importance of the variability analysis. In particular we will:

- Analyze the variability of important parameter of the DG MosFET i.e., 2D-model for FinFET device
- Use of Green's function approach for variability analysis of FinFET device
- Compare simulated variability with respected manual change

By modelling of the FinFET devices, we will estimate the variability of oxide thickness which will be important in the overall yield of the device. This is achieved by studying the impact of the process variation in FinFET device which will result in variation in the device performance. The GREENs function approach is also exploited to observe the simulation efficiency and the tradeoff between the accurate results and time efficiency is discussed.

2 Green's Function Approach to Variability Analysis

There are many sources of variability, the ones related to geometrical or doping variations or the others such as traps, variability due to strain, poly grains, implantations and annealing variability, fixed charges or the defects (Matsukawa et al., 2009). These all can be incorporated in random fluctuations. Random fluctuation causes degradation of the device performance on electrical as well as physical scales. These random fluctuations become more significant with higher levels of scaling (Bughio et al., 2017). The conventional method for solving the random fluctuations is Monte-Carlo simulating method. In Monte-Carlo simulations, generally, all parameters are varied simultaneously and the results are obtained. Monte-Carlo simulation offers a greater number of accuracy but this technique is very time-consuming as well as it needs a large number of computations. Shockley et al. (1966) proposed a non-conventional technique to solve non-linear systems using the linear approach called the Impedance field method. This method is based on the procedure of summing up the contributions from different sections of a device to the total terminal noise. This propagation of the fluctuation is represented by the impedance field, which, in a one-dimensional (1D) geometry, and is a scalar function (Bulashenko, 1998). The sections at which the impedance field method is applied are referred to as node points in the Sentaurus Device, a simulation tool used for variability analysis.

3 Methodology

While starting with the simulation for variability analysis, the key challenge was to choose proper simulation method to have efficient as well as accurate statistical variation results. Generally, the atomistic approach comes in mind but it has the capability to complicate the simulations of all the statistical variations which are simulated and overall effect of the device is evaluated which requires large number of computational resources. This atomistic also known as brute force method has been highlighted in the academic literature as a streamline to assess the effects of variability. However, the need to increase the computational efficiency of atomistic simulators leads us to alternative methods.

With the universal interest in resolving the computational complexity of the electronic devices, new method was evolved, widely known as impedance field method (IFM) (Sanchez, 2002). The advantage of significantly reducing the simulation by exploiting IFM technique with only slight effect on the statistical as well as deterministic simulations' accuracy. The basic idea used in IFM is to treat the randomness of the doping, geometrical variations, metal grains and other variability sources as perturbations of a reference device (Jain et al., 2020; Bughio et al., 2018; Bughio et al., 2017). This technique uses linear approach to analyze the characteristics of electronic devices and FinFET is device of interest in this paper (Bughio et al., 2017). FinFET is a non-linear device and IFM technique is used to perform our analysis.

For IFM technique to be applicable to Non-linear systems, we have to assume very small perturbation of the system, such that system can be linearized around the working point (Bughio et al., 2016; Agrawal et al., 2015). For sub-50nm scale, the effects of the other nodes are bound to add the noise to the system. Thus, the IFM techniques have the limitation to provide with accurate results of the simulated device. But IFM techniques provide with lesser amount of simulation accuracy and the advantage of lesser amount computational resources. There is always a trade-off between accuracy and computational time and resources.

4 Device Model

Numerical methods are used to solve the system for manual variations. Poisson and continuity equation mode are used for numerical analysis of our system. All parametric details for the structure definition and doping of the structure are shown in Table 1.

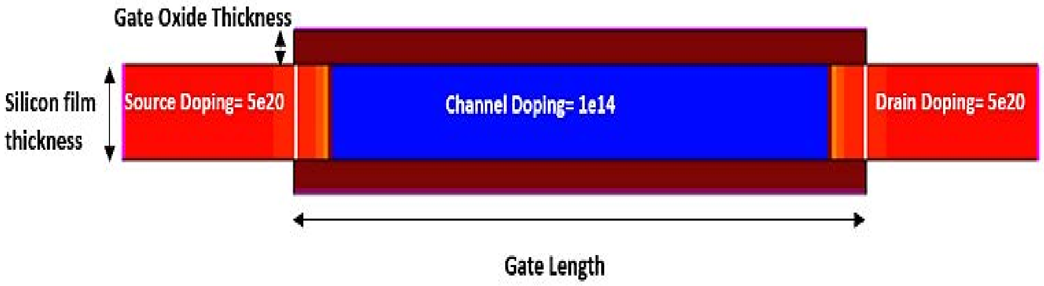

Figure 1: FinFET Device Structure.

Table 1: Parameter details for TCAD simulation

S.No.	Parameter	Value
1	Gate length (long gate case)	540nm
2	Gate length (short gate case)	40nm
3	Gate length (medium gate case)	140nm
4	Gate oxide thickness	2nm
5	Silicon oxide thickness	5nm
6	Source/Drain doping(n-type)	5e20
7	Channel doping (p-type)	1e14

The structure is defined in Sentaurus Structure Editor according to parameters mentioned in the Table 1. Mesh generation was very important phase of the simulation. It was also defined in the Sentaurus device code. Boundary files are defined as per location of the electrodes and they were defining in the separate file with ".bnd" file. Once the default structure and mesh are created, we need to define separate file including all the details and syntax to define all the electrical analysis. Similarly, for our in-house Greens simulator, we defined the structure, boundary conditions and applied electrical analysis to obtain the results.

5 Results and Discussion

In order to study the performance of the FinFET device, we performed the simulations at three different gate lengths already mentioned in Table I. Furthermore, to study the variability effects, we performed manual as well as GF simulations on the device for gate oxide variations. The device electrical parameters have been extracted at different oxide thickness to analyze the effect of device scaling and variations onto the device performances which are shared in Table II and Table III. For simplification, only 5% and 25% variations plots are shared for the validation of in-house simulator in Fig. 2. Thirdly, the effect of oxide variations on the drain current is also shared to understand that careful and precise oxide deposition is important to control the drain current variations.

From the results, we can conclude that, as the variations are increasing, the deviation between non-linear computations and Green's function increases for short-channel DG MosFETs. We can also observe that for 5% variations Greens function is in good compliance to manual variations even in short channel MosFETs as shown in Fig. 2. The region near sub threshold is very good for Greens variations as they approximate the non-linear behavior of the device conveniently.

Three devices were under observation; channel length of these devices was different from each other. Long, short and medium channel lengths were taken to understand the impact of oxide thickness variations. Tables 2 and 3 depict the change in amount of drain current and threshold voltage with the variation in oxide thickness. The results show good compliance with the analytical model shown in (Taur et al., 2004).

$$\mathrm{Id} = \mu\, \mathrm{C_{ox}} \frac{\mathrm{W}}{\mathrm{L}} \left[\mathrm{V_g} - \mathrm{V_t} \frac{\mathrm{V_{ds}}}{2} \right] \mathrm{V_{ds}} \qquad (1)$$

The term $\boldsymbol{C_{ox}} = \boldsymbol{\varepsilon_{ox}}/\boldsymbol{t_{ox}}$ is the parameter, which is manipulated in our simulations to study the impact of oxide variations. It is evident that, with the increase in the oxide thickness, drain current will decrease. We can deduct from our results, that the two models' Long channel and Medium channel, have the quite similar response to each other and shows good results for low values of variations, whereas for 25% oxide variations difference in manual and Green's variations increases dramatically. For short channel model, the response for variations is different but the difference in manual and Green's variations is quite similar to other models i.e., very good approximations for lower value of variations and acceptable amount of deviation between manual and Green's techniques for higher values of variations.

Table 2: Electrical Parametric Results for Manual Variations

S.no	Gate Oxide Variations [%]	Long Channel FinFET			Medium Channel FinFET			Short Channel FinFET		
		I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]	I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]	I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]
1	5	0.00826	7.26E-14	1.0446	0.027108	3.64E-13	1.02356	0.122	9.11E-14	0.931
2	-5	0.00847	7.23E-14	1.04876	0.032981	3.51E-13	1.02758	0.107	9.07E-14	0.927
3	10	0.007375	7.27E-14	1.04267	0.02879	3.60E-13	1.02165	0.126	9.12E-14	0.936
4	-10	0.008914	7.22E-14	1.05102	0.034674	3.48E-13	1.02972	0.102	9.06E-14	0.930
5	25	0.006934	7.33E-14	1.05495	0.027108	3.64E-13	1.01706	0.138	9.27E-14	0.937
6	-25	0.010588	7.16E-14	1.03279	0.041041	3.39E-13	1.03673	0.097	9.01E-14	0.927

Table 3: Electrical Parametric Results for Greens Variations.

S.no	Gate Oxide Variations [%]	Long Channel FinFET			Medium Channel FinFET			Short Channel FinFET		
		I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]	I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]	I_{on} [A/um]	I_{off} [A/um]	V_{th} [V]
1	5	0.00768	7.26e-14	1.0485	0.02416	3.66E-13	1.0233	0.120527	6.69e-12	0.93614
2	-5	0.00845	7.22e-14	1.0444	0.03290	3.51E-13	1.027	0.110626	8.28e-12	0.93186
3	10	0.00730	7.28e-14	1.0503	0.02853	3.59E-13	1.0211	0.125477	5.90e-12	0.93801
4	-10	0.00883	7.21e-14	1.0419	0.03436	3.49E-13	1.0291	0.105675	9.07e-12	0.92941
5	25	0.00616	7.33e-14	1.0549	0.02416	3.66E-13	1.0121	0.140329	3.52e-12	0.94283
6	-25	0.00997	7.16e-14	1.0327	0.03873	3.41E-13	1.0335	0.090824	1.14e-11	0.92034

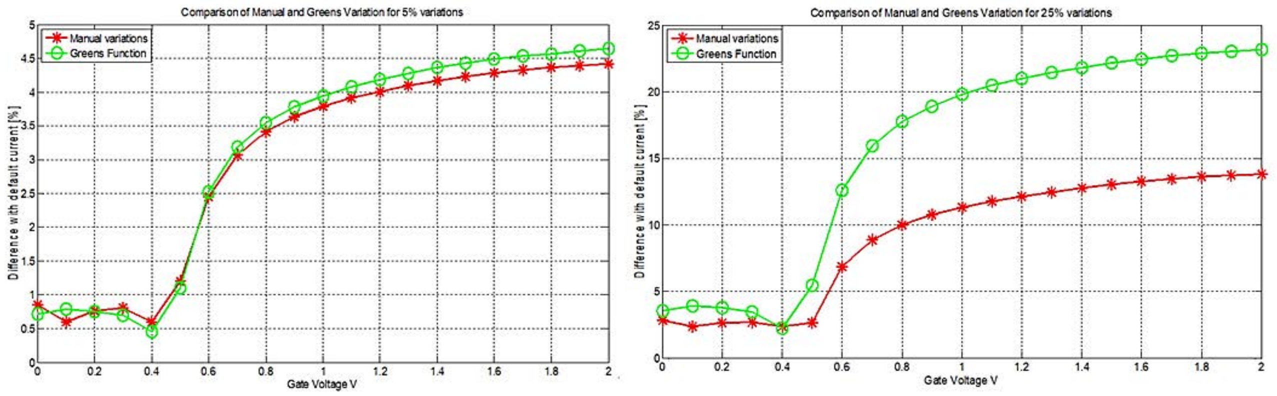

Figure 1: Comparison of Manual with Greens Function Simulations for 5% and 25% variations.

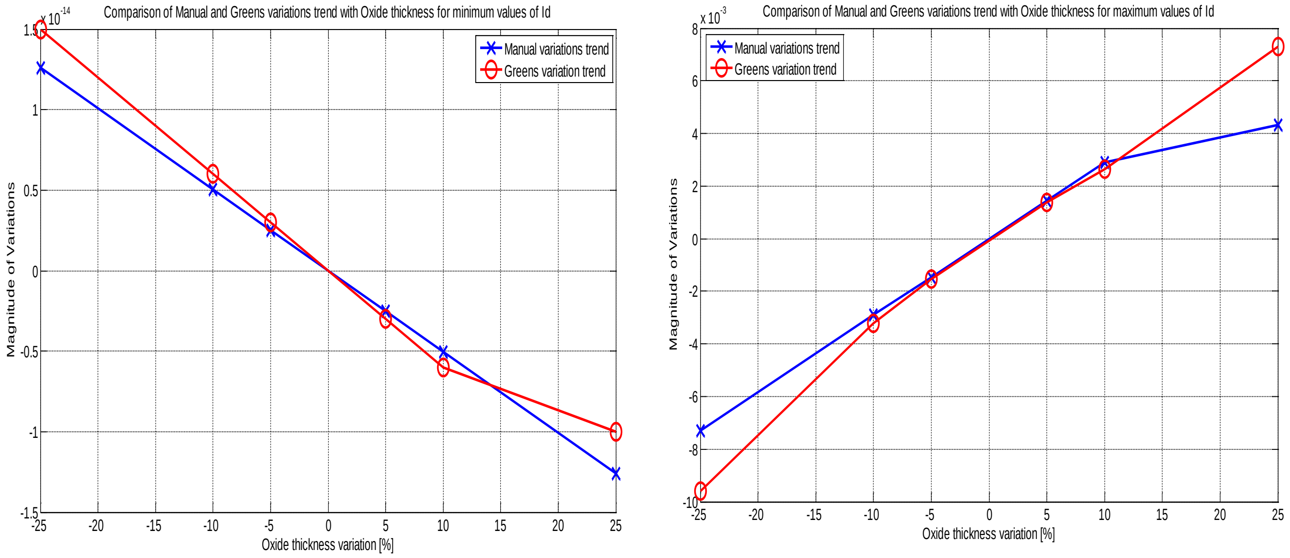

Figure 2: Variation trend with oxide variations (a) For minimum value Id (b) For maximum value Id.

6 Conclusion

As result of oxide thickness variations, it is reported that drain current decreases with increase in oxide thickness. Similar is the case with threshold voltage. Whereas, the leakage current increases with increase in oxide thickness. Greens function provided good simulation efficiency (around 95% simulation efficiency) with slight trade off with accuracy for similar computer specifications. The accuracy for short channel FinFET was higher than the other two variants but still negligible. It was also observed that the Greens function is very effective and provide its maximum efficiency near sub-threshold region but as we move towards the saturation region, it is effective but the degree of accuracy is reduced as compared to the sub-threshold region.

7 Availability of Data And Material

Data can be made available by contacting the corresponding author.

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Dr.Ahsin Murtaza Bughio, received his Ph.D. degree from Politecnico di Torino, Italy. Currently he is an Assistant Professor at Department of Electronic Engineering, Quaid-e-Awam University of Engineering Science & Technology (QUEST), Pakistan. His research interests include RF, FinFETS, Passive Modelling.

Dr. Junaid Iqbal is an Assistant Professor at Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science & Technology, Larkana – Campus, Pakistan. He got his Bachelor's Degree in Mechanical Engineering and a PhD degree in Mechatronics Engineering form Hanyang University, South Korea. His research focuses on Advanced Vehicle Dynamics & Control, and Robot Control.

Dr. Khalil Muhammad Zuhaib is an Assistant Professor at the Department of Electronic Engineering at Quaid-e-Awam University, Larkana Campus. He got a Bachelor's degree in Electronics Engineering and a Masters's degree Leading to a Ph.D. degree in Mechatronics Engineering from Hanyang University, South Korea. His research interest includes Robot Motion Planning and Multi-Agent Systems.

Dr. Umair A. Khan is an Associate Professor and Head of the Department of Computer Systems Engineering in Quaid-e-Awam University of Engineering, Science & Technology, Nawabshah, Pakistan. He received his Master's and PhD degrees from Alpen-Adria University, Klagenfurt, Austria. He previously worked at Fraunhofer Institute of Integrated Circuits, Erlangen, Germany, and Machine Perception laboratory, Hungarian Academy of Sciences, Budapest, Hungary as a research scientist. His research interests include Context Based Information Retrieval from Images and Videos using Deep Learning.

Ms. Nasreen Nizamani is an Assistant Professor in the Department of Electronic Engineering QUEST Nawabshah. Her fields of research are circuits, Systems and Signal & Image Processing. She is perusing her PhD study at Mehran UET Jamshoro.