

Statistical Modelling of Semi-analytical 10nm Bilayer Graphene FET for higher ION/IOFF ratio using Taguchi Method

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Abstract

The simulation and statistical modeling are conducted using Silvaco TCAD tools and L9 orthogonal array (OA) of Taguchi method respectively to design a proposed layout of 10 nm gate length (Lg) Bilayer Graphene Field Effect Transistor (Bi-GFET). The investigated process parameters are halo implant dose, halo implant energy, source/drain (S/D) implant dose and source/drain (S/D) implant energy, while the noise factors are halo implant tilt angle and source/drain (S/D) implant tilt angle. The process parameters and the noise factors are optimized using the L9 orthogonal array (OA) of Taguchi method to achieve the highest possible ION/IOFF ratio. Utilizing both signal-to-noise ratio (SNR) and analysis of variance (ANOVA), the most dominant process parameters upon I_{ON}/I_{OFF} ratio are identified as S/D

implant energy and S/D implant dose with 56% and 37% factor effects on SNR respectively. The largest factor effects on SNR of S/D implant energy shows that it has dominantly affected the I_{ON}/I_{OFF} ratio. The final results indicate that the 1.99^{13} atom/cm³ of halo implant dose, 174 keV of halo implant energy, 1.63×10^{14} of S/D implant dose, 17 keV of S/D implant energy, 24° of halo implant tilt angle and 90° of S/D implant tilt angle are the best parameter setting in obtaining the highest I_{ON}/I_{OFF} ratio of the device which is measured at 4.811×10^5 .

Key Words: ANOVA; I_{ON}/I_{OFF} ratio; SNR; Taguchi method.

1 Introduction

For decades, the field effect transistor (FET) shrinkage has been the key progress in integrated circuits. The FET scaling has enabled the integrated circuits become compact, leading to significant improvements in performance and the decreases in price per transistor (1). Due to the high complexity of ICs fabrication process, semiconductor fabrication plants have become extremely expensive. Furthermore, the scaling alone requires performance improvements from one generation of ICs to the next, thus motivating the chip-designers to introduce devices based on the fundamentally different physics or materials other than silicon (2). It will be necessary to introduce new materials, device concepts and optimization approaches to ensure that the device performance continues to be improved.

The significant discovery of graphene (3) has evoked serious research works to study the electrical properties of two-dimensional (2D) graphene field effect transistor (GFET). Enormous field-effect mobility as high as $15,000 \text{ cm}^2/\text{V-s}$ and a Fermi velocity of $\sim 10^8 \text{ cm/s}$ have been reported at room temperature (4). These excellent properties imply graphene as a possible candidate for future transistor technology. The significant benefit of graphene is emphasized on the superior electron/hole mobility compared to other semiconductors. However, the lack of bandgap limits the usage of two dimensional graphene for digital switching in which the high I_{ON}/I_{OFF} ratio is necessary.

Graphene FETs require an energy band gap of at least 400 meV to be a promising alternative of Silicon (5). Both theoretical and experimental results show that the maximum achievable energy gap induced by electric field in bilayer graphene is about 300 meV. Bilayer Graphene was extensively being modelled theoretically and experimentally simulated in (69) and is proven to be thermodynamically stable. The bilayer graphene is the only known material having a tunable band gap. Therefore, bilayer graphene offers possibilities of designing novel types of 2D FET devices inaccessible with the use of conventional semiconductor based 2D. The bandgap opening in bilayer graphene by vertical symmetry breaking has been achieved in two main flavors; either by creating a transverse electric field between the layers, i.e., electrostatic gating, or by external dopants. Hence, controllability of implant dopants in graphene channel becomes an important design consideration of Bi-GFETs to widen the gap between I_{ON} and I_{OFF} for better power consumption.

Taguchi method has become a useful tool to improve the productivity during research and development. Taguchi method has been proven to produce high quality products in a short period of time and at the lowest cost (10). Salehuddin et al. (2012) proved that Taguchi method was able to identify the process parameters which have the strongest effect on the response characteristics (11). The threshold voltage (V_{TH}) of MOSFET device was then optimized closer to ITRS specification by adjusting an adjustment factor (12). Afifah Maheran et al. (2013) had utilized Taguchi method to reduce variation of threshold voltage (V_{TH}) in High-k/Metal gate MOSFET. The best settings of the process parameters were determined by using analysis of variance (ANOVA). The process parameters which had least variance and most the mean value were adjusted to be in line with the desired value.

This paper attempts to describe the simulation design and modeling of four process parameters which are known as halo implant dose, halo implant energy, S/D implant dose and S/D implant energy with halo implant tilt angle and source/drain (S/D) implant tilt angle as the noise factors for obtaining the highest value of I_{ON}/I_{OFF} ratio of the proposed 10 nm gate length semi-analytical Bi-GFET.

2 Process Simulation

A 10nm planar n-channel Bi-GFET was simulated using ATHENA module of Silvaco TCAD tools. The initial step was to deposit aluminum as a backgate of the device. Next, the 20nm thickness of buried oxide (BOX) layer was developed on the top of the backgate. The BOX was used in order to control junction leakage, thereby mitigating short channel effects (SCEs) (13). Then, the 7nm thickness of silicon was deposited on top of the BOX. The silicon substrate was doped with 7×10^{14} atom/ cm^3 of boron. The thin silicon under the channel was fully depleted of mobile charges to avoid the floating body effect. The gate oxide (SiO₂) was growth at temperature of 815° C.

The doped bilayer graphene was growth on the top of SiO₂ using a conformal method. For this study, the doped bilayer graphene is assumed to be have no defects and operate at the ballistic transport (14), thereby the channel width is neglected. The high-k dielectric material used in this study is hafnium dioxide (HfO₂). The 1nm thickness of HfO₂ was then deposited on the top of bilayer graphene, followed by 10nm gate length (Lg) of tungsten silicide (WSi_x). The metal-gate workfunction of 4.5 eV was applied to the WSi_x gate (15). The correct metal-gate workfunction was required to be tuned in order to stabilize the VTH characteristic.

The halo implant process was then performed by doping the substrate with 1.95×10^{13} atoms/ cm^3 of indium at 170 kev and tilted at 22°. Halo doping is necessary for the ultra-small transistors to reduce the SCEs. The process was then followed by nitride spacer deposition. The S/D implant was performed by implanting arsenic with the dose of 1.63×10^{14} atoms/ cm^3 at 13 Kev and tilted at 7°. This process allows the accumulation of the Schottky tunneling of the S/D region that allow only electrons or holes being injected into the bilayer graphene channel. The aluminum layer was deposited on the top structures surface and any unwanted aluminum was etched to develop the contacts. Fig. 1 shows the detailed flowchart of 10nm Lg of Bi-GFET development via ATHENA module of Silvaco TCAD tools. The completed cross section of 10nm Lg of n-channel Bi-GFET is depicted in Fig. 2.

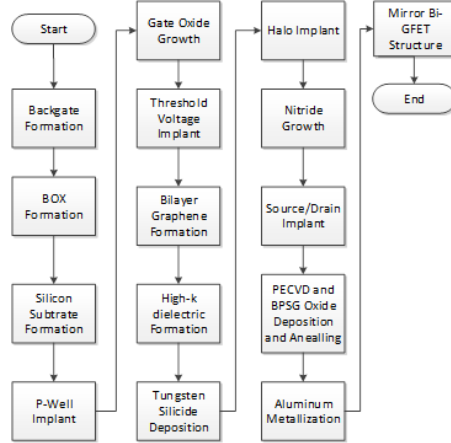


Figure 1. Flowchart of 10nm Bi-GFETs design using ATHENA Silvaco

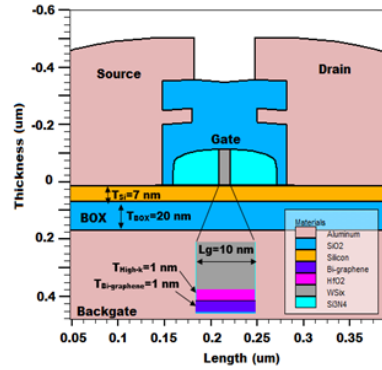


Figure 2. Cross section of the 10nm Lg of n-channel Bi-GFET device

3 Electrical Characterization

The electrical characterization of the 10nm n-channel Bi-GFET was performed using an ATLAS module of Silvaco TCAD tools. The optical and electrical properties of the bilayer graphene was predefined in the ATLAS script. The operation was presumed to be executed at room temperature ($T=300$ K). The bilayer graphene was modeled as a semi-metal with a bandgap of 0.55 eV (16). The bilayer graphene dielectric constant and effective field (E_{eff}) were

set to 2.4 and 0.4 MV/cm respectively (17). The graphenes 2D electron and hole densities of states were measured at room temperature using:

$$N_C = \frac{8\pi m_e kT}{h^2} \ln(1 + e^{-(E_C - E_f)/kT}) \quad (1)$$

$$N_r = \frac{8\pi m_h kT}{h^2} \ln(1 + e^{-(E_f - E_v)/kT}) \quad (2)$$

The effective masses of electrons and holes in graphene were set me

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0.06 mo and mh

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0.03mo where mo is the free electron mass (8,14,18). Fig. 3 shows the contour mode of the proposed Bi-GFET, displaying the tabulation of silicon, WSi_x , HfO_2 , bilayer graphene, silicon nitride (Si_3Ni_4), SiO_2 and aluminum. The effective channel length (L_{eff}) was observed to be 32nm. Fig. 4 depicts the drain current (I_D) versus gate voltage (V_G) curve at drain voltage $V_D = 1.0$ V for the Bi-GFET. The initial value of I_{ON} , I_{OFF} and I_{ON}/I_{OFF} ratio were observed to be $310.4 \mu A/m$, $2.501E-09$ A/m and $1.241E05$ respectively.

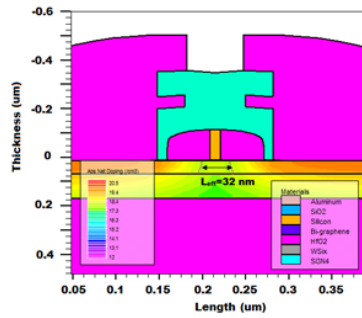


Figure. 3. Contour Mode of 10nm n-channel Bi-GFET device

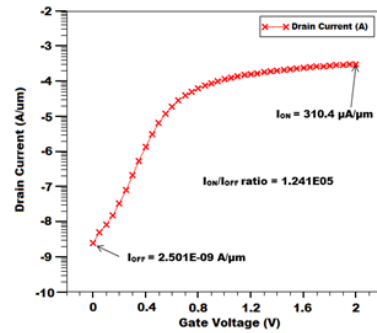


Figure 4. Graph of subthreshold ID vs. VG before optimization

4 Modeling of Process Parameter Variations via L9 OA of Taguchi Method

4.1 Selection of the Process Parameters and the Orthogonal Array

The influence of Halo implant dose, halo implant energy, S/D implant dose and S/D implant energy towards I_{ON}/I_{OFF} ratio were investigated in this study. Each of them were represented by alphabetical symbols: A, B, C and D. Two noise factors, halo implant tilt angle and S/D implant tilt angle were utilized to extract four different readings of I_{ON}/I_{OFF} ratio. The value of the process parameters and the noise factors at different levels are listed in Table 1 and Table 2.

Table 1. Process Parameters of N-Channel Bi-GFET Device

Symbol	Process Parameter	Units	Level 1	Level 2	Level 3
A	Halo Implant Dose	atom/cm ³	1.95E13	1.97E13	1.99E13
B	Halo Implant Tilt Angle	kev	170	172	174
C	S/D Implant Dose	atom/cm ³	1.63E14	1.65E14	1.67E14
D	S/D Implant Tilt angle	kev	13	15	17

Table 2. Noise Factors and Their Levels

Symbol	Noise factor	Units	Level 1	Level 2
U	Halo Implant Tilt Angle	degree	22	24
V	S/D Implant Tilt Angle	degree	7	9

The OA of the design of experiments (DoE) totally depends on the sum of degrees of freedom (DF) of the involved process

parameters. Since each process parameter consists of three levels of value, the total sum of the DF for the process parameters is equal to eight. Basically, the DF for the OA should be greater than or at least equal to those for process parameters. Hence, the L_9 (34) OA which consists of four columns and nine rows has been selected for this study. The experimental layout for the four process parameters using the $L_9(24)$ orthogonal array is shown in Table 3.

Table 3. L9 Orthogonal Array Taguchi Method

Exp.No	Process Parameter Level			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

4.2 Signal-to-noise Ratio (SNR) Analysis

The signal-to-noise ratio (SNR) was executed to measure the sensitivity of tested process parameters towards the I_{ON}/I_{OFF} ratio. The aim of SNR analysis is to distinguish the highest SNR among all the experimental I_{ON}/I_{OFF} ratio. The factor (process parameter) with the highest SNR implies that it has a higher signal than the random effects of the noise factors. In this study, the higher-the-better quality characteristic type was selected to achieve the highest possible I_{ON}/I_{OFF} ratio. The SNR (Higher-the-better), are expressed as (19):

$$\eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (3)$$

(3)

where n is number of tests and y_i is the experimental values of the I_{ON}/I_{OFF} ratio.

Table 4 tabulates the experimental results for the I_{ON}/I_{OFF} ratio and their corresponding SNR using (2). Since the experimental design is orthogonal, the effect of each process parameter can be separated out (20). For instance, the mean SNR for factor B (halo implant energy) at level 1 can be computed by averaging the SNR

for experiment row 1, 4 and 7 based on the allocation of level 1 for factor B as listed in Table 3. The mean SNR for each level of the rest of process parameters can be computed by a similar procedure. The SNR (Higher-the-better) for each level of process parameters with an overall mean of SNR were summarized in Table 5.

Table 4. Results for I_{ON}/I_{OFF} Ratio Based On L_9 OA of Taguchi Method

Exp no.	(U_1V_1) (x 10^5)	(U_1V_2) (x 10^5)	(U_1V_3) (x 10^5)	I_{ON}/I_{OFF} ratio (U_1V) (x10)	Mean	SNR (Higher-the-better) (dB)
1	1.241	1.317	3.443	3.674	3.46E-11	104.61
2	1.255	1.328	2.408	2.561	3.82E-11	104.11
3	1.402	1.493	2.830	3.027	2.98E-11	105.20
4	1.621	1.725	4.538	4.839	2.02E-11	106.91
5	1.044	1.110	1.989	2.125	5.51E-11	102.51
6	1.552	1.643	3.180	3.378	2.43E-11	106.11
7	1.153	1.221	3.198	3.409	4.02E-11	103.91
8	2.173	2.314	4.355	4.637	1.24E-11	109.01
9	1.292	1.373	2.631	2.812	3.50E-11	104.51

Table 5. Results for I_{ON}/I_{OFF} Ratio Based On L_9 OA of Taguchi Method SNR of Each Level of Process Parameters

Process Parameter	SNR (Higher-the-better) in dB			Overall mean SNR (dB)
	Level 1	Level 2	Level 3	
A	104.68	105.23	105.86	105.26
B	105.17	105.27	105.32	
C	106.60	105.23	103.94	
D	103.92	104.76	107.09	

Fig. 5 shows the SNR response graph for the I_{ON}/I_{OFF} ratio. The higher the SNR of a process parameter is, the lower variance will be around the optimal value. From the graph, it is clearly shown that factor A3, B3, C1 and D3 were the optimum process parameters level for the highest I_{ON}/I_{OFF} ratio. However, the relative significance among the process parameters towards the I_{ON}/I_{OFF} ratio are still needed to be distinguished. This will be discussed in the next section using the analysis of variance (ANOVA).

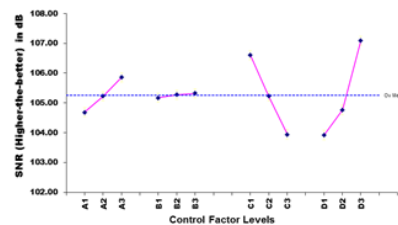


Figure 5. Factor effects graph for SNR (Higher-the-better)

4.3 Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) is conducted in order to determine which is the most significant process parameters towards the I_{ON}/I_{OFF} ratio. Table 6 shows the results of pooled ANOVA for I_{ON}/I_{OFF} ratio. The F-ratio was computed based on 95% level of confidence. Based on the results, factor D (S/D implant energy) and factor C (S/D implant dose) were identified as the most dominant process parameters that influenced the I_{ON}/I_{OFF} ratio due to their highest factor effect on SNR, 56% and 37% respectively. Factor A (halo implant dose) was considered as a significant factor with 7% factor effect on SNR. Finally, factor B (halo implant energy) was considered neutral factors as it did contribute no effect on SNR.

Table 6. Results of ANOVA

Factor	DF	SSQ	MS	F-value	Factor effect on SNR (%)	Dominant/Significant/Neutral
A	2	2	1	4	7	Significant
B	2	0	0	0	0	Neutral
C	2	11	5	18	37	Dominant
D	2	16	8	28	56	Dominant

4.4 Confirmation Test

The 10nm Bi-GFET device was re-simulated using the optimized process parameters levels predicted by L_9 OA of Taguchi method as listed in Table 7. Table 8 shows the simulation results which indicate that the highest recorded value of I_{ON}/I_{OFF} ratio was 4.811E5 with SNR of 109.09 dB. The optimized I_{ON}/I_{OFF} ratio was the highest among all the SNRs in Table IV, implying that the L_9 OA of Taguchi method had successfully optimized all the process parameters. Fig. 6 depicts the graph ID versus VG at drain voltage $V_D = 1.0$ V after the optimization. It can be observed that the I_{ON}/I_{OFF} ratio was improved by 74.2% if compared to the I_{ON}/I_{OFF} ratio before the optimization in Fig. 4.

Table 7. Optimized Process Parameters Predicted using L_9 OA of Taguchi method

Sym.	Process Parameter	Units	Best Value
A	Halo Implant Dose	atom/cm ⁻³	2.89E13
B	Halo Implant Tilt Angle	degree	24
C	S/D Implant Dose	atom/cm ⁻²	2.27E18
D	S/D Implant Tilt Angle	degree	77

Table 8. Confirmation results for I_{ON}/I_{OFF} ratio using L_9 OA of Taguchi Method

I_{ON}/I_{OFF} ratio				SNR (Higher-the-better) in dB
(U ₁ V ₁)	(U ₁ V ₂)	(U ₂ V ₁)	(U ₂ V ₂)	
2.165E5	2.305E5	4.520E5	4.811E5	109.09

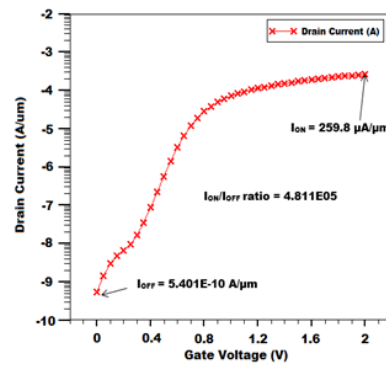


Figure. 6. Graph of subthreshold ID vs. VG after optimization

Fig. 7 depicts the comparison of I_{ON}/I_{OFF} ratio of Bi-GFET with other research results (7,21,22). It is observed that the I_{ON}/I_{OFF} ratio can be optimized by utilizing the L_9 OA of Taguchi method. It can be concluded that the external dopant profiles in the graphene channel can be modeled via Taguchi method in order to achieve higher I_{ON}/I_{OFF} ratio of the Bi-GFET.

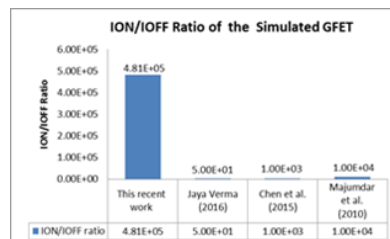


Figure 7. Comparison of I_{ON}/I_{OFF} ratio with other research works

5 Conclusion

As conclusions, the I_{ON}/I_{OFF} ratio of 10nm n-channel Bi-GFET has successfully been optimized by using L_9 OA of Taguchi method. The most significant process parameters identified from the ANOVA method were S/D implant energy and S/D implant dose with 56% and 37% factor effects on SNR accordingly. The highest I_{ON}/I_{OFF} ratio resulted from the L_9 OA of Taguchi method was 4.811×10^5 . There was a significant improvement of 74.2% compared to the I_{ON}/I_{OFF} ratio before the optimization. The final results have proved that the L_9 OA of Taguchi method is capable of finding the robust dopant profiles in the graphene channel for higher I_{ON}/I_{OFF} ratio of 10nm Bi-GFET device. For future work, several more process parameters will be added in the statistical model in order to further increase the I_{ON} characteristic of the device.

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