Optimization of process parameter variations for 16nm DG-FinFET using Response Surface Methodology-Central Composite Design

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Abstract. A 16 nm double-gate FinFET (DG-FinFET) designed are optimized with a mathematical modelling using a response surface method-central composite design (RSM-CCD), with the relationship between parameters and output responses are investigated and examined. The threshold voltage ($V_{TH}$), drive current ($I_{ON}$), leakage current ($I_{OFF}$) and subthreshold swing (SS) ramifications towards the adjustment of six process parameter that integrates polysilicon doping dose, polysilicon doping tilt, Source/Drain doping dose, Source/Drain doping tilt, $V_{TH}$ doping dose and $V_{TH}$ doping tilt is studied using the RSM-CCD using half-factorial of 86 experimental runs, which totals to 52 runs, consisting of 8 centre points, 12 axial points, and 32 factorials. Ultimately, the $V_{TH}$ after the result is optimized with RSM-CCD showcased an improvement at 0.1785 V, with $I_{OFF}$ achieved at 958.71 pA/μm despite performing less favourably after optimized. That said, an improvement towards $I_{ON}/I_{OFF}$ ratio at $2.049\times10^6$ compared to $1.666\times10^6$ proves that both optimization techniques have met the predictions of International Technology Roadmap for Semiconductors (ITRS) 2013.

1. Introduction

The utilization of electronic devices have been broadly purposed in terms of commercialization and with the advancement of smart electrical appliances, would imply that the application of Complementary Metal Oxide Semiconductor (CMOS) technology has turned to become an obligation so as to perform the obligatory tasks. This shows changes in CMOS technology demand compared to conventional electrical appliances over a century, whereby today these appliances are embedded with CMOS modules in order to put up with more programmable features. The prime instances of a CMOS component being the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) with copious types of MOSFETs are due to plenty of researches made over the course of its existence of many years [1-7]. The Silicon-on-insulator, Trigate and Fin-shaped field-effect Transistor (FinFET) are amongst the types of multi-gate FET (MuGFET) introduced and also applied in order to satisfy the requirement and also demands in fabricating further miniaturized devices that also outputting pronounced performance through scaling validation process while meeting the observation predicted in Moore’s Law [8]. The scaling for chips that are smaller has been highly possible due to the technology that encourages more effective cost in production than it was, while improved in its speed as well as reduced in physical attributes. Regardless,
the increment in process parameter variation against the fabrication of wafer has caused drawbacks and challenges to the transistor downscaling. All things considered, challenges might be prevailed in succeeding the downscaling drawbacks such as the short channel effect (SCE), the threshold voltage ($V_{TH}$) roll-off and drain induced barrier leakage (DIBL). The performance of the transistor can be elevated as the downscaling procedure is furthered by choosing FinFET as it consents the SCEs issues to be overcome while also decreasing the leakage current and subthreshold swing (SS) [9-10]. Comprehension of process variation as well as its manufacturing modelling is vital as it allows the device characteristics to be estimated, with the performance of the fabrication process’ allowing ample information towards the minimization effects to the parameters as well as the yield in performance [11-12].

In this Double-gate FinFET (DG-FinFET) structure, the depth of the silicon depletion has been reduced as the gate oxide thickness is considered based on the gate length. Moreover, with the impact of the parameter variation apposite to the $V_{TH}$ value, the parameters of process variation can be controlled to enhance both the off-state leakage current ($I_{OFF}$) and SS performances. Delineating the electrical characterization from the process parameters have proven to be challenging [13]. So as to improve the sturdiness of the transistor designs, various statistical methods have been verified to supplement the optimization towards different types of designs especially for Polysilicon/Silicon Dioxide (PolySi/SiO$_2$)-based DG-FinFET [14-19]. In addition to Taguchi methods, an empirical model can be developed by purposing the Response Surface Method (RSM) by combining multiple of statistical techniques for which allows the yields to be optimized in a shorter time as well as smaller costs. Responses are predicted precisely given that the model is well established. That said, the fundamental techniques for quantitative parameters include either linear (first-order function) and quadratic (second-order function) in forecasting one or multiple output responses. Central composite design (CCD) is one method that allows a second-order design [21] whereby its advantage is known in that it is capable of incomplete block execution. Therefore, in this study, Stat-Ease Design Expert (SEDE) software is used to analyze the aforementioned RSM-CCD due to its practicality in optimizing process developments as well as its specialized function in desirability function that is representing multiple response method in SEDE.

2. Methodology

2.1. Device fabrication

The fabrication of 16 nm DG-FinFET has been materialized by assigning both ATHENA and ATLAS modules from Silvaco International for every one of modules to allow physical construction and also electrical properties to be extracted for analysis to be done prior to the actual fabrication. This method enables the construction of the device to be more cost-effective due to potential in small adjustments to be made several times for each parameter until the desired design with favourable output responses is attained. Five geometrical properties are elected due to its inclination in prompting the effects on output responses as minor variations in alteration is done as shown in Table 1. Since the process parameters fluctuate against local parameter variations for which, studies have demonstrated to be 30% from overall, for which eventually initiating the variation [22].

| Parameters                  | Value (nm) |
|-----------------------------|------------|
| Gate Length, $L_G$          | 16         |
| SiO2 Thickness, $T_{OX}$    | 3.25       |
| Main substrate (silicon) length, $L_C$ | 35         |
| Polysilicon Length, $L_{4M}$ | 17.3      |
| Silicon Thickness, $T_{FIN}$ | 18.7      |
The construction of the device has been physically commenced with a P-type main substrate that acts as oxide layer with silicon bulk with <100> orientated as this functions as mask following the implantation of P-well. 1x10^{17} atom/cm^3 of Boron is then infused into the silicon substrate preceding the implementation of dry oxygen to the gate oxygen for 875°C to a Hydrochloric acid (HCl) of 3%. V_{TH} value meanwhile has been controlled by 1.95x10^{13} atom/cm^3 dose of Boron that is employed alongside 5keV of energy. The alterations with dose have been done in a small amount since the changes can occur across the gate concentration may be significant despite small adaptations being made. The parameter variations are elected based on the most significant variations acquired with small modifications being made. The adaptation of polysilicon meanwhile follows from the deposition of polycrystalline silicon as the multi-layered structure took its shape. The implantation of indium that is doped at 1.17x10^{13} atom/cm^3 with 1 keV of energy is then trailed with the formation of the sidewall spacer on the surface of silicon and polysilicon by a layer of Silicon Nitride (Si_{3}N_{4}). With the construction of the sidewall spacer formed, the SCEs subsequently is minimized after an n-type S/D areas doped to the sides of the p-type substrate. The reduction in the side capacitance has proceeded as the compensate implantation formed, alongside the 22x10^{18} atom/cm^3 of Arsenic for the implantation towards the S/D. Aluminium was lastly deposited and patterned afterwards from the contact window’s initial formation within the S/D region as the device fabrication is finalized with the metallization process.

2.2. Design of Experiment with Response Surface Methodology-Central Composite Design (RSM-CCD)

The CCD is the first order ($2^N$) designs that contain both axial points and additional centre that forecasts the tuning parameters of a second-order model subsequently. Through sequential experimentation for which the centre points, $n_c$ is at the origin with axial runs distance of the centre. That said the quadratic terms efficient prediction could be obtained with the assistance of additional axial points, given that the curvature of the surface is significant. Figure 1 shows the layout of CCD for $q = 2$ factors.

![Figure 1: Central Composite Design (CCD) for $q = 2$.](image)

Blockage on CCD may occur and still can be prevented by selecting both $a$ and $n_c$. A rotatable design offers equal precision of surface in all directions, where the design is identified to be rotatable only if it is rotated at the centre. In this study, a half-fractional of CCD for which can be obtained through Equation 1, rather than full-factorial as in Equation 2.

\[
\alpha = 2^{q/4} \quad \text{(1)}
\]

\[
\alpha = 2^{q-1/4} \quad \text{(2)}
\]
Therefore, by using SEDE software, the regression coefficient can be acquired in conjunction with the development of the second-order models. This is due to the fact that the first-order models’ problems are less predictable. Four output responses were obtained in $V_{TH}$, $I_{ON}$, $I_{OFF}$ and SS that may be dependent towards the variations of six process parameters considered in $V_{TH}$ doping dose, $V_{TH}$ doping tilt, Polysilicon doping dose, Polysilicon doping tilt, Source/Drain (S/D) doping dose and S/D doping tilt. RSM-CCD analysis is conducted due to its ability to optimize multiple characteristics at one time as opposed to Taguchi that focuses on only one characteristic, other than its desirability function for multi-response optimization. The process parameters and its variation of levels are listed as in Table 2.

| Sym. | Process Parameters | Units | Low     | High     | [-alpha] | [+alpha] |
|------|-------------------|-------|---------|----------|----------|----------|
| A    | $V_{TH}$ Doping Dose | Atom cm$^{-3}$ | 3.83E+13 | 3.85E+13 | 3.81E+13 | 3.86E+13 |
| B    | $V_{TH}$ Doping Tilt | Deg. | 3       | 5        | 1.62159  | 6.37841  |
| C    | Polysilicon Doping Dose | Atom cm$^{-3}$ | 2.08E+14 | 2.1E+14  | 2.07E+14 | 2.11E+14 |
| D    | Polysilicon Doping Tilt | Deg. | -22     | -20      | -23.3784 | -18.6216 |
| E    | S/D Doping Dose | Atom cm$^{-3}$ | 1.18E+18 | 1.2E+18  | 1.17E+18 | 1.21E+18 |
| F    | S/D Doping Tilt | Deg. | 70      | 72       | 1.29E+10 | 1.85E+10 |

A half-factorial CCD is used for 52 experiments run that consist of 32 factorials, 12 axial points and 8 centre points. The aforementioned experiments are arrayed and listed wherein subsequent to that, the device characteristic responses obtained, for which generates axial points of factor A, B, C, D, E, and F grounded on $-\alpha$ and $+\alpha$. The $\alpha$ is set based on the number of factors for which consequently is set as 2.37841 where the axial points for factor A were 3.8112159 $\times 10^{13}$ atom/cm$^{-3}$ and 3.8587841 $\times 10^{13}$ atom/cm$^{-3}$ for both respective $-\alpha$ and $+\alpha$.

3. Results

3.1. Analysis of Variance (ANOVA)

The adequacy of models developed that were tested through the analysis of variance (ANOVA) whereby the sum of squares (SSQ), degree of freedom, mean squares, F-value, and P-value were amongst the parameters that were consisted in the ANOVA conducted as shown in Tables 3, 4, 5 and 6 for the analysis of the respective $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS.

| Source | Sum of Squares | DF | Mean Square | F-value | p-value |
|--------|----------------|----|-------------|---------|---------|
| Model  | 0.0003         | 6  | 4.7082E-05  | 1.29035 | 0.2810  |
| A-$V_{TH}$ Doping Dose | 0.0002 | 1 | 0.0002 | 6.19586 | 0.0166 |
| B-$V_{TH}$ Doping Tilt | 3.5495E-06 | 1 | 3.5495E-06 | 0.09727 | 0.7566 |
| C-Polysilicon Doping Dose | 4.192E-09 | 1 | 4.192E-09 | 0.00012 | 0.9915 |
| D-Polysilicon Doping Tilt | 5.2865E-05 | 1 | 5.2864E-05 | 1.44881 | 0.2350 |
| E-S/D Doping Dose | 1.6336E-09 | 1 | 1.6335E-09 | 4.48E-05 | 0.9946 |
| F-S/D Doping Tilt | 1.0972E-09 | 1 | 1.0972E-09 | 3.01E-05 | 0.9956 |
| Residual | 0.0016 | 45 | 3.6488E-05 |         |         |
| Lack of Fit | 0.0016 | 38 | 4.3209E-05 |         |         |
| Pure Error | 0 | 7 | 0 |         |         |
| Cor Total | 0.0019 | 51 |         |         |         |
### Table 4. Analysis of variance (ANOVA) for $I_{ON}$

| Source                        | Sum of Squares | DF  | Mean Square | F-value | p-value  |
|-------------------------------|----------------|-----|-------------|---------|----------|
| Model                         | 1993524.3      | 27  | 73834.2334  | 13.4122 | 5.9938E-09 |
| A-VTH Doping Dose             | 2742.1981      | 1   | 2742.1981   | 0.4981  | 0.4871   |
| B-VTH Doping Tilt             | 6027.9112      | 1   | 6027.9112   | 1.0949  | 0.3058   |
| C-Polysilicon Doping Dose     | 4480.8663      | 1   | 4480.8663   | 0.8139  | 0.3759   |
| D-Polysilicon Doping Tilt     | 1510749.799    | 1   | 1510749.799 | 274.4329| 1.2258E-14|
| E-S/D Doping Dose             | 5741.1847      | 1   | 5741.1846   | 1.0429  | 0.3173   |
| F-S/D Doping Tilt             | 5787.3290      | 1   | 5787.3290   | 1.0513  | 0.3154   |
| Residual                      | 132119.7054    | 24  | 5504.9877   |         |          |
| Lack of Fit                   | 132119.7054    | 17  | 7771.7474   |         |          |
| Pure Error                    | 0              | 7   | 0           |         |          |
| Cor Total                     | 2125644.006    | 51  |             |         |          |

### Table 5. Analysis of variance (ANOVA) for $I_{OFF}$

| Source                        | Sum of Squares | DF  | Mean Square | F-value | p-value  |
|-------------------------------|----------------|-----|-------------|---------|----------|
| Model                         | 1913844.226    | 6   | 318974.0377 | 10.9707 | 1.67841E-07|
| A-VTH Doping Dose             | 107341.8871    | 1   | 107341.8871 | 3.691911| 0.0610   |
| B-VTH Doping Tilt             | 1585.6627      | 1   | 1585.6628   | 0.054537| 0.8164   |
| C-Polysilicon Doping Dose     | 173.8328       | 1   | 173.8328    | 0.005979| 0.9387   |
| D-Polysilicon Doping Tilt     | 1804739.468    | 1   | 1804739.468 | 62.07212| 5.1809E-10|
| E-S/D Doping Dose             | 3.1550         | 1   | 3.1550      | 0.000109| 0.9917   |
| F-S/D Doping Tilt             | 0.2204         | 1   | 0.2204      | 7.58E-06| 0.9978   |
| Residual                      | 1308369.721    | 45  | 29074.8827  |         |          |
| Lack of Fit                   | 1308369.721    | 38  | 34430.7821  |         |          |
| Pure Error                    | 0              | 7   | 0           |         |          |
| Cor Total                     | 3222213.947    | 51  |             |         |          |

### Table 6. Analysis of variance (ANOVA) for SS

| Source                        | Sum of Squares | DF  | Mean Square | F-value | p-value  |
|-------------------------------|----------------|-----|-------------|---------|----------|
| Model                         | 11.7852        | 27  | 0.4365      | 1.2068  | 0.3227   |
| A-VTH Doping Dose             | 0.0186         | 1   | 0.0186      | 0.0513  | 0.8226   |
| B-VTH Doping Tilt             | 2.10455E-05    | 1   | 2.1045E-05  | 5.82E-05| 0.9939   |
| C-Polysilicon Doping Dose     | 0.00074        | 1   | 0.0007      | 0.002054| 0.9642   |
| D-Polysilicon Doping Tilt     | 3.52196        | 1   | 3.5219      | 9.73726 | 0.0046   |
| E-S/D Doping Dose             | 1.2987E-06     | 1   | 1.2987E-06  | 3.59E-06| 0.9985   |
| F-S/D Doping Tilt             | 2.0836E-06     | 1   | 2.0836E-06  | 5.76E-06| 0.9981   |
| Residual                      | 8.68079        | 24  | 0.3617      |         |          |
| Lack of Fit                   | 8.68079        | 17  | 0.5106      |         |          |
| Pure Error                    | 0              | 7   | 0           |         |          |
| Cor Total                     | 20.46603       | 51  |             |         |          |
Based on Tables 3, 4, 5 and 6, the developed model was statistically significant when the P-value achieves 0.05 and lower, for which is equivalent to 95% confidence level, whereby the model is termed significant in its noise in the F-value model with a probability of 0.01%, and that “Probability > F” is lower than 0.05 or 5%. Therefore, factor A is considered significant based on the ANOVA made on $V_{TH}$, whereby its P-value scores less than 0.05. Meanwhile, factor D is considered significant towards the subthreshold swing, scoring 0.004653177. Overall, the multiple regression for each of $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS were obtained at 0.146792, 0.937845, 0.593953 and 0.575843 respectively as in Table 7 for which implying that the variations are able to be comprehended by the second-order models. In addition to that, the model validation can be determined by measuring the SNR via adeq precision. The SNR values for the respective $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS are measured at 4.90352, 18.5436, 15.52048 and 6.667497 for which indicates that all of the SNR provides an adequate signal, being valued at greater than 4.

**Table 7. Analysis for a better predictor than the current model**

| Factors          | $V_{TH}$      | $I_{ON}$     | $I_{OFF}$    | SS       |
|------------------|---------------|--------------|--------------|----------|
| Std. Dev.        | 0.0060        | 74.1956      | 170.5136     | 0.6014   |
| Mean             | 0.1752        | 1853.03      | 909.0159     | 94.5875  |
| C.V. %           | 3.4477        | 4.0040       | 18.7580      | 0.6358   |
| R²               | 0.1468        | 0.9378       | 0.5939       | 0.5758   |
| Adjusted R²      | 0.0330        | 0.8679       | 0.5398       | 0.0986   |
| Predicted R²     | -0.1842       | 0.5811       | 0.4368       | -1.4917  |
| Adeq Precision   | 4.9035        | 18.5453      | 15.5204      | 6.6675   |

Subsequently, the coefficient estimate is measured, as shown in Table 8. The expected change per in y per unit change in x after all remaining factors were fixed to constant. Therefore, the mean for the measured response data are the interceptions of the respective $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS. Coded units were formed to express the model coefficients for factor A, B, C, D, E, and F where a comparison is made between the relative magnitudes against other estimates relative effect coefficient.

**Table 8. Coefficient Estimate for $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS**

| Factors                      | $V_{TH}$   | $I_{ON}$   | $I_{OFF}$  | SS        |
|------------------------------|------------|------------|------------|-----------|
| Intercept                    | 0.1752     | 1921.608   | 909.0159   | 94.5380   |
| A-V$_{TH}$ Doping Dose       | 0.0023     | 7.9567     | -49.782    | -0.02072  |
| B-V$_{TH}$ Doping Tilt       | -0.0003    | 11.7969    | 6.0505     | -0.0007   |
| C-Polysilicon Doping Dose    | 9.84E-06   | -10.1711   | 2.0033     | 0.0041    |
| D-Polysilicon Doping Tilt    | -0.0011    | 186.76     | 204.1243   | 0.2851    |
| E-S/D Doping Dose            | 6.14E-06   | 11.5129    | -0.2699    | -0.00017  |
| F-S/D Doping Tilt            | -5E-06     | -11.5592   | 0.0713     | -0.00022  |

3.2. Confirmation based on point prediction of RSM-CCD

Finally, a confirmation as shown in Table 9 is succeeded where the predicted mean is generated at 0.1773 V, 2017.96 μA/μm, and 958.71 pA/μm, for the respective $V_{TH}$, $I_{ON}$, and $I_{OFF}$, followed by 94.74 mV/dec for the SS. The point prediction is obtained for which factor A is at 3.865×10$^{13}$ atom/cm$^3$, followed by $5^\circ$, 2.11982×10$^{14}$ atom/cm$^3$, -20.5292$^\circ$, 1.22×10$^{18}$ atom/cm$^3$ and 72.0064$^\circ$ for factor B, C, D, E and F respectively.
4. Conclusion

The response surface methodology-central composite design (RSM-CCD) has been implemented towards a 16nm PolySi/SiO₂ based DG-FinFET towards multiple responses in $V_{TH}$, $I_{ON}$, $I_{OFF}$, and SS. It is observed that the $V_{TH}$ achieved after it is optimized using the mathematical model which is at 0.1785V, achieved the closest to the targeted value from ITRS 2013 prediction, which is 0.179V which is marginally 99.7% closer as opposed to the predicted and before it is optimized. Through RSM-CCD, other advantages can be observed in that it allows multiple analysis to be completed compared to the Taguchi method, despite requiring more experimental runs on a single experimental array. Despite, the $I_{ON}$ performing better before it is optimized, the value is shown to be within the range targeted, in addition to the post-RSM-CCD results the shows its $I_{OFF}$ to have significantly improved by 20.45% at 958.73 pA/μm for which brings much lower $I_{ON}/I_{OFF}$ ratio to achieve better output at 2.049×10⁶ compared to 1.666×10⁶ obtained prior to the optimization process with RSM-CCD which signals an improvement towards power efficiency of the device. The results have proved that the RSM-CCD are capable of obtaining desired results by optimizing multiple responses simultaneously while conformed to the prediction made by ITRS 2013 for the year 2015.

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