# Application of Taguchi Method in Optimization of Shallow PN Junction Formation

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***Abstract*—In this research, optimization of shallow PN junction formation through dopan diffusion from Spin on Dopant (SOD) in Ultra Large Scale Integrated (ULSI) technology by using taguchi method was investigated. The shallow junction formation by using the polysilicon/Si structures has the advantages of lower sheet resistance in comparison with the conventional Si junction. Boron and phosphorus diffusion into silicon from SOD sources has been investigated using conventional furnace and rapid thermal diffusion. Diffusivity of boron in SOD was found to be much faster than in the normal oxide, and it was slower in the Si. Process simulation for shallow PN junction was used Silvaco TCAD Tools. The shallow PN junction with junction depth below than 30nm has been produced using rapid thermal diffusion. From the simulation result, the value of Sheet resistance (Rs) and Junction depth (Xj) were analyzed by using $L_{18}$ orthogonal array (OA) in Taguchi Method. Control factors that were used namely material, time and temperature. The analysis of variance shows the process parameter of material, and temperature is significant based on 95% confidence level towards junction depth and sheet resistance respond in the shallow PN junction device. So that the junction depth and sheet resistance decreased follows the material and temperature. As conclusion, taguchi method can be utilized to find optimum solution in fabricating to get a good performing device.**

***Index Terms*— Shallow PN Junction, Taguchi Method, Silvaco TCAD, Spin on Dopant, Spin On Glass.**

## I. INTRODUCTION

THE most recent development in the electronic world is the production of the small electronic device and smart. By decreasing the device feature size, it will reduce the cost for manufacturing and also provide improvement. Silicon technology has played a major role in sustaining the semiconductor industry growth [1]. The concept of device scaling in silicon transistor has consistently resulted in better device density and performance [2]. Production of small components that result from the formation of a P-N junction is basically using Spin On Glass (SOG) techniques. Spin on Glass also called as Spin On Dopant (SOD) for the deep sub-micron devices for the future of the ULSI. With the advantages of no transient enhanced diffusion and no metal contamination, the diffusion from highly doped SOG is a good technology for the shallow p-n junction formation [3, 4]. The process of absorption of boron and phosphorus into silicon from SOD resources will be explored. This project was used conventional furnace diffusion. The diffusion process from SOD was simulated as diffusion from a doped oxide source by using the equilibrium diffusion model. Diode realization will be carried out for the electrical characterization of these junctions.

PN Junction can be fabricated using multiple methods. However, diffusion is still a dopant method that mostly used in discrete semiconductor fabrication and monolithic integrated circuit. Diffusion is the movement of impurity atoms at the surface of the silicon into the bulk of silicon. It is the process of doping the silicon to introduce impurities. Diffusion takes places from higher concentration to lower concentration. Diffusion is done at very high temperatures above 10000$^{o}$C. In general, diffusion is good for heavy doping and creating deep junctions. Ion Implantation is the process by which impurity ions are accelerated to a high velocity and physically lodged into the target material [5, 6]. Annealing is required to activate ions. In order to implement this research, the software Silvaco TCAD Tools was used to format a shallow P-N Junction diode [7].

Dr. Genichi Taguchi was the person who introduced the Taguchi Method as early as 1980. Taguchi Method has six steps, which are problem identification, brainstorming session, an experimental design, run experiment, then analyze result and confirmation runs [8, 9]. These facts were verified by using three of Signal-to-Noise ratios (SNR) such as smaller-the-better, larger the better and nominal-the-best. In this research, sheet resistance (Rs) and junction depth (Xj) of the Shallow PN junction device belongs to the smaller-the-best quality characteristics. Taguchi Method involves an analysis that reveals which of the factors are most effective in reaching the goals and the directions in which these factors should be adjusted to improving and optimizing the result [9, 10]. Taguchi method uses special design orthogonal arrays to study the entire process parameter space with only a small number of experiments. The orthogonal array helps preserve the consistency of design, even though different researchers may assign different factors and with different columns [11].

## II. METHODOLOGY

For electrical characterization of P-N junctions, diodes were realized using different active windows. In order to form P-N junctions, the conventional furnace was used to diffuse SOD layer into silicon. Firstly, the size of junction that will be fabricated were declared before the next fabrication process with declaring 'mesh' in the first step of the program. Smaller value of mesh made the time taken to process the simulation longer. In this project, silicon with resistivity of 8Ω/cm$^2$ and orientation of <100> were used. Then the n-type silicon wafer has been formed after doping the phosphorus.

Next, the SOD- B150 Layer with 400 A was deposited onto the formed wafer. The oxide layer which contains boron as impurities was obtained from ATHENA for SOD- B150 layer model, and the selected boron density was $7x10^{21}$ion/cm$^3$. The commands to get simulated profile are almost same with SRP profile which some of the parameters in the doped oxide diffusion model were changed. These parameters are boron layer model diffusion into SOD (oxide) and boron diffusion into silicon [12]. For boron diffusion in SOD layer, half factor value (DIX.O) and activation energy (DIX.E) were changed while boron diffusion in silicon divided into two, which are intrinsic diffusion for neural vacancies and intrinsic diffusion for single positively charged vacancies. The intrinsic diffusion for neutral vacancies not affected the simulated diffusion profile, and its value never changed. The intrinsic diffusion for single positively charged vacancies was very important, especially for diffusion with high boron density [7, 4].

The deposited wafer by SOD-B150 layer was put into the conventional furnace in 900$^o$C within ten minutes in nitrogen ambient. Then, the SOD-B150 layer was etched out until no SOD-B150 layer left inside after the previous process [13, 14]. Finally, the 'extract' commands were written to obtain several important parameters such as the depth of junction (Xj), Sheet Resistance (Rs) and SRP profile graph for silicon wafer, which has diffused with SOD- B150. The 'extract' commands were display all the values. All the process showed in codes was repeated in different files with different temperature such as 850$^o$C, 900$^o$C and 950$^o$C within same times which are 15 minutes, 30 minutes and 45 minutes.

### A. Taguchi Method $L_{18}$ Orthogonal Array (OA)

In this research, an $L_{18}$ orthogonal array in taguchi method which has eighteen experiments are being used. Table 1 shows the values of the process parameter at the different levels. There are only three process parameters (control factors) was used for this experiment. The control factors are material, time and temperature. The material was varied for 2 levels while the time and temperature were varied for 3 levels. Table 2 shows the experimental layout using $L_{18}$ OA. Eighteen different experiments in the Shallow PN junction device were performed using the design parameter combinations in the specified orthogonal array table. Four specimens were simulated for each of the parameter combinations.

Table 1: Process parameters and their levels

| Symbol | Process Parameter | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Material | - | Boron | Phosphorus | - |
| B | Time | Minute | 15 | 30 | 45 |
| C | Temperature | Celsius | 850 | 900 | 950 |

Table 2: Experimental Layout using $L_{18}$ Orthogonal Array

| Exp. No. | Process Parameter Level | | |
|---|---|---|---|
| | A (Material) | B (Time) | C (Temperature) |
| 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 2 |
| 3 | 1 | 1 | 3 |
| 4 | 1 | 2 | 1 |
| 5 | 1 | 2 | 2 |
| 6 | 1 | 2 | 3 |
| 7 | 1 | 3 | 1 |
| 8 | 1 | 3 | 2 |
| 9 | 1 | 3 | 3 |
| 10 | 2 | 1 | 1 |
| 11 | 2 | 1 | 2 |
| 12 | 2 | 1 | 3 |
| 13 | 2 | 2 | 1 |
| 14 | 2 | 2 | 2 |
| 15 | 2 | 2 | 3 |
| 16 | 2 | 3 | 1 |
| 17 | 2 | 3 | 2 |
| 18 | 2 | 3 | 3 |

## III. RESULTS AND DISCUSSIONS

Simulation was done by using ATLAS and ATHENA modules in Silvaco TCAD tools. ATHENA was used to generate PN Junction structure with doping area. Graph to display values of Sheet resistance (Rs) and Junction resistance (Xj) is gained from ATLAS module. The data of Rs and Xj from simulation will be applied to the taguchi method to get the best value. In this project, the $L_{18}$ orthogonal array (OA) was used to analyze the value of Rs and Xj to get the optimal design. The optimized results from Taguchi Method were simulated in order to verify the predicted optimal design.q

### A. Result of Rs and Xj for shallow PN Junction device

Fig. 1 shows the PN Junction Structure. Fig. 2 shows the SRP Doping Vs Depth. The value for Xj is below 30nm. The value is about 25nm.

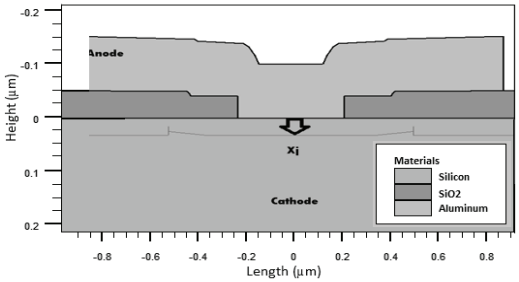


Figure 1: PN Junction Structure

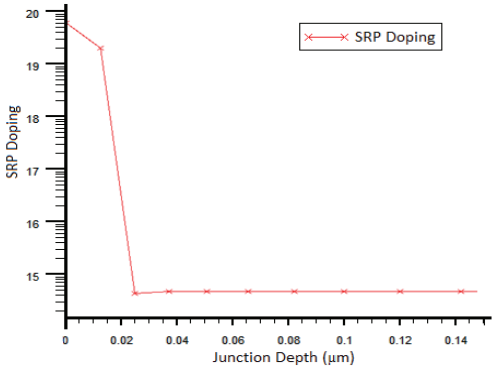


Figure 2: The SRP Doping Vs Depth.

Tables 3 and 4 show the fifty-four simulation values of Rs and Xj respectively. Besides three control factors, there are two types of noise factors, which are oxide diffusion temperature unit and oxide diffusion time. Each of the noise factors was varied for two levels to get four readings of Rs for every row of experiment.

Table 3: Result of Rs for Shallow PN junction

| Experiment no. | Sheet Resistance (Rs) | | | |
|---|---|---|---|---|
| | $Rs_1(U_1V_1)$ | $Rs_2(U_1V_2)$ | $Rs_3(U_2V_1)$ | $Rs_4(U_2V_2)$ |
| 1 | 1792.2 | 1880.96 | 1779.46 | 1786.67 |
| 2 | 512.29 | 513.445 | 510.602 | 511.559 |
| 3 | 170.795 | 170.98 | 170.524 | 170.678 |
| 4 | 1168.75 | 1172.83 | 1162.81 | 1166.18 |
| 5 | 345.682 | 346.229 | 344.88 | 345.335 |
| 6 | 116.85 | 116.939 | 116.72 | 116.794 |
| 7 | 919.479 | 922.101 | 915.652 | 917.821 |
| 8 | 275.548 | 275.902 | 275.029 | 275.323 |
| 9 | 93.8652 | 93.923 | 93.7804 | 93.8285 |
| 10 | 2758.74 | 2759.05 | 2758.28 | 2758.54 |
| 11 | 253.435 | 253.466 | 253.39 | 253.415 |
| 12 | 41.0597 | 41.0644 | 41.0527 | 41.0567 |
| 13 | 727.251 | 727.334 | 727.129 | 727.198 |
| 14 | 97.2832 | 97.2949 | 97.266 | 97.2757 |
| 15 | 13.3889 | 13.3903 | 13.3869 | 13.388 |
| 16 | 441.179 | 441.231 | 441.103 | 441.147 |
| 17 | 51.1719 | 51.1778 | 51.1631 | 51.1681 |
| 18 | 7.46063 | 7.46139 | 7.4595 | 7.46014 |

After eighteen experiments of $L_{18}$ array have been done, the next step is to determine, which control factors can give the effect to a device characteristics. Signal-to-noise (S/N) ratio was used to easily find out the optimal combinations. In this research, Rs and Xj of the Shallow PN junction device belongs to the smaller-the-best quality characteristics. The S/N Ratio (SNR) for each experiment in this device can be expressed as [8, 9]:

$$\eta = 10\mathrm{Log}_{10}\left[\frac{1}{n}\sum\left(Y_1^2 + Y_2^2 + .... + Y_n^2\right)\right] \qquad (1)$$

Table 4: Result of Xj for Shallow PN junction

| Experiment no. | Junction Depth (Xj) | | | |
|---|---|---|---|---|
| | $Xj_1(U_1V_1)$ | $Xj_2(U_1V_2)$ | $Xj_3(U_2V_1)$ | $Xj_4(U_2V_2)$ |
| 1 | 29.6975 | 29.6402 | 29.7817 | 29.7339 |
| 2 | 60.2257 | 60.1684 | 60.3099 | 60.2621 |
| 3 | 125.83 | 125.773 | 125.914 | 125.867 |
| 4 | 40.1629 | 40.1056 | 40.2471 | 40.1993 |
| 5 | 85.4651 | 85.4071 | 85.5493 | 85.5015 |
| 6 | 178.057 | 177.999 | 178.141 | 178.093 |
| 7 | 47.332 | 47.2747 | 47.4162 | 47.3684 |
| 8 | 104.132 | 104.075 | 104.216 | 104.168 |
| 9 | 218.07 | 218.013 | 218.155 | 218.107 |
| 10 | 462.998 | 462.941 | 463.082 | 463.034 |
| 11 | 581.467 | 581.41 | 581.551 | 581.504 |
| 12 | 706.627 | 706.57 | 706.711 | 706.664 |
| 13 | 515.461 | 515.404 | 515.545 | 515.498 |
| 14 | 641.909 | 641.851 | 641.993 | 641.945 |
| 15 | 825.95 | 825.893 | 826.034 | 825.986 |
| 16 | 545.062 | 545.005 | 545.146 | 545.098 |
| 17 | 684.762 | 684.704 | 684.846 | 684.798 |
| 18 | 918.082 | 918.024 | 918.166 | 918.118 |

Where n is the number of tests and $Y_i$ the experimental value of the Rs or Xj. By applying Eqn. 1, the S/N Ratio, η for each experiment in Shallow PN junction device was calculated and given in Table 5.

Table 5 Mean and S/N ratio using the value of Rs and Xj

| Exp. No. | Mean Sum of Squares | SNR (Smaller-the-better, dB) | Mean Sum of Squares | SNR (Smaller-the-better, dB) |
|---|---|---|---|---|
| 1 | 3.3E+06 | -65.15 | 8.8E+02 | -29.46 |
| 2 | 2.6E+05 | -54.18 | 3.6E+03 | -35.60 |
| 3 | 2.9E+04 | -44.65 | 1.6E+04 | -42.00 |
| 4 | 1.4E+06 | -61.35 | 1.6E+03 | -32.08 |
| 5 | 1.2E+05 | -50.77 | 7.3E+03 | -38.64 |
| 6 | 1.4E+04 | -41.35 | 3.2E+04 | -45.01 |
| 7 | 8.4E+05 | -59.26 | 2.2E+03 | -33.51 |
| 8 | 7.6E+04 | -48.80 | 1.1E+04 | -40.35 |
| 9 | 8.8E+03 | -39.45 | 4.8E+04 | -46.77 |
| 10 | 7.6E+06 | -68.81 | 2.1E+05 | -53.31 |
| 11 | 6.4E+04 | -48.08 | 3.4E+05 | -55.29 |
| 12 | 1.7E+03 | -32.27 | 5.0E+05 | -56.98 |
| 13 | 5.3E+05 | -57.23 | 2.7E+05 | -54.24 |
| 14 | 9.5E+03 | -39.76 | 4.1E+05 | -56.15 |
| 15 | 1.8E+02 | -22.53 | 6.8E+05 | -58.34 |
| 16 | 1.9E+05 | -52.89 | 3.0E+05 | -54.73 |
| 17 | 2.6E+03 | -34.18 | 4.7E+05 | -56.71 |
| 18 | 5.6E+01 | -17.46 | 8.4E+05 | -59.26 |

The effect of each process parameter on the S/N Ratio at different levels can be separated out because the experimental design is orthogonal. The S/N ratio for each level of the process parameters is summarized in Table 6. In addition, the total mean of the S/N ratio for the eighteen experiments is also calculated and listed in Table 6. Fig. 3 shows the S/N Ratio (Smaller-the-best) graph where the dashed line is the value of the total mean of the S/N ratio. Basically, the larger the S/N ratio, the quality characteristics for the sheet resistance and junction depth are better [11, 15].

Table 6: S/N response for the Sheet Resistance

| Symbol | Process Parameter | S/N Ratio (Smaller-the-Best) | | | Max - Min |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | |
| A | Material | -51.66 | -41.47 | - | 10.19 |
| B | Time | -52.19 | -45.50 | -42.01 | 10.18 |
| C | Temperature | -60.78 | -45.96 | -32.95 | 27.83 |

Overall Mean = -46.57dB

Table 7: S/N response for the Junction Depth

| Symbol | Process Parameter | S/N Ratio (Smaller-the-Best) | | | Max - Min |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | |
| A | Material | -38.16 | -56.11 | - | 17.95 |
| B | Time | -45.44 | -47.41 | -48.55 | 3.11 |
| C | Temperature | -42.89 | -47.12 | -51.39 | 8.5 |

Overall Mean = -47.14dB

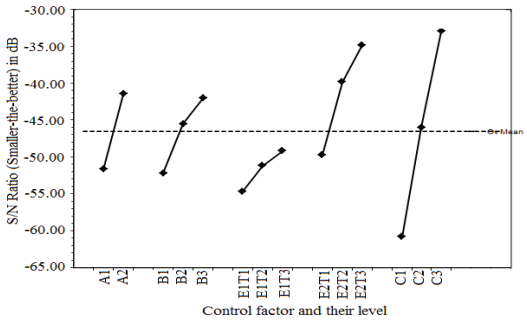


Figure 3: The S/N Ratio and mean graph for Rs

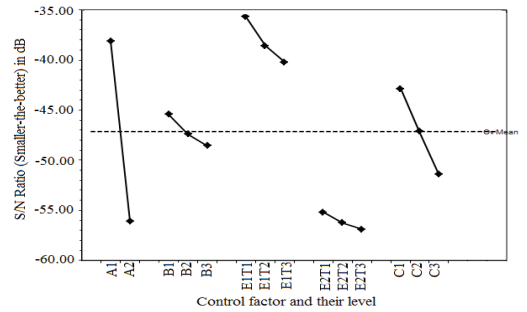


Figure 4: The S/N Ratio and mean graph for Xj

*B. Analysis of Variance (ANOVA)*

The effect of the different process parameter on the Rs and Xj were obtained by decomposition of variance, which is called analysis of variance (ANOVA) [4]. According to Table 8, temperature was found to be the major factor affecting the Rs (69%), whereas material (boron) was the major factor affecting the Xj (82%). Percent factor effect on S/N Ratio indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, will have a great influence on the performance [9, 11]. In this research, material and temperature were found to be the second-ranking factor affecting the Rs (14%) and Xj (12%) respectively.

Table 8: Result of ANOVA for Rs and Xj in Shallow PN junction Device

| Response | Symbol | Process Parameter | Degree of Freedom | Sum of Square | Mean square | F-Value | Factor Effect on S/N Ratio (%) |
|---|---|---|---|---|---|---|---|
| Rs | A | Material | 1 | 468 | 468 | 26 | [a]14 |
| | B | Time | 2 | 321 | 161 | 9 | [a]10 |
| | C | Temperature | 2 | 2327 | 1164 | 20 | [a]69 |
| Xj | A | Material | 1 | 1451 | 1451 | 247 | [a]82 |
| | B | Time | 2 | 30 | 15 | 3 | 2 |
| | C | Temperature | 2 | 217 | 109 | 18 | [a]12 |

At least 95% confidence.

In order to get the best setting that satisfies sheet resistance ($R_S$) and junction depth (Xj), some comparison of the best level input process parameters and factor effects among the output responses have to be done. Table 9 shows the comparison of the best level input process parameters and factor effects on SNR among the output responses. From Table 9, it can be observed that the best level of the input process parameters has been determined. There are two priorities that have to be considered in order to select the best level. First priority is whenever the majority of the same level setting that has been used will be determined as the best level without considering the factor effect on SNR. This is because when using the same level of input process parameters, the majorities will not contribute much change in the output responses. Second priority is whenever all the output responses are at the different level. The output response which has the highest factor effect on SNR will be selected as the best level.

Table 9: Comparison of the Best Level Parameters and the Factor Effects on SNR

| Process Parameter Symbol | Rs | | Xj | | Overall Best Level |
|---|---|---|---|---|---|
| | Level | Factor Effect % on SNR | Level | Factor Effect % on SNR | |
| A | 2 | 14 | 1 | 82 | 1 |
| B | 3 | 10 | 1 | 2 | 3 |
| C | 3 | 69 | 1 | 12 | 3 |

Factor A has the different level on each output response but level 1 of factor A has the highest factor effect on SNR for Xj. Therefore, level 1 of factor A is selected as the best level. Factors B and C also have the different level on each output response, but level 3 of both factors have the highest factor effect on SNR for Rs and Xj. Therefore, level 3 of factors B and C are selected as the best level. Therefore, the best level setting of process parameters was selected as $A_1$, $B_3$ and $C_3$.

### *C. Confirmation Test*

The confirmation test is used to verify the estimated result with the experimental results. Best setting of the process parameters for Shallow PN junction device that has effects on the output response which was suggested by Taguchi Method is shown in Table 10.

Table 10: Best Setting of the Process Parameters for Xj and Rs

| Symbol | Process Parameter | Unit | Level | Best Value |
|---|---|---|---|---|
| A | Material | - | 1 | boron |
| B | Time | minutes | 3 | 45 |
| C | Temperature | °C | 3 | 950 |

The confirmation test is not required in Shallow PN junction device design because the optimum combination of parameters and their levels, i.e. $A_1$, $B_3$ and $C_3$ respectively do correspond to experiment 9 of the orthogonal array (refer to Table 2). In the optimization approaches, the S/N ratios (smaller-the-best) of Rs and Xj for shallow PN junction device are -39.45dB and -46.77 dB respectively as shown in Table 11. Both values are within the predicted range. Figure 4.8 shows a graf results from the confirmation experiment for Xj and Rs.

Table 11: Results of the confirmation experiment for Xj and Rs

| Output Response | Set 1 ($U_1V_1$) | Set 2 ($U_1V_2$) | Set 3 ($U_2V_1$) | Set 4 ($U_2V_2$) | SNR (Smaller-the-best) |
|---|---|---|---|---|---|
| Rs ($\Omega$/cm$^2$) | 93.865 | 93.923 | 93.78 | 93.829 | -39.45 |
| Xj (nm) | 218.07 | 218.01 | 218.16 | 218.11 | -46.77 |

For Rs, -39.45dB is within the predicted range S/N ratio of -26.97dB to -40.01dB (-33.49±6.52dB). While for Xj, -46.77dB is within the predicted range S/N ratio of -40.16dB to -47.50dB (-43.83±3.67dB).r

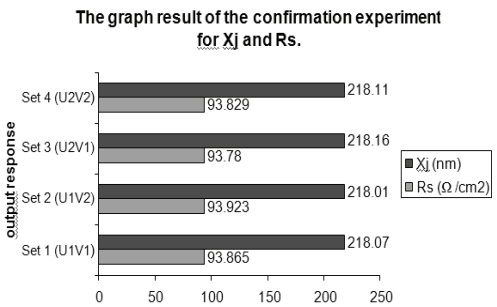


Figure 5: Confirmation experiment for Xj and Rs

These indicate that Taguchi method can predict the optimum solution in finding the Shallow PN junction fabrication recipe with small Xj and Rs values. The result shows that material (boron) and temperature have the strongest effect on Xj and Rs respectively. P-N Junction device has anode and cathode terminals. Junction depth (Xj) was colored yellow layer. This output structure was found when the simulation fabrication of the shallow P-N junction device runs. The material for N type is boron, and the material for P type is phosphorus.

This design method gave eighteen set experiments. The analysis of variance shows the process parameter of material (boron), and temperature are significant based on 95% confidence level towards junction depth and sheet resistance respond in the shallow PN junction device [12]. So that the junction depth and sheet resistance decreased follows the material (boron) and temperature.

## IV. Conclusion

This design method gave 18 set experiments. It has many variants that can be applied to the modeling device, and a lot of parameters can be used. The analysis of variance shows the process parameter of temperature, and material (boron) are significant based on 95% confidence level towards sheet resistance and junction depth respectively respond in the shallow PN junction device. So that the sheet resistance and junction depth decreased follows the temperature and material (boron) respectively. Analysis of variance also proved the factors of temperature, and material are significant for both response, sheet resistance and junction depth.

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