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Optimization of Process Parameters for Si Lateral PIN Photodiode

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Abstract: This paper is about four optimization factors of process parameters, namely the intrinsic region length, photoabsorption layer thickness, the incident optical power and the bias voltage in a Si lateral pin-photodiode so as to obtain high frequency response and responsivity. Optimization of these parameters is based on Taguchi optimization method. In terms of simulation for the fabrication and device electrical characterization, ATHENA and ATLAS software from Silvaco Int. were used respectively. The identified factors have three best levels which give different combination based on L9 orthogonal array by Taguchi optimization method. In order to find the optimum factors and levels, signal-to-noise ratios (SNR) of larger-the-better (LTB) was applied. The analysis showed that the entire identified factors gave significant effect on the optical properties of the Si lateral pin-photodiode. It is revealed that the best result for responsivity and frequency response after the optimization approaches were 0.62A/W and 13.1 GHz respectively which respond to the optimized value for intrinsic region length of 6 µm, photoabsorption layer thickness of 50 µm, incident optical power of 1 mW/cm^2 and bias voltage of 3 V. As a conclusion, the optimum solution in achieving the desired high speed photodiode was successfully predicted using Taguchi optimization method.

Key words: Taguchi method · Photodiode · Lateral · p-i-n · Simulation · Silvaco

INTRODUCTION

Photodiodes have a broad range of application including infrared sensors for optical fiber communication, computer, military and electronic system. PIN photodiode is the most widely used detector in optical applications because it has high sensitivity at the operating wavelength, high response speed and low noise. This is because the depletion region thickness (the intrinsic layer) can be tailored to optimize the quantum efficiency, transient response and frequency response [1]. The development of a lateral pin-photodiode based on silicon absorption layer is pursued because of its compatibility in monolithic integration of CMOS-based photonic devices as well as low cost and robustness of the silicon material itself.

The main properties of a photodiode often considered in analysis are its responsivity and frequency response. Ramaswamy *et al*. [2] reported a frequency response of 4.38 GHz at 5-V bias for a 7.4 µm intrinsic width photodetector on silicon-on-insulator (SOI) substrate. The Si photodiode in standard 0.18 µm CMOS technology exhibited frequency response of 8.7 GHz and responsivity of 0.018 A/W at 11.4-V bias [3]. In another research by Fujikata *et al*. [4] silicon nano-photodiodes produced a frequency response of 5 GHz at 850 nm optical wavelength. Feng *et al*. [5] produced a pin-modulator on silicon-on-insulator (SOI) substrate, with a frequency response of 12 GHz at 8-V bias voltage. Totsuka *et al*. [6] reported a responsivity of 0.34 A/W at 590 nm optical wavelength for the dimension of 1.18 mm (width) x 3.8 mm (length) x 5.0 mm (thickness). The active photoabsorption layer of pin-photodiode must be as thick as 1 µm to obtain high quantum efficiency and low bias voltages from 2 to 7 V and can be used for optimum operation with low dark current and high speed [7].

In this paper, an investigation on the optimization of process parameters on the frequency response and responsivity of a Si lateral pin-photodiode based on the device which was developed in the previous paper was

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undertaken [8-11]. A two dimensional model of a Si lateral pin-photodiode operating at the optical wavelength, λ from 700 nm to 800 nm was developed using an industrial based numerical software. Statistical optimization of the Si lateral pin-photodiode model was executed using Taguchi's L9 orthogonal array optimization method.

MATERIALS AND METHODS

Device Modeling: The Si lateral pin-photodiode was simulated on silicon substrate (n+-type) in two dimension using ATHENA software from Silvaco Int. Then, the n-well was developed using phosphorus diffusion with dopant concentration of 2.02 x 10^{19} cm^{-3} on the left side of the photodiode with diffusion temperature of 1000°C for 50 seconds. Whilst the p-well was diffused with boron concentration of 8.09 x 10^{19} cm^{-3} on the other side of the photodiode with temperature of 1000°C for 120 seconds. SiO_2 layer with thickness of 280 nm was deposited on the silicon substrate to act as a passivation layer. The electrode contacts were processed by depositing aluminum on the n-well and p-well areas of the silicon photodiode. The developed device structure is shown in Figure 1 and the dimensions of the measured device are presented in Table 1. The device's electrical and optical characteristics were executed using the ATLAS module from Silvaco Int.

The responsivity of a pin-photodiode is given by [11]:

$$R = \frac{I_T}{I_S}\left(\frac{\lambda}{1.24}\right) \tag{1}$$

where I_s is the source photocurrent, I_T is the cathode current and λ is the optical wavelength. The frequency response is defined as [11]:

$$f_{-3db} = 20^{*} \log\left(\frac{I_R}{I_{RO}}\right) \tag{2}$$

where I_R is the real cathode current and I_{Ro} is the real component current.

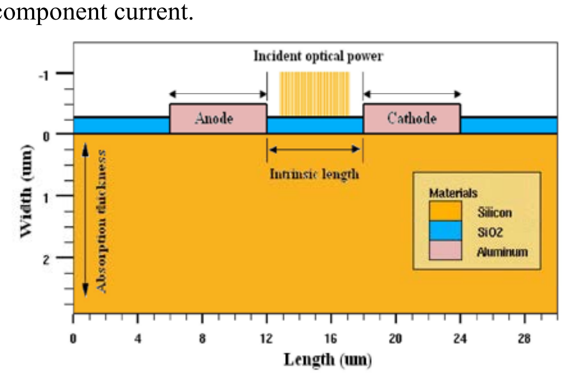

Fig. 1: The device structure of Si lateral pin-photodiode

Table 1: Dimensions of the Si lateral pin-photodiode device

Parameter	Value
Oxide thickness	0.28 µm
Electrode thickness	0.5 µm
Electrode length	6.0 µm

Table 2: Control factors and their levels

Set	Control Factors	Level 1	2	3	Reference
A	Intrinsic region length (µm)	6	11	16	[12]
B	Photoabsorption layer thickness (µm)	15	50	80	[13]
C	Incident optical power (mW/cm²)	1	10	20	[12]
D	Bias voltage (V)	1	2	3	[3]

Table 3: Noise factors and their levels

Set	Noise Factors	Level 1	2	Reference
E	Time diffusion of n-well (seconds)	50	60	[8]
F	Temperature diffusion of n-well (°C)	900	1000	[8]

L9 Orthogonal Array by Taguchi Optimization Method: In this research, four factors were identified namely the intrinsic region length, photoabsorption layer thickness, incident optical power and bias voltage which were tested at three levels using the L9 orthogonal array by Taguchi optimization method. These factors are portrayed in Figure 1. Whilst, the noise factors were the time and temperature of the n-well diffusion were tested at two levels. Using the SNR and Analysis of Variance (ANOVA) Pareto, it allows us to make accurate conclusion for the experiment either the factor is giving dominant effect or minimum effect. To find the optimum factors and levels, signal to noise ratio (SNR) of larger the better (LTB) was applied to examine the performance factors of the device namely the responsivity and the frequency response. The value for the variation was chosen according to previous research. Using L9 orthogonal array method, nine sets of experiments were used to vary the parameter for the intrinsic region length between 6 µm to 16 µm, the photoabsorption layer thickness between 15 µm to 80 µm, the incident optical power between 1 mW/cm^2 to 20 mW/cm^2 and the bias voltage between 1 V to 3 V as shown in Table 2. Then, the parameters of the noise factors for the diffusion time and temperature were tested at two levels as presented in Table 3.

The responsivity and frequency response were studied as the output characteristic of the pin-photodiode. Table 4 shows the L9 orthogonal array to be inserted into Variant 4 factor 3 level.

Table 4: Variant 4 factor 3 level of Taguchi optimization method

	Control factors			
Exp. No.	A	B	C	D
1	6	15	1	1
2	6	50	10	2
3	6	80	20	3
4	11	15	10	3
5	11	50	20	1
6	11	80	1	2
7	16	15	20	2
8	16	50	1	3
9	16	80	10	1

RESULTS AND DISCUSSION

Analysis of Responsivity and Frequency Response for Si Lateral Pin-Photodiode: The simulation results for the frequency response and responsivity of the Si lateral pin-photodiode is shown in Table 5 and Table 6 respectively. The frequency response and responsivity of the Si lateral pin-photodiode is attributed to SNR of larger-the-better in Taguchi optimization method. The SNR η can be expressed as:

$$SN = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad (3)$$

where μ is the mean and σ is the variance. By applying Eq. (3), η for each device was calculated and given in Table 7. The effect of each process parameter on the SNR at different levels can be separated because the experimental design is orthogonal. The SNR values for each level of the process parameters are summarized in Table 8. In addition, the total mean of SNR for these 9 experiments has been also calculated and listed in Table 8.

Table 5: Frequency response values for Si lateral pin-photodiode

	Frequency response (GHz)			
Exp. No.	1	2	3	4
1	14.97	13.50	16.93	18.40
2	11.27	13.55	11.83	16.31
3	12.34	11.65	14.07	16.73
4	9.85	9.90	9.85	9.90
5	9.89	9.83	9.83	9.89
6	9.83	9.89	9.89	9.89
7	9.93	9.95	9.94	9.94
8	9.85	9.86	9.86	9.86
9	9.76	9.77	9.76	9.78

Table 6: Responsivity values for Si lateral pin-photodiode

	Responsivity (A/W)			
Exp. No.	1	2	3	4
1	0.514	0.515	0.514	0.515
2	0.527	0.527	0.527	0.527
3	0.535	0.535	0.535	0.535
4	0.472	0.472	0.472	0.472
5	0.464	0.465	0.464	0.465
6	0.589	0.590	0.589	0.590
7	0.451	0.452	0.452	0.452
8	0.645	0.646	0.645	0.646
9	0.459	0.460	0.459	0.460

Table 7: SNR for frequency response and responsivity

	SNR (dB)	
Exp. No.	Frequency response	Responsivity
1	203.12	-5.77
2	202.17	-5.56
3	202.49	-5.43
4	199.89	-6.52
5	199.88	-6.67
6	199.89	-4.59
7	179.95	-6.90
8	179.88	-3.80
9	179.80	-6.75

Table 8: SNR for the frequency response and responsivity for each level.

		SNR (larger-the-best)				
Response	Process parameter	Level 1	Level 2	Level 3	Total mean SNR	Max-min
Frequency response	A	202.59	199.89	179.87	194.12	22.72
	B	194.32	193.98	194.06		0.34
	C	194.30	193.95	194.10		0.35
	D	194.27	194.00	194.08		0.19
Responsivity	A	-5.59	-5.93	-5.82	-5.78	-0.34
	B	-6.40	-5.34	-5.59		-1.06
	C	-4.72	-6.28	-6.33		-1.61
	D	-6.39	-5.69	-5.25		-1.14

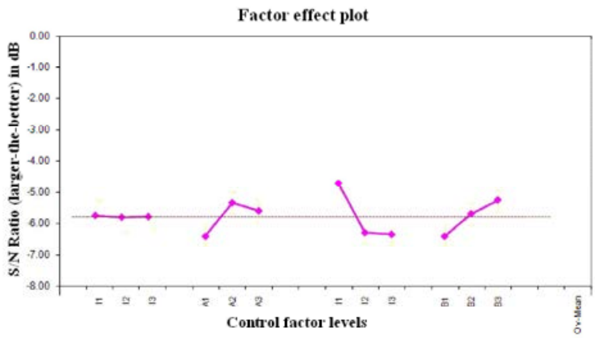

Fig. 2: Signal-to-ratio graph for responsivity in Si photodiode

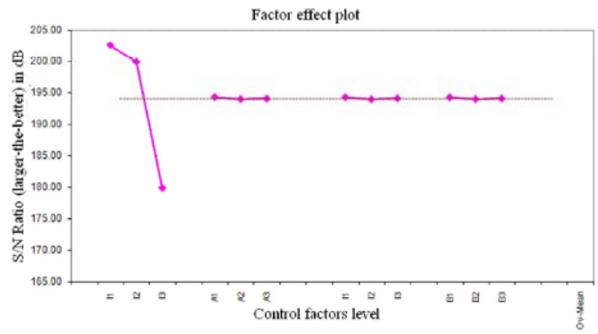

Fig. 3: Signal-to-ratio graph for frequency response in Si photodiode

Table 9: Result of ANOVA for responsivity and frequency response in Si lateral pin-photodiode

Response	Process parameter	Degree of freedom	Sum of square	Mean square	Factor effect on SNR (%)
Frequency response	A	2	924	642	100
	B	2	0	0	0
	C	2	0	0	0
	D	2	0	0	0
Responsivity	A	2	0	0	2
	B	2	2	1	20
	C	2	5	3	56
	D	2	2	1	22

Table 10: Best setting of the process parameters

Response	Process parameter	Unit	Best value
Frequency response & responsivity	Intrinsic region length	µm	6
	Photoabsorption layer thickness	µm	50
	Incident optical power	mW/cm2	1
	Bias voltage	V	3

Figure 2 and Figure 3 show the SNR graphs for the responsivity and frequency response of the Si photodiode, respectively, where the dashed line is the value of the total mean of SNR. Basically, the larger the SNR, the quality characteristic for the responsivity and frequency response are better.

Analysis of Variance (ANOVA): A better feel for the relative effect of the different process parameter on the responsivity and frequency response were obtained by decomposition of variance, which is called analysis of variance (ANOVA) [14]. The priority of the process parameters with respect to the responsivity and frequency response were investigated to determine more accurately the optimum combinations of the process parameters. The result of ANOVA for the Si lateral pin-photodiode device is presented in Table 9. Statistically, F-test provides a decision at some confidence level as to whether these estimates are significantly different. The percent factor effect on SNR indicates the priority of a factor (process parameter) to reduce variation. For a factor with a high percent contribution, it will have a great influence on the performance [14].

For the responsivity characteristic, the incident power optical was found to be the major factor affecting the responsivity (56%), whereas bias voltage and photoabsorbtion layer thickness was the second and third ranking factor (22%) and (20%) respectively. The percentage effect on SNR for the intrinsic region length is low at 2%. For the frequency response characteristic, intrinsic region length was found to be the most significant factor affecting 100% of the device performance. The optimized factors for responsivity and frequency response in Si lateral pin-photodiode device which had been suggested by Taguchi optimization method is shown in Table 10.

From the above parameters as shown in Table 10, the final simulation was performed to verify the accuracy of the Taguchi optimization method prediction. The result of the final simulation for Si lateral pin-photodiode device is shown in Table 11.

In this research, intrinsic region length has the strongest effect on the frequency response characteristics and incident power optical has the strongest effect on the responsivity of the Si lateral pin-photodiode device. The mean of best result for responsivity after the optimization approaches is 0.62 A/W. This value is within the predicted range of 0.599 to 0.702 A/W. The mean of best result for frequency response after the optimization approach is 13.1GHz. This value is within the predicted range of 12.8 GHz to 14.2 GHz. Previously, responsivity of 0.45 A/W and frequency response of 2.27 MHz were achieved at an optical wavelength of 850 nm for a 30 μm intrinsic width of a Si lateral pin-photodiode before optimization [8]. These results show that Taguchi optimization method can predict the optimum solution in finding the optical characteristic of the lateral Si pin-photodiode in a cost-effective method as opposed to a purely experimental design.

CONCLUSION

As a conclusion, the optimum solution in achieving the desired high speed photodiode was successfully predicted by using Taguchi optimization method. There are many physical limitations involved as the size gets smaller approaching the molecular or atomic limitations of the substrate and dopant. In this work, Taguchi optimization method was used to optimize the responsivity and frequency response of a Si lateral pin-photodiode. The incident power optical and intrinsic region length was identified as device factors that have the strongest effect on the responsivity and frequency response.

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