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SILICON BASED P-I-N PHOTODIODE DESIGN WITH USING TCAD SIMULATION

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Abstract. *The Silicon PIN photodiode (Si-PIN PD) with active area (10.0 x 10.0 mm², 12.0 x12.0 mm² and 20.0 x 20.0 mm²) was designed by using Silvaco ATLAS and ATHENA tools at Nuclear Radiation Detectors Applications and Research Center (NÜRDAM). To get Si-PIN PDs' specifications, capacitance-voltage (C-V) and dark current – voltage (I-V), spectral response measurements were accomplished with Bipolar and Shr model, and Newton method. The dark current and capacitance at -90 V of designed Si-PIN PD are (7.49 nA, 39 pF), (39 nA, 51 pF), (10 nA, 80 pF) for 10x10 mm², 12x12 mm², 20x20 mm² respectively. Si-PIN PDs have low dark current and capacitance at high reverse voltage and all photodiodes reach the full depletion mode at -20 V. Spectral response of each Si-PIN PD is 0.6 AW⁻¹. According to obtained results, designed Si-PIN PDs are likely to be used for medical application after fabrication and radiation test.*

Keywords: *silicon PIN photodiode, TCAD, current –voltage, capacitance – voltage, spectral response*

1. INTRODUCTION

Silicon has been used in microelectronics and nanoelectronics in the last decades, due to its high absorption coefficient and mobility, band gap, and abundance, cheapness. In Silicon PIN photodiode (P^+ - I-N^+), intrinsic region (I) creates natural wide depletion region that causes low capacitance, high efficiency, and resolution(1). So, Si-PIN PDs have numerous applications such as X-ray imaging and, gamma detection. Because of this, silicon-based photodiodes have been fabricated with different structure and photodiodes with guard rings indicates superior performance for radiation application. Low breakdown voltage is crucial disadvantage for semiconductor devices. In recent work, photodiodes structures with virtual guard rings have been studied to eliminate edge breakdown voltage and boost fill factor. One silicon PIN photodiode published with guard rings which has low dark current compared to PIN photodiode without guard ring (2,3). In other work, Intrinsic region effects on photodiode performance were investigated by using Silvaco TCAD simulation. In order to enhance performance of photodiode, parameters that effects breakdown voltage and dark current must be investigated(4). In this study, Silicon PIN photodiodes with three different active areas have been designed by using Silvaco TCAD simulation program.

2. THEORETICAL APPROACH

In Si-PIN PD structure depletion region located in intrinsic region which doesn't possess carriers. When Si-PIN PD irradiated, radiation creates electron – hole (e-h) pairs. These charges are drifted by electric field of depletion region and photo current is created. Electric field of depletion region increase with applied reverse biased voltage. This situation makes Si-PIN PD more sensitive under ionized radiation. The efficiency of photo diode can be explained with quantum efficiency and spectral response. This efficiency determined by using e-h pairs generated by indecent photon (Equation 1):

$$\eta = \frac{\frac{I_{photon}}{q}}{\frac{P_{optical}}{h\Upsilon}} \tag{1}$$

I_{photon} = photon generated current
q = Electron charge
$P_{optical}$ = Optical power

Spectral response can be defined as current produced by optical power, and expressed with Equation 2. (5–7)

$$R = \frac{I_{photo}}{P_{optical}} \tag{2}$$

2.1. Dark Current

Theoretically, the photodiode should not produce electric current in the dark, but a very low amount of electric current is measured due to the structure of the diode. This current is defined as the dark current (I_{dark}). There are four parameters that cause the formation of the dark current (Equation 3):

$$I_{Dark} = I_{Dif} + I_{thermal\ gen} + I_{Inteface} + I_{Surface} \tag{3}$$

When reversed biased is increased, electric field in the depletion region get stronger. This strong electric field breaks the balance among diffusion and drift of

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carriers. So, minority carries are drifted and internal minority carries take place them and diffusion current (I_{dif}) is occurred.

Thermal generation current $I_{thermal\ gen}$ is bulk current in depletion region. As reversed biased is applied, temperature inside photodiode rises. This temperature, excite electrons inside depletion region and electrons jump from valance band to conduction band. Thus, thermal caused current occurs.

Interface current ($I_{Interface}$) arise from interface between Si and SiO_2 in where interface states result in recombination and generation of e-h pair due to impurities, interface defects and broken bonds(8).

2.2. Guard Ring Effect on Leakage Current

Guard ring common way to reduce dark current. It is possible to improve breakdown voltage of a Si-PIN PD. Guard rings are formed around the active area. These guard ring surpass interface current and surface current thus total dark current decrease significantly. In addition, guard rings interrupt e-h pairs not to flow other areas (8,9).

3. Design Si-PIN PD with large active area

3.1. Simulation

Simulation carried out with Atlas and Athena tools of Silvaco TCAD. Mesh of Si-PIN PDs with 10.0 x 10.0 mm², 12.0 x 12.0 mm² and 20.0 x 20.0 mm² active area have been designed on 20 kΩ ,n type Si (1 0 0), substrate with 300 μm thick. In this architecture, four guard rings surround the active area of Si-PIN PD as shown in Figure 1.

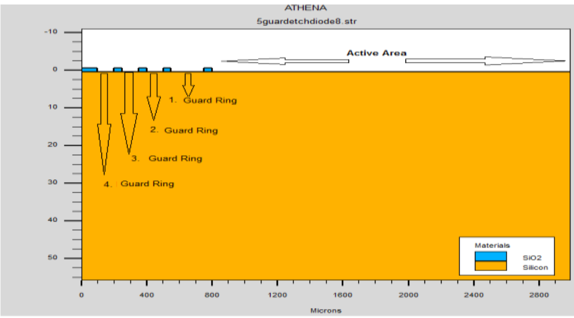

Figure 1. Formation of guard rings and active area

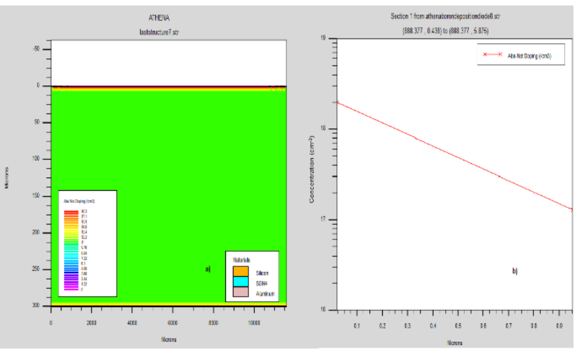

Figure 2. Boron diffusion for active and guard rings

The active area and guard rings are formed as p⁺ by thermal Boron diffusion simulation and their ion concentration are 1.5 x 10^{18} cm^3 (Figure 2).

Backside of the substrate is formed as n⁺ region by thermal phosphorus deposition. Its peak concentration is $1x10^{16}$ cm^3 (Figure 3).

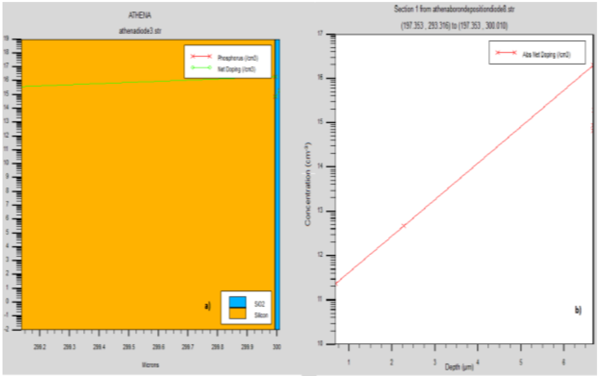

Figure 3. Phosphorus deposition backside of the substrate.

1 μm thick aluminum (Al) was coated on the front and back surfaces of the substrate to form the metal contacts of the silicon PIN photo diode. On the front surface, the etching process has been carried out in such a way that Al remains on the active area and guard rings. The front surface of the diode structure is coated with silicon nitrate (Si_3N_4) in order to eliminate the surface current formed on the surface of the Silicon PIN photo diode structure (Figure 4 and Figure 5).

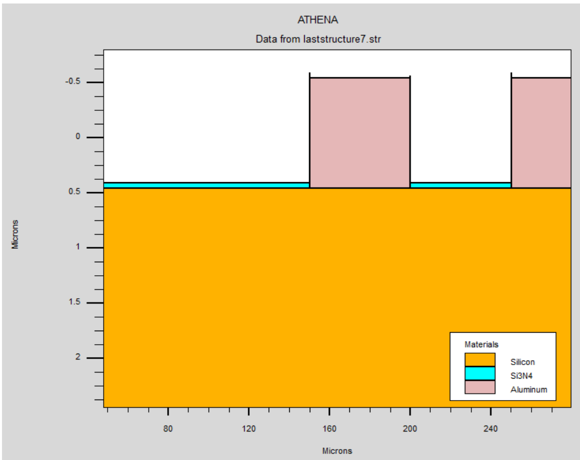

Figure 4. Aluminum and Silicon Nitride coating process

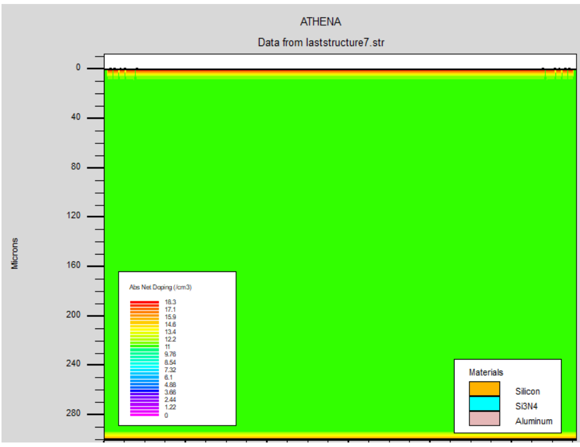

Figure 5. Silicon PIN photo diode structure with proses simulation completed

Si-PIN PD architecture design and details are shown in Figure 6 and Table 1.

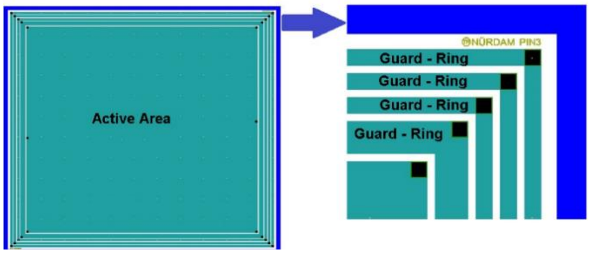

Figure 6. Si-PIN PD mask design

Table 1. Architecture of designed PIN PD

	With (μm)	Space between Guard-Rings (μm)
1st Guard-Rings	200	50
2nd Guard-Rings	100	50
3rd Guard-Rings	100	50
4rd Guard-Rings	100	50

3.2. Electrical Characteristics of Designed Si-PIN PD

Current -Voltage (I-V), Capacitance-Voltage (C-V) and spectral response (300nm -1100nm) of designed Si-PIN PD were carried out. To observe guard ring effect, I-V and characteristic of Si -PIN PD with three guards and Si-PIN PD with four guards are compared. The results were given in Figures (7, 8, 9).

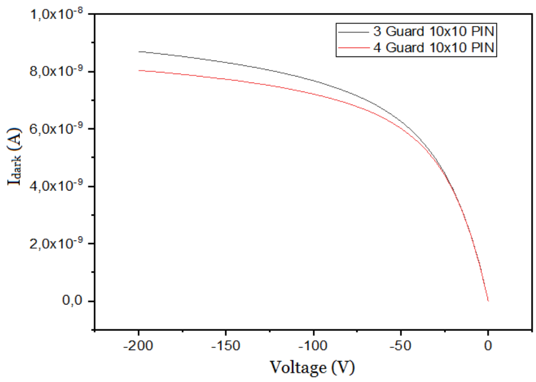

Figure 7. I-V characteristics of Si-PIN PD with 10.0 x10.0 mm² active area

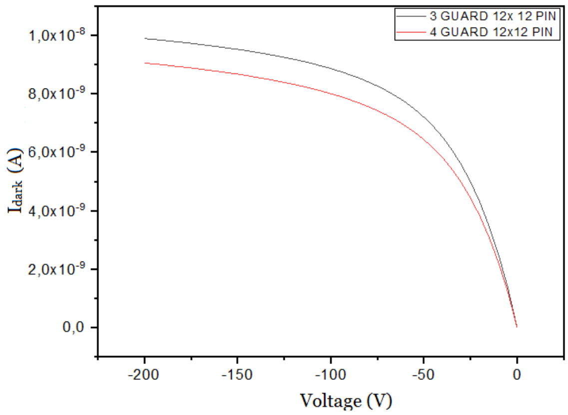

Figure 8. I-V characteristics of Si-PIN PD with 12.0 x 12.0 mm² active area

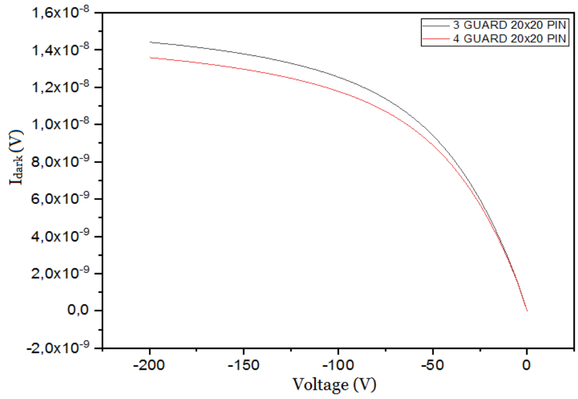

Figure 9. I-V characteristics of Si-PIN PD with 20.0 x 20.0 mm² active area

Each Si-PIN PDs with four guard rings has low dark current compared to Si-PIN PDs with three guard rings as seen in figures (7, 8 and 9). Dark current is below the 10 nA at -90 V. Even, above this voltage, designed Si-PIN PD works more stable, and dark current is still below the 20 nA for each photo diodes. Break down voltage above the 800 V, is constituting with multi guard ring structure and agreeable with studies in literature (4, 8, 10).

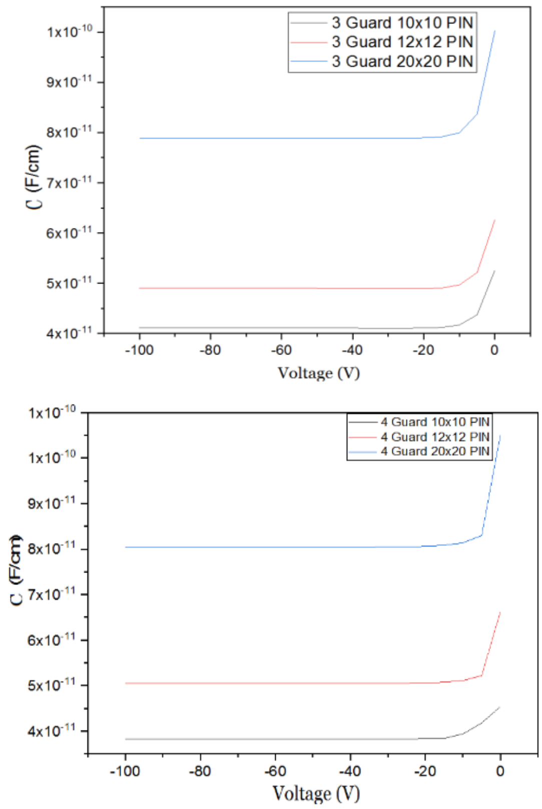

Figure 10. Capacitance characteristics of Si-PIN PD with three guard and four guard

C-V measurement was carried out at 1 MHz for Si-PIN PDs with 10.0 x10.0 mm², 12.0 x12.0 mm², 20.0 x20.0 mm² active area. Capacitances value of Si-PIN PD decrease exponentially with increased reversed voltage until -20V. Then, capacitances drop slightly after -20V. This situation indicates that designed Si-PIN PDs reach full depletion mode (Figure 10). Capacitance values at -90V of Si-PIN PDs are shown in Table 2.

Table 2. Capacitance value of Si-PIN PD

Active Area mm²	10x10	12x12	20x20
Capacitance for 3 guard (pF) @-90	41	49	78
Capacitance for 4 guard (pF) @-90V	39	51	80

Number of guard rings doesn't affect the capacitance value of Si-PIN PD. This situation is consistent with mathematical model. In mathematical model capacitance value depends on ion concentration, depletion region thickness and size of active area (11).

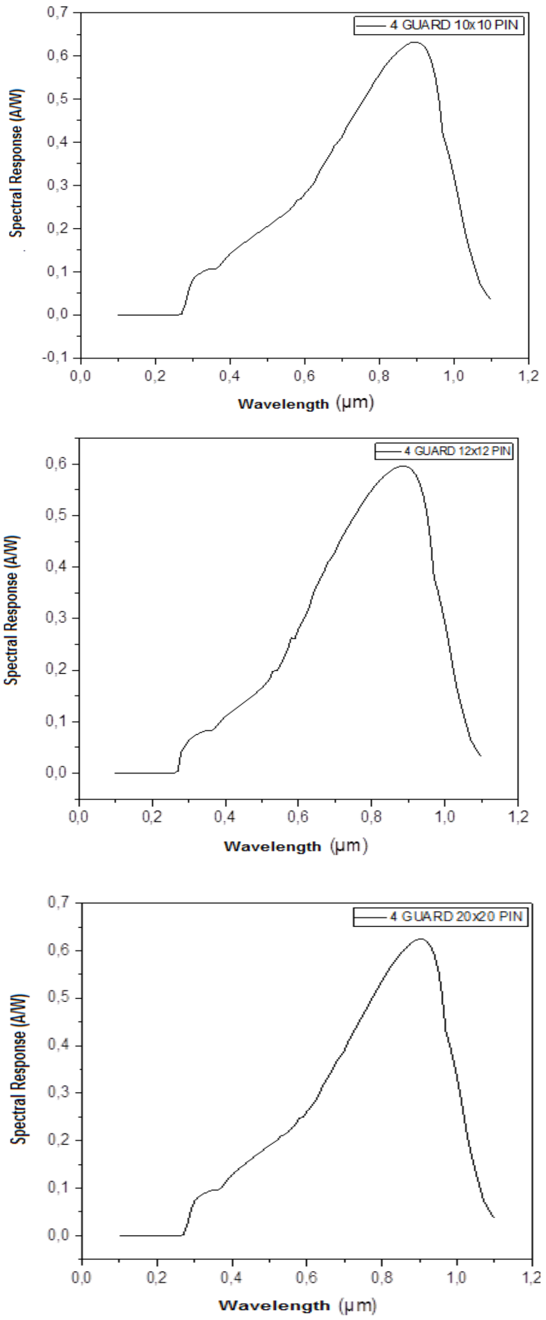

Figure 11. Spectral response of Si-PIN PD with 10.0x10.0 mm², 12.0 x12.0, 20.0 x20.0 mm²

Spectral response of Si-PIN PDs that have optimum structure has been carried out between 300 nm and 1100 nm. Maximum responsivity for each Si-PIN PD is 0.61±0.02 AW^{-1} at 820 nm (Figure 11). Guard rings affect on the spectral response of Si-PIN PD has not been simulated so result of spectral responds of Si-PIN PD with three guard has not been published in this paper.

5. Conclusion

Si-PIN PD with three different active area were designed by using Silvaco TCAD simulation program. The obtained dark current and capacitance at -90 V of designed Si-PIN PD are 7.49 nA - 39 pF, 39 nA- 51pF, 10nA-80 pF for 10x10 mm², 12x12 mm², 20x20 mm² respectively. Spectral responses of photodiodes are 0.61±0.02 AW^{-1} at 820 nm. Small responsivity changes can be related to mesh structure. Si-PIN PDs have low dark current and capacitance at high reverse voltage and all photodiodes reach the full depletion mode at -20 V. According to obtained results, designed Si-PIN PDs can be used in various fields such as medical applications.

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