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FABRICATION AND FIRST ELECTRICAL TESTS OF SILICON-BASED PIN PHOTODIODES FOR RADIATION APPLICATIONS

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Abstract. *Silicon-based PIN photo diodes with 3 x 3 mm² sensitive regions were successfully fabricated in this work. The electrical properties of PIN diodes were investigated intensively. The dark current of Silicon PIN photodiodes has been found to be 200nA at a reverse voltage of -70V. The PIN photo diodes have also been found to reach the full depletion mode and a capacitance value of 5.5 pF has been achieved at -40V. When the photo- sensitive region of the photo diode was illuminated with a help of 450 nm LED light. The photon current of 310 nA was obtained at a reverse voltage of -70V by using 450nm LED light. As the results of first evaluation, the experimental results also showed high dark current value and low photocurrent efficiency. The problems affecting the electrical performance of PIN diodes have been addressed in this research work. Additionally, all the results were carried out at room temperature.*

Keywords: *silicon PIN photodiode, dark current, photodiode fabrication, current-capacitance measurements, diode sensitivity*

1. Introduction

Silicon PIN photodiodes are essential components in various applications that require the detection of light or other electromagnetic radiation. These devices offer efficient and reliable light sensing capabilities, making them widely used in areas such as telecommunications, industrial automation, medical equipment, and scientific research [1]–[4]. The term "PIN" refers to the structure of the photodiode, which consists of three layers: the P-layer (positive charge), the I-layer (intrinsic or lightly doped), and the N-layer (negative charge). This structure allows photons to produce photo electrical current efficiently. Silicon is being a widely available and cost-effective material that is used commonly in the manufacturing of PIN photodiodes [5]–[7]. It possesses excellent light absorption properties within the visible and near-infrared spectrum, making it suitable for a broad range of applications [2], [8], [9]. The PIN photodiode operates based on the principle of the internal photoelectric effect. When photons strike the photosensitive area of the diode, they generate electron-hole pairs within the intrinsic layer. The electric field created by the voltage bias across the P-N junctions separates these charge carriers, resulting in a measurable current flow [1], [4], [8], [10], [11]. One of the key advantages of silicon PIN photodiodes (Si-PIN PDs) is their high sensitivity and low noise characteristics. They can detect even low levels of light and provide a proportional electrical output [2], [5], [11], [12]. Additionally, these photodiodes offer fast response times and may be designed with wide dynamic ranges to accommodate different light intensities. Moreover, Si-PIN PDs can also be optimized for specific applications by incorporating various features [5], [13–15]. For instance, anti-reflection coatings may enhance their optical efficiency, while wavelength- selective filters enable detection in specific regions of the electromagnetic spectrum [10], [14]. In summary, Si-PIN PDs are versatile light sensors with significant applications in numerous industries [12], [16]. Their reliable performance, cost- effectiveness, and customizable features make them invaluable tools for a wide range of ionized radiation detection and measurements [8], [17–19]. In this study, we fabricated silicon-based PIN photodiodes and obtained their preliminary electrical characterizations for radiation sensing applications.

2. Experimental details

Prior to the fabrication of Si-PIN PDs, the FZ p-type Si (100) with 650 μm thickness, 1kΩ substrates were cleaned by using RCA cleaning processes. It is extremely important to have clean substrates in Si-PIN PDs fabrication because any unwanted particles on

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substrates may affect electrical performance of photodiodes. The first photolithography process was performed to form the P^{++} regions. Samples were then loaded in the thermal diffusion furnace. To achieve the deposition of boron ions into the areas by lithography process, the boron tribromide (BBr_3) was used as a precursor gas. Afterwards, the second photolithography process was carried out to form the N^{++} regions. The phosphorus oxychloride ($POCl_3$) gas was doped with the thermal diffusion method to the doping areas determined by photo lithography, and the N^{++} regions and guard rings were formed.

After the ion doping process was completed, the 150 nm SiO_2 was grown on top of Si substrates by using oxidation method in the thermal diffusion furnace. The oxide layer is considered to be one of the most sensing areas of the Si-PIN PDs. Followed by the deposition of 7 nm thick Titanium using the electron beam physical vapor deposition (EBPVD) for 90 sec, the thickness of each material was measured with an Angstrom Sun spectrometer reflectometer. To realize optimum Ti layer, Ti was grown on a glass while the surface of photodiodes was coated through 90 sec. Then, glass and the glass with Ti covered was located on MAPD-3NK type of photo diode [20]-[26]. During this measurement, a voltage of 30 V was applied to the MAPD-3NK photodiode. Diode sensitivity was measured to be 15 mV and 11.6 mV respectively. These results illustrated that Ti transparency is 77%. Resistance of the Ti layer on glass was measured to be 2.75 kΩ. Finally, Si-PIN PDs electrodes were made by aluminum via DC magnetron sputtering. The structure of fabricated Si-PIN PDs has been depicted in Fig. 1.

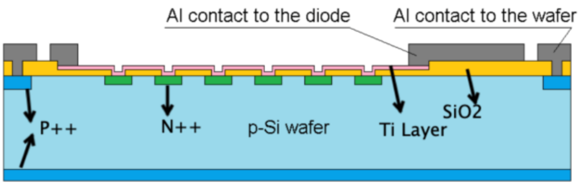

Figure 1. A schematic representation of a Si-PIN PD

The reverse current-voltage (I-V) and capacitance-voltage (C-V) responses of Si-PIN PDs were investigated by using Keithley source meters. A 450 nm laser was used to examine photo currents and the sensitivity of Si-PIN PDs. A rectangular, 1 ms duration signal of 10 kHz frequency and 4 V amplitude potential was supplied from a Tektronix generator to feed the laser diode. The signal produced on Si-PIN PDs. The diameter of the laser beam was focused to 30 µm using an optical focuser. Then, the sensitivity of the photodiode was investigated by injecting laser beam into the center of the photodiode's active area, between the electrodes and on the active region.

3. Results and Discussion

The current-voltage (I-V) characteristics of Si-PIN PDs were performed in a dark room at 22 °C. The reverse voltage is determined between 0 and -70 V. From acquired results, the dark current value of the photo diode was found at the level of -150 nA at the full depletion voltage of -40 V. When the reverse voltage applied to the photodiodes reaching -70 V, the dark current value increased to -200 nA and above as seen from Fig. 2. These dark currents were 10 times higher than the currents in the literature [5], [8], [12], [16]. This is maybe a result of existence of fabrication process impurities in PDs. Moreover, even if substrates were under ultra-high vacuum with surface cleaned by several cycles of argon ion sputtering, the presence of retained impurities may be observed. Therefore, these contribute to the behavior of dark current of a photodiode [6], [10], [19], [27].

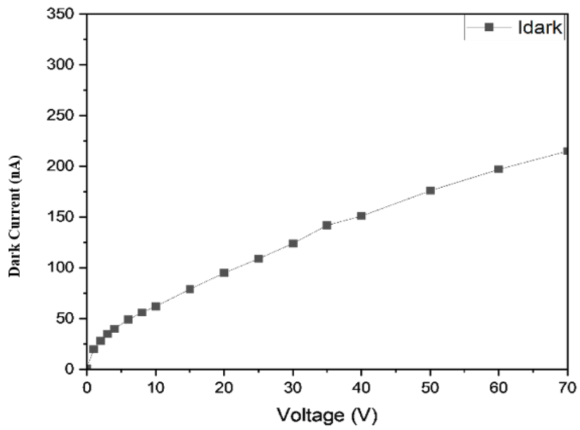

Figure 2. I-V data plot of a Si-PIN PD

The capacitance-voltage (C-V) curve of a Si-PIN PD is examined and is given in Fig. 3. The capacitance value decreased exponentially to -40 V and stabilized as voltage increased. As the voltage increases, Ti-SiO-Si electrons in the PIN diode accumulate at the SiO-Si boundary initiating the depletion region to form. The gradual voltage increase causes the width of the depletion region between the newly formed n-channel and the substrate to increase which results in the capacitance to decrease. In 80-90 V range, residual charge accumulation has reached the saturation. The capacitance of the new PIN PD in this range was measured to be 5.5 pF.

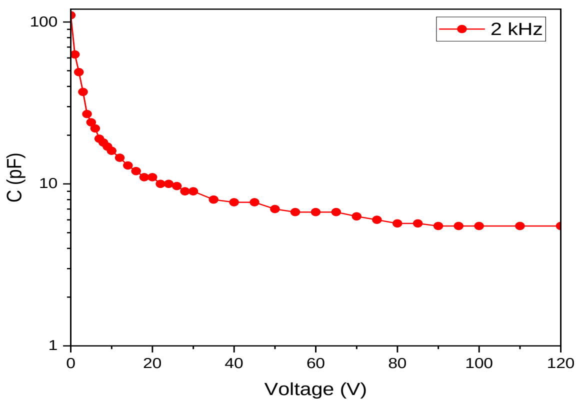

Figure 3. C-V data plot of a Si-PIN PD at 2 kHz frequency

In measuring the light signal behavior, we first placed the photodiode under the 450 nm focused laser beam and centered it. The behavior is shown in Fig. 5. The photo-signal produced was displayed on the oscilloscope at the same time. While the applied voltage was at 3 V, the amplitude of the photo-signal was around 12.5 mV.

While the applied voltage was 20 V, the amplitude of the photo-signal was obtained to be about 2 mV. In addition, it was observed that as the reverse voltage value applied to the photodiode increased, the photo current of the photodiode decreased from 350 nA to 310 nA (Fig. 4). The main reason for the low sensitivity of the active site is that semi-transparent titanium layer is thicker than it should be [6], [15], [27], [28]. When the resistance values of the Ti layers measured on structure, the values are measured as >200 MΩ. The transparency of Ti layer with 90 sec deposition time is 77% (on the glass). This is acceptable for Ti layer; however, the value is different on $Si\text{-}SiO_2$ surface. In addition, the resistance may be affected by annealing since Ti layer was annealed at ~400 °C so the resistance may be increased due to annealing [12], [27]-[30]. To solve the low signal issue, it was noticed that the resistance value should be reduced 100 times on the structure [8],[10].

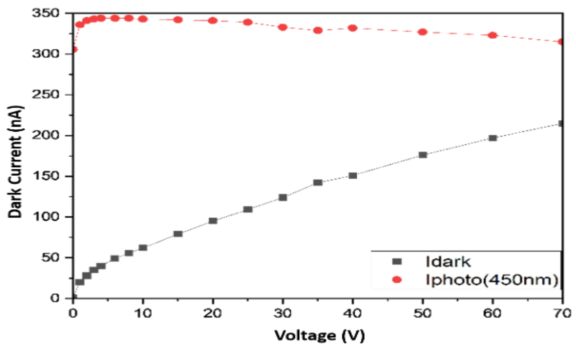

Figure 4. Comparison of Dark and Photo Current vs. to voltage of a Si-PIN PD

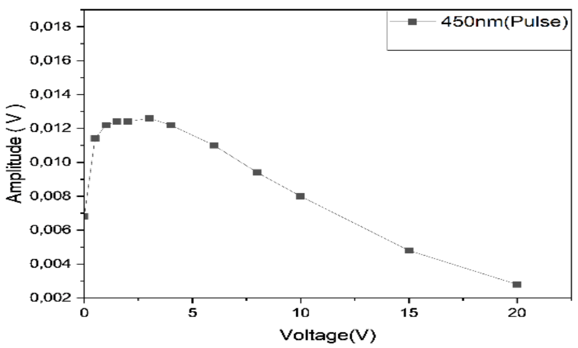

Figure 5. Light signal behavior of a Si-PIN PD under 450 nm laser pulse

4. Conclusion

In order to utilize the Si-PIN PDs for radiation detection, the dark current values need to be reduced at least by 10 times. To solve this problem, it is critical to reduce the contamination that may occur in the production process and make the ion doping processes more homogeneous. To detect a visible light by a Si-PIN PD, it must have high efficiency under high reverse voltage. According to the results we obtained, unfortunately the efficiency of the photo diode decreased under high voltage. To overcome this problem, the Ti layer in the sensor region of the photo diode should be at least 77% transparent.

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