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Fabrication and characterization of Si-PIN photodiodes

Emre DOĞANCI[1,2,*], Şenol KAYA[1,2], Aliekber AKTAĞ[1,2], Elif SARIGÜL DUMAN[3,4], Raşit TURAN[3,5], Hüseyin KARAÇALI[1,2], Ercan YILMAZ[1,2]

[1]Department of Physics, Faculty of Science, Bolu Abant İzzet Baysal University, Bolu, Turkey
[2]Nuclear Radiation Detectors Application and Research Center (NÜRDAM), Bolu Abant İzzet Baysal University, Bolu, Turkey
[3]Center for Solar Energy Research and Applications (GÜNAM), Middle East Technical University, Ankara, Turkey
[4]Department of Micro and Nano Technology, Graduate School Of Natural And Applied Sciences, Middle East Technical University, Ankara, Turkey
[5]Department of Physics, Faculty of Science, Middle East Technical University, Ankara, Turkey

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Abstract: In this work, characteristics of silicon-based p^+ type, intrinsic (I), n^- type (Si-PIN) photodiodes with active area of 3.5 × 3.5 mm^2, 5.0 × 5.0 mm^2, or 7.0 × 7.0 mm^2 and their possible usage in optoelectronics were studied. The devices were fabricated in the Radiation Detector Application and Research Center (NÜRDAM) of Bolu Abant İzzet Baysal University, Turkey. To acquire the device specifications, the current-voltage (I-V) and the capacitance-voltage (C-V) measurements were carried out in the photoconductive mode. Quantum efficiency and spectral responsivity measurements were performed in the photovoltaic mode. Both measurements were carried out in a dark environment at room temperature. The measured values of the dark current (I_{dc}) and the capacitance of photodiodes were –6.97 to –19.10 nA and 23 to 61 pF at –5 V, respectively. The quantum efficiency measurements of the devices increased up to 66%. P responsivity was found to be 0.436 ± 1 mA/W at 820 nm. The results indicate that the I_{dc} current and the performance of the devices were improved. Therefore, the devices can be utilized for optoelectronics applications and commercial usage.

Key words: Si-PIN photodiodes, dark current, spectral responsivity, quantum efficiency

1. Introduction

Silicon PIN photodiodes are mostly utilized as semiconductor devices for microelectronic applications such as industrial electronics, military applications, radiation detectors, and line scanners for thermal neutron detection [1–4]. Comprehending the device mechanism is a vital step to devise the operating and optical performance of a PIN photodiode. According to formerly published results on PIN photodiodes, the reverse-biased current mechanism is expressed with diffusion and recombination components [5,6]. Capacitance is related to device area, depletion width, and impurity concentration [7]. The spectral response is related to the bandgap of the material used and the material absorption coefficient [8]. Some fabrication techniques such as ion implantation and thermal deposition are also effective on device performance [9]. Although the cost-effective ion implantation method is used to control the doping rates and the doping is easier, the low-cost thermal doping method is preferred. Nevertheless, PIN photodiodes need some improvements to widen

*Correspondence: emredoganci8@gmail.com

their usage in the electronic applications. Such kinds of microelectronic devices should be fabricated many times to achieve higher performance. In this study, the first fabrications of Si-PIN photodiodes with 3.5 $\times$ 3.5 mm^2, 5.0 $\times$ 5.0 mm^2, and 7.0 $\times$ 7.0 mm^2 active areas were successfully carried out by using a photomask-lithographic process. Dimensions of active areas of the fabricated PIN-photodiodes were determined according to commercial products of HAMAMATSU (S5106) and FIRST SENSOR (PS7-6TO, PS13- 5bTO). The initial operational optical properties were then investigated in detail.

2. Experimental details

A slightly doped (100) N-type Si substrate having approximately 2.4 kΩcm surface resistivity was cleaned by the RCA cleaning process and was dried with ultrapure nitrogen gas. Immediately after the cleaning process, the SiO_2 layer was grown by wet oxidation at 1100 °C for 130 min. Due to SiO_2's solubility in H_2O during the oxidation process, the wet oxidation is faster than the dry oxidation process. Thus, a thick oxide layer can be grown easily and economically [10]. The thickness of the deposited layer was measured as approximately 1 μm with a spectroscopic reflectometer. Three different active areas (3.5 $\times$ 3.5 mm^2, 5.0 $\times$ 5.0 mm^2, 7.0 $\times$ 7.0 mm^2) having an intrinsic (I) region of 500 μm thick were designed in the photomask used in the lithography process. The p+ and n^- regions were opened with standard photolithography and a chemical etching process where the doping was achieved separately. The p+ channels were formed using boron tribromide gas (BBr_3), and the n^- channels were formed using phosphorus oxychloride ($POCl_3$) at 950 °C for 15 min in a diffusion furnace. The metal contacts were established via aluminum deposition by DC sputtering. The postmetallization annealing was performed at 350 °C in a nitrogen environment to reduce the contact resistivity. The fabricated Si-PIN photodiode and its schematic representation are shown in Figures 1a and 1b, respectively. The I-V characteristics were measured by a KEITHLEY 2636B source meter, and C-V characteristics were measured by HIOKI 3532 LCR meter. Quantum efficiency and responsivity of the Si-PIN photodiodes were also measured at room temperature in photovoltaic mode by PVE300 Photovoltaic EQE and IQE solution.

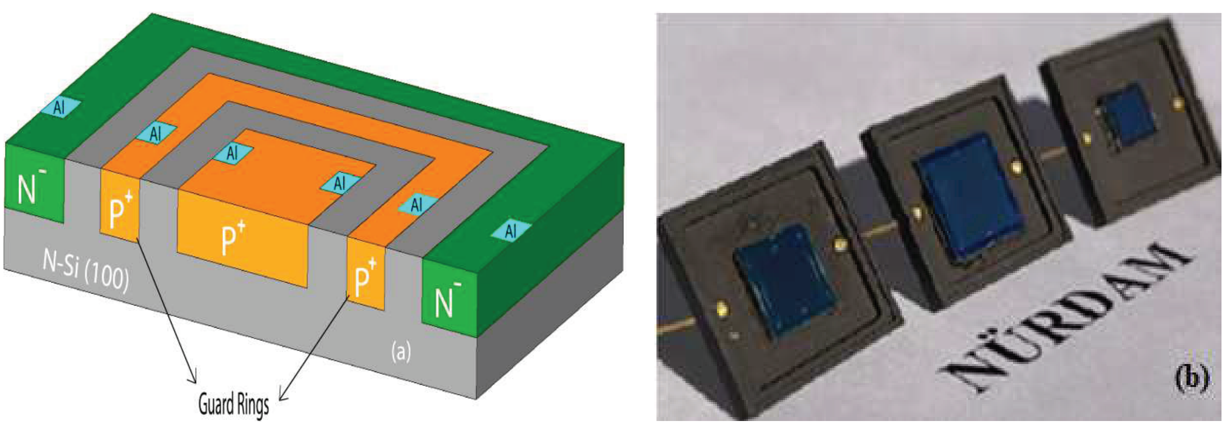

Figure 1. (a) 3D schematic of the fabricated Si PIN photodiodes and (b) photograph of the Si PIN photodiodes.

3. Results and discussion

The I-V measurements of all three fabricated Si-PIN photodiodes are illustrated in Figure 2. They were performed at room temperature in a dark environment. The dark current (I_{dc}) measurements are listed in the Table. As the applied reverse voltage increased, the I_{dc} increased until the voltage reached the breakdown voltage. The measured I_{dc} values are in good agreement with the mathematical model [11] that explains the dependency of the diffusion current to the active area of diodes and the current created in the depletion area. The orders of measured I_{dc} are consistent with those reported in [12] but higher when compared to the ones reported in [13] and [14]. The I_{dc} values of our measurements are possibly from tunneling effect and the active states in the I region as reported in [15]. As the applied reverse voltage is increased further to the breakdown voltage, the I_{dc} reaches its upper voltage dependence limit. This indicates that each fabricated Si-PIN photodiode may suffer from its own specific high voltage. The breakdown voltage (V_{br}) is determined from the voltage value corresponding to 10 μA for each Si-PIN photodiode (see Table). The active area dependency of V_{br} is associated with the penetration distance of the electric field.

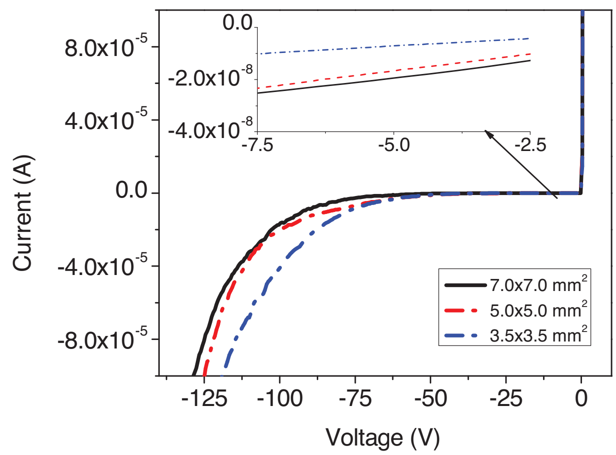

Figure 2. I-V characteristics of the Si-PIN photodiodes.

Table 1. Certain electrical parameters of the fabricated Si-PIN photodiodes

Active area (mm^2)	I_{dc} (at –5 V) (nA)	Breakdown Voltage (V_{br}) (at 10 μA) (V)	Capacitance (C) (at –5 V) (pF)	Doping concentration (N_I) ($\times 10^{12}$ cm^{-3})
7.0 × 7.0	–19.1	–93	61	1.78
5.0 × 5.0	–16.5	–84	41	2.42
3.5 × 3.5	–6.97	–77.5	23	3.45

Another crucial operational parameter is the C-V characteristic of Si-PIN photodiodes. The C-V measurements of three Si-PIN photodiodes are illustrated in Figure 3a. Small capacitance values are expected for high sensitivity of Si-PIN photodiodes and operational speed devices [16]. The capacitance values vs. reverse bias voltage of all three photodiodes dropped sharply between 0 V and –5 V initially. As the reverse bias voltage increased further, the C values decreased slightly (see Figure 3a). This indicates that the photodiodes proceed to full depletion region and work in full depletion mode at –5 V. The C values of photodiodes at the fully depleted region are listed in the Table. The obtained Si-PIN photodiode characteristics are consistent with those reported in [12]. The variations in C values in the Table are related to the active area of each Si-PIN photodiode.

In Figure 3b, the possible variations in the doping concentration (N_I), called electrical active states, are calculated by using the slope of the linear region of the inverse square of the depletion capacitance ($1/C^2$)

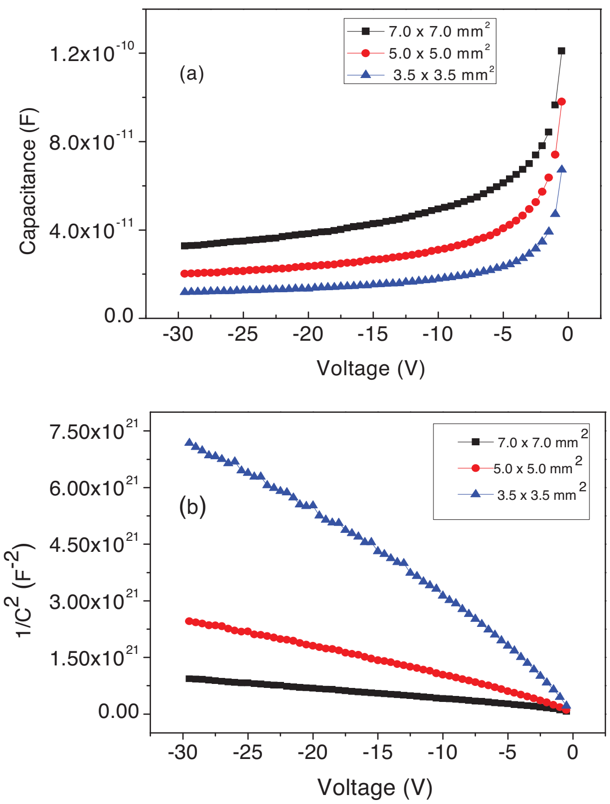

Figure 3. (a) C-V and (b) 1/ C^2 vs. V of Si-PIN photodiodes.

[17]. Obtained N_I values of photodiodes are listed in the Table. Ideally, it is expected that the N_I values are almost the same for similar processed samples. However, the observed variations in N_I values may be due to the inhomogeneity in the substrate surfaces and the diffusion of doped atoms towards the I region during the high-temperature fabrication process. The diffusion of doped atoms may form a possible transition between I and P/N regions. Hence, variations in N_I may contribute to the modulation of the I_{dc} and V_{br} under the applied reverse bias voltage.

The optical performance calculations of Si-PIN photodiodes have been performed via quantum efficiency (QE) measurements, which represent the number of carriers generated per incident photon by a photodiode. The QE of the photodiodes is strictly connected to incident light wavelength as well as applied reverse bias voltage and temperature [18]. It is expected that maximum spectral response (SR) and QE occur in a specific incident light wavelength, which almost corresponds to the bandgap of materials. The measured QE and SR are illustrated in Figures 4a and 4b, respectively. The QE of PIN photodiodes increases up to 66%, and a small decrease has been observed for the Si-PIN photodiode having 3.5 $\times$ 3.5 mm^2 active area. This slight QE decrease in the 3.5 $\times$ 3.5 active area Si-PIN photodiode is possibly due to the spot size nonuniformity measurements. The measured peak responsivity of all three photodiodes is 0.436 $\pm$ 1 A/W at 820 nm. All obtained values are consistent with the reported behavior of silicon at room temperature [14,19,20]. When the wavelengths are higher than 820 nm, the energy of incident photons is not enough to excite electrons from the valence band to conduction band, which decreases the generated electron density; consequently, the sensitivity of the device declines. On the other hand, for wavelengths lower than 820 nm, electron-hole recombination occurs at the surface due to the high photon absorption of silicon at higher incident photon energy. This process happens so fast that the photogenerated carriers cannot be collected by electrical circuitry [12,21,22].

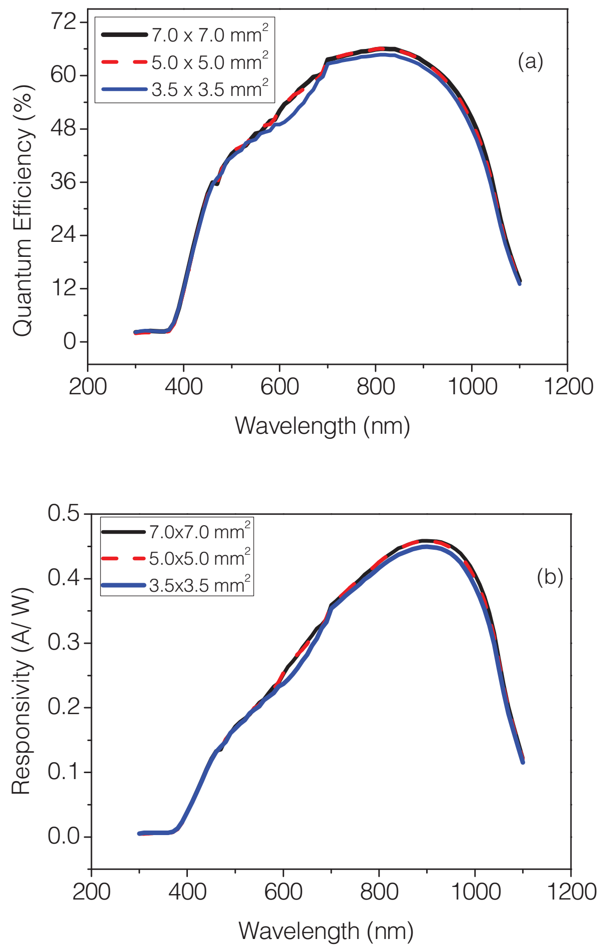

Figure 4. (a) Quantum efficiency and (b) spectral responsivity of three different active areas Si- PIN photodiodes.

4. Conclusion

In this study, Si-PIN photodiodes with three active areas have been fabricated and their electrical and operational characteristics have been specified. It has been observed that the PIN diodes reach full depletion mode at –5 V. I_{dc} is in the order of a few nanoamperes, while the capacitance of the devices is in the order of picofarads at –5 V. The calculated breakdown voltages are –93 V, –84 V, and –77.5 V for 7.0 $\times$ 7.0 mm^2, 5.0 $\times$ 5.0 mm^2, and 3.5 $\times$ 3.5 mm^2 active areas, respectively. In addition, the quantum efficiency of PIN diodes increases up to 66% and the peak responsivity of devices is 0.436 $\pm$ 1 A/W at 820 nm. In summary, although the capacitance characteristics are in good agreement with commercial Si-PIN photodiodes, the I_{dc} should be improved for commercial usage. They exhibit demanding performance for optoelectronic applications such as pulse light detection and bar code readers. In addition, they give some information to devise new generation PIN diodes with high performance.

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