Characteristics of Thermally-Annealed Homojunction Silicon Photodetector Prepared by Low-Pressure Plasma-Assisted Technique

Oday A. Hammadi

Department of Physics, College of Education, Al-Iraqia University, Baghdad, IRAQ

Abstract
In this work, the effect of thermal annealing on the characteristics of silicon homojunction photodetector was studied. This homojunction photodetector was fabricated by the plasma-induced etching of p-type silicon substrate and plasma sputtering of n-type silicon target in vacuum. The electrical and spectral characteristics of this photodetector were determined and optimized before and after annealing process. Maximum surface reflectance of 1.89 and 1.81%, maximum responsivity of 0.495 and 0.55 A/W, ideality factor of 1.80 and 1.99, maximum external quantum efficiency of 76 and 83.5 %, and built-in potential of 0.79 and 0.72V were obtained before and after annealing, respectively.

Keywords: Photodetectors; Homojunction; Spectral responsivity; Plasma-induced etching
Received: 15 January 2024; **Revised:** 10 March 2024r; **Accepted:** 17 March 2024; **Published:** 1 April 2024

1. Introduction

Homojunction is essentially a junction between the n and p-type portions of the same material formed by different impurity doping. The junction is termed as abrupt or graded, depending upon whether the impurity concentration in the material changes abruptly or gradually at the junction region [1]. When two layers of semiconductor materials of opposite carrier types are intimately joined, an exchange of charge carriers take place and Fermi level becomes continuous in both the layers. Electrons from n-type portion adjacent to the junction flow into the p-side while holes from p-type to n side and this flow is due to density gradient. Then there will be some uncompensated stationary charges forming a dipole array, leading to the barrier formation. This equalizes the Fermi levels and prevents further flow of charges to either side [2].

Silicon photodiodes are responsive to high-energy particles and photons and operate by absorption of photons or charged particles and generate a flow of current in an external circuit, proportional to the incident power. These devices can be used to detect the presence or absence of minute quantities of light with intensities in the range of 10^{-9}-10^{2} mW/cm^2 [3]. Silicon photodiodes are efficiently used in many applications, such as spectroscopy, photography, analytical instrumentation, optical position sensors, beam alignment, surface characterization, laser range finders, optical communications, and medical imaging instruments [4,5].

The photonic and optoelectronic devices based on silicon diodes still have their featured positions in their applications due to several reasons, among which the natural availability, ease fabrication and open technology are noticeably observed [6]. Despite the reasonably higher efficiencies achieved by similar devices (e.g., solar cells and photodetectors) fabricated from other semiconducting materials, the lower values of silicon devices can be compensated by their lower costs and higher reproducibility in correlation to the revolution in porous and nanocrystalline silicon structures [7,8].

Compared to the avalanche photodiodes, the silicon junction photodetectors have no internal gain but they are very fast and have very large bandwidths [9]. As well, silicon homojunctions are the fundamental structures of bipolar and MOS transistors, which represent the foundation of modern semiconductor electronics [10].

In the modern semiconducting materials technology, plasma processing techniques present very good candidates and alternatives for the conventional and expensive ones [11,12]. Construction and operation of plasma systems for semiconductor processing applications can be performed and optimized to reasonable degree. Such systems can be easily used for low cost and mass production of diverse structures and devices with very good quality [13].

In this work, a silicon homojunction is fabricated by plasma-assisted technique and characterized for photodetection applications. Also, the effect of thermal annealing on the characteristics of this homojunction is studied.

2. Experimental Part

A boron-doped p-type silicon wafer with orientation of <100>, electrical resistivity of 40-50 Ω.cm, diameter of 5 cm and thickness of 675 μm was used for the p-type side of the proposed homojunction. This wafer was etched by argon discharge plasma for 20 min and then heat treated for one hour at 150°C to get homogeneous rough layer of about 20 nm thick. The sample was then placed inside sputtering chamber to deposit an n-type silicon layer on its surface. This chamber was evacuated down to 0.001 mbar to prevent any active contaminants may reside inside from interact with the silicon samples [14]. The sputtering target was a phosphorous-doped n-type silicon wafer with orientation of <111>, electrical resistivity of 25-30 Ω.cm, diameter of 5 cm and thickness of 675 μm. The sputtering target was placed on the cathode while the p-type silicon substrate was placed on the anode and the inter-electrode distance was 4 cm. The sputtering plasma was generated by the electrical discharge of argon at pressure of 0.08 mbar, discharge voltage of 3.5 kV and discharge current of 45 mA. The sputtering time was 2 hours to form a 30 nm thick n-type silicon layer over the previously formed 20nm p-type silicon layer. The final sample formed on the p-type substrate was about 30nm thick n-Si/p-Si layer. In order to introduce the effect of thermal annealing on the characteristics of the fabricated structure, the final sample was gradually annealed for one hour at 20-320°C with a step of 5°C/min to induce the formation of homogeneous structure.

The electrical characterization of the fabricated homojunction includes the current-voltage and capacitance-voltage characteristics before and after thermal annealing process and determination of some parameters, such as ideality factor (n) and built-in potential (V_{bi}). The electrical measurements were carried out using a dc power supply 0-30 V, a Keithley 616 picoammeter and a Keithley 82 C-V system.

The optical characterization of the fabricated homojunction includes the measurements of reflectance from the surface, spectral responsivity and external quantum efficiency before and after thermal annealing process. The reflectance was measured by specular hemispherical method and the spectral responsivity was measured by using a pulsed xenon lamp, monochromator, bandpass filer, CCD array detector and data acquisition system. All optical measurements were carried out in the spectral range 350-1100nm.

3. Results and Discussion

Figure (1) shows the current-voltage (I-V) characteristics of the prepared silicon homojunction before and after thermal annealing process. It is clearly observed that these characteristics were slightly enhanced by thermal annealing as they are in accordance to the typical behavior of homojunction. As well, the ideality factor of the fabricated homojunction was increased from 1.80 to 1.99 after annealing. This enhancement can be attributed to the reduction in the saturation current, which is in turn related to the reduction in the charge carrier recombination.

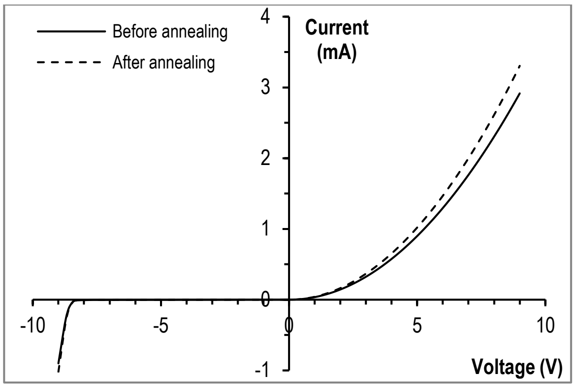

Fig. (1) The I-V characteristics of the fabricated homojunction before and after thermal annealing

Figure (2) shows the variation of inverse squared capacitance with the applied voltage (C^{-2}-V) for the fabricated homojunction before and after thermal annealing. The capacitance of the depletion layer of this homojunction was increased due to thermal annealing. This increase in the capacitance can be attributed to decrease in the built-in potential from 0.79 to 0.72 as the width of depletion layer is decreased because of the increasing recombination rate on both sides of this layer.

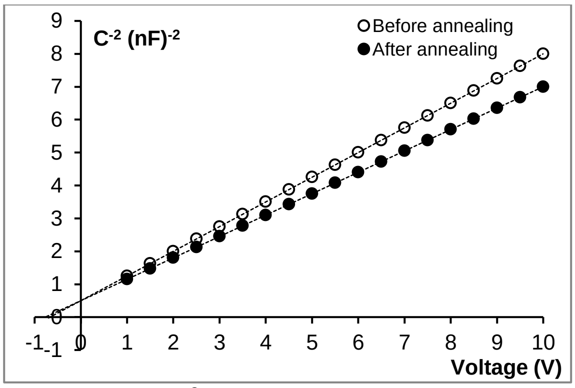

Fig. (2) The C^{-2}-V characteristics of the fabricated homojunction before and after thermal annealing. The built-in potential is determined to be 0.72V before and 0.79V after annealing

Figure (3) shows the effect of thermal annealing on the surface reflectance of the fabricated homojunction as it was reduced from 1.89 to 1.81% in the spectral range of 350-1100nm. Accordingly, the absorbance of this homojunction is supposed to increase by 0.08% due to this reduction in the surface reflectance and this enhancement in the absorption may lead to corresponding enhancement in the spectral response of the homojunction [15].

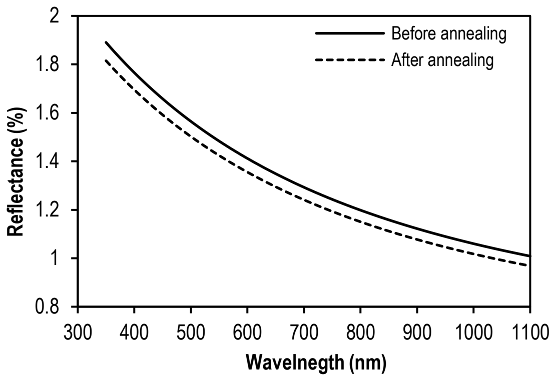

Fig. (3) Surface reflectance of the fabricated homojunction before and after thermal annealing

The spectral responsivity (R_λ) of the fabricated homojunction was measured in the range of 350-1100nm and presented in Fig. (4). The thermal annealing caused an enhancement in the spectral responsivity from 0.495 to 0.55 A/W as the annealing process made the homogeneity of the sensitive layer (n-Si/p-Si) structure better to respond to the incident radiation.

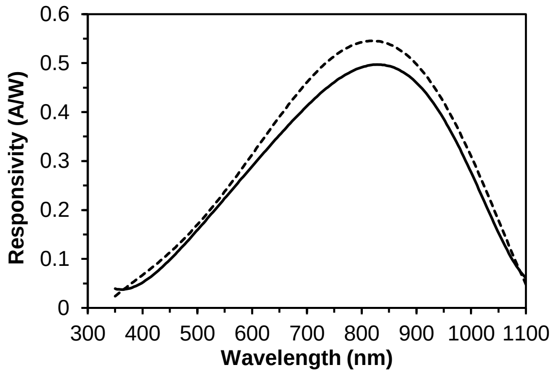

Fig. (4) Spectral responsivity of the fabricated homojunction before and after thermal annealing

As the fabricated homojunction can be employed in many applications of photonics and optoelectronics, the performance of this device should be assessed by introducing its efficiency. Therefore, the external quantum efficiency (EQE) of the fabricated homojunction was determined as a function of the wavelength of incident radiation before and after thermal annealing and was enhanced from 76 to 83.5%, respectively, as shown in Fig. (5).

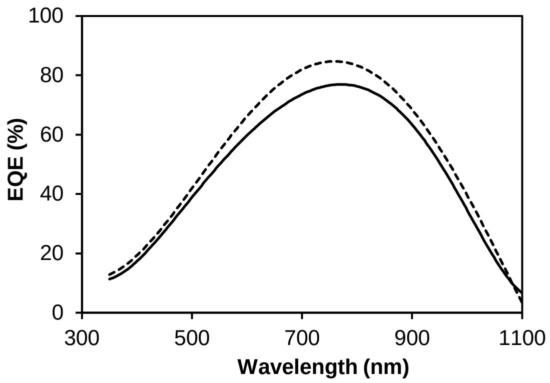

Fig. (5) Quantum efficiency of the fabricated homojucntion photodetector before and after thermal annealing

4. Conclusions

According to the results obtained from this work, the thermal annealing has reasonable effects on the characteristics of silicon homojunction photodetector fabricated by the plasma-induced etching of p-type silicon substrate and plasma sputtering of n-type silicon target in vacuum. Due to thermal annealing, the maximum surface reflectance and built-in potential of this photodetector were noticeably decreased while the maximum responsivity, the ideality factor and the maximum external quantum efficiency were increased. The fabrication procedure used in this work is reasonably new, low cost, easily controlled and reliable.

References

[1] F.J. Al-Maliki, O.A. Hammadi and E.A. Al-Oubidy, "Optimization of Rutile/Anatase Ratio in Titanium Dioxide Nanostructures prepared by DC Magnetron Sputtering Technique", Iraqi J. Sci., 60 (2019) 91-98.

[2] J. Dresner and F.V. Shallcross, "Crystallinity and Electronic Properties of Evaporated CdS Films", J. Appl. Phys., 34(8) (1963) 2390.

[3] Oday A. Hamadi, Khaled Z. Yahiya, "Optical and electrical properties of selenium-antimony heterojunction formed on silicon substrate", Sharjah Univ. J. Pure Appl. Sci. (UoS J PAS), 4(2), 2007, 1-11.

[4] Oday A. Hamadi, Ban A.M. Bader, Afnan K. Yousif, "Electrical Characteristics of Silicon p-n Junction Solar Cells Produced by Plasma-Assisted Matrix Etching Technique", Eng. Technol. J., 28, 2008, 995-1001.

[5] O.A. Hammadi, F.J. Al-Maliki and E.A. Al-Oubidy, "Photocatalytic Activity of Nitrogen-Doped Titanium Dioxide Nanostructures Synthesized by DC Reactive Magnetron Sputtering Technique", Nonlinear Opt. Quantum Opt., 51 (1-2) (2019) 67-78.

[6] Afnan K. Yousif, Oday A. Hamadi, "Plasma-Induced Etching of Silicon Surfaces", Bulg. J. Phys., 35(3), 2008, 191-197.

[7] Oday A. Hamadi, "Characteristics of CdO-Si Heterostructure Produced by Plasma-Induced Bonding Technique", Proc. IMechE, Part L, J. Mater.: Design and Applications, 222, 2008, 65-71, DOI: 10.1243/14644207JMDA56.

[8] Oday A. Hamadi, "Effect of Annealing on the Electrical Characteristics of CdO-Si Heterostructure Produced by Plasma-Induced Bonding Technique", Iraqi J. Appl. Phys. (IJAP), 4(3), 2008, 34-37.

[9] Aseel A.K. Hadi, Oday A. Hamadi, "Optoelectronic Characteristics of As-doped Silicon Photodetectors Produced by LID Technique", Iraqi J. Appl. Phys. Lett. (IJAPLett), 1(2), 2008, 23-26.

[10] Oday A. Hammadi, "Photovoltaic Properties of Thermally-Grown Selenium-Doped Silicon Photodiodes for Infrared Detection Applications", Photonic Sensors, 5(2), 2015, 152-158, DOI: 10.1007/s13320-015-0241-4

[11] Oday A. Hammadi, Mohammed K. Khalaf, Firas J. Kadhim, "Silicon Nitride Nanostructures Prepared by Reactive Sputtering Using Closed-Field Unbalanced Dual Magnetrons", Proc. IMechE, Part L, J. Mater.: Design and Applications, Accepted for publication: July 2015, DOI: 10.1177/1464420715601151.

[12] Oday A. Hammadi, Mohammed K. Khalaf, Firas J. Kadhim, "Fabrication of UV Photodetector from Nickel Oxide Nanoparticles Deposited on Silicon Substrate by Closed-Field Unbalanced Dual Magnetron Sputtering Techniques", Opt. Quantum Electron., 47(12), 2015, 3805-3813. DOI: 10.1007/s11082-015-0247-6

[13] Oday A. Hammadi, Mohammed K. Khalaf, Firas J. Kadhim, "Fabrication and Characterization of UV Photodetectors Based on Silicon Nitride Nanostructures Prepared by Magnetron Sputtering", Proc. IMechE, Part N, J. Nanoeng. Nanosys., accepted for publication: September 3rd 2015.

[14] O.A. Hammadi, M.K. Khalaf, F.J. Kadhim, B.T. Chiad, "Operation Characteristics of a Closed-Field Unbalanced Dual-Magnetrons Plasma Sputtering System", Bulg. J. Phys., 41(1) (2014) 24-33.

[15] O.A. Hammadi, "Production of Nanopowders from Physical Vapor Deposited Films on Nonmetallic Substrates by Conjunctional Freezing-Assisted Ultrasonic Extraction Method", Proc. IMechE, Part N, J. Nanomater. Nanoeng. Nanosys., 232(4) (2018) 135-140.

