Current-Voltage Characteristics of Silicon Nitride Nanoparticles Embedded in Porous Silicon Matrix

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Abstract
In this work, the effect of thermal annealing on the characteristics of heterojunction fabricated from silicon nitride nanoparticles embedded in porous silicon matrix formed on silicon substrate was studied. The porous layer was formed by photoelectrochemical etching method. The electrical and spectral characteristics of this photodetector were determined and optimized before and after annealing process. Maximum surface reflectance of 1.81 and 1.73%, maximum responsivity of 0.495 and 0.55 A/W, ideality factor of 1.72 and 1.81, 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: Porous silicon; Silicon nitride; Electrical characteristics; Heterojunctions
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1. Introduction

Heterojunctions have their positions in modern technologies since their first invention in the 20th century. As well, they have witnessed recently drastic progresses as promising devices for the future technologies. The fabrication of the heterojunctions on a porous silicon layer formed on the surface of a silicon substrate is an actual trend nowadays due to the simple technology, low production cost, effectiveness employment and good possibility to develop and modify their characteristics to meet the accurate practical requirements.

Silicon nitride (Si_3N_4) is a polymorphic material, presenting three crystallographic modifications designated as α, β and γ phases. The α and β phases can be produced under normal nitrogen pressure and have great importance in the production of advanced ceramics, while the recently discovered γ-Si_3N_4 can be formed only at extremely high pressures and has no practical use yet [1-3].

In a simple chemical picture, chemical bonding in α-Si_3N_4 and β-Si_3N_4 is due to the overlap of the sp^3 hybrid orbitals of silicon atoms with the sp^2 hybrid orbitals of the nitrogen atoms [4]. Each nitrogen atom has a remaining p nonbonding atomic orbital that is occupied by a single pair of electrons [5,6].

The α-Si_3N_4 and β-Si_3N_4 have trigonal and hexagonal structures, respectively, which are built up by corner-sharing SiN_4 tetrahedra. The cubic γ-Si_3N_4 is often designated as "c" modification in the literature, in analogy with the cubic modification of boron nitride (c-BN) [7].

The basic unit of Si_3N_4 is the SiN_4 tetrahedron. A silicon atom is located at the center of a tetrahedron, with four nitrogen atoms at each corner. The SiN_4 tetrahedra are joined by sharing corners in such a manner that each nitrogen atom is common to three tetrahedra. Thus, nitrogen has three silicon atoms as neighbors [8,9]. The structural difference between α-Si_3N_4 and β-Si_3N_4 can be explained by different arrangements of Si-N layers. The basic units are linked together to form wrinkled or puckered six-membered rings which surround large holes. These basal planes form the building blocks for the structures of α-Si_3N_4 and β-Si_3N_4 [10,11].

Silicon nitride (Si_3N_4) has the strongest covalent bond properties next to silicon carbide. Its optical and electrical properties at nanoscale are encouraging to fabricate photonic devices by depositing nano films of Si_3N_4 on semiconducting substrates [12]. At room temperature, it has high resistivity (~10^{13} Ω.cm), dielectric constant of 7.0 and wide energy gap of 5.06-5.25 eV [13,14].

Silicon nitride (Si_xN_y) thin films are common insulators in the semiconductor industry for the passivation of electronic devices because they form excellent protective barriers against the diffusion of water, sodium and potassium ions found in biological environments [15]. The Young's modulus of silicon nitride thin film is higher than that of silicon and its intrinsic stress can be controlled by the specifics of the deposition process. Silicon nitride is an effective masking material in many alkaline etch solutions [16].

In this work, the effect of thermal annealing on the characteristics of heterojunction fabricated from silicon nitride nanoparticles embedded in porous silicon matrix formed on silicon substrate is studied. The porous layer is formed by photoelectrochemical etching method. The electrical and spectral characteristics of this photodetector are determined and optimized before and after annealing process.

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 to form the porous silicon layer on its surface. The silicon substrate was cut into square pieces (1.5x1.5cm^2) and washed with ethanol and distilled water before been used. The sample was immersed in HF:ethanol solution (1:1) and subjected to laser irradiation by a 630nm diode laser of 5mW power. The applied voltage on the electrodes of the PECE cell was ranging in 0-30V as the current density was 30-35mA/cm^2. The etching time was controlled and different times were considered (15, 30, 45, 60, and 75min).

The electrical characterization of the fabricated heterojunctions includes the current-voltage and capacitance-voltage characteristics before and after a

Thermal annealing at 100°C inside an electrical over, 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.

3. Results and Discussion

Figure (1) shows the current-voltage (I-V) characteristics of the prepared silicon heterojunction 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 heterojunction. As well, the ideality factor of the fabricated heterojunction was increased from 1.72 to 1.81 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.

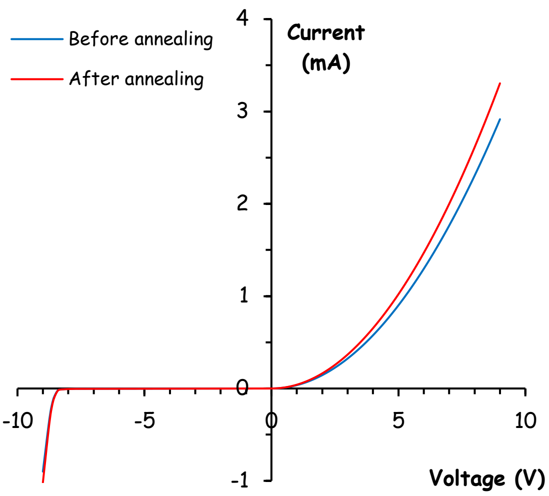

Fig. (1) The I-V characteristics of the fabricated heterojunction before and after thermal annealing

Figure (2) shows the variation of inverse squared capacitance with the applied voltage (C^{-2}-V) for the fabricated heterojunction before and after thermal annealing. The capacitance of the depletion layer of this heterojunction was increased due to thermal annealing. This increase in the capacitance can be attributed to decrease in the built-in potential from 0.63 to 0.68 as the width of depletion layer is decreased because of the increasing recombination rate on both sides of this layer.

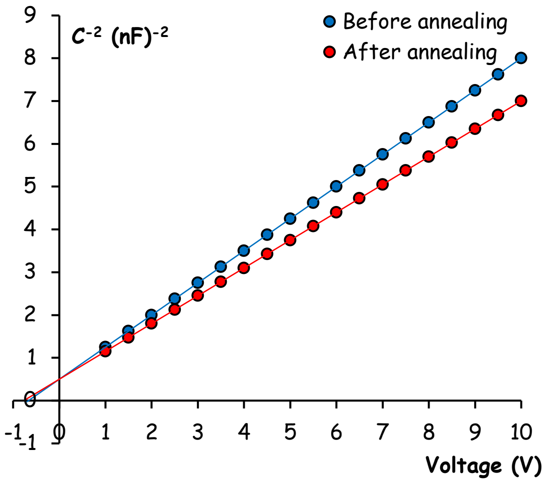

Fig. (2) The C^{-2}-V characteristics of the fabricated heterojunction before and after thermal annealing. The built-in potential is determined to be 0.72V before and 0.79V after annealing

Figure (3) shows the effect of thermal annealing on the surface reflectance of the fabricated heterojunction as it was reduced from 1.81 to 1.73% in the spectral range of 350-1100nm. Accordingly, the absorbance of this heterojunction 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 heterojunction [17,18].

The spectral responsivity (R_λ) of the fabricated heterojunction 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 (Si_3N_4/PSi) structure better to respond to the incident radiation.

As the fabricated heterojunction 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 heterojunction 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).

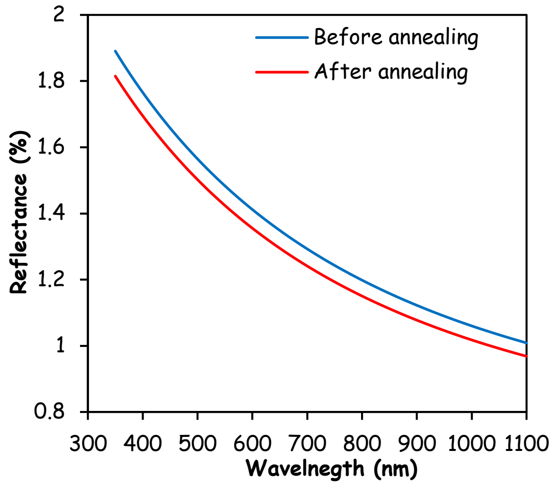

Fig. (3) Surface reflectance of the fabricated heterojunction before and after thermal annealing

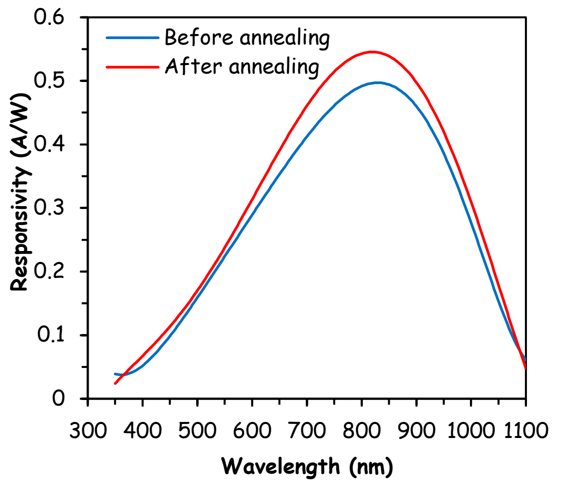

Fig. (4) Spectral responsivity of the fabricated heterojunction before and after thermal annealing

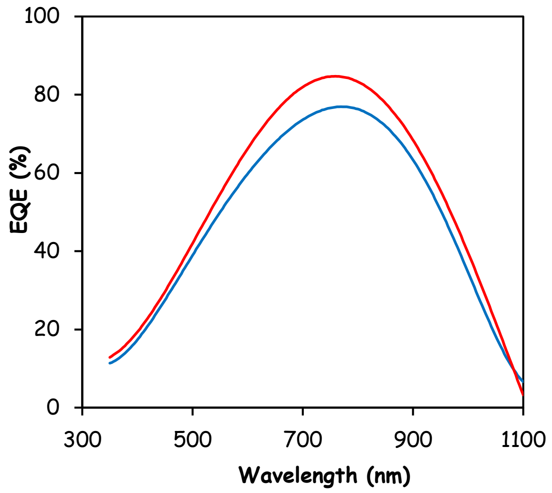

Fig. (5) Quantum efficiency of the fabricated heterojunction photodetector before and after thermal annealing

4. Conclusions

According to the results obtained from this work, the thermal annealing has reasonable effects on the characteristics of heterojunction fabricated by embedding silicon nitride nanoparticles in porous silicon matrix prepared by the photoelectrochemical etching method on silicon substrate. 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.

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