Incorporation of Titanium Dioxide Nanoparticles into Porous Gallium Arsenide Structure for Photodetection Devices

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Abstract

In this work, titanium dioxide (TiO_2) nanoparticles were incorporated in porous GaAs structure to fabricate photodetector of wide spectral responsivity (from UV to near-infrared regions). The porous structure was formed on gallium arsenide (GaAs) substrate by electrochemical etching. The TiO_2 nanoparticles were slowly dropped onto the porous structure in order to ensure filling the pores with nanoparticles. A maximum responsivity of 1 A/W and detectivity of 2.795×10^{12} Jones were achieved at 600 nm.

Keywords*:* Photodetectors; Heterojunction devices; Titanium dioxide; Gallium arsenide
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1. Introduction

Photodetectors still represent the main devices to convert light signals into electric signals to be measured and processed. They cannot be replaced in various applications such as ultrashort optical communications, medical imaging, environmental sensing, security systems and solar cells [1-5]. Researchers are working hard to achieve an ideal balance between high responsivity, fast response, quantum efficiency, and wide functional spectrum, in addition to other parameters, such as cots, stability and reliability [6-8].

Due to the quantum confinement and high surface area, nanomaterials provide superior tools to enhance light absorption, charge transfer, and invent new features throughout structure and interface engineering [9]. Amongst the most interested nanomaterials, titanium dioxide (TiO_2) is premium due to chemical abundance, thermal and chemical stability, wide controlled energy bandgap (3.0-3.2 eV), and unique photoelectrochemical (PEC) characteristics, which made it optimum candidate for applications based on UV and visible light [10]. However, its wide energy bandgap limits its performance in the near-infrared (NIR) region and longer wavelengths, which are crucial in communications and sensing [11]. Therefore, the combination of TiO_2 with other semiconductors with narrower bandgaps represents a promising strategy to enhance the absorption over wider spectrum, and to facilitate separation of photo-generated electron-hole pairs too [12]. One of the III-V semiconductors is gallium arsenide (GaAs), which has a direct energy bandgap of 1.42 eV at room temperature, can effectively absorb light in the visible and NIR regions in addition to high electron mobility [13,14]. These features are reasonably enhanced when porous GaAs is used as the electrochemical or chemical etching create a complex network of nanopores within the material that leads to a drastic increase in the effective surface area (may reach to several hundred larger than the flat surface) [15]. As well, the optical properties are enhanced via light scattering and trapping, surface reflectance reduction, and forming 3D extended mechanical structure to host and link other nanomaterials [16].

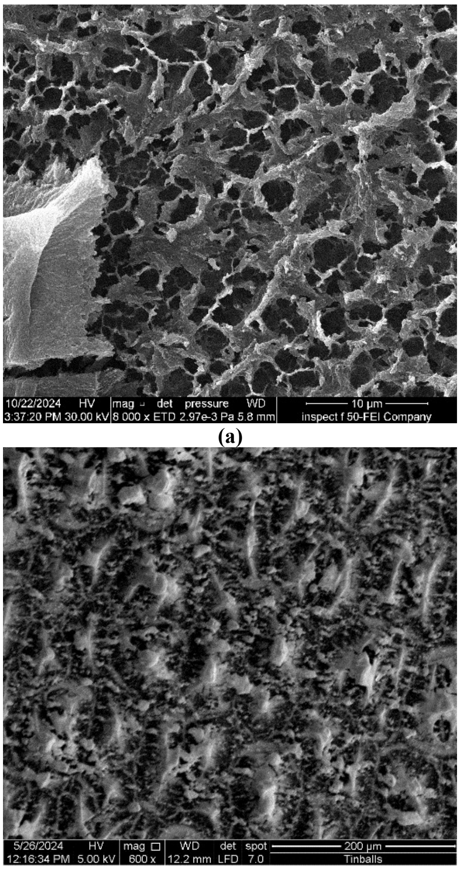
The main operation mechanism of the TiO_2/GaAs photodetector depends on the p-n heterojunction formed at the interface between two materials as the absorption of photons with appropriate energy results in electron-hole pair generation [17]. Due to the band bending as a consequence of the difference between Fermi levels at the interface, electrons and holes are selectively guided through the junction, effectively separated, and hence their recombination is prevented or minimized. Accordingly, a photocurrent is generated and measured in the external circuit [18]. The porous nanostructure shows additional features as it reduces the charge transfer paths towards the electrodes due to the nanoscale dimensions of the pore walls, which shortens the response time and enhance the collection efficiency [19]. Furthermore, surface and interface engineering can lead to phenomena such as trap-assisted charge transport or tunneling those affect the current-potential (I-V) characteristics of the detector [20].

Optical properties (mainly absorption coefficient and reflectance) of the heterojunction are sophisticatedly determined by size and concentration of TiO_2 nanoparticles, pore diameter and porosity of GaAs substrate, and deposition method [21]. Therefore, the enhancement of these parameters allows fine control of spectral responsivity, quantum efficiency, and response time of the photodetector [22].

This letter aims to explore the optoelectronic performance of photodetectors fabricated from TiO_2 nanoparticles deposited on the porous surface of p-type GaAs substrate to form p-n heterojunctions.

2. Experimental Part

A layer of porous structure was prepared on the surface of p-type GaAs substrate by electrochemical etching inside an electrolytic cell containing the GaAs substrate as the anode and a platinum wire as the cathode. Figure (1) shows the field-emission scanning electron microscope (FE-SEM) images of the prepared porous structure and TiO_2 nanoparticles incorporated into this porous structure.



(a)

(b)

Fig. (1) FE-SEM images of (a) porous GaAs structure prepared by electrochemical etching, and (b) TiO_2 nanoparticles

The electrolyte was prepared by mixing equal volumes of (1:1) of diluted hydrochloric acid (HCl) and methanol. The etching process was carried out in dark to avoid the undesired photoelectric effects. A dc voltage of 15 V was applied between the electrodes to produce dc current of 25 mA to produce localized oxidation and degeneration on active sites on the GaAs surface and hence create a porous nanostructure. Parameters such as electrolyte concentration, applied voltage, current density, and etching time were optimized to control the pore morphology (i.e., diameter, depth, and density). After completing the etching process, the sample was carefully washed with ethanol and deionized water to remove the electrolytic residuals, dried with nitrogen gas, and then transferred to the stage of depositing TiO_2 nanoparticles on the prepared porous structure. These nanoparticles were slowly dropped and left to fill the pores and dry before dropping the next drop. This was repeated 5 times to deposit a TiO_2 nanoparticles layer of 150 nm thickness. Figure (1b) shows the porous GaAs surface covered with TiO_2 nanoparticles, while figure (2) shows schematically the structure of the fabricated heterojunction photodetectors.

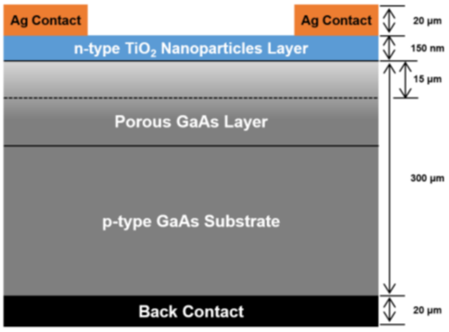


Fig. (2) Schematic diagram of the TiO_2NPs/P-GaAs heterojunction photodetector fabricated in this work

3. Results and Discussion

Figure (3) shows the spectral responsivity of the fabricated photodetector as a function wavelength in the spectral range 200-1000 nm. The photodetector shows very weak responsivity at wavelengths 200-250 nm, gradually increasing within 275-300 nm, and approximately linearly increasing beyond 325 nm. The spectral responsivity has increased from 0.05 A/W at 275 nm to 0.88 A/W at 500 nm. This increase is attributed to the efficiency of charge carrier generation within the TiO_2 layer (wide bandgap material) due to the absorption of high-energy photons. A saturation and steady state is reached at ~525 nm before the peak value of 1 A/W at 600 nm. A slight decrease in the spectral responsivity is observed within 625-650 nm due to the role of the narrow bandgap GaAs material, which efficiently absorbs the photons in the visible region. Beyond 650 nm, the spectral responsivity linearly decreases to reach zero at 975 nm as the photons have low energies to generate charge carriers. This curve combines the sensitivity of TiO_2 in the UV region and stability and efficiency of GaAs at longer wavelengths as TiO_2

plays the role of window and primitive generator of electrons whereas GaAs absorbs most incident photons to ensure high quantum efficiency. This device can be successfully employed in advanced and integrated photonic sensing systems.

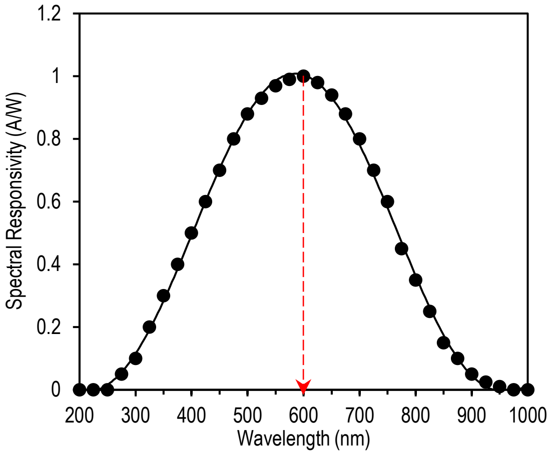


Fig. (3) Variation of spectral responsivity of the fabricated photodetector with wavelength

Figure (4) shows the variation of specific detectivity of the fabricated photodetector as a function wavelength in the spectral range 200-1000 nm. The maximum detectivity is achieved within a limited spectral range as a result of synergetic effects of both materials (TiO_2 and GaAs). The specific detectivity of the photodetector is approximately zero within 200-250 nm, then increases continuously at longer wavelengths. This enhancement is attributed to the enhanced signal-to-noise ratio (SNR) as TiO_2 starts to absorb short-wavelength photons positively in the UV region. Again, the optimum photodetector operation region is 550-650 nm with a maximum value of about 2.795×10^{12} Jones at 600 nm. The specific detectivity rapidly decreases beyond 700 nm to reach zero at 975 nm due to the edge determined by GaAs bandgap.

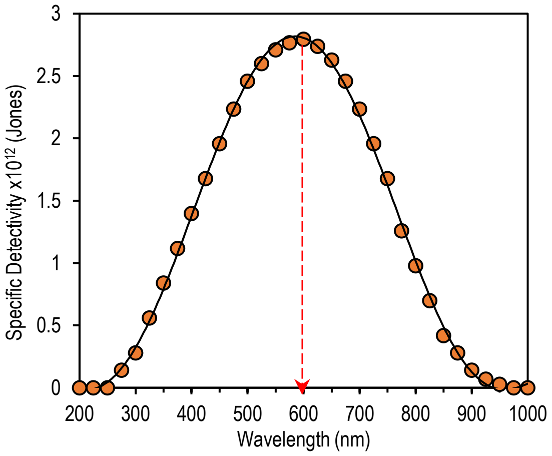


Fig. (4) Variation of specific detectivity of the fabricated photodetector with wavelength

4. Conclusion

In conclusion, the incorporation of TiO_2 nanoparticles into porous GaAs structure can be successfully employed in fabrication of heterojunction photodetectors. The fabricated device showed maximum spectral responsivity of 1 A/W and maximum specific detectivity of 2.795×10^{12} Jones at 600 nm. These results are attributed to the integrated features of p-n junction, whose TiO_2 side absorbs photons of high energies in the UV region, while the GaAs side absorbs photons in the visible and NIR regions.

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