Effect of Intermediate Layer Surface Condition on Photoresponse of Multilayer GaAs-based Devices

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Abstract

In this work, the effect of surface roughness of the active layer in a GaAs-based multilayer structure on the Photoresponse of this structure is introduced and analyzed. Results showed that the surface condition of the active layer of p^+-GaAs nanostructured layer in a GaAs-based multilayer structure has a powerful effect on the Photoresponse of such structures. The surface roughness of the active p^+-GaAs nanostructured layer was modified by varying the evaporation power used to prepare this layer.

Keywords: Silicon nitride; Thin films; Reactive sputtering; Nanostructures

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1. Introduction

Gallium arsenide (GaAs)-based photonics play a pivotal role in modern optoelectronic technologies due to their excellent optical and electronic properties [1]. GaAs offers a direct bandgap, enabling efficient light emission and absorption, making it ideal for devices such as lasers, photodetectors, and light-emitting diodes (LEDs) [2]. Its high electron mobility and versatility in forming heterostructures further enhance performance in photonic circuits [3,4]. Applications span telecommunications, where GaAs lasers drive high-speed optical data transmission, to sensing technologies in LiDAR and medical imaging [5]. Additionally, GaAs-based photonics are integral to quantum technologies, enabling single-photon sources for quantum communication and computing [6]. Their integration with silicon photonics ensures future scalability.

Surface roughness of the active layer significantly affects the performance of photonic devices [7]. It can cause scattering losses, reducing optical efficiency and degrading the device's overall performance. In lasers, rough surfaces increase threshold current and lower output power due to enhanced nonradiative recombination [8,9]. In photodetectors, surface irregularities can lead to increased dark currents and reduced responsivity. Surface roughness also impacts coupling efficiency in waveguides and optical cavities, disrupting light confinement and propagation [10-12]. To mitigate these effects, precise fabrication techniques like molecular beam epitaxy (MBE) or chemical vapor deposition (CVD) are employed to achieve smooth surfaces, enhancing device reliability and efficiency [13,14].

Modifying the surface roughness of thin films is crucial for optimizing their performance in photonic and electronic devices [15,16]. Techniques like chemical mechanical polishing (CMP) smoothen surfaces by combining mechanical abrasion with chemical etching [17]. Thermal annealing redistributes material at the atomic level, reducing surface irregularities [18]. Ion beam smoothing, involving low-energy ion bombardment, removes asperities while maintaining film integrity [19]. Atomic layer deposition (ALD) and molecular beam epitaxy (MBE) enable layer-by-layer growth with atomic precision, inherently reducing roughness [20,21]. Post-deposition treatments like plasma etching or wet chemical etching selectively polish films. Advanced approaches, such as laser-induced melting, can also create ultra-smooth surfaces effectively [22].

In this work, the effect of surface roughness of the active layer in a GaAs-based multilayer structure on the Photoresponse of this structure is introduced and analyzed.

2. Experimental Part

The fabrication of multilayer structures on a GaAs substrate using the thermal evaporation method is a widely employed technique in photonics and optoelectronics. Thermal evaporation involves the deposition of thin films by heating source materials in a vacuum chamber until they vaporize and condense onto a substrate, such as GaAs. This method ensures precise control over film thickness and composition, which is crucial for multilayer structures (Fig. 1).

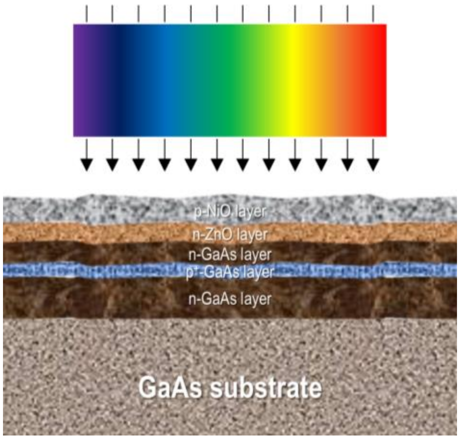


Fig. (1) Multilayer structure fabricated on GaAs substrate for Photoresponse applications

In a typical experiment, the GaAs substrate is first cleaned thoroughly to remove contaminants and native oxides using chemical cleaning processes, such as etching with HCl or ammonium hydroxide solutions. The cleaned substrate is then mounted inside the vacuum chamber, which is evacuated to achieve high vacuum conditions (~10^{-6} to 10^{-7} Torr).

Source materials, such as metals or dielectrics, are placed in crucibles and heated using resistive or electron beam heating. As the material vaporizes, it condenses uniformly on the substrate, forming the desired thin film. For multilayer structures, sequential evaporation of different materials is performed, with precise control over deposition rates and thickness using quartz crystal microbalances.

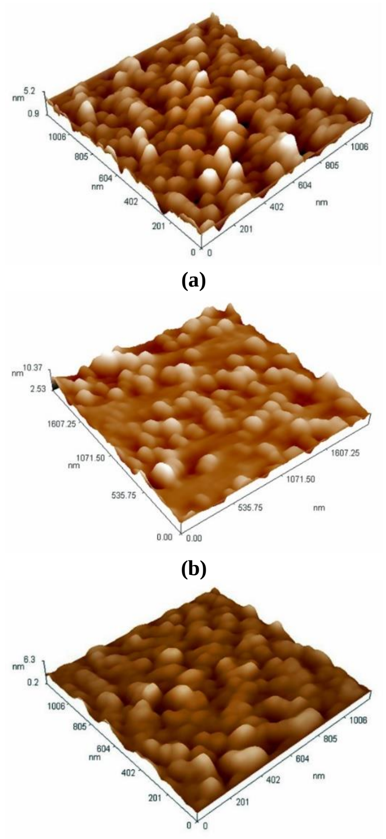
The resulting multilayer structure is characterized using techniques like atomic force microscopy (AFM) for surface morphology, X-ray diffraction (XRD) for crystallinity, and spectrophotometry for optical properties, ensuring quality and performance.

Structural tests such as XRD (Bruker, 1.54.5Å CuKα radiation), SEM (TESCAN Vega EasyProbe), AFM and SPM (Angstrom AA3000 SPM), and FTIR (Shimadzu FTIR-8400S), were performed on the prepared samples to introduce the structural properties of the silicon nitride nanostructures prepared in this work.

3. Results and Discussion

As shown in Fig. (2), the AFM images shows that the surface roughness of the prepared p^+-GaAs nanostructured layer was higher for the samples prepared at evaporation power of 250 W as the average roughness was 0.77 nm and the R.M.S roughness was 1.05 nm. These values were lower for the samples prepared at smaller and larger distances. However, the distribution of grains over the surface was noticeably much uniform for the sample prepared at evaporation power of 500 W when compared to those prepared at larger powers. This may be attributed to the spatial disturbance effects at larger distances. When working to produce such nanostructures, we look for higher ratio of surface area to volume in order to benefit from this parameter in photonic and tribology applications. Figure (3) shows the granularity cumulation distribution chart of the p^+-GaAs nanostructured layer prepared at evaporation power of 750 W. The average diameter is 89.13 nm.

Figure (4) shows the photoresponsivity as a function of wavelength of the fabricated structures with the active layer (p^+-GaAs nanostructured layer) prepared at different evaporation powers. The structure containing the p^+-GaAs nanostructured layer prepared at evaporation power of 250W shows maximum responsivity of 0.85 A/W at 645 nm. This maximum was increased to 0.865 A/W for the structure containing p^+-GaAs nanostructured layer prepared at evaporation power of 500W as the peak is shifted to 650nm. Also, the peak is shifted to 665nm with maximum responsivity of 0.88 A/W for the structure containing p^+-GaAs nanostructured layer prepared at evaporation power of 750W.



(a)

(b)

(c)

Fig. (2) AFM results of the p^+-GaAs nanostructured layer prepared at evaporation power of (a) 250 W, (b) 500 W and (c) 750 W

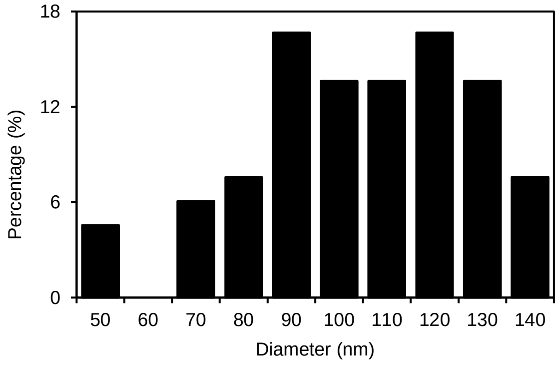
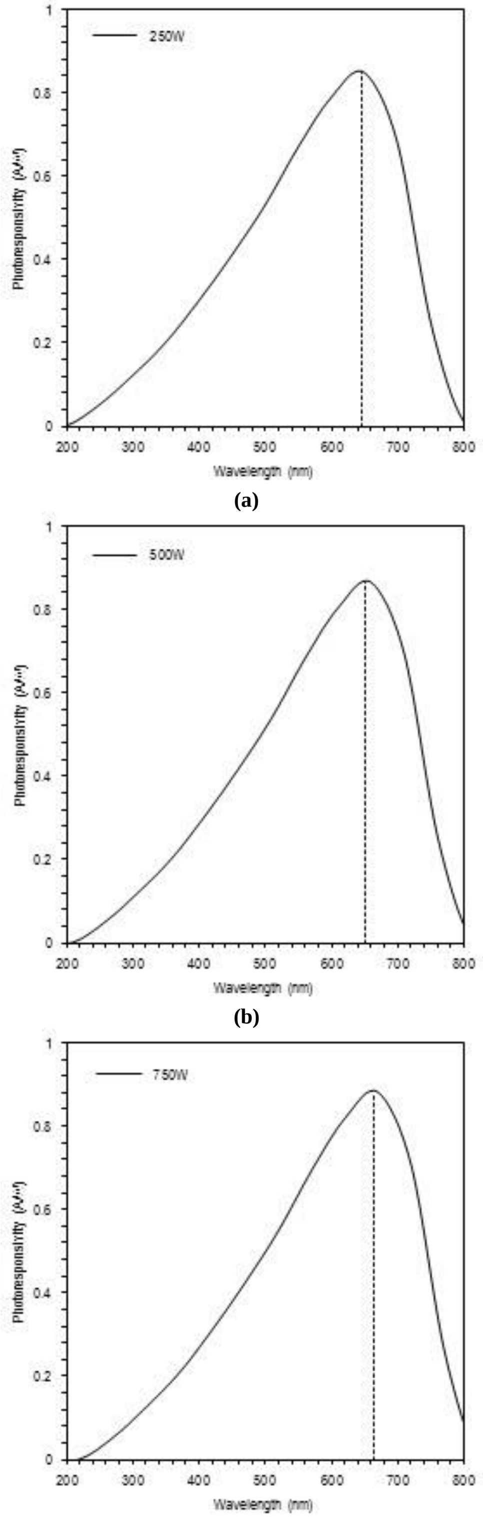


Fig. (3) Granularity accumulation distribution chart of the p^+-GaAs nanostructured layer prepared at evaporation power of 750 W



(a)

(b)

(c)

Fig. (4) Photoresponsivity of the GaAs-based multilayer structures containing p^+-GaAs nanostructured layer prepared at evaporation power of (a) 250 W, (b) 500 W and (c) 750 W

4. Conclusions

Results showed that the surface condition of the active layer of p^+-GaAs nanostructured layer in a GaAs-based multilayer structure has a powerful effect on the Photoresponse of such structures. The surface roughness of the active p^+-GaAs nanostructured layer was modified by varying the evaporation power used to prepare this layer.

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