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Morphological and Optical Studies of GaN/P-Si Nanostructure Using Pulsed Laser Deposition Method

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ABSTRACT

This article discusses the successful deposition of gallium nitride (GaN) thin films on porous silicon (P-Si) substrates using pulsed laser deposition (PLD) techniques. The primary objective is to develop a high-efficiency GaN/P-Si heterojunction photodetector. Porous silicon was prepared through a photo-electrochemical etching process, resulting in a high-surface-area template that enhances both the adhesion of the GaN film and its optoelectronic properties. Surface morphology analysis, conducted using atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM), revealed a well-defined nanostructured GaN surface characterized by moderate roughness and a densely packed arrangement of nanoparticles. These features optimize photon absorption and facilitate efficient charge carrier transport. Energy-dispersive X-ray spectroscopy (EDS) further confirmed the successful integration of materials through elemental composition analysis.

Keywords: *Gallium Nitride, Porous silicon, Photoelectrochemical etching, Pulsed laser deposition*

1. INTRODUCTION

Gallium nitride (GaN) is a wide-bandgap semiconductor (~3.4 eV). It has been the subject of much attention for its application in high-power electronics, ultraviolet photodetectors, and light-emitting devices due to its high thermal stability, high breakdown voltage, and superior radiation resistance [1-5]. However, the direct growth of GaN films typically needs to be performed on expensive and lattice-matched substrates such as sapphire or silicon carbide, which are not ideal for scalability and integration with conventional silicon-based microelectronics. Porous silicon (P-Si) has emerged as a promising alternative substrate for gallium nitride (GaN) growth [6-11]. The large surface area of the substrate, tunable porosity, and compatibility with standard silicon processing methods provide many advantages, including reduced lattice mismatch stress, increased mechanical support, and enhanced light scattering properties. P-Si is a suitable substrate for optoelectronic device integration, especially for photodetection and sensing applications [12-16]. Among the various techniques for GaN deposition, pulsed laser deposition (PLD) offers several advantages for forming thin films. PLD provides precise control over film thickness, stoichiometry, and microstructure, while functioning at relatively low substrate temperatures compared to methods like molecular beam epitaxy or metal-organic vapor phase epitaxy [17-20]. Furthermore, PLD allows for the fabrication of high-purity GaN films without the need for complex buffer layers. Previous research has successfully demonstrated the growth of GaN on phosphorus-doped silicon (P-Si) using PLD, resulting in favorable optical and structural properties, including pronounced photoluminescence peaks and robust interfacial adhesion [21-25]. However, further investigation is necessary to elucidate these heterostructures' morphological homogeneity, elemental distribution, and optical emission characteristics, particularly under optimized low-temperature growth conditions. In this study, we report the growth of GaN thin films on photo-electrochemically etched P-Si substrates using PLD at 300 °C. We systematically evaluate the structural and compositional properties of the resulting GaN/P-Si heterojunctions utilizing techniques such as atomic force microscopy (AFM), field emission scanning electron microscopy (FESEM), and energy-dispersive X-ray spectroscopy (EDS).

2. METHODOLOGY

2.1 Fabrication of P-Si Substrate

Porous silicon substrates were fabricated using photo-electrochemical etching, as illustrated in Figure 1. Commercial p-type silicon wafers were cut into 1 cm^2 pieces and then ultrasonically cleaned in absolute ethanol for 10 minutes to remove surface impurities. After cleaning, the samples were rinsed with deionized water and dried with compressed air. The etching process occurred in a Teflon cell containing an electrolyte solution of hydrofluoric acid (HF, 48%) and ethanol (99.9%) in a 1:2 volume ratio. A constant current density of 10 mA/cm^2 was applied, with the silicon serving as the anode and a platinum mesh as the cathode. A 660 nm infrared diode laser (100 mW) was directed at the substrate throughout the 10-minute etching process to ensure uniform pore formation. This approach resulted in a uniform porous layer with a high surface area, making it suitable for thin film deposition [26-28].

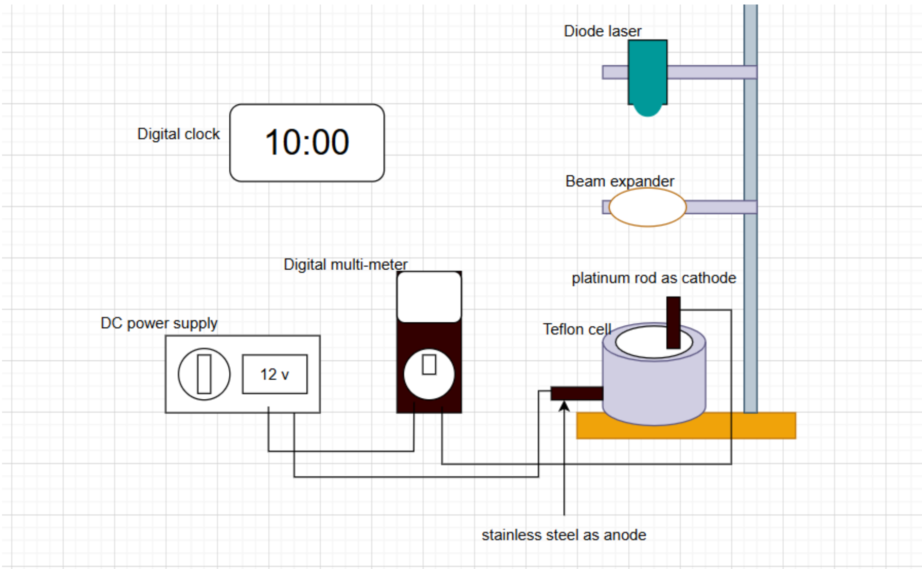


Figure 1. Fabrication of (P-Si) substrate using Photo-electrochemical etching with diode laser aid.

2.2 Preparation of Gan Target

The deposition target was prepared using powder GaN of 99% purity. The powder, about 3 grams, was compressed into a dense pellet by a hydraulic press under a 15 kg/cm^2 pressure. The target was 2 cm in diameter and 0.5 cm in thickness, making it suitable for PLD [29, 30].

2.3 Deposition of Gan Thin Films Via Pld

GaN thin films were deposited onto p-Si substrates using a pulsed laser deposition system with a Q-switched Nd: YAG laser operating at 1064 nm. The laser delivered 900 mJ per pulse, with a pulse duration of 10 ns and a repetition rate of 3 Hz. To enhance adhesion and promote crystalline quality, the substrates were preheated to 300 °C. The GaN target was positioned at a 45° angle relative to the laser beam and rotated during deposition to ensure uniform ablation. The substrates were placed 5 cm above the target to capture the plasma plume effectively. A lens with a focal length of 12 cm was utilized to focus the laser beam onto the target surface. The deposition occurred in a vacuum chamber maintained at a pressure of 10^{-2} mbar. These optimized parameters facilitated the formation of nanostructured GaN films with controlled stoichiometry and minimal contamination [31-33].

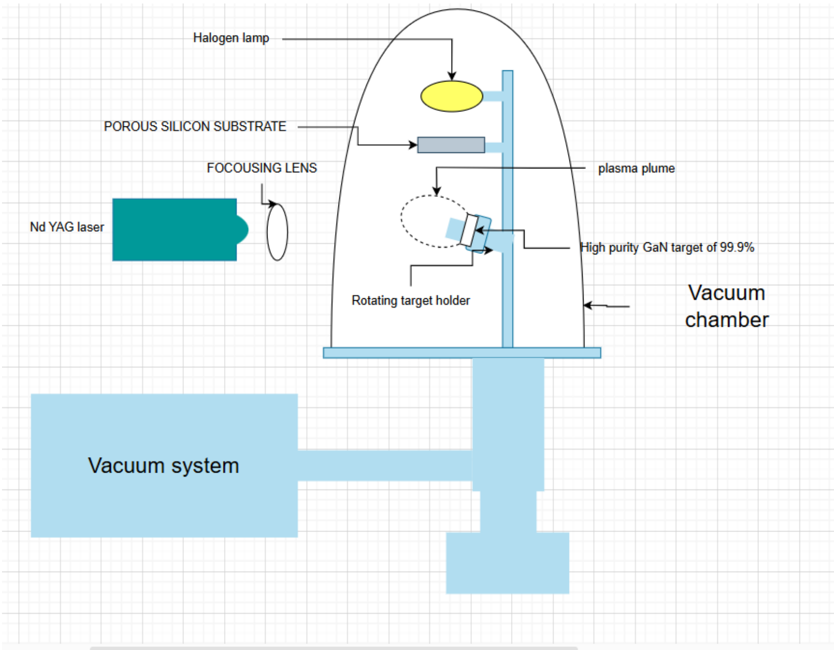


Figure 2. Configuration of the pulsed laser deposition apparatus.

3. RESULTS AND DISCUSSION

3.1 Surface topography

Three-dimensional Atomic Force Microscopy (3D AFM) was employed to investigate the surface of GaN films deposited on PSi substrates at 300 °C. As illustrated in Figure 3, the films exhibit a root mean square roughness (Sq) of 21.54 nm, indicative of moderate surface roughness. The average feature diameter of 45.70 nm suggests a nanostructured surface morphology, reflecting consistent grain formation. These surface characteristics are advantageous for optoelectronic applications, enhancing light interaction and surface reactivity. Such morphologies have been linked to improved optical and electrical properties, particularly in GaN/P-Si heterojunctions [34-37].

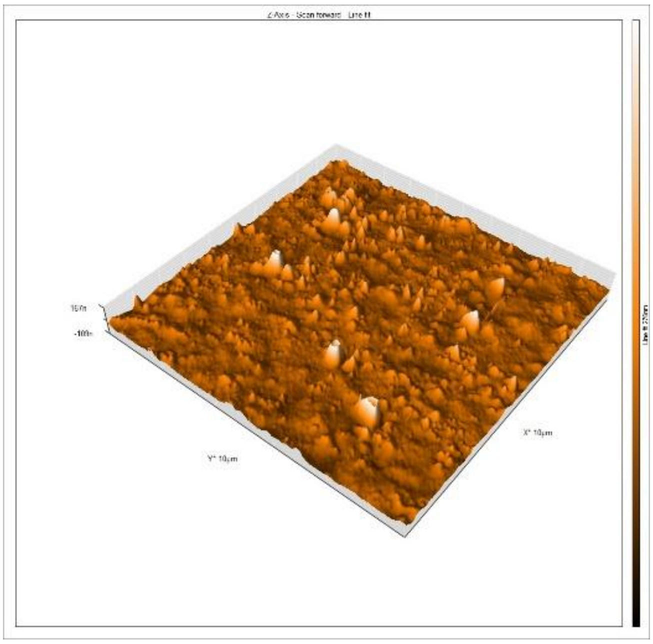
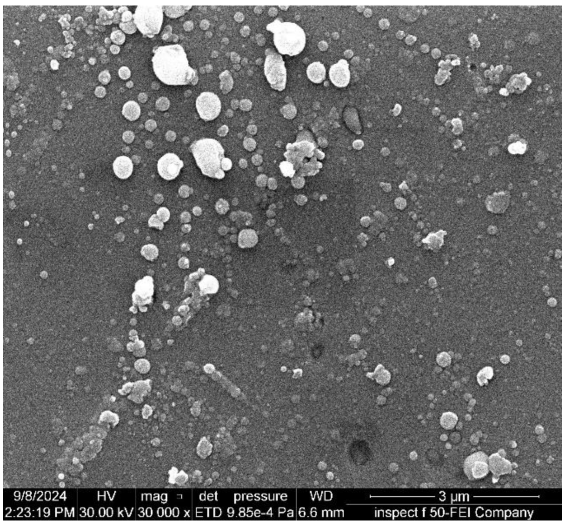


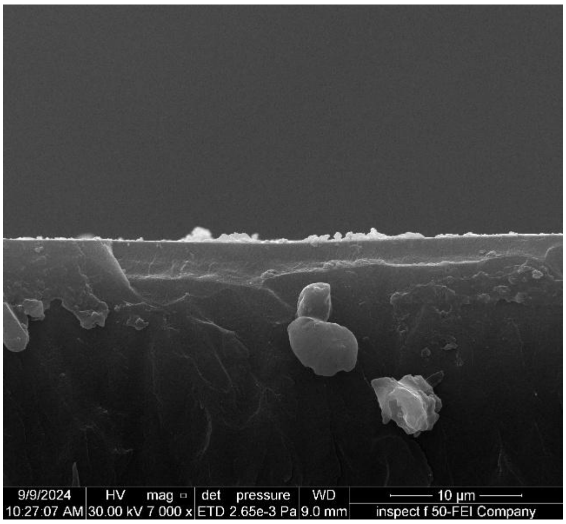
Figure 3. Presents AFM images of the constructed GaN/pSi heterojunction photodetectors, obtained with a 1064 nm laser wavelength.

3.3 Surface Morphology

Figure 4a showcases FESEM images that depict the surface morphology of GaN films deposited on a P-Si substrate using a 1064 nm laser wavelength. The top view reveals a granular surface characterized by spherical and hemispherical GaN nanoparticles, indicative of a typical Volmer–Weber (island) growth mode, captured at a magnification of 30,000×. The images indicate average particle diameters of 55.38 nm and 34.77 nm. As illustrated in Figure 4b, the GaN film uniformly covers the porous silicon substrate, with no visible cracks or voids. The structure consists of well-distributed spherical particles that exhibit a distinctive cauliflower-like appearance [38-41].



(a)



(b)

Figure 4. (a) illustrates 3 µm magnification FESEM images of GaN/P-Si, while (b) shows a SEM image of GaN /P-Si.

3.4 EDS of GaN / P-Si

The elemental composition of the GaN thin film deposited on porous silicon (PSi) was analyzed using Energy-Dispersive X-ray Spectroscopy (EDS), with the findings presented in both Table 2 and spectral form (Fig. 5). The EDS spectrum shows prominent peaks corresponding to silicon (Si), oxygen (O), carbon (C), nitrogen (N), and gallium (Ga). The most intense peak, observed at approximately 1.74 keV, corresponds to Si, indicating substantial contributions from the substrate due to its high porosity and the potential thinness of the GaN layer above. Low-energy peaks around ~0.5 keV indicate the presence of oxygen and nitrogen, with oxygen exhibiting a high atomic concentration of 50.1%. This is likely due to the formation of a native oxide layer on the PSi and exposure to atmospheric conditions following deposition. Low-intensity peaks identify gallium at 1.1 keV and 9.2 keV; however, its atomic percentage is low at just 0.6%, suggesting either partial coverage or a very thin deposition of GaN [42-45]. Additionally, carbon is detected at 13.5 at.%, possibly resulting from environmental contamination or residual organic material. Overall, the EDS data and spectrum confirm the formation of a GaN layer on PSi, highlighting its non-uniform and potentially discontinuous nature, as indicated by the low Ga signal and the predominance of substrate features. These observations align with the surface morphology noted in FESEM, which revealed discrete GaN nanoparticles dispersed across the porous silicon surface [46-50].

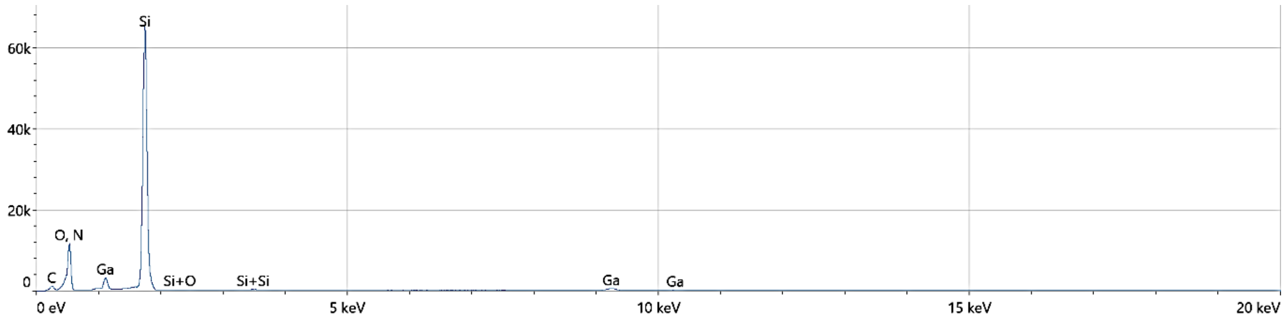


Figure 5. Presents the EDS for GaN/P-Si.

Table 1 AFM parameters were obtained for GaN/PSi nanostructures prepared using the PLD technique at a substrate temperature of 300 °C

T_{S} (C°)	Mean diameter (nm)	Root-mean-square height (nm)
300	45.70	21.54

Table 2 Composition of the elements of the GaN/P-Si

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	13.5	0.3	8.5	0.2
N	8.0	0.4	5.9	0.3
O	50.1	0.3	42.1	0.3
Si	27.9	0.1	41.2	0.1
Ga	0.6	0.0	2.3	0.1

4. CONCLUSION

This research successfully demonstrated the growth of GaN thin films on porous silicon (P-Si) substrates using the pulsed laser deposition (PLD) method. Comprehensive morphological and compositional analyses confirmed the effective deposition of GaN on the P-Si substrates. Atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM) revealed a nanostructured surface characterized by evenly distributed spherical GaN nanoparticles, indicative of an island-like growth morphology that favors high light trapping and enhanced carrier mobility. Energy-dispersive X-ray spectroscopy (EDS) verified the elemental composition; however, the low levels of gallium and the strong substrate signals suggest that the GaN layer may be thin or discontinuous. These findings indicate that the GaN/P-Si heterojunction, developed under optimized PLD conditions, possesses suitable morphological, optical, and elemental properties for photodetection applications. The combination of GaN's wide bandgap and the high surface area of porous silicon renders this heterostructure a promising candidate for future UV–visible photodetector applications.

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