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Optical Investigators of InGaN/P-Si Nanostructures Using Pulsed Laser Deposition Method

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ABSTRACT

Successfully deposited Indium gallium nitride (InGaN) thin films onto porous silicon (P-Si) substrates by pulsed laser deposition (PLD). Electrochemical etching is applied to the P-Si substrate to achieve a high surface area, facilitating enhanced adhesion and uniform growth of the InGaN layers. The formation of a wurtzite-phase InGaN structure, with pronounced diffraction peaks observed at the (002) and (004) planes, reflecting strong film–substrate interaction and high crystallinity, is confirmed by X-ray diffraction (XRD) measurements—a significant peak at 203.872 cm^{-1}, characteristic of InGaN vibrational modes revealed by a Raman spectroscopy. Photoluminescence (PL) analysis exhibited emission peaks at 510 nm, 700 nm, and 850 nm, corresponding respectively to band-edge transitions, deep-level defect emissions, and strain-induced states at the InGaN/P-Si interface. Collectively, these results show that InGaN/P-Si heterostructure demonstrates good optoelectronic properties, underscoring its viability for ultraviolet-visible-near-infrared photodetectors, light-emitting diodes, and a wide range of advanced optoelectronic device applications.

Keywords: *InGaN, Porous Si, Photo-electrochemical etching, PLD*

1. INTRODUCTION

Indium gallium nitride (InGaN) is a critical IIIV semiconductor compound characterized by a tunable direct bandgap, between 0.77 eV (InN) and 3.4 eV (GaN) [1-5]. The advantage of the property is that it can be used in optoelectronic devices between the ultraviolet and near-infrared spectrums as light-emitting diodes (LEDs), laser diodes, photodetectors, and solar cells [6-8]. InGaN is versatile in complex photonics technologies because it can be a candidate for changing optical and electronic properties by controlling composition [9-11]. Nevertheless, high-quality defect-reduced InGaN films have not been easily achieved because of lattice mismatch and mismatch in thermal expansion between them and the conventional substrates [12-14].

Porous silicon (P-Si) has also been viewed as one of the potential substrates to synthesize nitride films because of the large surface area and tunable pore structure, along with their light-trapping properties and the propensity to lead to adhesion of films and resistance to environmental factors. It improves the emission properties [15-19]. The presented problem can be solved by the fact that the large surface area of P-Si substrates can promote the strain release in the deposited films, decreasing the densities of defects and resulting in the growth of the nanostructures of the highest possible crystallinity, to be used in optoelectronic studies [20-23].

Premise on unique stoichiometry control, exceptionally high purity, and the production of uniform thin films using a solid substrate, pulsed laser deposition (PLD) has been regarded as a potentially applicable device on P-Si [24-28]. PLD coupled with P-Si substrates presents a route to produce high-quality InGaN nanostructures that achieve the desired structural and optical properties, so it can be applied in UV-visible-NIR optoelectronic devices [29-32]. This paper is devoted to the research of the preparation of InGaN nanostructures on the P-Si substrates with PLD and a critical study of the structure, optical, and vibration characteristics of the InGaN nanostructure through XRD, photoluminescence, and Raman measurements. This is to establish viability of the InGaN/P-Si heterostructure as a high-performance-optoelectronics platform, containing applications, such as LEDs, and broadband photodetectors.

2. METHODOLOGY

2.1 Porous Silicon (P-Si) Substrate Fabrication.

Porous silicon (P-Si) substrates were fabricated using a photo-electrochemical etching method, as illustrated in Figure 1. Initially, high-purity silicon wafers were cut into 1 cm^2 pieces and cleaned in an ultrasonic bath with absolute ethanol for 10 minutes to eliminate surface contaminants. The cleaned wafers were then thoroughly rinsed with distilled water and dried using compressed air. An electrolyte solution was prepared by mixing concentrated hydrofluoric acid (48%) with 99.9% ethanol in a 1:2 volume ratio, creating a stable environment for controlled etching. The etching process was carried out at room temperature with a current density of 10 mA/cm^2, where the silicon wafer acted as the anode and a platinum electrode served as the cathode within a Teflon etching cell. During the etching, an infrared diode laser (660 nm, 100 mW) was directed onto the silicon surface to promote pore formation and ensure uniformity in the etching process. After 10 minutes, the silicon substrate displayed a uniform porous structure with a high surface area, making it suitable for subsequent thin-film deposition [33, 34].

2.2 Preparing InGaN Target

High-purity indium gallium nitride (InGaN) powder, with a purity of 99%, was utilized to create an InGaN pellet target for deposition. To prepare the sample, 3 grams of the powder were accurately weighed. This measured powder was then compacted into a dense pellet using a hydraulic press set to 15 kg/cm^2. The final product was a pellet of indium gallium nitride with optimal dimensions for deposition procedures, measuring 2 cm in diameter and 0.5 cm in thickness.

2.3 Pulsed Laser Deposition Techniques

A solid-state Nd: YAG laser (NRY280, China, Q-switching mode, 1064 nm) operating at 900 mJ energy, 10 ns pulse duration, 3 Hz frequency, and 220 V power supply was used to grow InGaN nanostructures on a porous silicon (P-Si) substrate under a vacuum of 10^{-2} mbar using pulsed laser deposition (PLD). Before deposition, the P-Si substrate was preheated to 300°C to enhance adhesion and crystallinity. As shown in Figure 2, the InGaN target was mounted at a 45° angle on a rotating holder to the laser beam for uniform ablation. At the same time, the P-Si substrate was positioned horizontally 5 cm above the target to collect the deposition plume. A 12 cm focal length lens focused the laser on the InGaN target, generating a high-energy plume for clean, stoichiometric deposition. This method enabled the formation of a thin crystalline InGaN film on the P-Si substrate with controlled quality suitable for optoelectronic applications [35-38].

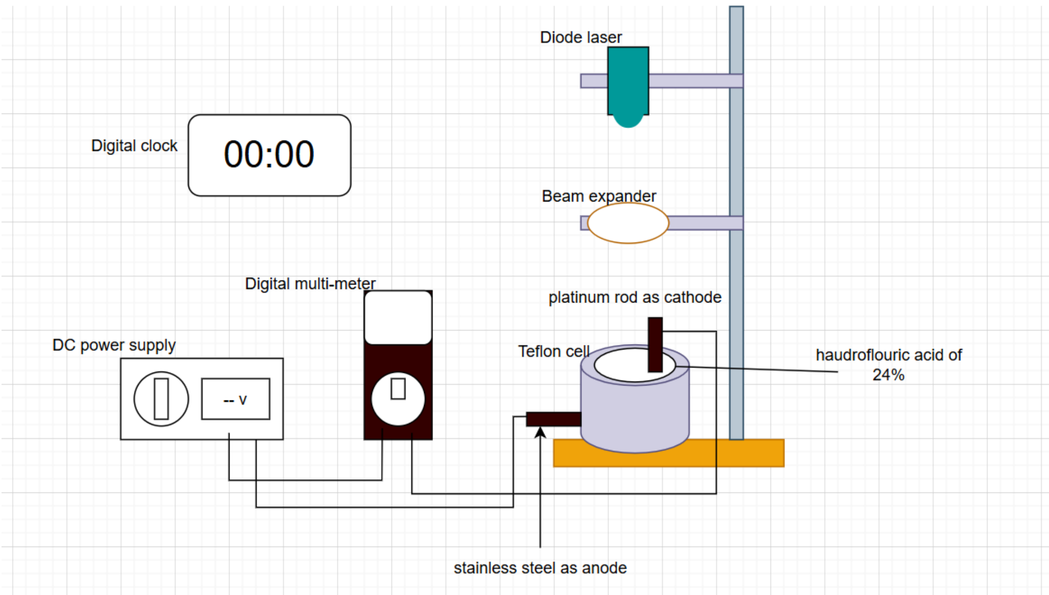

Figure 1. Schematic of the P-Si substrate fabrication system.

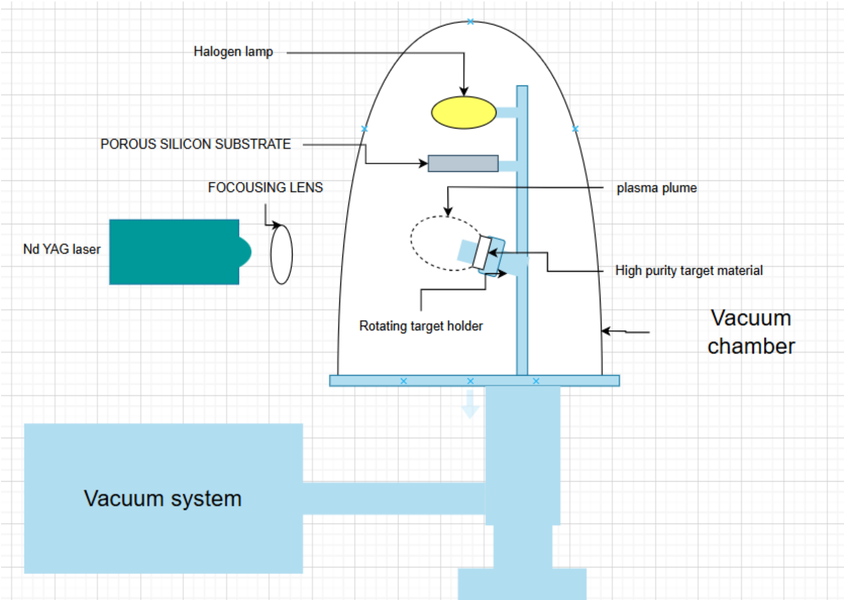

Figure 2. Setup for thin film growth via pulsed laser deposition.

3. RESULTS AND DISCUSSION

Structural and optical characteristics of InGaN/P-Si heterostructure were also studied systematically through X-ray diffraction (XRD), photoluminescence (PL), and Raman spectroscopy. Such analyses allowed insight into the nature of crystallinity and vibrational modes of the deposited inorganic gallium nitride films on porous silicon substrate, as well as optical emission characteristics. We should mention that the specific structural and optical characteristics of the P-Si substrate itself are reported in our prior work [39-42], so that this study was devoted only to the improvements obtained by the InGaN deposition and to the performance of heterostructures so created.

3.1 Photoluminescence (PL) Analysis of InGaN/P-Si Heterostructure

In Figure 3 (in InGaN / P-Si heterostructure), we can see peaks of PL spectra at 510 nm, 700 nm, and 850 nm. The band-edge and near-band-edge recombination emissions have their peak at 510 nm, a condition that implies high crystalline quality of InGaN, and the spikes in the 700nm range refer to deep-level defects and dislocation-related transitions on the layer of InGaN [43-46]. The emission at around 850 nm is taken as interface-related and strain-induced states emission because of the presence of InGaN/P-Si interface, which enlarges the emission spectra and the recombination channels of the carriers [47-49]. The findings show that a high-surface-area, optical-active InGaN/P-Si heterostructure with broad-spectrum photon activity could be formed, which is appropriate to be used in visible-near-infrared optoelectronic materials such as photodetectors and LEDs [50, 51].

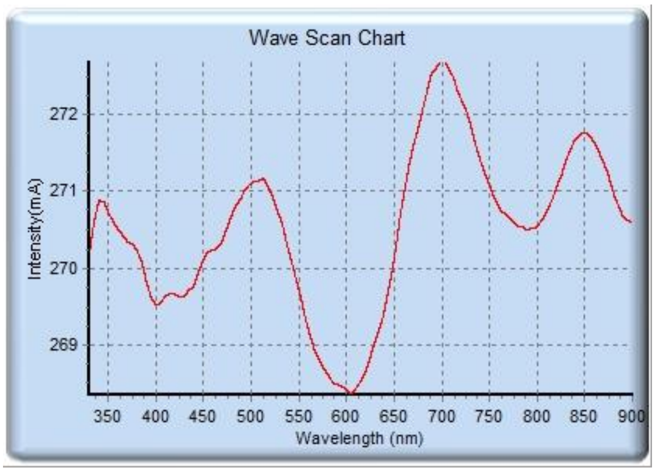

Figure 3. PL analysis of the InGaN layer deposited on P-Si.

3.2 Crystallographic Characterization Using XRD

Figure 4 shows the X-ray differences (XRD) pattern of the InGaN film, which was deposited on the P-Si substrate, showing individual diffraction peaks at about 33.2 and 69.5. Belong to the (002) and (004) wurtzite InGaN crystallographic planes, respectively, which also proves the c-axis directed growth along with the superior theme of the film crystal [52-54]. The realization of such sharp peaks without any significant secondary backgrounds proves the effective formation of the InGaN phase on top of the porous silicon substrate [55-57]. Furthermore, there are also the substrate-related peaks of P-Si and Si, where it is seen that the substrate allowed a facilitation to the deposition process. Such a degree of crystallinity is essential in delivering optimum optoelectronic properties in InGaN/ P-Si LEDs and photodetectors.

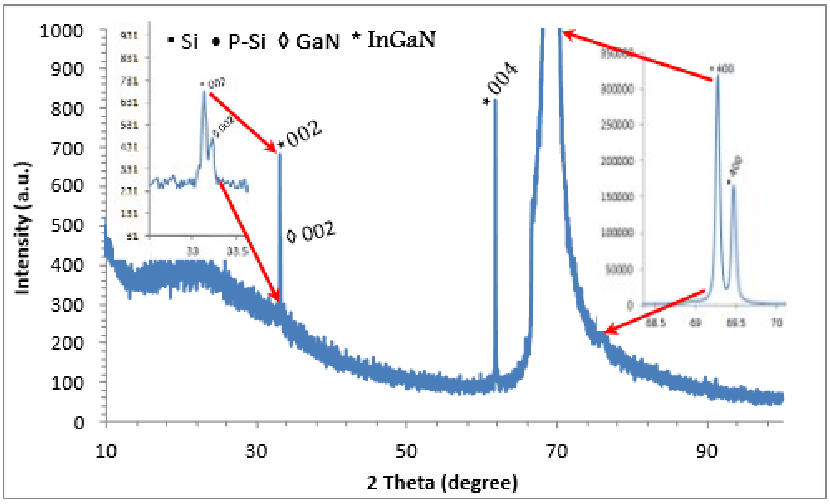

Figure 4. Crystallographic analysis of InGaN film grown on P-Si via XRD.

3.3 Vibrational Analysis Using Raman Spectroscopy

The Raman spectrum of InGaN/P-Si structure Figure 5 reveals a sharp peak at approximately 203.9 cm^{-1}, which corresponds to the E_2 (low) phonon mode characteristic in wurtzite InGaN. This result confirms the crystalline InGaN formation on the porous silicon substrate [58-60]. The other peaks observed at higher Raman shifts are attributed to multi-phonon and overtone modes, and substrate-related features of the porous silicon, manifesting the interaction at the interface and the stress distribution in the heterostructure [61-63]. The sharp and clear Raman features indicate good crystallinity of InGaN layer, supporting its use in optoelectronic devices.

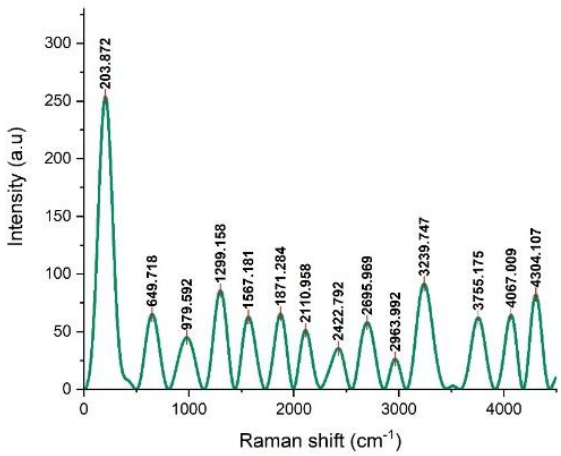

Figure 6. Raman spectral analysis of InGaN/P-Si heterostructure.

4. CONCLUSION

In this piece of work, a good quality was reached because InGaN nanostructures were deposited successfully on porous silicon substrate through pulsed laser deposition at 900 mj with a pulse duration of 10 ns at a vacuum of 10 -2 mbar. Highly crystalline wurtzite InGaN crystal was demonstrated by X-ray diffraction (XRD) as it showed sharp peaks at 33.2 º and 69.5 º representing the (002) and (004) crystal planes, respectively. The Raman spectroscopy showed a clear E2 (low) mode at around 203.9 cm^{-1}, indicating the crystalline nature. Photoluminescence experiments also showed intense brightening at 510 nm, 700 nm, and 850 nm, and were due to band-edge, defect, and strain/interface states in the visible to near-infrared range. Such conclusions demonstrate that the InGaN/p-si heterostructure that enables using a higher surface area of porous silicon to achieve improved film quality is a promising structure to use in UV-Visible-NIR photodetectors, and also in LEDs, to create high-efficiency, broad-spectrum optoelectronic devices.

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