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Optical Properties of Gallium Nitride Heterostructures Grown on Quartz Using Pulse Laser Deposition Method

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ABSTRACT

An optical analysis was conducted on a Gallium nitride (GaN) thin film grown on a quartz substrate using the physical vapor deposition technique (PVD), specifically, pulsed laser deposition (PLD). The film was grown using different laser wavelengths (1064, 532, and 355) nm from a Q-switch neodymium-doped yttrium aluminum garnet (Nd: YAG) laser, all performed under a vacuum pressure of 10^{-2} m bar. The absorption coefficient of the GaN thin film was determined by performing UV-Vis diffused spectroscopy at room temperature and measuring wavelengths ranging from 200 to 1000 nm. The absorption peak occurs at 227 nm when the wavelength is 1064 nm, at 217 nm when the wavelength is 532 nm, and at 222 nm when the wavelength is 355 nm. The optical energy gap is a crucial statistic for analyzing the properties of thin films and assessing their potential as gas sensors. The value of the direct energy gap (E_g) for the prepared films was established by analyzing the graph that shows the relationship between (α h) and the energy gap (ev) values at different wavelengths. The energy values were determined to be 3.36 eV, 3.62 eV, and 3.7 eV for 1064, 532, and 355 nm wavelengths, respectively.

Keywords: *Pulsed Laser deposition, GaN, Nanostructure, optical properties, Nanofilms*

1. INTRODUCTION

Optical devices utilize advanced electronic systems developed via considerable study on materials with broadband gaps over a long period. These devices may be altered at elevated temperatures, increased voltages, and enhanced power densities, making them extremely attractive for current electronic systems [1, 2]. Gallium nitride (GaN) has generated significant interest in recent times owing to its favorable characteristics, such as a direct and wide band gap of 3.4 eV, significant thermal conductivity [3, 4], thermal stability, elevated melting point [5], superior electron mobility [6], mechanical hardness, and high break-down voltage [7].

The unique characteristics of thin film have made it indispensable in industrial equipment. Gallium nitride (GaN) is a very thermally conductive material. It is well-suited for several applications, including sensors, solar cells, light-emitting diode devices, short-wavelength optical devices, high-power transistors, and beta-voltaic devices [8-19].

Several research studies have endeavored to create GaN nanostructures using different growth techniques, such as metal-organic chemical vapor deposition [20], reactive molecular beam epitaxy [21], thermal ammonization [22, 23], physical vapor deposition [24, 25], chemical vapor deposition (CVD) [26], sol-gel chemistry [27], electrochemical deposition [28], thermal vapor deposition [29], and pulsed laser deposition (PLD) [30].

The use of pulsed laser deposition (PLD) is intriguing due to its capability to enable on-site processing of multilayer structures involving multiple targets. PLD also makes it easier for stoichiometric deposition from the target to the substrate, gives you a lot of choices for doping complex compositions, and creates highly directed, energetic precursors by laser ablation of the target [31].

The solid-state Nd: YAG laser used in this investigation emitted light at 1064 nm, 532 nm, and 355 nm. It had a laser energy of 900 mJ and operated under a vacuum pressure of 10^{-2} m bar. Gallium Nitride (GaN) was utilized to cultivate a layer on a quartz substrate to enhance the efficiency of gas sensors. This work studied the optical characteristics of a thin film made of Gallium Nitride (GaN).

2. THEORETICAL BACKGROUND

Gallium Nitride (GaN) is a semiconductor material from the III-V nitride family. It possesses the hexagonal (wurtzite) structure and exhibits distinctive optical features. GaN has a comprehensive and adjustable direct band gaps of 3.4 electron Volt [32,33]. This allows for the creation of optoelectronic devices that operate using ultraviolet (UV) and visible light, including light-emitting diodes (LEDs), laser diodes (LDs), photodiodes, gas sensors, and UV detectors [34,35]. Furthermore, GaN exhibits exceptional characteristics such as elevated electron mobility, chemical stability, efficient luminescence, superior thermal conductivity, and high breakdown strength [36,37]. The benefits mentioned above contribute to developing GaN-based optoelectronic devices that exhibit extraordinary frequency and temperature capabilities, low inherent noise and dark current, and Ionizing radiation sensitivity. [38,39]. These devices have critical applications in the industrial, military, and space sectors [40,41]. The choice of procedures and parameters for GaN film fabrication significantly influences the films' electrical and optical properties [42,43]. Various techniques, such as molecular beam epitaxy, metalorganic chemical vapor deposition, and pulse laser deposition (PLD), have recently been employed to create high-quality thin-film GaN [44]. Furthermore, each method of cultivating GaN thin films under high vacuum conditions, with a rapid growth rate and a low substrate temperature, offers distinct benefits [45].

3. METHODOLOGY

3.1 Process of Preparing a Quartz Substrate

To enhance adhesive effectiveness, removing impurities and rigorously treating fingerprint regions with dimensions of (2 * 1) cm and a thickness of 1 mm is crucial. The first step of the cleaning process involves physical cleaning for ten minutes. Following this, the object undergoes sterilization through immersion in liquid ethanol for five minutes, followed by the application of hot air for drying purposes. After the cleaning phase was concluded, the quartz substrates were placed in sterile plastic containers, anticipating the deposition process. Quartz was chosen as a substrate due to its remarkable thermal resistance, enabling it to withstand high temperatures without suffering structural harm(Quartz was used as a substrate because of its ability to withstand high temperatures without breaking or cracking, such as fractures. Moreover, quartz exhibits a broader spectrum of wavelengths than other minerals [46].

3.2 Preparation of GaN Target

The gallium nitride (GaN) pellet was made by pounding GaN powder (Advanced- Material Company, high impurity of 99.99%- China) with a 15 kg/cm^2 hydraulic press. Figure 1 exhibits a GaN sample of 3 grams, with dimensions of 2 * 0.5 centimeters in diameter and thickness [47]

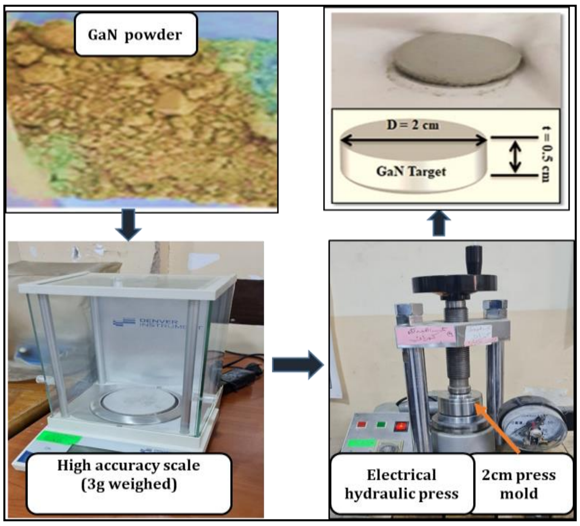

Figure 1. The process of fabrication of GaN pellet.

3.3 Fabrication of GaN / Quartz Substrate THIN FILM

A Q-switching Nd: YAG laser from Guangzhou Dany Optical Technologies CO., Ltd., China, was employed to deposit a thin layer of GaN onto a quartz substrate using the pulse laser deposition technique (PLD). The deposition was conducted at various laser wavelengths (1064, 532, and 355 nm) with a vacuum pressure of 10-2 mbar. The laser energy used was 900 mJ, and the surface temperature was maintained at 300°C, as shown in Table 1.

Table 1 The practical parameters of the PLD method used to produce a thin film of GaN/quartz substrate

Laser parameter	The values
Lasers wavelength	1064 nm,532 nm, and 355 nm
Pulsed laser energy	900 m Joule
Pulsed laser duration	7 ns
Frequency	3 Hz
Repetition rate	300 Hz
Power supply	900 v
Substrate temperature	300 C^0

The GaN target and quartz substrate were precisely placed inside the PLD vacuum chamber. In addition, the GaN target was affixed on a base that spun at a 45° angle. The quartz substrate is positioned horizontally, 5 cm above the flattened GaN target. Figure 2 shows the Q-switch Nd: YAG laser is used to drive a solid plume of GAN material onto a substrate. This is achieved by focusing the laser using a lens that has a focal length of 12 cm. The process ensures little contamination and specific stoichiometry of the deposited material [48]. The experimental setting of this work is depicted in Figure 3.

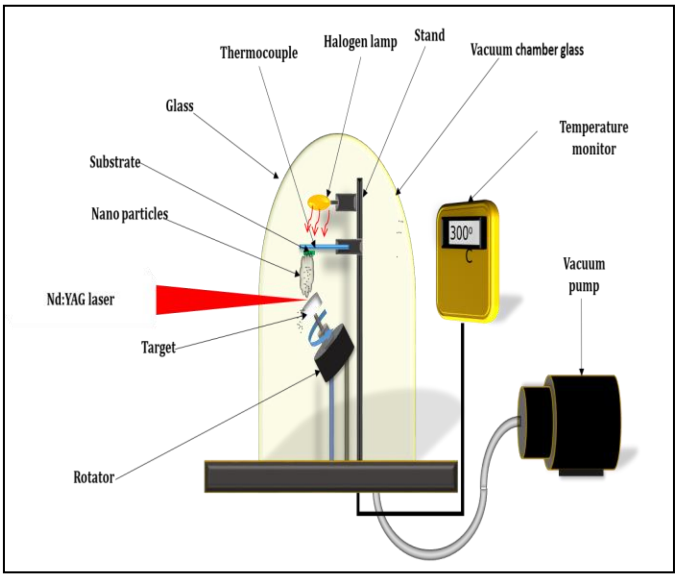

Figure 2. PLD method to fabricate GaN/quartz substrates with different laser wavelengths (1064nm,532nm, and 355nm).

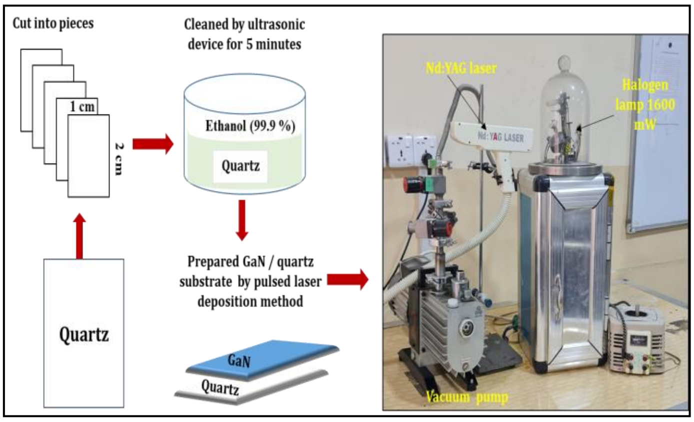

Figure 3. The experimental setup of the manufacturing GaN/quartz substrates with different laser wavelengths (1064nm,532nm, and 355nm).

3.4 UV-Visible spectrophotometer (UV-VIS)

The optical characteristics of the GaN grown over a quartz substrate were measured using an Ultraviolet-Visible spectrophotometer, China, SP-8001. This spectrometer has a wavelength range of 200-1000 nm and utilizes UV-Vis diffuse reflectance.

4. DATA COLLECTION AND ANALYSIS

We will use a double-beam UV-VIS spectrophotometer to measure and figure out optical properties like absorptions, transmission, and absorption coefficients as a function of wavelengths in nanometers between 200 nm and 1000 nm. We will also find the significance of the energy bandgap as a purpose of the optical energy gap. The energy gap was considered using the formula (1) [49]:

$$Eg\ (eV) = h\nu / \lambda\ (\mu m) = hc / \lambda\ (\mu m) = 1.24 / \lambda\ (\mu m) \qquad [1]$$

Where the optical energy gap is defined as Eg, the photon energy hν, h is plank s constant ($6.62*10^{-34}$ J.sec), ν is the photon frequency, c is the speed of light, and λ is the wavelength of the incident photon. The coefficient of absorption was plotted as a function of wavelength.

The subsequent formulation was used to estimate (2) [50]:

$$(\alpha h\nu) = B\ (h\nu - Eg)^{r} \qquad [2]$$

The absorption coefficient value (α) is derived using the equation where (hv) represents the energy of the photon, (B) is a constant, and (r) is a material-dependent constant. The optical band gap was determined from the linear relationship obtained by extrapolating the straight line of the curve between (h)1/r and (h). Equation (3) was utilized to estimate the absorption coefficient at a particular wavelength [50].

$$\alpha = 2.303\ (A / t) \qquad [3]$$

A = absorption and, t = thin film thickness.

The UV region's sharp edge guarantees the formation of a direct gap in the prepared films. It was calculated using the following expression [50]:

$$\alpha h\nu = A(h\nu - Eg)^{1/2} \qquad [4]$$

Where hv is the photon energy, α is the absorption coefficient, and A is the constant. The energy gap Eg was determined by extending the straight line of the plot of $(\alpha h\nu)^2$ versus hv with the incident photon energy.

5. RESULTS AND DISCUSSION

5.1 Absorption Properties of GaN Grown on a Quartz Substrate

Figure 4 shows the absorption spectra ranging from 200 nm to 1000 nm. The spectrum exhibits absorption peaks at specific wavelengths: 227 nm at 1064 nm, 217 nm at 532 nm, and 222 nm at 355 nm. The absorption measurements from the experiment show reduced broadening and indicate a greater concentration of GaN nanoparticles due to increased absorption [50].

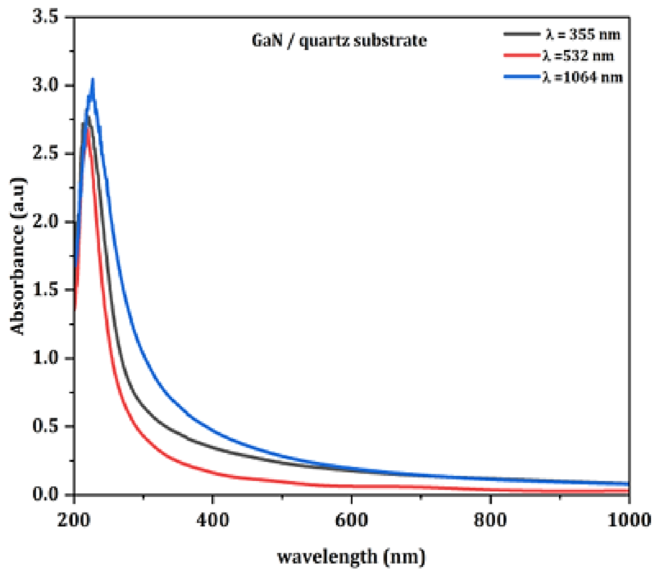

Figure 4. Absorption properties of GaN/quartz at different wavelengths (1064nm,532nm, and 355nm).

5.2 Absorption Coefficient of GaN Grown on the Quartz Substrate

Figure 5 exhibits the absorption coefficient at several laser wavelengths, specifically 1064, 532, and 355 nm. Every material possesses a distinct absorption coefficient, with larger values indicating a greater propensity to absorb incoming photons. This absorption process stimulates electrons, causing them to transition from the valence band to the conduction band. The peak corresponds to the wavelength at which photons experience the highest absorption level, while the lower values imply a lower level of photon absorption at that particular wavelength. The pronounced peak on the absorption coefficient curve indicates that the material lacks sufficient energy to induce the movement of an electron between energy levels.

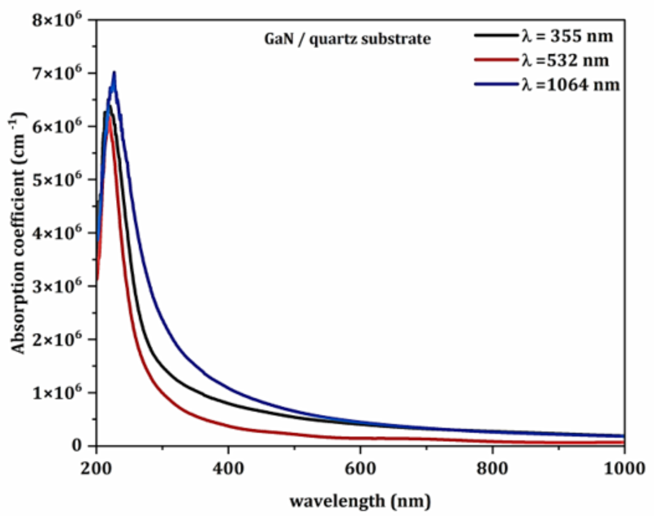

Figure 5. Absorption coefficient of GaN/ quartz at different wavelengths (1064nm,532nmand 355nm).

5.3 Transmission Properties of GaN Grown on a Quartz Substrate

Figure 6 shows the optical transmittance of the GaN nanofilms prepared at different deposition wavelengths. The transmittance is defined as the ratio of the intensity of the transmitted radiation to the initial intensity, and it depends on the thickness of the film, the type of material, and the nature of the surface. The figure clearly shows that the transmittance increases with the wavelength of 532 nm. The roughness of the surface of the film increases the interaction of electromagnetic radiation with the surface of the thin film. In contrast, the reflectivity increases with the increase in surface smoothness. Therefore, films with high roughness transmit better than smooth surfaces [50]. Transmittance spectrometer measurements showed that the t value of transmittance at the wavelength (1064nm) equals (23%), increases with 355 nm wavelength to reach (37%), and falls to (56%), and this is consistent with what was found by the researcher Oscar and his group [49].

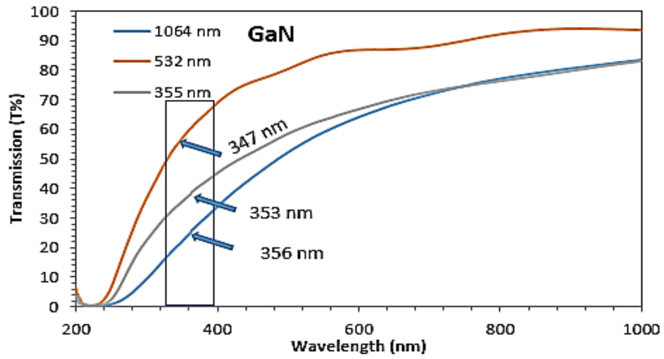

Figure 6. Transmission of GaN/quartz at different wavelengths (1064nm,532nm,355nm).

5.4 Calculation of the Energy Gap of GaN/Quartz at Different Laser Wavelengths

The optical energy gap is a crucial statistic for analyzing the characteristics of thin films and assessing their potential for gas sensor applications. The value of the direct energy gap (Eg) for the prepared films was calculated by analyzing the graph that relates the square of the produce of the absorption coefficient (α) and the photon- energy ($h\upsilon$) to the energy gap ($h\upsilon$) values for various wavelengths. This relationship is illustrated in Figure 7. The energy gap of nanoparticles is inversely proportional to their size, meaning that it decreases as their sizes rise. As the size of nanoparticles reduces, the number of atoms in them also decreases. This leads to the creation of fewer defect levels, causing the energy gap to increase. This phenomenon has been seen in studies [50]. The reduction in laser wavelength from 1064 nm to 532 nm and 355 nm resulted in a notable decline in transmission values, suggesting increased material removal from the target at shorter wavelengths, leading to faster deposition rates. As the wavelength lowered, the sample thickness grew, resulting in higher laser absorption by the target and a more intense plasma plume. Table 2 displays the energy gap for various laser wavelengths.

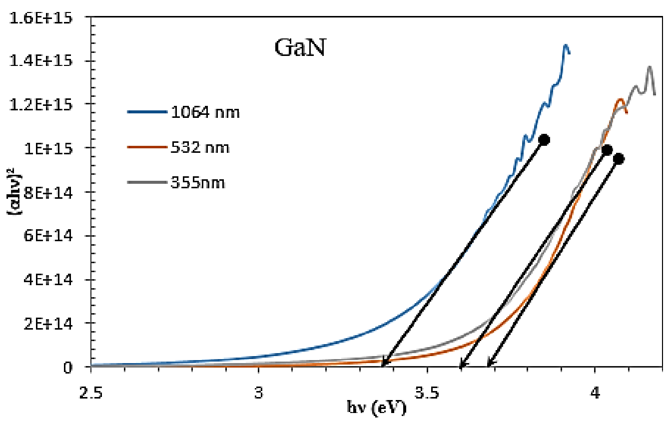

Figure 7. Energy gap of GaN/quartz substrate at different laser wavelengths (1064nm,532nm, and 355nm).

Table 2 The energy gap of the GaN/quartz thin film was measured at three different laser wavelengths: 1064 nm, 532 nm, and 355 nm

Laser wavelength (nm)	Energy gap (ev)
1064	3.36
532	3.62
355	3.7

6. CONCLUSIONS

This study used the pulsed laser deposition method to generate GaN thin films on a quartz substrate. The films were produced with a Q-switched Nd: YAG laser operating at three distinct laser wavelengths: 1064 nm, 532 nm, and 355 nm, with a laser intensity of 900 mJ. The absorption peak occurs at 227 nm when the wavelength is 1064 nm, at 217 nm when the wavelength is 532 nm, and at 222 nm when the wavelength is 355 nm, in that order. The sample's energy band gap was calculated to be 3.36 eV at 1064 nm, 3.62 eV at 532 nm, and 3.7 eV at 355 nm. The optimum method for fabricating GaN nanostructured thin coatings for gas sensing applications is laser deposition using a laser wavelength of 532 nm and an energy of 900 mJ.

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