International Journal of Nanoelectronics and Materials
IJNeaM
ISSN 1985-5761 | E-ISSN 2232-1535

Optical properties of Al_2O_3 thin film deposited by pulsed laser deposition technique

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Received 22 September 2023, Revised 21 April 2024, Accepted 10 August 2024

ABSTRACT

An aluminum oxide (Al_2O_3) thin film has been grown on a quartz substrate by the pulsed laser deposition (PLD) technique at room temperature under a vacuum pressure of 10^{-2}m bar at different laser wavelengths (1064 nm, 532 nm, and 355 nm). The optical properties concerning the absorption, transmission spectra, and energy gap were studied for the prepared thin film due to UV-visible spectrometer at room temperature with wavelength range (200-1000 nm). The absorption peak is 197 nm at wavelength 1064 nm, 196 nm at wavelength 532 nm, and 195 nm at wavelength 355 nm. The optical energy gap is an essential parameter for investigating thin films' properties. The value of the direct energy gap (Eg) for the prepared films was derived from the graph relationship between ($h\upsilon$ h) and the energy gap $(\alpha h\nu)^2$ values for the various wavelengths (4.5 eV at 1064 nm, 5.1 eV at 532 nm, and 5.5 eV at 355nm), indicating the potential use of the thin film as gas sensors.

Keywords: *Pulsed laser deposition, Al_2O_3, Nanostructure, Optical properties, Nanofilms*

1. INTRODUCTION

Aluminum oxide (Al_2O_3) exhibits favorable optical, chemical, and electrical characteristics, making it a promising material for various optoelectronic applications. It has been employed as a gate dielectric in transparent thin film transistors [1, 2], a barrier to prevent gas diffusion [3, 4], a protective layer for photovoltaic devices [5, 6], a coating for electrodes and photo electrodes in electrochemical energy storage systems [7, 8], and a means of preventing corrosion [9, 10]. Furthermore, α-Al2O3 has been extensively researched as a material that can withstand radiation, making it valuable for components and protective coatings in fusion technology [11, 12].

Al_2O_3 thin films have been fabricated using several techniques, including sputtering [13, 14], pulsed laser deposition (PLD) [15, 16], e-beam evaporation [17, 18], sol-gel [19, 20], and atomic layer deposition (ALD.) [21-23].

Pulsed laser deposition (PLD) is appealing because it allows for the on-site fabrication of multilayer structures using several targets. PLD facilitates stoichiometric deposition from the target to the substrate, offers a wide range of options for doping complicated compositions, and generates highly focused, energetic precursors through laser ablation of the target [24, 25].

In this study, an Al_2O_3 film was grown on a quartz substrate using the PLD technique, which was chosen due to its user-friendliness, flexibility, and speed in producing films with a robust plume of material that can be deposited with minimal contamination and precise stoichiometry [26, 27]. Al_2O_3 was produced at quartz using an Nd: YAG laser, a solid-state laser with wavelengths of 1064 nm, 532 nm, and 355 nm, a laser energy of 900 mJ, and a vacuum pressure of 10^{-2} mbar with a surface temperature of 300°C, to produce high thin film quality for gas sensing application. This research investigated the optical properties of a thin Al_2O_3 film.

2. METHODOLOGY

2.1. Preparation of Quartz Substrate

To optimize adhesion efficacy, it is essential to thoroughly eliminate contaminants and meticulously address fingerprint areas measuring (2 cm × 1 cm) and possessing a thickness of 1 mm. The initial stage of the cleaning procedure entails manual cleaning for ten minutes. Subsequently, the item is subjected to sterilization by immersion in liquid ethanol for five minutes, followed by hot air drying. Following the completion of the cleaning phase, the quartz substrates were then stored in sterile plastic containers in preparation for the deposition process.

Quartz was selected as a substrate based on its exceptional thermal resistance, allowing it to endure elevated temperatures without experiencing structural damage such as cracking or breaking. Additionally, quartz offers a broader range of wavelengths than alternative materials [28, 29].

2.2. Fabrication of Al_2O_3 target

The Al_2O_3 pellet was fabricated by compressing Al_2O_3 powder (3302 Twig Leaflane, Houston, 99.9% of high impurity, U.S.A.) using a hydraulic press with a pressure of 15 kg/cm^2. Figure 1 displays an Al_2O_3 sample weighing 3 grams with a diameter of 2 cm and a thickness of 0.5 cm [30, 31].

2.3. The Preparation of Al_2O_3 Thin Film over Quartz Substrate by PLD method

A Q-switching Nd: YAG laser (neodymium-doped yttrium aluminum garnet) (Guangzhou Dany Optical Technologies CO., Ltd., Chinese) with a vacuum pressure of 10^{-2} mbar (Guangzhou Dany Optical Technologies CO., Ltd., China) was used for pulse laser deposition (PLD) to deposit a narrow layer of Al_2O_3 (3302 Twig Leaflane, Houston, 99.9% of high impurity, U.S.A.) onto a quartz substrate as shown in Figure 2. The operational parameters of the PLD technique are laser wavelength (1064 nm, 532 nm, and 355 nm), pulse energy (900 mJ), pulse duration (7 ns), frequency (3 Hz), repetition rate (300 Hz), power supply (900 v), substrate temperature (300°C) as illustrated in Table 1.

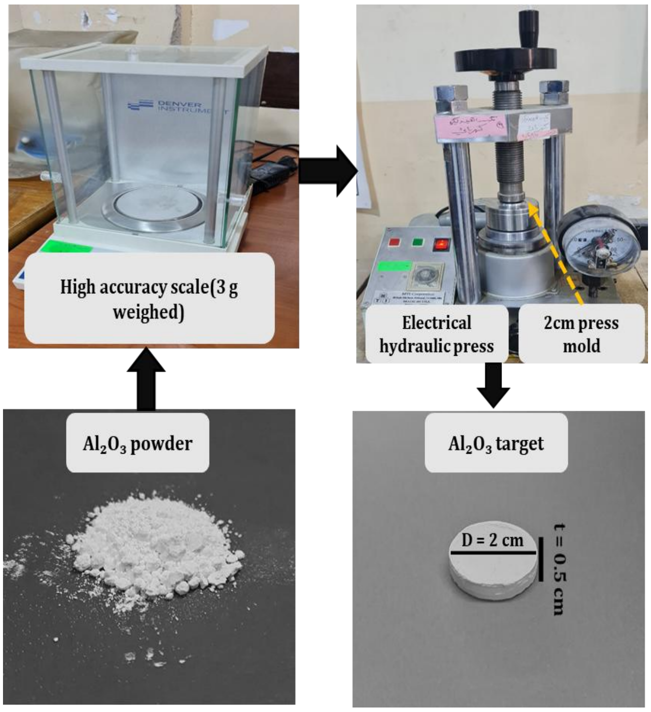

Figure 1. The process of fabricating the pallet of Al_2O_3

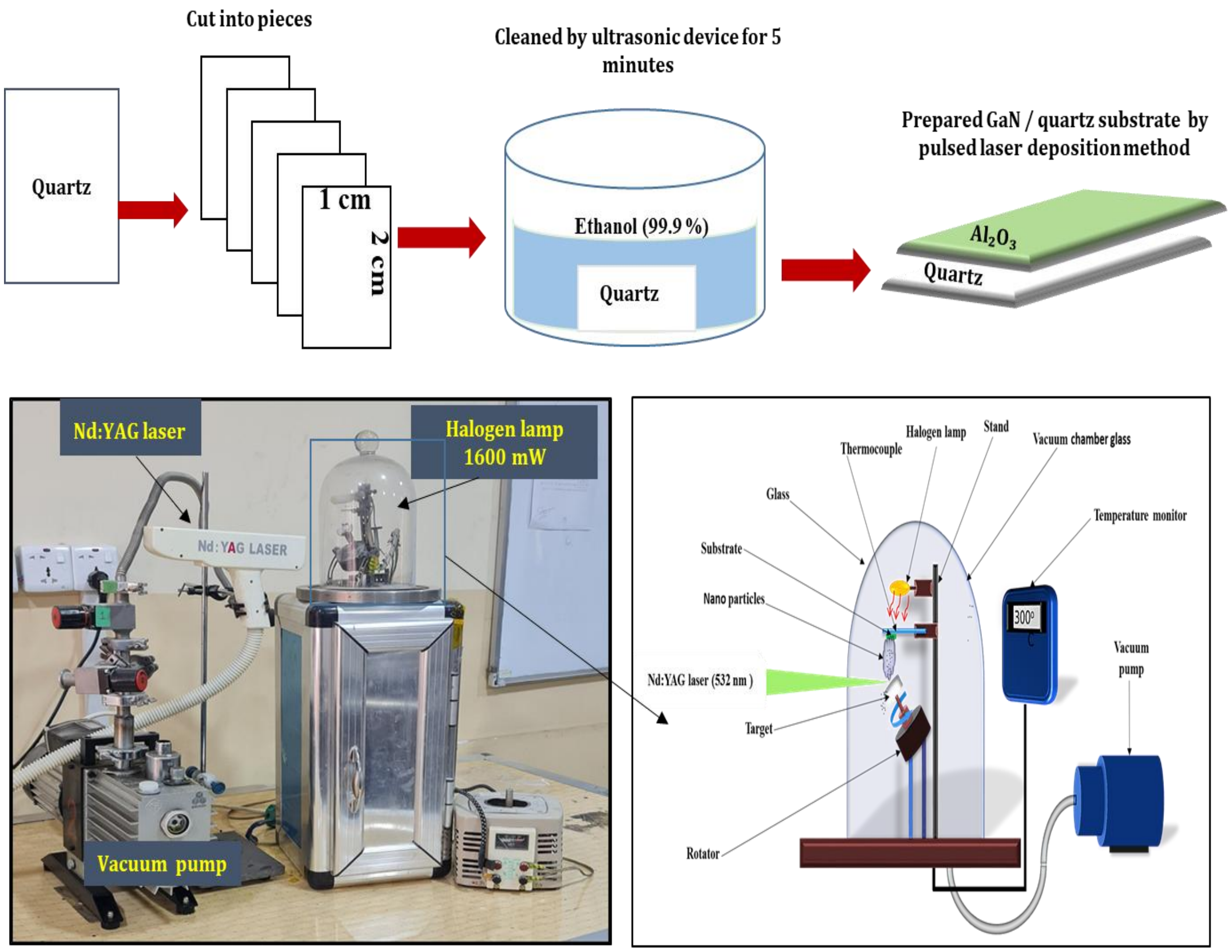

Figure 2. Experimental setup of producing Al_2O_3 / quartz substrate at different laser wavelengths (1064 nm, 532 nm and 355 nm)

Table 1. The operational parameters of the pulsed laser deposition (PLD) technique employed to fabricate an Al_2O_3 thin film on a quartz substrate

Laser Parameter	The values
Laser wavelength	1064 nm, 532 nm, and 355 nm
Pulse energy	900 mJ
Pulse duration	7 ns
Frequency	3 Hz
Repetition rate	300 Hz
Power supply	900 V
Substrate temperature	300°C

The Al_2O_3 target and quartz substrate were meticulously positioned within the vacuum chamber of the PLD system. In addition, the Al_2O_3 target was affixed to a rotating base at a 45° angle. The quartz substrate is fixed horizontally 5 cm above the flattened Al_2O_3 target at a distance of 5 cm. As depicted in Figure 2, the Q-switch Nd: YAG laser was subjected to the Al_2O_3 target by a focused lens with a focal length of 12 cm to generate a solid forward-directed plume of Al_2O_3 material that can be deposited on a quartz substrate with low contamination and specific stoichiometry.

2.4. UV-Visible spectrophotometer (UV-VIS)

To measure the optical properties of the reflectance, the UV-Vis diffuse reflectance UV-VIS spectrometer (Avantes DH-S-BAL-24048 UV-Vis, Netherlands) with a wavelength range of 200–1000 nm was employed.

3. DATA COLLECTION AND ANALYSIS

Using a double-beam UV-VIS spectrophotometer, optical properties like absorptions, absorption coefficients, transmission, and the value of the energy bandgap as a function of the optical energy will be measured and calculated over 200 nm–1000 nm.

The incident photon energy was calculated using the Equation (1) [32-35]:

$$E_g\,(eV) = 1.24 / \lambda\,(\mu m) \quad (1)$$

where E_g is the optical energy gap, and λ is the wavelength of the incident photon. The coefficient of absorption was plotted as a function of wavelength.

Equation (2) [36-39] was used to estimate:

$$(\alpha h\nu) = B\,(h\nu - Eg)^r \quad (2)$$

where (α) is the calculated absorption coefficient value, hv is the photon's energy, (B) is a constant, and (r) is a constant whose values depend on the material type. The optical band gap was deduced from the linear relationship (extrapolation of the straight line) of the curve between (h)1/r and (h). Using Equation (3), the absorption coefficient at a specific wavelength was estimated [40-42]:

$$\alpha = 2.303\,(A / t) \quad (3)$$

where A is absorption and t is thickness.

The U.V. region's sharp edge guarantees the formation of a direct gap in the prepared films. It was calculated using the following Equation (4) [43-45]:

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

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 hν with the incident photon energy.

4. RESULTS AND DISCUSSION

4.1. Absorption, Transmission Properties of Al_2O_3 / Quartz Thin Film

Figure 3 shows the absorption spectrum of Al_2O_3 / quartz substrate at different laser wavelengths (1064 nm, 532 nm, and 355 nm) in the absorption range of 200 nm to 1000 nm. It shows the absorption peak at 197 nm, 196 nm, and 195 nm at 1064 nm, 532 nm, and 355 nm of laser wavelength, respectively. The experimental spectrum absorption data exhibit less spectrum broadening, and a higher absorption suggests a higher Al_2O_3 nanoparticle concentration.

Figure 4 illustrates the optical transmittance of Al_2O_3 nanofilms deposited at different laser wavelengths 1064 nm, 532 nm, and 355 nm). The transmittance is the ratio of the transmitted radiation's intensity to the initial intensity. It depends on the thickness of the film, the type of material, and the nature of the surface. It is evident from the graph that the transmittance increases as the wavelength of 532 nm increases. The surface roughness of the film increases the interaction of electromagnetic radiation with the surface of the thin film, whereas the increase in surface uniformity increases reflectivity. Therefore, films with a high surface roughness have a higher transmittance than those with a uniform surface [46, 47].

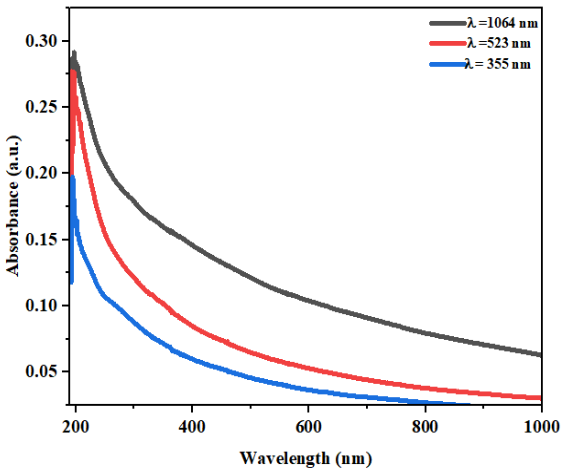

Figure 3. Absorption properties of Al_2O_3 / quartz substrate at different wavelengths (1064 nm, 532 nm, and 355 nm)

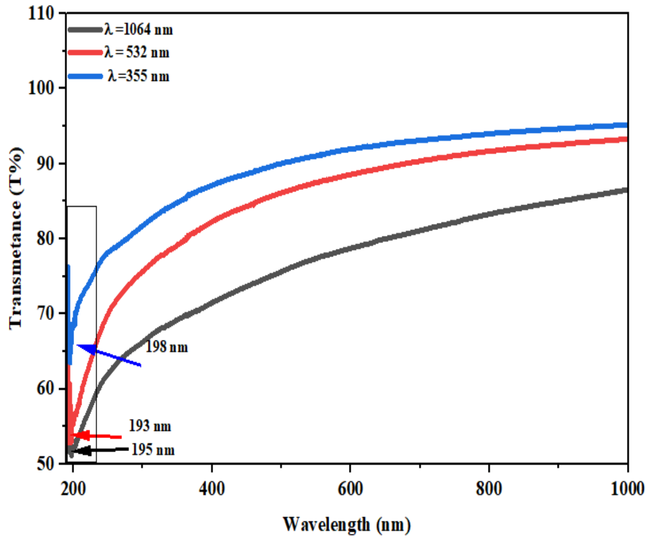

Figure 4. The transmission of Al_2O_3 / quartz substrate was at different wavelengths (1064 nm, 532 nm, and 355 nm)

All samples exhibited high transmission in the visible and infrared spectrums, with absorption maxima occurring in the ultraviolet range. Transmission values significantly decreased when the laser wavelength was lowered from 1064 nm to 532 nm, and 355 nm. This recommends that the target ablates more readily at shorter wavelengths, which raises the deposition rates. Because of this, sample thickness rose as the wavelength shortened, increasing laser-to-target absorption and intensifying the plasma plume.

4.2. Absorption Coefficient of Al_2O_3 / Quartz Thin Film

In Figure 5, each material has its absorption coefficient; those with greater values absorb incident photons more readily, meaning they excite electrons from the valence band to the conduction band. The peak represents the maximum point of photon absorption at that wavelength, while the lower values represent less efficient photon absorption at that wavelength. The acute point on the absorption coefficient curve indicates insufficient energy in the material to excite an electron between levels [48].

4.3. Energy Gap of AL_2O_3 / Quartz Substrate

The optical energy gap is an essential parameter for investigating thin films' properties and determining whether they can be used as gas sensors. As shown in Figure 6, the value of the direct energy gap (Eg) for the prepared films was derived from the graph relationship between $(\alpha * h\upsilon)^2$ and the energy gap ($h\upsilon$) values for the various wavelengths. The value of the energy gap was 4.5 eV, 5.1 eV, and 5.5 eV at 1064 nm, 532 nm, and 355 nm of laser wavelengths, respectively. The energy gap at 355 nm of laser wavelength was close to the theoretical value of Al_2O_3 (6.2 eV) [49, 50]. It is observed that the energy gap increased with decreased laser wavelength. Shorter wavelengths have higher energy; This leads to the removal of larger particles due to quantum confinement. Table 2 displays the energy band gap values for each laser wavelength.

5. CONCLUSIONS

The results of this work demonstrated that the production of Al_2O_3 thin films on a quartz substrate was accomplished by using a pulsed laser deposition technique. This technique utilized a Q-switched Nd: YAG laser at three distinct wavelengths: 1064 nm, 532 nm, and 355 nm, with a laser wavelength of 532 nm, and then 196 nm at a wavelength of 355 nm in consecutive order. It was determined that the energy of 900 mJ. The absorption peak occurs at 195 nm at

Table 2. Energy gap of Al_2O_3 / quartz thin film at different laser wavelengths (1064 nm, 532 nm, and 355 nm)

Laser Wavelength (nm)	Energy Gap (eV)
1064	4.5
532	5.1
355	5.5

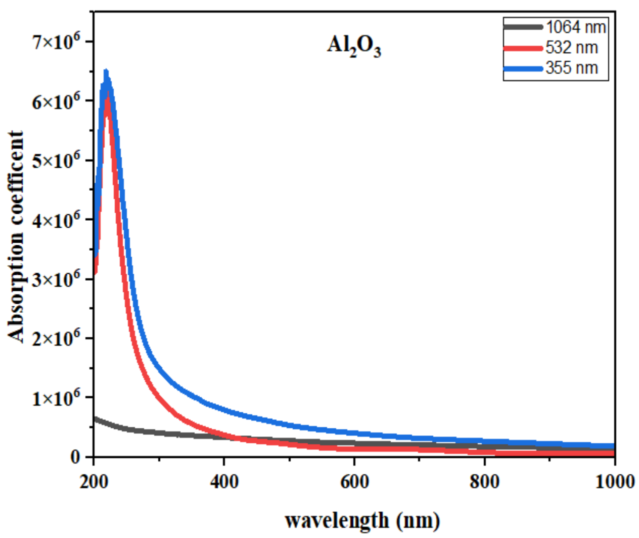

Figure 5. The absorption coefficient of Al_2O_3 / quartz substrate at different wavelengths (1064 nm, 532 nm, and 355 nm)

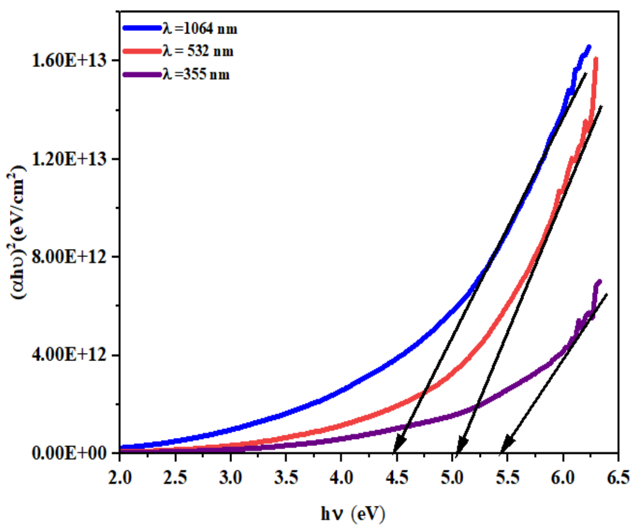

Figure 6. Energy gap of Al_2O_3 / quartz substrate at different wavelengths (1064 nm, 532 nm, and 355 nm)

a wavelength of 1064 nm, followed by 197 nm at a sample had an energy band gap of 4.5 eV (1064 nm), 5.1 eV (532 nm), and 5.5 eV (355 nm) according to the computations. When it comes to the fabrication of Al_2O_3 nanostructured thin film for gas sensing applications, Due to higher absorption, laser deposition equipped with 900 mJ of laser energy and 1064 nm of laser wavelength is the most effective method.

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