Engineering β-Ga_2O_3 Thin Films: The Role of Substrate in Sol-gel Spin-coating Growth

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Abstract*— Gallium oxide (β-Ga_2O_3) is an emerging ultra-wide bandgap semiconductor with potential applications in high-power electronics, optoelectronics, and sensing devices. The properties of β-Ga_2O_3 films are significantly influenced by the choice of substrate, which affects the crystalline structure, morphology, electrical characteristics, and overall film quality. In this study, β-Ga_2O_3 thin films were synthesized using the sol-gel spin coating method on different substrates. The effects of substrate-induced strain, surface roughness, and interfacial chemistry on film morphology, phase composition, and electrical behavior were systematically analyzed. The structural, morphological, and optical properties of the films were systematically analyzed using X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Vis spectrophotometry. XRD analysis revealed that the substrate type significantly affects the phase purity and crystallinity of β-Ga_2O_3. SEM imaging provided insights into film uniformity, surface roughness, and grain structure variations across different substrates. UV-Vis spectrophotometry was used to determine the optical bandgap, which varied slightly based on substrate-induced strain and film microstructure and transparency variations, highlighting the impact of substrate choice on light absorption and transmission. The results indicate that the substrate plays a crucial role in determining the crystallinity and defect density of β-Ga_2O_3 films. The results demonstrate that substrate selection plays a crucial role in optimizing β-Ga_2O_3 thin films for device applications, offering insights into tailoring material properties for specific functionalities. These findings provide insights into optimizing substrate selection for high-performance β-Ga_2O_3-based devices.

Keywords: β-Ga_2O_3, sol-gel method, thermal annealing

I. Introduction

β-Ga_2O_3, a wide-bandgap semiconductor with an energy gap of approximately 4.5-5.0 eV, has attracted significant attention for its potential applications in high-power electronics, ultraviolet photodetectors, and deep-UV optoelectronic devices. Its high breakdown field (~8 MV/cm) and chemical stability make it a promising candidate for next-generation power devices [1]. However, the structural, morphological, and optical properties of β-Ga_2O_3 thin films strongly depend on the choice of substrate and deposition conditions.

Among the various growth techniques, including molecular beam epitaxy (MBE), chemical vapor deposition (CVD), pulsed laser deposition (PLD), and magnetron sputtering, the sol-gel spin coating method offers a cost-effective and scalable approach for fabricating β-Ga_2O_3 thin films with controlled thickness and composition. The choice of substrate plays a crucial role in determining the crystallinity, surface morphology, and optical behavior of the films, influencing their suitability for specific device applications. Silicon (Si), quartz (SiO_2), and sapphire (Al_2O_3) are widely used substrates due to their availability and compatibility with semiconductor processing [2]. While sapphire provides a lattice-matched surface for improved crystallization [3], silicon-based substrates enable potential integration with existing electronic technologies.

In this study, β-Ga_2O_3 thin films were deposited on Si, SiO_2/Si, and sapphire substrates via sol-gel spin coating, followed by annealing to achieve phase formation. The structural, morphological, and optical properties of the films were systematically investigated using X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Vis spectrophotometry. By analyzing the influence of different substrates, we aim to provide insights into optimizing the growth conditions for high-quality β-Ga_2O_3 films tailored for electronic and optoelectronic applications.

II. Experimental Details

A. Materials

Gallium nitrate hydrate [Ga $(NO_3)_3$*H_2O] (99.9%, trace metals, Sigma Aldrich), 2-Methoxyethanol [$C_3H_8O_2$] (≥99.3%, Sigma Aldrich), Ethanolamine [C_2H_7NO] (≥99.0%, Sigma Aldrich) and n-type Si substrate with (100) orientation, HF, DI-water

B. Sample preparation

0.5M Gallium nitrate hydrate was dissolved in 2-methoxyethanol by stirring at 600 rpm for 2h keeping the temperature between 60-80°C until it became clear and homogeneous. Then ethanolamine added to the solution as a stabilizer to control solution viscosity and pH, and stirred in the same speed, without heating for 30min, molar ratio of ethanolamine and gallium nitrate hydrate was kept 1:1. After stirring, the solution was aged for 40 hours at room temperature to improve film uniformity during spin-coating.

SiO_2 buffer layer deposited via dry thermal oxidation method at 1000°C for 1hour in a muffle furnace for isolating Ga_2O_3 film from the silicon substrate. This SiO_2 buffer layer

helps prevent inter-diffusion and reactions during the high-temperature annealing that required for Ga_2O_3 crystallization.

The films were spin-coated at a rate of 3000 rpm for 30 seconds on the Si and SiO_2/Si substrates. After spin coating, the films were kept at 120° C on a hot plate for 10 min and then preheated in a muffle furnace at 500°C for 15 min. Above process was repeated six times. At last, the films were post-annealed at 1100°C in air for 2 hours. The thickness of obtained films was in the range from 80 nm to 150 nm.

III. Result and Discussion

Figure 1 shows the X-ray diffraction patterns of the Si substrate and Ga_2O_3 thin films deposited on different substrates Silicon (Si), SiO_2-grown silicon (SiO_2/Si), respectively.

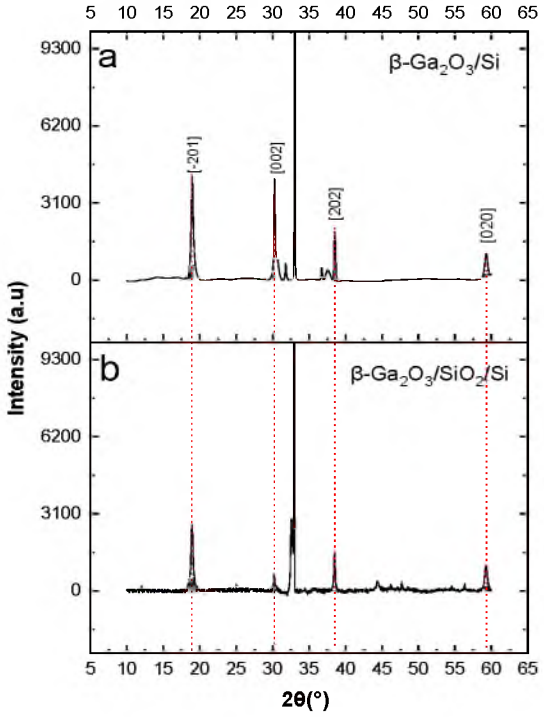

Fig.1. XRD of β-Ga_2O_3 deposited on (a) silicon and (b) SiO_2 grown Si substrates

It is seen from Fig.1, that the XRD pattern for the Si substrate demonstrates clearly (100) peak and (-201), (002), (202), (020) peaks of β-Ga_2O_3 phase. According to the XRD Scherrer analysis the crystal size of β-Ga_2O_3 film on SiO_2/Si larger than grown on Si substrate. But β-Ga_2O_3 film grown on Si shows higher peak intensity which means better crystallinity, while peaks of β-Ga_2O_3 grown on SiO_2/Si substrate are lower that shows more disordered orientation.

The strain due to lattice deformation estimated by modified Williamson - Hall (W-H), namely uniform deformation model (UDM).

The results of the UDM analysis for β-Ga_2O_3 films are shown in Fig.2.

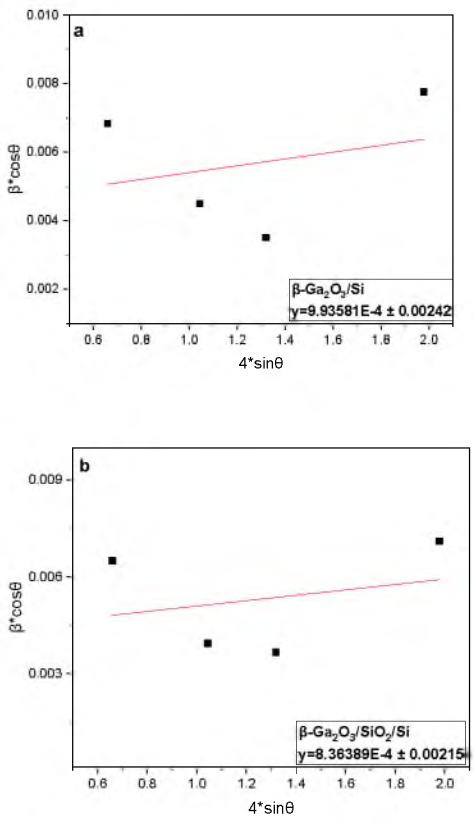

Fig.2. W-H analysis of β-Ga_2O_3 films deposited on (a) silicon and (b) SiO_2 grown Si substrates calcinated at 1100°C for 2h.

W-H analysis confirms that β-Ga_2O_3 grown on SiO_2/Si has lower strain (y=0.000836389) compared to growth on Si (y=0.000993581), indicating that SiO_2 acts as a strain-relieving buffer layer. This reduction in strain promotes larger crystalline size in β-Ga_2O_3 films grown on SiO_2/Si compared to those on Si. The improved crystallinity on SiO_2/Si suggests its potential as a preferred substrate for optimizing β-Ga_2O_3 thin films in electronic and optoelectronic applications.

IV. Conclusion

XRD and strain analysis show that β-Ga_2O_3 on SiO_2/Si has lower strain and larger crystal size, while films on Si have higher strain but better crystallinity and texture. The SiO_2 layer reduces stress, promoting grain growth but causing more misalignment. Thus, Si favors high crystallinity, while SiO_2 supports larger grains with lower strain, making substrate choice application-dependent.

References

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