Heteroepitaxial Growth of an Ultrathin $\beta$-Ga$_2$O$_3$ Film on a Sapphire Substrate Using Mist CVD with Fluid Flow Modeling

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ABSTRACT: $\beta$-Gallium oxide (Ga$_2$O$_3$) has received intensive attention in the scientific community as a significant high-power switching semiconductor material because of its remarkable intrinsic physical characteristics and growth stability. This work reports the heteroepitaxial growth of the $\beta$-Ga$_2$O$_3$ ultrathin film on a sapphire substrate via mist chemical vapor deposition (CVD). This study used a simple solution-processed and nonvacuum mist CVD method to grow a heteroepitaxial $\beta$-Ga$_2$O$_3$ thin film at 700 °C using a Ga precursor and carrier gases such as argon and oxygen. Various characterization techniques were used to determine the properties of the thin film. Additionally, a computational study was performed to study the temperature distribution and different mist velocity profiles of the finite element mist CVD model. This simulation study is essential for investigating low to high mist velocities over the substrate and applying low velocity to carry out experimental work. XRD and AFM results show that the $\beta$-Ga$_2$O$_3$ thin film is grown on a sapphire substrate of polycrystalline nature with a smooth surface. HR-TEM measurement and UV−visible transmission spectrometry demonstrated heteroepitaxial $\beta$-Ga$_2$O$_3$ in an ultrathin film with a band gap of 4.8 eV.

1. INTRODUCTION

This oxide material has been popular in the power semiconductor industry over the last decades. Nowadays, $\beta$-Ga$_2$O$_3$ has made a strong footprint in the power semiconductor research fields due to its excellent material physical properties such as ultra-wide band gap (4.6−5.3 eV), high critical breakdown voltage, and large Baliga’s figure of merit. Ga$_2$O$_3$-based FET and SBD devices are made thinner and lighter and capable of handling more power than existing semiconductor materials such as SiC and GaN. $\alpha$-Ga$_2$O$_3$ has a family of different phases, such as $\alpha$, $\beta$, $\epsilon$, $\delta$, and $\lambda$. Hexagonal crystal structure $\alpha$-Ga$_2$O$_3$ has a band gap of 5.3 eV and metastable phase, whereas the monoclinic structure $\beta$ phase (4.8 eV) is thermodynamically stable and widely available in bulk and the thin-film epitaxial form. $\beta$ gallium oxide growth technology is very long and promising due to material availability in bulk form and growth stability than the $\alpha$ phase.

High-quality $\beta$-Ga$_2$O$_3$ thin films are heteroepitaxially grown on different substrates Si, GaAs, MgO, and $\alpha$-Al$_2$O$_3$ via various successful growth methods such as molecular beam epitaxy, low-pressure chemical vapor deposition, metal-organic vapor phase epitaxy, halide vapor phase epitaxy, pulsed-laser deposition, hot wall metal-organic CVD, and RF magnetron sputtering. The low-cost sapphire substrate has a very large band gap (8.1 eV). It is a widely used substrate to grow high-quality heteroepitaxial $\alpha$-Ga$_2$O$_3$ via the mist CVD method for commercializing power device applications. Mist CVD is very popular for growing the $\alpha$ phase than $\beta$-Ga$_2$O$_3$ on the c-plane sapphire substrate. It is difficult to develop a very uniform and high-quality $\beta$ phase due to the significantly large lattice mismatch (6.6%) between $\beta$-Ga$_2$O$_3$ and the sapphire substrate. Hence, there is a lack of substantial studies on mist CVD-grown heteroepitaxial $\beta$-Ga$_2$O$_3$ films grown on the c-plane sapphire substrate at this particular growth temperature. Recently, Cheng et al. reported the $\beta$-Ga$_2$O$_3$ thin film (surface roughness 6.4 nm) grown on a sapphire substrate at 750 to 950 °C growth temperatures using a buffer layer of $\beta$-(Al$_{x}$Ga$_{1-x}$)$_2$O$_3$. Ultrathin films are in high demand in the aerospace and...
defense industry because of their many benefits for miniaturized devices, including increased speed, power, efficiency, and reduced weight. Our study focused on achieving a better surface quality $\beta$-Ga$_2$O$_3$ ultrathin film at 700 °C growth temperature with low mist velocity.

The thin-film material surface quality and thickness can be obtained by adequately controlling the growth parameter in the chemical vapor deposition (CVD) methods. The finite element method (FEM) is utilized to compute the temperature distribution and mist flow profile inside the 2d-geometrical mist CVD model. This simulation is the foundation of the mist CVD experiment framework and clearly explains the mist CVD growth process. The ultrathin $\beta$-Ga$_2$O$_3$ film could be more applicable in the aerospace industry. Material crystallinity, surface roughness, thickness measurement, surface element composition, and material optical property were investigated using characterization tools (including XRD, AFM, HR-TEM, XPS, and UV-visible transmission and PL spectroscopy). The simulation study and experimental characterizations will be reported in the following sections.

2. METHODS

2.1. Computational Methods. The simulation studies were performed using the commercial FEM package of COMSOL Multiphysics 5.5 for a better understanding in the chamber temperature distribution and mist flow velocity behavior in the deposition process for this experimental study. We have modeled a two-dimensional geometrical mist CVD setup to carry out our simulation work. This study used chemistry (chem), laminar flow (spf), transport of diluted species (tds), and heat transfer at the fluid (ht) interfaces. Argon gas is used as a carrier gas material in the growth chamber.

The reaction kinetics and physical properties of the species are modeled with the chemistry interface in the chemical reaction engineering module. In the reaction node, bulk species such as gallium acetylacetonate (A), in combination with solvent species, water (B), produces the bulk species gallium complex mist (C). Furthermore, the gallium complex mist was transported via the transport of the diluted species interface. The convection transport mechanism is adapted to carry out the mist to flow into the chamber. The argon gas is added with the chemistry species to transport species. In addition, the inflow concentration and outflow boundary conditions are defined.

The Navier-Stokes equation is used to compute the velocity of a single-phase fluid in the laminar flow region. The inlet velocity with the boundary conditions was set on the fully developed flow mode. The heat transfer interface describes heat flow (thermal energy) due to temperature differences and the subsequent temperature distribution and changes in the presence of mist. The external heat source in the growth chamber is the heat source given, and further inner heat flux is set. Temperature 1 is a surrounding surface with 475 K (200 °C). Temperature 2 is set to a furnace temperature of 973 K (700 °C).

Finally, the physics-controlled standard mesh is used to build the model to obtain the temperature and velocity profiles with and without mist. To couple multiphysics, the non-isothermal flow node is used to couple the laminar flow and heat transfer in fluids and the reacting flow diluted species node is used to couple laminar flow and transport of diluted species. The steady-state study is performed to obtain the temperature and velocity profiles with and without mist in the presence of carrier gas. The abovementioned four interfaces are executed to obtain temperature and velocity distribution with mist. The heat transfer and laminar flow interface are solved using the stationary study by disabling the chemistry and transport of the diluted species interface. The mist density depends on the temperature. Buck’s equation explains the saturation vapor pressure $P_s(T)$ ($P_j$) as a function of temperature $T$ (°C)$^{51}$

$$P_s(T) = 611.21 \times \exp\left[18.678 - \frac{T}{234.5}\right]$$

(1)

The mist density $\rho_{\text{mist}}(T)$ was estimated by adding the densities of dry air and water vapor as follows

$$\rho_{\text{mist}}(T) = \frac{\rho_s(T)H_R}{R_s(T + 273.15)} + \frac{\rho - \rho_s(T)H_R}{R_s(T + 273.15)}$$

(2)

where $H_R$ is the relative humidity, $p$ is the total pressure, and $R_s = 461.495$ (J/kgK) and $R_v = 287.058$ (J/kgK) are the specific gas constants of the water vapor and the dry air, respectively. The viscosity, thermal conductivity, and specific heat capacity of the mist were specified based on the report by
In our setup, it was estimated that the mist would be 60% humid.

2.2. Experimental Method. Figure 1 illustrates a schematic representation of the mist CVD growth process. The hot wall of the mist-CVD system consists of three essential components: mist vaporization, carrier gas transport, and deposition zone. For the Ga$_2$O$_3$ mist preparation, the precursor mist source is a 0.02 mol concentration of Ga(C$_5$H$_7$O$_2$)$_3$ (0.7341 gm) dissolved into 100 mL of deionized water. The thermal decomposition of acetylacetonate compounds accomplishes gallium oxide formation. Such a solution was obtained by dissolving a Ga metal in HCl. More HCl was added periodically to maintain vigorous hydrogen evolution on the sapphire substrate. Commonly, nitrogen (N$_2$) was obtained by dissolving a Ga metal in HCl. More HCl was added periodically to maintain vigorous hydrogen evolution on the gallium surface. The concentration of residual hydrochloric acid in the solution was almost zero. This means that most of the Ga ions in this gallium chloride solution were expected to form the hexahydrate complex [Ga(H$_2$O)$_6$]$^{3+}$ + 3Cl. Most Ga ions in the solution form hexahydrate complexes [Ga(H$_2$O)$_3$ + 6Cl$^-$]$_{33,34}$ An ultrasonic transducer of 1.7 MHz frequency atomizes the gallium precursor to produce mist in the mist generation unit. This mist was transferred to the furnace chamber with the help of argon (Ar) carrier gas and deposited on the sapphire substrate. Commonly, nitrogen (N$_2$) is utilized as a carrier gas in the process, but we employ Ar as a carrier gas in the thermal chamber to carry mist. Ar and N$_2$ are both effectively nonreactive. However, Ar is a monatomic gas which is inert to chemical reaction. Ar gas is heavier than nitrogen, so it is easy to transport the large mist volume to the deposition chamber. Before starting deposition, the α-Al$_2$O$_3$ substrates were rinsed with IPA, acetone, ethanol, and deionized water for 10 min each at room temperature. The Ga$_2$O$_3$ thin film on the sapphire substrate was obtained at a growth temperature of 700 °C (973 K) in the Ar and oxygen (O$_2$) atmosphere for 1 h. A horizontally placed quartz glass tube with a length and diameter of 60 and 5 cm, respectively, is placed on the thermal resistive heater. This reaction quartz tube inlet and outlet diameter is 0.5 cm. A mist generator and a ventilation fan are linked to the quartz tube input and outlet. This inlet and outlet position is in the middle of the quartz tube. A 1 × 1 cm$^2$ substrate is placed horizontally in the middle of the furnace tube. The utilized β-Ga$_2$O$_3$ thin-film growth parameters are listed in Table 1.

### Table 1. Growth Parameters of the β-Ga$_2$O$_3$ Thin Film

| Parameter               | Value                                      |
|------------------------|--------------------------------------------|
| source chemical        | Ga(C$_5$H$_7$O$_2$)$_3$                    |
| concentration          | 0.02 mol L$^{-1}$                          |
| solvent                | HCl, DI water                             |
| furnace temperature    | 700 °C (973 K)                             |
| growth time            | 1 h                                        |
| voltage and current    | 12 V, 0.23 A                              |
| substrate              | α-Al$_2$O$_3$                              |
| carrier gas Ar and O$_2$ | 250 and 100 SCCM                           |
| ultrasonic transducer  | 1.7 MHz, 24 V, 0.6 A                       |
| inlet and outlet diameter | 60 & 5 cm                                  |

The microstructure of the grown epilayer crystallinity was determined using X-ray diffraction measurements (HR-XRD, Smart lab, Rigaku, Japan) with a copper (Cu) wavelength source ($λ$ = 1.54056 Å). Park system atomic force microscopy (AFM) characterizes the thin-film structural morphology. Transmission electron microscopy determines the thin-film cross-sectional thickness (HR-TEM, Talos L120C). The surface chemical states of the material were characterized by an X-ray photoelectron spectroscopy (XPS, PHI Quantera II) system. A monochromatic Al K-α (1486.6 eV) at 25 W (15 kV and 3 mA) was used with incident angle and sample surface under base pressures of 90° and 2 × 10$^{-7}$ Pa, respectively. Perkin Elmer 350 dual beam UV-vis spectroscopy was used to determine the optical transmission spectra of the materials. Photoluminescence spectra were recorded to study material optical properties by a HeCd laser with an excitation wavelength and laser power of 325 nm and 5 mW, respectively.

3. RESULTS AND DISCUSSION

3.1. Temperature Distribution and Mist Flow Profiles.

The primary goal of this mist CVD FEM analysis is to investigate the temperature with different velocity profiles of mist carried gas Ar. This study provides flow behavior which is applied to the experimental approach. Gallium complex mist is produced by the reaction of gallium acetylacetonate with the solvent DI water. As previously stated, the surface and surrounding two temperature zones have been established. Figure 2a,b shows how a stationary study solves the temperature distribution without mist in carrier gas Ar and Ar gas flow inside the chamber. The temperature of the furnace tube increases to a maximum of 973 K (700 °C). In contrast, the temperature on the other side of the furnace remains low at 473 K (200 °C). The carrier gas Ar of constant flow rate (250 scm) does not affect the temperature distribution in the furnace.

Experimental work is related to the computational study of the mist CVD flow mechanism under growth temperature. We have computed the different mist carried gas Ar flow rates (250, 350, and 500 scm) to optimize the flow rate for experimental growth. Figure 2c–h shows the temperature distribution and mist velocity fields in the quartz tube with a moderate mist flow rate (250–500 scm). In Figure 2c, low-velocity mist significantly influences the temperature in the deposition chamber. Because of the positive temperature gradient, mist moves downhill near the inlet and eventually reaches the ground surface (Figure 2d). After that, mist creates a vortex along the tube top wall and moves down toward the substrate. In the growth chamber, the magnitude of mist flow velocity increases gradually over the substrate surface which can be seen in Figure 2j. While mist exits the heating zone, the mist floats to the top of the quartz tube due to the negative temperature gradient. The flow changed only when the mist almost arrived at the outlet; at this point, the position was changed from the upper to the lower side. In Figure 2e, at the medium mist flow rate (350 scm), mist moves in the furnace tube with lower to upper movements. Figure 2g,h shows the high temperature distribution across the chamber and high velocity mist flow rate (500 scm) in the quartz tube. Here, mist flows along the top wall of the tube due to high velocity and then tends to flow downward. During this time, mist flows along the substrate surface and leaves out with downward movements. This study compares the low- and high-velocity mist flow movements and their respective temperature distribution profile. In every cases, it is noticeable that mist particles adequately adsorb on the substrate.
mist carrier Ar flow has the same velocity throughout the substrate surface. Low and medium velocity behavior is similar, and their value is very close to each other. Lower mist velocity is expected to be applicable to carry out mist CVD experimental work of growing the $\beta$-Ga$_2$O$_3$ epilayer on the sapphire substrate.

3.2. Material Characterization Results. Figure 3a shows the XRD diffraction pattern of the bare sapphire substrate and polycrystalline microstructure of the pure phase of the $\beta$-Ga$_2$O$_3$ generated at 700 and 800 °C temperatures. At this 700 °C temperature, the most notable crystalline diffraction peaks $2\Theta = 18.5, 37.56$° (it shifted to 38.4° for $\beta$-Ga$_2$O$_3$), and 58°, which belong to the (−201), (40−2), and (−603) planes of the monoclinic $\beta$ phase and lattice parameters of $a = 12.23$ Å, $b = 3.04$ Å, and $c = 5.80$ Å and $\alpha = \beta = 90$° and $\gamma = 103.71$°. Other three very intense and distinct crystallographic peaks at $2\Theta = 21.00, 41.69$, and 64.5° can be recognized as the (0003), (0006), and (0009) Bragg reflections of the corundum structure c-plane sapphire, respectively. This result demonstrates that the $\beta$-Ga$_2$O$_3$ (−201) plane is parallel to that in the sapphire (0001) plane. The lattice constants of $\alpha$-Al$_2$O$_3$ are $a = 0.476$ nm and $c = 1.29$ nm. The distance between oxygen atoms is 0.275 nm for $\alpha$-Al$_2$O$_3$ (0006) and 0.304 nm for $\beta$ (−2 01). On the other hand, no significant diffraction peaks were found for the sample grown at 800 °C. At this temperature, very low order diffraction peaks of 44.35 and 58.7 °C are associated with the $\beta$ phase of the Ga$_2$O$_3$ (−601) and (−603) orientation. This low-order polycrystalline phase develops because the high substrate temperature likely breaks the atomic order.

Figure 3b illustrates the AFM scan Ga$_2$O$_3$ thin-film surface quality at growth temperatures of 700 °C over a 5 × 5 μm$^2$ sample area. Here, so many peaks of different crystal orientations are randomly distributed over the surface area. Several nuclei appear to be growing independently on the surface nature. At 700 °C, the thin-film surface average root mean square (RMS) value is 2.3 nm, and the surface roughness value is 1.9 nm. It indicates a smooth surface and helps to reduce disorder with lattice parameters and crystalline structure mismatch between the $\beta$-Ga$_2$O$_3$ and sapphire. These microscopic peaks have height of 5 nm. Thereby, this result suggests that the crystalline thin film gives a better surface texture. We conducted further study with a 700 °C sample due to higher crystallinity and better surface quality. This can be explained by the fact that an increase in temperature can make suboxide species (such as Ga$_2$O$_3$) easier to desorb from surfaces, which means that less suboxide species can be further oxidized to generate Ga$_2$O$_3$. The
improvement in surface roughness could be the result of increased adatom diffusion at high temperatures.

High-resolution transmission electron microscopy (HR-TEM) defined the cross-sectional view of Ga$_2$O$_3$ on the sapphire substrate. Figure 4a,b shows the HR-TEM images of the deposited polycrystalline Ga$_2$O$_3$ thin films on the α-Al$_2$O$_3$ substrate in 5 to 50 nm window regions. In Figure 4b, TEM images show the ultrathin Ga$_2$O$_3$ film obtained in 5 to 6 nm with a growth rate of 0.041 nm/min. Our previous study showed the 20 nm thin mixed-phase Ga$_2$O$_3$ film grown on the sapphire substrate at 470 to 600 °C. In this study, we achieved an ultrathin (5 nm) film of the pure β phase at 700 °C, but this phase transition does not correlate with thickness. This indicates that the growth rate is much slower in this mist CVD growth process. Several studies reported that the growth rate decreases with decreased flow rate. One possible reason for the lower growth rate is the lower flow rate of Ar carrier gas having lower driving energy to transport Ga mist flow into the deposition chamber and low adsorption over the surface. A lower density of the mist atom vapor phase solidified with activation energy to form the β phase oxide thin film. Here, growth controlling parameter mass transport and atom reaction occurred nonuniformly across the growth surface area. As can be seen in Figure 4d, single-area electron diffraction (SAED) provides a clear view of the interfacial region between the polycrystalline Ga$_2$O$_3$ and Al$_2$O$_3$, revealing that the monoclinic phase (−201) planes have an estimated...
interplanar d spacing of 0.44 nm, which is strongly validated by the XRD pattern. Several factors influence particle crystal formation. In this case, the transition from the hexagonal to monoclinic phase and atomic reconstruction at the interface lead to a polycrystalline or amorphous phase. As a result of this heteroepitaxial growth process, irregular atomic arrangements can be seen at the interface of the material. A closer look at the magnified TEM image of this layer indicates that it is not a mix of Al₂O₃ and gallium oxide layer. The rectangular diffraction patterns of Ga₂O₃ were perpendicular to the sapphire in the dark field virtual image, and these diffraction spots are pretty distinct, with a regular order of uniform distance. The SAED analysis indicated the presence of diffraction plane (−201) of β-Ga₂O₃ with good crystallinity on the Al₂O₃ surface.

Energy-dispersive X-ray spectroscopy (EDAX) was used for a cross-sectional view of the Ga₂O₃ sample elemental mapping and atomic percentage, as portrayed in Figure 5a–f. The EDX results show the chemical atomic percentage for each Ga, O, Al, and Pt of 1.20, 26.19, 34.84, and 37.76, respectively (Figure 5b). Here, Pt was coated on top of the thin film for a better interface. This finding shows that the Ga atomic percentage is a significantly lower value of 1.20 than other elements present. It is noted that an EDX high O element atomic percentage of 26.60 atomic % may represent both the Ga₂O₃ thin films and α-Al₂O₃ substrate. We can validate the presence of Ga₂O₃ thin films formed on the α-Al₂O₃ substrate based on the EDX study (distribution of O and Ga).

We have conducted XPS analysis, a surface-sensitive tool to determine the surface element atomic composition of the gallium oxide films formed at 700 °C. Ga and O composition is 46 and 38%, respectively. β-Ga₂O₃ comprises 44% Ga (III) and 59% O, as reported in Figure 6a. The photoelectron and Auger electron peaks for gallium and oxygen with carbon contamination can be seen in this spectrum. This carbon contamination arises from the oxygen functional carboxyl group of the sample surface. In Figure 6a, XPS characterization survey spectra clearly show Ga (Ga 2p, Ga 3s, Ga 3p, and Ga 3d, Ga LMM Auger), oxygen (O 1s and O 2s, O KLL Auger), and carbon (C 1s, CKVV Auger). The C 1s signals indicate carbon adsorbed on the sample surface during the ex-situ XPS measurement process. C 1s peak binding energy exists on the surface at 284.8 eV, which comes from contamination, particularly during energy calibration of the whole spectrum. Figure 6b shows the curve-fitting findings of the high-resolution Ga 3d core level spectrum, and the binding energy is ∼20.2 eV. Ga 3d electrons have higher kinetic energy and a deeper sampling depth than the low kinetic energy Ga 2p electrons. The Ga 3d core spectrum peak consists of Ga 3d₅/₂ and Ga 3d₃/₂, and their respective binding energies are 19.9 and 20.5 eV. The O 2s core level is a weak peak at higher binding energy (24.20 eV). As a result, this O 2s contribution may have a minor effect on the Ga 3d raw area, resulting in an overestimated Ga atomic concentration. A contribution from the oxygen 2s core level could also explain the modest and broad tail on the upper energy side of the prominent peak (at 24 eV). Figure 6c shows that the Gaussian fitting O 1s peak is deconvoluted into three subpeaks at 530.6, 531.7, and 533.4 eV, denoted as O₁, O₂, and O₃, respectively, where O₁ represents

**Figure 5.** (a) TEM–EDX measurement of a cross-sectional Ga₂O₃/Al₂O₃ interface image and the (b) EDX pattern of the elements Ga, Al, O, and C (inset. compositional atomic and weight percentage data). (c) Ga, (d) O, (e) Al, and (f) Pt element composition distributions are shown in different colors.
Figure 6. (a) X-ray photoelectron survey spectrum of the gallium oxide thin film. (b) Ga 3d curve fitting peaks. (c) O 1s curve fitting peaks.

Figure 7. (a) Optical transmittance spectrum of the β-Ga$_2$O$_3$ film grown on the sapphire substrate at 700 °C. The insets show Tauc plots of $(\alpha h\nu)^2$ as a function of photon energy $E$ for the β-Ga$_2$O$_3$ samples. (b) Photoluminescence spectra of the Ga$_2$O$_3$ thin film on the sapphire substrate at RT.
Ga–O bonding, $O_3^-$ represents O$^2-$ ions of surface oxygen vacancies, and $O_{3\text{III}}$ could be assigned to the C–O bond. In addition, another 529.7 eV is attributed to the O 1s satellite peak.

Figure 7a shows an absorbance vs. wavelength graph in the UV–vis spectrum, quantifying transitions from the ground to an excited state. In contrast, photoluminescence deals with transitions from the excited state to the ground state. Optical transmissibility of the Ga$_2$O$_3$ thin film was characterized from 200 to 800 nm at room temperature using a UV–visible dual-beam spectrometer, and sapphire substrate was used as a reference, as shown in Figure 7a. In the visible areas, this Ga$_2$O$_3$ sample shows high transmissibility of nearly 85%, and transmission nature began to decrease significantly from the visible to UV region. The absorption edge of the β-Ga$_2$O$_3$ thin-film sample shifted to a shorter wavelength. This characteristic shows the blue shift absorption edge in the transmission spectrum. The sharpness of the absorption edges indicates the crystalline nature of the β-Ga$_2$O$_3$$_\beta\alpha$, suggesting high-quality thin films. The better transmissibility provides high crystalline quality. The β-phase Ga$_2$O$_3$ behaves as near direct band gap semiconductors, and the Ga$_2$O$_3$ band gap may be calculated using the Tauc equation. The Figure 7a inset shows the Tauc equation, in which the absorption coefficient, $\alpha$ is proportional to the optical band gap, $E_g$.

\[
\text{Tauc equation, } (\alpha h\nu)^n = A(h\nu - E_g) \tag{3}
\]

where $n = 2$ (direct allowed transitions) and $n = 1/2$ (indirect allowed transitions). Here, $A$ is the constant and $h\nu$ is the photon energy. The $E_g$ can be extracted by extracting the linear region of Tauc’s plot. The excellent band gap value of the β-Ga$_2$O$_3$ thin-film was 4.87 eV at a grown temperature of 700 °C.

Figure 7b shows the PL spectra of the β-Ga$_2$O$_3$ thin-film at room temperature, and a prominent UV-blue emission band is noticeable. PL intensity can be reduced or varied due to two factors: nanostructure density on the substrate surface and nanostructure surface defects. It is difficult to identify the causes of the observed decrease in PL intensity. If the density of the nanostructure changes, only then does the PL intensity change without any noticeable difference in the intensity of the UV–visible region. Gaussian-fitted two PL spectra at the UV region (360 nm) and blue region (~465 nm) are recorded. $\alpha$-$\beta$ Binet and Gourier can report the expansion of the UV luminescence at 300 K. According to this model, electrons and holes are not trapping and can migrate through the solid and meet to form a self-trapped exciton which recombines and emits a UV photon. The relative intensity of the UV and blue luminescence only gives information about the surface defects. The emission from the blue region shows a weak peak of 465 nm (2.76 eV), which is induced by the recombination of an electron trapped in acceptor gallium or acceptor gallium oxygen vacancy with a trap hole in an acceptor oxygen vacancy.

4. CONCLUSIONS

The mist CVD method can be used to successfully grow the lower surface roughness β-Ga$_2$O$_3$ ultrathin films on the α-Al$_2$O$_3$ substrate at a temperature of 700 °C. The mist CVD mechanics are modeled using FEM to break down the bulk species into a mist for thin-film deposition in the presence of carrier gas. Furthermore, different mist velocity profiles were obtained from COMSOL simulation study and the lowest flow rate of 250 sccm (velocity 0.0021 m/s) was applied in the experimental study of the β-Ga$_2$O$_3$ ultrathin-film growth. The different characterization techniques confirmed the pure β phase of Ga$_2$O$_3$ thin films formed on the sapphire substrate surface. XRD findings show that the polycrystalline β phase was grown on the sapphire substrate. AFM and HR-TEM results show a uniform and smooth surface of the ultrathin (~6 nm) Ga$_2$O$_3$ film formed on the sapphire substrate. The UV–visible characterization demonstrates an obtained optical band gap of 4.87 eV. The mist CVD is a promising method for developing a uniform and ultrathin β-Ga$_2$O$_3$ film that may find new semiconductor applications.

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Notes
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