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Liquid Phase Deposition of Al_2O_3 Thin Films on GaN

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Much attention has been focused on replacing SiO_2 with Al_2O_3 as a dielectric insulation film for semiconductor device applications due to the latter's large band gap (~9 eV), higher dielectric constant (k = 10), high breakdown electric field (5 -10 MVcm^{-1}), good thermal stability (amorphous up to 1000o C), chemical stability against AlGaN (without inter-diffusion and interaction of Si and Al), and lower lattice mismatch to GaN. Because of these properties, ultra thin alumina films of nanometer scale are widely used as high-k material to replace SiO_2 in microelectronic devices such as dynamic random access memories (DRAMs) and metal-oxide semiconductor field effect transistors (MOSFETs) based on both Si and III-V compound semiconductors.
Many conventional methods for fabricating Al_2O_3 films are described in different papers, including thermal oxidation, metal organic chemical vapor phase deposition (MOCVD), direct current reactive magnetron sputtering, photo luminescent alumina films by pyrosol process, and atomic layer deposition (ALD) process. The growth of Al_2O_3 thin films as achieved by the above-mentioned techniques involves high substrate temperatures (>750℃). This causes thermal strain and defect states in the semiconductor oxide interface, which in turn degrade device performance. In this study, our aim was to deposit the thin Al_2O_3 insulating layer for GaN MOSHEMT device application to reduce the gate leakage current.

This LPD deposition system contains a temperature-controlled water bath that offers a uniform deposition temperature with ± 0.1℃ accuracy, a substrate holder, a Teflon beaker, a magnetic stirrer for the high homogeneity of the growth solution, a pH meter. Aluminum sulfate ($Al_2(SO_4)_3.18H_2O$) was placed in a Teflon beaker, and a small amount of water was added to form a nearly saturated solution of $Al_2(SO_4)_3$ as a source liquid. After the addition of $NaHCO_3$, the hydrolysis of Al^{3+} particles and the concentration of $Al(OH)_3$ colloid particles increased. As soon as the reaction was completed, de-ionized water was immediately added in order to increase the pH value to 3.80, which is the optimized pH value used for the deposition of an alumina film. The growth solution was transparent, and all the parameters were optimized with $Al_2(SO_4)_3$ = 0.0834 mol/L and $NaHCO_3$ = 0.211 mol/L (final concentrations). The chemical reaction of film growth can be described in the following:

$$Al_2(SO_4)_3 + 6NaHCO_3 \xrightarrow{\Delta} 2Al(OH)_3 + 3Na_2SO_4 + 6CO_2 \uparrow$$
$$2Al(OH)_3 \longrightarrow Al_2O_3 + 3H_2O$$

Fig. 1 shows the film thickness of Al_2O_3 with deposition time at different growth temperatures. It was observed that after more than 3 h, the pH value decreased from 3.80 to 3.67, and the solution slowly started to become turbid due to the precipitation phenomenon of $Al(OH)_3$. The slight decrease in pH value was caused by the consumption of $NaHCO_3$ in the reaction.

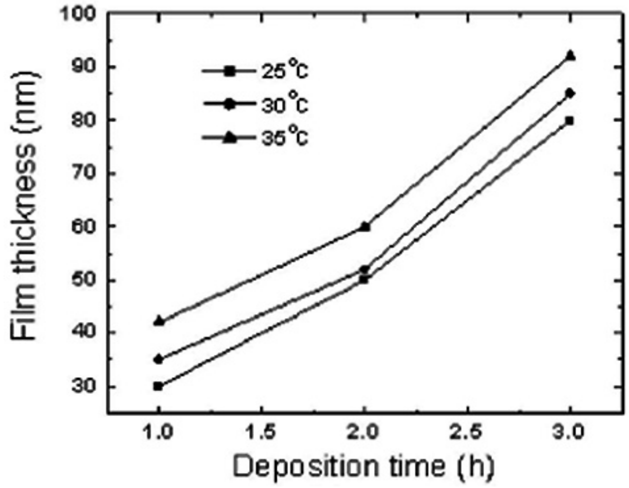

Fig. 1 film thickness vs deposition time

Temperature was also a big factor in controlling film growth quality and deposition rate. At a higher temperature (i.e., 40℃), film quality became poor, and the growth solution quickly became turbid. For different oxide thicknesses, the refractive index of the deposited samples varied from 1.50 to 1.65.

Fig. 2 displays the surface morphologies of oxides on GaN for different annealing temperatures. The AFM data (the scan rate was 1.3 Hz, and the set point was 0.158 V) shows that the root mean square surface (RMS) roughness of a 50 nm-thick Al_2O_3 film was (height modulation in the 2×2 μm2) only 1.025 nm after high-temperature annealing at 750℃, which was very low as compared to SiO_2 on a GaN substrate (5.2 nm). The surface morphology was improved after high-temperature annealing. Therefore, this smooth surface result provides potential for GaN MOS-HEMT device applications.

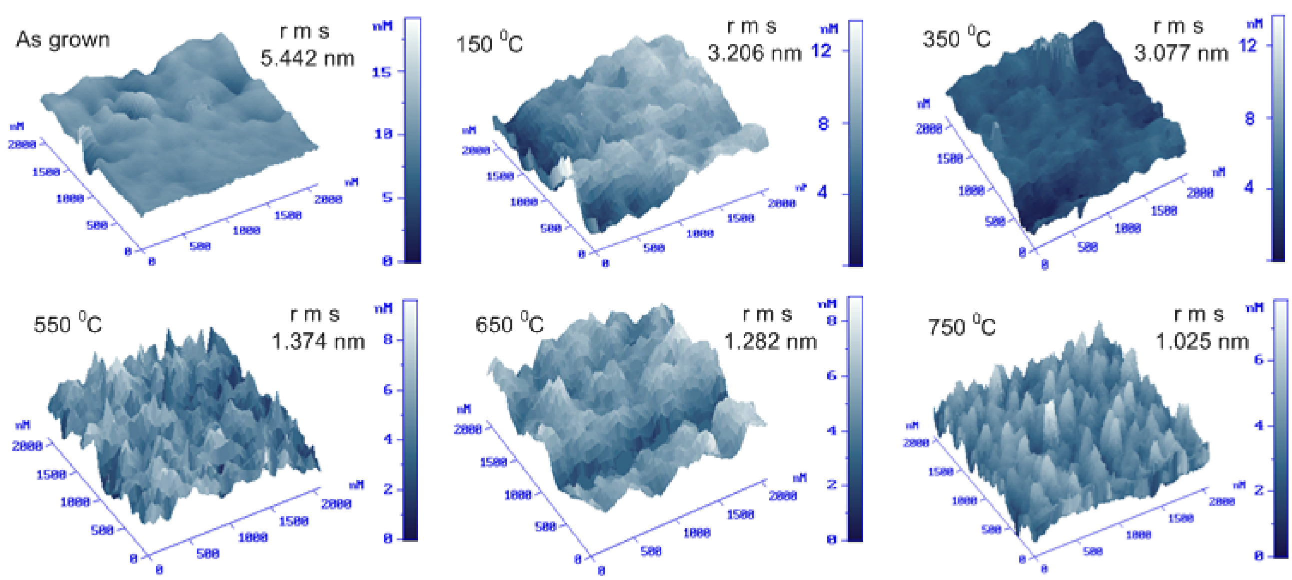

Fig. 2 AFM (3D image) surface morphology of Al_2O_3 oxide deposited on a GaN substrate for different annealing temperatures in N_2 ambient for 30 mins.

Fig. 3(a) shows the typical leakage current density of LPD-grown Al_2O_3 thin film on GaN annealed at 150℃ for 30 mins. At an electric field of 1 MV/cm, the corresponding leakage current densities ranged from 10^{-4} to 10^{-5} A/cm^2. The breakdown electric field was more than 10 MV/cm for a 50 nm oxide thickness. Furthermore, the leakage current density could be improved by a high-temperature annealing of oxide films. Fig. 3(b) shows the improvement of leakage current density with a higher annealing temperature in N_2 ambient. After annealing at 750℃, the leakage current density was reduced to the order of 10^{-6} to 10^{-7} A/cm^2 at an electric field of 1 MV/cm. This leakage current density of thin Al_2O_3 film on GaN was quite comparable or better than that of SiO_2 on GaN and Al_2O_3 on Si by sputtering. However, the result shows that the breakdown field was higher.

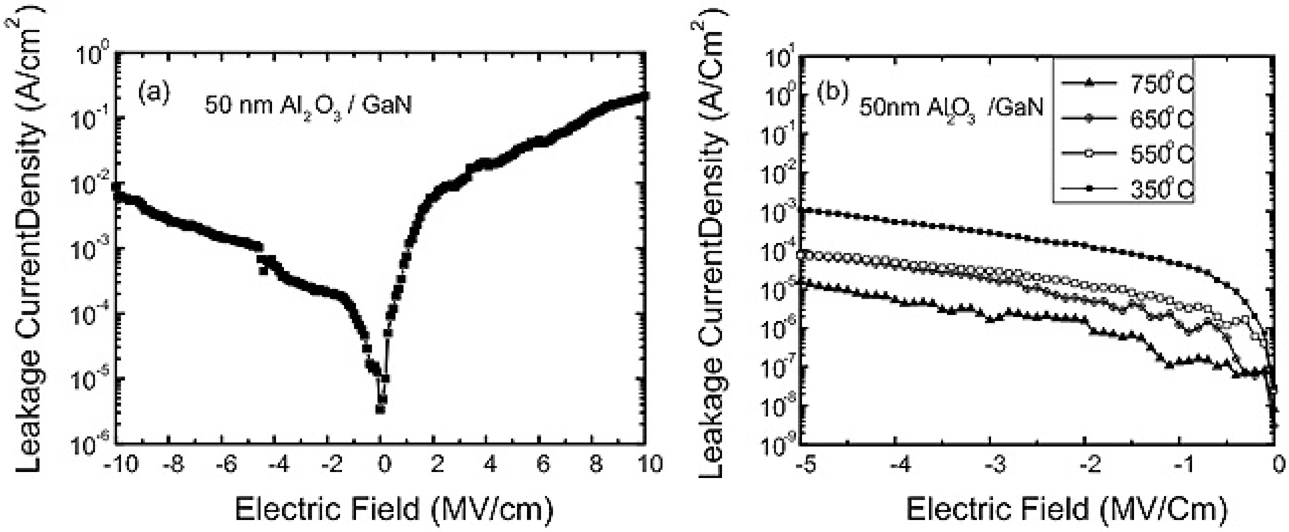

Fig. 3 (a) The log I-V characteristics for the 50 nm-thick Al_2O_3 on GaN annealed at 150℃ for 30 mins. (b) The improvement of leakage current densities with varying annealing temperatures.

Fig. 4 shows the typical C-V characteristics measured by 4280A at frequency 1 MHz. The thin line and thick solid lines in Fig. 8 represent the experimental results of the as-grown and annealed films at 150℃ for 30 mins in N_2 ambient, respectively. The approximate curve of ideal C-V characteristics based on theoretical calculation is also shown in broken lines. The interface charge density (D_{it}) and flat-band voltage (V_{FB}) can be determined by employing the equation $D_{it} = C_{ox}/q\ [(d¢_s/dV)^{-1}-1] - C_D/q$, where C_{ox} and C_D are the oxide and depletion capacitance, respectively. The surface potential ($¢_s$) is the potential difference across the space charge layer. At $¢_s = 0$, the applying bias voltage represents the V_{FB}. According to the plot and calculated results, the V_{FB} was +2 V and +0.2 V for the as-grown and annealed samples, respectively. The

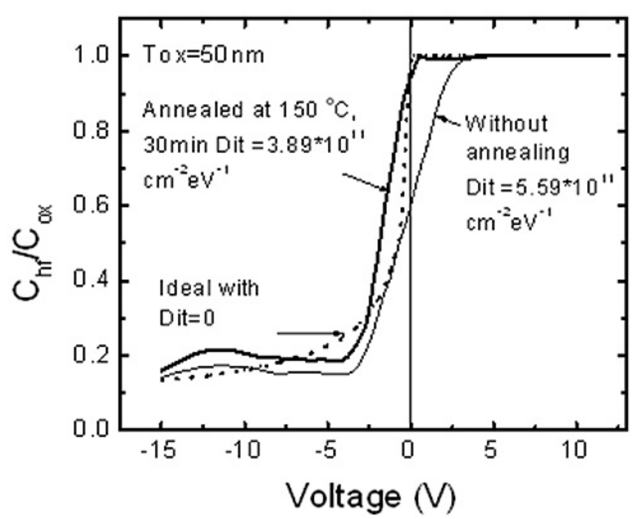

Fig. 4 The measured and ideal C-V characteristics at 1 MHz.

calculated interface trap densities were 3.89×10^{11} $cm^{-2}eV^{-1}$ for an oxide thickness of 50 nm on GaN annealed at 150℃ (30 mins) and 5.59×10^{11} $cm^{-2}eV^{-1}$ for the as-grown oxide film. Thus, after annealing, the average D_{it} near the mid gap of the LPD-grown oxide was reduced from 5.59×10^{11} $cm^{-2}eV^{-1}$ to 3.89×10^{11} $cm^{-2}eV^{-1}$.

In summary, we have achieved a low-cost, more efficient, and low-temperature (~30℃) liquid phase deposition of Al_2O_3 thin films on GaN. The refractive index and relative permittivity of oxide were 1.55 and 9.7, respectively. Moreover, the results showed that in terms of AFM pattern, leakage current density, breakdown electric field, and interface trap charge density, this LPD-Al_2O_3/GaN method provides a unique opportunity to make high-quality gate dielectrics for GaN MOSFET applications.