Electronic Materials Letters, Vol. 5, No. 2 (2009), pp. 83-86
DOI: 10.3365/eml.2009.06.083

Fabrication and Properties of AlN Film on GaN Substrate by Using Remote Plasma Atomic Layer Deposition Method

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AlN films on *n*-type GaN (0001) were prepared using a remote-plasma atomic-layer-deposition (RPALD) technique with a trimethylaluminum(TMA) precursor and nitrogen/hydrogen, argon/hydrogen radicals ranging in temperature from room temperature (RT) to 500°C. The growth rate per cycle was varied with the substrate temperature from 2.3 Å/ cycle at R. T. to 0.9 Å/cycle at 500°C. X-ray diffraction results showed that the as-grown AlN films on GaN substrates had amorphous phase structures. The estimated interface trap density measured was about $2.4 \times 10^{11}/cm^2eV$ at 1.08 eV below the conduction band edge. The leakage current densities measured at room temperature was about 5×10^{-10} A/cm^2 under a field of 1 MV/cm.

Keywords: MIS, Gallium nitride (GaN), Aluminum nitride (AlN), GaN MIS, AlN/GaN structure, Interface property

1. INTRODUCTION

Gallium nitride (GaN) is an attractive wideband gap semiconductor material because of its excellent physical properties, which are suitable for fabricating high-power, high-temperature, high-frequency electronic devices, and its blue light-emitting optoelectronic components. However, one of the major factors that limit the performance and reliability of GaN-based heterostructure devices is their relatively high gate leakage current. To solve the problem, one can use a high-quality insulating layer on the GaN layer to reduce the gate leakage current.[1] Also, GaN-based MIS (Metal-Insulator-Semiconductor) capacitors have been used to investigate the properties of the GaN-insulator interface as a precursor to MISFET (Metal-Insulator-Semiconductor Field Effect Transistor) devices. Although a number of gate dielectrics such as SiO_2,[2,3] Si_3N_4,[4,5] Al_2O_3[6,7] have been used in MOS-HFETs (Metal-Oxide-Semiconductor Heterostructure Field Effect Transistors) and MIS capacitors fabricated using different techniques, so far no commercial grade GaN MIS devices have been available.

For MIS gate dielectric material, aluminum–nitride (AlN) films grown by using molecular beam epitaxy (MBE)[8] and metal-organic chemical vapor deposition (MOCVD)[9] on SiC and physical vapor deposition (PVD)[10] on Si structures have been reported. The AlN may represent an attractive alternative to oxides as a dielectric material for GaN MIS devices because of its wide bandgap (~6.2 eV at 300 K), high thermal conductivity (2.85 W/cm°C at 300 K), high resistivity and its rather close lattice match to GaN (~2.4%), which allows the growth of high-quality epitaxial layers of GaN.

Much like CVD, the remote-plasma atomic-layer-deposition (RPALD) technique, which uses plasma, can result in increased reaction rates on surfaces, increased fragmentation of the precursor molecules, bombardment-enhancement of the removal of product molecules, or some combination of all of these steps, all at lower substrate temperatures than in conventional CVD[11]. It was also designed to place the substrate out of the plasma region to reduce both the level of impurity content and substrate damage. Therefore, it is expected to deposit high-quality insulating layers and improve both the gate leakage current and the interface properties in GaN-based MIS devices.

In this paper, the growth of AlN/GaN (0001) structures using the RPALD technique is reported for the first time. The crystalline structures of the grown AlN films were determined using X-ray diffraction (XRD). The electrical properties of the AlN/GaN structures were characterized using current-voltage (*I-V*) and capacitance-voltage (*C-V*) characteristics.

2. EXPERIMENTAL PROCEDURE

After the GaN substrates were cleaned, the thin films of AlN were deposited on undoped GaN at process temperatures ranging from room temperature (RT) to 500°C. A

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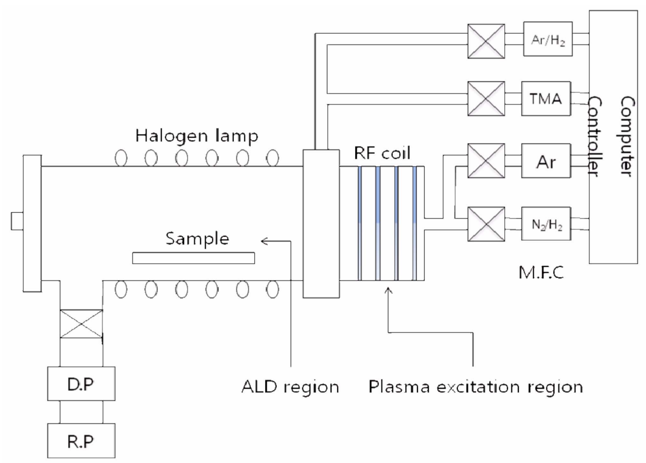

Fig. 1. Schematic illustration of the RPALD system for AlN film deposition.

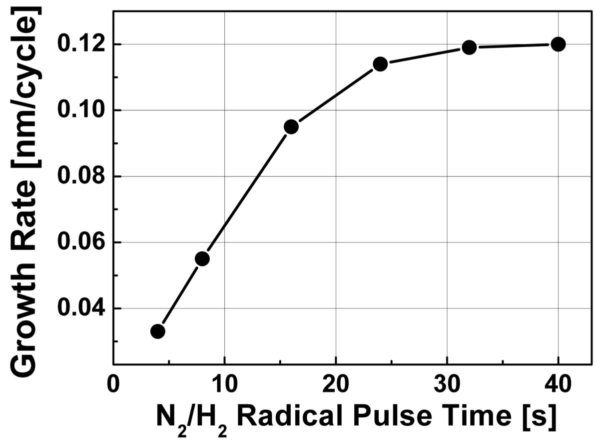

Fig. 2. Growth rate per cycle measured as a function of nitrogen/hydrogen radical pulse time.

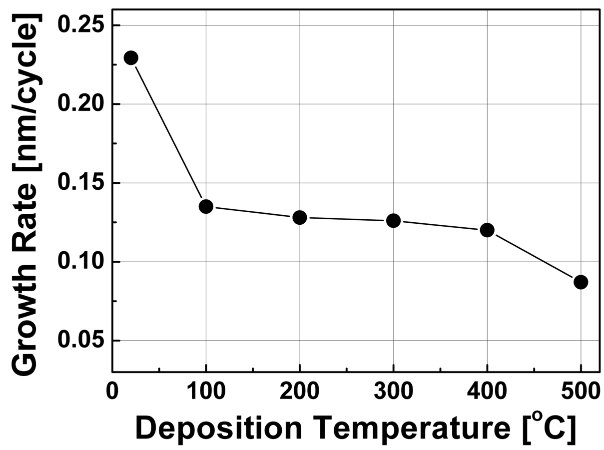

Fig. 3. Growth rate per cycle measured as a function of different process temperatures.

trimethylaluminum (TMA) precursor and nitrogen/hydrogen radicals were used in the RPALD system, as shown in Fig. 1. The apparatus consisted of a reactive and purging gas plasma excitation region, which is inductively coupled to a 13.56 MHz RF power supply, and an ALD region for GaN surfaces on substrates. The nitrogen/hydrogen radicals were produced by dissociating nitrogen/hydrogen gas in the remote plasma discharge region. High-purity Ar (99.999%) gas mixed with a hydrogen concentration of 3.98% was used as purging gas. To complete the process within the self-limited region, we maintained each pulse time at 2/4/32/4 s/cycle (2 s for TMA, 4 s each for Ar/H_2 and 32 s for N_2/H_2). Prior to dielectric deposition, the GaN samples were cleaned with a mixture of sulfuric acid and hydrogen peroxide (4:1 = H_2SO_4:H_2O_2) for 10 min at 70°C. The samples were further cleaned with hydrochloric acid and DI water (1:1 = HCl:DI water) for 10 min at 70°C.

The films were analyzed structurally using XRD. In order to characterize the electrical properties of the AlN/GaN structures, we used MIS capacitors, which were fabricated by the thermal evaporation of aluminum using a metal shadow mask. Post-metallization annealing was performed at 400°C in a N_2 ambient. The gate area was 4.2×10^{-4} cm^2. The C-V measurements at a frequency of 1 MHz were carried out using an automated HP 4192A LCR meter system. The interface trap density (D_{it}) was estimated using the 1 MHz high-frequency C-V method. An automated HP 4140B pA meter was used to measure the leakage current of the MIS capacitors.

3. RESULTS AND DISCUSSION

Figure 2 shows the growth rate per cycle measured as a function of nitrogen/hydrogen radical pulse time. At a process temperature of 300 , the growth rate saturated with 32s nitrogen/hydrogen radical pulse time and the saturation of growth rate with TMA pulse time occurred at 2 s. Therefore, the RPALD process pulse time was maintained at 2/4/32/4 s/cycle to acquire good films. The time required to complete one RPALD cycle was 42 s. Unlike Al_2O_3 RPALD,[12] the nitrogen radical pulse time took a long time and hydrogen gas was needed at the same process temperature ranges. This may be due to the different atomic layer growth mechanism between aluminum oxide and aluminum nitride.

In Fig. 3, the growth rate per cycle is plotted for different deposition temperatures. The growth rate per cycle decreased with the increasing deposition temperature from 2.3 Å/cycle at RT to 0.9 Å/cycle at 500°C, but little change was observed between 100°C and 400°C due to the self-limited reaction phenomena (it is called the ALD window). Although the high growth rate at low temperature is due to the condensation of the reaction species on the surface, the decreasing growth rate with increased process temperatures is suggested to be due to the increasing film density.

Figure 4 shows the thickness as a function of RPALD

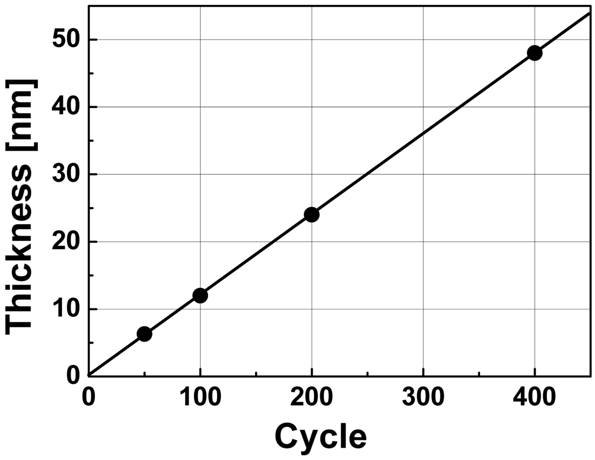

Fig. 4. Thickness as a function of RPALD cycles deposited at 300°C.

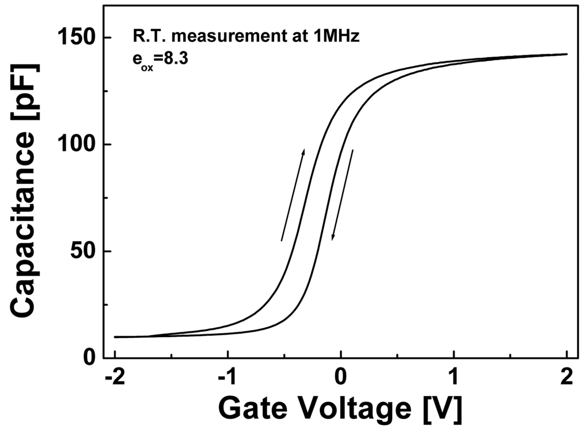

Fig. 6. C-V characteristics of an AlN/GaN MIS capacitor measured at room temperature.

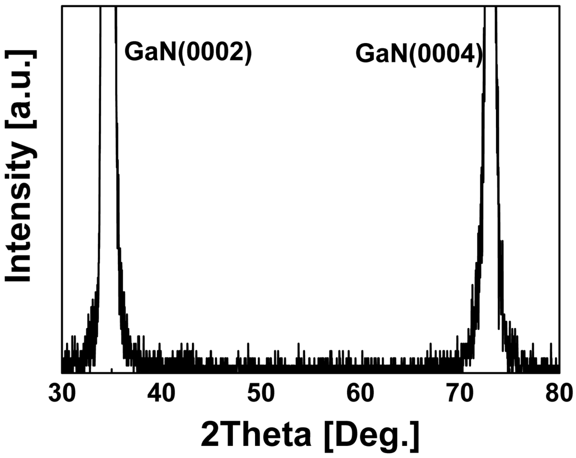

Fig. 5. XRD patterns measured using a θ-2θ scan mode for the AlN films on GaN (0001) oriented substrates for as-deposited films at 300°C.

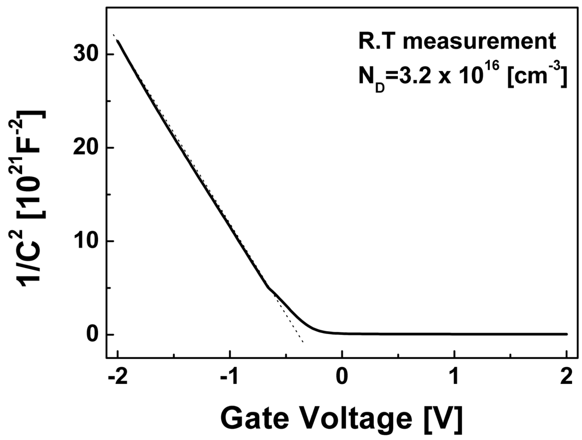

Fig. 7. $1/C^2$ characteristic of AlN/GaN MIS capacitor as a function of gate voltage.

cycles at a deposition temperature of 300°C. The thickness shows good linear property according to the number of cycles with an average growth thickness of 0.12 nm/cycle. This indicates a constant growth rate per cycle and the possibility of nanoscale deposition. The extrapolation line of the AlN growth rate intersects the 'y' axis at almost zero, which means there was no longer an interfacial layer between the AlN layer and the GaN substrate during the AlN RPALD process.

Figure 5 shows the XRD patterns measured using a θ-2θ scan mode for the AlN films on GaN (0001) oriented substrates for as-deposited films at 300°C. The pattern shows only peaks corresponding to GaN. No other peaks for AlN are observed, leading us to conclude that the films are amorphous in structure.

Figure 6 shows the 1MHz C-V characteristic of the MIS capacitor with a thickness of 20 nm measured using an HP4284A LCR meter at R.T. The gate voltage was swept from depletion to accumulation in darkness with a sweep rate of approximately 0.02 V per second and then swept back to depletion. A narrow hysteresis was observed for the RPALD AlN/GaN MIS capacitor indicating a small presence of mobile charges. Accumulation capacitance was used to determine dielectric constants ($\varepsilon_{AlN} = 8.3$). The refractive index of the films measured by ellipsometry with a wavelength of 632.8 nm ranged from 1.6 to 1.7.

The decrease in capacitance as the applied voltage becomes more negative is caused by the increase in thickness of the space charge region of the GaN substrate. The doping of the GaN (0001) wafer can be determined by this decrease in capacitance. The $1/C^2$ characteristic, as a function of gate voltage, is shown in Fig. 7. By fitting the $1/C^2$ vs. gate voltage from Fig. 6, the net donor density N_D is extracted to be 3.2×10^{16} cm^{-3}.

Figure 8 shows the interface trap density versus the energy gap of AlN/GaN MIS capacitors estimated using a high-frequency C-V measurement. The estimated interface trap

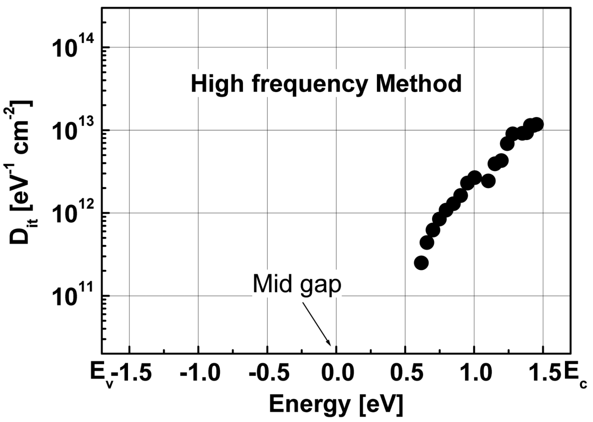

Fig. 8. Interface state density of AlN/GaN MIS capacitor estimated using the high-frequency C-V measurement.

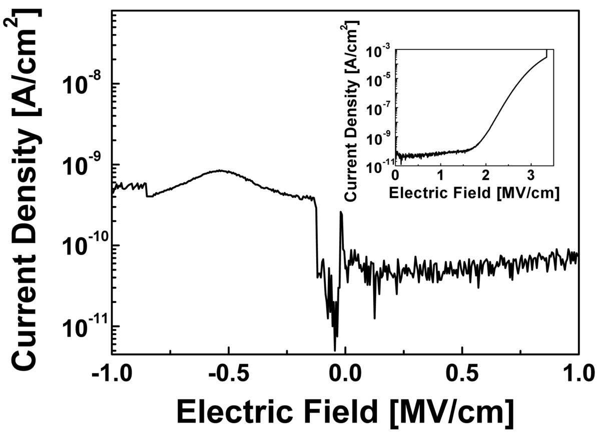

Fig. 9. Gate leakage current density versus oxide electric field measured at RT. The insert show J-E plots of the sample measured at high applied field.

density measured was about 2.4×10^{11}/cm^{2}eV at 1.08 eV below the conduction band edge.

Figure 9 shows a gate-leakage current density (J) versus electric field (E) curve measured at R. T. The leakage current density was maintained about 5×10^{-10} A/cm^2 at 1MV/cm, which is better by less than two orders of magnitude that achieved by pulsed-laser deposited AlN film.[13] The resistivity in an electric field of 1 MV/cm was more than 2.2×10^{15} $\Omega \cdot$cm. Also, the J-E plot for a 20 nm thick AlN film is shown in the insert. The J-E plot shows very low currents on the order of ~0.1 nA/cm^2 at low applied potentials. This current is attributed to a combination of leakage current and charging current due to capacitive charging. The rise in current starting at approximately 1.8 MV/cm can be identified as Frenkel-Poole emission,[14] which may be dominated by field-enhanced thermal excitation of trapped electrons into the conduction band. Catastrophic breakdown was observed at 3.3 MV/cm.

4. CONCLUSIONS

Using the RPALD technique, we prepared AlN films on *n*-type GaN (0001) structures for GaN MIS device applications. A TMA precursor, nitrogen/hydrogen radicals and argon/hydrogen purging gases were used in the RPALD process. The X-ray diffraction results showed that the as-deposited AlN film on the GaN substrate was in an amorphous phase. From the 1-MHz C-V characteristics, the dielectric constant (ε_{AlN} = 8.3) and the estimated interface trap density (~2.4×10^{11}/cm^2 eV at 1.08 eV below the conduction band edge) were obtained. The leakage current density was maintained at about 5×10^{-10} A/cm^2 for a 1 MV/cm.

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