Deposition of SiO$_2$ Layers on GaN by Photochemical Vapor Deposition

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SiO$_2$ insulating layers were first deposited onto GaN by photochemical vapor deposition (photo-CVD) technology using a deuterium ($D_2$) lamp as the excitation source. Physical, chemical, and electrical characteristics of the Al/SiO$_2$/GaN metal-insulator-semiconductor (MIS) capacitors are reported for the first time. It was also found that the limiting factor of SiO$_2$ growth rate was the number of SiH$_4$ and O$_2$ molecules available to provide excited Si and O atoms. Furthermore, it was found from high-frequency capacitance-voltage measurements that the photo-CVD SiO$_2$/n-GaN interface state density, $D_{it}$, was estimated to be $8.4 \times 10^{14}$ cm$^{-2}$ eV$^{-1}$ for the photo-CVD SiO$_2$ layers prepared at 300°C. With an applied field of 4 MV/cm, the oxide leakage current density was found to be only $6.6 \times 10^{-7}$ A/cm$^2$.


The excellent physical and electrical properties of GaN have made it a good candidate in high-temperature, high-power, and high-frequency applications.$^1$ High quality III-V ternaries such as Al$_x$Ga$_{1-x}$N and In$_x$Ga$_{1-x}$N were also demonstrated for heterojunction field effect transistors (HFETs),$^{2,3}$ bipolar junction transistors (BJTs),$^4$ and light-emitting diodes (LEDs).$^5$ Nitride-based blue and green LEDs$^6$ are already commercially available. The high dislocation density measured in these blue/green LEDs also suggested that the dislocation density in group III nitrides is not efficient recombination centers. Such a dislocation density also suggested that the number of surface states is small in GaN.$^7,8$ Recently, many searches were focused on the fabrication of GaN-based metal-insulator-semiconductor (MIS) capacitors with SiO$_2$,$^9,10$ Si$_3$N$_4$, and Ga$_2$O$_3$$^{11,12}$ as the insulating material. It has been reported that SiO$_2$ layers can be deposited onto GaN by plasma-enhanced chemical vapor deposition$^{13}$ and liquid-phase deposition.$^{14}$ Previously, it was shown that photochemical vapor deposition (photo-CVD) can also be used to grow high quality SiO$_2$ layers$^{14-18}$ on various semiconductor substrates. In using photo-CVD to grow thin films, selecting the proper light source with a radiation spectrum matching the absorption spectra of the reactance gases is very important. In this study, we used a deuterium ($D_2$) lamp as the excitation source. It is known that $D_2$ lamp emits strong ultraviolet (UV) and vacuum ultraviolet (VUV), which can effectively decompose SiH$_4$ and O$_2$, since O$_2$ could absorb photons in the wavelength region from 133 to 175 nm and SiH$_4$ could absorb photons in the wavelength region below 147 nm.$^{14,18}$ Thus, energy can be directly transferred from the $D_2$ lamp to the excited Si and O atoms. In addition, such a photo-CVD system offers better control in the oxide region and selective growth is possible. The quality of oxide layers grown by such a photo-CVD system is close to that grown by thermal oxidation, and the electrical properties of the photo-CVD grown oxide are acceptable for device applications.$^{14-18}$ In this paper, the deposition of SiO$_2$ layers on GaN and the properties of Al/photo-CVD SiO$_2$/n-GaN MIS capacitors are reported for the first time.

**Experimental**

Prior to the deposition of SiO$_2$ layers, an n-type GaN epitaxial layer was grown on (0001) sapphire substrates by metalorganic chemical vapor deposition (MOCVD).$^{19,34}$ The electron concentration of the n-type GaN epitaxial layer was about $5 \times 10^{17}$ cm$^{-3}$. The 50 nm thick SiO$_2$ films were subsequently deposited onto the GaN epitaxial layer by 150 W $D_2$ lamp photo-CVD under different process pressures and different substrate temperatures. The gas ratio was fixed at SiH$_4$/O$_2$ = 0.055.$^{10,14}$ For comparison, SiO$_2$ films with the same thickness were also deposited on the same GaN epitaxial layer by rf magnetron sputtering. Atomic force microscopy (AFM) and Auger electron spectroscopy (AES) were then used to characterize the deposited SiO$_2$ films. Al/SiO$_2$/GaN MIS capacitors were subsequently prepared by etching and metal evaporation. The capacitance-voltage (C-V) and current-voltage (I-V) characteristics of these fabricated MIS capacitors were then measured by an HP 4284B LCR meter and an HP 4156B semiconductor parameter analyzer, respectively.

**Results and Discussion**

Figure 1 shows SiO$_2$ growth rate as a function of process pressure for the photo-CVD SiO$_2$ layers grown at different substrate temperatures. It was found that the SiO$_2$ growth rate increases as the substrate temperature increases. It was also found that the SiO$_2$ growth rate increases linearly as the process pressure increases. Such a linear increase suggests that the limiting factor for growth rate is the amount of SiH$_4$ and O$_2$ molecules available to provide excited Si and O atoms. At higher pressure, the number of
excited Si and O atoms will increase so as to result in a higher SiO₂ growth rate. The refractive index of the 300°C photo-CVD grown SiO₂ layer prepared at 0.9 Torr is very close to that of the thermally grown SiO₂ layer prepared on top of Si substrates. Figures 2a, b, and c show the AFM images of bare GaN without SiO₂, photo-CVD SiO₂ grown at 300°C and sputtered SiO₂, respectively. It was found that the root mean square (rms) roughness was 1.85, 2.8, and 1.3 nm for bare GaN without SiO₂, photo-CVD SiO₂ grown at 300°C, and sputtered SiO₂, respectively. The smooth surface observed from the sputtered SiO₂ was probably due to its amorphous nature. Figures 3a and b show the AES depth profiles of sputtered SiO₂ and photo-CVD SiO₂ grown at 300°C, respectively. It could be seen from Fig. 3b that the depth profile was uniform in the insulating layer with an O/Si ratio almost equal to 2 for the photo-CVD SiO₂ grown at 300°C. In contrast, although the depth profile was also uniform in the insulating layer for the sputtered SiO₂, its O/Si ratio was only 1.5. Such a result suggests that the composition of the sputtered insulating layer is SiO₁.₅, instead of SiO₂. Such a result also suggests that there exist a large number of dangling bounds in the sputtered SiO₂ due to the lack of oxygen.

Figure 4 shows the C-V characteristics (1 MHz) of the photo-CVD SiO₂ grown at different temperatures. The ideal C-V curve...
was also plotted in the same figure. It was found that no significant hysteresis was observed as the gate voltage varied at 0.1 V/s from +5 V to −20 V and then back to +5 V for all three samples. The lack of hysteresis in these C-V curves indicated that the number of mobile ions in SiO₂ layer is negligibly small. At high frequency measurement (1 MHz), there is not enough response time for minority carriers (holes for n-GaN) to be generated in n-GaN, so that significant inversion characteristics could not be observed from this figure. Similar results were also observed by Casey et al. 1 Using the standard high frequency capacitance method, 2 we can thus calculate the interface state density from these C-V curves

\[ D_{\text{it}} = \frac{C_{\text{ox}}}{q} \left( \frac{d\Psi}{dV_g} \right)^{-1} - C_{\text{s}} \frac{q}{2} \]  

where \( C_{\text{ox}} \) and \( C_{\text{s}} \) were the oxide and depletion capacitance, respectively, \( \Psi \) was the band bending, and \( V_g \) was the gate voltage. From Eq. 1, it was found that \( D_{\text{it}} \) equals 1.2 \( \times 10^{12} \) cm\(^{-2}\) and 8.4 \( \times 10^{11} \) cm\(^{-2}\) eV\(^{-1}\) for photo-CVD SiO₂ layers on GaN prepared at 150 and 300°C, respectively. The smaller \( D_{\text{it}} \) for the photo-CVD SiO₂ layer deposited at 300°C could be attributed to the fact that a higher substrate temperature can significantly improve the SiO₂/GaN interfacial properties probably through supplying thermal energy to the Si and O atoms. Compared to Ga₂O₃ on GaN reported by Fu et al., 15 the \( D_{\text{it}} \) of our photo-CVD SiO₂ prepared at 300°C, as shown in Fig. 5.

Conclusions

In summary, Al/photo-CVD SiO₂/n-GaN MIS structures were fabricated by photo-CVD technique using a deuterium (D₂) lamp as the excitation source. It was found that the limiting factor for the SiO₂ growth rate is the number of SiH₄ and O₂ molecules available to provide excited Si and O atoms. It was also found that we could achieve a low interface state density, of 8.4 \( \times 10^{11} \) cm\(^{-2}\) eV\(^{-1}\). Furthermore, it was found that the leakage current was only 6.6 \( \times 10^{-7} \) A/cm\(^2\) with an applied field of 4 MV/cm for the 300°C photo-CVD grown Al/SiO₂/GaN MIS capacitor.

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Figure 5. The I-V characteristics of the Al/SiO₂/GaN MIS capacitors.

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