Gadolinium Oxide and Scandium Oxide: Gate Dielectrics for GaN MOSFETs

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Scandium oxide was deposited epitaxially on (0001) GaN via gas-source molecular beam epitaxy (GSMBE) using elemental Sc and an electron cyclotron resonance (ECR) oxygen plasma. HXRD indicated that the Sc_2O_3 has a lower defect density than similarly prepared films of Gd_2O_3. The scandium oxide was atomically smooth, with a rms roughness of 0.5–0.8 nm, and was uniform in stoichiometry as measured by Auger electron spectroscopy (AES) depth profiling. An interface state density of mid 10^{11} eV^{-1} cm^{-2} was determined from capacitance–voltage profiling using the Terman method. This interface state density was roughly a factor of five lower than that obtained from similar diodes made from SiO_2 on GaN.

Introduction GaN field effect transistors (FETs) have attracted considerable research interest due to their potential in high temperature and high power electronics. The insulated gate of the MOS structure reduces gate leakage current and therefore leads to increases in breakdown voltage. Gate dielectrics of AlN [1, 2], $Ga_2O_3(Gd_2O_3)$ [1, 3, 4], SiO_2 [5, 6], and Si_3N_4 [7] have all been previously reported. From this research, interface state densities estimated as low as 5×10^{10} $eV^{-1}cm^{-2}$ ($SiO_2/Si_3N_4/SiO_2$) [8, 9] and breakdown field strengths (E_{BD}) as high as 12.5 MV/cm ($SiO_2/Si_3N_4/SiO_2$) have been measured. Various deposition techniques such as PECVD, jet vapor deposition, MBE, MOCVD, and electron beam deposition have been used, as well as thermal oxidation of the GaN surface. Recently the bixbyite oxide Gd_2O_3, grown via gas source molecular beam epitaxy on n-GaN [10, 11], has been shown to provide an interface state density of mid 10^{11} eV^{-1} cm^{-2}. While Gd_2O_3 has shown promising results, its rather small bandgap, 5.3 eV, and large lattice mismatch to GaN, $\approx 20\%$ [12–14], leave substantial room for improvement. Sc_2O_3 is an attractive alternative as it has the same crystal structure as Gd_2O_3, but a larger bandagp, ≈ 6.3 eV, and a smaller lattice mismatch to GaN, $\approx 9.2\%$ [15]. In this study, bixbyite Sc_2O_3 has been grown on GaN from elemental sources using MBE, characterized and compared to previous work on Gd_2O_3.

Experimental All oxide growth was performed in a modified RIBER 2300 MBE equipped with a reflection high-energy electron diffraction (RHEED) system. Sub-

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strates employed were MOCVD GaN on sapphire (0001). Oxygen was supplied from a Wavemat MPDR 610 ECR plasma source (2.54 GHz) with 200 W forward power at 1×10^{-4} Torr oxygen pressure. A standard effusion cell operating at 1130–1170 °C was used for the evaporation of the 4-N scandium. The substrate temperature was measured using a backside thermocouple that was calibrated using the melting points of InSb and GaSb. All temperatures reported are actual. Materials characterization was provided from RHEED, five crystal high-resolution X-ray diffraction (HXRD), atomic force microscopy (AFM) and Auger electron spectroscopy (AES).

The GaN substrate preparation consisted of a wet chemical etch of HCl:H_2O (1:1) for 3 min, a DI rinse, a UV-ozone exposure for 25 min in a UV Cleaner model 42-220, a dip in buffered oxide etch (6:1, ammonium fluoride:hydrofluoric) for 5 min and a final DI rinse. The substrates were then indium mounted to molybdenum blocks and loaded into the MBE. At room temperature the surface of the substrates was polycrystalline according to the RHEED patterns. Upon heating the GaN to 700 °C, a streaky (1×3) pattern appeared. This was the starting surface for all the films grown in this study.

Results and Discussion It has previously been reported that the MBE growth of Gd_2O_3 produced extremely smooth surfaces as indicated from AFM and SEM. This was also the case for the Sc_2O_3; rms roughnesses of 0.5 to 0.8 nm were seen for substrate temperatures of 100 to 600 °C, respectively. The MOCVD GaN substrates have rms roughnesses of 1.0 to 2.0 nm. Using AES depth profiling and surface scans, it was shown that the MBE derived Sc_2O_3 was of uniform concentration throughout the film, as shown in Fig. 1. It was also found that the pretreatment of the GaN substrates removed the carbon contamination to levels below the Auger detection limits. The O:Sc ratio, as measured from comparing Auger peak to peak heights, was 0.85 to 0.90 for substrate temperatures of 600 and 100 °C, respectively. This variation in O:Sc ratio is within the error of the AES detection limits. The O:Sc ratio did not change as a function of cell temperature. These results are similar to those obtained from similar studies of the Gd_2O_3 oxide growth. A Sc_2O_3 standard was not available to compare against the thin film data. The growth rate of the scandium oxide was 0.67 nm/min for $T_{Sc} = 1130$ °C and 1.25 nm/min for $T_{Sc} = 1170$ °C. The growth rate did not appear to vary with changes in substrate temperature.

Scandium oxide exists in the bixbyite structure, which is an fcc array of Sc with oxygen atoms occupying 3/4 of the tetrahedral sites. Since it has cubic symmetry, the (111) closest packed plane has the same symmetry as the basal plane of the GaN. From high-resolution X-ray diffraction (HXRD) results, it was found that the scandium oxide
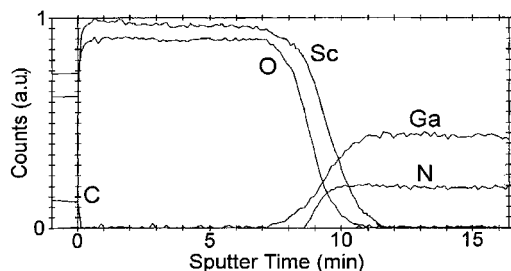

Fig. 1. Auger electron spectroscopy (AES) depth profile of Sc_2O_3 on GaN. The conditions of the oxide growth were $T_{Sc} = 1130$ °C and $T_{sub} = 100$ °C
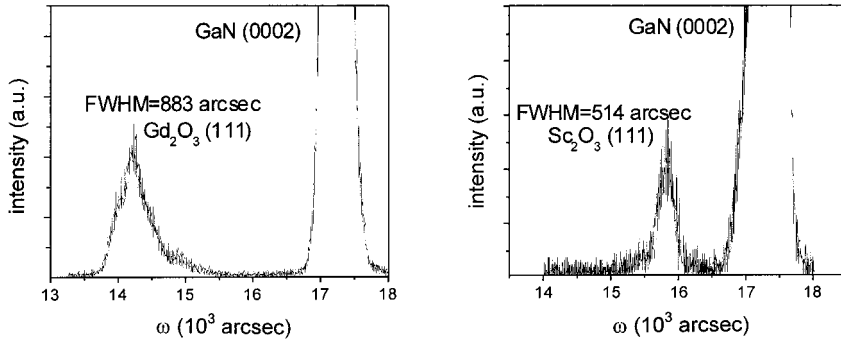
Fig. 2. HXRD scans of Gd$_2$O$_3$ on h-GaN (left) and Sc$_2$O$_3$ on h-GaN (right). Samples were grown at 600 °C. Plots are normalized to the GaN (0002) peak intensity

(111) plane grows parallel to the GaN(0001) surface. This was also seen in Gd$_2$O$_3$ films grown on GaN. The 20% mismatch between Gd$_2$O$_3$(111) and GaN(0001) leads to a highly defective single crystal layer, resulting in a full-width at half-maximum (FWHM) of over 800 arcsec in HXRD scans. The smaller mismatch between Sc$_2$O$_3$ and GaN(0001) should lead to a lower defect density and in fact the FWHM is substantially reduced at 514 arcsec as compared to the 883 arcsec found in Gd$_2$O$_3$, shown in Fig. 2.

Diodes were fabricated from Sc$_2$O$_3$ on n-GaN and were tested using $I–V$, $C–V$, and ac conductance methods. The diode size was 100 μm in diameter, with a gate metal of Pt/Au. The n-GaN ohmic contact consisted of a ring around the gate contact made from Ti/Al/Pt/Au. The ohmic contact was not annealed. From the $I–V$ results, a forward breakdown field of 0.7 MV/cm was calculated. From the $C–V$ data, the interface state density was calculated using the Terman method to be 4×10^{11} eV^{-1}cm^{-2} at 0.8 eV below the conduction band edge, as shown in Fig. 3. Additionally the interface state density was calculated from an ac conductance measurement and was found to be 2×10^{12} eV^{-1}cm^{-2} at a level of 0.8 eV below the conduction band. For comparison, SiO$_2$ was deposited on the n-GaN via plasma enhanced chemical vapor deposition (PECVD) and diodes of the same size were fabricated. Using the Terman method, the interface state density in these diodes was calculated to be 2×10^{12} eV^{-1}cm^{-2} at 0.8 eV below the conduction band.

Conclusions It was shown that scandium oxide can be deposited epitaxially on (0001) GaN using elemental Sc and an ECR oxygen plasma in GSMBE. HXRD indicates that
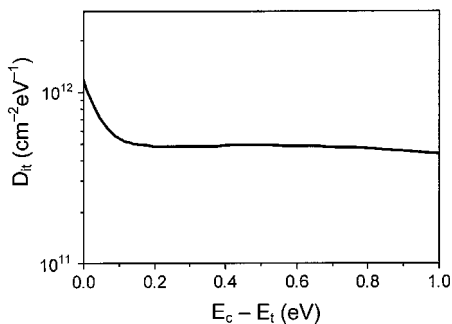

Fig. 3. Interface state density (D_{it}) as related to the conduction band edge

Sc_2O_3 has a lower defect density than similar films of Gd_2O_3. The scandium oxide is atomically smooth and uniform in stoichiometry. An interface state density of mid $10^{11}\,eV^{-1}\,cm^{-2}$ was determined by the Terman method. This interface state density is roughly a factor of five lower than that obtained from diodes made from SiO_2/GaN.

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