Effect of Proton Irradiation on Interface State Density in \( \text{Sc}_2\text{O}_3/\text{GaN} \) and \( \text{Sc}_2\text{O}_3/\text{MgO}/\text{GaN} \) Diodes

K.K. ALLUMS,1,4 M. HLAD,1 A.P. GERGER,1 B.P. GILA,1 C.R. ABERNATHY,2 S.J. PEARTON,1 F. REN,2 R. DWIVEDI,3 T.N. FOGARTY,3 and R. WILKINS3

1.—Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611, USA. 2.—Department of Chemical Engineering, University of Florida, Gainesville, FL 32611, USA. 3.—Center for Applied Radiation Research, Prairie View A&M University, Prairie View, TX 77446, USA. 4.—E-mail: allums@mse.ufl.edu

Proton irradiation of \( \text{Sc}_2\text{O}_3/\text{GaN} \) and \( \text{Sc}_2\text{O}_3/\text{MgO}/\text{GaN} \) metal-oxide semiconductor diodes was performed at two energies, 10 MeV and 40 MeV, and total fluences of \( 5 \times 10^9 \text{ cm}^{-2} \), corresponding to 10 years in low-earth orbit. The proton damage causes a decrease in forward breakdown voltage and a flat-band voltage shift in the capacitance-voltage characteristics, indicating a change in fixed oxide charge and damage to the dielectric. The interface state densities after irradiation increased from \( 5.9 \times 10^{11} \text{ cm}^{-2} \) to \( 1.03 \times 10^{12} \text{ cm}^{-2} \) in \( \text{Sc}_2\text{O}_3/\text{GaN} \) diodes and from \( 2.33 \times 10^{11} \) to \( 5.3 \times 10^{11} \text{ cm}^{-2} \) in \( \text{Sc}_2\text{O}_3/\text{MgO}/\text{GaN} \) diodes. Postannealing at 400°C in forming gas recovered most of the original characteristics but did increase the interfacial roughness.

**Key words:** Radiation, GaN, diodes

**INTRODUCTION**

GaN displays significantly greater resistance to ionizing radiation damage than GaAs and other compound semiconductors. Previous studies have shown a minimal change in the current-voltage characteristics of AlGaInGaN/GaN light-emitting diodes irradiated with 2 MeV protons at high fluence (\( 10^{12} \text{ cm}^{-2} \)),

Two of the most promising dielectrics for GaN are MgO and \( \text{Sc}_2\text{O}_3 \). Some of their relevant properties are given in Table I, while the band offsets are shown schematically in Fig. 1. For comparison, data for SiO\(_2\) are also shown in the figure. Both dielectrics form high-quality interfaces with GaN (an example is shown in the cross-sectional transmission electron micrograph at the top of Fig. 2 for MgO/GaN), but a drawback with the MgO is its reaction with air, leading to roughening of the interface and the oxide receding from the edge of the sample after storage in atmosphere, as shown in the scanning electron microscopy image at the bottom of Fig. 2. For that reason, we cap the MgO with \( \text{Sc}_2\text{O}_3 \) to prevent the MgO degradation in atmosphere.

In this paper, we report on the electrical characterization of GaN MOS diodes exposed to 40 MeV protons at a fluence equivalent to approximately 10 years in low-earth orbit. The ultimate goal of this work is to develop a radiation-stable MOSFET device that can withstand radiation from low-earth orbit or space-based applications.

(Received June 28, 2006; accepted October 27, 2006; published online February 23, 2007)
EXPERIMENTAL

The structures were grown by metal organic chemical vapor deposition on C-plane Al₂O₃ substrates. The layer structure consisted of a 3-μm-thick GaN buffer with doping $5 \times 10^{16} \text{ cm}^{-2}$ and 400 Å of Sc₂O₃ or 20 Å of Sc₂O₃ on top of 400 Å of MgO. The details of the oxide deposition conditions have been reported previously. Mesa isolation was achieved with Cl₂/Ar inductively coupled plasma etching (300 W source power, 40 W rf chuck power). Ohmic contacts were formed by lift-off of e-beam deposited Ti/Al/Pt/Au subsequently annealed at $850 \pm 17^\circ\text{C}$ for 30 s. Schottky contacts of diameter 100 μm of electron beam deposited Pt/Au were also patterned by lift-off. The MOS capacitors were irradiated with 10 MeV or 40 MeV protons to a fluence of $5 \cdot 10^9 \text{ cm}^{-2}$ at Texas A&M Cyclotron, corresponding to an energy deposition of $5 \cdot 10^{10} \text{ MeV/cm}^2$ or $2 \cdot 10^{11} \text{ MeV/cm}^2$, respectively, for the two different energies. The projected range of these protons in our devices is >50 μm, so that they traverse the entire device and stop in the Al₂O₃ substrates. The devices were measured ~50 h after completion of the irradiation. A schematic of the completed devices is shown in Fig. 3. The diode characterization employed capacitance-voltage (C-V) and current-voltage (I-V) measurements, x-ray reflectivity (XRR) to examine interfacial smoothness, and photoluminescence (PL) to monitor changes in optical properties. The Terman method was used to extract the interface state density, $D_{it}$, from the C-V characteristics. This method is useful for calculating interface traps of $10^{10} \text{ cm}^{-2} \text{ eV}^{-1}$ and above but is generally found to underestimate the trap density. Even at $300^\circ\text{C}$ in conventional GaN MOS devices, the generation rate is still too low to

<table>
<thead>
<tr>
<th>Bandgap (eV)</th>
<th>Dielectric Constant</th>
<th>Melting Point (K)</th>
<th>Mismatch to GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>7.3</td>
<td>9.8</td>
<td>3,073</td>
</tr>
<tr>
<td>Sc₂O₃</td>
<td>6.3</td>
<td>14</td>
<td>2,678</td>
</tr>
<tr>
<td>GaN</td>
<td>3.4</td>
<td>9.5</td>
<td>2,773</td>
</tr>
</tbody>
</table>

Fig. 1. Relative alignment of bandgaps for promising dielectrics on GaN.

Fig. 2. Transmission electron microscopy cross section of MgO/GaN interface (top) and scanning electron microscopy cross section of deterioration of MgO on GaN after long-term (a few weeks) exposure to ambient (bottom); scale 200 μm.

Fig. 3. Schematic of MOS diodes used in this study.