Comparison of Surface Passivation Layers on InGaN/GaN MQW LEDs

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***Abstract*—The effect of different surface passivation films on blue or green (465-505 nm) InGaN/GaN multi-quantum well light-emitting diodes (LEDs) die were examined. SiO_2 or SiN_x deposited by plasma enhanced chemical vapor deposition, or Sc_2O_3 or MgO deposited by rf plasma enhanced molecular beam epitaxy all show excellent passivation qualities. The forward current-voltage (I-V) characteristics were all independent of the passivation film used, even though the MBE-deposited films have lower interface state densities (3-5×10^{11} eV^{-1} cm^{-2}) compared to the PECVD films (~10^{12} eV^{-1} cm^{-2}). The reverse I-V characteristics showed more variation, but there was no systematic difference for any of the passivation films. The results suggest that simple PECVD processes are effective for providing robust surface protection for InGaN/GaN LEDs.**

***Index Terms*—Light-emitting diodes, Passivation, Dry etching, Leakage current, Reliability**

I. INTRODUCTION

InGaN/GaN multi quantum well (MQW) light-emitting diodes (LEDs) are used in numerous lighting applications, including full color displays, traffic lights and automobile interior lighting and running lights[1-17]. Ultra-violet LEDs with AlGaN active regions are also attracting interest for bio-remediation and bio-molecule detection. The most widespread application for nitride LEDs will almost certainly be in white lighting, where color-combining of red, green and blue LEDs or pumping of phosphors can be used for general room lighting[1-5]. There are several process modules during the fabrication of these LEDs in which the surface may be exposed to potentially damaging plasma environments. Firstly, the mesa etch to make contact to the *n*-side of the *pn* junction is generally created by dry etching because of the resistance of the GaN to wet chemical etching. Secondly, one can also employ surface passivation films such as SiN_x or SiO_2 deposited by plasma enhanced chemical vapor deposition (PECVD) for encapsulation of the LEDs and reduction of surface-related leakage current. In these situations, the GaN surface is exposed to energetic ion bombardment and chemically reactive species (especially hydrogen in the case of PECVD films) that may enhance surface-related leakage and recombination.

There has been surprisingly little work done to quantify the effect of plasma damage during deposition of surface passivation films on the performance of GaN-based LEDs. The quality of the semiconductor surface can be a major issue in the performance of the device because of the recombination induced due to surface dangling bonds and adsorbed impurities from the ambient. The recombination rate, R, at the surface is usually expressed as $R=S\cdot A\cdot n$, where S is the surface recombination velocity, A the surface area and n the carrier density. A poorly passivated surface may lead to degraded output characteristics and to reliability problems[1]. Two alternative candidates for LED passivation are Sc_2O_3 and MgO[18]. These novel oxides do not contain hydrogen (in contrast to the conventional dielectrics that employ SiH_4 as a precursor) and may have

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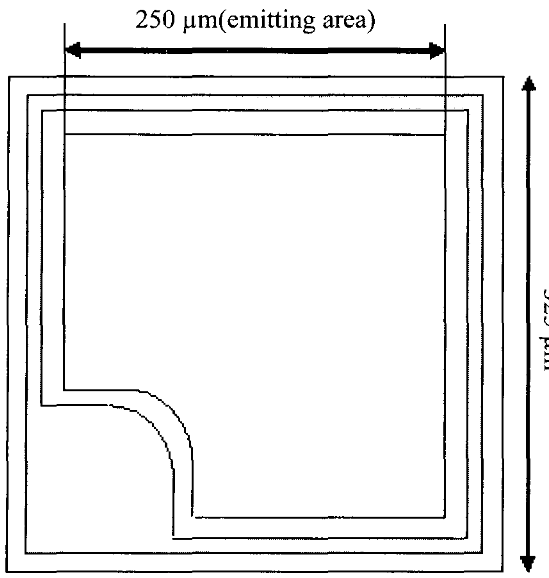

Fig. 1. Schematic plan view of the LED die

advantages in that respect because atomic hydrogen diffuses rapidly and could enter the GaN LED over extended periods of device operation and reduce the effective *p*-type doping. Sc_2O_3 is often used as an optical coating for high power photonic devices and has a bandgap of 6.3 eV. Based upon the reported work function of 4 eV, it is likely that the electron affinity is ~0.85 eV. MgO is a rock salt dielectric with bandgap ~8 eV which has been explored as an intermediate buffer layer for growth of ferroelectric materials on semiconductors or as a potential gate dielectric for GaAs or Si. The work function is 3.1-4.4 eV and the electron affinity is 0.7 eV. Both MgO and Sc_2O_3 have shown excellent results for eliminating current collapse in AlGaN/GaN heterostructure field effect transistors (HFETs) and providing effective surface passivation[18].

In this paper, we report on a comparison of the passivation properties of SiO_2, SiN_x, MgO and Sc_2O_3 for use on blue and green InGaN/GaN MQW LEDs. Despite the lower interface state densities for the MBE-grown oxides, we find that all the films investigated are effective on InGaN/GaN LEDs.

II. Experimental

The GaN LEDs were commercial unpackaged die from UniRoyal Optoelectronics with two different emission wavelengths, namely 465 and 505 nm. A schematic plan view of the LED structures is shown in Fig. 1. The maximum output powers were 3 mW in the first case and 1.6 mW in the final case. The forward turn-on voltages were ~3.2 V for the 465 nm devices and ~3.7 V for the 505 nm devices. The epitaxial structures with InGaN multi-quantum wells and GaN cladding layers were grown by metal organic chemical vapor deposition on sapphire substrates. Prior to plasma exposure, the existing SiO_2 passivation layer was removed by wet etching (BOE : DI = 1: 1) for about a minute. PECVD of SiN_x film was carried out in an rf (13.56 MHz) powered reactor (Plasmatherm SLR-730) using SiH_4, NH3 and N2 as the precursors at 250 °C. The MgO and Sc_2O_3 were deposited by rf plasma-activated MBE at a substrate temperature of 100 °C. They were ~ 10 nm thick. The LED samples were cleaned initially with a UV-ozone exposure for 25 min prior to indium mounting and loading into the vacuum system. An additional thermal clean at 300 °C for 5 minutes was performed under UHV conditions. The precursors for MgO were elemental Mg and radio-frequency plasma-activated oxygen. A standard effusion cell operating at 380 °C was used for evaporation of the Mg, while the O_2 source was operated at 300 W forward power (13.56 MHz) and 8.2×10^{-6} Torr. The Sc_2O_3 was deposited using elemental Sc evaporated from a standard effusion cell at 1190 °C and the O_2 source was operated at 300W forward power (13.56MHz) and 8.2×10^{-6} Torr. These are the same deposition conditions used for passivation of GaN-based

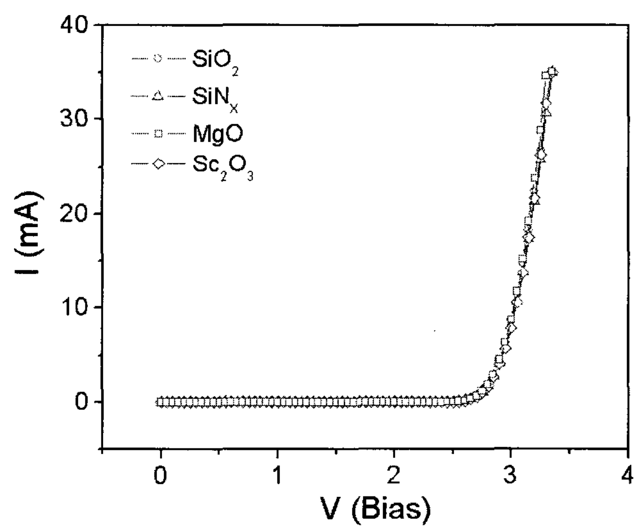

Fig. 2. Forward I-V characteristics from blue InGaN/GaN LEDs passivated with the four different films

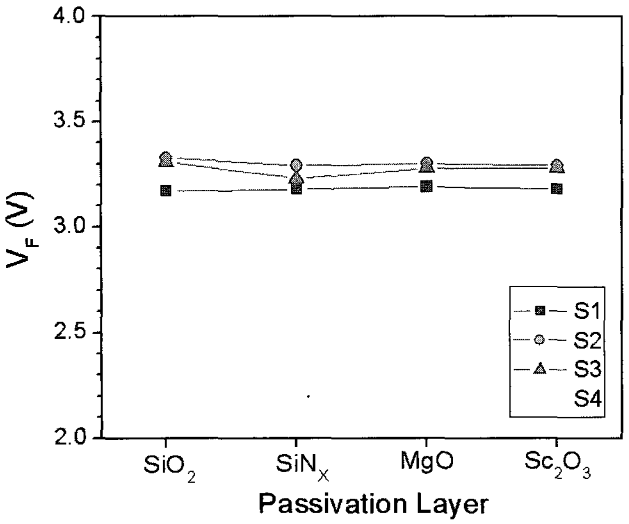

Fig. 3. Forward turn-on voltages from three different blue LEDs (samples S1-S3) and one green LED (sample S4) passivated with SiO_2, SiN_x, MgO and Sc_2O_3

HFET structures[18]. The current-voltage (I-V) characteristics were recorded at room temperature on an Agilent 4156C parameter analyzer with the die heat-sink on a probe station. We measured ten devices for each passivation condition and used the average of this data in each case. The turn-on voltage of the LEDs was defined as the voltage at which they were drawing 20 mA of current and the reverse breakdown was defined as the voltage at which the current density was approximately 100 mA/cm^2.

III. Results and Discussions

Figure 2 shows the forward current characteristics from 465 nm diodes passivated with the different films. Within experimental error, there is no effect of the passivation film on the forward current and therefore on the optical output power of the LEDs. The forward turn-on voltage (defined as the voltage at which the current is 20 mA) is unaffected by the type of passivation film, as shown in Fig. 3. The ideality factor of all the LEDs was ≥ 2, indicating that recombination is the dominant transport mechanism and especially may contain surface leakage components.

The reverse bias current of the LEDs showed more variation with the different passivation films. An example is shown in Fig. 4, comparing SiO_2 with passivation. In this case the SiN_x produces a larger reverse breakdown

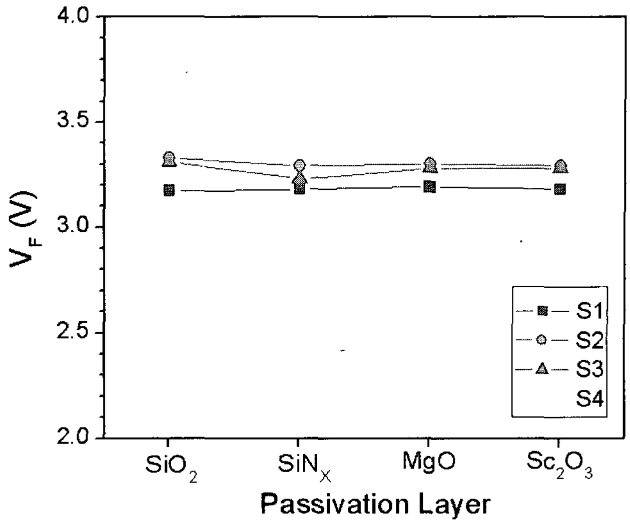

Fig. 4. Reverse I-V characteristics from blue LEDs passivated with either SiO_2 or SiN_x

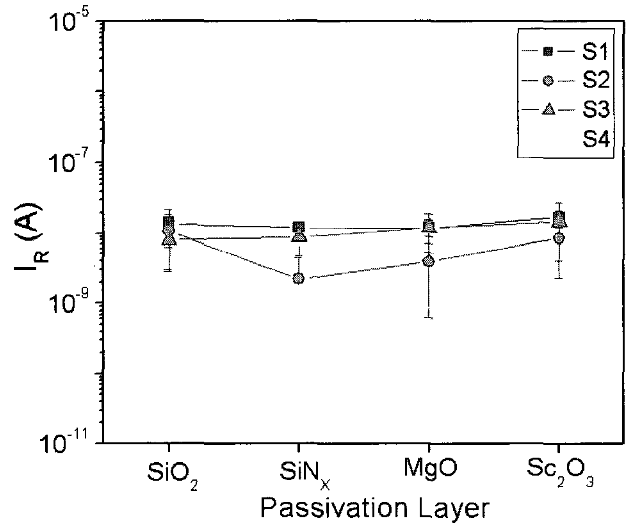

Fig. 5. Reverse leakage current at -5V from three different blue LEDs (samples S1-S3) and one green LED (sample S4) passivated with SiO_2, SiN_x, MgO and Sc_2O_3

voltage (lower reverse current). Our previous results have shown that hydrogen-containing plasmas may create a nitrogen deficiency in the near-surface region of the GaN and this would be more pronounced in the case of the SiN_x because of the additional presence of the NH3. However, after measuring a large number of samples with all the different passivation films, we could not see a systematic trend in the data. An example is shown for three different blue LEDs in Fig. 5. Within experimental error, there is no significant difference for the LEDs . This suggests that any advantages accrued with the oxide passivation films are incremental at best and are probably dominated by effects such as the completeness of surface cleaning and sample-to-sample variations. There was also no clear dependence on the emission wavelength of the LED, so that the indium-content of the active regions does not appear to influence the effectiveness of the passivation.

IV. Summary and Conclusions

In conclusion, four different passivation films are found to be effective on InGaN/GaN MQW LEDs. Even though the MBE-deposited oxide layers do not have hydrogen in the precursors and exhibit lower interface state densities than the PECVD films, there are no significant differences in the I-V characteristics and in the optical output power of the LEDs. The PECVD films are simpler to deposit and the cost per die is smaller than for MBE-grown passivation films, so they should continue to be favored for manufacturing applications.

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