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Effect of Surface Treatment on the Performances of Vertical-structure GaN-based High-power LEDs with Electroplating Metallic Substrate

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1. Introduction

Recently, many attempts have been made to develop GaN-based light-emitting diodes (LEDs) for full-color display and high-efficiency lamps solid state lighting [1-2]. Efforts to enhance the external efficiency of the conventional GaN-based LEDs, by means of vertical-conducting structure, surface texturing, or transparent conduction layer, etc., have been proposed [3-4]. However, it is necessary to further enhance the light intensity of the single LED chip for high power applications such as flash lamp and solid-state light. One attainable approach for increasing output optical power of LEDs comes obviously by enlarging the chip size. Wierer *et al*. [5] have presented the performance of large-size (1×1 mm^2) high-power GaN-based LEDs operated under higher injection current. Nevertheless, the poor thermal and electrical conductivity of commonly used sapphire substrate have hindered efficient heat dissipation and increased process complexity. To alleviate the current crowding effect of lateral GaN-based LEDs, the separation of GaN epilayer from the sapphire substrate was first presented by means of laser lift-off (LLO) technique [6]. In this study, a patterned LLO process to define the device region and separate the GaN epilayer from sapphire substrate simultaneously, as well as an electroplated nickel layer to serve as metallic substrate for the GaN-based epilayers are proposed. N-side-up large-area (0.6×0.6 and 1×1 mm^2) GaN-based LEDs with vertical-conducting structure (abbreviated as VM-LEDs) were successfully fabricated and demonstrated. Surface treatment employing ICP and chemical etching to improve the ohmic behavior of the top n-GaN to a Ti/Al/Ti/Au electrode is studied. Effects of the cathode electrode processing on both the electrical and optical characteristics of the VM-LEDs is reported and discussed.

2. Experiments

The GaN-based epilayer structure used in this work was grown on a c-plane sapphire substrate by metalorganic chemical vapor deposition (MOCVD). The GaN epilayer transfer process begins with the e-beam-evaporated deposition of a highly reflective metal system comprising Ni/Au-Ti/Al/Ti/Au film as an ohmic contact to p-GaN and also as an adhesive layer to the subsequent electroplated nickel layer. The electroplating process was conducted under a constant current of around 1.7 A with the plating solution kept at about 55^{o}C before the patterned LLO process. A 248 nm KrF excimer laser was directed through a copper mask to the backside of the sapphire substrate. Through adjusting the spot size and the space between the two neighbor regions exposed to the laser beam, without any further photolithographic process, device region of desired size could be realized during the separation of the epilayer structure from the sapphire substrate. Figure 1(a) demonstrates the top view of samples after the patterned LLO process. Squared-shape GaN epilayer with various chip sizes (0.36×0.36–0.09×0.09 mm^2) were demonstrated. The surface of the separated GaN device was then etched to remove the un-doped GaN layer using $Cl_2/He/CH_4$ inductively coupled plasmas (ICP) etching. To improve the contact properties and release possible damage incurring from the ICP etching process, an additional chemical KOH wet etching and following HF/HCl treatment onto the n-GaN were conducted before formatting the Ti/Al/Ti/Au contact pad. The schematic device structure of the fabricated VM-LEDs is shown in Fig. 1(b). Note that the n-GaN epilayer is with a rough surface after ICP and chemical treatment. The fabricated VM-LEDs are with two different sizes of 1×1 (referring to as L-size) and 0.6×0.6 mm^2 (M-size), respectively. Note that regular LEDs (with conventional p-side up lateral structure on sapphire substrate) were also made for comparison.

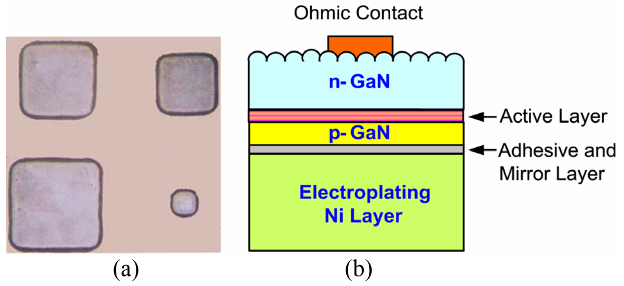

Fig. 1 (a) Optical microscopy (OM) picture of samples with four different chip sizes after the patterned LLO process. (b) Schematic cross section of a VM-LED with surface roughening by plasma.

3. Results and Discussion

Figure 2 shows the scanning electron micrographs of the GaN epilayer surface after ICP etching using Cl_2(10 sccm)/He(10 sccm)/CH_4(2.7 sccm) at RF power of 120 W for 280 sec and then followed by chemical wet etching. It is seen that a rough surface with ball-features of 0.3–0.8 μm in diameter was formed after ICP etching, which is expected to improve light extraction efficiency. Comparison of the measured I-V characteristics of VM-LEDs with ICP etching only and regular LEDs was shown in Fig. 3. Under an injection current of 350 mA, the measured forward voltage drop (V_F) of the L and M-size VM-LEDs are 3.89 and 4.05 V, respectively, which are relatively lower than that of the regular ones. The decrease in V_F of the VM-LEDs should be mainly attributed to use of metallic substrate which enables a relatively much less current crowding as well as a shorter and higher conductivity of the current conduction path. Figure 4 shows the measured optical performance (*Lop-I* characteristics) for the VM- and regular LEDs with different device sizes. As compared to that of the regular LEDs of the same size, about 140% improvement in Lop at 350 mA has been obtained for both sizes of the VM-LEDs.

Effect of the chemical wet etching is also investigated. As shown in Fig. 5, it is seen that, with an additional KOH wet etching for 90 sec, it leads to the highest enhancement in Lop. For the L-size VM-LED, an increase in Lop by 227% and 195% has been obtained at 350 and 800 mA, respectively. The increase in Lop is due to the additional wet etching has led to the formation of hexagonal cone-like features of surface (Fig. 2(d)) which is further improve the extraction efficiency.

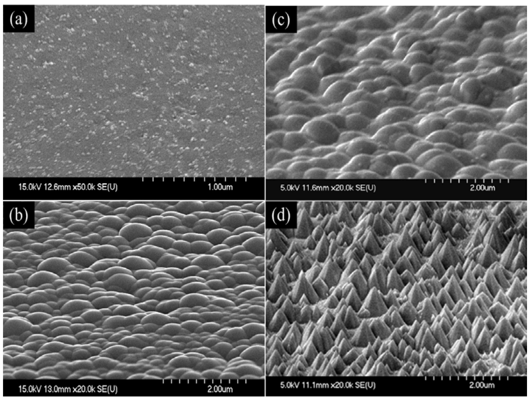

Fig. 2 SEM micrographs of the GaN surface after patterned LLO process: (a) without surface treatment; (b) with ICP etching for 280 sec only; (c) with ICP and HCl etching; and (d) with ICP, KOH and HF/HCl etching.

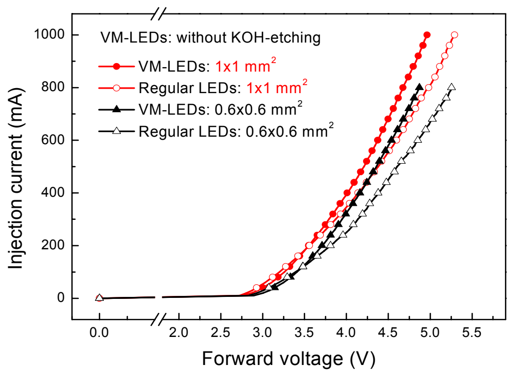

Fig. 3 Comparison of the measured I-V characteristics of VM-LEDs with ICP-etching for 280 sec and regular LEDs.

4. Conclusion

In summary, the use of a patterned LLO technique and an electroplating-Ni process as well as surface roughening through plasma and chemical wet etching were proposed for the fabrication of large-area VM-LEDs. It has been shown that with ICP etching for 280 sec and followed by an additional KOH etching for 90 sec as well as HF/HCl treatment for the n-GaN epilayer would have the largest benefit in both the ohmic contact and light output performance of the VM-LEDs. As compared to the regular LEDs of the same size, an increase in light output power by 227% (195%) at 350 (800) mA has been obtained from the L-size VM-LEDs. It is expected that the technologies proposed in this work would be very useful for high power LEDs fabrication.

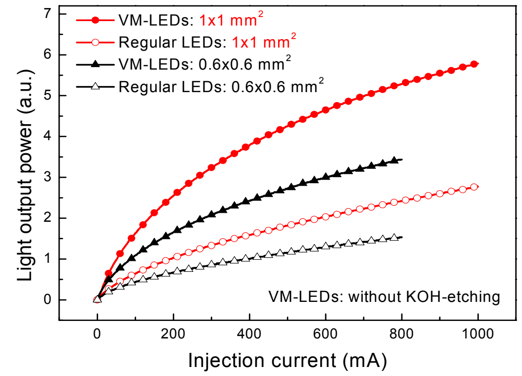

Fig. 4 Comparison of the measured Lop-I characteristics of VM-LEDs with ICP-etching for 280 sec and regular LEDs for various chip sizes.

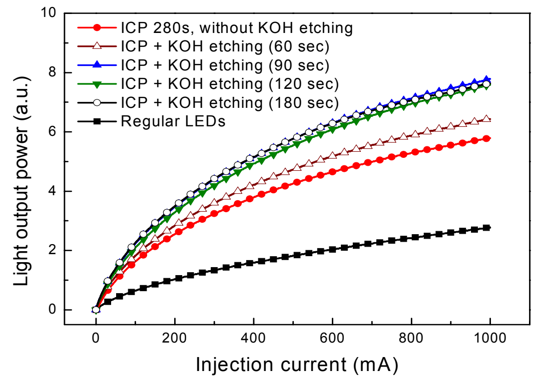

Fig. 5 Comparison of the measured Lop-I characteristics of VM-LEDs and regular LEDs with the size of 1×1 mm^2 for different KOH wet etching times.

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