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Improved light output and electrical performance of InGaN/GaN light-emitting diode by surface texturing of the n-type GaN

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1. Introduction

Recently, gallium nitride (GaN)-based device technologies have included light-emitting diodes (LEDs), laser diodes (LDs) and photodetectors (PDs) [1,2]. With the recent development of high-quality GaN crystalline film, the development of very bright blue LEDs and cw LDs at room temperature has progressed greatly. The most commonly used growth substrate, sapphire, still constrains the quality of the GaN film because of the lattice and thermal expansion coefficient mismatch between the sapphire and GaN [3]. Additionally, the sapphire substrate suppresses LED, LD and transistor device performance because it has poor thermal and electrical conductivity. All contacts in devices fabricated on sapphire substrates, must be made from the top of the device. Therefore, the use of laser lift-off (LLO) to transfer the GaN films from the sapphire substrate has been widely studied [4]. Moreover, a textured surface can enhance the light extraction efficiency of LEDs due to the scattering of photons from the textured semiconductor surface [5,6]. Some increase in extraction efficiency was observed with these methods. However, these approaches typically require complicated processes involving lithographic patterning and subsequent dry etching, or a high temperature annealing process. In this letter, we attempt to combine the techniques of wafer bonding, LLO and texturing an n-GaN surface by wet etching to realize high performance LEDs.

2. Experimental

The GaN films used herein were deposited by metal-organic chemical vapor deposition on a (0001) sapphire substrate. An undoped GaN buffer layer with a thickness of 1.5 μm was formed. On this layer is deposited a 3-μm-thick Si doped n-type GaN and a 2-μm-thick Mg-doped p-type GaN. The carrier concentrations were measured to be 5×10^{18} cm^{-3} and 5×10^{17} cm^{-3}, respectively, by Hall measurements. Then, indium tin oxide (ITO) was deposited to a thickness of 180 nm and annealed at 500 °C in a N2 environment. The epitaxy-wafer is deposited on Ag and metal bonding materials (Pd/In) are deposited on the silicon substrate. The epitaxy-wafer was bonded to the silicon substrate using hot-pressure. Then, the sample was scanned at a wavelength of 248 nm. The laser beam was irradiated at the sapphire substrate and GaN. Following LLO, the sapphire substrate was separated from the GaN epitaxy. The samples were dipped into a boiling HCl solution (HCl: (di-ionized) water ＝1:1) for 2 min to clean the surface of Ga. The samples were etched using Cl2 ICP to yield no un-doped GaN. Following ICP treatment, the samples were dipped into a boiling HCl solution (HCl: (di-ionized) water ＝1:1) for 5 min to clean their surfaces. To enable n-type contact formation, the undoped GaN was etched away to expose the n-GaN layer by wet chemical etching. The KOH solution was used to etch the n-GaN surface. The solution was heated instead of being subjected to photo irradiation. Because the etching temperature (150℃) exceeded the boiling point of water, ethylene glycol was used as the solvent of KOH. After the texturing process, the n-GaN surface was cleaned with H_2SO_4: H_2O_2:H_2O (5 :1 :1) solution. Then, Cr/Pt/Au and Al/Ti/Au metals were deposited on the textured n-GaN surface and the back surface of the Si substrate, respectively, to obtain the ohmic contacts. Details of the device fabrication steps are shown in Figs. 1(a)-1(h). After the n-contact and p-contact metal deposition, the vertical-electrode wafer-bonded type (VB-type) GaN LED with textured surface could be obtained. Here, VB-type LED samples with surface texturing and conventional GaN LED samples were not encapsulated for the electrical and optical measurements.

3. Results and discussions

After the VB-type GaN structure was obtained, the top surface of the n-GaN layer was etched with a wet chemical solution in order to obtain the textured surface. Figures 2 (a, b, and c) show the scanning electron microscopy images of n-GaN layers which were surface textured by etching with 50% KOH solutions, at 150℃ for 60 sec, 120 sec, and 180 sec, respectively. For these samples, a surface covered with hexagonal conelike structures could be obtained. However, for the sample etched with KOH solution at 150℃ for 120 sec, the size of the hexagonal conelike structures is larger than that for the samples etched with KOH solution at 150℃ for 60 and 180 sec. It is well known that the roughness of the textured surface of LEDs must be near to or larger than the emission wavelength in order to enhance the external quantum efficiency. The top surface of the n-GaN layer was etched with KOH solution at 150℃ for 120 sec, the encompassed size of based plane size of the hexagonal conelike structures of over 400 nm is easily and quickly obtained. The optimum etching parameters are 120 sec etching time and 50% KOH solution. It is important to evaluate the effect of surface texture on LED performance.

Figure 3 shows the Luminescence-current-voltage (L-I-V) characteristics of the VB-type LEDs with a textured surface (ICP+120 sec etching in 50% KOH solution) and conventional LED. Here, the VB-type LED chips were not encapsulated for the electrical and optical measurements. The VB-type LEDs with surface texturing exhibited a maximum luminance intensity of 250 mcd (at 20 mA) with a forward voltage of 2.87 V. The luminance intensity is over two times larger than that of the conventional LED (at 20 mA). Clearly, the standard LEDs exhibit the smallest brightness and easily saturate when injected at high current. Correspondingly, the VB-type LEDs can be operated with high current injection without saturation. The Si substrate plays an important role in the thermal heat sink. The VB-type LEDs with textured surface exhibit the highest brightness. This means that light can escape from the n-GaN/air interface because of the change in light path caused by surface scattering due to the surface texture. Because of the use of the surface texturing technique, the light can escape easily from the air/semiconductor interface, which increases the light extraction efficiency.

4. Conclusions

In summary, InGaN/GaN LEDs with vertical electrodes were fabricated by wafer bonding and LLO processes. Using hot KOH solution, a textured n-GaN surface could be obtained. It was found that under high current injection, the VB-type LEDs with textured surface exhibited better performance than conventional LED. This feature is attributed to the Si substrate providing a good heat sink and surface roughening enhancing the external quantum efficiency.

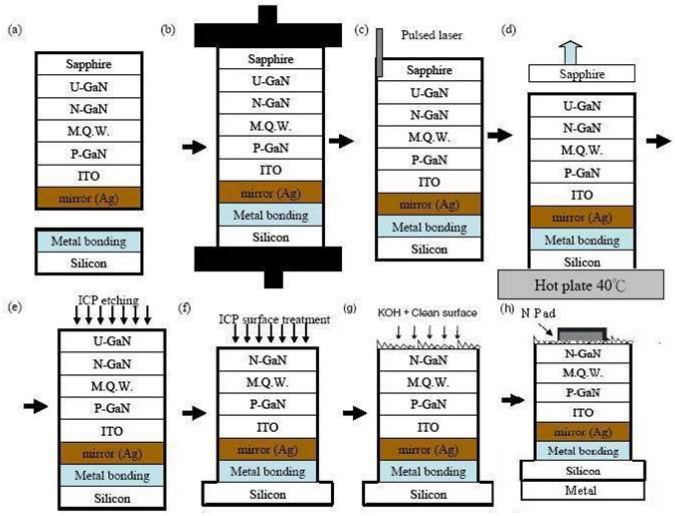

Fig. 1. Schematic diagram of fabrication steps for n-side-up InGaN/GaN LED structure: (a) P-type metal deposition, (b) Si substrate bonding, (c) laser lift-off the sapphire substrate, (d) separation, (e) ICP etching of u-GaN layer, (f) u-GaN removal and surface texturing by ICP, (g) chemical wet-etching and cleaning of u-GaN surface, and (h) evaporation of contact metal.

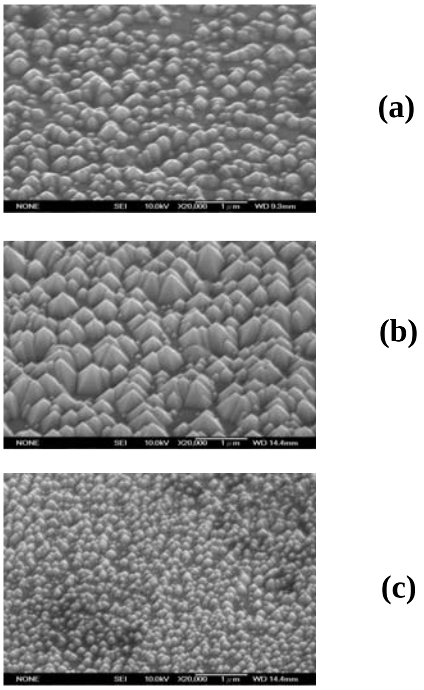

Fig. 2. SEM images of n-GaN etched with 50% KOH solutions at 150℃ for (a) 60 sec, (b) 120 sec, and (c) 180 sec.

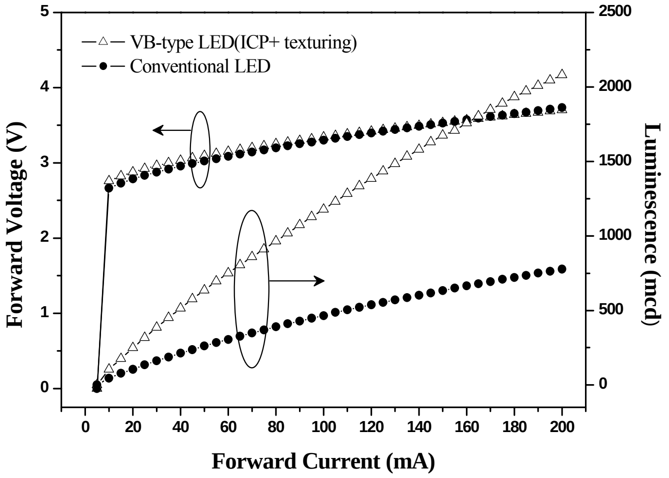

Fig. 3. L-I-V curves of VB-type GaN LEDs with surface texturing as compared with that of conventional GaN LED with sapphire substrate.

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