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Surface texturing for wafer-bonded GaN/mirror/Si light-emitting diodes

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1. Introduction

GaN-related alloy semiconductors with wide band gap ranging from 3.4 to 6.2 eV at room temperature are the focus of current research because of the promising applications for UV or blue emitters and detectors. Especially, for the applications of the next generation lighting, it is necessary to develop the high-power and high-light-excitation blue light-emitting diodes (LEDs). However, the performance of GaN LEDs is poor for high power applications if the LEDs were fabricated on the sapphire substrate due to the poor thermal conductivity. To solve this problem, the GaN epilayers with LED structure can be transferred to the other substrate with good thermal conductivity such as Si or metallic material by wafer bonding and laser lift-off (LLO) technologies. Moreover, a textured surface can enhance the light extraction efficiency for the LEDs application. For the high efficient red/amber LEDs, the textured surfaces can directly be obtained by plasma etching on the top of epilayer. However, the thickness of the p-GaN cladding top layer is thin about 0.3 μm. It is not desirable to directly etch the p-caldding GaN layer,because it will increase the resistance of p-GaN layer after surface textured process, and such treatment might cause electrical deterioration. Using the wet etching process can avoid the plasma damage on the LEDs surface. The photochemical etching for roughened LED surface has been reported previously [1]. However, there exists etching uniformity and etching rate problems. In our previous study, a high efficient AlGaInP LED with mirror substrate (MS) has been reported [2]. Here, we try to combine the techniques of the wafer bonding, LLO and textured n-GaN surface by wet etching technology (without additional photo illumination) to make the high performance and brightness blue LEDs.

2. Experimental details

GaN films used in this work were grown on (0001) sapphire substrate using metal organic chemical vapor deposition. The GaN LEDs epilayers were listed in order from substrate to surface: 300 nm GaN nucleation layer, 1 μm GaN undoped layer, 0.2 μm Si-doped n-AlGaN layer and 2 μm n-GaN layer, undoped 5-period GaN/InGaN MQW, 0.1 μm Mg doped p-AlGaN and 0.2 μm p-GaN. First, the samples were cleaned by standard solvent, dipping into HCl solution (HCl: H_2O=1:1) for 1 min, immersing into boiling aqua regia (HCl: HNO_3=3:1) for 10 min, and rinsing in running de-ionized water. After clean process, the square mesa structure of 300 μm × 300 μm was fabricated by an inductively-coupled-plasma etcher for electric current isolation. The SiO_2 layer using to preserve the side-wall was grown by plasma enhanced chemical vapor deposition. Then, Pd (200 nm) metal was deposited on p-GaN layer used as the contact layer. Here, the Pd layer is not only as Ohmic contact layer, but also as the reflective mirror layer. After annealing, the bonding metals Ti/Au (12 nm/1 μm) were deposited by E-beam system. The LEDs epi-layer was bonded to the Si substrate by thermal-pressure bonding and then subjected to the LLO process. After LLO process, the GaN LEDs epi-layers were transferred to Si substrate with reflective metal mirror. Here, the top layer of LED/mirror/ Si substrate is n-type GaN epilayer.

The various concentration KOH was used to roughen the n-GaN surface. In order to obtain the uniform roughened surface, the solution was heated instead of phtoirradiation. The etching rate was 0.1~1 μm/min at 120-160 °C. After textured process, n-GaN surface was cleaned by H_2SO_4:H_2O_2:H_2O (5:1:1) solution. Then Ti/Al/Ti/Au metals (12/60/60/1000 nm) were deposited on the textured n-GaN surface to obtained the Ohmic contact. After the n-contact metal deposition, the vertical-type bonding (VB) GaN LED with and without textured surface can be obtained.

3. Results and discussion

Figure 1 shows the contact characteristics of Pd metal and p-GaN layer as the samples annealed at different temperatures. It was found that the as deposited Pd/p-GaN sample can not present Ohmic contact property. As the annealing temperature increasing to 500°C, the Pd metal presents linear with p-GaN layer. The specific contact resistances between Pd and p-GaN was 8.1×10^{-3} Ω-cm^2 evaluated by using a rectangular transmission-line-method pattern. Due to the fact that Pd layer is not only as Ohmic contact layer, but also as reflective metal mirror, high annealing temperature is not suggested. For this VB GaN LED, the forward voltage is about 3.0 V as injected at 20 mA. It is lower than that of standard GaN LED with sapphire substrate (3.2 V).

Figures 2 (a) and (b) show the scanning electron micrograph images of n-GaN layer surface texture by 37% and 50% KOH concentrations etching at 150 °C for 1 min, respectively. For both samples, the hexagonal cone-like surface can be obtained. However, as the sample etching by 37% KOH, the size of hexagonal cone-like feature is larger than that etching by 50%. At higher KOH concentrations, the water molar concentration decrease, a negative charge could build up on the n-GaN surface in the KOH solution, hindering the diffusion of OH^- ions. It results in decreasing the etching rate. This phenomenon is also observed in the previous report of Stocker *et al* [1]. The lower etching rate makes the smaller size of hexagonal cone-like feature. In order to obtain the effective light extraction, the size of hexagonal cone-like should be near the emission wavelength. In our study, the 300~500 nm feature size can easily be obtained as the samples etching in 37% KOH at 150 °C for 1 min.

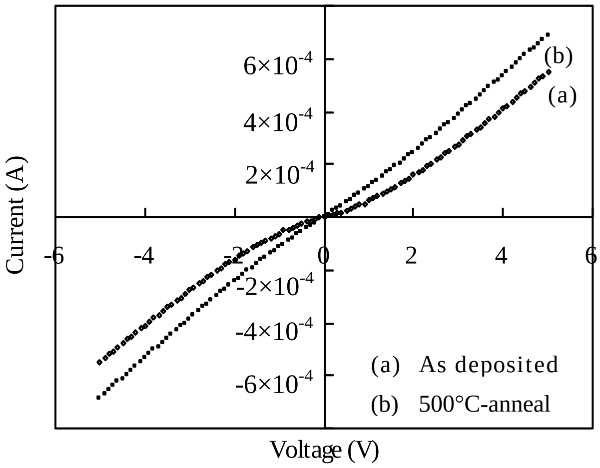
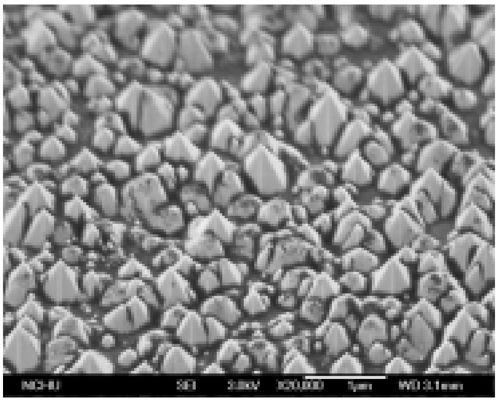


Fig. 1 I-V characteristics for the Pd contact on p-type GaN with different anneal temperature

(a) 37% KOH-1 min



(b) 50% KOH-1 min

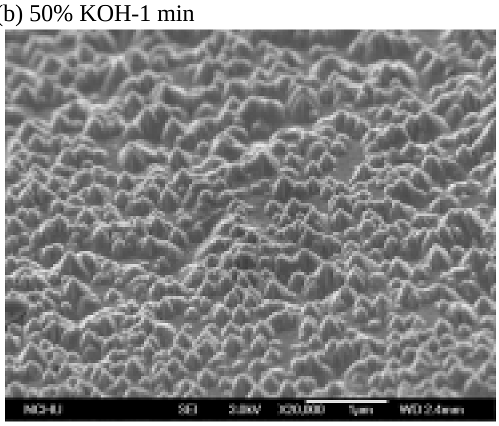


Fig. 2 SEM micrographs of n-GaN etched by (a) 37% and (b) 50% KOH solutions at 150°C for 1 min.

It is important to evaluate the effect of surface texture on the LEDs performance. Figure 3 shows the L-I characteristic of the standard, VB without textured surface and VB with textured LEDs. Obviously, the standard LEDs present the smallest brightness and easily saturate as injected to high current. For the VB type LEDs can stand for high current injection. Especially, the VB type LEDs with texturing surface present the highest brightness. These results can be attributed to the VB and surface textured processes result in the reflective thermal dissipated substrate and increasing in the extraction efficiency.

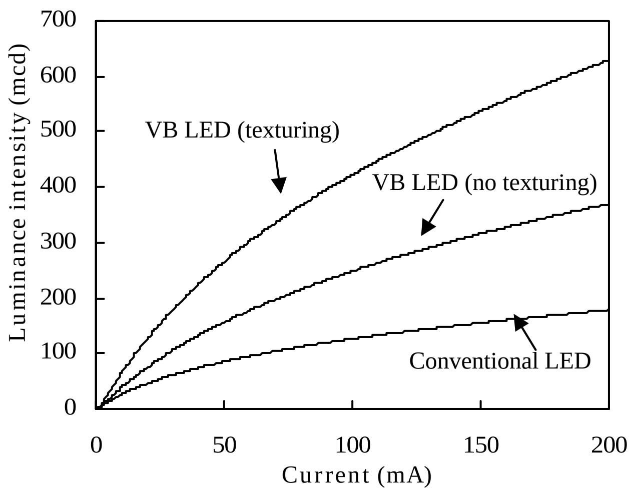


Fig. 3 L-I curves of conventional, VB (no texturing), and VB (texturing) GaN LEDs

4. Conclusions

In summary, GaN/mirror/Si LEDs with vertical electrodes were fabricated by wafer bonding and LLO processes. It was found that the surface with textured can get the better performance than the sample without a textured surface. Using the hot KOH solution, a textured n-GaN surface can be obtained. These processes can be applied to fabricated the large-area high brightness and high power blue LEDs.

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