Improved light extraction of GaN-based light-emitting diodes with surface-textured indium tin oxide electrodes by nickel nanoparticle mask dry-etching*

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GaN-based light-emitting diodes (LEDs) with surface-textured indium tin oxide (ITO) as a transparent current spreading layer were fabricated. The ITO surface was textured by inductively coupled plasma (ICP) etching technology using a monolayer of nickel (Ni) nanoparticles as the etching mask. The luminance intensity of ITO surface-textured GaN-based LEDs was enhanced by about 34% compared to that of conventional LED without textured ITO layer. In addition, the fabricated ITO surface-textured GaN-based LEDs would present a quite good performance in electrical characteristics. The results indicate that the scattering of photons emitted in the active layer was greatly enhanced via the textured ITO surface, and the ITO surface-textured technique could have a potential application in improving photoelectric characteristics for manufacturing GaN-based LEDs of higher brightness.

Keywords: GaN-based light-emitting diodes, nickel nanoparticle, extraction efficiency, surface roughening

PACC: 8140T, 7865K, 7360L

1. Introduction

Wide band-gap GaN-based semiconductors have been attracting great attention due to their extensive applications for optoelectronic devices in the blue and ultraviolet (UV) wavelength regions.[1,2] Recently, as the brightness increases, GaN-based light-emitting diodes (LEDs) have played a more and more important role in many promising fields,[3,4] such as backlighting sources for liquid-crystal displays, exterior automobile lighting, traffic signals, and solid-state lighting.

It is well known that the external quantum efficiency of GaN-based LEDs is still much smaller than the internal quantum efficiency because the total internal reflection occurs at the semiconductor-air interface due to the refractive index difference of GaN-based materials and air. For GaN-based LEDs, the indium tin oxide (ITO) film has been widely used as a current spreading layer and window material due to its high transparency and its low electrical resistivity.[5] However, the refractive indexes of ITO material and air are 2.1 and 1.0, respectively. According to Snell's law, the light critical angle ($\theta_c = \sin^{-1}(n_{air}/n_{ITO})$, where n_{air} and n_{ITO} are the refractive indexes of air and ITO material, respectively) at ITO-air interface is smaller, and so only a small fraction of the light generated in the active region can be extracted from the surface of conventional GaN-based LEDs. In order to enhance the probability of escape for photons of GaN-based LEDs, several techniques have been developed to change the surface properties of LED chip, such as building nano-ring structures,[6] nano-patterning top metal,[7] using photonic crystal structures,[8,9] and surface roughening.[10−12] Among these, surface roughening is an efficient and simple way to improve the light extraction efficiency. ITO surface-textured GaN-based LEDs or p–GaN surface-textured GaN-based LEDs have been fabricated by various surface-texture technologies. However, the thickness of the top p–GaN layer is very thin in the structure of conventional GaN-based LEDs, and so the surface roughening treatment often destroys the electrical characteristics.[13] Because of the difficulties in controlling the damage to the p–GaN layer, it is desirable to choose an ITO current spreading layer as a

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roughening object by using effective surface roughening technologies, such as inductively coupled plasma (ICP) dry-etching technology. Recently, significant progress in improving the light extraction efficiency by roughening the ITO layer has been made. Chang *et al.*[14] showed that the light output power of GaN-based LEDs could be increased by 12% by means of ITO surface roughening using imprint lithography and wet etching techniques. Horng *et al.*[15] obtained an enhancement of about 60% in the output power at 20 mA by texturing the ITO transparent layer using lithography and ICP etching technology. Leem *et al.*[16] proposed a maskless wet-etching technique for texturing the ITO layer and gained about 30% improvement in light output. However, most of this research involved complicated fabrication steps, thus they are time-consuming and expensive.

In this paper, we present a practical approach to fabricating ITO surface-textured GaN-based LEDs using ICP dry etching technology with a monolayer of nickel nanoparticles as the etching mask. The luminance intensity of ITO surface-textured GaN-based LEDs was enhanced by about 34% compared to that of conventional LED without a textured ITO layer. Detailed experimental procedures and the optoelectrical characteristics of the fabricated GaN-based LEDs will be discussed in the following sections.

2. Device fabrication

The GaN epitaxial wafers used in this work were grown using metal-organic chemical vapour deposition (MOCVD) with the Thomas Swan closely-spaced showerhead reactor on (0001) sapphire substrates.[17] Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl) and ammonia (NH_3) were used as Ga, In, Al and N sources, respectively. The n-type doping source was silane (SiH_4) and the p-type doping source was cyclopentadienylmagnesium (Cp_2Mg). The epitaxial wafer structure consists of a low-temperature 25-nm thick GaN buffer layer, a 2.0-μm thick undoped GaN layer grown at 1050 °C, a 2-μm thick Si-doped n–GaN layer, an InGaN/GaN multiple-quantum wells (MQWs) active layer, a 10-nm thick p-type $Al_{0.1}Ga_{0.9}N$ layer, and a 180-nm thick Mg-doped p–GaN layer. After the p–GaN was activated by an annealing treatment at 750 °C in nitrogen (N_2) ambience, partial surface of the LED epitaxial wafer was etched to form a mesa by ICP etching using a patterned SiO_2 film as a mask until the n-type GaN layer was exposed. Then an ITO film with a thickness of 350 nm was deposited onto the p–GaN layer to serve as the transparent current spreading layer by electron beam evaporation.

The surface-textured ITO layer was formed by nickel nanoparticle mask and ICP etching. The detailed ITO surface-textured procedures were carried out as follows. Firstly, Ni nanoparticles with a diameter range of 100 nm were disolved in absolute ethyl alcohol using citric acid as a dispersant, where the concentrations of Ni nanoparticles and citric acid in mixed solution were 10 wt% and 0.2 wt%, respectively. Then the mixture was dispersed with ultrasound treatment for 15 minutes. Secondly, the prepared dispersion of nickel nanoparticles was spin-coated onto the ITO surface at a rotation speed of 4000 rpm for 45 seconds (s) to form a self-aligned monolayer film. After the sample was heated in an oven for 10 minutes at 120 °C in a N_2 atmosphere, the Ni nanoparticle mask on the top of ITO layer was formed, and a typical surface atomic force microscope (AFM) morphology was shown in Fig. 1. In addition, ICP etching was performed on the sample surface in a Cl_2/Ar (35/5 sccm) plasma with an ICP power of 300 W and an RF power of 150 W at room temperature. In order to show the effects of different surface roughness on device performance, the ICP etching time was set to 0, 120, 160, and 200 s. After ICP etching, the samples were dipped into absolute ethyl alcohol and cleaned with an ultrasonic washer to remove the vestigial Ni nanoparticles. Then the samlpes were washed in deionized water and baked in an oven, and the textured structures on the ITO surface were prepared. Furthermore, the transparent contact layer (TCL) was fabricated by a standard photolithographic process. At last, Cr/Ni/Au (5 nm/20 nm/1000 nm) was deposited onto samples by electron beam evaporation to form p electrode and

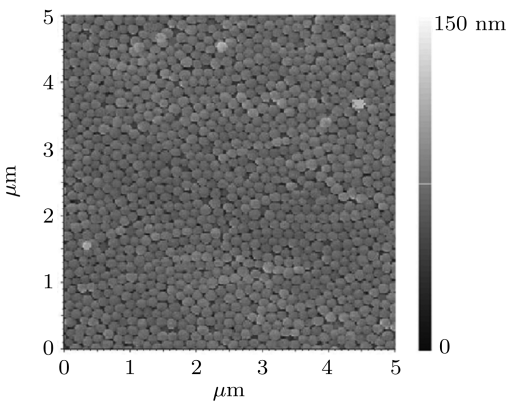


Fig. 1. AFM image of Ni nonaparticle monolayer.

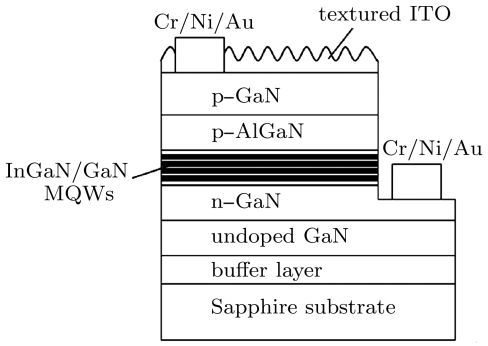


Fig. 2. Schematic diagram of GaN-based LED structure with a textured ITO surface.

n electrode. As a result, ITO surface-textured GaN-based LEDs were fabricated, and the schematic diagram is shown in Fig. 2.

3. Results and discussion

The surface morphologies of the ITO layer before and after the ICP etching process were examined by atomic force microscopy (AFM, NT-MDT Corporation). Figure 3 shows the surface morphologies of textured ITO films under different ICP treatment times. The root-mean-square (RMS) roughness value of the ITO layer before ICP etching process was only 3 nm. And it was found that RMS roughness value of the textured ITO layer was increased as ICP etching time was increased. The RMS roughness under the ICP etching time of 120, 160, and 200 s are measued to be 30.4, 50.6, and 78.5 nm, respectively. The corresponding current–voltage (I–V) characteristics of these ITO surface-textured GaN-based LEDs and conventional LEDs with a flat ITO layer were measured by an LED parameter analyser and tester (MPI Corporation). Figure 4 shows the I–V characteristics of LED chips for different ICP treatment times. It was found that the forward voltages of GaN-based LEDs with ICP etching treatment of 0 s (i.e. conventional LEDs), 120 s, 160 s, and 200 s were respectively 3.24, 3.37, 3.43 and 3.67 V, measured at an injection current of 20 mA. The forward voltages of the LEDs under ICP treatment for 120 and 160 s are similar to that of the conventional LED at 20 mA. The slightly higher voltage might result from improper dry etching which damaged the ITO film slightly, thus affecting the sheet resistances and current spreading.[16] Only the LED sample after a 200-s ICP treatment presented an inferior electrical property, this could be due to the fact that the ICP etching time was so long that it destroyed the ITO film and even the p–GaN surface.[15] Additionally, the I–V measurements also demonstrated that ITO surface-textured LEDs which suffer a reasonable ICP etching should exhibit nearly the same electrical properties as the conventional LEDs.

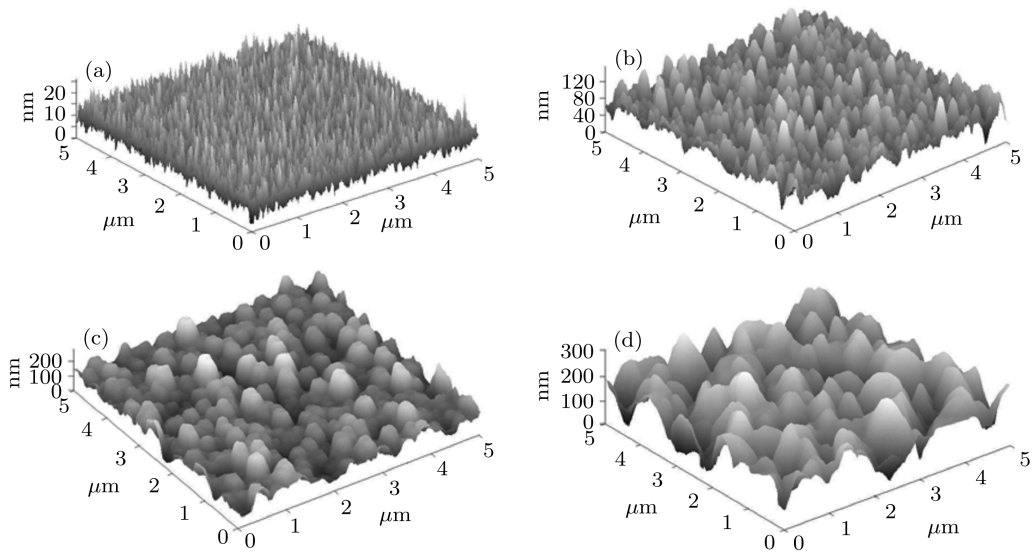


Fig. 3. AFM images of surface-textured ITO morphologies under different ICP treatment times (a) 0 s (i.e. original ITO surface), (b) 120 s, (c) 160 s, and (d) 200 s.

Figure 5 presents the dependence of luminance intensity on the injection current (L–I) characteristics of the fabricated GaN-based LEDs under different times for ICP treatment. It is clearly seen that the luminance intensities of the ITO surface-textured LEDs are all higher than those of the conventional LEDs.

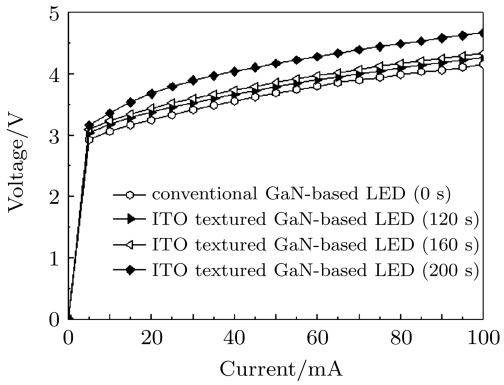


Fig. 4. The I–V forward curves of conventional LEDs and ITO surface-textured LEDs.

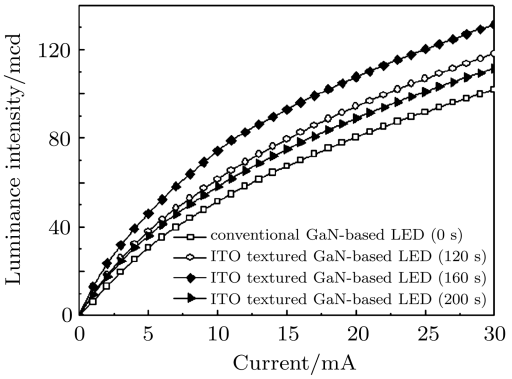


Fig. 5. The dependence of luminance intensities on currents of conventional GaN-based LEDs and ITO surface-textured GaN-based LEDs.

Furthermore, the luminance intensity of LEDs with the textured ITO layers under 160 s ICP treatment (107.6 mcd) exhibited about 34% improvement compared with that of the conventional LEDs (80.5 mcd) at 20 mA. The light output power versus injection current characteristics of the LEDs with the textured ITO layers under ICP treatment of 160 s and conventional LEDs are shown in Fig. 6. It can be seen that the light output powers of the LEDs with the surface-textured ITO layers are increased compared with conventional LEDs. The significant improvement in the luminance intensity and the light output of ITO surface-textured GaN-based LEDs can be attributed to the enhancement of light extraction efficiency via the textured ITO surface, and the textured ITO surface can greatly increase the probability of photons escaping outside from the LED.[16] In addition, the ITO surface-textured morphologies can be controlled more effectively to improve the light output by adjusting ICP treatment time. Therefore, it is possible to make greater improvements in light extraction efficiency by optimizing textured conditions in future research.

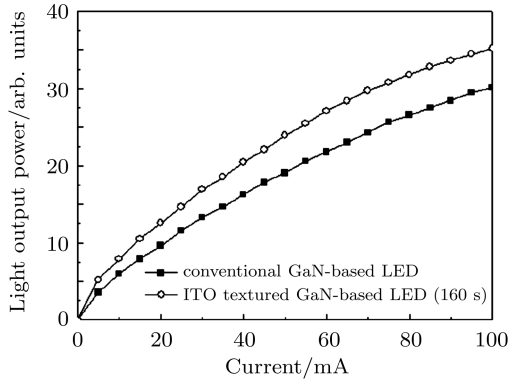


Fig. 6. The dependence of light output power on current characteristics of conventional LEDs and surface-textured LEDs after ICP treatment of 160 s.

Figure 7 shows the room-temperature electroluminescence (EL) spectra of the fabricated ITO surface-textured LEDs after ICP treatment of 160 s and conventional LEDs at 20 mA. It can be seen that the MQW emission peaks of these two LEDs both occurred at 448 nm, and the EL emission intensity of the ITO surface-textured LEDs is clearly higher than that of the conventional LED. This could also be attributed to the enhanced light extraction efficiency of the textured ITO surface.[14]

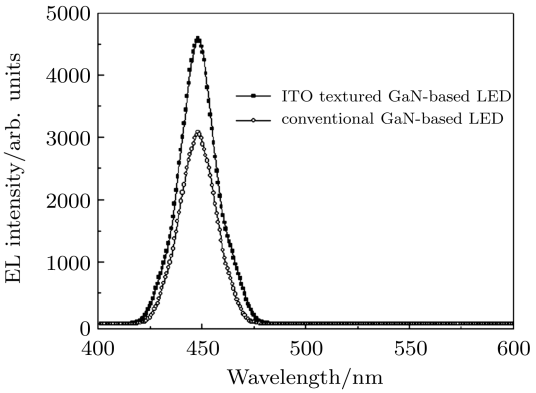


Fig. 7. Room-temperature EL spectra of conventional LEDs and surface-textured LEDs after 160 s ICP treatment.

4. Conclusions

In summary, this investigation describes the light-output improvement of GaN-based LEDs by roughening the ITO current spreading layer using a Ni

nanoparticle mask and ICP etching technology. The textured ITO surface enhanced escape probability of photons inside the LED structure, thus the light output of GaN-based LED at 20 mA was increased by 34 %. The results also indicate that the electrical properties of the fabricated GaN-based LED can be well-controlled by adjusting the ICP treatment time on the ITO surface. This surface-textured technique on the ITO current spreading layer should be valuable for increasing the external quantum efficiency and reducing the production costs of GaN-based LEDs of higher-brightness.

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