Light-extraction efficiency and forward voltage in GaN-based light-emitting diodes with different patterns of V-shaped pits*

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We present a new method of making a textured V-pit surface for improving the light extraction efficiency in GaN-based light-emitting diodes and compare it with the usual low-temperature method for p-GaN V-pits. Three types of GaN-based light-emitting diodes (LEDs) with surface V-pits in different densities and regions were grown by metal–organic chemical vapor deposition. We achieved the highest output power and lowest forward voltage values with the p-InGaN V-pit LED. The V-pits enhanced the light output power values by 1.45 times the values of the conventional LED owing to an enhancement of the light scattering probability and an effective reduction of Mg-acceptor activation energy. Moreover, this new technique effectively solved the higher forward voltage problem of the usual V-pit LED.

Keywords: V-shaped pits, light-extraction efficiency, forward voltage

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1. Introduction

Recently, GaN-based light-emitting diodes (LEDs) have progressed tremendously in applications such as backlighting, signals, and general lighting. Despite the recent achievements — the internal quantum efficiency (IQE) of LEDs is now up to 80% — the light-extraction efficiency (LEE), which is only 26% for a planar GaN LED, still needs to be enhanced.[1–3] A major factor responsible for the poor light-extraction efficiency is the total internal reflection (TIR) when the angle of incidence exceeds the critical angle θc determined by Snell's law. This is connected with the refractive index, which for GaN is 2.5 at 460 nm, whereas that of air is 1.0. This causes a great amount of light to reflect back into the semiconductor at normal incidence. The critical angle of total internal reflection for GaN-air interface is merely 23°, which severely limits the extraction efficiency of a GaN-based LED.[4]

For decades, considerable efforts have been devoted to further increasing the light-extraction efficiency of LEDs. A number of approaches such as patterned sapphire substrate,[5] chip shaping,[6] random surface texturing,[7–10] photonic crystals,[11,12] and graded-refractive-index antireflective contacts[13] have been reported. For a textured surface, etching damage was induced in the p-GaN due to the formation of surface defects such as vacancies, impurities, and residuals as a result of the dry etching process.[14] And the periodic photonic crystal nanopattern in p-GaN fabricated by plasma dry etching often results in damage to the p-GaN layer and sometimes even to the MQW.[15] On the other hand, the surface texturing techniques such as V-shaped pits formed at lower temperatures in p-GaN[9,16] are feasible for industrial application. However, there is some difficulty in decreasing the forward voltage in low-temperature p-GaN V-shaped pits (LT p-GaN V-pits), which arises from the poor activation performance of p-GaN at low temperatures.

In this letter, we report a new method of V-shaped texturing by doping a certain amount of trimethyindium (TMI) into the p-GaN layer, which can reduce the forward voltage and enhance the LEE. As a result, the LED with p-InGaN V-shaped pits (p-InGaN V-pits) texturing shows much better light-output power than the LED with planar p-GaN and the LT p-GaN V-pit LED.

2. Structure and parameters

InGaN LEDs that emit at 460 nm were grown on a *c*-plane (0001) sapphire substrate by low-pressure metal–organic chemical vapor deposition (MOCVD). The LED structures consist of a buffer layer on sapphire substrate, a 2-μm thick undoped GaN layer, a 3-μm thick Si-doped n-type GaN layer, an MQW-active layer consisting of seven periods of undoped InGaN wells and Si-doped GaN barriers, an Mg-doped p-type AlGaN electron blocking layer, and a 300-nm Mg-doped p-GaN layer at 920 °C (actual temperature). The wafers were annealed at 600 °C for 10 min under air for p-type GaN dopant activation. The ITO layer was deposited onto the p-GaN layer to form a p-side contact layer and a current spreading layer. The Cr/Au was deposited onto the ITO layer as p-side and n-side electrodes. After the fabrication of the LEDs, the device performance, including the output power and forward voltage

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characteristics, was investigated. The surface morphologies were examined by scanning electron microscopy (SEM, Hitachi S-4800). The current–voltage and light-output power measurements were carried out using a probe station system. A schematic of the V-pit devices is shown in Fig. 1.

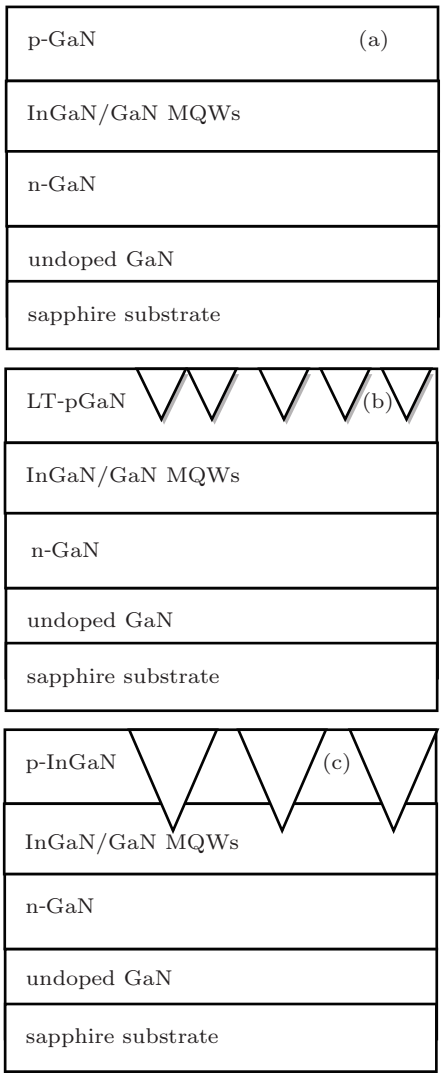


Fig. 1. Schematic diagram of GaN-based LED structures with Ref-LED (a), LT p-GaN LED (b), and p-InGaN LED (c).

Three types of LED samples were fabricated to investigate the influence of V-shaped pits formations on the light-output power and the forward voltage in LEDs. The reference-LED as the planar LED was fabricated by using the standard LED fabrication process as described above. The LT p-GaN V-pit LED is also fabricated by using the same standard LED fabrication process except that the temperature of the Mg-doped p-GaN layer is at 820 °C. To fabricate the p-InGaN V-pit LED we used the same standard LED process except that the Mg-doped p-GaN layer is doped with a certain amount of TMI (trimethyindium, In) flow, and the temperature was still at 920 °C. For convenience, the reference-LED, LT p-GaN V-pit LED and p-InGaN V-pit LED are denoted henceforth as Ref-LED, LT p-GaN LED, p-InGaN LED, respectively.

3. Results and discussion

3.1. Scanning electron microscopy

The surface morphology of the V-pits has been analyzed with SEM (scanning electron microscopy) measurements. Figures 2(b) and 2(d) show typical SEM images obtained from the top-view of the surfaces of the p-GaN layer for the LT p-GaN LED and p-InGaN LED, respectively. The V-pit size differs a lot between the LT P-GAN and p-InGaN LEDs, the diameters being of about 300 nm in the former, and about 600 nm in the latter. The difference can be attributed to two basic V-pit formation mechanisms. The V-pits develop in the LT p-GaN LED mainly because Ga atoms might not have enough energy to migrate to proper sites or to activate their desorption at low temperatures.[17] Thus, the lateral growth rate of GaN will become smaller. The V-pits can be formed at low temperatures no matter if there is TMI flow, and we named this type of V-pits low temperature V-pits.[18] Formation of the other type of V-pits, which appears in the p-InGaN LED, depends on TMI flow. As both the thickness of the InGaN/GaN MQWs and the TMI mole fraction of the bulk InGaN increase, the V-shaped pits are generated from pure or mixed screw TDs. The strains in MQWs with a high TMI mole fraction and low surface mobility of adatoms on the InGaN layer are responsible for this type of V-pits.[19] They are very large and finally nearly cover the whole surface, and we named this type of V-pits In-doped V-pits. The typical diameter of In-doped V-pits is about 600 nm, which is larger than that of low temperature V-pits (300 nm).

Figures 2(a) and 2(c) show tilted SEM images of the p-InGaN and LT p-GaN V-pits. We can see that the LT p-GaN surface has a greater pit density than the p-InGaN surface, at least double. Moreover, in the LT p-GaN surface the pits tend to connect, which is not common in the p-InGaN surface. This feature of LT p-GaN surface can be explained in that the deactivation process of Ga atoms is related to the gas flow, especially the ammonia and hydrogen flows at low temperature,[17] and the flow may vary by region. The quantity of V-pits in the LT p-GaN surface is much greater than that in the surface of the p-InGaN LED. We assume that the V-pits in LT p-GaN surface are formed everywhere at low temperature as Ga atoms become less active. Also, it seems that the V-pits in p-InGaN surface are more likely to form in areas with greater strain or in regions with greater fluctuation of TMI composition, although this phenomenon has not been proved yet.

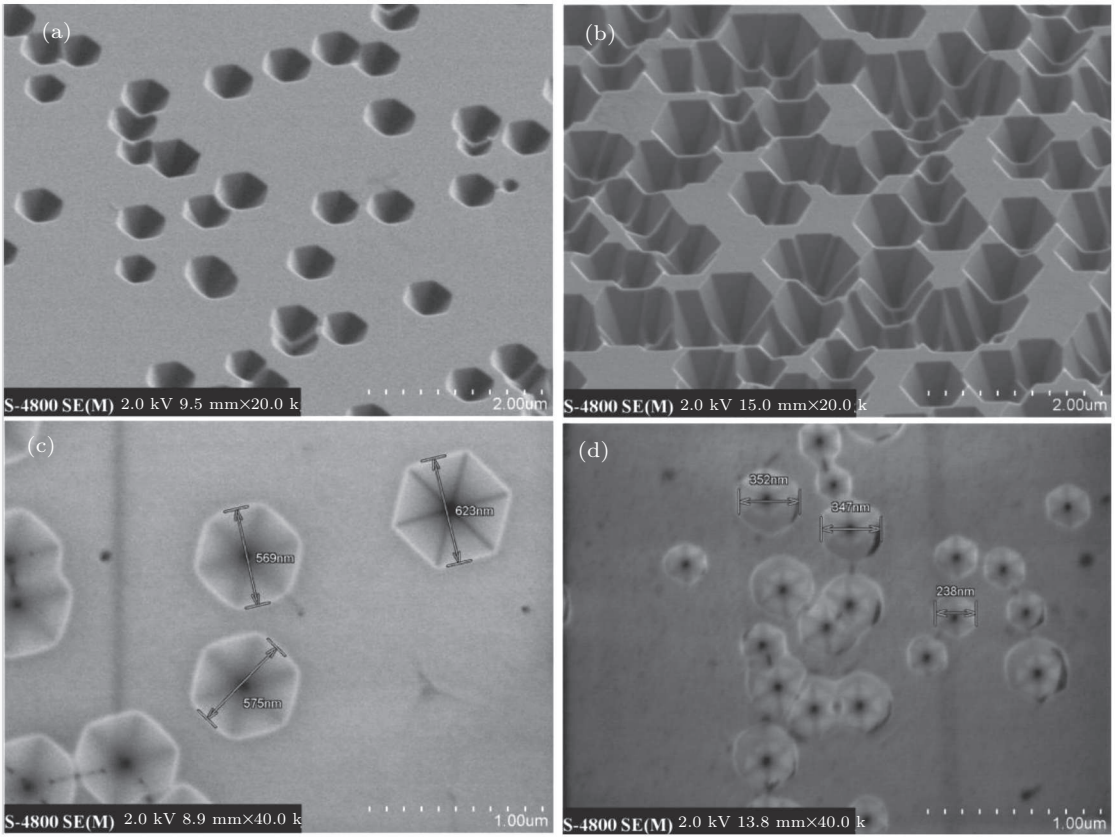


Fig. 2. Top-view SEM images of the p-GaN surface for (a) p-InGaN LED, (c) LT p-GaN LED, respectively. The measured diameters in the p-InGaN LED are around 600 nm and in the LT p-GaN LED they are around 300 nm. Tilted SEM images of the p-GaN surface for (b) p-InGaN LED, (d) LT p-GaN LED.

3.2. *I–V* measurement

The curves of the LED light output power versus the injection current (*L–I* curves) of the three samples are plotted in Fig. 3. It can be seen that the light output powers of the two samples both increase as the forward injection current increases. At a current of 100 mA, the p-InGaN LED shows 45.2% higher light output than the Ref-LED, whereas that of the LT p-GaN LED is only 10.9% higher than for the Ref-LED. The pronounced performance of p-InGaN LED is attributable mainly to two aspects. First, for the origin of the V-pits, doping a certain amount of TMI flow in the p-GaN layer can effectively reduce Mg-acceptor activation energy, E_A, from 200 meV–180 meV in GaN:Mg down to about 50 meV–100 meV or even 43 meV, and the hole concentration can be enhanced to 5×10^{18} cm^{-3}.[20,21] This is the most important reason for the higher output power of the p-InGaN LED. Second, the diameter of the V-pits in LT p-GaN LED is very large which can enhance the contact area and the escape cone and make a better enhancement in the LEE. The result is exactly proved by the far-field radiation profiles of the p-InGaN LED and LT p-GaN LED, which are shown in Fig. 5.

The average *I–V* characteristics of the LEDs are shown in Fig. 4. The forward voltage is a little higher in the p-InGaN LED (about 3.19 V) than in the Ref-LED (about 3.10 V) at 20 mA, but the forward voltage in LT p-GaN LED is very high, up to 3.39 V. The root of higher forward voltage is the bad contact between the V-pit layer and the ITO layer. The forward voltage in the p-InGaN LED is relatively close to that in the Ref-LED, because the Mg-acceptor activation energy in the p-InGaN LED is very low, and the p-type resistivity in Mg-doped InGaN alloys has been found to be lower than that of Mg-doped GaN.[20]

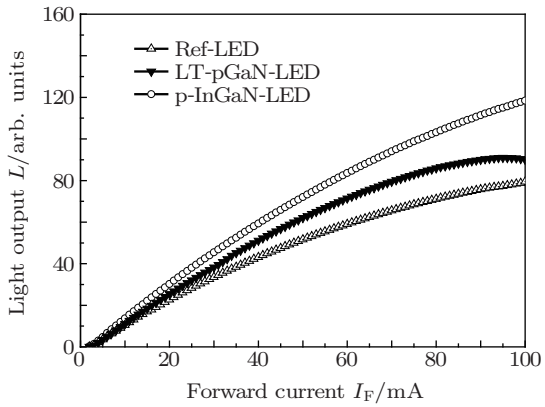


Fig. 3. Light output power versus forward current plots of the reference, LT p-GaN, and p-InGaN LEDs.

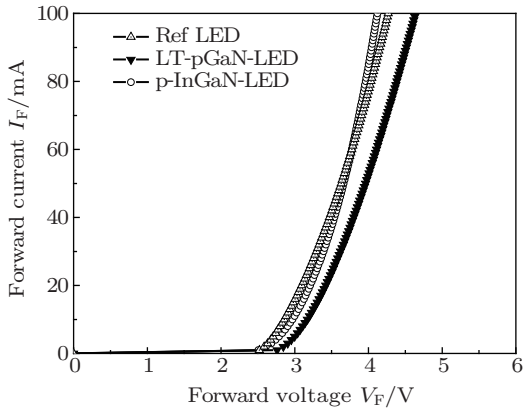


Fig. 4. Forward voltage versus forward current plots of the reference, LT p-GaN, and p-InGaN LEDs.

3.3. Far-field emission pattern

The far-field measurements were taken from −90 to 90, and the emission patterns of LT p-GaN and p-InGaN LEDs were measured at a current density of 20 A/cm^2. The far-field measurement setup consisted of a semicircular structure on which the optical fiber can be rotated 180° in a single plane. The measured LEDs were placed in the center of the semicircular structure; hence the optical fiber is kept at a constant distance from the measured LED as the optical fiber rotates through 180° in the plane to collect the emissions at various angles. From Fig. 5, the top lights and the side lights of the p-InGaN LED shows stronger radiant intensity than the other two LEDs. The reason is consistent with the *L–I* curve. The angle out of the LED surface is plotted radially and the intensity of the light extraction was detected as a function of the radiation angle.

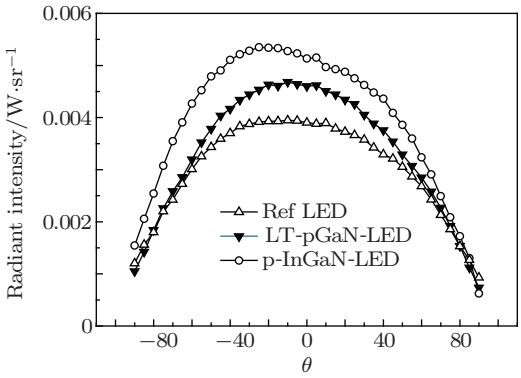


Fig. 5. Far-field emission patterns of the reference, LT p-GaN, and p-InGaN LEDs.

4. Conclusion

In summary, we have demonstrated two textured V-pit LEDs and compared their electrical and optical properties with the reference LED. The results show that the LED with p-InGaN V-pits is 45.2% better in light-extraction efficiency than a standard planar p-type GaN LED. The vital application value of this p-InGaN V-pit LED lies in the good forward voltage not being higher like the usual V-pit LED. The physical origin for the performance improvement is attributable mainly to the lower Mg-acceptor activation energy obtained by doping TMI flow in p-GaN.

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