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Study on light extraction of nitride LED

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Abstract: *Light-emitting diodes (LED) have attracted people's attention due to their special features such as low power consumption and high durability. At the same time, their low-carbon, energy-saving, and environmental protection features, make LED frequently applied in areas such as display, photos, and optical communications. With the acceleration of the development of solid-state photo technology, LED has become the most promising environmentally friendly lighting source to be used widely. However, due to the physical properties of GaN-based materials, the low light extraction rate severely limits the sustainable development of LEDs. As a result, how to improve the light extraction efficiency (LEE) of LEDs is one of the most important research in the field of solid-state lighting. One of the reasons for the relatively low LEE comes from the phenomenon of total internal reflection inside the chip, resulting in photon absorption and loss of capacitance, which greatly reduces the LEE of GaN-based LEDs. This paper mainly summarizes the methods of patterning the titanium layer, patterning/roughening Indium-tin Oxide (ITO) transparent electrode layer, patterning sapphire substrate, special-shaped chip, back shadow, photonic crystal, and stealth cutting to capture high LEE of the LEDs.*

Keywords: *Light-emitting diodes, GaN-based materials, Light extraction efficiency, Total internal reflection*

1. Introduction

The LEDs made by wide-bandgap GaN-based materials possess relatively high efficiency in photoelectric conversion efficiency and long service time[1,2]. Therefore, they are widely used in sterilization, polymer curing, medical and biochemical detection, and other fields. However, with the impact of the special feature of its raw material, larger refractive index between sapphire and GaN, sapphire, and air drag the probability of total reflection total internal reflection is relatively low LEE, then further limiting the development of the application of LED[3,4]. As a result, the light extraction problem of LED still has great value to research. In a traditional LED with a regular hexagonal shape, photons will reflect back and forth multiple times[5]. During that reflection process, some photons will reach the side wall of the device, then escape from the materials and form successful light extraction; Some other photons were absorbed during the process of reflections. In recent years, many researchers have developed new structures and substrate patternings in order to allow more photons to escape from the device, such as roughening the sidewall, moth-eye, cone, cylinder, and cone[6,7]. These new structures are used to reduce the total internal reflection, thereby increasing the LEE. The LEE of the chip can reach up to 77.75%. Based on the principle of total reflection and total internal reflection, this paper summarizes the influence of new light extraction structures designed by several research institutions on the LEE of GaN-based LED chips.

2. Light extraction efficiency and chip structure design of GAN-based LED

2.1. Patterned passivation layer technique

The passivation layer in the LED chip mainly plays the role of protection, insulation, avoiding short circuits and adsorption of impurities, and reduction of current leakage. At the same time, it also reduces Fresnel loss and critical angle loss. Patterning the passivation layer is one of the methods to improve the efficiency of LED light extraction. The patterned surface can break the total reflection interface in the chip, which means that there is more light occuring diffuse reflection scattering at the interface.

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2.2. Patterned/ coarsening of ITO technique

ITO transparent conductive film is used to improve the current expansion capability of LED chips. At the ITO and GaN interfaces, since the indexes of refraction are different (n_{GaN}=2.5, n_{ITO}=1.9), the light will be fully reflected. What is more, the light originated from the active regions will be limited in the LED chip. The patterned ITO can destroy the specular total reflectiontotal internal reflection, then improving the light extraction efficiency of LED chips. In addition, ITO coarsening is a special means to obtain the irregular surface, which can also improve the light extraction efficiency of LED [8-10]. However, one thing we must know is that whether it is patterned or coarsened, the ITO will destroy the original current path, weaken the horizontal expansion ability of the current, and increase the forward voltage. Therefore, the actual light efficiency improvement of the LED is very limited.

2.3. Patterned sapphire substrate technique

Sapphire is currently one of the most common substrate materials for growing GaN-based LED. Because the large lattice constant and thermal expansion coefficient between the sapphire and GaN epitaxial layers differ too much, the epitaxial layer will have dislocations after growth process, thus reducing the internal quantum efficiency of the LED chip. Periodic structures with the micro or nano scales on sapphire substrates can effectively improve the reflection of light. Therefore, patterning sapphire substrates, a technique for dry etching or wet corrosion on sapphire substrates, is an effective approach to improve the efficiency of light extraction. Besides, the technique can also improve the crystal quality and internal quantum efficiency of the GaN epitaxial layer by releasing stress. Therefore, based on patterned sapphire substrate technique, the light extraction efficiency of the chip will be improved by the refraction or scattering of the light that incident on its substrate.

2.4. Special-shaped chip technique

In a traditional rectangular LED chip, which has paralleling sidewalls, light is fully reflected at the interface between the sidewall and the air and is reflected back and forth between the two paralleling sidewalls. In this process, the energy of the light will be absorbed and converted into heat, resulting in a reduction of the light extraction efficiency. However, if the sidewall of the LED chip is corroded into an inverted ladder shape, the reflection angle of the light will be changed. Thus, the reflection angle of most of the light will be smaller than the critical angle of total internal reflection[11-23]. Nevertheless, special-shaped chips also have their drawbacks. It is difficult to internally etch inclined sidewalls and is not easily controlled, which means that it will also have a significant impact on subsequent breaking processes, causing mass production to be difficult to achieve.

2.5. Back plating technology

Since the photons generated in quantum wells are dispersed in all directions, the photons shot towards the substrate will be absorbed by the substrate and converted into heat, thereby reducing the light extraction efficiency of the LED. Therefore, by adding a metal film or reflective coating mirror structure on the LED substrate, the light originally directed towards the substrate is reflected back to the light-emitting surface, thereby increasing the light extraction efficiency of the LED.

2.6. Photonic crystal technology

The purpose of using photonic crystal technology in LED chips is to improve light extraction by adopting photonic crystal structures. Theoretical analysis and experimental evidence both support the options that introducing a photonic crystal structure on the surface or inside the LED can significantly enhance its brightness[24-30]. At present, there are three main technologies for producing LEDs with photonic crystal structures: electron beam lithography technology, nano-imprinting technology, and laser holographic interference technology. While electron beam lithography provides precise preparation, its expensive equipment and limited production capacity hinder its widespread use in the large-scale manufacturing of photonic crystal LEDs. On the other hand, nanoimprint technology has advantages in high resolution, production capability, and cost-effectiveness. However, repeated use of nanoimprint templates can lead to contamination of the surface of the LED epitaxial layer, which adversely affects the quality of the photonic crystal LED. Therefore, nanoimprint technology is not suitable for widespread industrial production. In comparison, laser holographic interference technology has obvious advantages, including affordability, rapid fabrication, and suitability for producing photonic crystals on substrates with large surface areas. Figure 1 shows a graphical sapphire substrate with photonic crystal structure.

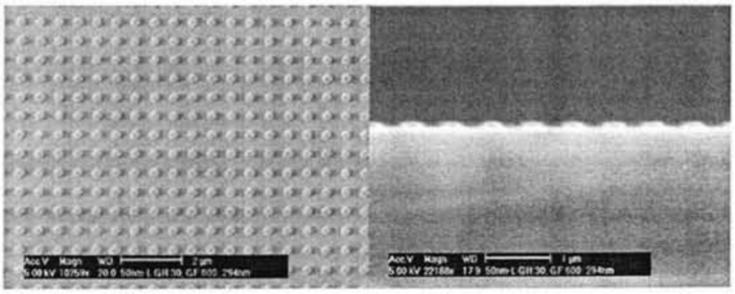

Figure 1: Graphic sapphire substrate containing photonic crystal structure.

In the field of traditional LED devices, the integration of photonic crystal structures has enormous potential to significantly improve light extraction efficiency. This improvement stems from the unique photonic bandgap effect demonstrated by photonic crystals, which enhances the spontaneous emission of light in the direction perpendicular to the LED surface. Extensive research has been conducted to explore the impact of two-dimensional photonic crystal structures on altering the spatial distribution of LED spontaneous radiation intensity[31]. Investigations in this area by Fan et al. have produced convincing evidence, highlighting the immense effectiveness of two-dimensional photonic crystals in enhancing light extraction efficiency. Moreover, many research groups have adopted different manufacturing processes to fabricate GaN-based LEDs with photonic crystal structures, realizing a noticeable improvement in light extraction efficiency. For instance, Lin et al. manufactured the world's first LED device containing a photonic crystal structure using electron beam etching technology, which is a groundbreaking milestone[32]. Their experimental results indicate that the output power of the LED equipped with a photonic crystal structure is 2.3 times that of a regular LED lacking this structure. Similarly, Bao et al. fabricated a blue GaN-based LED with a photonic crystal structure using nanoimprint technology.This approach produced a prominent result was fabricated by Baukui et al. This approach produced an outstanding result, with the light output power of the LED increasing by 60%. In addition, Kim et al. generated a precisely arranged photonic crystal structure on the transparent electrode layer of a GaN-based LED using laser holographic interference technology. This innovative technique significantly improved the LEDs light extraction efficiency by 2.1 times. The achievements made by integrating photonic crystals into LED technology are indeed astounding, demonstrating the tremendous progress in the field[25].

2.7. Invisible cutting technology

Invisible cutting technology focuses a long-wavelength laser beam inside the material, using high energy to cut the LED wafer. Subsequently, external force is applied to the wafer to cut it into smaller chips. Reduces the absorption of light by sapphire sidewalls. This is because the surface that has been ablated by the laser has a certain absorption effect on visible light, hence invisible cutting has a smaller ablation area than conventional laser cutting. Comparing figure 2 and figure 3, it shows that the ablation area of invisible cutting is smaller than that of ordinary laser cutting, because the side wall of the laser ablation has a certain absorption of visible light, so the invisible cutting can reduce the absorption of light on the sapphire side wall.

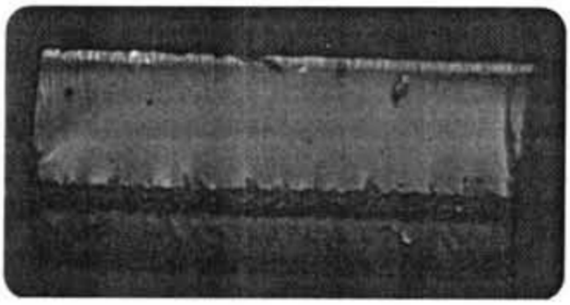

Figure 2: Invisible cut LED chip section.

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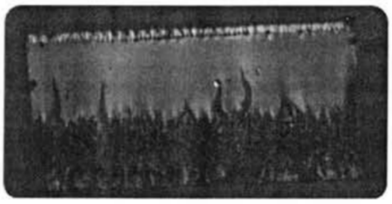

Figure 3: Common laser cut LED chip section.

Experimental measurements have shown that the light power of this model is 10 percent higher than that of chips cut using ordinary laser cutting technology and it is shown in figure 4.

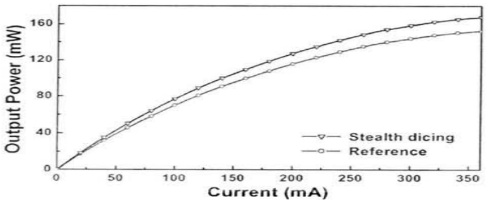

Figure 4: Comparison of LED LOP for invisible cutting and ordinary laser cutting.

The advanced nature of the invisible cutting process eliminates the cumbersome steps of cleaning during production, improves the cutting speed, and continuous optimization of the product manufacturing process boosts the future trend of LED chip cutting equipment in the industry.

3. Conclusion

This article summarizes the reasons for the relatively low LEE of GaN-base LED, which originates from the loss of the total internal reflectionnce of the photons inside the chips. It also concludes the optimization and upgrading of LED chip structure by many researchers and reducing the impact of these negative phenomena on LEE of LEDs. At last, this article fully summarizes the patterned passivation layer, patterned/roughened ITO, the patterned sapphire substrate, special-shaped chip, back plating, photonic crystal, and stealth cutting, etc. to improve LED light extraction efficiency.

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