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Improving light extraction efficiency in InGaN/GaN light-emitting diodes by backside metal coating

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GaN-based multiple-quantum well (MQW) light-emitting diodes (LEDs) of green light with thinning process and backside metal coating have been demonstrated. The devices have electrical characteristics similar to those of conventional broad-area devices. However, due to optimum selection for kind and thickness of metals and more light output reflected upward by backside metal coating, the light extraction efficiency is greatly enhanced. These designed devices provide a simple and low-cost manufacture, thus improving the conventional device.

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Keywords: Backside metal coating, Light extraction efficiency, GaN-based LEDs

1. Introduction

GaN-based light-emitting diodes (LEDs) had significant development in the past decade. At present, GaN-based LEDs are being marketed and used for a variety of applications, including full-color display, traffic signals, exterior automotive lighting, backlights for cell phones, and white LEDs. GaN-based LEDs has provided higher performance in the short-wavelength part of the visible and ultraviolet spectrum than other material system [1]. However, there is still a great requirement to improve internal quantum efficiency (η_i) as well as light extraction efficiency (η_{ext}). Internal quantum efficiency is mostly determined by crystal quality and epitaxial layer structure and is close to 100% for visible LEDs of conventional light-source materials. The typical η_i value for blue GaN-based LEDs has reached more than 70% [2], and a recently-grown ultraviolet (UV) LED grown on a low-dislocation GaN substrate has shown an η_i of about 80% [3]. Meanwhile, there is much room for the improvement of η_{ext}. Recently, many good approaches have been submitted, e.g. fabricating current blocking layers (CBLs) [4], textured surface [5-6], surface roughening [7-8], and omni- directional reflectors (ODRs) [9], and distributed Bragg reflector (DBR) [10-11]. LED chips having a CBL insert beneath the p-pad electrode and are significantly increased in light-output power. The surface of LEDs processed by textured pattern or roughing reduces reflection loss and various reflectors used in high-efficiency LED, such as ODR and DBR, have been demonstrated. These methods effectively promote light extraction efficiency, however they involve complicated processes, and increase the prime cost for manufactory fabrication.

In this paper, we report a high output performance green-light GaN-based LED with simple post-processes by wafer thinning and backside metal coating. The light from carrier combination of active layer in the LED, in theorem, has a half probability to face the bottom and it often does not supply light output power in unpackaged LEDs. Based on the sapphire substrate with high-transparency in visible-light spectra, the backside mirror-like layer of a metal coating enhances the usages of downward light, and then no complicated growth or low quality thin films can compare with DBR in GaN-based system.

2. Experimental

The InGaN/GaN MQW LED structure was first grown by metal-organic chemical vapor deposition (MOCVD) on a c-plane sapphire and it consisted of a thick n-type GaN buffer layer, an n-type GaN lower cladding layer, an InGaN/GaN multiple quantum well active region, a p-type AlGaN upper cladding, and a highly doped GaN contact layer. The source materials used in this study were methyl-organometallics and ammonia (NH_3). The doping sources were Si_2H_6 for n-type layers and cyclopentadienylmagnesium (CP_2Mg) for p-type layers. LED mesa structures were obtained by standard photolithographic patterning followed by dry-etching to expose the n-type cladding layer. The chosen metal is Ti/Al/Ti/Au for the n-contact and Ni/Au for the p-contact on the top of the device. A detailed schematic diagram of the cross-section of the devices and top-view pattern are shown in Fig. 1. After fabricating the primary structures of the LED, the sapphire (Al_2O_3) substrate is thinned to 150-μm thickness and polished by backside thinning process. Then for all samples expect reference samples, the evaporative metal coating layer on the bottom side of the substrate is formed as a reflector in order to reflect the portion of the light, which generates from the active region and goes toward the substrate. For our structure design, the backside metal layer is not concerned with ohmic contact, and differed from that reported by Ban et al. [12]. Three usually evaporative metals are chosen, such as Al, Au and Ag, and these were coated on the glasses (Corning #1373F) with different thicknesses for reflectance measurement. The InGaN/GaN MQW LEDs with backside metal coating were characterized by electro-luminescence (EL), current-voltage (I-V) and light current (L-I) measurements.

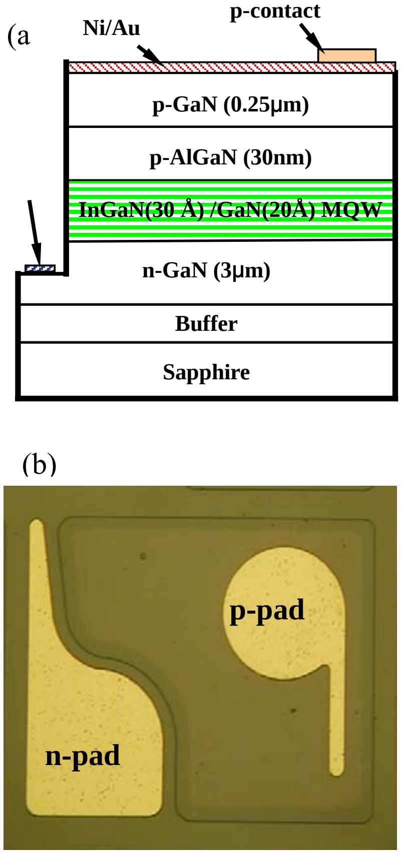

Fig. 1. (a) Schematic diagram showing the primary structure of the InGaN/GaN MWQ LED chip and (b) its top view.

1. Results and discussion

According to the reflective theorem of light, the skin depth (δ) determines whether the light is transparent or reflected. The equation of skin depth is as followings:

$$\delta = (\lambda/\pi c\mu\sigma)^{1/2} \qquad (1)$$

where λ is the wavelength in vacuum, c is the speed of light, μ is the permeability, and σ is the static conductivity.

Therefore, the longer wavelength has more excellent transparency than the short ones under thin films and the higher static conductivity of metal has shallower skin depth and higher reflectivity. The high static conductivity of metal, e.g. Al, Au, and Ag, is a popular choice. The skin depth of these metals is estimated to be around several dozens to several hundred nanometers by their parameters. So three metal thin films of chosen 200-nm thickness were deposited on glasses for reflectance measurement as shown in Fig. 2, and then the metal Al and Ag have a high and flat distribution of reflectance between wide ranges (400-1000 nm) but Ag holds a higher reflectance and a fast fall reflectance exists below light wavelength of 600 nm for metal Au. For light emitting wavelength of 525 nm, the Ag has a reflectance of 97.8% which is higher than metal Al (91.6%) and Au (56.5%). In addition, Ag is a good candidate for backside reflector.

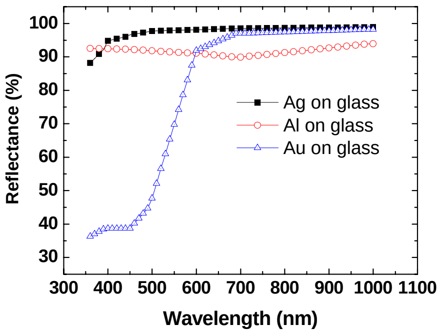

Fig. 2. The reflectance measurement of these three 200-nm-thickness metal coating deposited on glasses.

Fig. 3 shows the EL intensity of LEDs with varied backside metal coating of 200-nm-thickness film, the LED with Ag coating has the highest intensity, especially at near main peak position. After determining the kind of metal, the optimum thickness of metal is further investigated.

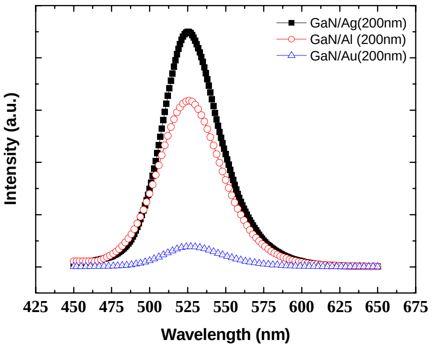

Fig. 3. The EL intensity of LEDs with varied backside metal coating of 200-nm-thickness film.

The light-current (L-I) measurement of LEDs with Ag backside coating of varied thickness and that with no coating are shown in the Fig. 4, and all of LEDs with Ag backside coating have higher light output power than the one with no coating, and the 200-nm-thickness sample has the same power as the one with 300-nm-thicknes, which has a similar reflective phenomenon as shown in the reflectance experiments for metal Ag with these two thickness samples (not shown). The reflective ability is undistinguishable with the Ag coating thickness of above 200nm, thus the 200-nm thickness is adopted in the experiment. In statistics, the light output powers of unpackaged LEDs of 200- and 300-nm-thicknes Ag backside coating increase similarly by 167% compared to that of an original GaN LEDs under current of 20mA, in which the powers of LEDs of 50- and 100-nm- thickness Ag coating still have 54% and 76% increase than the original ones, respectively. The output power at 100mA of LED chips has little roll-off phenomenon and simultaneously reveals an increase by 35%, 58%, and 144% for the 50-, 100-, and 200-nm- thickness samples, respectively. This method is simple and effectively improves external quantum efficiency.

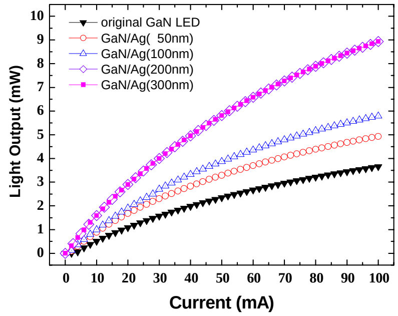

Fig. 4. Output powers measured from LEDs with Ag backside coating of varied thickness and original LED.

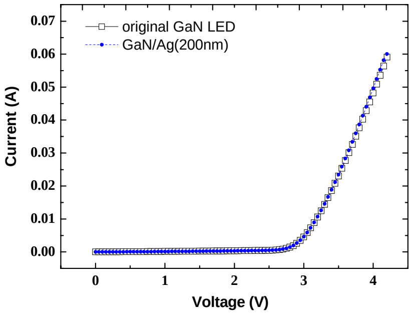

Fig. 5. The I-V characteristics of LED with 200-nm-thickness metal Ag coating and original LED. They coincide in this figure.

Fig. 5 shows that the current-voltage (I-V) measurement and the electrical characteristics of LEDs with Ag coating do not change, the V_f is also about 3.4 V and both curves coincide completely. This designed method unchanged the path of current but reflected more light output upward.

4. Conclusions

In this study, the external quantum efficiency of bare LEDs is improved efficiently by a simple method with thinning process and backside metal coating. The optimum selection of metal and its thickness can promote the light output power using a high-transparency of visible-light spectra substrate. The 525 nm InGaN/GaN MQW LEDs with 200-nm-thickness Ag backside coating is presented and has a 167% and 143% increase compared to that of an original GaN LEDs under current of 20 and 100 mA, respectively. Notably, the electrical properties do not change, for instance, V_f of 3.4 V. Especially, such devices with high output power are employed in surface mount technology and the backside metal also offers the benefit of thermal conduction.

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