Optical and electrical characteristics of GaN vertical light emitting diode with current block layer*

Guo Enqing(郭恩卿)†, Liu Zhiqiang(刘志强), Wang Liancheng(汪炼成), Yi Xiaoyan(伊晓燕), and Wang Guohong(王国宏)

Research and Development Center for Semiconductor Lighting, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract: A GaN vertical light emitting diode (LED) with a current block layer (CBL) was investigated. Vertical LEDs without a CBL, with a non-ohmic contact CBL and with a silicon dioxide CBL were fabricated. Optical and electrical tests were carried out. The results show that the light output power of vertical LEDs with a non-ohmic contact CBL and with a silicon dioxide CBL are 40.6% and 60.7% higher than that of vertical LEDs without a CBL at 350 mA, respectively. The efficiencies of vertical LEDs without a CBL, with a non-ohmic contact CBL and with a silicon dioxide CBL drop to 72%, 78% and 85.5% of their maximum efficiency at 350 mA, respectively. Moreover, vertical LEDs with a non-ohmic contact CBL have relatively superior anti-electrostatic ability.

Key words: current block layer; efficiency drop; vertical LED; non-ohmic contact

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1. Introduction

As a future generation green solid lighting source, GaN LEDs have undergone much development and have been applied in many fields, such as city lighting, traffic lighting, and back lighting. High luminous, high power and high efficiency LEDs are the key and difficult point during research. Recently, epitaxy GaN material on sapphire substrate technology has been widely used, and lateral LEDs based on this technology can work satisfactorily under a 100 A/cm^2 input current density. However, under a large input current density, the LED junction temperature will rise drastically due to the poor thermal conductivity of the sapphire substrate, and it will cause the luminous efficiency to drop drastically[1−4]. Compared with lateral LEDs, vertical LEDs have many advantages with regard to current spreading, thermal cooling and luminous efficiency, and so this kind of LED attracts more and more researchers' attention and may become the main chip structure, especially for general lighting, in future. However, the light emitted from the multiple quantum well (MQW) under the top metal electrode of the vertical LED will be absorbed mostly by the electrode, and this part of the light has a direct relationship with the current injected into the MQW under the top electrode. Introducing one CBL into the LED is an effective way to suppress this part of the current mentioned above. A GaN LED with a CBL has already been demonstrated and the external quantum efficiency of the LED could be improved by adding a CBL to the LED[5−7]. However, the efficiency drop of a GaN LED with a CBL was not discussed in previous papers. In this article, GaN LEDs with a non-ohmic contact CBL and with a silicon dioxide CBL are fabricated. The results show that the light output power of vertical LEDs with a non-ohmic contact CBL and with a silicon dioxide CBL are 40.6% and 60.7% higher than that of vertical LEDs without a CBL at 350 mA, respectively. The efficiencies of vertical LEDs without a CBL, with a non-ohmic contact CBL and with a silicon dioxide CBL drop to 72%, 78% and 85.5% of their maximum efficiency at 350 mA, respectively. Moreover, vertical LEDs with a non-ohmic contact CBL have relatively superior anti-electrostatic ability.

2. Analysis

In a practical LED device, the injection current density at different places in the MQW is not uniform. So when the LED is operating under certain input currents, the internal quantum efficiency in different places may vary. So the efficiency of a practical LED device is related to the current distribution.

The internal quantum efficiency in a tiny area $\Delta x \Delta y$ was defined as η, and η is a function of the injection current density i. The light extraction efficiency in a tiny area $\Delta x \Delta y$ was defined as ξ, and ξ is only related to the optical parameters of the

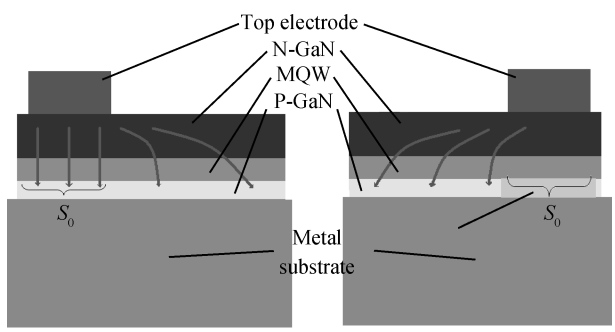

Fig. 1. Schematic diagram of basic structures of LEDs without and with a CBL.

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† Corresponding author. Email: guoeq@semi.ac.cn

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LED epitaxy material and the structure of the LED. The whole LED plane area S can be divided into several parts, which are different from each other. To simplify the problem, S was divided into the area under the top electrode S_0 and the remaining area S_1. Figure 1 shows the basic structures of LEDs without and with a CBL. Area S_0 is shown. Approximately, in area S_0, the light extraction parameter ξ was supposed to be zero since the light was almost absorbed and could not escape. Then the external efficiency E of the whole device can be depicted as

$$E = \left[\iint_{S_0} i(x,y)\eta(i(x,y))\xi(x,y)\mathrm{d}x\mathrm{d}y + \iint_{S_1} i(x,y)\eta(i(x,y))\xi(x,y)\mathrm{d}x\mathrm{d}y\right] \times \left[\iint_{S_0} i(x,y)\mathrm{d}x\mathrm{d}y + \iint_{S_1} i(x,y)\mathrm{d}x\mathrm{d}y\right]^{-1} = \frac{\iint_{S_1} i(x,y)\eta(i(x,y))\xi(x,y)\mathrm{d}x\mathrm{d}y}{\iint_{S_0} i(x,y)\mathrm{d}x\mathrm{d}y + \iint_{S_1} i(x,y)\mathrm{d}x\mathrm{d}y}. \tag{1}$$

In vertical structure LEDs with a CBL, the CBL structure is fabricated under the area S_0, and it will reduce the injection current density $i(x,y)$ in S_0. So, the external efficiency E of the whole device is increased. In vertical structure LEDs without a CBL, when the operation current grows, the current density in S_0 grows faster than in other areas because the dynamic resistance of the LED will decrease as the current density increases, and the efficiency drops even faster. In other words, a CBL in vertical structure LEDs can also reduce the efficiency drop effect.

3. Experiment

Here, we have investigated the performance of GaN vertical LEDs with a CBL structure and without a CBL structure. The epitaxy material of LED wafers studied here were grown by metal-organic chemical vapor deposition (MOCVD), and the epitaxy layers consist of 2.0 μm thick undoped GaN, 2.5 μm thick n-GaN, five periods of 10 nm thick GaN/3 nm thick InGaN MQW, a p-GaN/$Al_{0.2}Ga_{0.8}N$ electron blocking layer, and 100 nm thick p-GaN.

Three kinds of vertical structure LED were fabricated using the GaN LED wafers mentioned above: samples A, B and C. Samples A, B and C are GaN LED without a CBL, with a non-ohmic contact CBL and with a silicon dioxide CBL. The chip sizes of all samples are 1 × 1 mm^2. Figure 2 shows the basic device structures of samples A, B and C. The fabrication processes of sample A consist of chip isolation using a laser scriber system, NiAgNiAu (5/2000/300/500 Å) high reflectivity P electrode metal layer deposition by EB system, Cu substrate electroplating with a thickness of 200 μm, a sapphire substrate removing by LLO process, and CrAu N electrode deposition by an EB system. Sample B is a vertical structure LED with a non-ohmic contact CBL. The difference between samples B and A is that an additional non-ohmic contact CBL structure was added before the P electrode metal was deposited. The 100 × 100 μm^2 non-ohmic contact CBL pattern

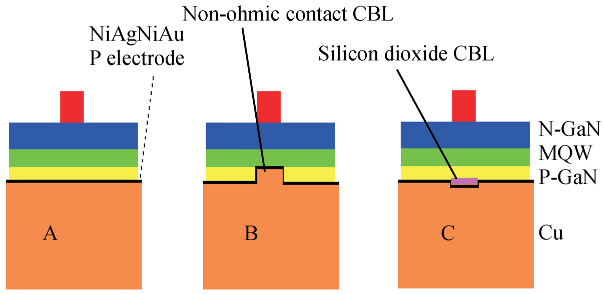

Fig. 2. Structure diagram of samples A, B and C.

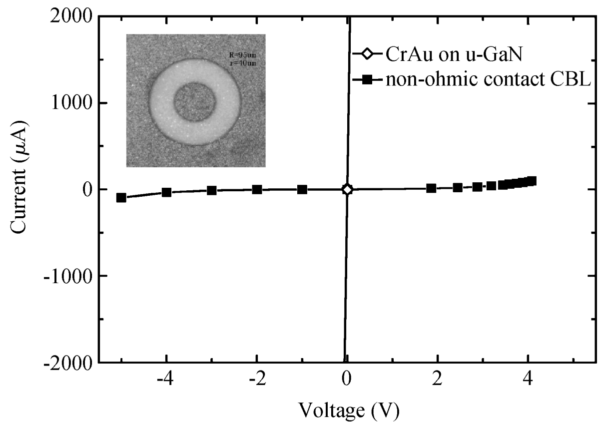

Fig. 3. I–V curve of the non-ohmic contact CBL (square) and circinal CrAu electrodes (diamond) on u-GaN; the inset picture is the circinal CrAu electrode on u-GaN with a 50 μm inner radius and a 100 μm outer radius.

was defined by photolithography, and then the p-GaN layer was etched by a ICP system. Sample C is also a vertical structure LED with a silicon dioxide CBL. The silicon dioxide CBL consists of a 100 nm silicon dioxide film deposited on the p-GaN layer using PECVD.

To obtain the I–V characteristics of the non-ohmic contact CBL (NiAgNiAu metal layer on $Al_{0.2}Ga_{0.8}N$ layer), a 100 × 100 μm^2 mesa was defined on the GaN epitaxy wafer by a laser scriber, and the p-GaN layer on the mesa was also etched by the ICP system. Then the same NiAgNiAu P electrode metal layer was deposited on the mesa by the EB system. Then a Cu substrate was electroplated with a thickness of 200 μm. Then a sapphire substrate was removed by the LLO process. Then a 100 × 100 μm^2 CrAu N electrode was deposited by the EB system. The voltage between the Cu substrate and CrAu electrode versus the current curve is shown in Fig. 3. The I–V of CrAu electrodes on u-GaN is also shown in Fig. 3.

4. Results and discussion

4.1. Light output power and efficiency drop

All of the samples were tested by a Model LED-632HC LED tester from WEI MIN INDUSTRIAL CO., LTD. Figure 4 shows the dependence of light output intensity on the current curve. Compared with sample A, the output power of samples B and C were improved by 40.6% and 60.7%, respectively.

The photoelectric efficiency is defined as the light output

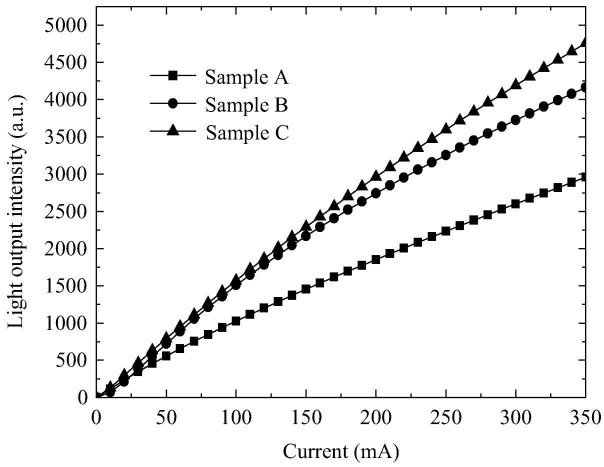

Fig. 4. Light output intensity curve of the vertical structure LED.

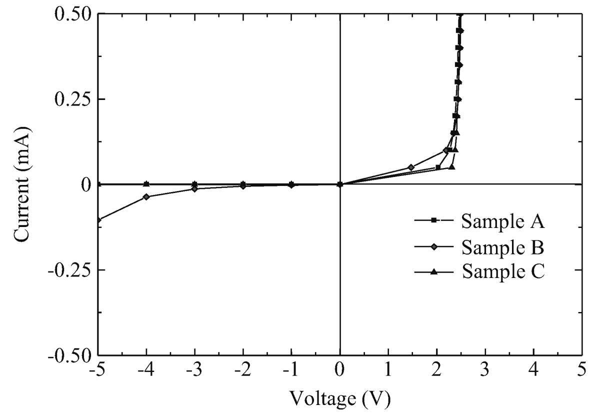

Fig. 6. I–V map of vertical LEDs.

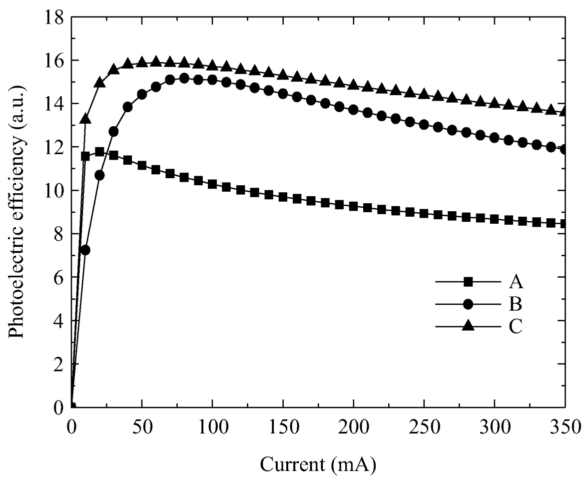

Fig. 5. Current–efficiency curve of the vertical structure LED.

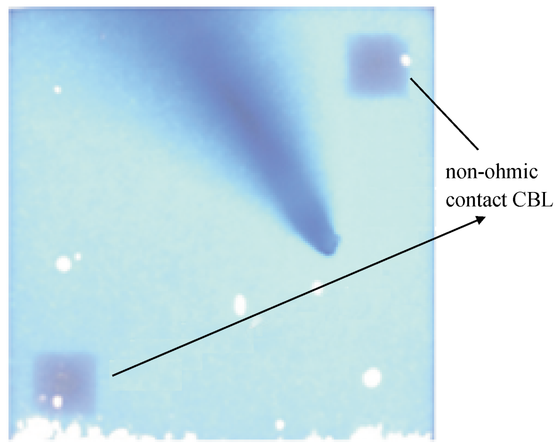

Fig. 7. Microscopic light emitting image of sample B (N electrode was still not deposited) at 10 mA.

intensity divided by the operation current. Obviously, the photoelectric efficiency is almost proportional to the external quantum efficiency E of the whole device and is very easy to obtain. Figure 5 shows the dependence of photoelectric efficiency on the operation current map. The efficiencies of samples A, B and C drop to 72%, 78% and 85.5% of their maximum efficiency at 350 mA, respectively. The maximum efficiency points of samples A, B and C are about 20, 80 and 60 mA, respectively.

As shown in Fig. 6, the difference in voltage between samples A and C at the same current is quite small. The reverse leakage current (IR) of sample B is about 120 μA under –5 V due to the non-ohmic contact CBL I–V characteristic. Meanwhile, the IR of samples A and C is about 0.1 μA. When sample B operated at forward biased condition, a small part of current could also pass through the non-ohmic contact CBL and forward current leakage was formed, as shown in Fig. 6. So we could see in Fig. 5 that in the small injection current region, the efficiency of sample B was lower than that of sample A. Fortunately, the leakage current at the non-ohmic contact CBL did not increase as fast as that at the rest region in the LED when the operation current of the LED increased. For sample B, no p-GaN exists in the CBL region, and so there was no light output when currents were applied, as shown in Fig. 7. So the efficiency of sample B is much higher than that of sample A at a large forward current operation condition. Sample C is very frangible because NiAg metal film cannot adhere firmly to the silicon dioxide layer, though the efficiency of sample C is greater than that of sample B.

4.2. Electrostatic test

Human body and machine touching may produce a very large transient reverse electrostatic voltage on the LEDs. For most of the LED, a reverse current at –5 V is smaller than 1 μA. So LEDs are very vulnerable without an extra current escape path under large reverse voltage bias conditions. The human body model (HBM) electrostatic test was carried out for the three samples. As shown in Fig. 8, more than 80% of LEDs from samples A, B and C survived a 1500 V test, since they were all vertical structure LEDs with a superior electric conductivity substrate, while very few lateral LED chips with the same epitaxy material can pass a 1200 V test. The survival rate of sample B under a 1500 V test was highest at about 95%. This may be explained by the fact that the non-ohmic contact CBL could play a role as an electrostatic escape path in sample B.

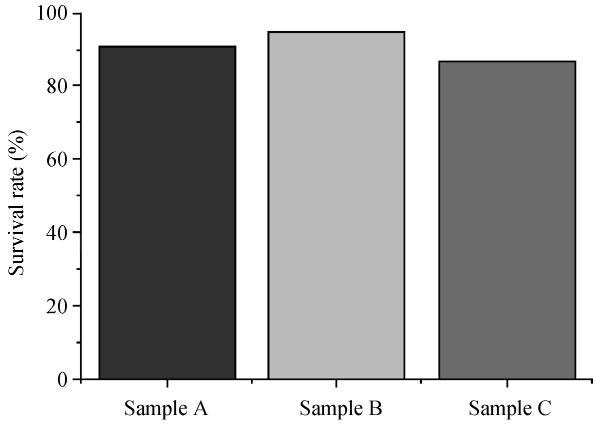

Fig. 8. Survival rate of vertical LEDs after a 1500 V HBM electrostatic test.

5. Conclusion

In summary, the optical and electrical characteristics of vertical structure LEDs with a non-ohmic contact CBL, with a silicon dioxide CBL and without a CBL structure were investigated. Compared with vertical LEDs without a CBL, the light output power of vertical LEDs with a non-ohmic contact CBL and with a silicon dioxide CBL were improved by 40.6% and 60.7% at 350 mA, respectively. The efficiencies of vertical LEDs without a CBL, with a non-ohmic contact CBL and with a silicon dioxide CBL drop to 72%, 78% and 85.5% of their maximum efficiency at 350 mA, respectively. Moreover, vertical LEDs with a non-ohmic contact CBL have a relatively superior anti-electrostatic ability.

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