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Enhanced light extraction efficiency of GaN-based light-emittng diodes by nitrogen implanted current blocking layer

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ABSTRACT

GaN-based light emitting diodes (LEDs) with a nitrogen implanted current-blocking layer (CBL) were successfully demonstrated for improving the light extraction efficiency (LEE) and radiant intensity. The LEE and radiant intensity of the LEDs with a shallow implanted CBL with nitrogen was greatly increased by more than 20% compared to that of a conventional LED without the CBL due to an increase in the effective current path, which reduces light absorption at the thick p-pad electrode. Meanwhile, deep implanted CBL with a nitrogen resulted in deterioration of the LEE and radiant intensity because of formation of crystal damage, followed by absorption of the light generated at the multi-quantum well (MQW). These results clearly suggest that ion implantation method, which is widely applied in the fabrication of Si based devices, can be successfully implemented in the fabrication of GaN based LEDs by optimization of implanted depth.

1. Introduction

GaN-based materials have attracted considerable attention in optoelectronic devices because of their direct and wide band gap and excellent electronic, optical, and thermal properties [1]. GaN-based light-emitting diodes (LEDs) have found enormous applications in illumination, back-light unit of liquid crystal displays, and projection displays [2]. On the other hand, the external quantum efficiency (EQE) of GaN-based LEDs is insufficient, so that high-power LEDs cannot meet practical needs. The external quantum efficiency is equal to the multiplication of the internal quantum efficiency (IQE) by the light extraction efficiency (LEE). The former relates to the substrate properties and epitaxy quality, and the latter relates to chip processing. Therefore, an increase in the LEE of GaN-based LEDs by chip processing is one of the most important issues for EQE enhancement in solid-state lighting [3,4].

Several methods of current-blocking structures have been studied intensively. The conventional methods for fabricating a current-blocking layer (CBL) are formation of SiO_2 layer [5], plasma selective treatment of a p-GaN structure [6], current-blocking hole [7], and selective activated CBL [8]. Among these methods, the CBL with SiO_2 layer is widely applied for the formation of CBL. However, it requires the deposition of SiO_2 and wet etching process for forming the SiO_2 CBL, which is relatively complex and cannot produce a planar insulating layer. Furthermore, the wet etching process makes it difficult to control the correct pattern size because of over etching. In addition, the plasma selective treatment of the p-GaN structure can increase the *p*-type conductivity when post-treatment thermal annealing over 600 °C is carried out [9]. The current-blocking hole and selective activated CBL methods are relatively complex and impractical.

In order to overcome these problems, this paper proposes a method to form an insulating region by nitrogen implantation [10] as a CBL in GaN-based lateral LEDs. The enhanced LEE of the nitrogen implanted CBL LEDs shows that the nitrogen implant CBL effectively prevents shadowing and light absorption in the pad-electrode. In addition, the nitrogen implant CBL reduces the need for an additional insulating layer, a SiO_2 CBL layer. This decreases the risk of an incorrect pattern size because of the over wet-etching problem. In addition, the nitrogen implanted CBL LED can maintain the high resistance during post-ITO deposition annealing.

2. Experimental

All InGaN-GaN samples used in this study were grown by metal organic chemical vapor deposition (MOCVD) on a 2-inch c-plane (0001) sapphire substrate. Ammonia (NH_3), trimethylgallium (TMG), trimethylindium (TMI), bis-cyclopentadienyl-magnesium (Cp_2Mg), and silane (SiH_4) were used as the precursors and dopants. First, the LED consisted of a 2-μm-thick heavily doped *n*-type GaN, seven-pairs of $In_xGa_{1-x}N$-GaN multiple quantum wells (MQWs) with a total thickness of 90 nm, and a 0.19-μm-thick

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p-type GaN layer. Second, to fabricate LEDs with the nitrogen implanted CBL, the mesa structure was formed using an inductively coupled plasma (ICP-RIE) system, to expose the n-GaN layer for *n*-type ohmic contact formation. Third, a 2-μm- thick positive PR (GXR-601) was deposited by spin coating on the p-GaN layer, where a CBL region with a p-pad electrode pattern was defined by photolithography. Subsequently, nitrogen implantation under three different implanted energy conditions, 18, 120 and 250 KeV, were used to form a CBL in the p-GaN top layers of each of the three different LEDs, where the dose of the nitrogen implantation was maintained as $9.92 \times 10^{14}\,\mathrm{cm}^{-2}$. The projected range ($R_p$) was calculated to be approximately 30, 90 and 200 nm using the SRIM-2008 (Stopping and Range of Ions in Matter-2008) software. We designed to form the nitrogen implanted CBL layer at the surface region (Rp ~ 30 nm), at the middle of the p-GaN (Rp ~ 90 nm), and at the bottom of the p-GaN (Rp ~ 200 nm). After implantation, the positive PR was removed by acetone. An ITO-based p-electrode was then deposited onto the p-GaN top layer both as a current spreading and light transmitting layer. Finally, a patterned Cr-Al-Ni-Au electrode was deposited on the exposed *n*-GaN layer and ITO-based p-electrode for the n-contact electrode and p-pad metal, and they were diced into individual chip sizes of $525 \times 525\,\mu\mathrm{m}^2$. All the LED samples were packaged for measuring the typical current-voltage (I–V), radiant intensity-current (L-I), IQE, EQE, and LEE. Fig. 1 shows a schematic diagram of the fabricated InGaN-GaN LEDs with the CBL inserted by nitrogen implantation with three different ion energies for forming three different R_p in the p-GaN top layer. The current and light-emission paths are also illustrated.

3. Results and discussion

Fig. 2 shows the I–V, L-I characteristics and beam-profiles at an applied current of 80 mA of the conventional LED and lateral LEDs with a nitrogen implanted CBL with different R_p. Characterization was performed using a Keithley-2635A source-meter, spectro-radiometer and 8-inch integrating sphere. As shown in Fig. 2(a), the measured forward voltages at an applied current of 80 mA were 3.26 V, 3.28 V, 3.29 V, and 3.34 V for the conventional LEDs, lateral LEDs with the implant CBL having a R_p of 30, 90, and 200 nm, respectively. The injected current was forced to spread out instead of directly flowing along the shortest path between the p-pad electrode and n-contact metal [5]. Therefore, the effective current path was increased due to the slight increase in series resistance, which resulted in the slight increase in the forward voltage.

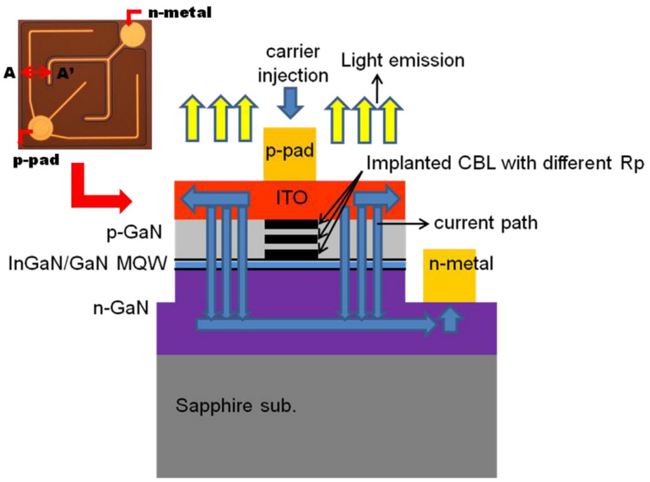

Fig. 1. Top view of the fabricated chip and a schematic diagram of a cross-section of the A-A′ structure of the GaN-based lateral LEDs with nitrogen implanted CBL which has different Rp. The blue lines located in the LED structure show the current path, and the yellow lines located beside the p-pad show the light-emission path. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

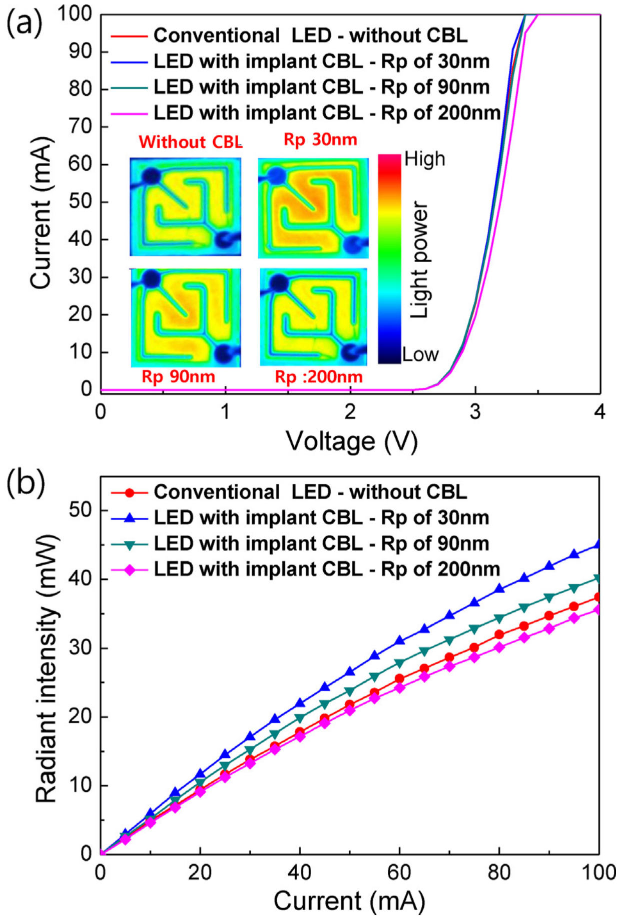

Fig. 2. (a) I–V curves of the conventional LED and lateral LEDs with nitrogen implanted CBL, which has different Rp. Shown in the inset are beam-profiles at an applied current 80 mA of LEDs. (b) L-I characteristics of LEDs.

On the other hands, the radiant intensity of the LEDs with the implant CBL having a R_p of 30 nm was greatly increased by more than 20% compared to those without the CBL, as shown in Fig. 2(b), which can be attributed to the increase in the effective current path, which reduces light absorption at the thick p-pad electrode. This result clearly suggests that ion implantation method, which is widely applied in the fabrication of Si based devices, can be successfully implemented in the fabrication of GaN based LEDs. Meanwhile, the increase in the R_p to 90 and 200 nm deteriorated the radiant intensity of the LEDs with the implant CBL. These results can also be confirmed in the beam-profiles, which were measured using a ML-3740 beam-profile camera at an applied current of 80 mA, as shown in the inset of Fig. 2(a). The beam-profiles presented that the LEDs with implant CBL having a R_p of 30 nm showed the highest light power, meanwhile, the LEDs with implant CBL having R_p of 90 and 200 nm yielded much lower light power. These results can be related to the formation of crystal damage during the deep implantation of nitrogen with high energy over 100 KeV, followed by the absorption of the light.

Fig. 3(a) shows the EQE of LEDs with implant CBL having a R_p of 30, 90 and 200 nm, as well as the EQE of conventional LEDs. The EQE of the LEDs with the implant CBL having a R_p of 30 nm was