IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 5, Number 4, August 2013

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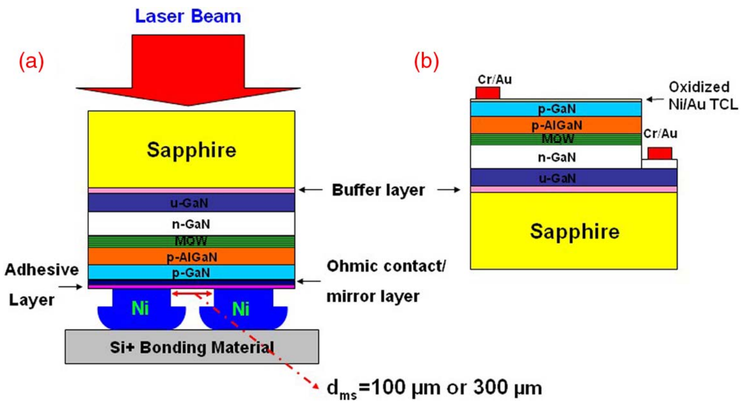

DOI: 10.1109/JPHOT.2013.2274768
1943-0655

Auto-Split Laser Lift-Off Technique for Vertical-Injection GaN-Based Green Light-Emitting Diodes

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DOI: 10.1109/JPHOT.2013.2274768
1943-0655 © 2013 IEEE

Manuscript received June 17, 2013; revised July 14, 2013; accepted July 15, 2013. Date of publication July 25, 2013; date of current version August 6, 2013. This work was supported in part by the National Natural Science Foundation of China under Grants 91023048, 61106044, and 61274052 and in part by the Doctoral Program Foundation of Institutions of Higher Education of China under Grant 20110121110029. Corresponding author: B. P. Zhang (e-mail: bzhang@xmu.edu.cn).

Abstract: An auto-split laser lift-off (LLO) method for fabrication of vertical-injection GaN-based green light-emitting diodes (ASV-LEDs) is demonstrated. The ASV-LEDs exhibited a significant improvement in the light output and thermal dissipation, as compared with that of conventional LEDs on sapphire. The intrinsic physical mechanism of the auto-split LLO technique is studied by a Frank–Read dislocation clustering model. The laser energy density and mesa spacing are shown to be key factors in the auto-split LLO method. It is believed that this method offers an alternative way to fabricate high-performance GaN-based thin-film LEDs.

Index Terms: Auto-split laser lift off, GaN, light-emitting diodes (LEDs).

1. Introduction

InGaN-based semiconductors are promising materials for blue-green light emitting diodes (LEDs) and have attracted considerable attention because of numerous applications, particularly in the areas of LCD screen backlighting and general illumination [1]–[4]. The vast advances of high efficiency InGaN based LEDs had been achieved by addressing the fundamental limitation in the III-Nitride based technology. Specifically, these approaches include the methods to suppress charge separation in active regions [5]–[7], the use of nano-patterned sapphires for reducing dislocation density in GaN [8]–[10], and various microphotonics methods to improve light extraction in LEDs [11]–[13]. So far, sapphire has been the most commonly used substrate for the LED fabrication. However, sapphire is a poor heat and electric conductive material, and the LED on it needs to have both electrodes on the same side, resulting in large chip size and potentially higher series resistance. In order to solve such problems, methods such as the replacement of sapphire by electrically and thermally conducting metal supporters has been proposed to fabricate GaN-based vertical structured LEDs (V-LEDs) and exciting results have been reported [14]–[16]. Wafer bonding and laser lift-off (LLO) techniques are key processes in these now devices. In addition, the fabrication of vertical injection configuration also has a positive impact on suppression of the efficiency droop [17]. The current crowding in III-Nitride LEDs is a contributing factor in leading to efficiency droop in LEDs, which can be addressed by vertical injection design of the LED devices [17], [18]. However, it is

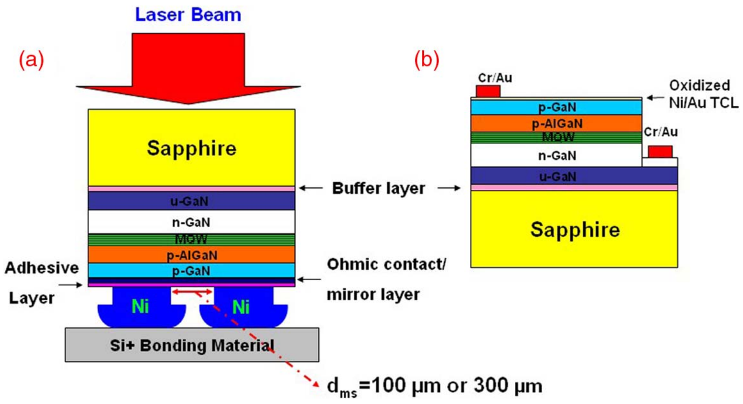

Fig. 1. Schematic device structure of samples using the proposed auto-split technology at some specific processing stages. (a) I- and II-sample at the auto-split LLO processing stage. (b) Schematic cross section of a conventional GaN-based LED. Note that device structures shown in the present figure were not to scale.

important to note that the intrinsic factors limiting the efficiency droop can be attributed to the carrier leakage [19]–[23] and Auger process [24]–[26] in InGaN-based LEDs at high current density.

However, the fabrication procedure of V-LEDs was proved complicated. Inductively coupled plasma (ICP) is usually used twice for etching away the u-GaN, for electric current isolation and for defining the chip size [27]–[29]. In our recent work, a new method called auto-split LLO technique is proposed in which ICP etching is used once and the definition of chip size is completed simultaneously during the removal of the sapphire substrate by LLO [30]. However, the intrinsic mechanism of the auto-split LLO technique is still not fully understood and the factors influencing the auto-split technique are not well studied yet.

In this work, the fabrication of GaN-based auto-split vertical-injection green light emitting diodes was reported and demonstrated. The intrinsic physical mechanism of the auto-split LLO process and the fracture of the freestanding GaN film were explained by a Frank-Read dislocation clustering model.

2. Experimental Details

The fabrication procedure employed for the devices is reported elsewhere [30]. Two kinds of auto-split samples (abbreviated as I- and II-sample) are studied in this study, as shown in Fig. 1(a). The only difference between the two samples is the mesa spacing. The mesa spacing is 100 μm for I-sample and 300 μm for II-sample. Fig. 1(a) illustrates schematically the layer structure and key fabrication processes of the GaN-based Auto-split V-LEDs (abbreviated as ASV-LEDs). First, Ni/Ag/Ti/Au metal layers were deposited on the p-GaN surface and then annealed at 500 °C for 5 min in an O_2 ambient for the formation of both p-ohmic contact and reflection mirror. After annealing, light reflectance of 96% at the wavelength of 525 nm was obtained [31]. Following was Ni electroplate where thick photoresist was used to define the size of area of the electroplated Ni as well as the chip size $(300 \times 300\ \mu\text{m}^2)$. Then, the samples were bonded to silicon and subjected to the KrF excimer laser for laser lift off. The spot size of the KrF laser beam was about 1 mm $*$ 1 mm. The laser beam is transparent for the sapphire, yet it will be absorbed by GaN at the interface. Absorption of the laser energy at the GaN/sapphire interface makes the temperature of GaN high enough to decompose into gaseous nitrogen and gallium droplets, resulting in the lifting off of the sapphire substrate.

Fig. 2(a) and (b) show the surface morphology of the I-sample with the laser energy density of 550 mJ/cm^2 and 650 mJ/cm^2, respectively. As shown in Fig. 2(a), the sapphire substrate can be lifted off, however, no obvious difference is found between the freestanding area and the Ni-supported area. On the other hand, compared to Fig. 2(a), the mesa contour can be observed clearly in Fig. 2(b).

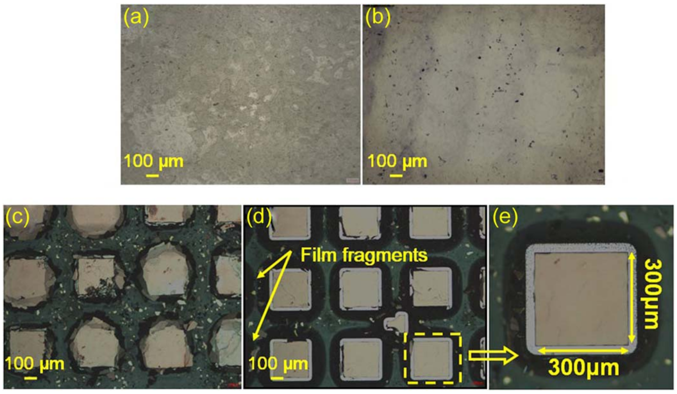

Fig. 2. Optical microscope top-view image of the samples after the LLO process. (a) I-sample at 550 mJ/cm^2, (b) I-sample at 650 mJ/cm^2, (c) II-sample at 550 mJ/cm^2, (d) II-sample at 650 mJ/cm^2, and (e) Magnified part of the dashed square region in (d).

These indicate that there was plastic strain in the freestanding film of I-sample under the laser energy density of 650 mJ/cm^2.

Fig. 2(c) and (d) depict the surface morphology of the II-sample with the laser energy density of 550 mJ/cm^2 and 650 mJ/cm^2, respectively. In Fig. 2(c), it is found that most of the freestanding film was crumbled into fragments. Simultaneously, the metal contacts without the Ni supporting were also crumbled into fragments. Comparison with Fig. 2(a) demonstrates that mesa spacing plays an important role in the fracture of the freestanding film. In Fig. 2(d), almost all the freestanding film was broken into pieces. Fig. 2(e) is the enlarged picture of the dashed rectangle given in Fig. 2(d). A note feature from this image is that the mesa was very intact and the mesa edge was very abrupt, without any freestanding film connected to the device membrane, indicating that the auto-split LLO process is successfully realized with both lifting off the sapphire substrate and defining the chip size simultaneously.

After the auto-split LLO process, Ga droplet was removed using HCl solution. The undoped GaN was then etched away by ICP to expose the n-GaN Layer. For better light extraction, surface roughening of n-GaN with a 6-mol KOH solution was carried out for 10 min. Finally, Cr/Au metal layer was deposited as n-electrode. Note that conventional LEDs, as shown in Fig. 1(b), of the same chip size with two electrodes on the same side of the device were also fabricated with the same wafer for comparison.

3. Results and Discussion

Figs. 3 and 4 show the electrical and optical properties of ASV-LEDs fabricated by the II-sample under the laser energy density of 650 mJ/cm^2. The comparison of current-voltage (I-V) characteristics of the ASV-LEDs and conventional LEDs is shown in Fig. 3. The corresponding forward voltages at 20 mA dc injections were 4.18 and 4.25 V, respectively. The reduction in V_F of ASV-LEDs should be attributed to the considerable improvement in current spreading and the realization of a much shorter vertical conduction path between the two electrodes. The inset of Fig. 3 exhibits the typical reverse characteristics of the ASV-LEDs and conventional LEDs. It is seen that the ASV-LEDs have a relatively inferior reverse characteristic. This might be attributed to the increase of dislocations during the LLO process, which may penetrate through the MQW region, and/or cause damages to the periphery of the device. Optimization of the LLO process to minimize the damage seems necessary. Fig. 4 shows the measured Lop-I characteristics of the ASV-LEDs and conventional LEDs. The inset is the typical picture of light emission from an ASV-LED at 20 mA with an emission wavelength of 525 nm. The ASV-LED was found to have an increase in light output of about 121% over that of conventional LED at 100 mA. The improvement in Lop of the ASV-LED should be mainly attributed to the fact that the vertical structure itself provides larger light

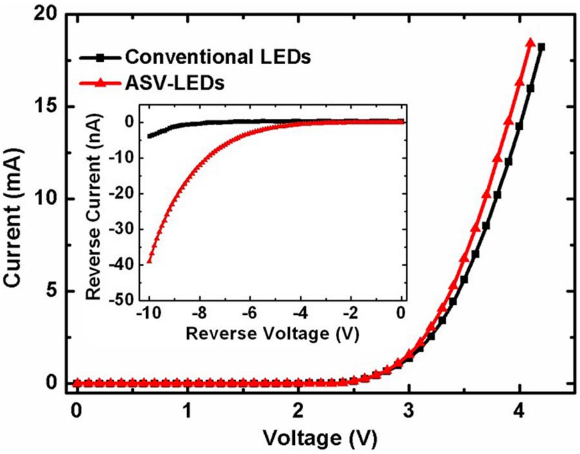

Fig. 3. Comparison of typical forward I-V characteristics of ASV-LEDs and conventional LEDs. The inset shows the reverse current characteristic of the LEDs.

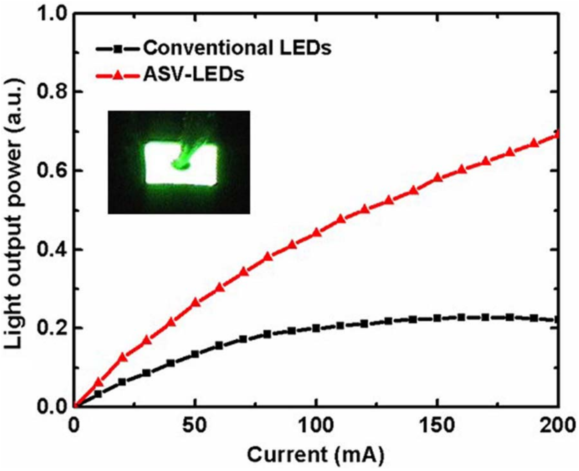

Fig. 4. Comparison of typical Lop-I characteristics of ASV-LEDs and conventional LEDs. The inset shows the typical picture of light emission from the ASV-LEDs at 20mA.

extraction area, superior thermal dissipation, surface roughening of n-GaN layer, and higher light reflection. Our results suggest that the auto-split LLO technique would be attractive for GaN-based thin-film LEDs.

In the following, the intrinsic mechanism of auto-split LLO process is discussed. There is a common feature in the observed fracture of the freestanding films shown in Fig. 2 and in our previous work [30]. It is that the cracking pattern is very similar to "ceramic fragmentation", indicating that the properties of GaN film are consistent with that of brittle ceramic materials [32]. Such a pattern of cracks is the so-called brittle fracture.

It is well known that defects are the initiation of the crack formation, being responsible for the fracture of brittle solids [33], [34]. Under the action of an applied stress, defects will move and accumulate. These cause the formation and propagation of cracks, and finally result in the brittle fracture. In our work, defects are mainly due to the mismatch in lattice constants (14%) and in thermal expansion coefficients (34%) between GaN and sapphire substrate. During the laser irradiation process, the absorption of laser light predominantly occurs through excitations such as

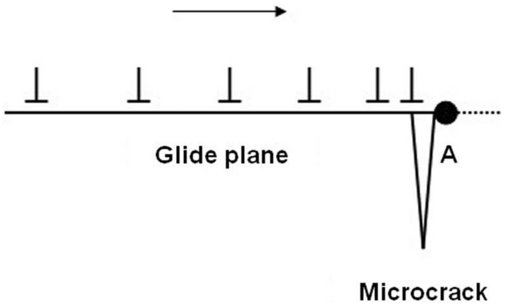

Fig. 5. Frank-Read dislocation clustering model for GaN film.

transitions of valence band electrons to the conduction band (interband transitions). The photon-generated carriers will relax to the band bottom by transferring energy to the lattice, leading to the temperature rise at the GaN/sapphire interface. This causes thermal decomposition of the GaN into Ga and N_2. The vaporization pressure of N_2 will cause moving and clustering of defects, which will result in the formation of microcrack, and finally, cause the fracture of the freestanding GaN film.

In order to illustrate the clustering of the defects and the formation process of microcrack, a classical Frank-Read model can be adopted [34]. As shown in Fig. 5, when $\sigma_{vp} - \sigma_c^{\text{GaN}} \geq 0$, the dislocations began to move on the slip plane, where σ_{vp} and σ_c^{GaN} are the vaporization pressure and the lattice friction of GaN, respectively. These dislocations pile up at some barriers indicated by A. The barrier can be the surface pits or other sliding planes [33], [35]. From dislocation theory, the effective force working on one dislocation is written as $(\sigma_{vp} - \sigma_c^{\text{GaN}})b$, where b is the Burgers vector of a dislocation. The total force from all the dislocations piling up at the barrier A is therefore $(\sigma_{vp} - \sigma_c^{\text{GaN}})nb$, with n the number of the dislocations. This means that the accumulated dislocations can be considered as a single "superdislocation" of Burgers vector nb.

The "superdislocation" causes formation of a microcrack. It is known that the nucleation of a microcrack is accompanied by creation of new surfaces. According to the Griffith energy-balance concept, the energy needed for the formation of microcrack can be represented by the energy needed in creating the new surfaces. Then the condition for the formation of a microcrack can be written approximately as

$$\left(\sigma_{vp} - \sigma_c^{\text{GaN}}\right)n = \pi\gamma_B/b \tag{1}$$

where γ_B is the surface energy of GaN.

When $(\sigma_{vp} - \sigma_c^{\text{GaN}})n \geq (\pi\gamma_B/b)$, the total force exerted by all the dislocations on the obstacles A is equal to or greater than the surface energy of GaN, meeting the needs of the formation of new crack surface. Then, microcracks will be nucleated along the "superdislocation" boundary. As can be seen from Eq. (1), because σ_c^{GaN}, γ_B, and b are the intrinsic constants of GaN, then the fracture of freestanding GaN film depends on the vaporization pressure σ_{vp} and the number of the dislocation. It can be seen that the vaporization pressure needed to form a microcrack reduces as the number of dislocations increases. In other words, the formation of the microcrack becomes easier with the increase of dislocations.

Because of the pressure of N_2, the microcrack will move and propagate. The length of the crack propagation increases under higher vaporization pressures. Finally, the "running" crack will divide the freestanding film into pieces of fragments.

According to Tavernier's work [35] and our previous work [30], [36], the vaporization pressure of N_2 is exponentially proportional to the laser energy density. Moreover, the number of the dislocations in the freestanding film increases with the mesa spacing. Hence, the fracture of the freestanding film is proportional to two parameters: (1) laser energy density and (2) mesa spacing. These are in excellent agreement with our experimental results.

4. Conclusion

Vertical-injection GaN based green light emitting diodes was successfully fabricated by auto-split LLO technique. As compared to conventional LEDs on sapphire substrates, the ASV-LEDs exhibited a significant improvement in both electrical and optical properties. The mechanism of the auto-split LLO process was explained by a Frank-Read dislocation model, which is in good agreement with experimental results. Laser energy density and mesa spacing were shown to be the key factors of the auto-split LLO process. It is expected that the auto-split LLO technique can be a potential candidate for the fabrication of high performance GaN-based blue-green LEDs for solid-state lighting in the foreseeable future.

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