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Near-Complete Elimination of Size-Dependent Efficiency Decrease in GaN Micro-Light-Emitting Diodes

*Jun Zhu, Tokio Takahashi, Daisuke Ohori, Kazuhiko Endo, Seiji Samukawa, Mitsuaki Shimizu, and Xue-Lun Wang**

Herein, a successful elimination of the size-dependent efficiency decrease in GaN micro-light-emitting diodes (micro-LEDs) is achieved using damage-free neutral beam etching (NBE). The NBE technique, which can obtain ultralow-damage etching of GaN materials, is used in place of the conventional inductively coupled plasma to form the micro-LED mesa. It is found that all the fabricated micro-LEDs with sizes ranging from 40 to 6 µm show external quantum efficiency (EQE) versus current density characteristics similar to those of large-area GaN LEDs, with a maximum in EQE curves at a current density of as low as about 5 A cm^{-2}. Furthermore, all the fabricated micro-LEDs, even the 6 µm one, show a similar value of maximum EQE with a variation of less than 10%, clearly indicating a negligible size dependence of emission efficiency of micro-LEDs fabricated by the NBE technique at least down to the size of 6 µm. These results suggest that the NBE process is a promising method of fabricating high-efficiency sub-10 µm GaN micro-LEDs required for high-efficiency, high-brightness, and high-resolution micro-LED displays.

1. Introduction

There is much current interest in developing micro-light-emitting diode (micro-LED) display, which is expected as a low-power consumption, high-brightness, and high-resolution display for next-generation wearable information devices.[1–3] One of the most serious technical obstacles toward the realization of high-performance micro-LED displays is the strong decrease in internal quantum efficiency (IQE) with the decrease in chip size to below a few tens of micrometers, especially at the current density region lower than 20 A cm^{-2}.[4–7] In the fabrication of conventional GaN-based micro-LEDs, inductively coupled plasma (ICP) etching was typically used to define the LED mesa, during which high-density crystalline defects acting as nonradiative recombination centers will be inevitably generated on the sidewall surface of the LED mesa over a depth of a few tens of nanometers due to ion bombardment and high-energy and high-density ($\approx$50 mW cm^{-2}) UV photon irradiation from the plasma.[8,9] These plasma-induced defects will significantly reduce the IQE value of micro-LEDs due to their very large sidewall surface area to volume ratio compared with the conventional large-area LEDs, especially at low current densities. For example, at the current density of 1 A cm^{-2}, the external quantum efficiency (EQE) of a 10 µm-sized GaN/InGaN micro-LED is typically more than ten times lower than that of a large-area (>100 µm) LED.[4,6] For high-performance displays, light intensity needs to be varied over a dynamic range of as wide as 100 000:1, meaning that a minimum luminance value as low as $\approx$0.01 cd cm^{-2} is required for a display with a maximum luminance of 1000 cd cm^{-2}.[10] Therefore, a high IQE at the

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low current density region is a prerequisite for the realization of high-performance micro-LED displays. To achieve this goal, a low-damage mesa etching technique, which can significantly reduce the nonradiative defects on the sidewall surface of a GaN micro-LED compared with the conventional ICP process, is highly required.

Samukawa and coworkers developed a novel defect-free etching technique for semiconductor materials, that is, the neutral beam etching (NBE) technique.[11,12] The neutral beam suppresses the incidence of charged particles and UV photon radiation onto the substrate, and is able to expose the substrate only to energy-controlled neutral beam. This system consists of an ICP source and a carbon aperture plate where the UV/vacuum UV photon irradiation can be prevented and energetic ions can be effectively converted to the neutral beam by passing through the aperture from plasma. The beam energy can be controlled by applying the bias power on the aperture plate. As a result, the NBE process can suppress the charge accumulation and formation of UV photon-induced defects on the substrate surface. This technique has been used to fabricate $In_{0.3}Ga_{0.7}N$/GaN nanodisks with a diameter of as small as 10 nm, and enhancement in IQE values of the nanodisk with respect to an unetched reference sample by a factor of 100 times has been reported through photoluminescence study.[13]

The motivation of the present work is to realize GaN micro-LEDs with efficiencies independent of chip size using the NBE technique to fabricate the mesa structure of GaN micro-LEDs.

2. Experimental Section

A series of square-shaped GaN/InGaN micro-LEDs with mesa sizes in the range of 40–6 μm was fabricated by the NBE process using a blue-emitting (≈440 nm) GaN LED wafer grown on a c-plane sapphire substrate by metal organic vapor phase epitaxy. A similar series of samples was also fabricated using the conventional ICP process as a reference. **Figure 1** shows a schematic drawing of the fabricated device. The LED layer structure contains a five-period InGaN (2 nm)/GaN (12 nm) multiple quantum well (MQW) active layer and a 150 nm-thick Mg-doped p-GaN layer. AlGaN electron blocking layer was not included for simplicity. For the NBE etching, Cl_2 was used as the etching gas. An ICP and RF power of 400 and 5 W were used. More detailed information about NBE etching can be found in previous studies.[12,13] The ICP etching was performed using a commercial ICP machine (Samco, RIE-400iPS). A mixture of BCl_3 and Cl_2 was used as the etching gas, and an ICP and RF power of 150 and 30 W were used.

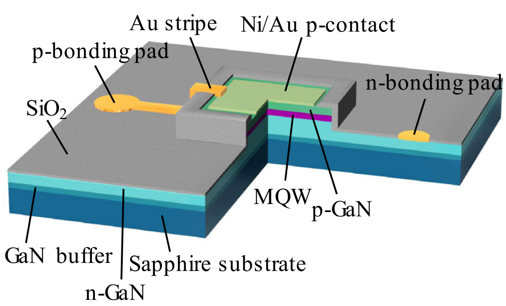

Figure 1. Schematic illustration of the GaN/InGaN micro-LED fabricated in this work.

After formation of the micro-LED mesa, a 200 nm-thick SiO_2 layer was deposited on the sample surface by plasma-enhanced chemical vapor deposition (PECVD) at 350 °C to serve as a passivation and electrical isolation layer. Tetraethoxysilane (TEOS) was used as the Si precursor in PECVD. Next, square-shaped Ni (2 nm)/Au (5 nm) semitransparent p-type electrodes were formed on the mesa top surface in a window opened into the SiO_2 layer by vacuum evaporation and liftoff. The size of the p-electrode was designed to be 1 μm smaller than the size of the micro-LED mesa. Then, the sample was annealed in N_2 at 500 °C for 2 min to form ohmic contact. Next, Cr/Au p- and n-type bonding pads were formed on the surface of the SiO_2 electrical isolation layer and the n-GaN layer, respectively. Finally, a 2 μm-wide Au stripe was prepared to connect the Ni/Au p-electrode and the Cr/Au p-type bonding pad. The wafer was lapped to about 150 μm and cut into $1 \times 1\ mm^2$ chips. The fabricated LED chips were bonded to TO-18 packages with Ag paste without resin encapsulation and light was extracted from the p-GaN side through the Ni/Au semitransparent electrode. The light output power was measured using a calibrated Si photodiode placed at a distance of 2 mm from the LED chip with a receiving full angle of about 130° which could collect about 80% of total emission assuming a Lambertian emission pattern.[14] Herein, the device efficiency was discussed in terms of EQE defined by the following equation

$$\mathrm{EQE} = \frac{P_{out} \cdot e}{h\nu \cdot I} \tag{1}$$

where P_{out} is the measured light output power, h is the Planck constant, ν is the frequency, I is the injection current, and e is the electron charge.

3. Results and Discussion

Figure 2a,b shows the low-magnification cross-sectional transmission electron microscopy (TEM) image of a typical 6 μm micro-LED mesa etched by the NBE and the ICP process, respectively. The sidewall of the NBE-etched mesa showed an intersecting angle of about 98° with respect to the mesa top (0001) surface which is about 16° smaller than that of the ICP-etched sample (≈114 °C). The mesa height of the NBE and ICP samples was about 370 and 650 nm, respectively. Figure 2c,d shows the high-resolution lattice image near the sidewall surface of the NBE- and ICP-etched samples, respectively. Clear lattice images were observed on the outmost sidewall surface of both the NEB- and ICP-etched samples, indicating that the etching quality of both processes is reasonably high. However, we would like to mention here that point defects, such as N vacancy, which are known as the main defects of ICP-etched GaN layers are difficult to be distinguished by TEM observation. The dark line appeared near the sidewall surface in both the NBE- and the ICP-etched samples was an artifact of TEM observation and is probably related to thickness fluctuations of the TEM sample near the surface.

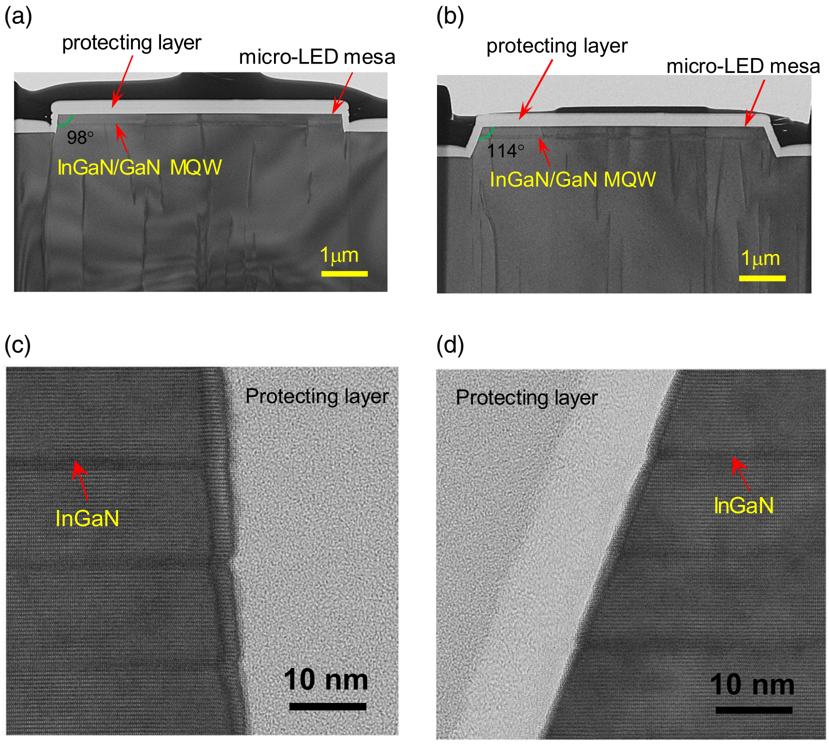

Figure 2. Cross-sectional TEM images of a 6 μm micro-LED mesa fabricated by a) the NBE and b) the ICP process. c,d) The high-resolution lattice image near the sidewall surface of the NBE- and the ICP-etched samples, respectively.

In the measurement of light output power, we observed a very unusual behavior in the current density dependence of EQE of the fabricated micro-LEDs. The EQE at the very beginning of current injection was found to be very low. However, we found that the EQE value increases rapidly after aged for a certain time period under continuous current injection. **Figure 3**a shows the current density dependence of EQE of the 6 μm micro-LED fabricated by the NBE process, where a series of EQE versus current density curves measured at different aging times was given. A current density of 50 A cm^{-2} was used in the aging experiment. Immediately after current injection (aging time = 0 min), the light output power below the current density of 10 A cm^{-2} was out of the measurement range of the Si power meter (≈10 nW). The EQE value at the current density of 10 A cm^{-2} was increased by more than ten times from 0.12% to 1.38% after aged for 5 min at the current density of 50 A cm^{-2}. We would like to mention that it takes about 40 s to finish one light output power versus current measurement which is much shorter than the minimum aging time (5 min) used. The rate of EQE improvement becomes slower gradually with further increase in the aging time, and the EQE value tends to saturate after aged for about one and a half hours. To understand this unusual behavior of EQE values, we also investigated the variation of current density–voltage (I–V) characteristics with the aging time. Figure 3b shows three I–V curves of the 6 μm micro-LED measured at the beginning of current injection, after aged for 5 and 160 min, respectively. One can see from the logarithmic plot of Figure 3b that the device without current injection aging showed a significant subthreshold turn on with a voltage of as low as about 1.67 V at the current density of 0.001 A cm^{-2}, which is a voltage much lower than that of a typical GaN/InGaN LED (≈2.4 V).[15] After aged for 5 min, the I–V curve shifts toward high voltage side by an amount of about 0.68 eV to 2.35 eV at the current density of 0.001 A cm^{-2}, and the I–V curve near the turn-on region stays stable with further increase in the aging time. A diode ideality factor of about 2.47 was estimated from the I–V curve (near the turn-on region) aged for 160 min which is a reasonable value of a GaN LED.[15] It is also worth to note that the series resistance (R_s) decreased from 26.3 kΩ after 5 min aging to 13.1 kΩ after aged for 160 min (see the linear scale plot in the inset of Figure 3b). The low EQE value and the significant subthreshold turn-on behavior in the I–V characteristics clearly indicate that there is substantial carrier transport through nonradiative defects in the initial stage of current injection. As shown in Figure 3c, we also found that the EQE value at the beginning of current injection increases with the increase in chip size. The strong size dependence of initial EQE values shown in Figure 3c clearly suggests that the nonradiative defects giving rise to the low EQE value and the subthreshold turn-on behavior in the I–V curves at the beginning of current injection are mainly those located on the sidewall surface of the micro-LED chip. It has been known for a long time that certain types of nonradiative defects can be recovered by current injection-induced annealing effect in III–V compound semiconductors such as GaAs, InGaP, and InP.[16–18] Changes of defect charge state induced by trapping injected carriers have been proposed as the mechanism behind the observed defect recovery effect.[17] We suppose that similar effect is probably

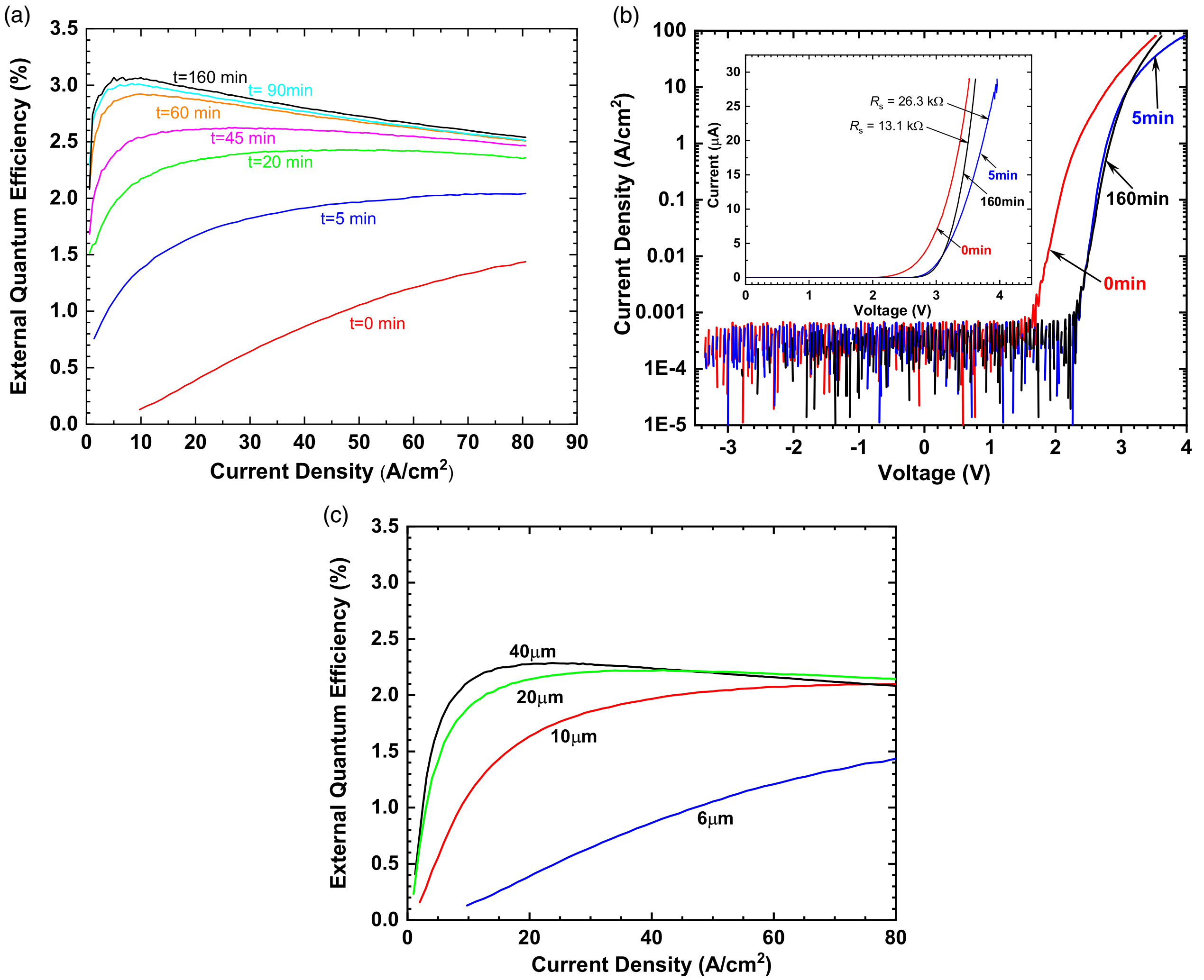

Figure 3. a) EQE as a function of current density of the 6 μm micro-LED fabricated by the NBE process measured after different times of current injection aging. A current density of 50 A cm^{-2} was used in the aging experiment. The number in the figure indicates the aging time. b) Semilogarithmic scale plot of three *I–V* curves of the same 6 μm micro-LED as in part (a) measured at the beginning of current injection, after aged for 5 min, and after aged for 160 min. The inset shows the linear scale plot of the same *I–V* curves. c) EQE as a function of current density of micro-LEDs with different sizes fabricated by the NBE process at the beginning of current injection.

responsible for the great current injection-induced improvement in the EQE value and the *I–V* characteristics of the micro-LEDs fabricated in this work, though we are not very clear about the origin of the nonradiative defects formed on the sidewall surface at this moment. Similar aging effect was also observed in samples fabricated by the ICP process. As will be discussed later again, the nonradiative defects responsible for the aging effect were most likely introduced during device processes after mesa etching, but not during the mesa etching process by NBE or ICP. One possibility is the plasma damage induced during the deposition of the SiO_2 electrical isolation layer by PECVD. Indeed, Wong et al. reported that SiO_2 passivation layer deposited on the sidewall surface of GaN micro-LEDs by PECVD could reduce and that deposited by atomic layer deposition (ALD) could increase the light output power of GaN micro-LEDs with respect to devices without a passivation layer.[7] Therefore, optimization of the deposition process of the SiO_2 passivation and electrical isolation layer seems to be a possible way of suppressing the generation of the nonradiative defects responsible for the aging effect. Anyway, as these defects can be recovered by current injection aging, we removed the influence of these defects by aging all the devices used in this work at the current density of 50 A cm^{-2} until their optical and electrical properties became stable to investigate the effect of the NBE mesa etching process on the improvement of micro-LEDs efficiencies.

Figure 4a,b shows the current density-dependent EQE characteristics of micro-LEDs with different sizes fabricated by the ICP and NBE process, respectively. As expected, the EQE of ICP-etched samples showed significant decrease when the chip size was reduced from 40 to 6 μm. At the current density of 5 A cm^{-2}, the EQE value decreased from 3.44% for the 40 μm device to about 0.66% for the 6 μm device. In particular, the EQE of the 6 μm device increases monotonically with increasing current density and never reaches a maximum up to the maximum

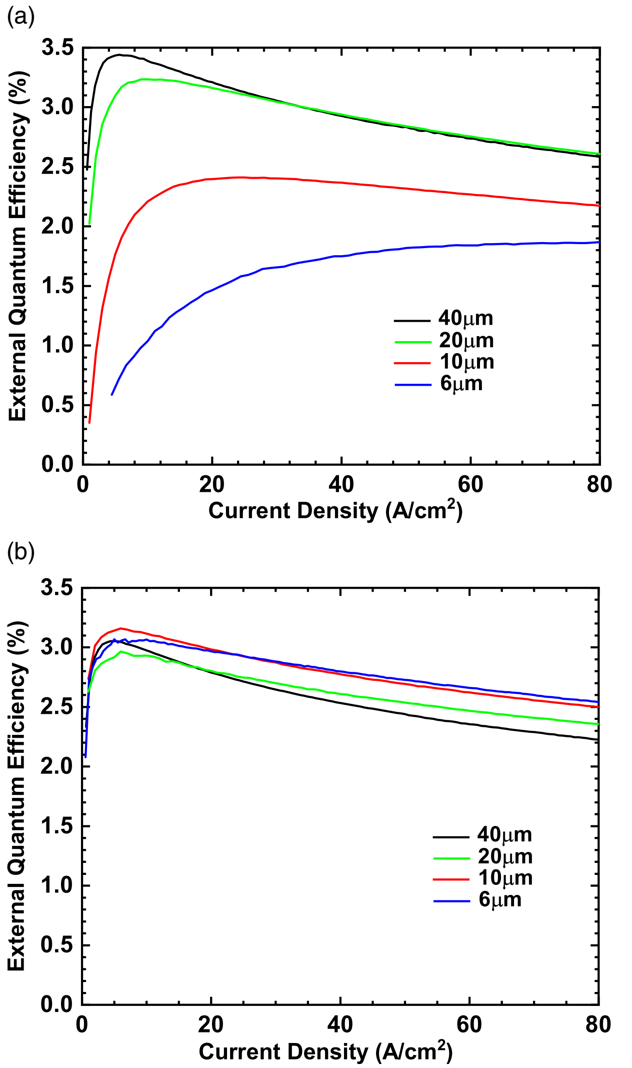

Figure 4. EQE as a function of current density of micro-LEDs with different sizes fabricated by a) the ICP and b) the NBE process. All the devices were aged under current injection at the current density of 50 A cm^{-2} until the EQE vs current density characteristics became stable.

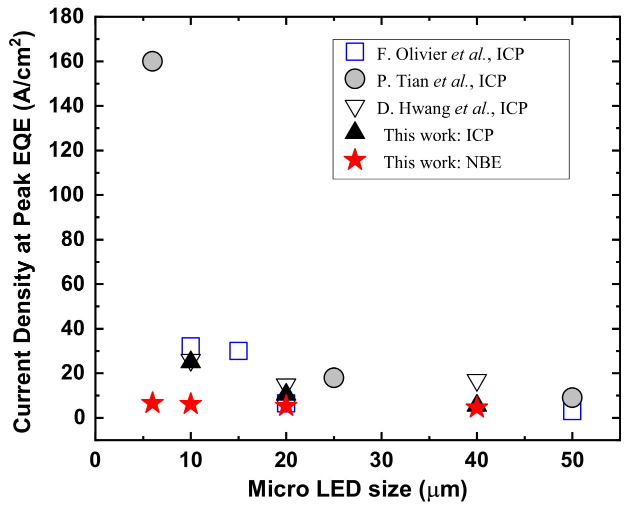

Figure 5. Summary of current density as peak EQE as a function of chip size of GaN micro-LEDs reported in the literature and those fabricated in this work. Open squares, solid circles, and open triangles represent data taken from the studies by Olivier et al.,[4] Tian et al.,[6] Hwang et al.,[21] respectively. Solid triangles and solid stars are data obtained in this work.

current density of 80 A cm^{-2} measured in this work, meaning that nonradiative recombination is dominant even at a current density as high as 80 A cm^{-2}. These characteristics are similar to those typically observed from GaN/InGaN micro-LEDs fabricated using the ICP process.[4,6] In contrast, all the NBE-etched devices showed current density versus EQE characteristic similar to that of large-area GaN/InGaN LEDs. The EQE value of all the four devices increases rapidly with increasing current density, reaches a maximum at the current density of about 5 A cm^{-2}, and then decreases with further increase in the current density due to the well-known efficiency droop effect in GaN LEDs grown on c-plane sapphire substrates.[19] More importantly, the maximum EQE values at about the current density of 5 A cm^{-2} for all the four devices varied only by an amount less than 10%. The four devices also showed very similar EQE values at an even lower current density of 1 A cm^{-2} which are about 2.58%, 2.63%, 2.74%, and 2.74% for the 40, 20, 10, and 6 μm micro-LEDs, respectively. It is noteworthy that the 40 μm device showed slightly lower (by about 10%) EQE values compared with the other devices especially at higher current density region. This can probably be explained by the fact that a smaller micro-LED can sustain a higher current density due to a better thermal dissipation and thus suffers from a weaker efficiency droop effect.[20] Nevertheless, the results shown in Figure 4 clearly indicate that the size-dependent efficiency decrease typically observed in ICP-etched GaN micro-LEDs has been successfully eliminated almost completely at least down to the chip size of 6 μm using the NBE process.

The size-independent feature of the EQE values of the NBE-etched micro-LEDs suggests that nonradiative defects induced during the NBE etching process can be essentially ignored, which is a conclusion supported by the observation of enhanced IQE values in $In_{0.3}Ga_{0.7}N$/GaN nanodisks fabricated by the NBE process.[13] This result implies, in turn, that the nonradiative defects responsible for the low EQE and the subthreshold turn-on behavior in the *I–V* characteristics in the initial stage of current injection shown in Figure 3 are not generated during the mesa etching process by NBE or ICP but generated during processes after mesa etching, most likely some kind of plasma damage induced during PECVD deposition of the SiO_2 passivation layer as discussed earlier. We hope that we could realize GaN micro-LEDs with size-independent efficiencies by optimizing the deposition process of the sidewall passivation layer without the necessity of initial current injection aging.

Finally, current density at peak EQE as a function of chip size for micro-LEDs reported by several groups in the literature and those fabricated in this work is shown in **Figure 5**. A lower current density at the peak EQE indicates a higher IQE for LEDs with a similar Auger recombination rate and can thus be used as a figure of merits characterizing the IQE of a GaN LED. All the devices shown in Figure 5 were grown on c-plane sapphire substrates with an emission wavelength around 450 nm. Therefore, it is reasonable to assume that all these devices have a similar Auger recombination rate because the Auger recombination rate of GaN/InGaN LEDs grown on c-plane sapphire substrates was reported to depend mainly on the emission wavelength.[22,23] As can be seen in this figure, the current density at peak EQE of micro-LEDs fabricated by the conventional ICP process increases rapidly when the chip size was reduced to below 10 μm. In contrast, the current density at peak EQE of the micro-LEDs fabricated by the NBE process is essentially independent of chip size at least down to the size of 6 μm. This summary indicates again that the NBE process is a powerful technique for fabricating high-efficiency sub-10-μm GaN micro-LEDs required for high-resolution micro-LED displays.

4. Conclusions

In conclusion, the NBE etching technique, which can obtain ultralow-damage etching of semiconductor materials, has been applied to the fabrication of GaN micro-LEDs, aimed at eliminating the well-known size-dependent efficiency decrease issue of conventional GaN micro-LEDs. The EQE value of all the NBE-etched devices with sizes ranging from 40 to 6 μm increases rapidly with increasing current density, reaches a maximum at the current density of about 5 A cm^{-2}, and then decreases with further increase in the current density, similar to the EQE versus current density characteristics of conventional large-area GaN LEDs grown on c-plane sapphire substrates. It was further demonstrated that the maximum EQE value around the current density of 5 A cm^{-2} only showed a less than 10% variation among devices with different chip sizes, including the 6 μm device, whereas reference devices fabricated by the conventional ICP process showed a fivefold reduction in the EQE value at the current density of 5 A cm^{-2} when the chip size was reduced from 40 to 6 μm. These results clearly indicate that the size-dependent efficiency decrease issue generally encountered in GaN micro-LEDs fabricated by the conventional ICP technique has been successfully eliminated using the NBE technique. We believe that results presented in this work represent a significant step toward the realization of high-performance GaN micro-LED displays.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

efficiencies, GaN, micro-light-emitting diodes, neutral beam etching

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