InGaN light-emitting diode with embedded air-gap disks through laser-drilling and electrochemical processes

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Abstract

InGaN-based light-emitting diode (LED) with an embedded air-gap disks structure was fabricated through a laser drilling process and an electrochemical (EC) wet etching process. The disk-shaped air-gap structure was formed surrounding the laser-drilled hole as a light reflective structure to enhance the light extraction efficiency. The light output power of the treated LED structure had an approximate 22% enhancement when compared to a conventional LED at 20 mA. High light emission intensity of the treated LED structure is observed at the 40µm-diameter embedded air-disk patterns on the mesa region. The InGaN LED structures with the laser-drilling holes and the embedded air-disks can reduce the light trapping effect and increase the light extraction efficiency at the device’s central mesa region.
InGaN-based LEDs have attracted interest because of their wide applications such as in traffic signals, as backlights in liquid crystal displays, and as solid state lighting sources. To improve the external quantum efficiency of GaN-based LEDs, the internal quantum and light extraction efficiencies must be increased. However, a conventional LED has low light extraction efficiency at the central mesa region because of the large refractive index differences between the GaN (2.5) and the air (1.0) interface. Photonic crystal structures, a nanorod structure, photoelectrochemically treated microhole-array pattern, embedded air protrusions, laser-induced periodic structures, air void structure, conical air prism arrays, embedded air voids/SiO₂ nanomasks, embedded air voids grown on a selective-area Ar-implanted sapphire, laser-induced dumbbell-like air-voids, and air-gap embedding GaN template have all been used to increase light extraction efficiency in InGaN-based LEDs on Al₂O₃ substrates. The doping selective etching process on heavily doped GaN:Si layers had been reported for the chemical lift-off process in InGaN LED structures. Most of the embedded air-gap structures in the InGaN LEDs were fabricated through the epitaxial re-growth process.

In this study, one-step epitaxial grown InGaN-based LED structure with an embedded air-disk structure was fabricated through a laser-drilling process and an electrochemical (EC) wet etching process. The embedded air-disk structure with a 0.2µm-thick air-gap and a 40µm-diameter acted as a light reflective structure to enhance the light extraction efficiency at the central mesa region. The surface morphology and the optical properties of the EC-treated LED structure are discussed in detail.

The epitaxial layers of the InGaN-based LED were grown on a 2” diameter patterned c-face (0001) sapphire substrate through a metal-organic chemical vapor deposition (MOCVD) system. The LED structure consisted of a 30nm-thick low-temperature GaN buffer layer at 530°C, a 1.2 µm-thick
unintentionally doped GaN layer, a 0.2 µm-thick heavy-doped Si-doped n-type GaN layer, a 0.2 µm-thick unintentionally doped GaN layer, a 2 µm-thick Si-doped n-type GaN layer, an InGaN/GaN multiple quantum well (MQW) active layer (consisting of five pairs of 3nm/12nm thick InGaN/GaN well/barrier layers), and a 0.2 µm-thick p-type GaN:Mg layer. An 250nm-thick Indium Tin oxide (ITO) layer was deposited on the p-GaN surface as the transparent conductive layer (TCL) using the E-gun evaporation system. The etching depth of the mesa region was 1.0µm to define the n-type and p-type GaN regions through the plasma dry etching process. The Cr/Au (10 nm/100nm) metal layers were deposited as the n-type contact and the p-type contact through the E-gun evaporation system, and then annealed at 500°C for 10min in ambient air. The LED structure fabricated through dry plasma etching and the metallization process was defined as the standard LED (ST-LED) structure. The 10 µm-diameter laser-drilled holes were fabricated on a mesa region (650×195µm² in size) by using a triple frequency ultraviolet Nd:YVO₄ (355 nm) laser for the front-side laser drilling process. The area of the laser-drilled hole pattern was about 2% of the mesa region. The laser-drilled depth on the mesa region was about 2.8 µm that contact with the 0.2 µm-thick n+-GaN:Si sacrificial layer for the following EC-etching process. The laser drilling depth can be well controlled the laser pulse energy by using a optical variable attenuator. The samples were immersed in a 0.5M oxalic acid solution with an external dc bias fixed at 15V and 20min process time for the electrochemical (EC) wet etching process. The LED with EC treated laser-drilled hole structure was defined as the air-disk LED (AD-LED) structure. The schematic diagram of the AD-LED structure is shown in Fig. 1. The n⁺-GaN:Si sacrificial layer had been partially etched surrounding the laser drilled hole to form the disk-shaped air-gap structure in the AD-LED structure. The surface morphologies of the LED samples were observed by using a JEOL JIB-4601F focused ion beam scanning electron microscopy (FIB-SEM). The line-scan micro-photoluminescence (µ-PL) spectra were measured, using a 325 nm He–Cd laser as the excited source, by a monochromators (JOBIN YVON iHR550) with a TE-cooled charge coupled device detector. The electroluminescence (EL) spectra, light-output power, and the
intensity profiles were characterized on the chip level using an optical spectrum analyzer, a current source, and a beam profiler.

The EL spectra of the ST-LED and the AD-LED were measured by varying the injection current from 1mA to 30mA as shown in Fig. 2(a) and Fig. 2(b), respectively. In Fig. 2(c), the light output power and the peak EL emission wavelength of both LED structures were measured at room temperature. High light output power of the AD-LED structure had a 22% enhancement compared with that of the ST-LED at a 20mA operating current. The high light output power of the AD-LED was caused by increasing the light reflectance at the bottom EC-treated air-disk structure. The peak wavelengths of the EL spectra were blueshifted from 453.6 nm (1 mA) to 450.6 nm (20 mA) for the ST-LED and from 454.6 nm (1 mA) to 451.1 nm (20 mA) for the AD-LED structure, respectively. By increasing the injection current, the peak wavelengths of the EL spectra had shown the blueshift phenomenon in both LED structures which was caused by the band filling effect in the tilted InGaN quantum well structures. The tilted band diagram of the InGaN well layer is caused by compress strain induced piezoelectric field in InGaN layer. In Fig. 2(d), the operation voltage and the relative efficiency were measured by varying the injection current. The operation voltages at 20mA were measured at 3.12V for ST-LED and 3.19V for the AD-LED, respectively. The slightly voltage increased in the AD-LED was caused by slightly reducing the emission area and increasing the resistance of the treated LED structure.

The relative efficiencies were measured as the values of 32.4/24.5 (2mA/20mA) for the ST-LED structure and 37.0/29.2 (3mA/20mA), respectively, for the AD-LED structure, respectively. The peak efficiency of the AD-LED has a 14% enhancement compared with the ST-LED structure. By increasing the injection current to 20mA, the efficiencies had 24% and 21% reductions for the ST-LED and the AD-LED compared to each peak efficiency. The fabrication process of the embedded air-disk structure didn’t affect the emission wavelength of the treated AD-LED structure.

After laser drilling process, the top ITO layer and the InGaN epitaxial layer were laser ablated to
reach the bottom 0.2 µm-thick n’-GaN:Si sacrificial layer for the following EC-etching process. The laser drilled LED samples can be analyzed by using electrical probing test directly without degrading the device performance. In industry, the laser scribing process is the standard fabrication step for the chip dicing process. The depth of the chip dicing process is about 40µm from top LED epitaxial layer to the bottom sapphire substrate. The residual material from the bottom sapphire substrate is hard to remove that can be removed by immersed in a hot H₃PO₄ solution. In this experiment, the etching depth is about 2.8µm on the epitaxial layer of the top LED structure. The residual material can be removed by the following EC-etching process. The series resistance of the AD-LED was slightly increased by reducing 2% of the emission area, the area of laser drilled holes, in the LED chips. Compared with the plasma dry etching process, the ITO layer surrounding to the plasma etching region should be etched to prevent the surface leakage current from the dry etching sidewall region. The effective emission area will be reduced by reducing the area of the ITO conductive layer far from the dry etched sidewall region. For the deep etching process, the long etching time, the thick dry-etching mask, and the etching pattern distortion should be considered in the plasma dry etching process. The deep depth etched pattern can be controlled by using an optical variable attenuator in laser drilling process. In the AD-LED structure with the embedded air-disk structure, the laser drilling hole and the EC etching process can create the light extraction patterns in the large mesa region of the large chip-size LED structures.

At a 20mA operation current, the light-intensity profiles of both LED samples were measured by using a beam profiler, as shown in Figs. 3(a) and 3(b). In the ST-LED structure, the light emission intensity was distributed uniformly at the central of LED mesa region. Slightly high EL intensity of the ST-LED was observed surrounding the p-type region that caused by the current crowding effect. The AD-LED structure exhibits a high light intensity at the disk-shaped pattern region that had strong light reflectance on the EC-etched air-disk structure embedded in the bottom of LED structure. High magnified light-intensity profiles of the AD-LED with the laser-drilled holes pattern was
observed in Fig. 3(c). The patterned sapphire structure, the laser-drilled holes, and the disk-shaped patterns with high light intensity surrounding the laser-drilled holes were observed. In Fig. 3(c), the EL emission intensities around the laser-drilled hole patterns were higher than it at the non-treated mesa region. The triangle-shaped pattern sapphire can be observed clearly in the EL emission image at the non-treated mesa region. The light extraction efficiency can be increase by using the pattern sapphire substrate in the commercialized fabrication process of Nitride-based LEDs. This indicated that the disk-shaped air-gap structure formed surrounding the laser-drilled hole can provide a high optical reflective structure compared with the pattern sapphire structure. The cross-sectional SEM image of the EC-treated laser-drilled hole pattern was shown in Fig. 3(d) that the sample was prepared by using the focus ion beam (FIB) system. The diameter of the laser-drill hole was measured at about 10µm, and the depth was large than 2.8µm, like a funnel-shaped structure, to contact with the n⁺-GaN:Si sacrificial layer. The 40µm-width of the air-disk pattern was formed through the selective lateral wet etching process. The thickness of the lateral-etched air-disk structure was about 0.2µm as shown in the inserted SEM micrograph in Fig. 3(d). Some of the residual nanoporous GaN layer was observed in the air-disk structure. After removing the n⁺-GaN:Si layer, the etched interface is clearly observed in the air-disk structure. The diameter of the EC-etched air-disk structure was measured at about 40µm the light-intensity profiles and SEM micrograph as shown in Figs. 3(c) and 3(d), respectively. The EC-treated air-disk structure can provide a high light reflectance at u-GaN/air-gap interface to increase the light extraction efficiency in the AD- LED structure.

In Fig. 4(a), the line-scan µ-PL emission spectra of the AD-LED structure were measured at room temperature by using a 40mW 325nm He-Cd lasers as an excitation laser source. The laser light was focused on the mesa surface with a 2µm-diameter laser spot. The µ-PL emission spectra as a function of the scanning position were shown in Fig. 4(a) that the scanning conditions are 2µm scanning step and 200µm scanning width. In the mapping µ-PL emission spectra, the strong GaN
band-edge peak at 363nm and the weak InGaN MQW peak at 443nm were observed at the three laser-drilled hole patterns. The µ-PL emission spectra at the non-treated region, the hole-edge region, and the air-disk region were measured, respectively, as shown in Fig. 4(b). The peak wavelengths of the InGaN MQW active layers, the p-type GaN:Mg layer, and the GaN layer were measured at 443nm, 388nm, and 363nm, respectively. The strong PL intensities of the GaN and the GaN:Mg peaks were observed at the laser-drilled hole edge region compared with it at non-treated region. The line intensity profile of MQW (443nm), GaN:Mg (388nm), and GaN (363nm) peaks were observed in Fig. 4(c). In Fig. 3(b), the PL spectrum at hole-edge region was measured when the laser spot focused at the sidewall of laser-drilled hole pattern. The 368nm GaN peak and 388nm GaN:Mg peak can be observed clearly at the cone-shaped laser drilled hole pattern that the PL emission light can be extracted by the drilled hole pattern. In the line-scan PL spectra, the GaN and GaN:Mg PL peaks had be emphasized in the log-scale plot of the PL spectra that pointed out the distribution the laser drilled hole pattern on the mesa region. The hole edge region is located at the cone-shaped laser drilled hole pattern that top InGaN layer had been removed through the laser drilled process. The 443nm InGaN luminescence is measured from the surrounding InGaN layers that excited by the scatted laser light with low laser excitation power density. The stronger PL intensity of 443nm InGaN emission peak can be observed clearly at the designed air-disk region compared to non-treated region. The stronger EL emission intensity at air-disk region was observed compared it at non-treated region as shown in Fig. 3(c). The periodic PL intensity profile of the InGaN active layer was observed clearly when crossing the laser-drilled hole pattern, the air-disk region, and the non-treated region. The PL peaks of the GaN layer were localized around the laser drilled hole pattern clearly in the line-scanning intensity profile. The stable emission peak wavelength of the InGaN active layer was observed at 443nm that indicated the InGaN active layer didn’t affect by forming the embedded air-disk structure. The high PL intensities were observed close to the laser-drilled hole patterns that caused by the high light reflectance process occurred at the embedded air-disk regions.
The high light extraction of the air-disk structures were fabricated in the AD-LED structure through a laser drilling process and an electrochemical wet etching process. The air-disk structure were formed through the one-step epitaxial growth process and the selective wet etching process on the high doping concentration of GaN:Si layer. The InGaN LED with the laser-drilling holes and the embedded air-disks structure can reduce the light trapping effect and increase the light extraction efficiency on the mesa region for the high efficiency large chip-size InGaN-based LED applications.

Acknowledgments

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Figure Captions

Figure 1  Schematic diagram of the AD-LED structure is shown.

Figure 2  EL emission spectra of (a) the ST-LED and (b) the AD-LED were measured by varying the injection current from 1mA to 30mA. (c) The EL emission wavelength and the light output power as a function of injection current were measured. (d) The operation voltage and relative efficiency were measured by varying the injection current.

Figure 3  Light-intensity profiles of (a) the ST-LED and (b) the AD-LED were measured by using a beam profiler. (c) High magnified light-intensity profile of the AD-LED with the laser-drilled holes pattern was observed. (d) The cross-sectional SEM image of the EC-treated laser-drilled hole pattern was measured. The thickness of the air-disk structure was observed in the insert SEM image.

Figure 4  (a) Line-scan µ-PL emission spectra of the AD-LED structure were measured by using a 325nm He-Cd lasers as an excitation laser source. (b) The µ-PL emission spectra at the non-treated region, the hole-edge region, and the air-disk region were measured. (c) The line intensity profile of MQW (443nm), GaN:Mg (388nm), and GaN (363nm) peaks were observed across three laser drilled holes.
Figure 1

Step 1: Laser drilling process on mesa

- Cr/Au
- p-GaN:Mg layer
- MQW active layer
- n-GaN:Si layer
- p-GaN layer
- n-GaN:Si layer
- n-GaN layer
- Step 2: EC selective etching process
- Al₂O₃ Substrate
Figure 2
Figure 3
Figure 4