High-efficiency light-emitting diode with air voids embedded in lateral epitaxially overgrown GaN using a metal mask

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Abstract: We report high-efficiency blue light-emitting diodes (LEDs) with air voids embedded in GaN. The air void structures were created by the lateral epitaxial overgrowth (LEO) of GaN using a tungsten mask. The optical output power was increased by 60% at an injection current of 20 mA compared with that of conventional LEDs without air voids. The enhancement is attributed to improved internal quantum efficiency because the air voids reduce the threading dislocation and strain in the LEO GaN epilayer. A ray-tracing simulation revealed that the path length of light escaping from the LED with air voids is much shorter because the air voids efficiently change the light path toward the top direction to improve the light extraction of the LED.

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References and links
1. Introduction

III-nitride based light-emitting diodes (LEDs) have rapidly developed for the next generation solid-state lightings. Although InGaN-based LEDs are commercially available, LEDs still require further improvement of the external quantum efficiency (EQE). The low EQE of LEDs is mainly attributed to the low internal quantum efficiency (IQE) and low light extraction efficiency (LEE). The low IQE is due to the low crystal quality of GaN epilayer [1] and strong polarization-induced electric fields in highly strained InGaN/GaN multiple quantum wells (MQWs) [2,3]. The large mismatch of lattice constants and thermal expansion coefficients between GaN and sapphire degrade the quality of GaN epilayers by introducing threading dislocations that act as non-radiative recombination centers in InGaN/GaN MQWs [1]. Furthermore, the existence of the quantum confined Stark effect (QCSE) induced by the strong built-in piezoelectric field in InGaN/GaN MQWs results in a reduction in the carrier recombination rate by increasing the spatial separation between the electron and hole wave functions involved in the radiative recombination [2,3]. Another major reason for the low EQE is a low LEE, which mainly results from the total internal reflection of light caused by the difference in the refractive indexes of GaN (n = 2.5) and air (n = 1) [4].

Among the many recent approaches to an improvement in EQE, an air void structure embedded in LEDs has been actively studied as a means to increase the IQE and LEE for the fabrication of high efficiency optoelectronic devices [5–7]. Until now, most LEDs with air voids have been fabricated using an additional crystallographic wet etching process [5–7]. However, excessive wet etching process can cause epitaxial growth problems, such as surface pits and a rough surface. This study investigates InGaN/GaN blue LEDs with embedded air void structures that were realized by the lateral epitaxial overgrowth (LEO) of GaN using a tungsten (W) mask. The W mask and air void structures inserted into the GaN epilayer reduced threading dislocation and relieved strain. Furthermore, the air void structures embedded in LEDs improved light extraction by changing the light path.

2. Experiments

Figure 1(a) shows a schematic of an LED with air voids produced by the LEO of GaN using a W mask. GaN LEDs with emission at 460 nm were grown on a c-plane (0001) sapphire by metalorganic chemical vapor deposition (MOCVD). After the growth of a 25 nm-thick GaN nucleation layer at 550 °C, a 2.5 μm-thick undoped GaN cladding layer was grown at 1020 °C. A line-shaped photosresist (PR) mask pattern with a width of 4 μm and a spacing of 10 μm between patterns was formed on a GaN cladding layer in the <1-100> GaN crystal direction by the photolithography method. Then, a 30 nm-thick W layer was deposited on the PR pattern as an LEO mask by electron-beam evaporation. Arrays of line-shaped W masks on the GaN cladding layer were obtained after the lift-off process. Figure 1(b) shows a plan-view scanning electron microscopy (SEM) image of the W masks. After the overgrowth of 2 μm-thick undoped GaN, a 2 μm-thick n-GaN was grown on the GaN epilayer covered with W masks. Figures 1(c) and (d) show cross-sectional SEM images of a coalesced LEO GaN epilayer that was grown using a W mask. As shown in Figs. 1(c) and (d), the full coalescence of the LEO GaN was achieved, and the W patterns were fully covered by the GaN epilayer. Note that air void structures can be created under the W mask without an additional wet etching process. The formation of the air void structure is attributed to the decomposition of GaN by the chemical reaction of GaN with hydrogen (H₂) and W during the LEO process.
It was reported that the W mask is not dense and the hydrogen molecules and their radicals pass through the W mask, resulting in the decomposition of the GaN epilayer under the W mask [8]. Then, five periods of InGaN/GaN MQWs were grown at 770 °C, followed by the growth of a 200 nm-thick $p$-GaN layer at 980 °C. Finally, LEDs with air voids were fabricated and the details of the procedure for the fabrication of the LEDs with a size of 300 × 300 μm$^2$ was reported elsewhere [9].

Fig. 1. (a) Schematic of air voids embedded LEDs using a W mask. (b) Plan-view SEM image of a W mask. (c), (d) Cross-sectional SEM images of an LEO GaN epilayer grown on a W mask.

3. Results and discussion

The surface of a LEO GaN epilayer with air voids was characterized using an atomic force microscope (AFM) (not shown). The surface pit density of the LEO GaN epilayer in the window region was $4 \times 10^8$ cm$^{-2}$ and that of the mask region was $6 \times 10^7$ cm$^{-2}$. The surface pit density of the as-grown GaN epilayer without air voids was $5 \times 10^8$ cm$^{-2}$, which is similar to that of the LEO GaN epilayer in the window region. The surface pits formed in the GaN epilayer are known mainly due to the propagation of the threading dislocations. The AFM results indicate that the threading dislocations are terminated when they encounter the W mask, resulting in a decrease in the threading dislocation density of LEO GaN in the mask region [9,10]. To identify the strain relaxation in the LEO GaN epilayer caused by the formation of air voids, a Raman measurement was performed. The shift of $E_2$ phonon mode peaks of a GaN epilayer on the Raman spectrum represents the strain state of the epilayer [11,12]. As shown in Fig. 2(a), the $E_2$ phonon mode peaks of the as-grown GaN and LEO GaN epilayer with air voids appear at 571.4 and 569.6 cm$^{-1}$, respectively. The relaxation of residual strain can be calculated using the following equation [11]:

$$\Delta \omega = \omega - \omega_0 = K \cdot \sigma_{\text{xx}},$$

(1)
where $\omega_\gamma$ and $\omega_0$ represent the Raman peaks of the LEO GaN and as-grown GaN epilayers, respectively. A redshift of 1.8 cm$^{-1}$ of the LEO GaN epilayer with respect to an as-grown GaN corresponds to a relaxation of compressive stress $\sigma_{xx}$ by 0.428 GPa when a proportionality factor $K_\gamma$ of 4.2 cm$^{-1}$/GPa is used for the hexagonal GaN [11]. The relaxation of strain is attributed to the formation of the air voids in the GaN cladding layer. This result shows that a high quality strain-released GaN epilayer can be grown using a W mask and air voids.

Figure 2(b) shows the room temperature and temperature-dependent photoluminescence (PL) spectra of the InGaN/GaN LEDs grown on a GaN epilayer with and without air voids. The PL spectra were measured from the top side of the samples at room temperature using a He–Cd laser ($\lambda = 325$ nm) with an excitation laser power of 50 mW. As shown in Fig. 2(b), the PL intensity of air voids embedded LED is much higher than that of the conventional LED. The integrated PL intensity of the LED with air voids is increased by about two times compared to that of the conventional LED. The large enhancement of the PL intensity can be attributed to the improved IQE of the InGaN/GaN MQWs due to the reduction of dislocation density and the relaxation of strain in the GaN epilayer [9,10]. To confirm the improvement in the IQE, the temperature-dependent PL was measured at temperatures from 10 to 300 K. The inset of Fig. 2(b) shows an Arrhenius plot of the integrated PL intensities of LEDs with and without air voids. The integrated PL intensity of the MQWs can be fitted by using the following equation [13,14]:

$$I(T) \propto \frac{1}{1 + \sum_i C_i \exp(-E_i/k_B T)}$$

where $I(T)$ is the integrated PL intensity of the MQWs, $C_i$ is the constant related to the density of the non-radiative recombination centers, $E_i$ is the activation energy of the corresponding non-radiative recombination centers, and $k_B$ is Boltzmann’s constant. Above 130 K, the calculated $E_i$ is 90 meV for LEDs with air voids and 57 meV for conventional LEDs, and the calculated constant $C_i$ is 18 for LEDs with air voids and 25 for conventional LEDs. The large value of $E_i$ for LEDs with air voids is due to the reduction in threading dislocations in the GaN epilayer, which leads to a high energy barrier for carrier capture by threading dislocations. The small constant $C_i$ for an LED with air voids also means that LEDs with air voids have a lower density of non-radiative recombination centers than LEDs without air voids. In the case of IQE, the IQE of LEDs with air voids is estimated to be 34%, which is about two times higher than the 18% for conventional LEDs without air voids. These results indicate that a significant relaxation of strain and reduction of defects such as screw and edge-
type threading dislocations in the GaN epilayer and MQWs contributes to the increased IQE value.

Furthermore, the LEE can also be enhanced by air voids because the air voids at the interface between GaN and sapphire should be able to change the path of the light escaping from the LEDs. To confirm the improvement of LEE by air voids, the LEE of LEDs with and without air voids was calculated using the Monte-Carlo ray-tracing method. The simulation model for LEDs with air voids consisted of 330 μm-thick sapphire ($n = 1.7$) and air void structures ($n = 1$) with a width of 4 μm and a height of 3 μm surrounded by 7.5 μm-thick GaN ($n = 2.5$). The MQWs active region with an IQE of 100% was inserted into the GaN. The total amount of light emitted from the LED was detected by receivers covering all directions. Figure 3 shows the results of ray-tracing simulations for LEDs with and without air voids. As shown in Figs. 3(a) and (b), the light more effectively escapes from the LED with air voids than from the conventional LED. In particular, Fig. 3(c) shows that the light is more efficiently extracted from the top side of the LED with air voids. These results clearly indicate that the path length of light escaping from the LED with air voids is much shorter because the air voids efficiently change the light path toward the top direction to improve the light extraction of the LED.

![Monte-Carlo ray-tracing result for (a) a conventional LED and (b) the LED with air voids. (c) Far field patterns of an LED with air voids and a conventional LED.](image)

Figure 4(a) shows the current-voltage (I-V) characteristics of blue LEDs with and without air voids. As shown in Fig. 4(a), the forward voltage of the LED with air voids is 3.35 V at 20 mA, which is the same as that of the conventional LED without air voids. The 12.8 Ω series resistance of the LED with air voids is slightly lower than the 13.1 Ω of a conventional LED. Furthermore, the LED with air voids shows a reverse-bias leakage current of $5 \times 10^{-5}$ A at $-10$ V, which is slightly lower than the $8 \times 10^{-5}$ A of the conventional LED without air voids. These results indicate that the threading dislocations responsible for leakage currents are reduced by the W mask and air voids. To investigate the optical properties of the LEDs, the
optical output power was measured. The optical output power of the LED was measured from the top side of the LEDs using a 2 cm-diameter Si photodiode connected to an optical power meter. Figure 4(b) shows the optical output power of LEDs with and without air voids as a function of injection current. As shown in Fig. 4(b), the optical output power of LEDs with air voids is increased by 60% at 20 mA of injection current compared to that of conventional LEDs. The large increase in optical output power can be attributed to an improvement in the IQE of the MQWs caused by the reduction of threading dislocation and relaxation of strain in the GaN epilayer. Moreover, the LEE is also improved by reflection and redirection of the light by the air void structures embedded in the LEDs. However, the observed enhancement of optical output power of LED with air void structures is lower than the expected value presumably due to the lower carrier injection efficiency in electroluminescence compared to PL process, and the ray-tracing simulation of light extraction process based on the very simple modeling of detailed structure of air voids in LEDs.

![Fig. 4. (a) I-V characteristics of the LEDs with and without air voids as a function of injection current. (b) Optical output power of the LEDs with air voids as a function of injection current.](image)

4. Summary

In summary, we demonstrate a high-efficiency blue LED with air voids embedded in an LEO GaN epilayer using W masks. The optical output power of blue LEDs with air voids is increased by 60% at 20 mA compared to that of conventional LEDs without air voids. The increase in optical output power was attributed to an improvement in the IQE and LEE of the LEDs produced by the air void structures.

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