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Effect of GaN Microlens Array on Efficiency of GaN-Based Blue-Light-Emitting Diodes

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In this study, GaN-based vertical light-emitting diodes (VLEDs) were fabricated by a laser lift-off (LLO) process and the effects of microlens formation by plasma etching on the optical properties of the LLO GaN-based VLED devices were investigated. By forming a 5–10 μm microlens array on the LLO GaN-based VLEDs, the measured light emission intensities at 460 nm and in the direction normal to the surface of the device increased by approximately 40% and 100% compared with those of the LLO GaN-based VLED without the microlens array for 10 μm and 5 μm microlens arrays, respectively.
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KEYWORDS: laser lift-off GaN-based vertical light-emitting diode (VLED), microlens, ITO contact, light extraction efficiency, Lambertian emission pattern

GaN-based light-emitting diodes (LEDs) have been intensively studied for use in full-color outdoor LED displays, LED lighting and so on.[1–6] In particular, researchers are currently making efforts to develop highly bright LEDs for white LEDs.[7,8] To increase the efficiency of conventional GaN-based LEDs, various attempts have been made such as texturing the top electrode surface, optimizing the multi- quantum well layer and applying an indium-tin oxide (ITO) or ITO/thin metal contact instead of the conventional thin metal p-type contact.[9–13]

However, when surface texturing was attempted, many difficulties were encountered in the case of conventional GaN devices with p-GaN on top, due to the high sensitivity of p-GaN to process-induced damage and due to the thin p-GaN top layer used for texturing.[9,11,14] Because of difficulties, the successful application of surface texturing to conventional lateral GaN devices with p-type GaN on top has not yet been reported.

Therefore, in this study, a reversely constructed GaN-based vertical LEDs (VLEDs), with n-GaN on top were fabricated by a laser-lift-off (LLO) process. As a way of texturing the n-GaN located on top of the device, microlens arrays were formed by a plasma etch process and its effect on the light extraction efficiency and the angular distribution of the emitted light were investigated and compared with those by a planar surface LLO GaN-based VLEDs.

To investigate the light extraction efficiency relating to the surface texturing of the LLO device, a lens-shaped photoresist array was formed by a photoresist re-flowing method on the surface of LLO n-GaN. AZ1512 photoresist was used and the post baking was performed on the hot plate at 200°C. The diameters and height of the photoresist microlens mask were 5–10 μm and 1.5 μm, respectively. For the GaN lens array formation, a dry etching method by an inductively coupled plasma was used. Etch gas chemistry, operating pressure, plasma generation power, and applied substrate dc-bias voltage were 100% Cl_2, 10 mTorr, 1400 W, and −150 V, respectively. At this condition, the GaN etch rate was 460 nm/min and the etch selectivity of GaN to photoresist was 0.8. The etching was performed until the phtoresist was etched away, therefore, until the GaN microlens array was formed on the LLO n-GaN surface.

To decrease the forward voltage of the devices without decreasing light extraction efficiency, 175 nm thick indium tin oxide (ITO) film was applied as a transparent n-contact to the surface of n-GaN with the micro-lens array using an ion beam assisted ITO evaporation method at room temperature. In this method, to improve the electrical and optical properties of the deposited ITO, O_2 ion beam was applied during the ITO evaporation and the details of the ITO deposition method can be found elsewhere.[15] Before depositing the ITO film on the GaN surface, a surface treatment using vaporized HCl for 15 seconds was carried out followed by an organic solvent cleaning.

Finally, vertical LLO GaN-based VLED devices with a GaN micro-lens array was fabricated by separating each devices, and the electrical and optical properties of the devices were investigated using a semiconductor parameter analyzer (HP4145A) and using an optical emission spectrometer (OES, PCM402, SCTECH) installed in a probe station. Also, planar LLO GaN-based VLED devices without the lens array was fabricated to compare the optical properties. Light emitting distribution at 460 nm was also measured by varying the light emitting detection angle from 0 to 80 degrees from the normal direction of the device surface using the OES.

Figures 1(a) and 1(b) show the schematic diagrams of the LLO GaN-based VLED devices with/without the micro-lens array formed in this study and the scanning electron microscopic images of the 10 μm micro-lens array formed on the surface of n-GaN of the device, respectively. As shown in the Fig. 1(a), the micro-lens array was formed on the top of the device and the ITO layer was deposited on the top of the GaN device with/without the micro-lens array. As the pad metal layer, Cr/Au was formed at the center of the device. For the GaN micro-lenses shown in the Fig. 1(b), after the etching, the measured height of the GaN micro-lens was about 1.2 μm and the measured diameter of micro-lens was about 10 μm. The coverage of the micro-lens on the device was about 32%. The deposition of ITO to the surface of n-GaN was necessary in our experimental condition. By the deposition of 175 nm ITO on the n-GaN surface, the forward operating voltage were decreased from 5–6 V to 3.3–3.8 V at 20 mA. The measured optical transmittance of the ITO film at 460 nm was higher than 95%, therefore, the

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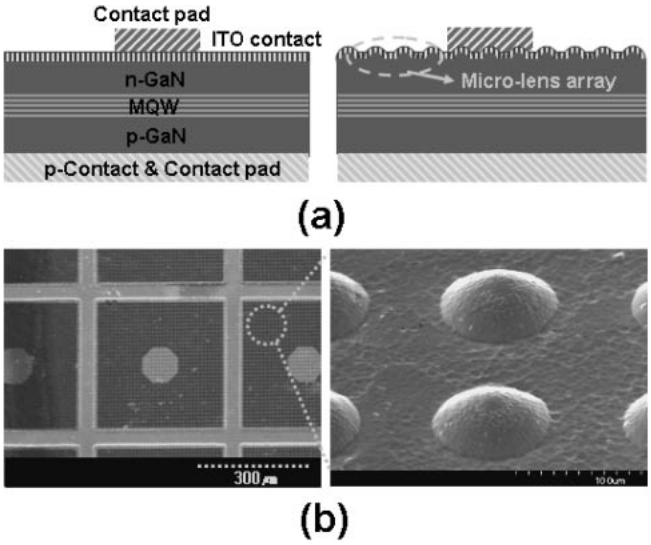

Fig. 1. (a) the schematic diagrams of the LLO GaN-based VLED devices with/without the micro-lens array formed in this study and (b) the scanning electron microscopic images of the 10 μm micro-lens array formed on the surface of n-GaN of the device.

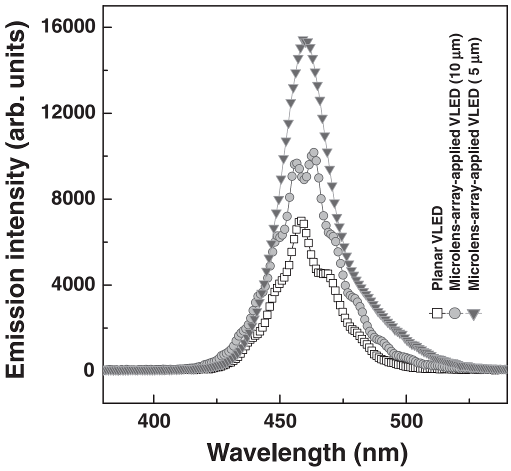

Fig. 2. Measured light emission intensities of the LLO GaN-based VLEDs with and without the micro-lens array measured at the surface normal of the device using OES. As the micro-lens array, 5 μm array and 10 μm array were used.

forward operating voltage was decreased to the voltage close to that of the conventional lateral GaN-based LEDs without significantly decreasing the light emission efficiency.

Figure 2 shows the detected light emission intensities of the LLO GaN-based VLEDs with and without the micro-lens array measured at the surface normal of the device using OES. As the micro-lens array, 5 μm array and 10 μm array were used. As shown in the figure, by the formation of the micro-lens array on the surface of the GaN, the increase of light emission intensity was obtained. For the VLEDs with 5 μm and 10 μm micro-lens arrays, about 100% and 40% increase of light emission intensity compared to the planar surface VLED could be obtained, respectively. The increase of light emission intensity of the VLEDs with the micro-lens array at the surface normal of the device was related to the increase the extraction efficiency due to the increase of critical angle at the interface between GaN/ITO and air by the surface curvature and the increase of light emission distribution to the normal direction of the device.

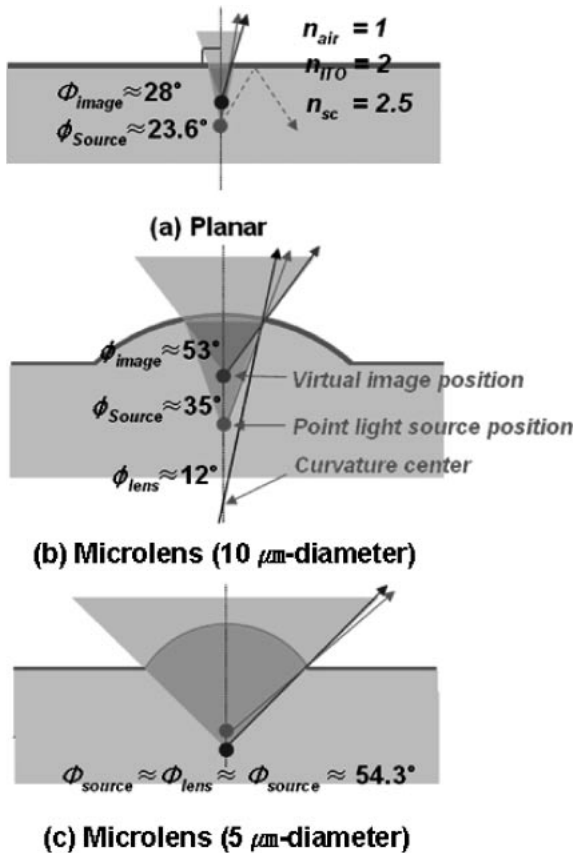

Fig. 3. Schematic diagram on the effect of micro-lens formed on the LLO GaN-based VLED devices on the increase of critical extraction angles for 5 μm and 10 μm micro-lens.

Figure 3 shows the schematic diagram on the effect of micro-lens formed on the LLO GaN-based VLED devices on the increase of critical extraction angles for 5 μm and 10 μm micro-lens. The quantum well which is the light source is located about 3 μm below the flat surface, the thickness of the micro-lens is about 1.2 μm, and the curvature radius of the micro-lens is about 10 μm. Also, due to the optical effect of ITO thin layer, two spherical surfaces consisted of GaN/ITO and ITO/air interfaces were considered. Therefore, from the following spherical surface refraction equation,[16)]

$$\frac{n_1}{O} + \frac{n_2}{I} = \frac{n_2 - n_1}{R} \tag{1}$$

the following lens equation composed of two spherical surfaces can be obtained

$$\begin{aligned}\frac{n_{\mathrm{GaN}}}{O} + \frac{n_{\mathrm{ITO}}}{I} + \frac{n_{\mathrm{ITO}}}{I + t_{\mathrm{ITO}}} + \frac{n_{\mathrm{air}}}{I'} \\ = \frac{n_{\mathrm{GaN}} - n_{\mathrm{ITO}}}{R} + \frac{n_{\mathrm{ITO}} - n_{\mathrm{air}}}{R + t_{\mathrm{ITO}}}.\end{aligned} \tag{2}$$

From this eq. (2), the location of the virtual light source (I') of 1.5 μm can be obtained by inserting values such as $n_{\mathrm{GaN}} = 2.5$ (for refractive index for GaN), $n_{\mathrm{ITO}} = 2.0$ (for refractive index for ITO), $n_{\mathrm{air}} = 1.0$ (refractive index for air), $O = 3.0$ μm (distance of the object), $R = 10$ μm (radius of lens curvature), and $t_{\mathrm{ITO}} = 0.175$ μm (thickness of the ITO layer). Especially for the planar surface, the values $R = \infty$

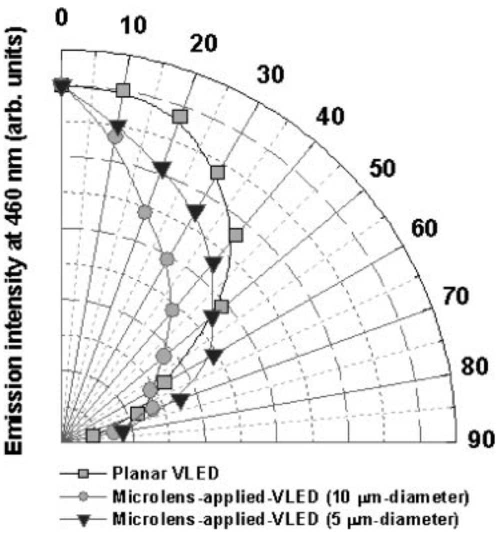

Fig. 4. Measured normalized light emission intensity distribution of the LLO GaN-based VLED devices with and without the micro-lens array measured by OES as a function of the light emitting detection angle from the surface normal of the devices.

was inserted. By locating the virtual light source at about 1.5 μm (for 10 μm lens) and 3.1 μm (for 5 μm lens) from the top of the lens, the detectable critical extraction angles for the total reflection obtained by the following Snell's law,[16,17)]

$$n_{sc} \sin \varphi_{source} = n_{air} \sin \varphi_{ext}. \qquad (3)$$

were changed from 23.6° to 53° and to 54.3°, respectively as shown in the Fig. 3. Therefore, increase of light extraction is believed to be obtained by the formation of micro-lens in our study even though the above equation assumed a point light source instead of a planar light source.

The formation of micro-lens also changes the light extraction distribution. Figure 4 shows the measured normalized light emission intensity distribution of the LLO GaN-based VLED devices with and without the micro-lens array measured by OES as a function of the light emitting detection angle from the surface normal direction of the devices. As shown in the figure, the planar surface vertical LED shows the circular emission intensity distribution while the VLEDs with the micro-lens arrays show parabolic emission intensity distributions. This distribution of intensity can be explained by the Lambertian emission pattern;[17)]

$$I_{air} = \frac{P_{source}}{4\pi r^2} \frac{{n_{air}}^2}{{n_{SC}}^2} \cos \varphi_{ext} \qquad (4)$$

In the eq. (3), I_{air} is the measured light intensity, P_{source} is the light emitted power from the quantum well, r is distance from the light source to the interface, and the angle φ_{ext} indicates the extraction angle into air from the ITO. In the planar VLED, the circular emission intensity distribution pattern in figure could be understood as a lambertian emission pattern in the eq. (4). However, in the case of VLEDs with the micro-lens array, by assuming a point light source and by locating the light source at the virtual light source position of the micro-lens in the eq. (2), a parabolic emission intensity distribution having more light emission to the normal directional of the device surface can be expected by putting $\varphi_{ext} = \varphi_{sc} - \varphi_{lens}$ due to the curvature of the micro-lens and the formation of virtual light source, where φ_{sc} is the angle measured from the light source position and φ_{lens} is the angle measured form the lens curvature center. Therefore, higher light intensity detected at the surface normal direction is believed to be partially related to the parabolic distribution of the emitted light in addition to the more light extraction from the device surface.

In this study, using a LLO method, GaN-based VLEDs were fabricated and the effects of micro-lens formed on the surface of the LLO GaN-based VLED devices on the light emission intensity were investigated. The formation of micro-lens arrays on the top of the VLED increased the light emission intensity measured at the surface normal up to 100% even though the micro-lens coverage on the surface is only about 32%. The increase of light emission intensity measured at the surface normal direction of the devices was partially related to the increase of light extraction efficiency due to the increase of critical angle and also partially related to the formation of a parabolic emission intensity distribution instead of a typical lambertian cosine distribution.

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