Optical Properties of the Partially Strain Relaxed InGaN/GaN Light-Emitting Diodes Induced by p-Type GaN Surface Texturing

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***Abstract*—Partial strain relaxation from the light-emitting diode (LED) with surface-textured p-GaN was observed. The textured device possesses less efficiency droop and a higher current level at the efficiency maximum, as compared with the planar one. The results suggest that surface roughening affects not only the external light extraction but also the internal quantum efficiency. Furthermore, the photoluminescent (PL) measurement at low temperature reveals that the percentage increment of the optical power of the textured LED over that of the planar LED becomes lower. In addition to the effect of frozen nonradiative defect states, the PL difference is related to the strain-correlated quantum-confined Stark effect.**

***Index Terms*—Light-emitting diode (LED), strain relaxation, surface texturing.**

I. Introduction

EXTERNAL light extraction has been a very popular topic for GaN-based light-emitting diodes (LEDs) [1]–[4]. Various surface roughening techniques have been proposed to enhance extraction efficiency, which include growing an additional rough p-GaN layer [1] and texturing the transparent conducting contact [2] or the p-GaN layer [2]–[4]. On the other hand, the root causes that affect the internal quantum efficiency (IQE) were usually considered separately from light extraction. A common method to calculate IQE is based on the assumption that defect states are completely frozen at the temperature close to 0 K [5]–[7] at which the IQE is regarded as 100% since all the injected carriers contribute to radiative recombination. Despite the simplicity, only a relative value can be obtained from this method, and it is difficult to identify the absolute IQE of LEDs with different device structures. What is more, the method underestimates the other factors that may vary with temperature. For example, for a GaN-based LED epistructure, a lattice mismatch between InGaN and GaN results in a strain-related quantum-confined Stark effect (QCSE) [8], [9]. It creates the internal electric field that leads to the separation of electrons and holes in the quantum-well region and decreases the IQE. Therefore, in addition to the nonradiative light emission, the strain-induced electron–hole separation affects the IQE at low temperature. In this letter, partial strain relaxation from the LEDs with a surface-textured p-GaN layer was observed. The optical properties were explored by comparing with that of the planar one. Low-temperature photoluminescent (PL) measurement was employed to correlate the effects of nonradiative defect reduction with the strain-induced QCSE.

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II. Device Fabrication

The LED epistructure was grown by metal organic chemical vapor deposition on a c-plane sapphire substrate. The material structure is composed of a 25-nm GaN buffer layer, a 2-μm Si-doped n-type GaN layer, five periods of the $In_{0.2}Ga_{0.8}N$/GaN multiple quantum well (MQW) structure in which each period is 17 nm, and a 160-nm Mg-doped p-type GaN layer. The device fabrication is very similar to that described in [10]. In short, we employed inductively coupled plasma reactive ion etching (ICP-RIE) to define the 300×300 μm^2 mesa area. The sample was then coated with a SiO_2 thin film by plasma-enhanced chemical vapor deposition but with the via open on the light-emitting area. The sample was spin casted with silica nanoparticles with a diameter of approximately 100 ± 10 nm. Next, we etched the sample using ICP-RIE with the presence of the silica nanoparticle mask to roughen the p-type GaN surface. The etch depth is 50 nm. After removing the silica particles and the SiO_2 thin film, Ni/Au (20/250 nm) and Ti/Au (16/160 nm) metal stacks were evaporated for the p-type and n-type contact electrodes, respectively.

III. Experiment Result and Discussion

We first conducted Raman scattering measurement to study the strain in the InGaN/GaN structure with and without p-GaN surface roughening. The nanorods on the samples were defined using the same nanoparticle coating and etching conditions described in the previous section. As indicated in Fig. 1, two phonon modes are identified. The peak near 569 cm^{-1} is

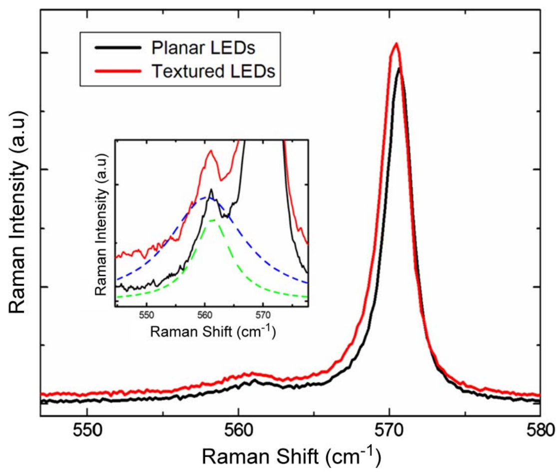

Fig. 1. Room-temperature Raman scattering spectra of both (black line) planar and (red line) textured LEDs. Inset: Close-up view of (solid lines) the InGaN E_2^H modes. The fitting curves are shown in dashed lines.

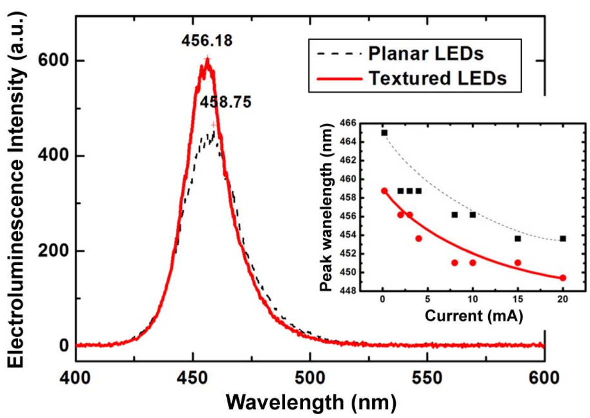

Fig. 2. Room-temperature EL spectra of textured and planar LEDs at a bias current of 2 mA. (Inlet: Peak wavelength of EL spectra at the injection current from 0.2 to 20 mA of both devices).

from the E_2^H mode of GaN [11], while the other peak near 560 cm^{-1} is the E_2^H mode of InGaN [12]. As shown in the inset of Fig. 1, the InGaN E_2^H modes are 561.35 and 560.59 cm^{-1} for the planar and textured structures, respectively. The smaller E_2^H mode shift in the Raman spectrum indicates a relaxed strain for the textured device, as compared with the planar structure, in the InGaN/GaN MQWs. The results suggest that, by etching the p-GaN layer, the strain induced from the lattice mismatch between the InGaN and GaN layers in the MQWs can be relaxed. In addition, the percentage change of the strain relaxation can be estimated from the red shift of the E_2 phonon mode [11]. The calculated strains ε, given the information of the Raman shift, are 1.50% and 1.42% in the planar and textured epistructures, respectively. That is, with surface roughening in the p-GaN layer, around 5.33% reduction of the strain is obtained.

We next characterized the optical properties. To avoid self-heating, we applied pulsewidth-modulated injection currents with a 0.5% duty cycle in a 100-ms period on LEDs. The electroluminescent (EL) spectra in Fig. 2 provide further evidence of the relaxed strain of the textured p-GaN LED. The peak emission wavelengths at an injection current of 2 mA are 456.2

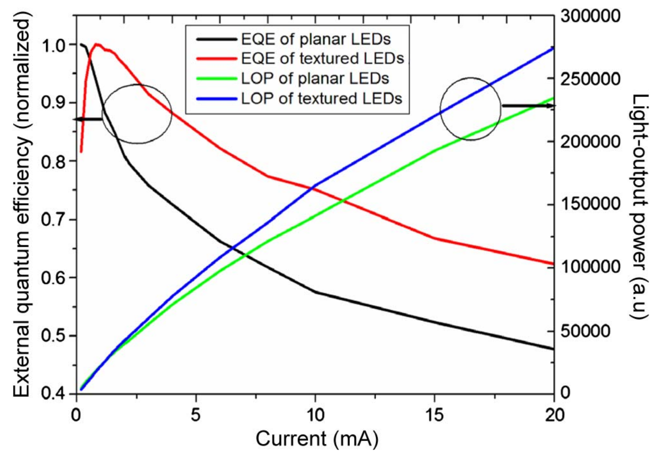

Fig. 3. (Right axis) LOP and (left axis) normalized EQE as a function of forward currents for planar and textured LEDs.

and 458.8 nm for the textured and planar LEDs, respectively. The blue shift of the textured p-GaN is due to the partial strain relaxation, which results in less band-edge tilt and a better spatial alignment of the electrons and holes. Moreover, from the inlet of Fig. 2, with the increase of injection currents from 0.2 to 20 mA, the planar LEDs possess a slightly larger blue shift (11.4 nm) than the textured one (9.5 nm) due to the effect of carrier screening.

The relaxation of the strain in the textured LEDs leads us to explore the effect of the efficiency droop. Fig. 3 shows the light-output power (LOP) of both devices. At an injection current of 20 mA, the LOP of the textured LED is 17% higher than that of the planar device. The improvement can be made much higher by adjusting the process conditions. However, the optimum LOP is not the main topic in this letter. The LOP increase of the textured LEDs has been discussed extensively and was attributed to the improved external light extraction [1]–[4]. However, with the existence of partial strain relaxation in the textured LEDs, we believe that the LOP is also related to the IQE improvement. The normalized external quantum efficiency (EQE) of these two devices reveals more facts. As shown in Fig. 3, the EQE of the planar LED reaches its peak, i.e., $\eta_{\rm peak}$, at a bias current of 0.2 mA, while the textured LED reaches its peak at a relatively larger current of 0.8 mA. Furthermore, the efficiency droop, defined as $(\eta_{\rm peak} - \eta_{20\,{\rm mA}})/\eta_{\rm peak}$ (where $\eta_{20\,{\rm mA}}$ is the EQE at 20 mA), is 52.2% for the planar LED and 37.6% for the textured device. The textured p-GaN not only improves the optical output but also leads to a higher maximum-EQE current level and less efficiency droop.

In order to understand how IQE is affected by strain relaxation (in addition to nonradiative recombination), we next performed a temperature-dependent PL experiment. The p-GaN surface texturing was achieved using the same process condition as that for the Raman measurement. To avoid variations of the surface reflection due to p-GaN texturing, PL excitation and excited light collection were carried out from the back side (sapphire) of the sample. In Fig. 4, at room temperature, the enhancement of the PL-excited LOP of the textured epistructures is 17% higher than that of the planar one. At 50 K, the enhancement shrinks to 11%. The results in Fig. 4 indicate that the IQE of the planar structure cannot be assumed to

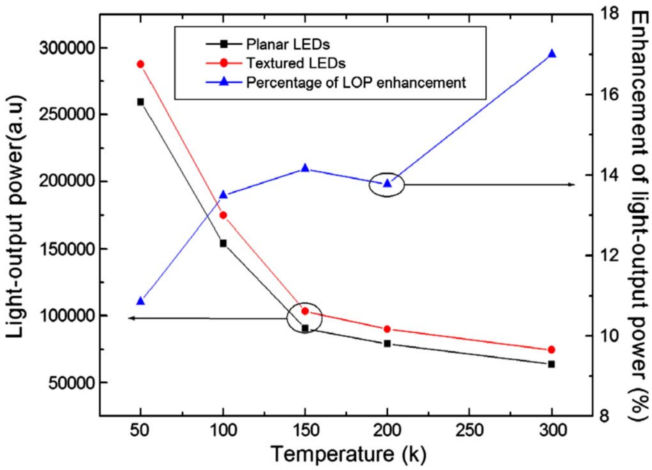

Fig. 4. (Left axis) Temperature-dependent PL intensity of textured and planar LEDs. (Right axis) Percentage of light output enhancement of the textured device over the planar one.

be 100% at low temperature as the excited output power of the textured one is actually higher. Moreover, the decrease of the percentage improvement of the textured structure at low temperature, as compared with that at room temperature, can be explained by the following two factors. First, the EQE is composed of radiative and nonradiative recombination. It is higher on the textured structure because the radiative recombination weighting is higher. As the temperature is decreased, nonradiative recombination becomes insignificant. Thus, the percentage difference between the LOPs of the textured and planar structures becomes smaller. Second, we suspect that it is attributed to the difference of the radiation lifetime under the influence of the QCSE of both devices. For the planar LED, QWs initially have a longer radiative lifetime because of the stronger QCSE, and thus, carriers recombine slowly. At low temperature, the decrease of nonradiative recombination drives a rapid buildup of the carrier density in the QW and screens the polarization field. Then, the electron–hole overlap is improved by carrier screening and results in the larger enhancement of output light in the planar structure. As a result, the planar structure has a larger increase of the excited LOP when the temperature drops.

IV. Conclusion

A 5.33% relaxation of the strain in the InGaN/GaN MQW was obtained by observing the Raman wavelength number shift from the planar to the textured p-GaN epistructures. With the relaxed strain, the textured p-GaN LED has less efficiency droop. The aforementioned results indicate that the improved LOP of the textured p-GaN LED is attributed not only to the extraction efficiency but also to the IQE. Furthermore, the PL measurement reveals that the percentage increment of the optical power of a textured LED over that of a planar LED becomes lower at low temperature. Thus, other than the freezing of nonradiative defect states, the strain-correlated QCSE has played a role. The improved electron–hole overlap of the planar LED at low temperature helps to increase the IQE.

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