Investigation of Low-Temperature Optical Characteristics of InGaN/GaN Based Nanorod Light Emitting Arrays

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Abstract

For InGaN/GaN based nanorod devices using top-down etching process, the optical output power is affected by non-radiative recombination due to sidewall defects (which decrease light output efficiency) and mitigated quantum confined Stark effect (QCSE) due to strain relaxation (which increases internal quantum efficiency). Therefore, the exploration of low-temperature optical behaviors of nanorod light emitting diodes (LEDs) will help identify the correlation between those two factors. In this work, low-temperature EL spectra of InGaN/GaN nanorod arrays was explored and compared with those of planar LEDs. The nanorod LED exhibits a much higher optical output percentage increase when the temperature decreases. The increase is mainly attributed to the increased carriers and a better spatial overlap of electrons and holes in the quantum wells for radiative recombination. Next, while the nanorod array shows nearly constant peak energy with increasing injection currents at the temperature of 300K, the blue shift has been observed at 190K. The results suggest that with more carriers in the quantum wells, carrier screening and band filling still prevail in the partially strain relaxed nanorods. Moreover, when the temperature drops to 77K, the blue shift of both nanorod and planar devices disappears and the optical output power decreases since there are few carriers in the quantum wells for radiative recombination.

INTRODUCTION

III-nitride wide bandgap semiconductors have been widely used in optoelectronic devices, such as blue and green light emitting diodes. While most commercial LEDs are fabricated based on the planar structure, nanostructure light sources have attracted considerable attention as they may have the potential of better light extraction due to the increased sidewall areas and higher radiation directionality due to vertical light guiding effect along the rods [1, 2]. In the past couple years, GaN based nanorod LED arrays have been fabricated and characterized at room temperature [1-6]. Strain relaxation in the InGaN/GaN multiple quantum well (MQW) layers has resulted in a reduced QCSE [3, 7] and thus the peak wavelength is nearly constant with various injection currents [3]. On the other hand, the top-down etching induced sidewall damage has created a large amount of defects and leakage currents that limit the light output power. We previously demonstrated nanorod LED arrays with low reverse bias leakage using the chemical mechanical polishing (CMP) process [8]. For such a nanorod device, the optical output power is balanced between the effects of non-radiative recombination due to sidewall defects (which decrease light output efficiency) and mitigated QCSE due to strain relaxation (which increases internal quantum efficiency). Therefore, the exploration of low-temperature optical behaviors of nanorod LEDs will help identify the correlation between those two factors.

In this work, we first performed Raman scattering measurement to identify strain relaxation in the InGaN/GaN quantum well region of both the nanorod and planar structures. In the next step, optical output power and electroluminescent (EL) spectra at the temperature between 300K and 77K of the nanorod devices were extracted and compared with that of the planar devices.

FABRICATION

The LED epitaxial growth and nanorod array fabrication are similar to those described in our previous work [8]. In short, the GaN based LED sample is grown by metal organic chemical vapor deposition (MOCVD) on a c-plane sapphire substrate. The material structure is composed of a 2μm Si doped n-type GaN layer, a five-period of In0.2Ga0.8N/GaN multiple quantum well (MQW) structure, and a 160nm Mg doped p-type GaN layer. The nanorod array was achieved by performing nanosphere lithography in the LED epi-structure [3]. The nanorod diameter is around 100±10nm and the rod etching depth is about 290nm. The sample can then be employed for Raman scattering measurement to reveal strain properties of the nano-structure. The nanorod array was defined in a mesa pattern with a size 250x250 μm^2. In order to prevent electric shorting between contacts on the p-type and n-type layers, we filled the nanorod spacing by a 300nm-thick SOG (spin-on glass) layer using a reflow process at 130°C for 10 mins. The SOG can also serve to passivate sidewall defects induced during the ICP etching.

Next, the CMP process employing Al2O3 particle slurry with the diameter around 800nm was applied to remove the SiO^2 deposited right on the tips of nanorods. Details of the CMP process are described in our previous research [8]. In the last step, via holes were opened by RIE (reactive ion-etching) to enable the deposition of the n-type (Au/Ti (120nm/10nm)) contact electrodes. Finally a thin metal stack (Au/Ni 5nm/5nm) was coated for current spreading (p-thin layer) and the p-type contact electrode (Au/Ti 120nm/10nm) was then deposited. The schematic diagram of the nanorod LED array is shown in figure 1.

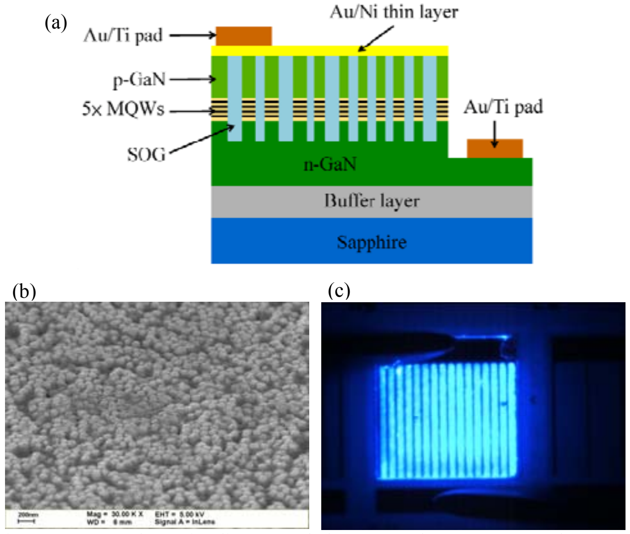

Figure 1. (a) Schematic diagram of the nanorod LED arrays. (b) SEM picture of the nanorod arrays with SiO^2 passivation after CMP process. (c) Light emission of the LED device.

RESULTS

Figure 2 shows Raman spectra of the nanorod epi-structure. For comparisons, the results of the planar LED structure are also shown. Basically, two phonon modes are identified from Raman spectra. The peak near 569 cm^{-1} corresponds to the E_2^H mode of GaN (see figure 2(a)) [9, 10], while the shoulder line around 560 cm^{-1} is the E_2^H mode of InGaN (see the close-up view in figure 2(b)) [11]. The InGaN E_2^H phonon mode of nanorods shows a lower wave number than that of the planar structure. Since the 100nm-diameter nanorods are not small enough for the effect of phonon confinement, the Raman shift toward a lower frequency in the nanorod structure is mainly due to strain relaxation [11, 12].

We next performed EL measurement on the nanorod devices at low temperature. The optical output at the injection currents from 2mA to 20mA is demonstrated in figure 3. From 300K to 190K, the EL intensity of the nanorod LED array increases as the temperature is decreased. At 20mA, the EL intensity increases by 55.4% when the temperature drops from 300K to 190K. It is also observed that within the range of the injection current (2mA to 20mA), the EL intensity shows similar behaviors. The optical intensity increase at low temperature has been widely discussed on planar LEDs by photoluminescent (PL) measurement [13, 14], which is mainly attributed to the frozen of defect states and the corresponding decrease of the non-radiative recombination. For comparisons, the low-temperature EL results of a planar LED with the same mesa area 250×250 μm^2 were extracted and are shown in figure 4. The variation of EL intensity between 300K and 190K is relatively mild for the planar device. At the injection current 20mA, the EL intensity reaches its maximum at 220K and is 4.9% higher than that at 300K. Since the effect of non-radiative recombination is more severe for nanorods due to sidewall etching, the higher percentage increase of EL intensity of nanorods at low temperature is mainly attributed to the frozen of defect states. Furthermore, due to the relaxed strain in the nanorods, as compared with the planar epi-structure, the mitigated QCSE results in a better electron-hole overlap in the quantum wells. Thus the increased carriers (due to less recombination with the sidewall defects) in the quantum wells of nanorods have a better chance to be radiatively recombined than that of the planar devices.

As the temperature is lower than 190K, both nanorod and planar devices show a remarkable reduction of EL intensity. The monotonic decrease of EL intensity with temperature can be explained by the phenomena of carrier overflow [15-17] and low-effective hole concentration [18]. At low temperature, carriers that are designated to be captured by MQW overflow to the cladding layer. They are then either extinguished due to non-radiative recombination or to radiative recombination in the GaN cladding layer. Light emission at 3.3eV at the temperature 77K (see figure 5) supports the above statement. This explanation is also consistent with previous research that carriers escape from the MQW region at low temperature [15, 16]. Also, at low temperature, the activation energy of Mg dopants is increased and thus the effective hole concentration becomes lower [19], leading to less efficient radiative recombination. As a result, when the temperature drops beyond 190K, the effect of EL intensity decreases since carrier overflow and low-effective hole concentration become more significant than the enhancement of radiative recombination.

The effect of QCSE on EL light output at low-temperature leads us to further explore the EL spectra at low-temperature. The EL spectra of a nanorod array and a planar LED at the injection current from 2mA to 20mA are shown in figure 5(a) and (b), respectively. They reveal several interesting phenomena. First, at 300K, the EL spectra of the nanorod LED possess nearly constant photon energy of around 2.76eV, while those of the planar LED are blue shifted from 2.73eV to 2.77eV. The blue shift of planar LEDs is attributed to the carrier screening due to QCSE [3] and band filling of localized states [20].

The behavior of EL spectra of a nanorod LED array at low temperature becomes different from that at room temperature. As the temperature declines to 190K, the EL spectra start to show a blue shift from 2.75eV to 2.78eV with the increase of current from 2mA to 20mA for the nanorod LED array, while the blue shift for the planar LED becomes even stronger. From the EL intensity in figure 3, a large portion of the injected carriers that should have been non-radiatively recombined with defects at room temperature now appear in the quantum wells in nanorod structure. Thus, despite the mitigated QCSE for nanorod LEDs, the effect of band filling still prevails and blue shift can be observed as more injected carriers contribute to radiative light emission [20]. The blue shift of EL peak photon energy with the current increase becomes weaker as we cool the temperature from 190K to 77K. It is intriguing to observe that at 77K, the blue shift of EL spectra vanishes in both nanorod and planar LEDs. The absence of the blue shift indicates that carriers are not effectively captured by MQW, implying carrier overflow at low temperature. As shown in both figure 5(a) and (b), at 77K, light emission at around 3.3eV, which corresponds to band edge transition in the GaN layers, is observed. At such a temperature, the effect of band filling related blue shift becomes less significant.

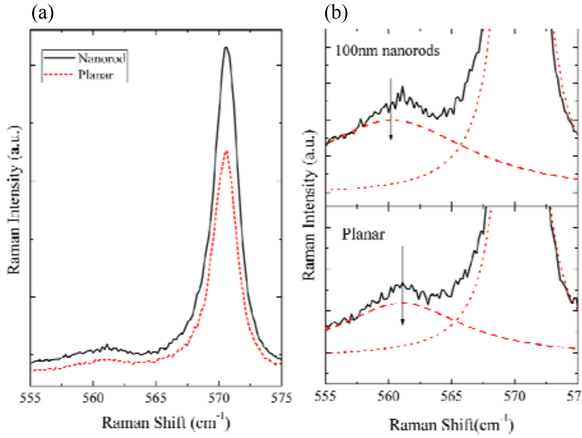

Figure 2. (a) Room temperature Raman scattering spectra of the planar and 100nm nanorod structures (b) close-up view of the E_2^H mode of InGaN

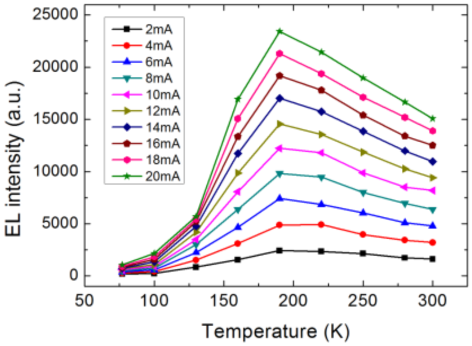

Figure 3. EL intensity at various temperatures of the nanorod LED arrays.

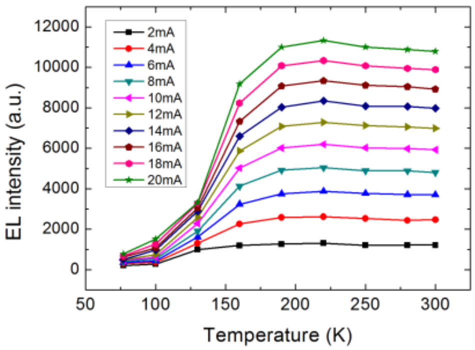

Figure 4. EL intensity at various temperatures of the planar LED.

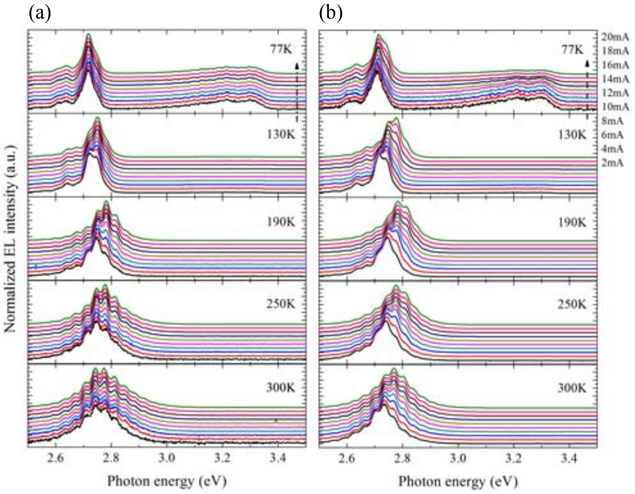

Figure 5. Normalized EL spectra of (a) nanorod and (b)planar LEDs at 77K, 130K, 190K, 250K, and 300K. The injection current ranges from 2mA to 20mA.

CONCLUSION

Low-temperature EL properties of InGaN/GaN nanorod arrays have been explored and compared with planar LEDs. It is found that the optical output of a nanorod LED array increases by 55.4% when the temperature drops from 300K to 190K, while only 4.9% increase to its maximum output power at 220K for a planar LED. We believe the increase is mainly attributed to the suppressed non-radiative recombination and a better spatial overlap of electrons and holes in the quantum wells. Furthermore, as the temperature drops beyond 190K, the optical intensity shows a monotonically decrease for both the planar and nanorod devices, which is mainly associated with carrier overflow to the GaN cladding layers and to the frozen of Mg^+ dopant in the p-GaN layer. Next, while the nanorods show nearly constant peak energy in the EL spectra at various injection currents at 300K, the blue shift from 2.75eV to 2.78eV has been observed at 190K. The results suggest that with the increased number of carriers in the quantum wells (less non-radiative recombination), carrier screening and band filling still prevail in the partial strain relaxed nanorods. Moreover, when the temperature drops to 77K, the blue shift of both nanorod and planar devices disappears as there are fewer carriers in the quantum wells for radiative recombination.

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