

Nano-Patterned Sapphire Substrates-Induced Strain-Related Quantum-Confined-Stark-Effect Behaviors of InGaN-Based Light-Emitting Diodes

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Abstract – This paper reports nano-patterned sapphire substrates (NPSSs)-induced strain-related quantum-confined-stark-effect (QCSE) behaviors of InGaN-based light-emitting diodes (LEDs). From the analysis of the micro-photoluminescence (μ -PL) system, the crystal quality and light output power are continuously enhanced due to the decrease of space between two air hexagonal holes. Compared with the conventional sample without NPSSs, the maximum of the enhanced PL relative intensity is up to 61% through the sample of 100nm-space air hexagonal arrays. With the increase of μ -PL excitation power density, the PL peak energy through the sample of 100nm-space air hexagonal arrays exhibits an offset of only 24.93meV, and the PL peak intensity keeps increasing linearly. As verified by the experimentally measured data, QCSE within MQWs reaches to the weakest state, based on the InGaN-based LED, which is grown upon NPSSs with the space of 100nm, compared with the InGaN-based LED with conventional sapphire substrates (CSSs) due to the higher NPSSs-induced strain, which results in the lower polarization fields.

1. Introduction

InGaN-based LEDs are typically grown along the c-plane sapphire substrates. However, the large lattice mismatch and thermal expansion between the epitaxial GaN film and sapphire substrate result in high threading dislocation densities (TDs) and significant biaxial strain, which causes piezoelectric electrical polarization between heterojunctions. Moreover, the wurtzite crystal structure induces large spontaneous electrical polarization as well [1]. Therefore, the internal quantum efficiency of InGaN-based LEDs is degraded due to the existence of TDs and polarization fields, which result in the spatial separation of the electron and hole wave functions, called QCSE [2].

On the other hand, even if the internal quantum efficiency is close to unity, the external quantum efficiency of InGaN-based LEDs would be poor due to the total internal reflection at the interface between the semiconductor and the outer medium. Considering the refractive indices of GaN ($n=2.5$) and air ($n=1$), the critical angle of total internal reflection for GaN-air interface is merely 23° and it severely limits the light extraction efficiency of InGaN-based LEDs.

Recently, the single growth method by NPSSs has attracted much attention owing to the reduction of GaN

TDs and the enhancement of light output power [3]. Nevertheless, until now, no paper has reported the NPSSs-induced strain effect on QCSE of InGaN-based LEDs. In this paper, the NPSSs-induced strain-related QCSE behaviors of InGaN-based LEDs are reported.

2. Influence of NPSSs-induced strain on QCSE

In order to carry out the experiment, electron-beam lithography and wet-etching technology are used to achieve NPSSs with exact dimensions. The air hexagonal arrays with the diameter of 400nm, depths of about 300nm, and different spaces, varied from 100 to 800nm, are fabricated on the c-plane sapphire substrate. The surface morphology, periodicity, depth, space, and diameter of the accomplished NPSSs are re-examined with the instrument of FEI Dual-Beam NOVA 600i Focused Ion Beam as shown in Fig. 1(a).

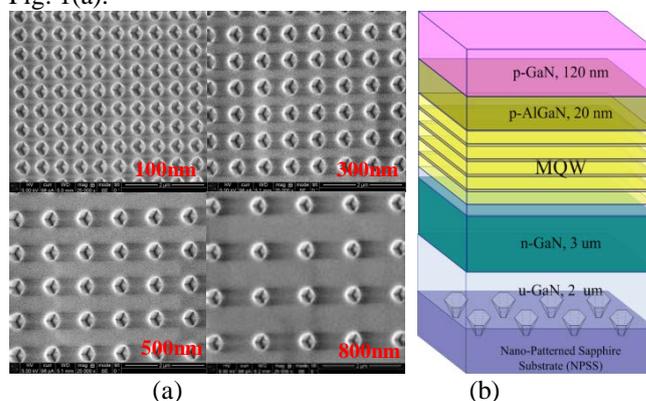


Fig. 1 (a) SEM images of NPSSs with different spaces, varied from 100nm to 800nm. (b) Schematic figure of InGaN-based LEDs with NPSSs.

Next, prior to the growth, substrates are thermally baked at 1100°C in hydrogen gas to remove surface contamination. The InGaN-based LED sample, which consists of a 25nm thick GaN nucleation layer, a $2\mu\text{m}$ thick undoped GaN buffer layer, a $3\mu\text{m}$ thick n-GaN layer, five pairs of InGaIn/GaN multiple quantum wells, a 20nm thick p-AlGaIn electron blocking layer, and a 120nm thick p-GaN layer, is grown on the NPSSs with an atmospheric-pressure metal organic chemical vapor deposition (AP-MOCVD) as shown in Fig. 1(b). The InGaN-based LEDs with CSSs and NPSSs are grown

under the same growth conditions.

To accomplish the accuracy of the measured data, the μ -PL system is equipped with C-Focus system, which corrects microscope focus drift. Fig. 2 indicates the room temperature PL relative peak intensity of the InGaN-based LEDs with the NPSSs, which have different spaces, varied from 100 to 800nm, compared with the sample with CSSs. In the inlet of the figure, the room temperature μ -PL spectrum is revealed. With the decrease of space, both of the crystal quality and light output power are continuously enhanced, and the PL peak wavelength always exhibits a blueshift in contrast with the InGaN-based LED with CSSs. Compared with the InGaN-based LED without NPSSs, the maximum of the enhanced PL relative peak intensity reaches 61% through the sample of 100nm-space air hexagonal arrays, which also has the largest blueshift due to the NPSSs-induced strain [4].

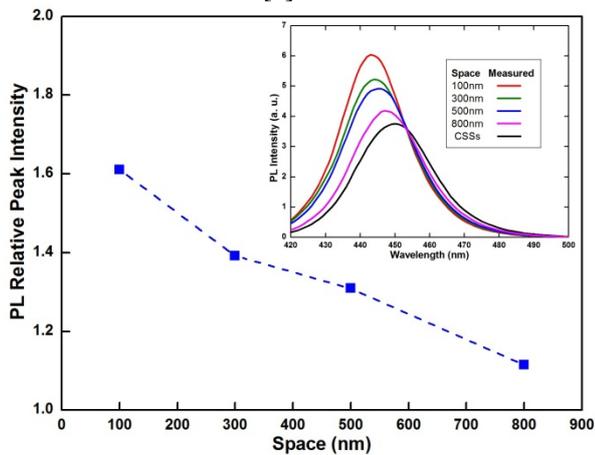


Fig. 2 The room temperature PL relative peak intensity of the InGaN-based LEDs with the NPSSs, compared with the sample with CSSs. In the inlet of the figure, the room temperature μ -PL spectrum is revealed.

To investigate the effect of nano-patterned structures on the QCSE within the InGaN/GaN MQWs, excitation power dependent μ -PL measurement is carried out as shown in Fig. 3 [5]. With the increase of the excitation power density, the PL peak energy through the sample of 100nm-space air hexagonal arrays exhibits an offset of only 24.93meV. The phenomenon of the small offset for the InGaN-based LED, which is grown upon the NPSSs with 100nm-space air hexagonal arrays is a result of the reduced QCSE within the MQWs due to the NPSSs-induced strain.

Fig. 4 shows the PL peak intensity versus excitation power density of the InGaN-based LEDs, which is grown upon the CSSs and the NPSSs with different spaces, varied from 100 to 800nm. With the decrease of space, the continuously linear enhancement of the PL peak intensity occurs from the increase of excitation power density, compared with the InGaN-based LED without NPSSs [6]. Saturation in the PL relative peak intensity of the InGaN-based LED with CSSs under high excitation power is attributed to the significant QCSE within the MQWs.

3. Discussion

From the analysis of the constant excitation power and excitation power dependent μ -PL measurement, there are three functions of NPSSs-induced strain: One is to enhance the PL relative peak intensity. Another is to reduce the

offset of the PL peak energy. The other is to reinforce the linearity of the PL peak intensity while the increase of excitation power occurs. Those behaviors could be reasoned by considering the function of the QCSE within the MQWs. With the decrease of the space, the NPSSs-induced strain becomes larger and larger, which causes the reduction in the function of QCSE within the MQWs. The abatement of QCSE within the MQWs elevated the overlap between electron and hole wave functions, which enhance the internal quantum efficiency of InGaN-based LEDs.

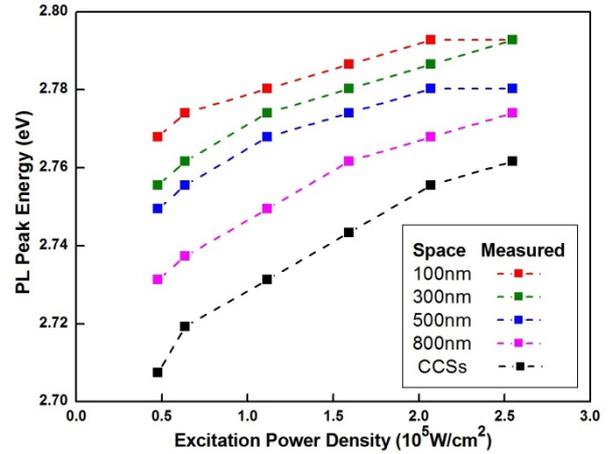


Fig. 3 The room temperature excitation power dependent μ -PL peak energy.

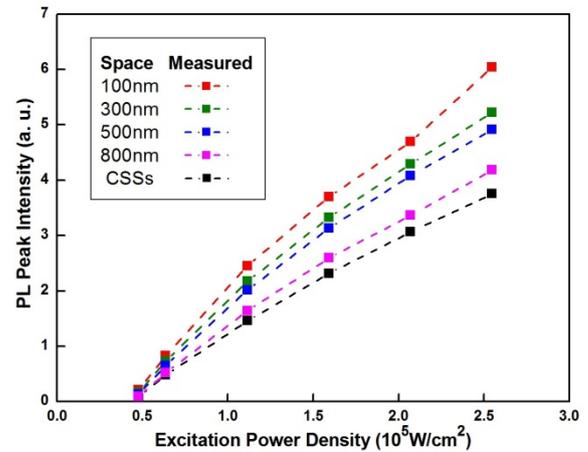


Fig. 4 The room temperature excitation power dependent μ -PL peak intensity.

4. Conclusion

In this paper, the NPSSs-induced strain-related QCSE behaviors of InGaN-based LEDs have been reported. As verified by the experimentally measured data, QCSE within MQWs reaches to the weakest state, based on the InGaN-based LED, which is grown upon NPSSs with the space of 100nm, in contrast with the InGaN-based LED with CSSs due to the higher NPSSs-induced strain, which results in the lower polarization fields.

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