Characteristics of a-Plane Green Light-Emitting Diode Grown on r-Plane Sapphire

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Abstract—**In this work, we have successfully grown a-plane green light-emitting diodes (LEDs) on r-plane sapphire and investigated the device characteristics of a-plane green LEDs. The apparent emission polarization anisotropy was observed and the polarization degree was as high as 67.4%. In addition, the electroluminescence (EL) spectra first revealed a wavelength blue-shift with increasing drive current to 20 mA, which could be attributed to the band-filling effect, and then the EL peak become constant. The current–voltage curve showed the forward voltage of a-plane LED grown on r-plane sapphire substrate was 3.43 V and the differential series resistance was measured to be about 24 Ω as 20-mA injected current. Furthermore, the output power was 240 μW at 100-mA drive current.**

Index Terms—**A-plane GaN, electroluminescence (EL), green light-emitting diodes (LEDs), polarization degree.**

I. INTRODUCTION

RECENTLY, nitride-based light-emitting diodes (LEDs) have been attracting great attention due to the potential in solid-state lighting. However, the conventional c-plane nitride-based quantum wells (QWs) suffer the quantum-confined Stark effect (QCSE) [1], [2], due to the existence of spontaneous and piezoelectric polarization fields parallel to [0001] c-direction. It results in spatial separation of electron and hole wavefunctions in the QWs, which reduces carrier recombination efficiency and causes red-shifted emission. For example, 450-nm blue LEDs can achieve an external quantum efficiency (EQE) of 30%–40%, while records for 520-nm green LEDs merely reach 20% [3]. This is because the higher InN fraction incorporated in multiple quantum wells (MQWs) results in larger QCSE and more serious InN separation. Therefore, eliminating QCSE is one of the essential methods to increase quantum efficiency especially in green LEDs. To avoid such polarization effects, several methods of epitaxial growth of the QWs along crystallographic directions without polarization have been proposed, such as $[10\bar{1}0]$ m axis and $[11\bar{2}0]$ a axis GaN growth using different substrates [4], [5]. Unlike traditional c-plane growth, polarization discontinuities do not occur at the heterointerfaces along either the m- or the a-axis.

Hence, internal electric fields are absent in nonpolar QWs resulting in a flat-band condition. In addition, the nonpolar GaN films exhibit optically polarized spontaneous emission, which is explained by the crystal field oriented along the c-axis of wurtzite GaN and its effect on the valence-band splitting induced by large anisotropic compressive strain within the wells [6]. Once these polarized LEDs are used in liquid crystal display units, a great chance of energy saving is possible since the residual intensity of polarized light passing through a sheet polarizer is stronger than that of unpolarized light. The studies of a-plane InGaN–GaN LEDs have been reported covering emission range from the ultraviolet (UV) to the cyan (490 nm) [7]–[10]. Although green a-plane LEDs have been grown on r-plane sapphire and GaN bulk substrate [11], more detailed device physics of green a-plane LEDs, for example, the shift of emission peak under pulsed bias and the emission polarization anisotropy, are still ambiguous. In this study, a potential green a-plane InGaN–GaN LED on r-plane sapphire has been fabricated successfully. A series of experiments in terms of electrical properties including the electroluminescence (EL) under pulsed bias and polarization characteristics using a stable driven current were performed and detailed analysis will be given in this study.

II. EXPERIMENTS

First, a 30-nm low-temperature GaN nucleation layer was grown by low-pressure metal–organic chemical vapor deposition on r-plane sapphire substrates, followed by the growth of 1-μm-thick high-temperature undoped GaN. Subsequently, a 1.5-μm-thick Si-doped n-GaN with an electron concentration of 3×10^{18} cm^{-3} was grown. The *in-situ* SiN$_x$ nanomask was inserted between undoped GaN and Si-doped GaN for defect reduction in nonpolar a-plane GaN films [12]. Then, ten pairs of MQWs were grown at a temperature of 780 °C and were capped by a 0.17-μm-thick p-GaN layer with a hole concentration of 6×10^{17} cm^{-3}. The structural properties of the as-grown a-plane MQWs were determined using a Bede D1 triple axis X-ray diffractometer (XRD). Then, for EL measurements, 300×300 μm^2 diode mesas were defined by

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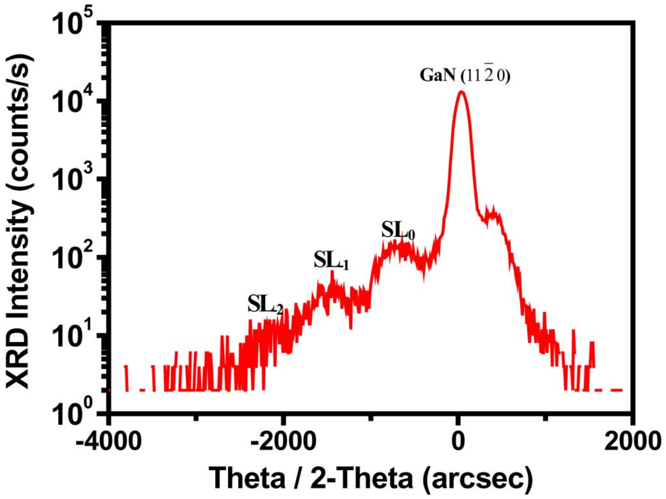

Fig. 1. XRD $\theta/2\theta$ scans for the MQWs grown on a-plane GaN template.

chlorine-based reactive ion etching. Ti–Au (100/200 nm) and Ti–Al–Pt–Au (30/180/40/150 nm) were used as p-GaN and n-GaN contacts, respectively.

III. Results and Discussion

The structural features of InGaN–GaN MQWs are very important for device performance of LEDs, for instance, indium composition and interface. Therefore, the XRD measurement was performed on the a-plane MQWs sample to examine the well width and identify the indium composition. Fig. 1 shows typical $\theta/2\theta$ scans for the InGaN–GaN MQWs grown on the a-plane GaN template. Three clear satellite peaks could be found which indicated good crystal quality of the MQWs. The structural parameters of the QW's well width could be calculated by analyzing the angular positions of the main satellite peaks and the growth time of wells and barriers. The indium composition of the QW was obtained around 20.1%, and the well and barrier thickness was estimated to be 45 and 200 Å, respectively, for the MQWs grown on the a-plane GaN template.

In Fig. 2(a), the room-temperature EL spectra of the a-plane LED was measured at drive currents ranging from 1 to 100 mA. The spectra was measured under pulsed bias (the pulse duty cycle = 10%) to prevent red shift of emission peak due to the heating effect [9]. The EL peak emission first exhibited blue shift with the current increasing and then became constant at 506 nm, which differed from that reported by Detchprohm *et al.* [11]. They reported there was a red shift in the dominant peak as the drive current increased. The heating effect due to CW operation accounts for the apparent red shift in wavelength. In order to identify the quantity of emission shift, we plot the EL peak as a function of pumping current as shown in Fig. 2(b). An initial blue shift (∼127 meV) was observed when the drive current was increased from 1 to 20 mA. No shift in the emission wavelength was observed above 20 mA. Since the QCSE is absent in the a-plane MQWs, the blue shift induced by screening effect is not considerable. Hence, we attributed the initial blue shift with the increase in drive current to the band filling effect as a result of high inhomogeneous indium incorporation [9], [10]. The inset shows the image of a-plane LED chip lightened at 20-mA drive current which emitted pure green light.

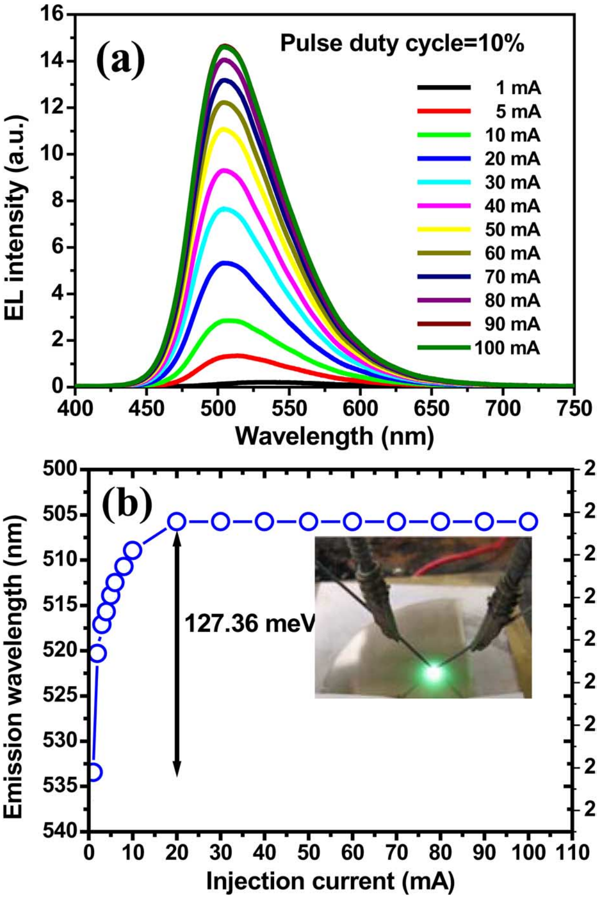

Fig. 2. (a) Room-temperature EL spectra with pulse bias for a-plane green LED. (b) EL peak emission shift as a function of pulse current. Inset shows the image of a-plane LED chip lightened at 20-mA drive current.

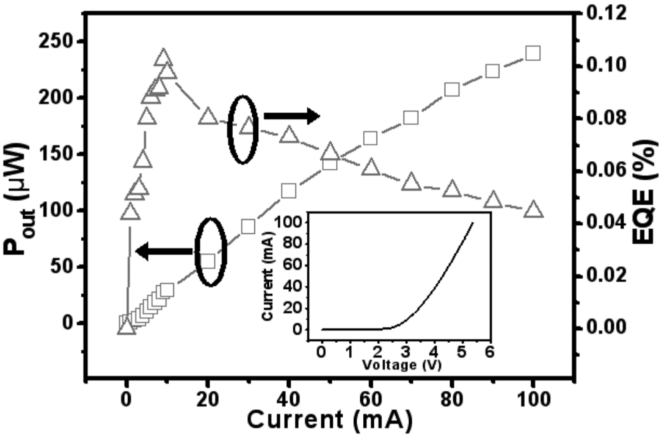

Fig. 3. Output power and EQE as a function of drive current. Inset shows the I–V characteristic of green LED under forward bias.

Fig. 3 reveals the variation of output power and EQE as a function of drive current. The inset shows the current–voltage (I–V) characteristic under forward bias. The I–V curve of the LED exhibits a turn-on voltage between 2–3 V. The forward voltage at 20-mA drive current was 3.42 V and the differential series resistance was estimated to be 24 Ω. The output power

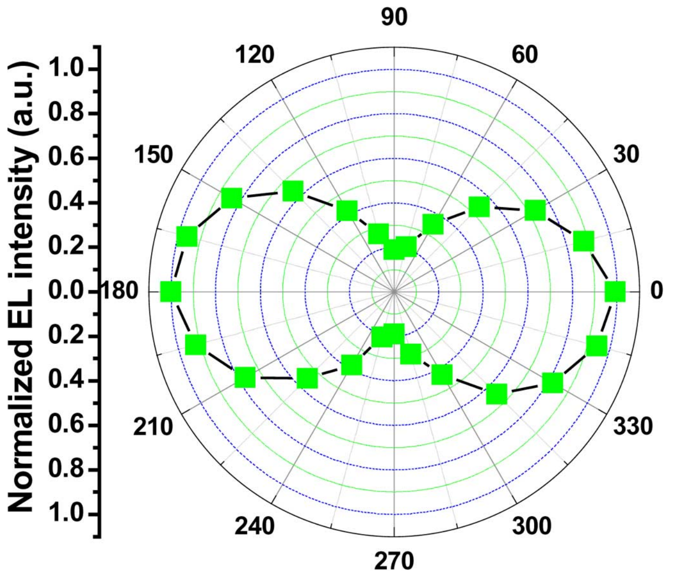

Fig. 4. Variation of EL intensity with angular orientation of the polarizer at 20-mA operation current.

increased linearly as the current increased. The output power was 55 μW at 20 mA and 240 μW at 100 mA, respectively. The EQE first increased as the drive current increased until the maximum value reached 0.1% at a drive current of 9 mA. After that, it decreased gradually as the drive current increased. Compared with the previous report [11], the EQE of our green LEDs exhibited higher value at the same current density of 12.7 $\mathrm{A/cm^2}$. There could be two reasons accounting for the efficiency enhancement. One is the *in situ* SiN_x nanomask is employed to reduce the defect density [12]. The other is the thermal effect is eliminated as a result of pulse operation. The degree of polarization of EL intensity of our devices was analyzed by rotating a polarizer between the polarization angle of 0° and 360° as shown in Fig. 4. The polarization ratio is defined as $\rho = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ is the intensity of light with polarization perpendicular to the c-axis and $I_{\min}$ is the intensity of light with polarization parallel to the c-axis. From Fig. 4, the degree of polarization was estimated to be about 67.4%. Compared with the UV a-plane LEDs $(\rho = 28.7\%)$ [7], the EL polarization degree of green LEDs has a 2.34-fold increase. A similar behavior was observed by Koyama *et al.* [13]. They reported that the PL anisotropic polarization in nonpolar LEDs will gradually increase with the red shift of the emission peak, which could attribute to the large valence band splitting of the $\mathrm{In}_x\mathrm{Ga}_{1\text{-}x}\mathrm{N}$ wells of high x. Consequently, for our green LEDs, the higher polarization ratio compared with that of UV a-plane LEDs could be due to the higher indium incorporation in MQWs.

IV. SUMMARY

In conclusion, we have demonstrated a-plane green InGaN–GaN LEDs grown on r-plane sapphire and investigated their EL characteristics. A series of experiments showed that high indium composition is allowed to incorporate into a-plane GaN which encourage the development of green LEDs along the nonpolar direction. Although the QCSE was eliminated in a-plane green LEDs, the EL spectra still exhibited blue shift with the current increasing due to band-filling effect as a result of inhomogeneous indium incorporation. The EL polarization anisotropy was observed clearly in a-plane green LEDs and the polarization degree had a 2.34 times increase compared with that of UV a-plane LEDs, which could be attributed to large valence band splitting induced by high indium concentration in the wells.

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