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Internal quantum efficiency behavior of a-plane and c-plane InGaN/GaN multiple quantum well with different indium compositions

Te-Chung Wang[1], Tsung-Shine Ko[1], Tien-Chang Lu[*,1], Hao-Chung Kuo[,1], Run-Ci Gao[1], Jenq-Dar Tsay[2], and Sing-Chung Wang[1]**

[1] Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan
[2] Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute, Taiwan

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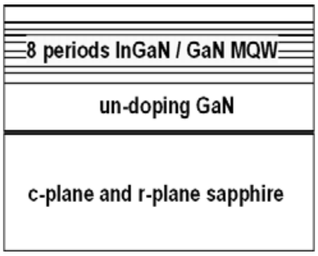
[*] Corresponding author: e-mail timtclu@faculty.nctu.edu.tw, Phone: +886-3-5712121ext56384, Fax: +886-3-5716631
[**] e-mail hckuo@faculty.nctu.edu.tw, Phone: +886-3-5712121ext31986, Fax: +886-3-5716631

We had investigated the potential of non-polar a-plane InGaN/GaN multiple quantum well (MQW) for high indium content blue/green emission. By comparisons of a-plane and c-plane MQW with different indium compositions, we concluded that without piezoelectric field, high indium content non-polar a-plane InGaN/GaN MQW is suitable for green light emitting diode (LED). Furthermore, similar to c-plane GaN InGaN/GaN MQW, the localized state might enhance the performance of a-plane MQW while the indium composition about 24% although the threading dislocation density (TDD) is quite high. On the other hand, the indium phase separation might also occur on *a*-plane InGaN/GaN MQW while the indium composition about 30% so that the photoluminescence intensity of the sample 810 °C low down and spectrum bandwidth broaden.

1 Introduction The radiative quantum efficiency of nitride light emitters grown along [0001] *c* direction is low due to the presence of built-in electric fields, by the spontaneous and piezoelectric polarizations separating the electron and hole spatial distributions to incline the band structure and reduce oscillator strength in the quantum wells [1]. Since the performances of III-nitride devices are limited by the polarization-related internal electric fields, non-polar GaN is currently the subject of intense research due to the potential to improve the internal quantum efficiency (IQE) of GaN optoelectronic devices. To eliminate such polarization effects, growth along non-polar orientations has been respectively explored for $[11\bar{2}0]$ *a*-plane GaN on $[10\bar{1}2]$ *r*-plane sapphire [2] and *a*-plane SiC [3], $[10\bar{1}0]$ *m*-plane GaN on [100] $LiAlO_2$ substrates [4], and direct grown on the a-plane or m-plane GaN substrate [5]. And several kinds of techniques to reduce the defect density were also developed such as TELOG [6], ELOG, insitu-SiN_x [7] etc.

Despite many reports about the advantages of non-polar plane had published, it is still not clear about the internal quantum efficiency behavior for different indium composition/wavelength on the devices. According to the theoretical calculation, without the influence of polar effect, the spontaneous polarization field and piezoelectric field both could be eliminated and it is highly potential to realize high bright LED at blue-green wavelength. For sure the phenomenon, we prepared four groups of samples consist of a-plane and c-plane InGaN/GaN MQW with the same geometric structure and with different indium compositions at different growth temperatures.

2 Experimental First, as Fig. 1 shown, the *a*-plane and *c*-plane GaN templates with 1.5 μm thickness were grown at the same condition by multi-wafer low pressure metal-organic chemical vapor deposition (LP-MOCVD) on *r*-plane sapphire and *c*-plane sapphire substrates using conventional two-step growth technique. Then, eight periods of 45 Å-thick InGaN well/180 Å-thick GaN barrier MQW were grown on both templates. In order to compare the IQE behavior between a-plane and c-plane InGaN/GaN MQW with different indium compositions, we prepared four groups of MQW samples with different growth temperatures followed as 870 °C, 850 °C, 830 °C, 810 °C.



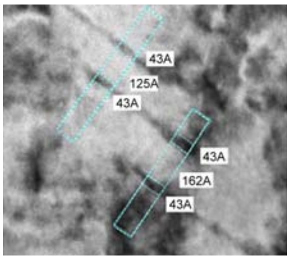


Figure 1 (left) Schematic of MQW on c-plane and r-plane sapphire substrates.
Figure 2 (right) TEM image of a-plane 830°C MQW.

Although many a-plane research results were reported, the indium composition of a-plane InGaN/GaN MQW still could not precisely calculated included elasticity theory. The anisotropic in-plane strain difference between orthogonal crystal axes affects the Poisson ratio more complex. According to TEM image of a-plane 830 °C MQW shown as Fig. 2, we could find the TDDs $(>10^{10}\,\mathrm{cm}^{-3})$ seriously influence the MQW structure. And we calculate the compositions and thicknesses according to the X-ray data of c-plane MQW that grown at the same time. Figure 3 shows the X-ray $\theta/2\theta$ scan of a-plane and c-plane InGaN/GaN MQW, the indium compositions are about 9%, 14%, 24%, 30% specifically as growth temperature decreasing.

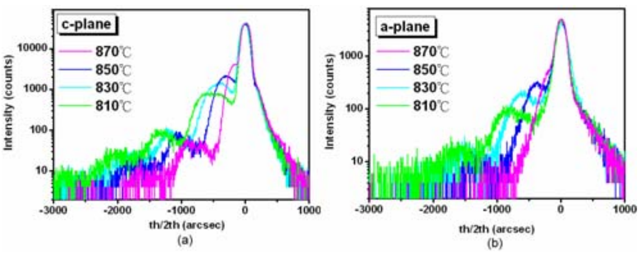


Figure 3 X-ray θ/2θ scan of (a) c-plane and (b) a-plane MQW.

Before the discussion of IQE behavior of a-plane and c-plane MQW with different indium compositions, we have to briefly clarify the main idea how we simply conclude IQE behavior from the theoretical definition of IQE. The IQE of the luminescence generated by carrier recombination is defined by

$$\eta(T) \equiv \frac{I_r(T)}{I_0} = \frac{1/\tau_r(T)}{1/\tau_r(T) + 1/\tau_{nr}(T)} = \frac{1}{1 + \tau_r(T)/\tau_{nr}(T)} \qquad (1)$$

where $I_r(T)$ and I_0 denote the radiative integrated intensity and excitation power, respectively. And $\tau_r(T)$ is the radiative carrier recombination lifetime and $\tau_{nr}(T)$ is the nonradiative carrier recombination lifetime obtained by TRPL measurement, respectively. According to some TRPL reports, usually the carrier recombination lifetime $\tau_{nr}(T) >> \tau_r(T)$ at extreme low temperature (~0 K) so that we obtain the Eq. (2) and (3) from Eq. (1) as:

$$\eta(\sim 0°K) = \frac{I_r(\sim 0°K)}{I_0} \cong 1 \quad \text{at nearby 0 K} \qquad (2)$$

$$\eta(300°K) = \frac{I_r(300°K)}{I_0} = \frac{\tau_{nr}(300°K)}{\tau_r(300°K) + \tau_{nr}(300°K)} \quad \text{at } 300°K \qquad (3)$$

from (2) and (3), we could obtain an inexact result

$$\eta(300°K) \cong \frac{I_r(300°K)}{I_r(\sim 0°K)} \qquad (4)$$

Furthermore, we suppose IQE $\eta(300°K) \propto \frac{I_r(300°K)}{I_r(20°K)}$ for easier stabilize and control the measurement system to study the IQE behavior of MQW with different indium compositions. Finally, we could investigate the IQE behaviors of a-plane and c-plane MQW at 20 K and 300 K by using the ratio of I(300 K)/I(20 K) from temperature-dependant photoluminescence (PL).

3 Results and discussion Room temperature PL (300 K, bold lines) and low temperature PL (20 K, dash lines) spectrums of *c*-plane and *a*-plane MQW grown with different temperature were shown as Fig. 4. In Fig. 4a, the

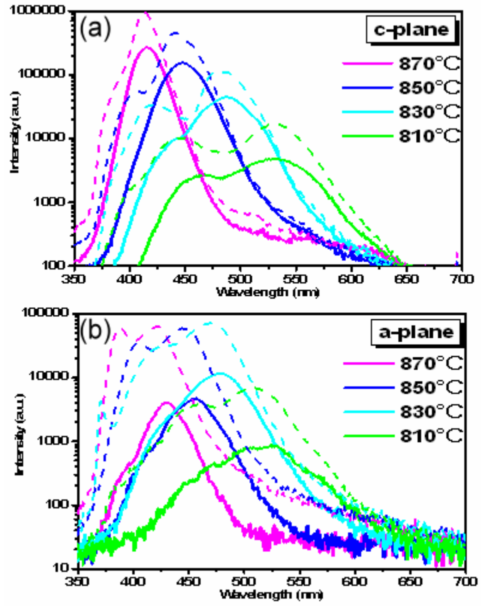


Figure 4 Room temperature PL (300 K, bold lines) and low temperature PL (20 K, dash lines) spectrums of (a) c-plane and (b) a-plane MQW.

PL intensities of *c*-plane MQW main emissions both at 300 K and 20 K obviously decay with indium compositions increasing while growth temperature decreasing. This phenomenon reveals the well-known piezoelectric field on c-plane InGaN/GaN MQW. As the result of the presence of built-in electric fields by the spontaneous and piezoelectric polarizations, the electron and hole are separated in spatial distributions to incline the band structure and reduce oscillator strength in the quantum wells. So that the internal quantum efficiency of c-plane MQW should gradually decrease with indium composition increased.

Furthermore, $\tau_r(T)/\tau_{nr}(T)$ ratio should increase not only with temperature increasing but also indium composition increasing on c-plane InGaN/GaN MQW according to eq. (1). However, in Fig. 4b, the main emission intensities of *a*-plane MQW with different indium compositions at 20 K were almost the same except the sample 810 °C. From Eq. (1), the phenomenon could be explained by stable $\tau_r(T)/\tau_{nr}(T)$ ratio even while indium composition increasing. To compare with the result of c-plane MQW, it is the evidence for the benefit of non-polar InGaN/GaN MQW and we believe that without the polarization field along a-axis, the IQE do not be influenced by strain induced piezoelectric field either. But the PL intensity of the sample 810 °C at 20 K suddenly dropped and the spectrum bandwidth broadened unlike the other a-plane MQW samples. We suggest the phenomenon result of indium phase separation and further discuss later.

According to the above inference, we could investigate the trends of IQE with different indium on different plane by the ratio of I(300 K)/I(20 K). As shown in Fig. 5, to compare the main emission integrated intensities ratio at 300 K versus 20 K, we could find that the ratio I(300 K)/I(20 K) of a-plane MQW is lower than c-plane in each group of samples. It could result in the defect absorption from worse crystal quality, to date, the defect densities of a-plane templates ($>10^{10}$ cm^{-3}) are around two orders more than c-plane templates ($\sim10^{8}$ cm^{-3}). However the ratio I(300 K)/I(20 K) of *a*-plane 830 °C MQW with higher indium is obviously higher than 870 °C MQW and 850 °C MQW with less indium. The phenomenon had also occurred on c-plane InGaN/GaN MQW similarly as so called indium-rich localized state. And the IQE could be enhanced due to an increase in radiative recombination caused by the recombination of excitons localized in indium-rich regions. So that indium localized state might enhance the performance of InGaN/GaN MQW on both planes while indium below 24%. Finally, it is different from piezoelectric filed effect and $\tau_r(T)/\tau_{nr}(T)$ ratio should decrease with indium composition increasing on both plane.

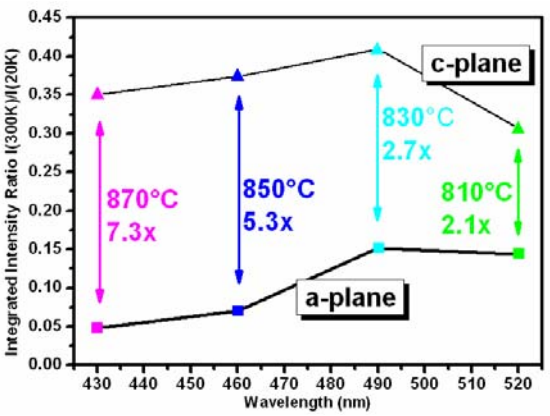


Figure 5 Main emission integrated intensities ratio I(300 K)/I(20 K) of c-plane and a-plane MQW.

On the other hand, the indium phase separation might also occur on *a*-plane InGaN/GaN MQW as c-plane sample while the indium composition go beyond the limits, more than 30%, so that the intensity of the sample 810 °C quickly dropped and spectrum bandwidth broadened. The phenomenon of indium phase separation causes not only the emission intensity drop & broaden but also indium zero order peak of InGaN/GaN MQW X-ray θ/2θ scan drop & broaden as Fig. 3 shown. From Eq. (1), $\tau_r(T)/\tau_{nr}(T)$ ratio should increase while indium composition over 30%. Finally the ratio of I(300 K)/I(20 K) of 810 °C MQW dropped. Nevertheless, we are still exciting about the intensity of a-plane MQW at 300 K in blue-green range because the intensity is close on the intensity of c-plane MQW while the TDD of a-plane MQW is more than two orders. It reveals that non-polar a-plane InGaN/GaN MQW possesses highly potential to realize high bright light emitting device at blue-green wavelength.

4 Conclusion In summary, the mainly effects in InGaN/GaN MQW which are piezoelectric effect on polar c-plane, localization state effect while indium below 24%, indium phase separation while indium more than 30%, and carrier absorption by defect all influence the performance of devices. By temperature-dependence PL of the non-polar a-plane and polar c-plane InGaN/GaN MQW with different indium compositions, those above effects are clarified. And then the ratio of I(300 K)/I(20 K) is a useful factor to investigate the trend of IQE. Finally, we conclude that non-polar a-plane InGaN/GaN MQW is highly potential to realize the high IQE and high bright LED at blue-green wavelength.

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