INTERNAL QUANTUM EFFICIENCY OF (11-22) InGaN/(In)GaN MULTIPLE QUANTUM WELLS

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Temperature-dependent photoluminescence measurements and internal quantum efficiency of InGaN/(In)GaN multiple-quantum-well heterojunctions grown on (11-22) GaN/sapphire templates were investigated. The internal quantum efficiency of the InGaN quantum wells were calculated according to the temperature-dependent photoluminescence and ABC model.

Keywords: Quantum wells, semipolar (11-22) InGaN, internal quantum efficiency (IQE), ABC model.
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1. INTRODUCTION

InGaN/GaN multiple-quantum-well (MQW) based light emittingdiodes (LEDs) and laser diodes (LDs) attract intense interests the performance of nitride based UV and visible LEDs and LDs [1, 2]. However, c-plane InGaN based QW LEDs suffer from the reduction in efficiency at high operating current density, i.e., “efficiency drop” [3–9]. Various possible explanations were proposed as the mechanism for the efficiency droop in high power nitride LEDs as follows: 1) decreased carrier localization at In-rich regions at high injection densities [1]; 2) carrier leakage [3]; 3) electron leakage [4]; 4) large Auger recombination at high carrier density [5, 6]; and 5) junction heating [7]. Specifically, the employment of thin layer of large bandgap material has been reported to have the potential of carrier leakage suppression and thus enhancement of IQE at high current density [8]. All this theoretical analysis have shown that the lattice-matched InGaN is the optimal material candidate for this thin barrier layer attributed to largest bandgap material available with lattice-matching to GaN. In the present work, we determine the IQE of GaInN/GaN MQWs in photoluminescence (PL) measurements; from the dependence of integrated PL intensity on excitation power and temperature dependent relative measurements [9-11].

2. EXPERİMENTS

The MOVPE growth was done in a commercial Aixtron-200/4 RF-S HT reactor using the standard precursors ammonia (NH3), trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindium (TMIn) and triethylgallium (TEGa).On the top of the (11-22) oriented GaN template, 2.8 nm thick InGaN quantum wells were grown at a temperature of about 720°C. The growth temperature for the 8 nm thick GaN barriers was 755°C [12].

3. METHODS AND RESULTS

Temperature dependent PL measurement have been calculated from low temperature to room temperature (14-300K) and the dominant wavelength was ~500 nm (fig.1,2). In comparison to the sample $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ with the $In_{0.2}Ga_{0.8}N/GaN$, a considerable higher PL intensity was observable at the low temperature and at 300K temperature this difference was lower. (fig.3). According to this PL measurements the IQE have been calculated by using a Eq.1 [15].

$$IQE = \frac{I_{Pl}\,(TK)}{I_{Pl}\,(14K)} \tag{1}$$

where, I_{PL} is the PL intensity.

It was observed that at the low temperatures (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs demonstrated a higher IQE to compare with the (11-22) $In_{0.2}Ga_{0.8}N/GaN$ QWs. For instance at 100K the IQE of $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs and $In_{0.2}Ga_{0.8}N/GaN$ QWs were 78% and 64% respectively (Fig.4). However, it can be easily seen that at the room temperature the IQE shows a higher value for $In_{0.2}Ga_{0.8}N/GaN$ QWs in comparison with $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs, 20% and 18%respectively (fig.3,4).

Next, we present a theoretical ABC model. According to the well-known ABC model, there are three main carrier-recombination mechanisms in a bulk semiconductor are Shockley–Read–Hall non-radiative recombination, expressed as An, bimolecular radiative recombination Bn^2, and Auger non-radiative recombination Cn^3, where A, B, and Care the proportional to n, n^2 and n^3, respectively, with n representing the carrier concentration [13].

Then, the IQE can be expressed as

$$IQE = \frac{Bn^2}{An+Bn^2+Cn^3} \tag{2}$$

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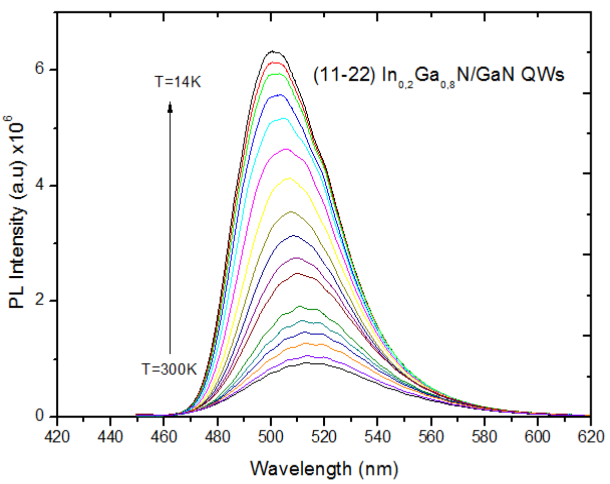

Fig. 1. The *PL* measurements of (11-22) $In_{0.2}Ga_{0.8}N/GaN$ QWs.

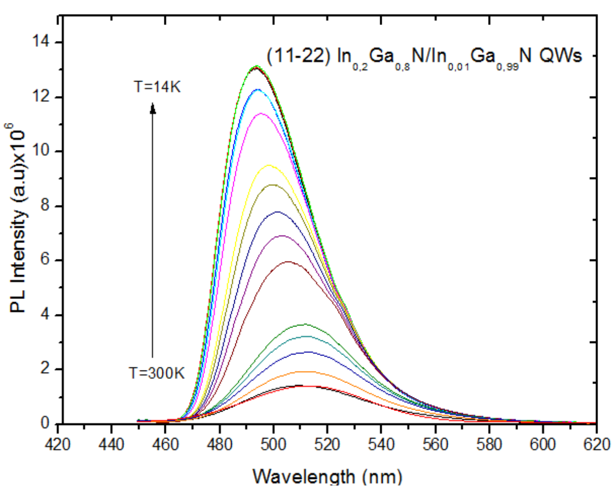

Fig. 2. The PL measurement of (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs.

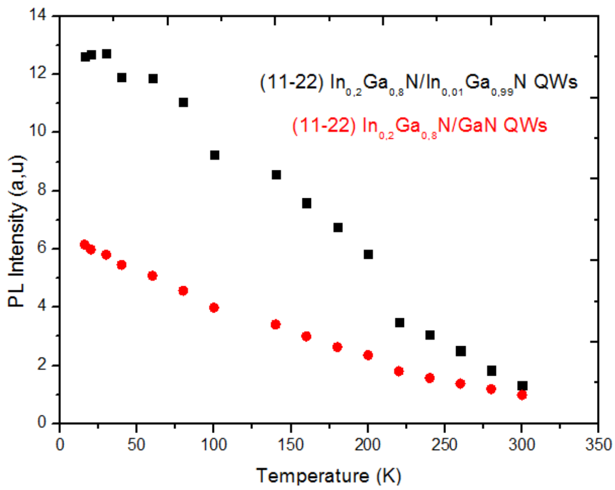

Fig. 3. The dependence of integrated PL intensity on temperature of (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs and $In_{0.2}Ga_{0.8}N/GaN$ QWs.

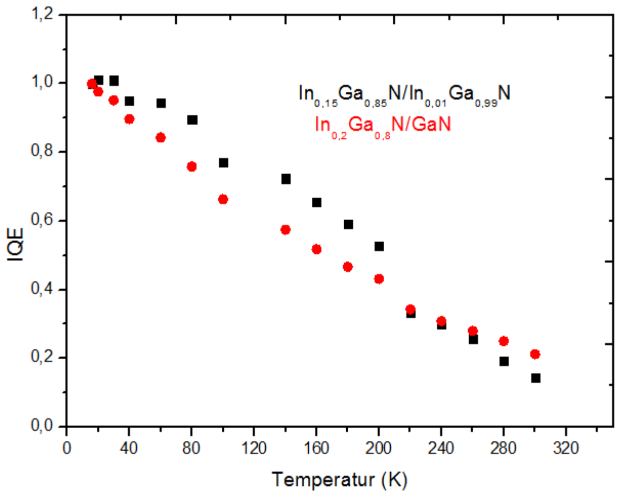

Fig. 4. The IQE of (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs and $In_{0.2}Ga_{0.8}N/GaN$ quantum wells at different temperature.

The ratio of the integrated *PL* intensity I_{PL} and the power of the excitation source power P_{PL} is proportional to the IQE:

$$\frac{I_{PL}}{P_{PL}} = \eta_1 \frac{Bn^2}{An+Bn^2+Cn^3} \quad (3)$$

with η_1 denoting an unknown constant. The carrier generation rate G is proportional to the power of the excitation source. In steady state, the carrier generation rate is equal to the recombination rate, $G = R$ and the IQE at steady state can be expressed as:

$$G = R = An + Bn^2 + Cn^3 \text{ or } G=\eta_2 P_{PL} \quad (4)$$

$$IQE = \frac{Bn^2}{G} \quad (5)$$

with η_2 denoting an other unknown constant, the integrated PL intensity can be expressed as:

$$I_{PL} = \eta_2 Bn^2 \quad (6)$$

where η is a constant determined by the volume of the excited active region and the total collection efficiency of luminescence[14]. Combing Eq.3, 4, 5 and Eq.6, one can derive the relation between the parameters I_{PL} and P_{PL} as below[16]:

$$P_{PL} = A\sqrt{\frac{1}{B\eta_1\eta_2}}\sqrt{I_{PL}} + \frac{1}{\eta_1} I_{pL} + C\sqrt{\frac{\eta_2}{B^3\eta_1^3}}\left(\sqrt{I_{PL}}\right)^3 \quad (7)$$

P_{PL} is a cubic polynomial function of $\sqrt{I_{PL}}$ with the constant term to be zero. By applying again a polynomial fit to the curve of P_{PL} versus $\sqrt{I_{PL}}$, one obtains the value of as the coefficient of the quadratic term with which the absolute value of $\frac{1}{\eta_1}$ *and* the IQE can be calculated according to Eq.2.

The PL intensity of QWs are increased with increasing excitation source power (fig. 5). The IQE was obtained of (11-22) $In_{0.2}Ga_{0.8}N$/GaN QWs and (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs. At lower excitation power, it gets increased by 20 percentage points and reaches almost 100 %. Whereas the semi-polar InGaN/GaN layers show a constant IQE at higher excitation power, the efficiency of the InGaN/InGaN sample seems to decrease again (fig 6).

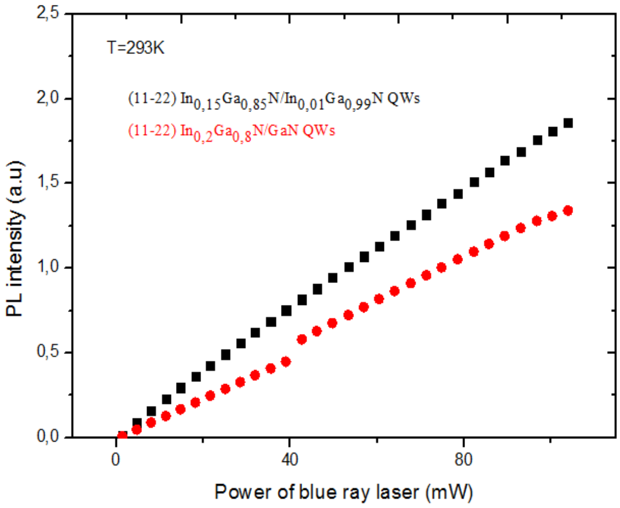

Fig. 5. The dependence of integrated *PL* intensity on temperature of (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ (black) QWs and $In_{0.2}Ga_{0.8}N$/GaN QWs (red).

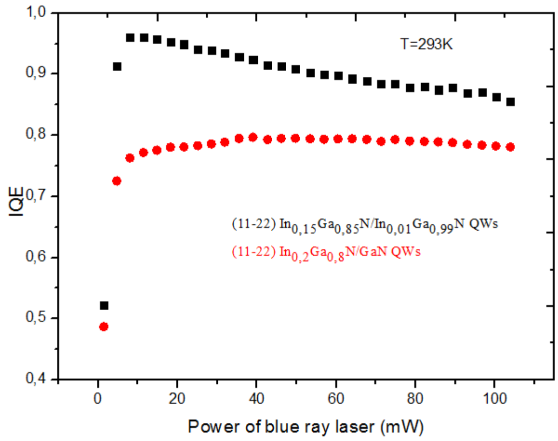

Fig. 6. The IQE at different excitation power.

4. CONCLUSION

Semi-polar (11-22) InGaN/(In)GaN QWs were grown with 5 period 2.8nm InGaN QWs and 8nm barriers. According to the temperature dependent *PL* measurements it was observed that at the low temperatures (11-22) $In_{0.15}Ga_{0.85}N/In_{0.01}Ga_{0.99}N$ QWs demonstrated a higher IQE to compare with the (11-22) $In_{0.2}Ga_{0.8}N$/GaN QWs. Using the ABC model the IQE was obtain of both samples. At lower excitation power, it gets increased by 20 percentage points and reaches almost 100 %. Whereas the semi-polar InGaN/GaN layers show a constant IQE at higher excitation power, the efficiency of the InGaN/InGaN sample seems to decrease again.

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