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Growth and characterization of semipolar InGaN/GaN multiple quantum wells and light-emitting diodes on ($10\bar{1}\bar{1}$) GaN templates

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ABSTRACT

InGaN/GaN MQW samples were grown by metal organic chemical vapor deposition (MOCVD) on **(**$10\bar{1}\bar{1}$**)** oriented GaN templates. Effects of growth temperature and reactor pressure on the photoluminescence (PL) properties were investigated. The emission intensity improved significantly when the QWs were grown at 100 Torr, compared to higher pressure growths. The effect of well-width on the luminescence properties was investigated and an optimum well width of 40 Å was determined. Excitation dependent PL measurements revealed no shift in the PL emission wavelength suggesting the absence of electric field in the quantum wells. Furthermore, LEDs fabricated on **(**$10\bar{1}\bar{1}$**)** GaN templates, emitting at 439 nm, showed no shift in the EL emission wavelength with the increase in drive current, reconfirming the absence of polarization.

INTRODUCTION

Conventional Group-III-nitrides-based light-emitting diodes (LEDs) and laser diodes [1-2], grown along the polar *c*-direction, are characterized by the presence of polarization discontinuities at the heterointerfaces of the quantum wells (QWs) [3]. These gives rise to electric fields and cause band bending, which results in the quantum confined stark effect in the QWs. The consequences of this effect are decreased recombination efficiency, red-shifted emission, and blue shifting of the emission with increasing drive current [4-5]. An alternative means of reducing and possibly eliminating the polarization effects is to grow the devices on semipolar planes. Semipolar planes extend diagonally across the hexagonal unit cell and form an angle with the *c*-plane other than 90˚ and the polarization vector is tilted with respect to the growth direction. This result in reduced polarization effects compared to *c*-plane GaN. Also, for specific strain states on specific semipolar planes, there will be zero net polarization in the growth direction [6]. Therefore, optoelectronic devices grown and fabricated along semipolar direction promise to be an effective means of improving their performance over conventional devices. Recently, growth of semipolar GaN on various substrates has been demonstrated [7-9]. Growth of semipolar GaN on spinel [8] and sapphire [9] substrate was found to be stable under a wide range of growth conditions. Visible LEDs with InGaN/GaN multiple-quantum wells (MQWs) have also been demonstrated along semipolar orientations [7-10]. In this letter, we have investigated the photoluminescence (PL) characteristics of $In_xGa_{1-x}N$/GaN MQWs grown on ($10\bar{1}\bar{1}$) oriented GaN templates. For comparison, the electroluminescence (EL) characteristics of LEDs with semipolar ($10\bar{1}\bar{1}$) oriented $In_xGa_{1-x}N$/GaN MQWs were studied.

EXPERIMENTAL DETAILS

Five periods InGaN/GaN MQW structures were re-grown by metal-organic chemical vapor deposition on semipolar ($10\bar{1}\bar{1}$) GaN templates grown by hydride-vapor phase epitaxy on (100) spinel substrate. Details of the growth and structural properties of the semipolar GaN templates may be found elsewhere [8]. The regrowths were carried out in a Thomas Swan vertical close-spaced showerhead MOCVD reactor and the sample structure consisted of a 1 µm-thick Si-doped GaN layer, followed by 5 periods of InGaN/GaN MQWs with undoped InGaN wells and Si-doped GaN barriers. The structures were capped with 0.3 µm of *p*-GaN for the fabrication of LEDs. TMGa, TMIn, Cp_2Mg, DiSi and NH_3 were used as precursors. Following the growth, the MQW structures were investigated by symmetric high-resolution x-ray diffraction (HRXRD) ω–2θ scans were recorded with a Philips MRD X'Pert PRO triple axis diffractometer with $CuK_{\alpha 1}$ radiation. The In composition in the well and the QW dimensions were obtained from the X-ray ω–2θ scans and the detailed analysis will be published elsewhere. Room-temperature PL measurements were carried out using the 325 nm line of a He-Cd laser with a cw excitation power density of ~ 20 W/cm^2.

RESULTS AND DISCUSSION

Figure 1 shows the PL emission spectrum for different growth temperature of the MQWs. The emission peak red-shifts with the decrease in the growth temperature because of the increased In incorporation in the MQWs. The inset of Fig. 1 shows the dependence of the peak emission intensity and the full-width at half-maximum (FWHM) on the growth temperature. The brightest emission intensity was obtained for a growth temperature of 880 ºC. However, the FWHM increased with the decrease in the growth temperature.

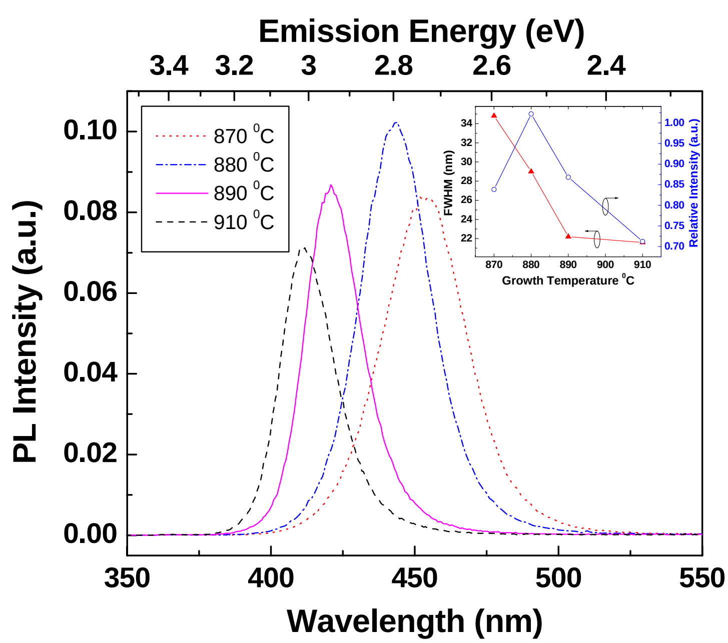

Figure 1. Effect of growth temperature on PL emission characteristic. The inset shows the relative PL emission intensity and the full-width at half maximum for different temperature.

This is attributed to the increased compositional inhomogeneity associated with the increased In incorporation at lower growth temperature [14].

Figure 2 shows the effect of reactor pressure on the PL emission characteristic. The emission intensity increased with the decrease in the reactor pressure. The decrease in the reactor pressure lead to a red-shifted PL emission and this is due to increased In incorporation at lower growth pressure.

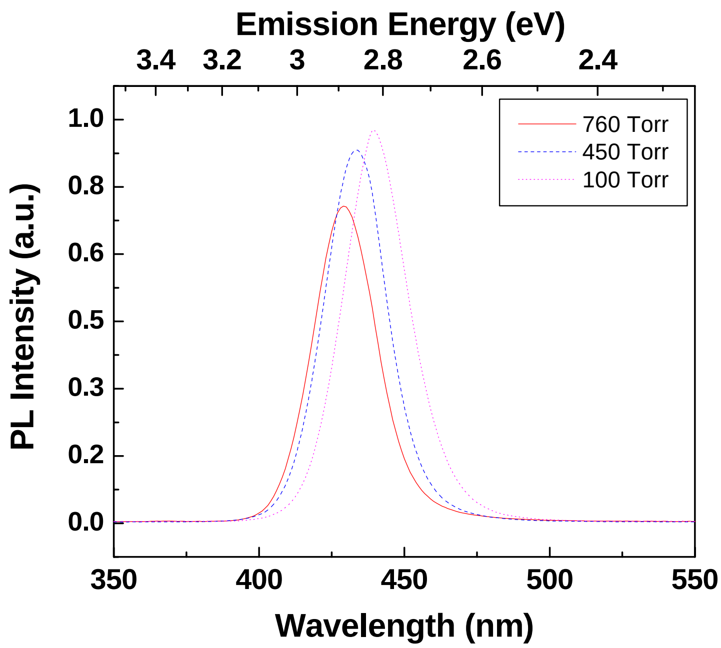

Figure 2. Effect of reactor pressure on PL emission characteristic.

Figure 3 shows the dependence of the PL emission characteristic on the well-width for a fixed In composition. The well-width was varied from 20 Å to 50 Å for a constant barrier-width of 75 Å. The highest emission intensity was observed for a well width of 40 Å and this optimum well-width is wider compared to the optimum well-width for *c*-plane which is ~25 Å [14]. This is due to the reduced polarization fields in the semipolar quantum wells. Similar observation was made by Keller *et al.* in V-shaped *c*-plane InGaN/GaN QWs where the polarization fields were mitigated by employing graded QW structure, thereby reducing the electric-field [15]. The inset of fig. 2 shows the variation of the emission energy and the full-width half-maximum (FWHM) with the well-width. The increase in the emission energy with the decrease in the well-width (≤ 40 Å) is a result of the increased quantum confinement which raised the ground-state energy of the carriers. The increase in the FWHM with the increase in the well-width is thought to originate from compositional inhomogeneity in the QWs. In contrast, the decrease in the emission intensity with the decrease in the well-width is primarily an effect of the increased penetration of the electron wave function into the barriers, causing a decreased probability of carrier recombination in the well [15]. Additionally, the influence of nonradiative carrier recombination due to interface related defects increases with the decrease in the well-width.

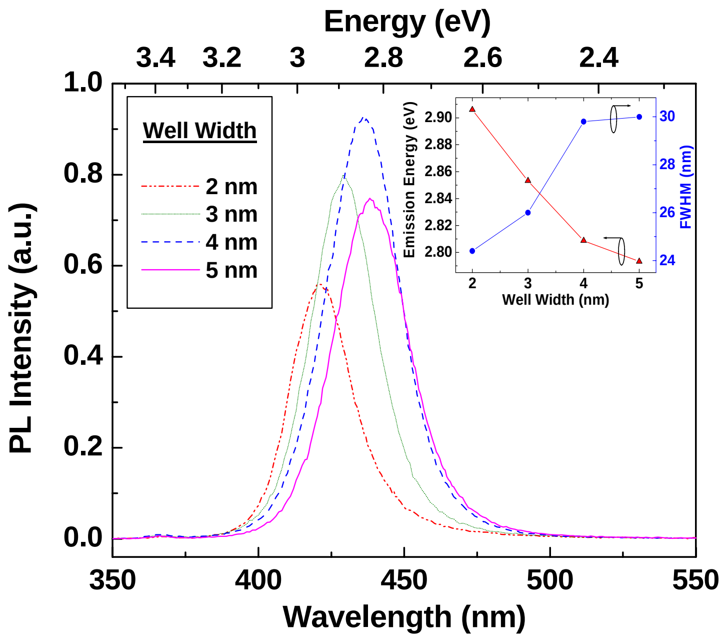

Figure 3. Dependence of well-width on PL emission. The inset shows the variation of the emission energy and the FWHM with the well width.

Figure 4 shows the PL spectra of a MQW structure under different excitation power. The pump power density was changed by more than 10 orders of magnitude. Strong band-edge emission was observed at 439 nm. Unlike *c*-plane InGaN/GaN MQWs of similar composition, there was no evidence of PL peak emission wavelength shift for excitation power density from 3.8 mW/cm^2 to 38 W/cm^2. This suggests the absence of polarization field in the semipolar QWs.

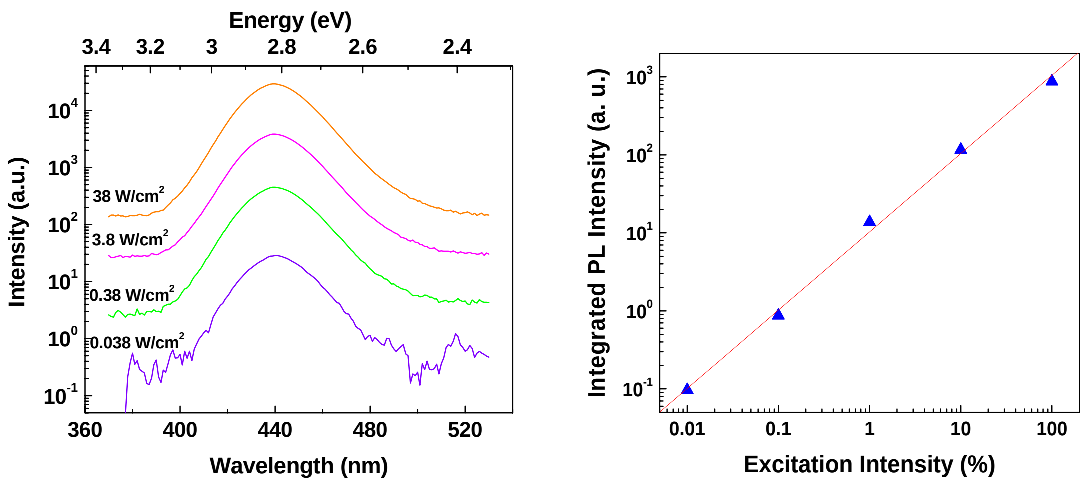

Figure 4. Excitation dependent PL spectra of a $(10\bar{1}\bar{1})$ InGaN/GaN MQW sample.

Also the integrated PL intensity was found to increase linearly with the excitation intensity which suggests free carrier recombination and exciton recombination.

To further confirm the absence of the polarization field, the EL spectrum of the semipolar $(10\bar{1}\bar{1})$ oriented LED was measured as a function of dc drive currents (figure 4). The emission wavelength was 439 nm and there was absolutely no shift in the emission peak when the current was increased from 5 mA to 200 mA. This observation is an evidence of the reduction of polarization fields in the MQWs.

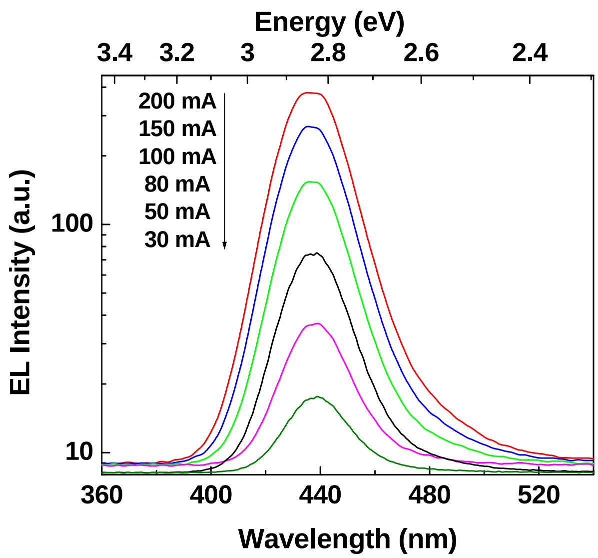

Figure 5. EL emission characteristic of the semipolar $(10\bar{1}\bar{1})$ InGaN/GaN MQW blue LED

CONCLUSION

In conclusion, 5-period semipolar $(10\bar{1}\bar{1})$ InGaN/GaN MQWs and LEDs were grown by MOCVD on $(10\bar{1}\bar{1})$ oriented GaN templates and their PL and EL emission characteristics were investigated. Low pressure growth resulted in improved PL emission characteristics. An optimum well-width of 40 Å was determined from the well-width dependent PL measurement. Excitation dependent PL measurement revealed no shift in the emission peak. EL measurement also revealed drive current independent emission peak suggesting the absence of polarization-induced electric fields inside the semipolar QWs.

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