Broadly tunable cubic phase InGaN/GaN quantum wells grown by metal-organic chemical vapor deposition.

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ABSTRACT

Conventional c-plane wurtzite InGaN/GaN quantum wells are subject to a large internal field that acts to separate electrons and holes and thereby lowers the rate of radiative recombination. This effect is exacerbated for higher indium contents and so may contribute to the lower efficiency of c-plane wurtzite InGaN/GaN QWs when emitting at green and amber wavelengths. In comparison, InGaN/GaN QWs grown in the cubic zincblende phase along the (001) direction are free of such fields and so exhibit recombination lifetimes that are shorter by two orders of magnitude and independent of indium content. Here, we report on zincblende QWs grown by metal-organic chemical vapor deposition at different temperatures. This results in different indium contents and thereby allows tuning of the emission band from blue to yellow. For each indium content, the spectrally integrated emission quenches as the temperature rises. However, the ratio of room temperature to low temperature emission improves for higher indium contents, increasing from 18 % to 34 % as the emission peak is tuned from 2.8 eV to 2.1 eV. This behavior is attributed to the thermal escape of carriers from the QWs playing an important role in the temperature dependent quenching of emission.

Keywords: quantum wells; zincblende; InGaN/GaN

1. INTRODUCTION

The external quantum efficiency of blue-emitting LEDs based on InGaN/GaN quantum wells (QWs) grown in the wurtzite (wz) crystal phase along the c-axis can exceed 80%[1]. This excellent performance is achieved despite the strong (i.e. MV.cm^{-1} scale) polarization fields across the QW which tend to drive the electrons and holes apart, and thereby reduce the rate of radiative recombination[2]. However, the efficiency of this type of LED decreases significantly as the emission is tuned to longer wavelengths by the incorporation of a greater amount of indium in the QW, dropping to ~40% and ~20% for emission in the green and amber spectral regions, respectively[3]. Several reasons for this decrease in efficiency have been suggested including greater alloy fluctuations[3], an increase in the density of trench defects[4], and the strengthening of the polarization field[2]. This last explanation has motivated the study of wz phase devices grown along alternative crystal directions, which either reduces or eliminates the polarization across field the QW. However, these efforts have yet to achieve longer wavelength emitting LEDs that are competitive with their counterparts grown along the conventional c-axis[5].

An alternative approach is to grow the InGaN/GaN QWs in the cubic zincblende (zb) phase with the growth axis oriented in the (001) direction. This both eliminates the field across the QW[6] and brings a further benefit in that less indium needs to be incorporated in the QW to achieve green or amber emission since the bandgap of zb-GaN is 0.2 eV less than that of wz-GaN[7]. Much of the prior work on zb-QWs has used molecular beam epitaxy as the growth technique[8–10] but recently growth methods based on the more commercially-viable metal-organic chemical vapor deposition (MOCVD) technique have been developed[11]. Whilst some tuning of the emission peak of these MOCVD-grown QWs has been demonstrated by increasing the QW width[11], the effect of varying the indium content has not yet been systematically explored.

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In this work, a study of the emission properties of zb-QWs for which the indium content has been controlled by varying the temperature at which they are grown is described. It is demonstrated the QW emission can be tuned across the visible spectrum by this method. Further, it is also demonstrated that the thermal quenching of the emission reduces with increasing indium content, indicating that the thermal escape of carriers from the QWs is a significant process and that it can be mitigated by increasing the QW depth.

2. EXPERIMENTAL METHODS

A schematic of the sample structure is given in Figure 1. The samples were grown by MOCVD on 3C-SiC/Si (001) substrates, where the Si was miscut at 4°, using an Aixtron 1 x 6 in. close-coupled shower head reactor. Each of the three samples comprised: a 44 nm thick nucleation layer grown on the substrate; a 600nm thick GaN layer; a further 200 nm thick non-intentionally doped layer; an underlayer containing a low concentration of indium; and a multiple QW structure, consisting of 5 QWs with a nominal width of 2.5 nm, each topped by a 7.5 nm thick barrier. The samples differed only in the temperature at which the QWs were grown, which was varied between 684 °C and 740 °C.

Temperature-dependent photoluminescence (PL) measurements were obtained using an evacuated, closed-cycle helium cryostat with samples placed on the cold finger. The samples were excited by a continuous wave HeCd laser emitting at a wavelength of 325 nm (3.8 eV) with a power of 26 mW that was focused to a spot size of 80 µm at the sample. The PL emitted was collected and dispersed in a Horiba iHR550 spectrometer before detection by a Horiba Syncerity CCD array. The excitation density at the samples was adjusted by using neutral density filters.

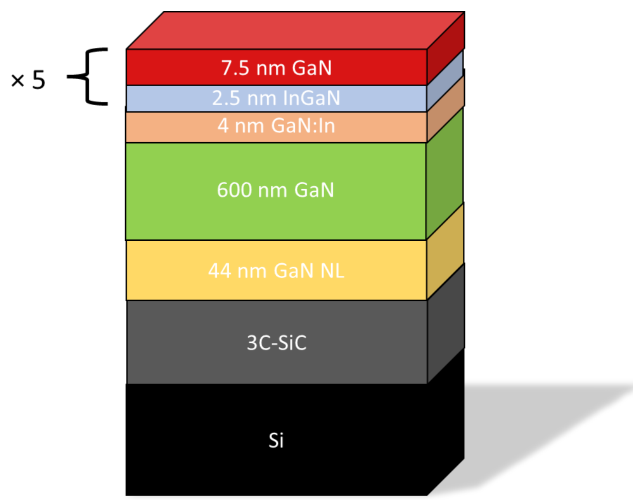

Figure 1. Schematic of the structure of the samples, which differ only in the temperature at which the QW layer was grown.

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3. RESULTS.

Figure 2a compares the emission spectrum at low temperature and 300 K for the QWs grown at 740 °C; a similar comparison for the QWs grown at 684 °C is shown in Figure 2b. At 300K, the sample with the QWs grown at the highest temperature has a peak at about 2.7eV (459 nm), corresponding to the blue part of the visible spectrum. As the QW growth temperature is reduced the emission redshifts such that for the lowest growth temperature the peak wavelength is at 2.1 eV (590nm), corresponding to yellow emission, as shown in Figure 2b. The variation with QW growth temperature of the peak emission energy and full width half maximum (FWHM) of the emission band at 300 K for all the samples is shown in Figure 3a, which illustrates that while the peak emission energy decreases with temperature, the FWHM remains roughly constant. The spectra shown in Figure 2a are smooth and comprise a peak with a low energy shoulder; broadly the same shape of emission band has been reported previously for zb-QWs emitting at a similar wavelength with the shoulder attributed to the impact of stacking faults[11,12]. In contrast, the low temperature spectrum for the QW grown at the lowest temperature (Figure 2b) shows a main peak, centered at 2.1 eV at this temperature; a weaker peak around centered around 2.8 eV and spanning the region from 2.6-3.4 eV, with a shoulder evident at about 3.2 eV. The relative amplitude of the broad peak around 2.8 eV decreases significantly by 300 K, and some emission is now seen between 3.3 and 3.4 eV. The main peak is thus attributed to emission from the QW. A feature similar to the one at 3.1-3.4 eV seen in Figure 2b has been reported previously for zb GaN epilayers[12] and was attributed to the confinement of carriers between closely spaced stacking faults in the GaN. The origin of the broad feature about 2.8 eV is not yet clear, but it could be associated with recombination in the underlayer or could correspond to the 'blue band' reported previously for zb-GaN epilayers and associated with recombination at defects and impurities[13]. This band might also be present in the other samples but is obscured under the main QW peak.

The thermal quenching of the emission is quantified by finding the ratio of the spectrally integrated PL at 300 K and at low temperature, and the variation of this with the growth temperature of the QWs is shown in Figure 3b. This ratio increases from 18% to 34% as the QW growth temperature is decreased and the emission peak position is tuned from 2.8 eV to 2.1 eV. This suggests that the thermal escape of carriers is an important factor in the reduction of emission intensity as the temperature increases since greater energy is required to escape from the deeper QWs.

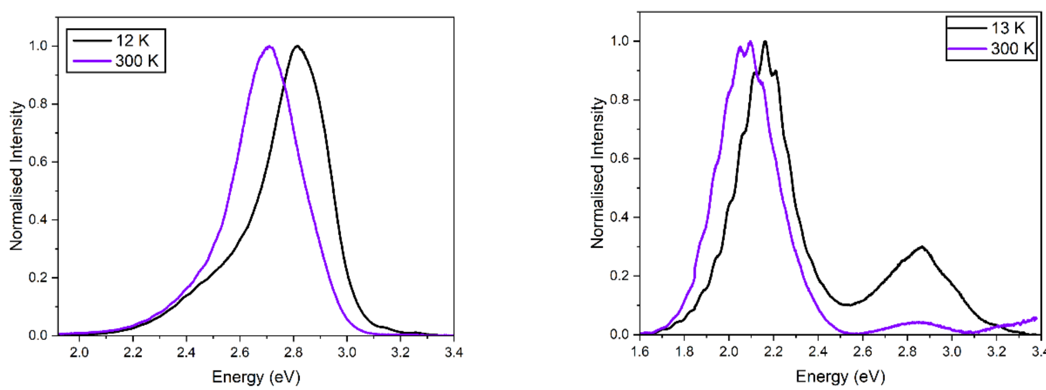

Figure 2. A comparison of the low temperature and 300K PL spectra for QWs grown at temperatures of a) 740 °C and b) 684 °C. The laser excitation power density at the samples was 10 $W.cm^{-2}$.

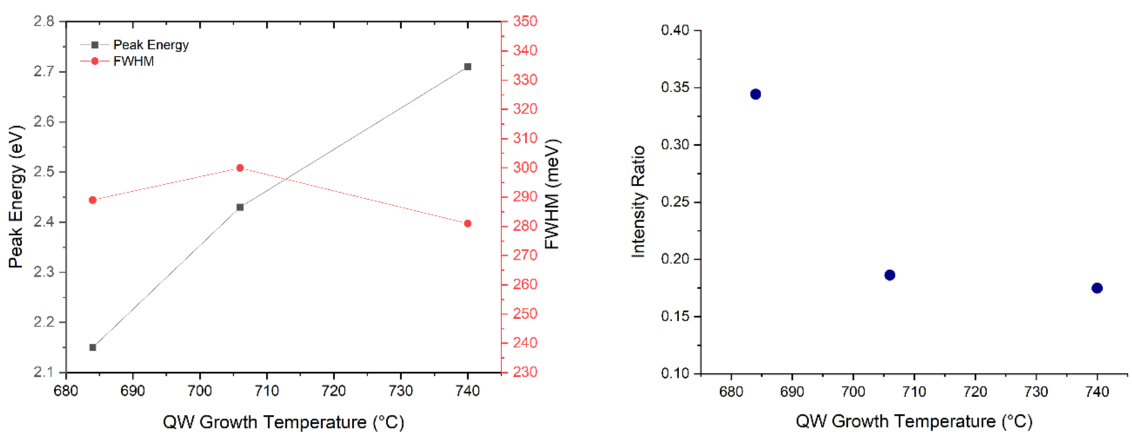

Figure 3. a) Comparison of room temperature QW peak energy and FWHM as a function of QW growth temperature, and b) ratio of integrated QW emission at 300 K to that at 11.5 K for each of the QW growth temperatures.

4. CONCLUSIONS.

The effect of varying the QW growth temperature on the emission spectrum and intensity was investigated for devices grown in the zincblende crystal phase by metal-organic chemical vapor deposition. The peak emission wavelength could be thereby tuned from the blue to the yellow part of the spectrum by reducing the QW growth temperature from 740 °C to 684 °C. Moreover, the thermal quenching of the emission was also reduced by decreasing the growth temperature, suggesting that thermal escape is an important factor determining the radiative recombination efficiency in zincblende InGaN/GaN QWs.

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