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Temperature dependent photoluminescence of highly strained InGaAsN/GaAs Quantum Well (λ=1.28-1.45 μm) with GaAsP strain-compensated layer

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1. Introduction

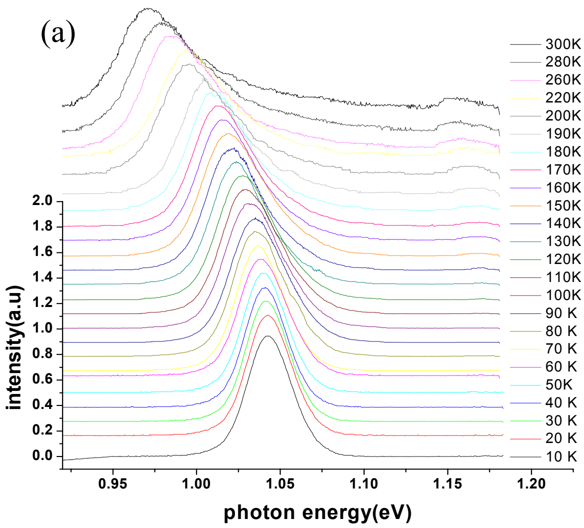
The InGaAsN quaternary alloy system currently attracted a large interest in the recent years due to their capability to obtain emission on GaAs substrate in the 1.3–1.55 μm wavelength range.[1-2] The large conduction band offset leads to the improvement of temperature performance compared to conventional InP-based materials, and the GaAs system provides high performance AlGaAs/GaAs DBR mirrors and allows the use of well established oxide-confined GaAs-based VCSEL manufacturing infrastructure. However, GaInAsN is a very challenging materials system from a growth point of view: (1) a higher indium composition would increase the compressive strain to a critical point for the structural quality of the layer undulation of the interfaces, beginning of the plastic relaxation;[3] (2) it is difficult to incorporate N into the InGaAs QW and the introduction of N into QW decrease the lattice parameter of the alloy therefore, the strain of the layer and to shift its emission wavelength to longer wavelength. However, larger N concentrations are found to broaden the luminescence linewidth of the alloys, increases the non-radiative (monomolecular and Auger) recombination and thus lower the material gain and increase transparency carrier density.[4-5] Recently, Yeh *et al.* found that that incorporation of higher nitrogen content than 0.7% in InGaAsN significantly deteriorated the laser characteristics and temperature of laser performance.[4] In this work, we present the detailed analysis of temperature and power dependent photoluminescence of a 1.45 μm emitting InGaAsN QW and a 1.3 μm InGaAsN-GaAs-GaAsP SC-QW with less nitrogen contend grown with identical conditions. High resolution TEM was performed to understand the crystal and the interface quality of InGaAsN-GaAs with different Nitrogen content.

2. Experiments

All structures reported here were grown by utilizing low pressure MOCVD. The active regions are all based on the 60 Å $In_{0.4}Ga_{0.6}As_xN_{1-x}$ QW, sandwiched with GaAs-GaAsP materials. The In and N contents of the InGaAsN material were determined from calibration samples measured by photoluminescence (PL), x-ray diffraction and secondary mass ion spectroscopy measurements. The details of growth optimized can be found in ref. 6. The surface morphology of the sample was smooth and mirror-like, exactly like that of a GaAs homo-epitaxial layer. Cross-sectional TEM thin foils were prepared by mechanical polishing followed by argon-ion milling. Measurements of the optical luminescence are conducted by utilizing an Ar^+ laser with an emission wavelength at 514 nm and a thermal-electrical cooled InGaAs detector.

3. Results and Discussion

Figure 1 shows the temperature dependence PL spectra of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW and $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW. At 10 K, the PL emission of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW is at 1.042 eV with FWHM of 30 meV. A single peak and symmetrical structure was observed in PL spectra when the temperature was below 190 K. As temperature increased above 190 K, the PL spectra thermal broadened with lower intensity as expected. For $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW, two main emission peaks were observed at 0.882 eV and 0.909 eV. As the temperature increasing, the high energy peak persisted around 0.905 eV while the low energy peak continues red-shift to lower energy. In addition, the intensity of high energy peak decreases much faster with temperature than the low energy peak and the high energy shoulder of the 0.9 eV band shrunk with temperature. The PL emission of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW and low energy band of $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW both showed the typical behavior of band-gap emission: a decrease of the emission energy with increasing temperature due to thermal expansion, which is well described by the Varshni model.[7] The high energy peak of $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW shows little dependent on temperature.



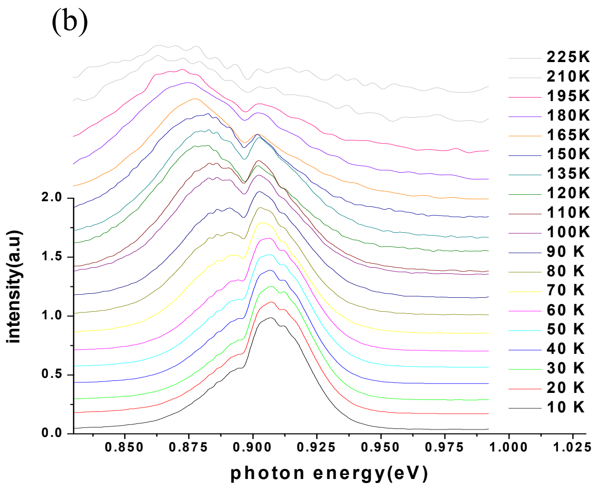


Fig. 1 Temperature dependent PL spectra of (a) $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW (b) $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW

We suggest the high energy emission originated from quantum dot-like structure. The high emission energy of 0.9 eV band may due to the quantum-confined induced shift while the persistent of the high energy peak with temperature can be understood by the less electron-phonon interaction in the dots-like structure. As temperature rise, the electron in the dots-like region thermal escape into the quantum well and caused the thermal quench the PL intensity.

To further exploring the emission properties, excitation power dependent PL measurement was performed (not shown here). The line shape and the FWHM of the PL emission of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW were independent of the laser power at 10 K. For $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW, the 0.88 eV band dominated the spectrum at low excitation. As excitation power increasing, the 0.9 eV band appeared and dominated the spectrum gradually. This result indicates the 0.9 eV band more apparent at higher carrier density. The effective carrier density decreases at higher temperature due to carrier thermal escape and results in the quench of the 0.9 eV band, as shown in fig. 1(b).

In order to directly investigate the crystal quality and interface of quantum well, we examined the cross section of the single quantum well by high resolution transmission electron microscopy. A very clear interface of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW on atomic-layer level was obtained, as shown in fig. 2(a). No dislocations were observed in low magnification images, either. This TEM observation shows that the structural quality of the $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW is similar to that of conventional Ⅲ-Ⅳ materials. For $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW, the rough interface shows a deteriorated material quality, as indicated in fig. 2(b). In addition, small dark regions were formed in the interface with a size of about 10 nm.

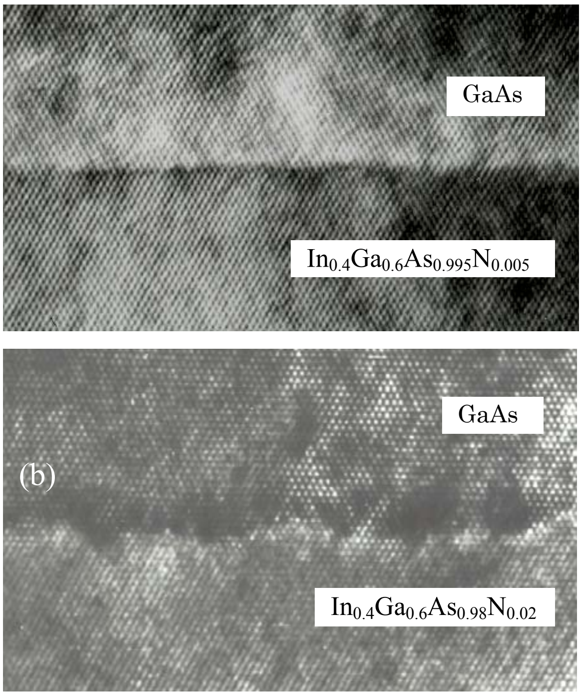


Fig. 2 HRTEM image of (a) $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW (b) $In_{0.4}Ga_{0.6}As_{0.98}N_{0.02}$ SQW

4. Conclusion

We correlate the temperature dependent PL and power dependent PL results with HRTEM measurement on $In_{0.4}Ga_{0.6}As_xN_{1-x}$ SQW grown by MOCVD. The $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ SQW shows sharp interface and good emission properties which were attributed to band to band emission. For high nitrogen content (> 2 %), the interface is rough and was observed with dark island regions. Two emission peaks was observed where the high energy peak might be due to the dots-like emission from the dark island while the lower energy peak from the band to band transition.

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