Bandgap control for the lattice-matched InGaAs/InAlAs/InP single quantum wells

Y Wang1,2,3, X Z Sheng1, Q L Guo2 and B L Liang3

1 School of Science, Beijing Jiaotong University, Beijing 100044, P. R. China
2 College of Physics Science & Technology, Hebei University, Baoding 071002, P. R. China

E-mail: hbuwangying@126.com

Abstract. In0.53Ga0.47As/In0.52Al0.48As single quantum well (SQW) grown by molecular-beam epitaxy on the InP (001) substrate is investigated by using photoluminescence (PL) spectroscopy and time-resolved photoluminescence (TRPL). At the low temperature of 8 K and excitation intensity of 1 W/cm², the emitting wavelength of QWs shifts from 1387 nm to 1537 nm when the well width increases from 5 nm to 50 nm, approaching the emitting wavelength of bulk In0.52Al0.48As. The emitting wavelength of QWs can be flexibly tailored by varying the thickness of the InGaAs layer.

1. Introduction

The In0.53Ga0.47As/In0.52Al0.48As heterostructures lattice-matched to InP (001) substrate have been studied extensively due to their unique properties.[1-3] The InGaAs/InAlAs QW heterostructures, including single-quantum well, multiple-quantum wells, and superlattices, have special advantages for applications in long-wavelength optical communications as well as high-speed electronic and photonic devices.[4] First, InGaAs has a high electron mobility and a high peak velocity which make the material very attractive for high-speed devices.[5] Second, The InGaAs/InAlAs quantum well (QW) structure are very suitable for optical communication applications because they allow the emission wavelength to be shifted from the 1.65 μm (bulk InGaAs lattice-matched to InP) to the 1.3-1.55 μm region by varying well thicknesses. [6-8] Third, InGaAs/InAlAs system which has a large conduction-band offset enables a strong electron confinement, and subsequently a high-temperature stability and a high-speed modulation capabilities, making the system very attractive and suitable for quantum cascade lasers, inter-subband detectors, and devices based on nonlinear optical properties. [9, 10]

In this experiment, we have fabricated lattice-matched In0.53Ga0.47As/In0.52Al0.48As/InP quantum well with different well width of 5 nm, 15 nm, 25 nm and 50 nm by molecular beam epitaxy (MBE) to tailor the bandgap of the heterostructures. The photoluminescence (PL) and time-resolved photoluminescence (TRPL) were performed to investigate the effect of well width on PL emission.

2. Experiments

The QW samples were grown by a solid-source molecular beam epitaxy on semi-insulating InP (001) substrate at a growth temperature of 515 °C. The samples consist of a lattice-matched In0.53Ga0.47As single quantum well (SQW) with nominal well width of 5 nm, 15 nm, 25 nm and 50 nm by molecular beam epitaxy (MBE) to tailor the bandgap of the heterostructures. The photoluminescence (PL) and time-resolved photoluminescence (TRPL) were performed to investigate the effect of well width on PL emission.
effect, a 3 nm lattice-matched InGaAs layer was growth on the top for all the QW samples. For reference, one InGaAs layer only sample and one InAlAs layer only sample were also grown to calibrate the composition and to measure the bandgap of bulk InAlAs and InGaAs. After growth, all samples show a mirror-like surface. We did not observe haziness and cross-hatching under a Normaski microscope.

Then the QW samples were characterized by photoluminescence (PL) and time-resolved photoluminescence (TRPL). For the PL measurements, the samples were mounted in a closed-cycle cryostat and excited by a 532 nm laser. The laser beam is focused to a spot of ~20 μm in diameter. The PL signal was detected by a liquid nitrogen cooled CCD detector array attached to a 50 cm Acton spectrometer. The TRPL was measured by a PicoHarp 300 time-correlated-single-photon-counting (TCSPC) system with a NKT super-continuum pulse laser as the excitation.

3. Results and discussions

3.1. Low temperature photoluminescence

![Figure 1. Schematic of QW structures](image)

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![Figure 2. (a) and (b) are PL spectra for InGaAs bulk, InAlAs bulk and all the QW samples obtained at 8K with an excitation intensity of 1 W/cm²](image)

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Figure 2 shows PL spectrum for InGaAs bulk, InAlAs bulk and all the QW samples measured at 8 K with a laser intensity of 1 W/cm². From Figure 2(a), the bandgap of InGaAs material is estimated to be 0.772 eV and the bandgap of InAlAs material is 1.562 eV. It means that the total band offset between InGaAs and InAlAs is 0.79 eV. Figure 2(a) also shows that the PL linewidth (Full Width at the Half Maximum, FWHM) of two reference samples are 6.3 meV and 24.3 meV, respectively. Meanwhile
their PL spectra show symmetric Gaussian profile. [11] Under the same excitation intensity, the emission of InAlAs bulk material is stronger than that of the InGaAs bulk. It is likely that the radiative recombination centers in the interface between the InAlAs layer and InP (001) substrate have better confinement.

Figure 2(b) also shows that the emission peaks are quite different for the QW of different width. The PL peaks at 0.894 eV, 0.829 eV, 0.824 eV and 0.807 eV, are attributed to the $e_1$-$h_1$ excitonic transition between the first electron level and the first heavy hole level in the 5 nm, 15 nm, 25 nm and 50 nm InGaAs/InAlAs QW, respectively. It can be observed that the QW PL peaks gradually approach to that of the InGaAs bulk when the QW width increases from 5 nm to 50 nm, but they stand far away from PL peak of the InAlAs bulk. It means that the carriers corresponding to the $e_1$-$h_1$ excitonic transition in InGaAs/InAlAs QWs have very strong confinement while we flexibly tailor the thickness of QWs. The PL intensity of the four QW samples have the same order of magnitude, but FWHM of the emission peak increases with decreasing the well width, being 6.60 meV, 11.10 meV, 8.44 meV and 13.69 meV for 50 nm, 25 nm, 15 nm and 5 nm QWs, respectively. It can be explained that the QW samples have better performance of interface roughness. The FWHM of the PL peak is related to the fluctuations in the confinement potential of InGaAs/InAlAs interface. Among the samples, the FWHM of 25 nm QW shows a slight deviation, maybe due to the fluctuation of the growth condition.

In order to test the quality of the QWs, we have measured the excitation-intensity dependent PL. Figure 3 shows the FWHM as a function of the laser excitation intensity. It can be seen that the FWHM of 15 nm, 25 nm and 50 nm QW have almost no change when the excitation intensity is less than 100 W/cm$^2$. But the FWHM of 5 nm QW exhibit a decrease. It means that the emission of 5 nm QW is strongly affected by the fluctuations of InGaAs/InAlAs interface. For the 5 nm QW, more excitons are trapped at the interface, resulting in a broad spectrum even under the low excitation intensity at low temperature.

![Figure 3](image3.png)  
Figure 3. The FWHM of PL spectra as a function of excitation intensity

![Figure 4](image4.png)  
Figure 4. TRPL spectra of all QW samples

### 3.2. Time-resolved photoluminescence

To investigate the QW emission decay time, TRPL measurement was carried out at 77 K using a TCSPC module with a NKT super-continue pulse laser as the excitation. The PL decay curve detected at the peak wavelength of 1385 nm, 1500 nm, 1515 nm, and 1540 nm, respectively. As shown in Figure 4, the rise time of the transient photoluminescence almost coincides for all samples. Therefore, the carrier capture and relaxation in the QW samples are independent of the well width. Through
single exponential fitting, the lifetime is determined to be 0.431 ns, 1.144 ns, 1.854 ns and 2.154 ns for the 5 nm, 15 nm, 25 nm and 50 nm QWs, respectively. The PL decay time increases monotonically with increasing emission wavelength, which corresponds to the well width. This result can be explained that the exciton wave function in a thinner QW layer has a better overlap due to the carrier localization. As a result, the oscillator strength increases, leading to a decrease of exciton lifetime.

4. Conclusion
In conclusion, we have fabricated the lattice-matched InGaAs/InAlAs QW samples on InP (001) substrate. The photoluminescence and time-resolved photoluminescence are investigated for all samples. The FWHM of PL spectrum indicates that all samples have good crystal quality, and the emission from thicker QW is less affected by the fluctuations at the InGaAs/InAlAs interface. The PL decay time of InGaAs QW increases monotonically with increasing emission wavelength, indicating that a thinner well has a better exciton oscillator strength.

Acknowledgement:
This research is supported by the “Hebei Province 100-Talents Program” (Grant # E2013100013), the Natural Science Foundation of Hebei Province (Grant # A2012201013), and the Natural Science Foundation of China (Grant #61575016).

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