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Optical Characterization of InAs Quantum Dots Fabricated by Molecular Beam Epitaxy

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Optical characterization were performed on patterned InAs dots based on InAs/InAlAs hetero-structure and the self-assembled InAs dots grown on GaAs. Unexpectedly high peak energy shift in photoluminescence (PL) and cathode luminescence (CL) was observed from InAs dots based on InAs/InAlAs heterostructure. PL results of self assembled InAs dots grown on GaAs also showed unexpectedly high peak energy. CL spectra from each single InAs dot suggested luminescence from highly strained dots contribute to shift the average luminescence peak towards high energy. According to these optical characterization, the inherent strain distribution is found to play an important role in the analysis of luminescence from dots of strained material systems.

1. INTRODUCTION

Recently, several fabrication techniques of quantum dots have been proposed such as selective growth technique[1,2], selective etching thechnique[3] and self-assembled formation technique[4-6]. However, effect of strain on quantum dots in lattice mismatched system has not so far been discussed, although it is important to investigate the electronic and optical properties of InAs quantum structures which is interesting material system for high temperature operation of quantum effects [7]. This paper shows the cathode luminescence (CL) and photoluminescence (PL) measurement results of the InAs quantum dots fabricated by selective etching and self-assembled island formation technique.

2. FABRICATION OF InAs DOTS

2.1 InAs dots based on InAs/InAlAs hetero-structure

InAs dots based on InAs/ $In_{0.52}Al_{0.48}As$ hetero-structure was formed by wet chemical etching on InAs quantum well structures grown by molecular beam epitaxy (MBE). InAs well thickness of 20Å - 40Å was chosen, since the critical thickness of the InAs in $In_{0.52}Al_{0.48}As$/ $In_{0.53}Ga_{0.47}As$ system is known to be ~45Å. The typical structure consists of 6000Å of $In_{0.52}Al_{0.48}As$ buffer layer grown on a semi-insulating InP substrate, 20Å of InAs quantum well, 1000 Å of undoped $In_{0.52}Al_{0.48}As$ barrier layer, and 50Å of $In_{0.53}Ga_{0.47}As$ cap layer as illustrated in Fig.1. Then, the column-shaped mesa structure are fabricated by the conventional optical lithography and the wet chemical etching. The lateral size of InAs dots were controlled by changing the etching time. In this study, the InAs dots with the nominal lateral size of 1000Å, 2000Å, 4000Å and 1.6μm were investigated. The uniformity of the column-shaped pattern was reasonably good. For example, measured average lateral size and standard deviation of nominally 1000Å dots were 964Å and 12.7, respectively.

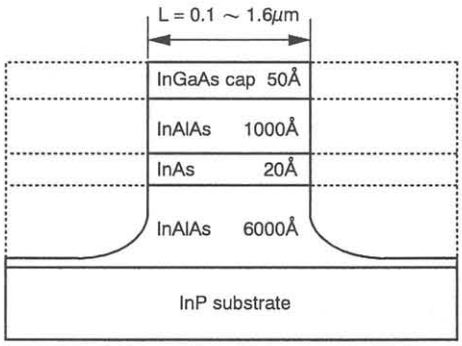


Fig.1 Schematic diagram of InAs quantum dot structure.

2.2 Self-assembled InAs dots grown on GaAs

GaAs/InAs system is known to include about 7% of lattice mismatch. Recently, growth of self-organized InAs dots on GaAs by Stranski-Krastanow growth mode have been reported [4-6]. In this study, InAs dots were grown on (100) GaAs layer at substrate temperature of 480°C. During

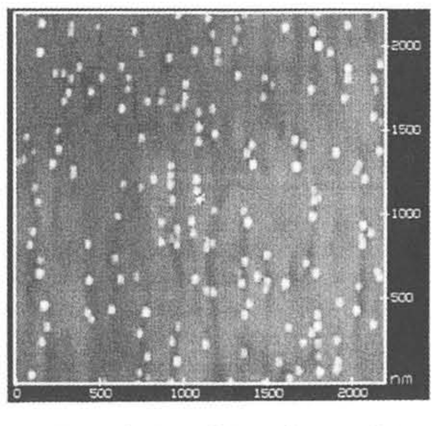


Fig.2 AFM image of InAs dots on GaAs

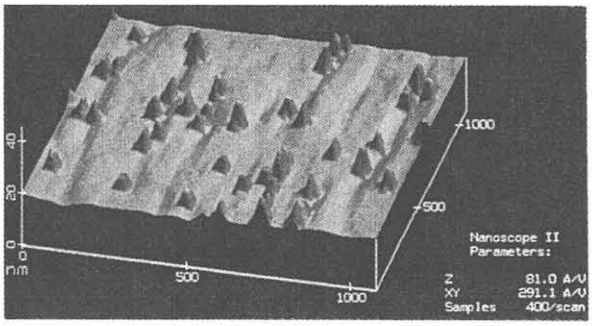


Fig.3 3D AFM image of InAs dots on GaAs

the growth of InAs dots, the arsenic beam equivalent pressure of $7.5x10^{-6}$ Torr and the InAs growth rate of 0.05 ML/s were used. Total amount of InAs deposition was 2.2ML using a multiple sequence of 2 seconds of the InAs growth followed by 4 seconds of arsenic exposure. Figure 2 shows the AFM image of the InAs dots. An example of 3 dimensional image is also shown in Fig.3. Measured average lateral size and the height of InAs dots were found to be 580Å and about 50Å, respectively.

3. MEASUREMENT RESULTS

3.1 CL and PL spectra of InAs dots based on InAs/InAlAs hetero-structure

Figure 4 shows CL spectra of InAs quantum dots fabricated by wet-chemical etching with heterostructure shown in Fig.1. CL spectra of 2D quantum well is also shown as a reference. In the figure, the dot size was 1.6 μm square, and the scanning area of electron beam was about 12 μm square. It is found that the CL peak energy of the quantum dots shifts toward higher energy. The observed 3meV peak shift is not consistent with calculated shift of only 0.013 meV based on lateral carrier confinement. The

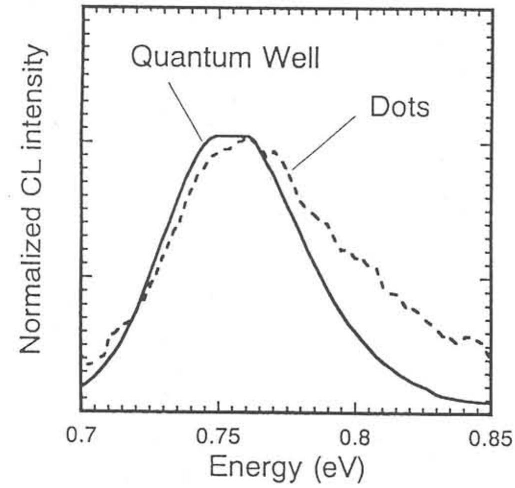


Fig.4 CL spectra of 2D QW and 1.6 μm squared quantum dots measured by scanning electron beam mode.

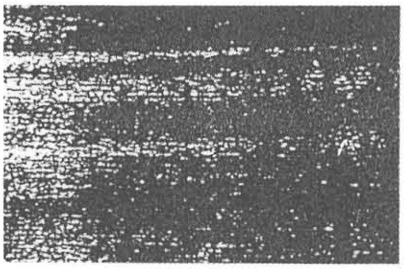
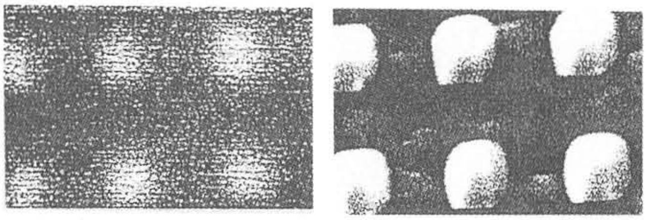


Fig.5 CL image of 2D quantum well in the area of 12μm square.



(a) (b)

Fig.6 (a) CL and (b) SEM image of quantum dots of 1.6μm square.

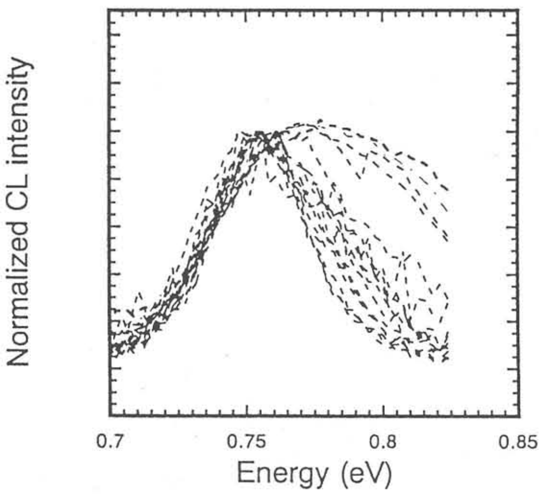


Fig.7 CL spectra from each 1.6μm squared quantum dot by fixing the position of electron beam. It is seen that the CL spectra consist of the spectra with lower peak energy and with higher peak energy.

unexpectedly high energy shift have also been observed by PL measurements of InAs quantum dots. For example, 22meV shift was observed for 0.2μm dots, although the calculated shift caused by the lateral carrier confinement is 1meV. Figure 5 shows the CL image of 2D quantum well. The position dependent luminescence was observed before the fabrication to pillar-shaped pattern. The CL and SEM image of quantum dots shown in Fig.6 (a) and (b) indicates uniform carrier distribution in the 1.6μm squared dots. The CL image suggests that lateral carrier confinement by depletion region of side edge is not effective. A different mechanism should be sought other than the lateral carrier confinement to account for the unexpectedly blue shift of CL and PL peak energy.

Figure 7 shows the CL spectra from 1.6μm squared each single quantum dot by fixing the position of electron beam. It is seen that the CL spectra consist of the spectra with lower peak energy and with higher peak energy. It is also seen that the line shape of the CL spectra with lower peak energy are similar to that of 2D quantum well. On the other hand, full width at half maximum of the CL spectra with higher peak energy is found to be large in comparison with that of 2D quantum well. This result indicates that the non-uniform strain distribution in 2D quantum well reflects the existence of InAs dots with various inherent strain. Luminescence from the dots with higher peak energy seems to contribute to the unexpectedly high energy shift of CL and PL peak energy measured as the integrated intensity in the large excitation area.

3.2 PL spectrum of Self-assembled InAs dots grown on GaAs

Figure 8 shows the sample structure for PL measurement of InAs dots on GaAs. After the growth of GaAs buffer layer, $Al_{0.3}Ga_{0.7}As$/ GaAs/ $Al_{0.3}Ga_{0.7}As$ layer

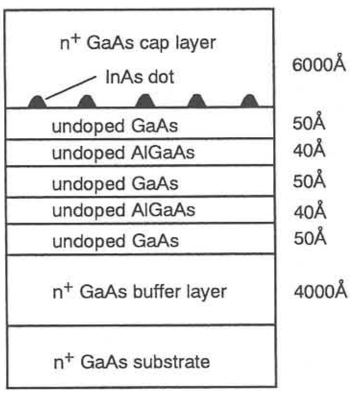


Fig.8 Sample structure of InAs dots on GaAs.

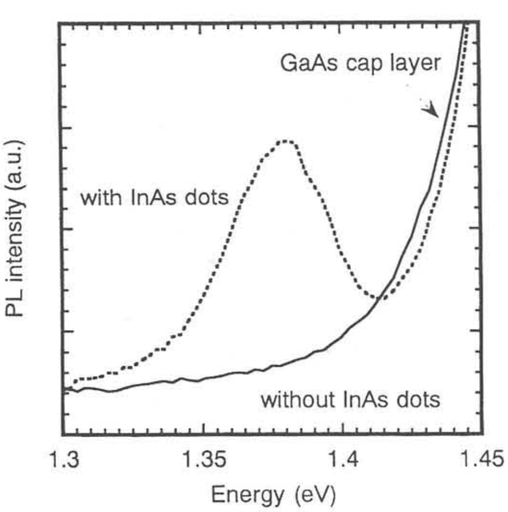


Fig.9 PL spectra of InAs dots on GaAs.

and undoped GaAs layer on (100) GaAs substrate, InAs dots were grown at a substrate temperature of 490°C. In order to decrease the surface recombination at InAs surface, GaAs cap layer was grown on the InAs dots. The sample structure without InAs dots was also grown as a reference sample. Figure 9 shows the PL spectra of the samples with and without InAs dots measured at 22K. The observed peak energy and the FWHM of InAs dot were found to be 1.378eV and 50meV, respectively. Since the calculated value of energy shift based on the carrier confinement should be ~250meV, the observed PL peak energy is unexpectedly high. The reason for the unexpectedly high peak energy is unknown at present, although there are several possibilities; e.g., (i) change of the bandgap caused by strain, (ii) formation of InGaAs alloy during the GaAs overgrowth and (iii) change of the dot size during the GaAs overgrowth. Further analysis such as X-ray diffraction is needed to verify the inherent strain in the self-assembled dots.

4. CONCLUSION

Optical characterization were performed on patterned InAs dots based on InAlAs/InGaAs hetero-structure and the self-assembled InAs dots grown on GaAs. Unexpectedly high peak energy shift of PL and CL from patterned InAs quantum dots were accounted for by the inherent strain in each dot. PL peak energy from self-assembled InAs dots was also found to be unexpectedly high. According to these optical characterization, the inherent strain distribution turned out to play an important role in the analysis of luminescence from both patterned and self-assembled InAs dots. Further analysis is needed to verify the inherent strain in the self-assembled dots.

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