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Luminescence Properties of InAlAs/AlGaAs Quantum Dots Grown by Modified Molecular Beam Epitaxy

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Self-assembled InAlAs/AlGaAs quantum dots (QDs) on GaAs substrates were grown by using modified molecular epitaxy beam in Stranski-Krastanov method. In order to study the structural and optical properties of InAlAs/AlGaAs QDs, atomic force microscopy (AFM) and photoluminescence (PL) measurements are conducted. The size and uniformity of QDs have been observed from the AFM images. The average widths and heights of QDs are increased as the deposition time increases. The PL spectra of QDs are composed of two peaks. The PL spectra of QDs were analyzed by the excitation laser power- and temperature-dependent PL, in which two PL peaks are attributed to two predominant sizes of QDs.

Keywords : InAlAs, Quantum dot, Photoluminescence

I. Introduction

Quantum dots (QDs) structures have been attracted as significant research owing to their potential such as high temperature stability, high frequency response, and low threshold current. Self-assembled QDs grown by molecular beam epitaxy (MBE) can be obtained in Stranski-Krastanov (S-K) mode. Most of III-V QDs such as In(Ga)As/GaAs and In(Ga)As/InP emitting in the infrared range has been applied in optoelectronic devices, photo detector, and laser diode to improve the device performance [1-6]. Also, In(Ga)As QDs have been studied for single dot spectroscopy, which have a low density of QDs. In case of InAlAs QDs, they have short surface diffusion of Al, resulting in its high bonding energy with As [7-9]. In spite of disadvantage in terms of density, InAlAs QDs have large band gap, which has achieved emission in the red region of visible range [7,10-14]. In particular, highly strained InAlAs on GaAs substrate can be obtained red-emitting QDs ranging to 1.88 eV [14]. In conventional MBE growth of InAlAs, however, the Al atoms migrate slowly on the As surface. In order to solve the problem, we proposed modified MBE method, which is controlled In, Al, and As fluxes during QDs growth. The size, shape, and uniformity of InAlAs QDs grown by modified MBE are improved compared to those of QDs grown by conventional MBE method.

In this study, we investigated the effect of deposition time on the structural and optical properties of InAlAs/AlGaAs QDs grown by modified MBE. The formations of QDs were analyzed by atomic force

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microscopy (AFM) measurement. The luminescence properties of QDs were studied by the excitation laser power- and temperature-dependent PL measurements. The two PL peaks for InAlAs/AlGaAs QDs are attributed to the bimodal size distribution of QDs.

II. Experimental Details

InAlAs/AlGaAs QDs formed by S-K growth mode were grown on a semi-insulating GaAs (001) substrate by modified MBE system. A GaAs buffer layer was grown at substrate temperature of T_s=600°C, and then a 30-nm-thick $Al_{0.4}Ga_{0.6}As$ layer was deposited at the same temperature. After decreasing growth temperature to 560°C, InAlAs QDs were grown by S-K mode. In the first step, In, Al, and As fluxes were supplied for the deposition time of t, and then the fluxes of In and As except Al flux were kept supply for the time of t. During the second step, the shutter of Al was closed, and finally the flux of As was continuously supplied for 10 s. This sequence was repeated two times for the growth of InAlAs QDs. After depositing the InAlAs QDs, a 50-nm-thick $Al_{0.4}Ga_{0.6}As$ cap layer was grown. In addition, for the AFM measurements, InAlAs QDs were grown on the top of $Al_{0.4}Ga_{0.6}As$ cap layer. The schematic sample structure and shutter sequence are illustrated in Figs. 1(a) and 1(b), respectively. The

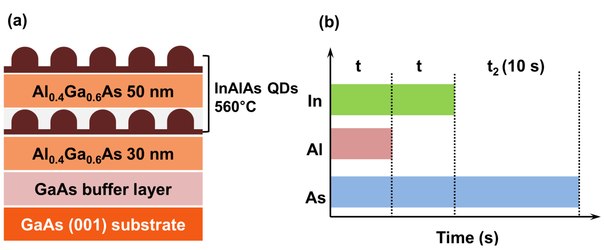

Figure 1. (a) Schematic structures of InAlAs/AlGaAs QDs. (b) Illustration of a shutter sequence for the growth of InAlAs QDs. This sequence was repeated for two times during the growth of QDs.

deposition time of t is changed from 2.8 to 4.0 s. InAlAs QD samples grown by using the deposition times of 2.8, 3.1, 3.4, and 4.0 s are denoted as QD1, QD2, QD3, and QD4, respectively. The size and size distribution of QDs on the surface were measured by a XEI-100 AFM in non-contact mode. For the optical investigation of InAlAs QDs, PL measurements were performed by using the 325 nm line from a He-Cd laser for excitation. Temperature-dependent PL was measured in temperature-range from 10 to 240 K by using a closed-cycle helium cryostat. The luminescence was collected by the CCD detector (ANDOR DV420A-BU2).

III. Results and Discussion

Fig. 2(a) shows the 10 K PL spectra of InAlAs QD samples, and the dotted lines present the Gaussian fitted peaks. The PL spectra for all samples except QD4 mainly consist of two emission peaks, and the PL peak around at 830 nm is from GaAs substrate. The PL peak for QD3 appears at the lowest energy, and

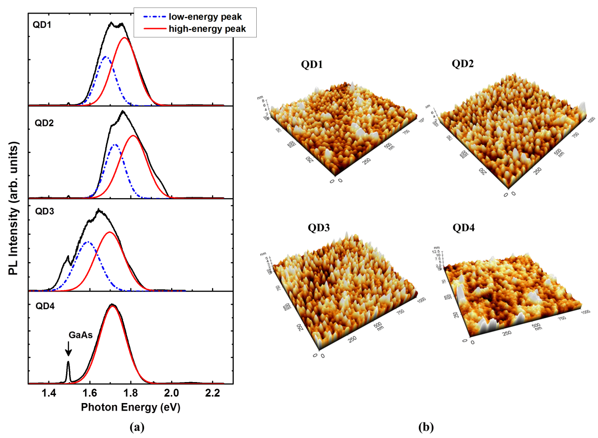

Figure 2. 10 K PL spectra (a) and AFM images (b) for QD1, QD2, QD3, and QD4. The solid black lines are measured PL peak and the dash-dot blue and solid red lines are obtained by Gaussian peak fitting. The AFM images are scanned from 1 μm×1 μm.

Table 1. Summary of the structural and optical information of InAlAs QDs. The average width and height of QDs are obtained from the AFM images. The PL peak position and FWHM for QD1, QD2, and QD3 are obtained by Gaussian peak fitting. The PL spectrum for QD4 shows a single PL peak.

Sample	QD1	QD2	QD3	QD4
Average QD width (nm)	34.7±7.2	35.7±5.5	38.0±6.2	34.7±7.5
Average QD height (nm)	1.9±0.9	3.5±1.6	3.9±1.2	3.5±1.3
PL peak (eV)	1.68	1.72	1.59	1.71
	1.77	1.81	1.70	
FWHM (meV)	108.2	111.3	143.6	149.6
	142.8	155.4	163.8	

the full width at half maximum (FWHM) for QDs shows the most broad than that for the other samples. These results indicate that the dot size and uniformity of QDs for QD3 are larger and lower, respectively, compared to those for other samples. At low temperature, the FWHM is determined by the uniformity of dot size, the size distribution of QDs is larger, the FWHM is broader [15]. The PL peak for larger QDs is appeared at higher energy compared to that for smaller QDs. The PL intensity for QD1, which have the smallest average width and height, is the strongest than that for other samples because QD1 has the highest QD density.

The surface morphologies of QDs are presented in Fig. 2(a) obtained by AFM measurements in the area of 1 μm×1 μm. The size (width and height) of QDs increases with increasing the deposition time from 2.8 to 3.4 s. Detailed values are presented in Table 1. As the deposition time increases from 2.8 to 3.4 s, the aspect ratio increases from 18.3 to 9.74, respectively. However, the QD size (width and height) and shape for QD4 are deteriorated with the deposition time of 4.0 s compared to those for QD3. Moreover, the InAlAs clusters in the AFM image are observed

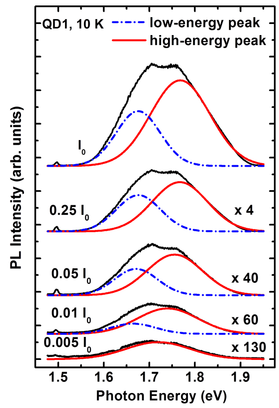

Figure 3. Excitation laser power-dependent PL spectra of QD1 measured at 10 K. Gaussian fitted PL peaks with predominant group are denoted to low-energy peak (large dots) and high-energy peak (small dots).

for QD4, which have unfavorable influence on device efficiency because they can be performed as non-radiative recombination centers.

The excitation laser power-dependent PL spectra for QD1 are shown in Fig. 3. At the lowest excitation power density (0.005 I_0), the high-energy peak (red dotted line) is only observed. As excitation laser power is increased from 0.005 I_0 to I_0, the low-energy PL peak is appeared and both PL peak intensities

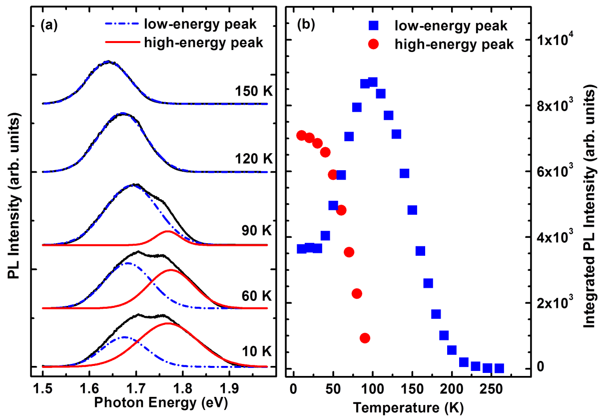

Figure 4. (a) PL spectra and (b) integrated PL intensity for QD1 as a function of temperature.

increase rapidly as shown in Fig. 3. The relative PL intensity of high- and low-energy peaks increase in nearly same as raising excitation power density. These results proposed that the origins of low- and high-energy peaks are not from ground-state and excited-state of InAlAs QDs [10,12]. QD2 and QD3 show the same trend with QD1 except for QD4.

Fig. 4(a) shows the temperature-dependent PL spectra for QD1. With increasing temperature from 10 to 90 K, the PL intensity of the high-energy peak (red solid line) decreases rapidly while the PL intensity of the low-energy peak increases. The increased PL intensity of the low-energy peak is attributed to the increased carriers thermally escaped from relatively smaller QDs (high-energy peak). As the temperature increases further, the PL intensity of the low-energy peak starts to decrease with temperature, indicating the increased nonradiative recombination.

The integrated PL intensities of two PL peaks from QD1 are shown in Fig. 4(b) as a function of temperature. As increasing temperature, the integrated PL intensity of the high-energy peak decreases rapidly and disappears around at 100 K. On the other hand, the integrated PL intensity of the low-energy peak increase steadily with increasing temperature up to 100 K, and then starts to decrease as temperature increases further as shown in Fig. 4(b). These results can be explained that carriers confined at relatively small QDs (high-energy) are thermally excited to wetting layer or GaAs barrier, and then these carriers are recaptured to relatively large QDs (low-energy) [16]. From the excitation power- and temperature-dependent PL results, two PL peaks of QD1 are attributed to the bimodal size distribution.

IV. Conclusion

Self-assembled InAlAs/AlGaAs QDs grown on GaAs by MBE have been investigated by using AFM and PL measurements. The average size (width and height) and shape (aspect ratio) of InAlAs QDs increases as the deposition time increases from 2.8 to 3.4 s, while the average size and shape of QD4 grown for the deposition time of 4.0 s are deteriorated compared to those of QD3. The PL spectra for InAlAs/AlGaAs QDs are composed of two PL peaks, low-energy peak and high-energy peak, attributed to relatively large QDs and small QDs, respectively. The two PL peaks are due to the bimodal size distribution of predominant QD sizes. With increasing temperature from 10 to 100 K, the increase of PL intensity for the low-energy peak (larger dots) is ascribed to the tunneling process of thermally excited carriers from smaller dots to larger dots. The size/shape, uniformity, and density of InAlAs QDs can be controlled by varying the total fluxes of InAlAs and InAs.

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