Growth of Room-Temperature 1.32- μ m-Emitting InAs Quantum Dots Using {GaAs/InAs} Quasi-Monolayers

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InAs QDs on the strained {GaAs/InAs} quasi-monolayers (QML) with an alternative growth mechanism were grown by using molecular beam epitaxy. The photoluminescence (PL) emission peak of the InAs quantum dots (QDs) with 10 periods of strained {GaAs/InAs} QMLs was red-shifted by 180 meV at 10 K from that of the reference InAs QDs sample which had no {GaAs/InAs} QML. The InAs QDs with 10 periods of {GaAs/InAs} QMLs also showed a strong PL emission at 1.32 μ m at room temperature. As the number of various periods of QMLs in the InAs QD samples was varied, the emission wavelength of the InAs QDs moved significantly toward long wavelength emission.

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I. INTRODUCTION

In the past several years, self-assembled quantum dots (QDs) grown by using the Stranski-Krastanov (S-K) growth mode have attracted much attention because of interest in both their fundamental physics and potential applications such as optoelectronic [1-4] and electronic devices [5,6]. In particular, the engineering of the confinement energy level in self-assembled III-V quantum dots (QDs) is a critical issue in the development of lasers and phototransistors. Control of the interband transition energy of QDs has been achieved by adjusting the size of the QDs, changing the material of the QD or potential barrier [7,8], and so on. The particular purpose of a QD laser is to serve as a light source for fiber-optic communication systems at a wavelength of 1.3 μ m. The

1.3- μ m emission was first demonstrated in self-assembled InGaAs/GaAs QDs formed by using an alternating supply of group-III and group-V source materials in metal-organic vapor phase epitaxy (MOVPE) [9]. The 1.3- μ m emission from QDs has been improved with molecular beam epitaxy (MBE) using an alternating growth. For sub-ML deposition, equal amounts of In (0.15~0.5 ML) and Ga (0.15~0.5 ML) were alternately deposited with the As supplied only during 5 seconds at each pause time in between column III depositions [10]. Moreover, other researchers used this alternating technique for achieving long wavelength emission. However, there are no detailed explanations on the structural and the optical properties of QDs grown by using this technique [11].

In this work, we report the optical properties of InAs QDs grown by using quasi-monolayers (QMLs) of GaAs and InAs. These properties were obtained using photoreflectance (PR) and photoluminescence (PL) measurements. The emission peak position of InAs QDs with

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InAs 1.5 ML	Epi-layer	GaAs 200 Å	S1	GaAs 200 Å	S4
GaAs buffer	3000 Å	InAs 2.5 ML	QD	GaAs 1.5 ML	× 5
Sub SI-GaAs (100)		GaAs buffer	3000 Å	InAs 0.8 ML	QD
		Sub SI-GaAs (100)		GaAs buffer	3000 Å
				Sub SI-GaAs (100)	
		GaAs 200 Å	S2		
GaAs 250 Å	PR2	InAs 2.5 ML	QD		
InAs 1.5 ML	2D-Layer	GaAs 1.5 ML	Strained		
GaAs buffer	3000 Å	InAs 0.5 ML	layer		
Sub SI-GaAs (100)		GaAs buffer	3000 Å		
		Sub SI-GaAs (100)			
		GaAs 200 Å	S3		
GaAs 250 Å	PR3	InAs 2.5 ML	QD	GaAs 200 Å	S5
InAs 1.2 ML	2D-Layer	GaAs 1.5 ML	Strained	GaAs 1.2 ML	×10
GaAs buffer	3000 Å	InAs 0.8 ML	layer	InAs 1.2 ML	QD
Sub SI-GaAs (100)		GaAs buffer	3000 Å	GaAs buffer	3000 Å
		Sub SI-GaAs (100)		Sub SI-GaAs (100)	

Fig. 1. Schematic structures of the samples.

QMLs is red-shifted compared to the reference sample. In particular, the PL spectrum of InAs QDs with 10 periods of QMLs has $1.32\text{-}\mu\text{m}$ emission at room temperature without forming dislocations.

II. EXPERIMENTAL

The samples used in the present work were grown by using a Riber 32P molecular beam epitaxy (MBE) system with semi-insulating GaAs (100) and As_4 . Four QDs samples with different QML structures were grown to study the effects of the strained {GaAs/InAs} QML, whose thickness is not enough to form QDs. Also, 2.5 ML single InAs QD samples without the strained {GaAs/InAs} QML were grown as a reference (S1). Before depositing the InAs QDs, the substrate temperature was set to 580°C for the growth of a GaAs buffer layer, then, the substrate temperature was lowered to 480°C for the growth of QMLs and InAs QD layers. The formation of QDs was verified by using *in-situ* reflection high-energy electron diffraction pattern (RHEED) to observe the 2D-3D transition. Two of the InAs QD samples were 2.5 ML of InAs QDs on 1 period of 1.5 ML GaAs/0.5 ML InAs (S2) and 2.5 ML InAs QDs on 1 period 1.5 ML GaAs/0.83 ML InAs (S3). The other two samples were 5 periods of 1.5 ML GaAs/0.83 ML InAs (S4) and 10 periods of 1.2 ML GaAs/1.2 ML InAs (S5). We did not intentionally attempt QD growth in S4 and S5. However, after the second deposition of a {GaAs/InAs} QML in S4 and S5, spotty patterns were introduced in RHEED screen, indicating the formation of QDs due to the accumulated strain energy from the stacked {GaAs/InAs} QMLs. The schematics of sample structures are shown in Fig. 1.

We used photoreflectance (PR) measurements to determine the existence of wetting layer (WL) in the QDs samples. The modulated reflectance as a function of the surface and the interfacial electric fields in the QDs sample was produced by using a mechanically chopped 5 mW

Fig. 2. Photoreflectance spectra of (a) a QML QW, (b) a strain induced QD, and (c) QML QDs at room temperature.

He-Ne laser beam (a wavelength of 632.8 nm) at 800 Hz for generating electron-hole pairs. The probe light from a quartz tungsten halogen lamp passed through a monochromator and irradiated the surface of the samples. The reflected light from the sample was collected by using a lens and was detected with an InGaAs photodiode. Then, the detected signal was fed into a lock-in amplifier. The differential reflectance (ΔR) was provided through a lock-in amplifier with the detected light signal, and the absolute reflectance (R) was given by the detector output directly. The PR signal ($\Delta R/R$) was recorded as a function of energy. The schematic diagram for the experimental setup is shown in our previous work [12].

In the PL measurement, an Ar^+ laser at a wavelength of 514.5 nm was used as an excitation source to generate electron-hole pairs, and the luminescent signal was detected by using a liquid-nitrogen-cooled Ge detector. The PL measurements were performed at 10 K and 300 K.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the PR spectra obtained from the samples of InAs with 1.5 ML (PR2), InAs with 1.2 ML (PR3), and InAs with 1.5 ML (epilayer) on GaAs at room temperature. In Fig. 2(a), the PR spectrum of the epilayer shows the two transitions from GaAs due

to heavy-hole (HH) and light-hole (LH) splitting [13]. In the PR spectra shown in Fig. 2(a), there are two main features from the InAs quantum well (PR2, PR3) and the GaAs layer. One feature, the fundamental near band-edge transition of GaAs layer is combined with the splitting of HH band and LH transitions, is observed in PR spectra shown in Fig. 2(a). In addition, a PR signal from the InAs quantum well (QW) is observed below the GaAs band-edge transition. More specifically, we considered the InAs QW as the InAs WL. With increasing InAs QW thickness, the InAs QW related peaks are shifted to lower energy. These features are mainly due to a reduction in the quantum confinement effects with increasing thickness of the InAs QW considered as an InAs WL. These results are evidence that the InAs QW can be interpreted as an InAs WL. Figure 2(b) shows the PR spectra obtained from the conventional 2.5 ML InAs QDs (S1) and 2.5 ML InAs QDs on 1-period strained {GaAs/InAs} which has 0.5 ML InAs (S2) and 0.83 ML InAs (S3). With increasing InAs QML thickness, the InAs-WL-related peaks designated by WL in Fig. 2(b) are shifted to lower energy. This result is agree well with the tendency of PR the signal for the InAs QW shown in Fig. 2(a). These results are mainly due to the effects of the QML InAs strained layer and the quantum size effects. The effect of the thin {GaAs/InAs} strained layer may be explained as follows; the lattice constant of the strained InAs QML on GaAs is smaller than that of the bulk InAs. Therefore, the GaAs QML on the strained InAs QML has a weakly tensile stress. Thus, the InAs QD layer on the strained {GaAs/InAs} QML may be suffering low stress. Figure 2(c) shows the PR spectra obtained from QML-QDs with different InAs QML thicknesses (0.83 ML and 1.2 ML), 5 and 10 periods of the {GaAs/InAs} QML, and different barrier materials (AlAs and GaAs) respectively. Only one main feature due to GaAs layer is seen for each PR spectrum. That is, the PR signal of each sample associated with the fundamental band-edge transition of GaAs layer is mainly shown, and the WL-related transitions are not observed in PR spectra of Fig. 2(c). From these results of the PR measurements, we carefully suggest that InAs QDs without the InAs WL are grown by using alternative deposition of QML-GaAs and QML-InAs.

Figure 3(a) shows the normalized PL spectra of InAs QD samples measured at 10 K. The PL peak positions of InAs QDs with the strained {GaAs/InAs} QML are red-shifted systematically from that of the reference sample (S1). The blue-shifted PL peak position of S2 is mainly caused by the effect of QD growth temperature [14]. The InAs QDs of S2 were grown at a little lower temperature than the others. The PL emission peak of the InAs QDs in S3 is red-shifted by ~ 86 meV from that of S2. This result is due to the strained-layer effects with increasing InAs QML thickness. Thus, the InAs QDs on 1-period {GaAs/InAs} QML can achieve an energetically lower thermodynamic state due to the lower lattice mismatch. The PL emission peak of S4, which is an InAs QD sample

Fig. 3. (a) Normalized PL spectra of all samples at 10 K and (b) PL spectra of the reference sample (S1) and QML QD (S5) at 300 K.

with 5 periods of a QML (1.5 ML GaAs / 0.83 ML InAs) is red-shifted by ~ 151 meV from that of the reference InAs QDs sample S1. The PL peak position, which is shifted toward long wavelength, could be explained by the closely stacked effects of InAs QDs and by the thin strained {GaAs/InAs} QML effects as mentioned above.

Figure 3(b) shows PL spectra from the reference sample (S1) and from the 10-period {GaAs/InAs} QML QD sample (S5) at room temperature. As shown in Fig. 3(b), the PL spectra of S1 and S5 at room temperature clearly attest to the high quality of the InAs QDs formed. In the 10 K PL measurement, the PL peak position of S5 is red-shifted by about 180 meV compared with that of S1, and correlatively, at room temperature, the PL emission of S5 is 1.32 μm , which is a very noticeable result, and the intensity is about 5 times stronger than PL intensity of S1.

IV. CONCLUSIONS

InAs QDs were grown by using QML with different InAs layer thicknesses and their optical properties were investigated by using PR and PL measurements. From the results of the PR spectra, the InAs wetting layer was not observed when the QDs were formed on the strained {GaAs/InAs} QML. The lack of an InAs WL in the {GaAs/InAs} QML QDs manifests that QDs grown by using QML are not formed by the S-K growth mode. The PL emission peak position from QDs grown by using 10 periods of {GaAs/InAs} QMLs was red-shifted by 180 meV from the PL peak position of the conventional InAs QD sample because of the quantum size and the strain effects. Our experimental results show that the energy levels of the InAs QDs can be changed by using strained {GaAs/InAs} QMLs.

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