

InAs/GaAs quantum dots grown on different GaAs substrates with graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ strain-reducing layer

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Abstract Self-assembled InAs quantum dots with graded composition strain-reducing layer (SRL) grown on exact substrates were studied. It is shown that a graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL leads to growth quality improvement, emission efficiency enhancement, and wavelength blue-shift. Samples grown on 2° misoriented substrates with different In contents in graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL were also investigated, and emission efficiency enhancement and wavelength blueshift were found when graded SRL was introduced and when the change rate of In content in graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL was enlarged.

Keywords quantum dots (QDs), strain-reducing layer (SRL), gradient composition, misoriented substrate

1 Introduction

Quantum dots (QDs) have attracted considerable attention because of their atom-like properties, which make them promising for the improvement of performance of optical devices [1,2]. There has been considerable interest in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ strained-reducing layer (SRL) over InAs QDs due to its reducing the strain of InAs QDs and suppressing Indium (In) segregation from QDs, which can help InAs QDs increase density and emit longer wavelength photons [3,4]. It has been found that a higher In composition x in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL is useful for obtaining longer wavelength emission, but the luminescence intensity is reduced. One of the reasons is that carriers in InAs QDs possess a lower barrier and less quantum confinement since the $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL with bigger In content x has a smaller bandgap [5]. Compared with the intensive focus on $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL with fixed In contents x , little attention is

being paid to $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL with graded In content x .

In this paper, we grow InAs/GaAs QDs with graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL by metal-organic chemical vapor deposition (MOCVD); the effect of graded SRL and In composition on QD performance are investigated by atomic force microscopy (AFM) and photoluminescence (PL) measurement. Emission efficiency enhancement and wavelength blueshift are observed in InAs/GaAs QDs with graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL on both exact and 2° misoriented substrates.

2 Experimental details

All the samples were grown by a Thomas Swan close-coupled-showerhead low-pressure MOCVD system. Trimethylindium (TMIn), trimethylgallium (TMGa), arsine (AsH_3) were used as source materials. H_2 was used as carrier gas.

We deposited five types of InAs QD samples on different GaAs substrates under the Stranski-Krastanow mode for comparison. Samples A and B were grown on exact substrates, while Samples C, D and E were grown on 2° misoriented substrates.

Sample A was InAs/GaAs QDs with a fixed In composition in the InGaAs SRL, which consisted of a 300 nm thick GaAs buffer layer deposited at 680°C , 1.85 monolayer (ML) InAs QDs covered by 5 nm $\text{In}_{0.105}\text{Ga}_{0.895}\text{As}$ cap layer grown at 505°C , then 22 nm GaAs spacer layer at 600°C , and finally 1.85 ML of uncapped InAs QDs at 505°C . Sample B was InAs/GaAs QDs with a graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL. It differed from sample A in that the In content x in $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL linearly decreased from 0.140 (at the interface of InAs and $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL) to 0.070 (at the interface of $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL and GaAs spacer layer).

Sample C, sample D and sample E were grown on 2° misoriented substrates; sample C was InAs/GaAs QDs

with a fixed In composition in the InGaAs SRL. Similar to sample A, it consisted of a 300 nm thick GaAs buffer layer, 1.86 ML InAs QDs, a 5 nm $\text{In}_{0.106}\text{Ga}_{0.894}\text{As}$ SRL, a 22 nm GaAs spacer layer, and a 1.86 ML uncapped InAs QDs. The growing temperature for the InAs QDs and SRL was 513°C. Sample D was InAs/GaAs QDs with a graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL; it differed from sample C in that the In content x in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL linearly decreased from 0.135 to 0.077. Sample E had the same parameters as sample D except that the In content x in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL linearly decreased from 0.151 to 0.060, so the change rate of In content in sample E was larger than that in sample D.

Table 1 compares the parameters for samples A–E.

Atomic force microscopy (AFM) measurements were performed by a Veeco NanoScope MultiMode system in ambient conditions in contact mode. Photoluminescence (PL) spectra measurements were carried out under the excitation of 514.5 nm line of the Ar^+ laser, using a cooled InGaAs detector and lock-in amplifiers.

3 Results and discussion

Figure 1 shows the AFM image of sample A, with the scan area being $2\ \mu\text{m} \times 2\ \mu\text{m}$. The QD density of sample A is $2.2 \times 10^{10}/\text{cm}^2$, and the mean height and diameter of QDs are 1.86 and 25.9 nm, respectively. By contrast, the AFM image of sample B (not shown here) indicates that the density, mean height and diameter of QDs in sample B are $1.6 \times 10^{10}/\text{cm}^2$, 2.2 nm and 27.8 nm, respectively.

Compared with QDs in sample A, the QDs in sample B have a bigger mean size and less large islands. The large islands are caused by the strain fields associated with the big QDs in the first layer of InAs QD and are usually plastically relaxed islands and nonradiative recombination centers [6–8]. The graded InGaAs SRL gives higher In content immediately adjacent to InAs QDs. As a result, the strain reduction effect is more evident, which leads to a bigger mean size and less presence of large islands in sample B.

Figure 2 gives the PL spectra of sample A (dashed line) and B (solid line). The ground-state (GS) and excited-state (ES) emission peaks of the two samples are marked. The GS and ES emission in sample A peaks at 1318.9 and 1226.2 nm, respectively. With the help of the graded

InGaAs SRL, the GS and ES emissions in sample B slightly move to 1317.7 and 1220.0 nm, and their intensity get enhanced. The difference in PL intensity originates from the QD growth quality. As stated above, although sample A has a larger QD density, it has more big incoherent islands than sample B, which degrades its optical properties and makes its PL intensity weaker.

Both samples A and B show multi-peak emissions, which are confirmed to be ground-state and excited-state emissions. Figure 3 presents the PL spectra of sample B under different optical excitation powers. The excitation power in the lower line and upper line is P_0 , $10P_0$, respectively. The transition wavelengths of the ground-state, first excited-state, second excited-state are 1317.7, 1220.0, and 1128.6 nm, respectively. The energy spacing between the ground-state and first excited-state, the first excited-state and second excited-state are 75.4 and 82.3 meV, respectively, which are relatively high and suggest good temperature stability. Emission from the wetting layer is obviously observed at the wavelength of 976.0 nm when the pump power is $10P_0$.

PL measurements were taken for samples C, D and E, which are grown on 2° misoriented substrates. Table 2 gives the peak wavelength and integrated intensity of GS emissions for the three samples. The results show that the GS peak wavelengths are 1199.3, 1182.2 and 1174.0 nm, and the integrated PL intensities are 8336, 10374, and 10742, respectively. Comparing these three samples with samples A and B, which are grown on exact substrates, 2° misorientation leads to a blueshift of about 120 nm. This effect can be explained by the energy barrier formed at the multi-atomic step kinks, which prohibits the migration of In adatoms during the early stage of cap layer growth and attributes to a decrease in the sizes and a better size uniformity for the InAs QDs [9,10].

Compared with sample C, samples D and E, with graded InGaAs SRLs, show PL intensity enhancement and slight wavelength blueshift. Samples D and E are both grown with a 5 nm graded InGaAs SRL, the In content x in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL in sample D was linearly decreased from 0.135 to 0.077; while sample E has a bigger change rate of In content in $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL with x linearly decreasing from 0.151 to 0.060. The PL intensity of sample E is stronger than that of sample D because a larger change rate of In content in SRL has a stronger effect on strain reduction and In segregation suppression of the QDs.

Table 1 Parameters of InAs QD samples grown on different GaAs substrates

sample	substrate angle/(°)	temperature for InAs QDs/°C	thickness for InAs QDs/ML	cap layer
A	0	505	1.85	5 nm $\text{In}_{0.105}\text{Ga}_{0.895}\text{As}$ SRL
B	0	505	1.85	5 nm graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL, x decreases from 0.140 to 0.070
C	2	513	1.86	5 nm $\text{In}_{0.106}\text{Ga}_{0.894}\text{As}$ SRL
D	2	513	1.86	5 nm graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL, x decreases from 0.135 to 0.077
E	2	513	1.86	5 nm graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL, x decreases from 0.151 to 0.060

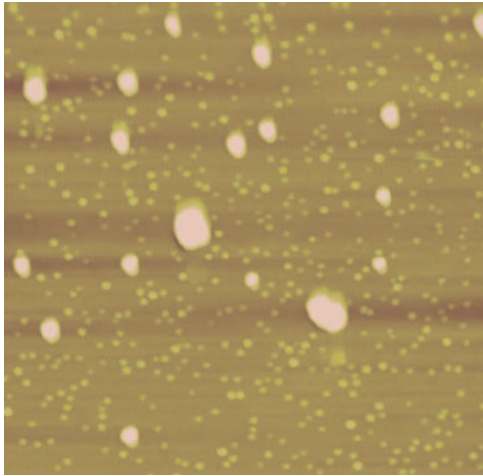


Fig. 1 AFM image of sample A

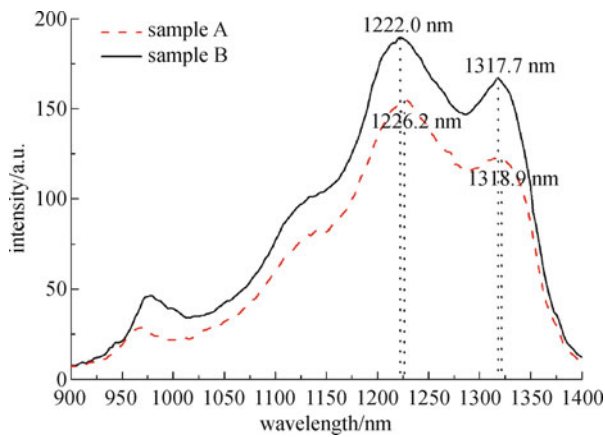


Fig. 2 PL spectra of samples A and B

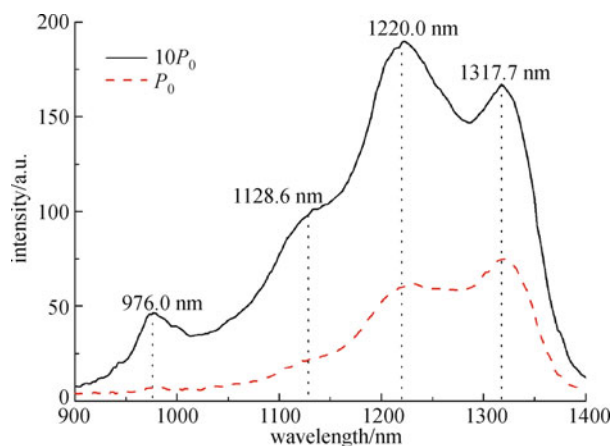


Fig. 3 PL spectra of sample B under different excitation powers

Table 2 GS wavelength and intensity of samples C, D, and E

sample	C	D	E
GS wavelength/nm	1199.3	1182.2	1174.0
intensity/a.u.	8336	10374	10742

4 Conclusions

In summary, InAs/GaAs QDs with graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL were grown on different GaAs substrates by MOCVD, and the effect of variant In composition in $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL was investigated. For samples with graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL, growth quality improvement, emission efficiency enhancement and small wavelength blueshift are observed on both exact substrates and 2° misoriented substrates. Samples grown on 2° misoriented substrates emit at a shorter wavelength around 1180 nm. This indicates stronger PL intensity when the change rate of In content in graded $\text{In}_x\text{Ga}_{1-x}\text{As}$ SRL is enlarged.

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