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Role of different cap layers tuning the wavelength of self-assembled InAs/GaAs quantum dots

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Abstract

We have investigated the effect of different cap layers on the photoluminescence (PL) of self-assembled InAs/GaAs quantum dots (QDs). Based upon different cap layers, the wavelength of InAs QDs can be tuned to the range from 1.3 to 1.5 μm. An InAlAs and InGaAs combination layer can enlarge the energy separation between the ground and first excited radiative transition. GaAs/InAs short period superlattices (SLs) make the emission wavelength shift to 1.53 μm. The PL intensity of InAs QDs capped with GaAs/InAs SLs shows an anomalous increase with increasing temperature. We attribute this to the transfer of carriers between different QDs.

1. Introduction

In(Ga)As quantum dot (QD) structures on a GaAs matrix have been intensively investigated [1–5] because of the possibility of extending the wavelength of the optical emission from structures on GaAs substrates up to 1.3 or 1.5 μm. Hitherto, some approaches have been put forward to tune the wavelength of InAs QDs to the telecommunication range (1.3–1.5 μm) [6–9]. One effective method, is to insert InAs QDs in the InGaAs well [2]. Another way is to cap InAs QDs with a thin AlAs layer [10]. There are also many other approaches focusing on optimizing the growth parameters such as substrate temperature, growth rate, etc. In contrast, the easier way is capping QDs with a strain-reducing layer (SRL). Here we propose and realize different methods to extend the optical emission range by capping QDs with InGaAs, InAlAs and InGaAs combination layers and GaAs/InAs SLs, respectively.

2. Experimental details

Three sorts of samples were grown in a VG V80 MKII molecular beam epitaxy (MBE) system on (100) GaAs semi-insulating substrates. A schematic diagram of the different structures is depicted in figure 1. After the deoxidization of the substrate at 580 °C, an initial 500 nm GaAs buffer layer was grown at a substrate temperature of 600 °C. Then the growth was interrupted

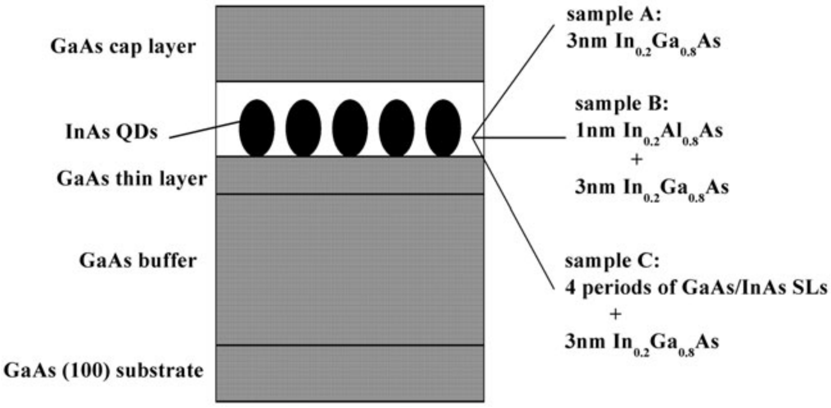

Figure 1. Schematic layer diagram of the sample structures.

in order to reduce the substrate temperature to 510 °C. Subsequently, a layer of 10 nm GaAs was deposited, followed by the growth of InAs quantum islands by depositing 3.5 ML InAs under a repeated growth sequence of 0.1 ML InAs and a 5 s interruption. Then different cap layers were deposited on top of InAs islands, i.e. 3 nm $In_{0.2}Ga_{0.8}As$ for sample A and a 1 nm $In_{0.2}Al_{0.8}As$ and 3 nm $In_{0.2}Ga_{0.8}As$ combination layer for sample B, and four periods of GaAs/InAs SLs and 3 nm $In_{0.2}Ga_{0.8}As$ for sample C, respectively. Finally, the substrate was heated up to 600 °C for growth of 50 nm GaAs layer. The growth rates of GaAs and InAs were 0.5 and 0.1 μm h^{-1}, respectively, with the arsenic (As_4) back pressure kept at 3×10^{-8} mbar. During growth of InAs QDs and GaAs/InAs SLs, the surface was monitored by reflection high-energy electron diffraction (RHEED).

The uncapped samples were grown under the same condition for the AFM measurements, which were carried out using a Park Scientific Instruments microscopy, model VP, operating in the contact mode. The red line (632.8 nm) of a He–Ne laser was used as an excitation source for the photoluminescence (PL) measurements. The obtained signals were detected by a liquid nitrogen cooled Ge detector.

3. Results and discussion

Figure 2 shows a typical 1 μm × 1 μm surface AFM image of the QDs capping with four periods of GaAs/InAs SLs. The islands have an average size of ∼100 nm and height ∼6 nm. Generally, the islands are distributed in a uniform way, while some islands coalescent to a larger size (as pointed out by the arrows in the figure), which accounts for the emission of longer wavelengths. Relatively low density of the larger islands, however, may cause the weaker emission intensity, as confirmed by the following PL test.

The PL spectra of samples A, B and C at room temperature are shown in figure 3. Two main peaks in the PL spectra of samples A and B are assigned to the ground state transition and the first excited transition, as reported in [5]. The emission wavelength of InAs QDs in sample A is located at 1.27 μm with a full width at half maximum (FWHM) of 24.5 meV, and the energy separation between the ground and the first excited transitions is 57 meV. Using an InAlAs and InGaAs combination layer instead of InGaAs, the emission wavelength of InAs QDs in sample B shifts to 1.33 μm with a FWHM of 21.3 meV, and the energy separation between the ground and the first excited transitions increases to 86 meV, indicating a better confining potential barrier in this sample. The redshift of the ground state transition of sample B can be

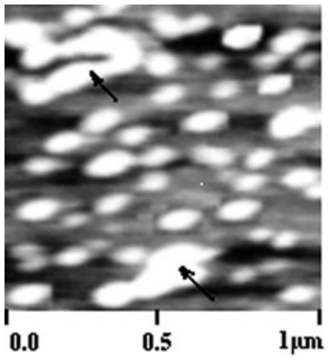

Figure 2. Surface 1 μm × 1 μm AFM image of 3.5 ML InAs capped with four periods of GaAs/InAs SLs.

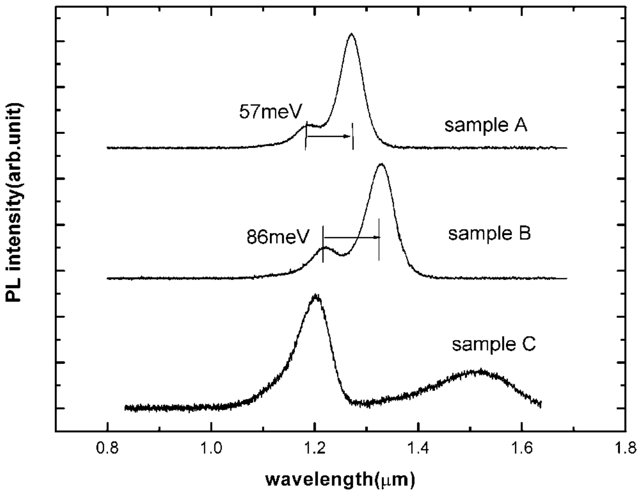

Figure 3. Room temperature PL spectra of the InAs QDs in samples A, B and C, respectively.

attributed to the larger QD height. Given the higher substrate temperature (510 °C), Al atoms are immobile on the InAs QDs. That is to say, the strong bonding energy between an Al atom and In atom prevents the In atoms from diffusing to the wetting layer (WL). As a result, the QD decomposition is reduced and the QD height remains larger than that of QDs capped with InGaAs. Generally speaking, the higher InAlAs barrier will cause a blueshift of PL energy. However, the redshift resulting from the larger QD height outweighs the blueshift caused by the higher InAlAs barrier at higher substrate temperature. Reduction of the In segregation and intermixing due to the InAlAs cap layer also give rise to this effect and can effectively preserve the QD size uniformity, resulting in a narrower linewidth of InAs QD ground state transitions of sample B.

The wider energy separation between the ground and the first excited transition of sample B should be a direct result of the higher confining potential barrier of InAlAs. It will be of benefit for suppressing the thermal runaway of the threshold current density due to the carrier excitation to and recombination from a higher-energy level, thus improve the QD laser temperature characteristics [11].

When capping InAs QDs with GaAs/InAs SLs and an InGaAs combination layer, the PL wavelength of InAs QDs in sample C extends up to 1.53 μm with a FWHM of 86 meV. The PL peak position shift to longer wavelength after inserting GaAs/InAs SLs between InAs QDs and the InGaAs SRL is attributed to strain reduction and increasing size of QDs during SL growth.

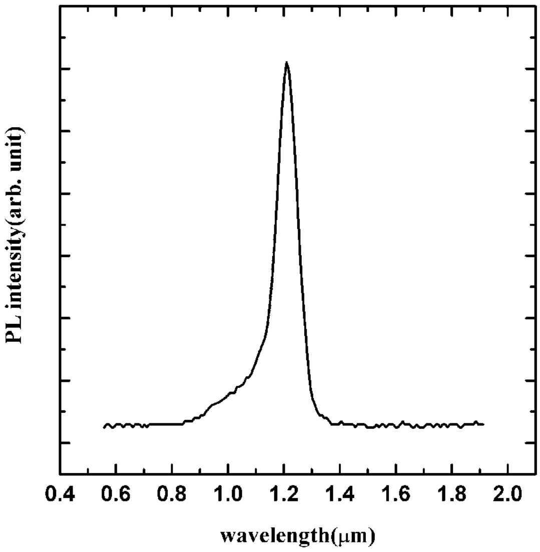

Figure 4. PL spectrum of the GaAs/InAs SLs capped with a $In_{0.2}Ga_{0.8}As$ SRL at room temperature.

Furthermore, coalescence of QDs is also an important factor worth noticing, as confirmed by the AFM result above.

The stronger peak at 1.2 μm should associate with GaAs/InAs SLs. To verify this conclusion, a sample identical to sample C was grown, except that 3.5 ML InAs QDs were not deposited. The PL test result coincides with our expectation, as shown in figure 4. The peak position of GaAs/InAs SLs is also located around 1.2 μm, identical with the position of the stronger peak in sample C, as shown in figure 3. The AFM result shows a lot of islands (not shown here), indicating the formation of InGaAs QDs. By alternating growth of GaAs and InAs, InGaAs QDs are formed, i.e. a QD superlattice, as pointed out in [12]. The evolution of the RHEED pattern during capping the InAs QDs further verified this conclusion. Similar to the case of capping InAs reported in [13], the RHEED pattern changes to short streaky diffraction rods with weak intensity within the deposition of 2 ML GaAs. However, the RHEED pattern changes back to clear chevrons after depositing 1.5 ML InAs, indicating complete rebuilding of InGaAs QDs on the surface. Interestingly, this evolution is repeated during each period of the GaAs/InAs SLs.

Figure 5 shows the temperature dependence of the PL spectra of sample C. Three peaks can be clearly observed at lower temperature, as marked by A, B and C in the figure. The PL intensity of peak B shows a gradual decline with increasing temperature. Peak C is quenched when the temperature increases up to 250 K. Further investigation through a power-dependence PL test indicates that peak C originates from the excitation states (not shown here). The appearance of the excited states and the strong intensity of the QD spectrum at room temperature, indicate an improved carrier collection efficiency into the QDs. However, the relative intensity of peak B remains very weak below 150 K and subsequently it becomes stronger with the temperature increasing up to room temperature. The lower PL intensity of peak B at low temperature can be assigned to the lower density of InAs QDs than of InGaAs QDs, since four periods of InGaAs QD superlattices (SLs) are additionally generated in sample C. In addition, the uncontrolled coalescence of InAs QDs (as shown in figure 2) also contributes to this effect, since mismatch dislocations may form in the larger dots. The anomalous increase of peak B's PL intensity should result from carrier transfer between different QDs. When temperature increases, the increased electron–photon interaction makes

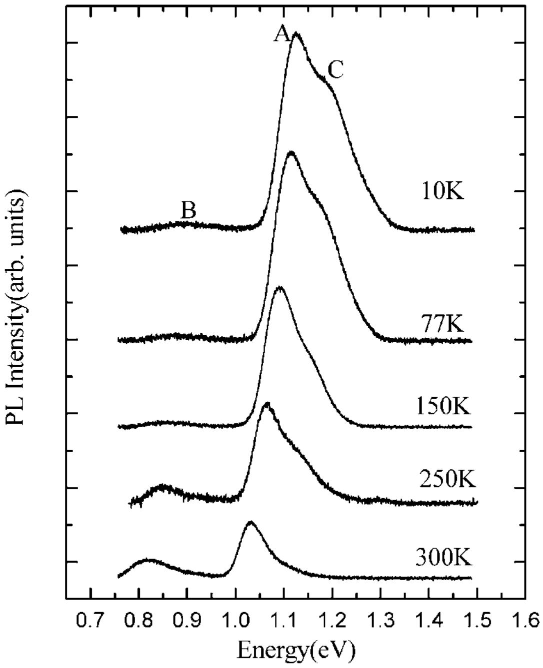

Figure 5. Temperature-dependence PL spectra of sample C.

the possibilities for carriers to transfer between different QDs increase markedly. In particular, the easier carrier escape from the InGaAs QDs than from the InAs QDs, due to the lower confinement potential barrier, accelerates this transfer. In other words, to occupy a position of favourable energy, carriers escaping from InGaAs QDs are injected into adjacent InAs QDs. As a result, photo-generated carriers relax into energetically low-lying states, giving rise to the redshift of the exciton energy and a stronger PL intensity of peak B.

The gradual transfer of the PL intensity from the higher-energy peak (peak A) to the lower-energy one (peak B) with increasing temperature is further evidenced in figure 6. As shown in the figure, the integrated PL intensity of peak A follows the Arrhenius law ($I = I_0/C \cdot \exp(-E_a/kT)$) very well while that of peak B shows some deviation, especially in the high temperature range (150–300 K). Clearly, the deviation results from the anomalous increase of peak B's PL intensity. The immeasurable PL above room temperature also gives rise to this deviation. The supplementary dot line in the figure is just a rough estimate of the quenching of peak B. From these Arrhenius plots, we obtain a thermal activation energy of 180 meV for InGaAs QDs, which is comparable to 230 meV, the energy difference between the PL emission and the WL. This indicates that the WL serves as an intermediate channel for carrier transfer between different QDs. These results are consistent with previous works [14, 15].

Obviously, the lower intensity of peak B will be disadvantageous for potential device applications. To avoid this drawback, we need to increase the InAs dot density and control the dot coalescence by optimizing the growth parameters. Further investigation is ongoing.

4. Conclusions

By capping InAs QDs with different cap layers, we can tune the emission wavelength of the QDs from 1.3 to 1.5 μm. The effect of cap layers on the PL properties was investigated. It is found that a InAlAs and InGaAs combination layer can widen the energy separation between

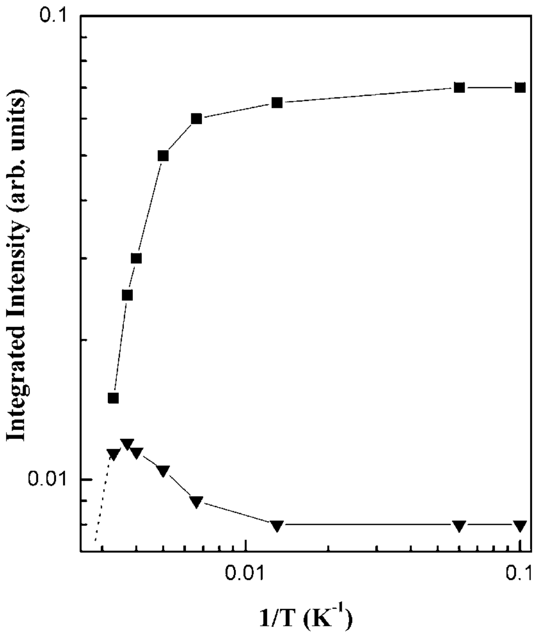

Figure 6. Temperature dependence of the integrated intensities of peak A (squares) and peak B (triangles). The supplementary dot line is a rough anticipation of the quenching of peak B above room temperature.

the ground and first excited radiative transition. GaAs/InAs short period SLs make the PL intensity of InAs QDs show an anomalous increase with increasing temperature. The cause is attributed to the transfer of carriers between different QDs.

Acknowledgments

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