CHIN. PHYS. LETT. Vol. 26, No. 6 (2009) 067801

GaAs-Based Metamorphic Long-Wavelength InAs Quantum Dots Grown by Molecular Beam Epitaxy *

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(Received 9 March 2009)

A bilayer stacked InAs/GaAs quantum dot structure grown by molecular beam epitaxy on an $In_{0.05}Ga_{0.95}As$ metamorphic buffer is investigated. By introducing a InGaAs:Sb cover layer on the upper InAs quantum dots (QDs) layers, the emission wavelength of the QDs is extended successfully to 1.533 μm at room temperature, and the density of the QDs is in the range of 4×10^9–$8 \times 10^9 cm^{-2}$. Strong photoluminescence (PL) intensity with a full width at half maximum of 28.6 meV of the PL spectrum shows good optical quality of the bilayer QDs. The growth of bilayer QDs on metamorphic buffers offers a useful way to extend the wavelengths of GaAs-based materials for potential applications in optoelectronic and quantum functional devices.

PACS: 78.55.Cr, 68.65.Hb, 81.15.Hi

So far, considerable effort has been devoted to developing high performance long wavelength 1.31 μm to 1.55 μm lasers to meet the needs of next-generation fiber telecommunication systems with higher speed and larger capacity of data processing.[1,2] Lattice-matched InP-based material structures are a common choice for the fabrication of such lasers. However, the critical drawbacks of InP substrates, such as being more expensive, with smaller wafer size, and worse temperature stability, motivate people to develop new kinds of long wavelength materials for replacing them. Due to the unique advantages of GaAs substrates, such as being cheap, having larger wafer sizes, better temperature stability, and being compatible with the AlGaAs/GaAs distributed Bragg reflector, GaAs-based telecommunication devices have become a hot topic in recent years.

The issue of how to extend emission wavelengths to 1.31–1.55 μm of GaAs-based materials is a troublesome problem. Due to the large lattice mismatch between InAs and GaAs ($\Delta a/a = 7.6\%$), it is impossible to directly grow 1.55 μm long wavelength InGaAs quantum wells (QWs), or quantum dots (QDs), on GaAs substrates. Alternatively, GaAs-based InGaAs metamorphic QWs and QDs solutions are developed.[3,4] Compared to the GaAs-based QWs, GaAs-based QDs are expected to have better performance due to their unique advantages, such as high temperature stability and low threshold current, etc. Great effort has been made towards improving the quality of GaAs-based InAs QDs, including using the low growth rate to grow InAs QDs and a fast growth rate to grow GaAs cap layers, employing strained InAs/InGaAs QDs to reduce the threading dislocations, and even bilayer stacked QDs to realize the 1.55 μm emission on GaAs substrates.[5–7] However, the emission wavelengths still remain in the 1.50 μm range for most of the above structures.

In this letter, to further extend GaAs-based QDs into the 1.55 μm range, we propose a combined structure of bilayer stacked QDs grown on metamorphic buffers. Such metamorphic QDs heterostructures are grown on an InGaAs/GaAs metamorphic buffer layer, allowing us to control the emission wavelengths of the QDs by changing the indium composition of the buffer layers and cover layers, growth temperatures of the QDs layers, and indium deposition amount of the QDs layers, thus providing us with a flexible way of turning the emission wavelengths. We also introduce Sb as a surfactant in the growth of a metamorphic layer, which finally becomes a key factor in enlarging the emission wavelengths.

All the samples for the present study were grown on n+ GaAs (100) substrates by solid source molecular beam epitaxy (Veeco Mod Gen II system) equipped with a valved arsenic cracker. After removing the oxide, a 300 nm GaAs buffer was grown at 615°C. Then the substrate temperature was reduced to 390°C. A 300 nm $In_xGa_{1-x}As$ metamorphic buffer layer and 1.5 nm AlAs layer were grown for all the samples followed by *in situ* thermal annealing at 700°C under an arsenic flux of 8×10^{-6} Torr for 10 min. The thin AlAs layer served as a protective layer to avoid indium desorption. The *in situ* thermal annealing reduced the defect densities. After annealing, 80 nm $In_xGa_{1-x}As$ and 2 nm GaAs was grown before the QDs and the substrate temperature was raised from 390°C to T_1 at the same time. The bilayer QDs struc-

*Supported by the National Natural Science Foundation of China under Grant Nos 60625405 and 10734060, and the National Basic Research Program of China under Grant No 2006CB921504.

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tures consist of two layer InAs QDs separated by a 10 nm GaAs spacer layer. The growth rate of the bottom InAs QDs layer was 0.1 ML/s. After deposition of θ_1 ML InAs at T_1, the GaAs spacer layer was deposited. Then the substrate temperature was raised to T_2 for growth of the upper InAs QDs layer with a growth rate of 0.016 ML/s. After θ_2 ML InAs depositions, a 5-nm $In_yGa_{1-y}As$:Sb layer, a 2-nm GaAs and a 40-nm $In_xGa_{1-x}As$ were deposited sequentially. The 2-nm GaAs layers before and after bilayer QDs were deposited to avoid indium phase separation and to obtain smoother surfaces. To analyse morphologies, another bilayer of QDs was grown on the top. The details of the epitaxial structures of the samples are displayed in Fig. 1. The morphologies of the top QDs were evaluated using a Nanoscope IIIa AFM in contact mode. PL measurements were carried out at room temperature (RT) for all the samples under 632.8 nm laser excitation from a He-Ne laser and detected by a cooled Ge detector. The growth conditions of all samples are listed in Table 1.



Fig. 1. Structure of bilayer stacked QDs grown on an $In_{0.05}Ga_{0.95}As$ metamorphic buffer.

Indium composition of metamorphic buffers (MBs) always plays an important role in controlling the wavelength and crystal quality. Figure 2 shows the RT PL spectra of two metamorphic bilayer InAs QD structures grown on $In_xGa_{1-x}As$ MBs with x at 0.05 and 0.06, respectively, The PL intensity dropped deeply when varying the indium composition x of MBs from 0.05 to 0.06 in samples C1 and A3, but without much red shift (from 1.506 μm to 1.508 μm). This means that the stress of the second InAs QDs may change little, so does the confinement effect of the cap layer which offers to the carriers. The decrease of PL intensity with x at 0.06 demonstrates that more dislocations have been introduced into the MB layer due to the indium composition increase.[8] For the purpose of better crystal quality, we choose 0.05 as an optimized parameter for x in the following research.

Recently, our group have demonstrated a 1.58 μm metamorphic InGaAs/GaAs QW laser by using the surfactant effect of Sb to smooth the surface of the InGaAs cover layers.[4] Wu et al also investigated the optical properties of the samples with and without Sb in the cover layers.[9] Thus, InGaAs cover layers combined with Sb have been proposed here. To increase the wavelength, we investigate the influence of indium composition y in the cover layers. As shown in Fig. 3, when we change indium composition y in the cover layer ($In_yGa_{1-y}As$:Sb) from 0.2 to 0.25 (samples A3 and A6), the peak wavelength makes a red-shift of 27 nm (from 1.506 to 1.533 μm) without much PL intensity decrease. We attribute this to the Sb involved as a surfactant, which improves the surface kinetics, thus maintaining a two-dimensional growth mode under high surface stress and allows an increase of the indium composition to make a red-shift.[10] Then, the indium composition is increased to 0.3 (sample B1). However, the PL intensity is dramatically reduced, which is mainly because of too much strain relaxation in the strain reducing layer.

Table 1. Growth conditions of samples A1 to D3. Here x is the indium composition in the metamorphic buffer layers, y is the indium composition in the $In_yGa_{1-y}As$:Sb cover layers, θ_1 and θ_2 are the deposition amounts of indium in the two QD layers, respectively, T_1 is the temperature for the growth of the first layers InAs QDs and T_2 is the growth temperature of the upper InAs QDs layers.

Sample number	Indium compositon (x)	Indium compositon (y)	InAs deposition amount (ML) θ_1	θ_2	Growth temperature (°C) T_1	T_2
A1	0.05	0.2	2.9	3.04	530	470
A2	0.05	0.2	2.9	3.04	530	470
A3	0.05	0.2	2.9	3.68	530	470
A4	0.05	0.2	2.9	4.00	530	470
A5	0.05	0.2	2.9	4.32	530	470
A6	0.05	0.25	2.9	3.68	530	470
A7	0.05	0.25	3.1	3.68	530	470
B1	0.05	0.3	2.9	3.68	530	470
C1	0.06	0.21	2.9	3.68	530	470
D1	0.05	0.25	2.9	3.68	530	480
D2	0.05	0.2	2.9	3.68	520	470
D3	0.05	0.2	2.9	3.68	510	470

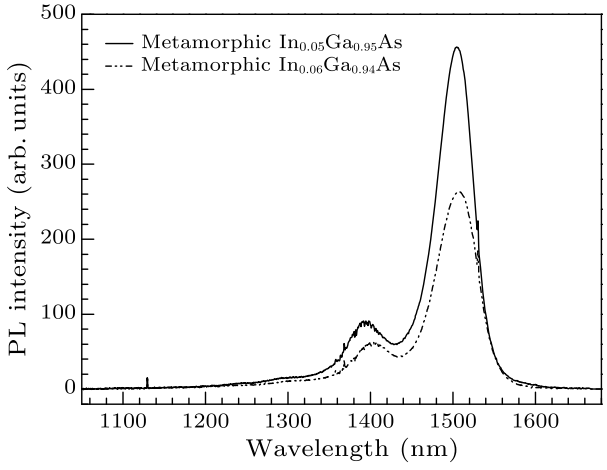


Fig. 2. Photoluminescence of bilayer InAs QDs with different indium composition x in the metamorphic buffer layers.

To understand how the two layers of InAs QDs influence the optical properties, we study the relationship between the different amounts of In deposited (θ_1 and θ_2) in the two layers. When fixing the deposition amount of indium $\theta_2 = 3.68$ ML in the second layer, sample A6 with $\theta_1 = 2.9$ ML and sample A7 with $\theta_1 = 3.1$ ML were prepared to make a comparison. The PL spectra show that variation of the θ_1 value does not have much influence on the wavelength and PL intensity. To the best of our knowledge, this is because the emission only comes from the second layer, and the first InAs QDs layer is used to provide nucleation sites for the second layer.[11]

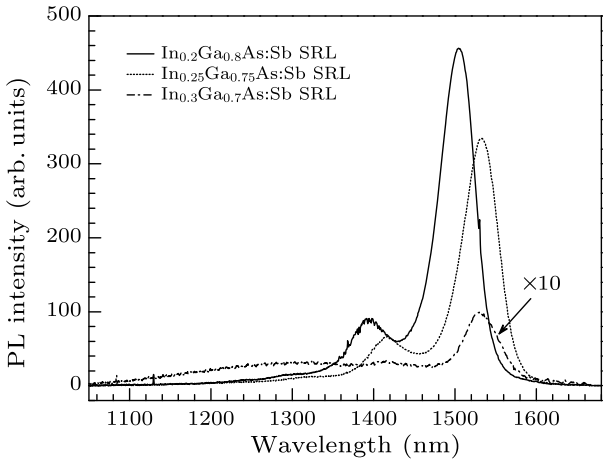


Fig. 3. Photoluminescence of bilayer InAs QDs with different indium composition y in the $In_yGa_{1-y}As$:Sb cover layers.

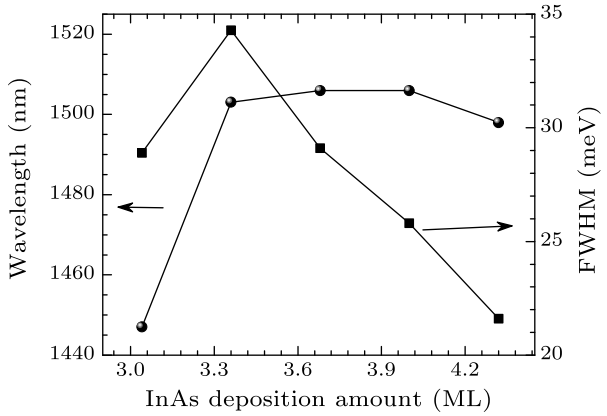


Fig. 4. Wavelength and FWHM as a function of deposition amount θ_2 in the second InAs QDs layers as measured by photoluminescence spectra.

In Fig. 4, we present the bilayer QDs RT emission wavelengths and the PL full width half maximum (FWHM) versus the In deposition amount of θ_2 for samples A1 to A5. The different In deposition amounts in the second QD layer have a great influence on the optical properties when θ_1 is fixed. When the In deposition amount of θ_2 reaches 3.68–4.00 ML, the wavelength reaches the maximum, and then decreases with more indium deposited. By increasing θ_2 up to 3.68 ML we realize that the red-shift is particularly due to the increase of the InAs QDs volume. As the volume of QDs becomes larger, more and more defects such as dislocations have been involved, especially for the bigger QDs, because they are growing much faster than the small ones.[12] Some incoherent islands are formed by the aggregation of several QDs, and the growth of these larger islands is concurrent with the dissolution of the larger QDs.[13] Thus, the light emission mainly comes from smaller QDs, which makes the blueshift occur when the In deposition amount of θ_2 is above 4.0 ML. Also, FWHM reaches the maximum with θ_2 at 3.36 ML mainly because the QDs uniformity in size may be influenced by the growing volume of QDs, which greatly affects the optical quality of the QDs. The FWHM then decreases with the increase of the continuous In deposition amount θ_2, which will subsequently increase the average size of QDs.

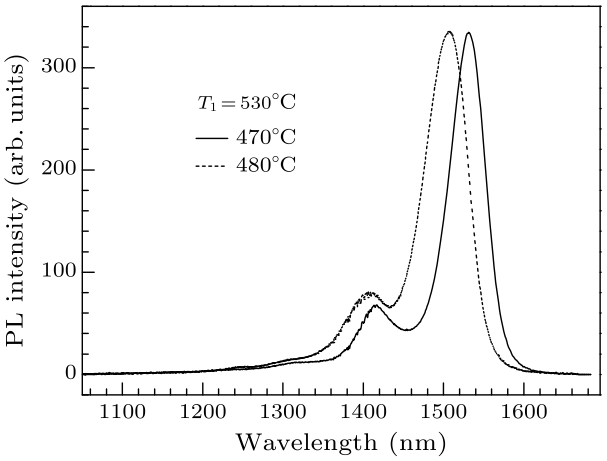


Fig. 5. Photoluminescence of bilayer InAs QDs with different growth temperature T_2 for the upper QDs layers when T_1 is fixed.

Figure 5 shows the RT PL spectra of bilayer InAs QDs with different growth temperatures T_2 for samples A6 and D1. Here θ_1 and θ_2 are fixed to 2.9 ML and 3.68 ML separately with $T_1 = 530$°C. The wavelength increase with the decrease of T_2, which may be due to the fact that the emission only comes from the second layer QDs, and the growth of the second layer InAs QDs at a lower temperature, results in a higher aspect ratio, as well as reduced intermixing.[14] Moreover, strain relaxation is also likely to contribute to the red-shift. Figure 6 shows the RT PL spectra of bilayer InAs QDs with different growth temperatures T_1 for samples A3, D2 and D3 when $T_2 = 470$°C. In contrast, the wavelength increases with increasing T_1. When T_1 reaches 530°C, the wavelength reaches the maximum. AFM measurement shows that the density of upper layer QDs decreases with increasing temperature T_1 as shown in the inset of Fig. 6. When $T_1 = 510$°C, the density of upper layer QDs reaches a maximum of 8.2×10^9 cm^{-2}. Since the total In deposition amount

for the second layer of QDs is fixed and the density of the second QDs is related to the first layer of QDs, larger QDs are involved in the upper layer which finally induces the red-shift.[15]

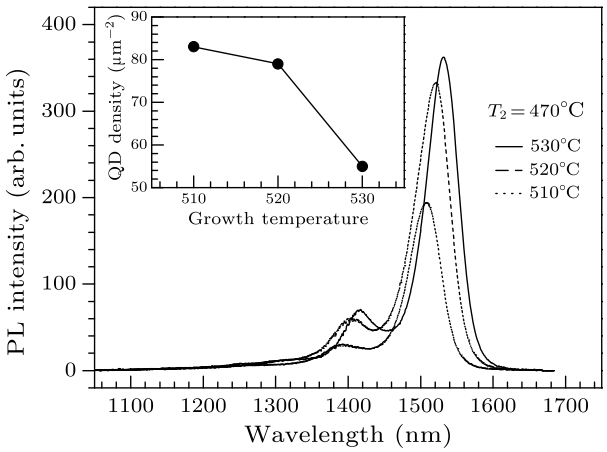


Fig. 6. Variation of QDs densities with growth temperature T_1 (inset) and photoluminescence of bilayer InAs QDs with different growth temperature T_1 for the first QDs layers when T_2 is fixed.

In conclusion, we have investigated molecular beam epitaxy (MBE) growth of bilayer stacked InAs/GaAs QD structures grown on $In_{0.05}Ga_{0.95}As$ metamorphic buffers. By optimizing the growth temperatures for the upper and lower layers of InAs QDs and introducing Sb as a surfactant for growing of InGaAs covering layers on the upper InAs QDs, the emission wavelength of InAs QDs has been extended successfully to 1.533 μm at room temperature and the density of the QDs around 4×10^9–$8 \times 10^9\,\mathrm{cm}^{-2}$. Strong intensity and narrower FWHM of the PL spectrum show the good quality of the QD structures. The experimental results show that the bilayer QDs grown on metamorphic buffers are promising structures for the fabrication of GaAs-based long wavelength devices.

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