Effect of $In_xGa_{1-x}As$ Interlayer on Surface Morphology and Optical Properties of GaSb/InGaAs Type-Ⅱ Quantum Dots Grown on InP (100) Substrates *

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The effects of indium composition in InGaAs interlayer on morphology of GaSb/InGaAs quantum dots (QDs) and on optical properties of GaSb/InGaAs QD material system are studied. AFM images show that the change of the indium composition in InGaAs interlayer can alter the GaSb QD morphology. It is found that low indium composition in InGaAs interlayer can promote the formation of QDs, while high indium composition can inhibit the formation of QDs. The photoluminescence (PL) spectra of GaSb/InGaAs QDs at 8 K under low excitation power indicate that the third root of the excitation power is linear with the peak position, which provides a direct evidence for their luminescence belonging to type-Ⅱ material optical transition. The PL spectra at 8 K under an excitation power of 90 mW show that the optical properties of GaSb/InGaAs QD material system can be affected by the indium composition in the InGaAs interlayer, and the PL peak position is linear with the indium composition. The optical properties of GaSb/InGaAs QDs can be improved by adjusting the indium composition in the InGaAs interlayer.

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In recent years, low-dimensional semiconductor materials with type-Ⅱ band alignment have increasingly attracted attention.[1–5] Group Ⅲ–Ⅴ semiconductor materials with type-Ⅱ band alignment, such as GaSb/GaAs[1,3] and InAs/GaSb,[6,7] are the focus of much research. Their unique band alignment characteristics can help in the realization of photoelectric devices with excellent properties. The growth of InAs quantum-dot field-effect transistors (QD-FET) glimmer detector on GaAs substrates has many excellent properties,[8–10] while it still suffers from some problems, such as low working temperature and small gain factor. However, by employing GaSb/InGaAs quantum dots (QDs) in QD-FET, the absorption peak position can be easily redshifted to 1.3–1.55 μm, and the sensitivity and response factor can be improved.[11] Thus the growth of high-quality GaSb/InGaAs QDs is particularly important.

The epitaxy growth of GaSb QDs is mostly focused on GaAs substrates.[12–14] The growth kinetics of QDs on InP substrates is very different from that on GaAs substrates.[15,16] Recently, the growth of GaSb QDs on InP substrates has been reported, indicating that the optical properties of GaSb/InGaAs type-Ⅱ QDs can be more precisely controlled than that of the widely studied GaSb/GaAs QDs,[17] and the optical properties of this QD material system can be adjusted by both QD-relevant structural characteristics (zero-dimensional structure) and indium composition in InGaAs matrix,[11] while in this epitaxy material system, the InGaAs interlayer where the GaSb QDs grow is only 5 nm thick, which is too thin to eliminate the interference of the other epitaxial layer.

In this work, we investigate the effects of an $In_xGa_{1-x}As$ interlayer, especially its indium composition, on QD morphology and optical properties of GaSb/InGaAs type-Ⅱ QDs. Three groups of samples (A, B, and C) with InGaAs interlayers with different indium compositions are prepared. All of the samples are grown on (100)-oriented semi-insulation Fe-doped InP substrates by a solid-source V80 molecular beam epitaxy (MBE) system. The specific epitaxy structures for the three groups of samples are listed in Table 1.

The detailed growth process of the experimental samples is as follows: first, the surface oxides of the InP substrate were desorbed at a substrate temperature of approximately 530℃. Second, a 300-nm-thick $In_{0.53}Ga_{0.47}As$ buffer layer matched with the InP substrate was deposited on the InP substrate at a growth

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rate of 5000 Å/h, and a 200-nm-thick $In_xGa_{1-x}As$ interlayer with different indium compositions was deposited. Then, five-monolayer (ML) GaSb QDs were deposited at a growth rate of 0.13 ML/s. There was a 180-s growth interruption before the QD growth and a 120-s growth interruption after the QD growth. Afterwards, a 100-nm-thick $In_xGa_{1-x}As$ interlayer was grown at a rate of 5000 Å/h. Finally, a top layer of surface GaSb QDs was deposited under identical conditions. After the epitaxy growth was complete, the samples were cooled under Sb_4 flux. The first QD layer was used for measurement of the GaSb/InGaAs optical properties, and the second QD layer was used for the QD morphology characteristics. In the growth process of the samples, the temperature was 475℃.

Table 1. Structure for samples A, B and C.

Samples	A	B	C
GaSb QDs		0.13 ML/S 5ML	
Interlayer	100-nm $In_{0.53}Ga_{0.47}As$	100-nm-thick $In_{0.45}Ga_{0.55}As$	100-nm-thick $In_{0.6}Ga_{0.4}As$
GaSb QDs		0.13 ML/S 5ML	
Interlayer	200-nm-thick $In_{0.53}Ga_{0.47}As$	130-nm-thick $In_{0.45}Ga_{0.55}As$ 70-nm-thick $In_xGa_{1-x}As$ continuously graded x from 0.53 to 0.45	130-nm-thick $In_{0.6}Ga_{0.4}As$ 70-nm-thick $In_xGa_{1-x}As$ continuously graded x from 0.53 to 0.6
Buffer layer		300-nm-thick $In_{0.53}Ga_{0.47}As$	
Substrate		(100) semi-insulating InP	

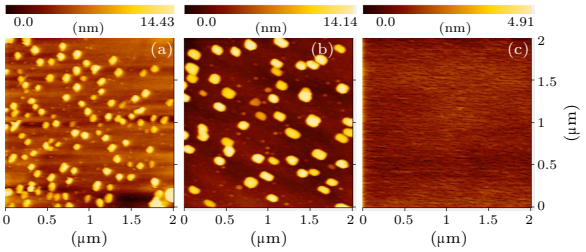

Fig. 1. AFM images for samples A, B and C. Indium composition in the InGaAs interlayer is (a) 0.53, (b) 0.45 and (c) 0.6.

The morphology and optical properties of the QDs were measured and characterized by atomic force microscopy (AFM) and photoluminescence (PL), respectively. The AFM measurements were conducted in a tapping mode in air, and the PL measurements were excited at a temperature of 8 K, using a 532 nm laser source with an excitation power from 0 mW to 90 mW.

Figure 1 shows the AFM images of samples A, B and C grown on different buffer layers, $In_{0.53}Ga_{0.47}As$, $In_{0.45}Ga_{0.55}As$ and $In_{0.6}Ga_{0.4}As$, respectively. The QD density, average size and height for sample A were around $3.5 \times 10^9\,cm^{-2}$, 80 nm, and 9 nm, respectively. However, for sample B, the QD density is $1.7 \times 10^9\,cm^{-2}$, which is lower than that of sample A, and the lateral and vertical sizes are 110 nm and 11 nm, respectively, which are larger than that of sample A. The surface of sample C is flat and no QDs appear on it.

The influence of the InGaAs interlayer on QD morphology has been intensively studied in the InAs/InGaAs material system, and strain accumulation plays an important role in the nucleation and growth process of the InAs/InGaAs QD system.[17,18] The same reason could be used to explain different GaSb surface morphologies where the GaSb layer was grown on the InGaAs interlayer with different indium compositions.

The mismatch rate between GaSb and $In_{0.53}Ga_{0.47}As$ is only 3.9%. The strain occurs in the GaSb layer when the GaSb layer is grown on the $In_{0.53}Ga_{0.47}As$ interlayer. The GaSb layer exceeds the critical thickness and GaSb QDs start forming, and the morphologies of the QDs become gradually obvious with further growth. Thus the size and density of QDs are ideal, as sample A shown in Fig. 1(a). For sample B, low indium composition in interlayer ($In_{0.45}Ga_{0.55}As$ interlayer) causes the lattice mismatch between InGaAs and GaSb greater compared with that in sample A. The strong strain generated by the lattice mismatch, accumulates to the GaSb layer, leads to lower critical transition thickness and breaks through two-dimensional (2D) growth model into the 3D early, promoting the formation of QDs. After breakthrough of the 2D growth model, the size of QDs becomes larger and larger with continuous growth. Then, the large QDs adsorb small QDs around them, making the size of GaSb QDs larger and the density lower, as shown in Fig. 1(b). The surface of sample C is flat, and no GaSb QDs appear on it, which also resulted from the strain. When the GaSb layer is deposited on higher indium composition in the InGaAs interlayer ($In_{0.6}Ga_{0.4}As$ interlayer), the lattice mismatch between $In_{0.6}Ga_{0.4}As$ and GaSb is smaller, thus the strain accumulated in the GaSb layer is weaker compared with that in sample A. The weak strain increases the critical transition thickness of GaSb QDs and leads to the GaSb layer being unable to break through the 2D growth model into the 3D, therefore inhibits the formation of QDs and makes the surface of sample C flat and no obvious GaSb QDs appear. The 2D–3D growth model transitions were also be observed and verified by the streaky reflection high-energy electron diffraction (RHEED)

pattern in the MBE growth process of GaSb/InGaAs QDs. In short, different indium compositions in the InGaAs interlayer can change the GaSb QD morphology. Within certain thicknesses of GaSb QDs, low indium composition in the InGaAs interlayer can promote the formation of GaSb QDs, while high indium composition in the InGaAs interlayer can inhibit the formation of GaSb QDs.

The PL mechanism of the QDs is related to the electronic accumulation at the interface between GaSb/InGaAs and can be explained through the energy band alteration of GaSb/InGaAs heterojunction. The electric field near the GaSb/InGaAs interface caused by spatial separation of electrons and holes will make the band bend and form approximately triangular wells adjacent to the heterojunction. With the increase of the excitation power, the number of electrons and holes at the interface between GaSb/InGaAs increases, which results in the increase of triangle trap well depth and slope. In this case, electronic discrete energy levels within the triangle trap rise and the band gap increases, which result in the QD PL peak blue shift. Figure 2 shows the PL peak energies of GaSb/InGaAs QDs at 8 K with an excitation power in the range 0.2–90 mW.

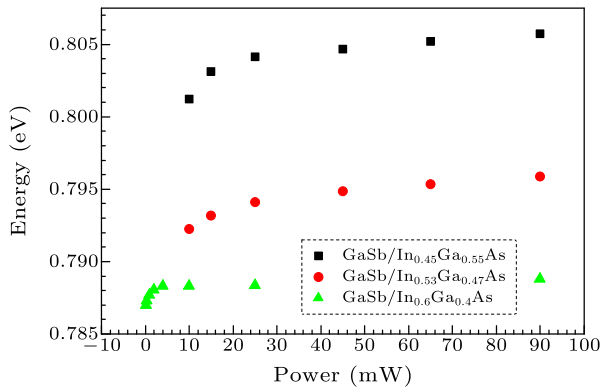

Fig. 2. The PL peak energies of GaSb/InGaAs QDs at 8 K with the excitation power in the range 0.2–90 mW.

As illustrated in Fig. 2, for samples A and B, the peak positions blue shift as the excitation power increases from 10 mW to 90 mW. Here the PL spectra in the case of excitation power below 10 mW are too imprecise to record. While for sample C, the blueshift phenomenon exists in a range of the excitation power, varying from 0.2 mW to 4 mW, and as the excitation power increases further, the type-Ⅱ QD peak position remains unchanged, this case results from the saturation of electrons and holes in the interface of InGaAs and GaSb. In spite of saturation, the luminescence still belongs to the type-Ⅱ optical transition. The PL peak blueshifts with the increase of the excitation power is a special character of type-Ⅱ heterostructures.[11] The change of peak position with the excitation power for sample C is different from that for samples A and B. The causes of this phenomenon are related to indium composition in the InGaAs interlayer. Compared with samples A and B, sample C is observed with blue shift phenomenon under lower excitation power, which is mainly related to the indium composition in the InGaAs interlayer. The lattice mismatch between $In_{0.6}Ga_{0.4}As$ and GaSb is smaller, which leads to a weaker strain in the GaSb layer generated in GaSb epitaxy on $In_{0.6}Ga_{0.4}As$ interlayer. This weak strain increased the thickness of the wetting layer and made it unable to break through the 2D growth model into the 3D. The thicker wetting layer makes the electrons and holes at the interface of InGaAs and GaSb become saturated under smaller excitation power. When the excitation power reduces to below the critical value, type-Ⅱ QD luminescence phenomenon could be observed. To illustrate the specific changes of different excitation powers versus the PL peak, the relationship between the third root of the excitation power and the peak position is depicted in Fig. 3.

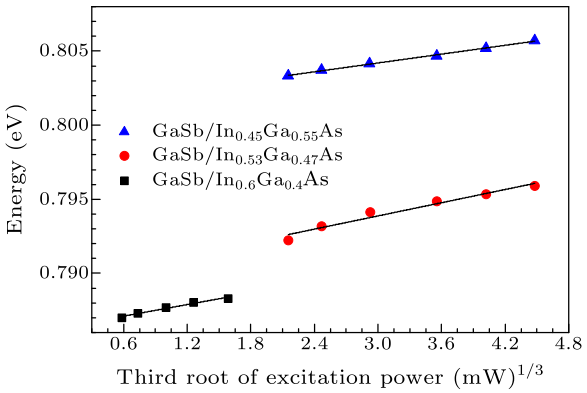

Fig. 3. The fitting curves of the peak energies versus the third root of the excitation power.

That the PL peak energy linearly depends upon the third root of the excitation power is further evidence of the type-Ⅱ QDs optical transition on semiconductor heterostructures.[11] The relationship between PL peak position and the excitation power satisfies

$$E_{\mathrm{PL}} = E^0_{\mathrm{PL}} + CP^{1/3},$$

where E^0_{PL} stands for the case where the excitation power is zero, and C is a constant related to the characteristics of the GaSb/InGaAs heterojunction itself.[19] From Fig. 3, it can be found that the relationship between the third root of the excitation power and peak position is linear, which can prove that the luminescence is a type-Ⅱ QDs material optical transition.

Figure 4 depicts the PL spectra for samples A–C at 8 K with excitation power 90 mW. Here the excitation power 90 mW is selected to obtain clearer PL spectra for further analysis. In the PL spectra obtained at 8 K under an excitation power of 90 mW, the peak wavelengths of samples A–C are 1557 nm,

1539 nm and 1573 nm, respectively, and the corresponding band gap energies are 0.7964 eV, 0.8057 eV and 0.7883 eV, respectively. The relationship curve of PL peak position versus indium composition in the InGaAs interlayer is depicted in Fig. 5.

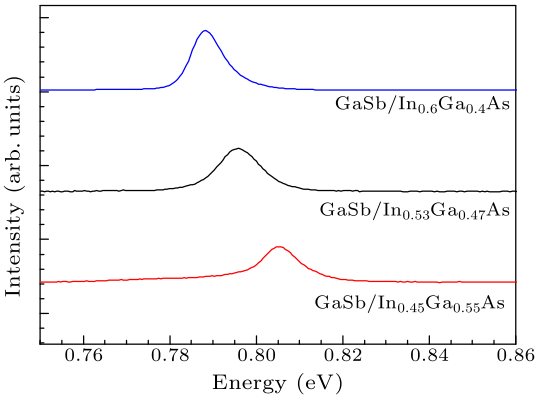

Fig. 4. The PL spectra for samples A–C at 8 K with excitation power 90 mW.

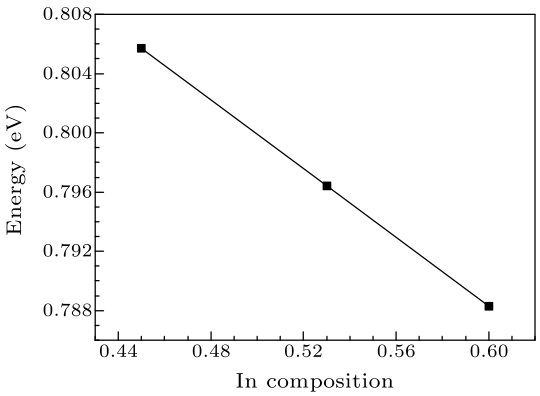

Fig. 5. The relationship curve of PL peak position versus indium composition in the InGaAs interlayer.

As shown in Fig. 5, the PL peak position has a nearly linear relationship with the indium composition in the InGaAs interlayer. The change of indium composition in the InGaAs interlayer has obviously modified its band gap. The curve in Fig. 5 indicates that the band gap of the InGaAs interlayer narrows in a nearly linear way with the increase of the indium composition, which can obtain assisted support from the well-known Vegard law. Considering that the type-II optical transition in the GaSb/InGaAs QD material system mainly utilizes the conduction band of the InGaAs interlayer, it is not difficult to anticipate that the PL peak position generates redshift with the increase of the indium composition in the InGaAs interlayer under the same excitation power. The results show that the GaSb/InGaAs QDs optical properties can be adjusted by the indium composition in InGaAs QDs materials, and the optical properties of GaSb/InGaAs QDs can be much better controlled by adjusting the indium composition in InGaAs.

In conclusion, we have demonstrated that the surface morphology of the QD could be changed by varying the indium composition in the InGaAs interlayer within certain thicknesses of the GaSb QDs layer. The low indium composition in the InGaAs interlayer can promote the formation of QDs and high indium composition inhibits the formation of QDs. The PL spectra of GaSb/InGaAs QDs at 8 K prove that this kind of luminescence is a type-II QDs material optical transition. The PL peak position is linear with the third root of the excitation power under certain ranges of excitation power. Meanwhile, the optical properties of GaSb/InGaAs QD materials can be adjusted by adjusting the indium composition in the InGaAs interlayer, and the relationship between light wavelength and indium composition is linear. As a result, adjusting the indium composition in the InGaAs interlayer can better control the optical properties of GaSb/InGaAs materials.

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