Semiconductors, Vol. 37, No. 5, 2003, pp. 559–563. Translated from Fizika i Tekhnika Poluprovodnikov, Vol. 37, No. 5, 2003, pp. 578–582.

LOW-DIMENSIONAL SYSTEMS

Structural and Optical Properties of InAs Quantum Dots in AlGaAs Matrix

D. S. Sizov, Yu. B. Samsonenko, G. E. Tsyrlin, N. K. Polyakov, V. A. Egorov, A. A. Tonkikh, A. E. Zhukov, S. S. Mikhrin, A. P. Vasil'ev, Yu. G. Musikhin, A. F. Tsatsul'nikov, V. M. Ustinov, and N. N. Ledentsov

Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia

Submitted June 25, 2002; accepted for publication June 28, 2002

Abstract—Structural and optical properties of InAs quantum dots (QDs) grown in a wide-bandgap $Al_{0.3}Ga_{0.7}As$ matrix is studied. It is shown that a high temperature stability of optical properties can be achieved owing to deep localization of carriers in a matrix whose band gap is wider than that in GaAs. Specific features of QD formation were studied for different amounts of deposited InAs. A steady red shift of the QD emission peak as far as ~1.18 μm with the effective thickness of InAs in $Al_{0.3}Ga_{0.7}As$ increasing was observed at room temperature. This made it possible to achieve a much higher energy of exciton localization than for QDs in a GaAs matrix. To obtain the maximum localization energy, the QD sheet was overgrown with an InGaAs layer. The possibility of reaching the emission wavelength of ~1.3 μm is demonstrated. © *2003 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The investigations of self-organized quantum dots (QD) on GaAs substrates are motivated, among other factors, by the prospect of applying them in high-efficiency light-emitting devices [1]. Interest in heterostructures with self-organized QDs in the InAs/GaAs system is due to the possibility of expanding the spectral range of GaAs-based structures to wavelengths $\lambda = 1.3$–1.5 μm, which would open the way for the design of lasers with an emission wavelength longer than in InGaAs/GaAs QD lasers [2]. In particular, vertical-cavity surface-emitting lasers were designed [3], and 1.3-μm stripe lasers with a record-breaking low threshold current density and high internal differential efficiency have been fabricated [4, 5]. One of the most important parameters for lasing is the energy depth of carrier localization in QDs: the higher the confining barrier, the lower the threshold current density and the better the temperature stability of parameters [6].

We now consider the quantity

$$\Delta E = \Delta E_e + \Delta E_h = E_{pl}^{\mathrm{GaAs}} - E_{pl}^{\mathrm{QD}},$$

where ΔE_e is the energy spacing between the conduction band bottom and the electron ground state in a QD; ΔE_h is the spacing between the hole ground state in a QD and the valence band top; and E_{pl}^{GaAs} and E_{pl}^{QD} are the energies of electron–hole transitions for recombination in the matrix and QD, respectively. This quantity characterizes the energy of the electron localization in a QD with respect to a nonlocalized exciton in the matrix. An emission wavelength up to 1.4 μm has been achieved in In(Ga)As/GaAs QD structures [7], with ΔE_e not exceeding 0.55 eV. However, the use of a wide-bandgap AlGaAs matrix for QDs provides for a significant rise in ΔE.

As shown in [8], InAs QDs in $Al_{0.5}Ga_{0.5}As$ grow by the Stranski–Krastanow mechanism, with the transition to island growth after the deposition of 2.1 InAs monolayers (ML). This amount of deposited InAs is higher than in the case of growth on the GaAs surface, owing to a difference in the kinetics of indium deposition onto GaAs and AlGaAs surfaces [8]. In these structures, ΔE exceeded 0.6 eV. Temperature dependences of photoluminescence (PL) indicated a higher temperature stability of the optical properties of QDs in AlGaAs compared with QDs in a GaAs matrix, with the exciton localization energy in the latter case being smaller. The study of the effect of the $Al_xGa_{1-x}As$ matrix composition on QD optical properties revealed that the widening of the matrix band gap results in a smaller decrease in the PL intensity with rising temperature; this fact also indicates the strong effect of the exciton localization depth on the temperature stability of QD optical properties [9].

Here we present a detailed study of InAs QD formation in an $Al_{0.3}Ga_{0.7}As$ matrix. The effect of the amount of deposited InAs on the optical properties of QDs in the $Al_{0.3}Ga_{0.7}As$ matrix was also studied. It has been shown that the overgrowth of the QD layer with an InGaAs layer opens the way to obtain emission in the range up to ~1.3 μm.

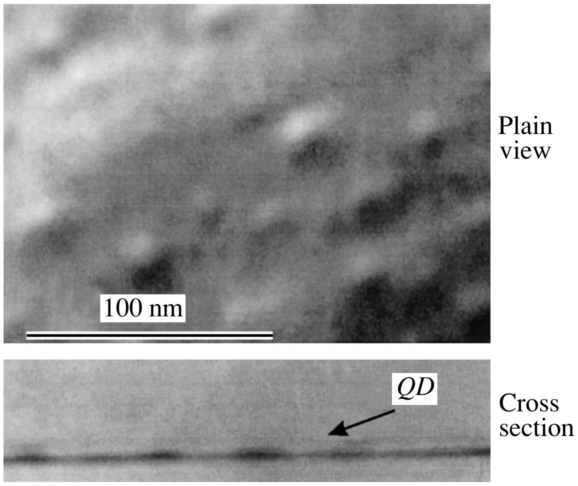

Fig. 1. TEM images of QDs in an $Al_{0.3}Ga_{0.7}As$ matrix.

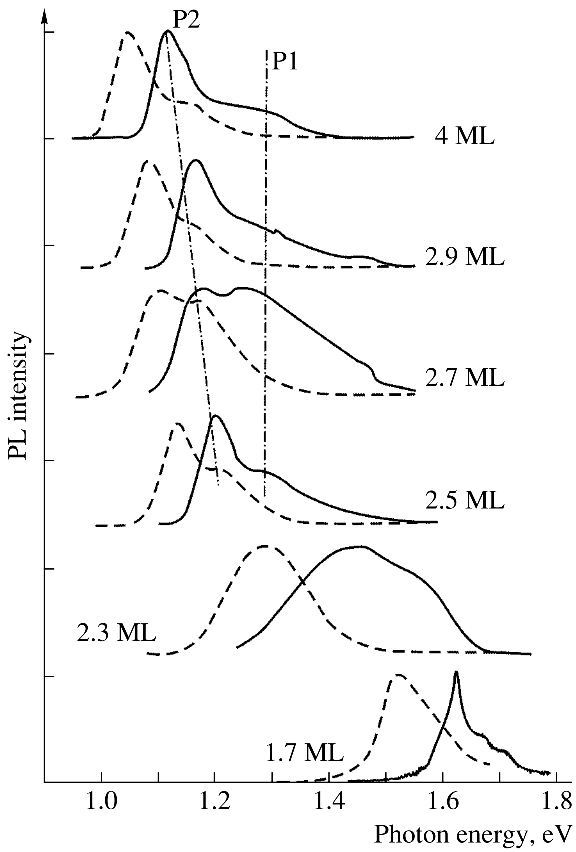

Fig. 2. PL spectra of QD structures with differing amounts of InAs deposited in the $Al_{0.3}Ga_{0.7}As$ matrix recorded at 77 K (solid lines) and 300 K (dashed lines).

2. EXPERIMENTAL

QD structures were grown by MBE. After the deposition of a GaAs buffer layer, a 0.1-μm-thick $Al_{0.3}Ga_{0.7}As$ layer was grown, with a sheet of InAs QDs deposited in the middle of this layer. To prevent carrier leakage to the surface and substrate, which is followed by nonradiative recombination, the $Al_{0.3}Ga_{0.7}As$ layer with QDs was confined by short-period superlattices (five AlGaAs/GaAs periods, 20/20 Å) on the sides of the substrate and surface. All layers, except the InAs QD sheet and the subsequent 5 nm of AlGaAs, were grown at the temperature of 600°C. QDs were formed by depositing a thin InAs layer at 485°C. The effective thickness of the InAs layer was varied between 1.7 and 4.5 ML, and the RHEED patterns recorded *in situ* demonstrated the formation of nanoislands after depositing more than 2 ML of InAs. The InAs growth rate was 0.1 ML s^{-1}. The sheet of InAs islands was then overgrown with a thin (5-nm) $Al_{0.3}Ga_{0.7}As$ layer at the temperature of InAs deposition to prevent the evaporation of InAs upon the subsequent rise in temperature [10]. In one of the samples, the sheet of InAs nanoislands was overgrown with an $In_{0.12}Ga_{0.88}As$ layer in an effort to increase the emission wavelength, and only then was the 5-nm $Al_{0.3}Ga_{0.7}As$ layer deposited. To compare optical properties, samples with InAs QDs in a GaAs matrix were also grown.

The PL was excited with an Ar-ion laser (λ = 514.5 nm, the excitation power density P_{ex} = 500 W cm^{-2}) and detected with a cooled Ge photodiode.

A TEM study was performed with a PHILIPS EM 420 electron microscope with a 100-kV accelerating voltage.

3. RESULTS AND DISCUSSION

Figure 1 shows the cross-sectional and plan-view TEM images of a structure containing QDs in an $Al_{0.3}Ga_{0.7}As$ matrix. The effective thickness of the InAs layer deposited in this structure was 2.5 ML. Three-dimensional (3D) InAs nanoislands and a thin two-dimensional (2D) InAs wetting layer [11] are seen in the images. According to TEM data, the lateral dimension and height of the nanoislands are ~18 and 5 nm, respectively, which corresponds to a typical QD size in a GaAs matrix [12]. Therefore, the use of $Al_{0.3}Ga_{0.7}As$ solid solution instead of pure GaAs as the matrix material causes no fundamental change in the QD formation mechanism.

Figure 2 shows the QD PL spectra for structures with differing amounts of InAs in the $Al_{0.3}Ga_{0.7}As$ matrix, recorded at temperatures T = 77 and 300 K. The spectrum of the sample with an effective InAs thickness of 1.7 ML contains a relatively narrow peak with a broadened short-wavelength wing. This type of spectrum shape indicates that the 2D InAs layer is retained and its thickness is lower than the critical value for QD formation. With the InAs thickness increasing to 2.3 ML, the PL peak is considerably broadened (to 240 meV) and red-shifted. A large line broadening indicates the beginning of 3D-island formation [13]. This result is consistent with the RHEED data showing that the QD formation in an $Al_{0.3}Ga_{0.7}As$ matrix begins at an effective InAs thickness of ~2 ML. A further increase in the InAs layer thickness red-shifts the PL peak to 1.18 μm at T = 300 K. In addition to a P2 peak related to the ground state, a short-wavelength shoulder P1 is observed; it can be related to recombination via smaller QDs or excited states.

Figure 3 shows the PL peak positions for QDs in $Al_{0.3}Ga_{0.7}As$ and GaAs matrices as functions of the InAs layer thickness. The calculated energy of the transition between electron and heavy hole states in an InAs/$Al_{0.3}Ga_{0.7}As$ quantum well (QW) with a thickness of 1 ML [14] is also shown. The PL peak of a QD in the $Al_{0.3}Ga_{0.7}As$ matrix exhibits a strictly monotonic red shift as the amount of InAs increases. The rate of shifting is higher when the effective thickness of the InAs layer is between 1.7 and 2.5 ML. This thickness corresponds to the onset of QD formation. In the GaAs matrix, the QD PL line position depends on the InAs layer thickness in a somewhat different manner: the peak position is virtually independent of the amount of deposited InAs at a thickness above 2.3 ML. Different behaviors of the QD PL peak positions in $Al_{0.3}Ga_{0.7}As$ and GaAs matrices can originate from different conditions of QD formation during the growth process. We believe that, in this case, we are dealing with differences in the kinetics of the surface processes during InAs deposition onto $Al_{0.3}Ga_{0.7}As$ and GaAs surfaces [8], including those differences related to the morphology of the $Al_{0.3}Ga_{0.7}As$ surface.

Because of the nearly complete termination of the shift of the PL line for QDs in the GaAs matrix, ΔE does not exceed ~0.42 eV. At the same time, ΔE is ~0.76 eV for QDs grown in the $Al_{0.3}Ga_{0.7}As$ matrix in the same mode. These results are indicative of deeper exciton localization in the $Al_{0.3}Ga_{0.7}As$ matrix. In our opinion, the reason for such a high ΔE is, in addition to the structural properties of the QDs themselves, the great height of the confining $Al_{0.3}Ga_{0.7}As$ barrier.

Figure 4 shows the temperature dependence of PL for a sample with QDs formed by deposition of 4 ML InAs in the $Al_{0.3}Ga_{0.7}As$ matrix. Two peaks, P_1 and P_2, 150 meV apart are well resolved at low temperatures. The relative intensity of the short-wavelength peak decreases with rising temperature. This temperature dependence of the intensity of these peaks indicates that they are related to recombination in QDs with different sizes. In this situation, the decrease in the short-wavelength peak intensity is due to carrier excitation into the matrix and the recapture of carriers by deeper QDs. The formation of two QD types can be related to specific features of the surface morphology of $Al_{0.3}Ga_{0.7}As$ [7], as well as to the kinetics of processes occurring during deposition in the InAs/$Al_{0.3}Ga_{0.7}As$ system.

The insert in Fig. 4 shows temperature dependences of the integral intensity, energy E_m, and FWHM of the PL peak for structures with 2.3 and 4 ML of InAs. The

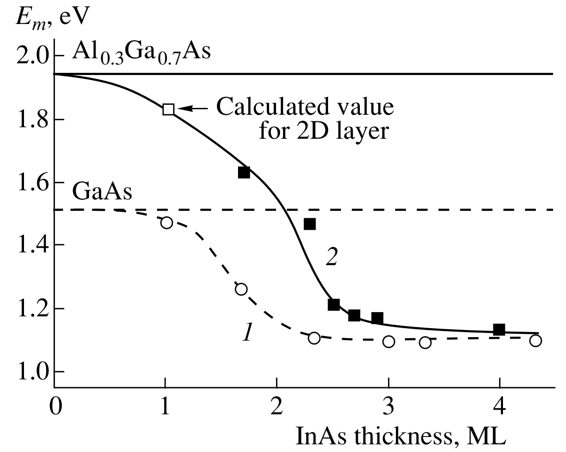

Fig. 3. The PL peak spectral position E_m vs. the amount of deposited InAs: (*1*) in a GaAs matrix, (*2*) in an $Al_{0.3}Ga_{0.7}As$ matrix.

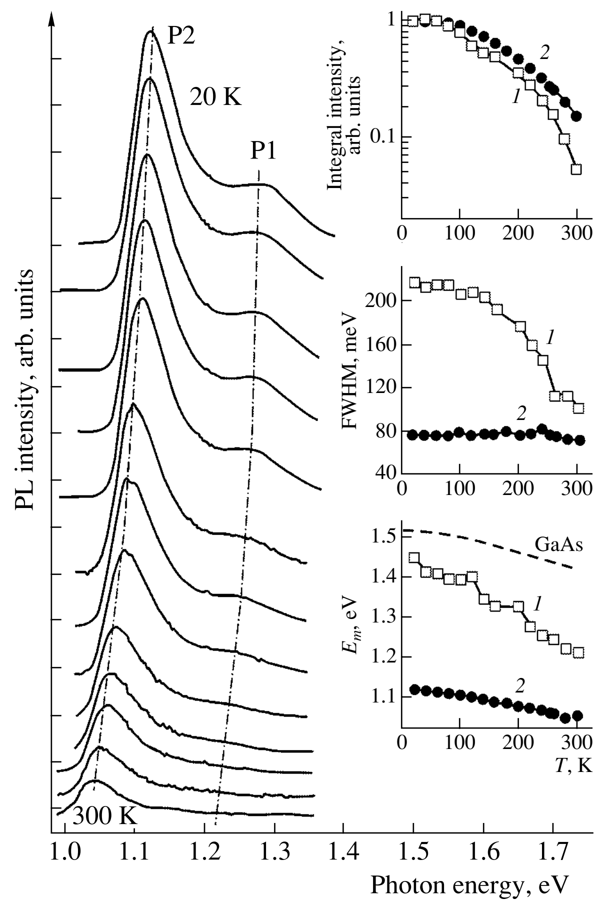

Fig. 4. The PL spectra at different temperatures for QDs in an $Al_{0.3}Ga_{0.7}As$ matrix. The effective thickness of the InAs layer was 4 ML. The spectra (top-down) correspond to the temperature variation from 20 to 300 K. Insert: temperature dependences of the integral intensity, full width at half-maximum (FWHM), and peak energy for structures with an InAs layer effective thickness of (*1*) 2.3 and (*2*) 4 ML.

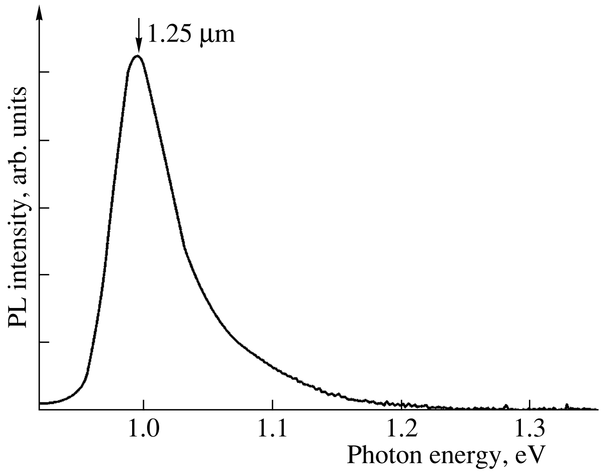

Fig. 5. The room-temperature PL spectrum of InAs QDs overgrown with an $In_{0.12}Ga_{0.88}As$ layer in an $Al_{0.3}Ga_{0.7}As$ matrix.

dependences are normalized to the integral intensity at the lowest temperature. The decrease in the PL integral intensity for a structure with 2.3 ML of InAs is three times that of a structure with 4 ML of InAs. The temperature-induced decrease in the PL integral intensity is due to nonradiative recombination of carriers thermally excited into the matrix. Since the average energy of the exciton localization in QDs formed by the deposition of 2.3 ML of InAs is less than that for 4 ML InAs, carrier excitation at low temperatures is more probable in the former case. This results in a stronger decrease in the emission intensity for the 2.3-ML InAs structure. Further, the thermal excitation of carriers is more probable for the least localized QD states responsible for the short-wavelength portion of the spectrum. This accounts for the considerable decrease in the linewidth for QDs formed by 2.3-ML InAs deposition. The temperature shift of the PL peak, in this case, is stronger than that for the 4-ML InAs structure, because it is caused not only by the temperature-related decrease in the band gap, but also by the redistribution of carriers between isolated QDs differing in their exciton localization energy. An insignificant temperature-induced decrease in the QD PL intensity for the 4-ML InAs structure is indicative of not only deep exciton localization, but also a low defect density in these samples.

Figure 5 shows the PL spectrum of the structure with an $Al_{0.3}Ga_{0.7}As$ matrix and QDs overgrown with an InGaAs layer. After deposition of an InAs layer with an effective thickness of 2.5 ML, an $In_{0.12}Ga_{0.88}As$ layer was deposited. A similar technique for QD growth in a GaAs matrix makes the QD emission wavelength much longer, 1.3 μm [15], and yields high-efficiency lasers for this spectral range. The increase in the wavelength may originate from several causes: the increase in the QD effective size owing to stimulated phase separation in InGaAs, the decrease in the elastic stress fields in QDs, and the quantum-mechanical effect associated with placing a QD in an InGaAs QW [15]. We have obtained room-temperature emission at a wavelength $\lambda = 1.25$ μm from such QDs grown in an $Al_{0.3}Ga_{0.7}As$ matrix (Fig. 5). Owing to a high potential barrier, the ΔE value in these structures is 0.86 eV. Therefore, the exciton localization energy for QDs in AlGaAs is considerably higher than that in a GaAs matrix.

4. CONCLUSION

The structural and optical properties of QDs in an $Al_{0.3}Ga_{0.7}As$ matrix have been studied. QDs in $Al_{0.3}Ga_{0.7}As$ are formed by the Stranski–Krastanow mechanism, which is the same way they are formed in a GaAs matrix. However, the critical thickness for the transition to island growth for QDs in $Al_{0.3}Ga_{0.7}As$ is slightly higher (~2 ML) than in a GaAs matrix.

In the case of an $Al_{0.3}Ga_{0.7}As$ matrix, the red shift of the QD PL spectral line is observed as the average InAs thickness increases up to 4 ML. By contrast, the red shift almost terminates at ~2.3 ML for QDs grown in a GaAs matrix. The overgrowing of QDs in the $Al_{0.3}Ga_{0.7}As$ matrix with an InGaAs layer allowed us to raise the emission wavelength to 1.25 μm, and to obtain an energy of exciton localization in a QD that was considerably higher than that for a GaAs matrix at the same emission wavelength.

The high temperature stability of the optical properties of QDs in a wide-gap $Al_{0.3}Ga_{0.7}As$ matrix offers promise for the design of light-emitting devices with improved thermal characteristics.

ACKNOWLEDGMENTS

This study was supported by INTAS, the Russian Foundation for Basic Research, and the Ministry of Industry and Science of the Russian Federation program “Physics of Solid-State Nanostructures”.

REFERENCES

1. Y. Arakawa and H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).
2. V. M. Ustinov and A. E. Zhukov, Semicond. Sci. Technol. **15**, R41 (2000).
3. J. A. Lott, N. N. Ledentsov, V. M. Ustinov, *et al.*, Electron. Lett. **36**, 1384 (2000).
4. S. S. Mikhrin, A. E. Zhukov, A. R. Kovsh, *et al.*, Fiz. Tekh. Poluprovodn. (St. Petersburg) **36**, 1400 (2002) [Semiconductors **36**, 1315 (2002)].
5. M. V. Maximov, L. V. Asryan, Yu. M. Shernyakov, *et al.*, IEEE J. Quantum Electron. **37**, 676 (2001).
6. B. V. Volovik, D. S. Sizov, A. F. Tsatsul’nikov, *et al.*, Fiz. Tekh. Poluprovodn. (St. Petersburg) **34**, 1368 (2000) [Semiconductors **34**, 1316 (2000)].

7. K. Kokie, H. Ohkawa, and M. Yano, Jpn. J. Appl. Phys. **38**, L417 (1999).
8. Y. S. Kim, U. H. Lee, D. Lee, *et al.*, J. Appl. Phys. **87**, 241 (2000).
9. M. V. Maximov, A. F. Tsatsul'nikov, B. V. Volovik, *et al.*, Phys. Rev. B **62**, 16671 (2000).
10. D. S. Sizov, M. V. Maksimov, A. F. Tsatsul'nikov, *et al.*, Fiz. Tekh. Poluprovodn. (St. Petersburg) **36**, 1097 (2002) [Semiconductors **36**, 1020 (2002)].
11. V. A. Shchukin, N. N. Ledentsov, P. S. Kop'ev, and D. Bimberg, Phys. Rev. Lett. **75**, 2968 (1995).
12. A. F. Tsatsul'nikov, A. R. Kovsh, A. E. Zhukov, *et al.*, J. Appl. Phys. **88**, 6272 (2000).
13. J. M. Moison, F. Houzay, F. Barthe, *et al.*, Appl. Phys. Lett. **64**, 196 (1994).
14. R. Heitz, T. R. Ramachandran, A. Kalburge, *et al.*, Phys. Rev. Lett. **78**, 4071 (1997).
15. M. Krjin, Semicond. Sci. Technol. **6**, 27 (1991).

Translated by D. Mashovets