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The influence of the chemical composition of the surrounding layers on the optical properties of InGaP(As) quantum dots

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The results of a study of the effect of the location and chemical composition of InGaAs quantum wells in GaAs/AlGaAs/InGaP/InGaAs heterostructures on the optical properties of InGaP(As) quantum dots obtained by molecular beam epitaxy due to the substitution of phosphorus with arsenic in the InGaP layer during epitaxial growth are presented. It is shown that a blue shift of the quantum dots array photoluminescence maximum is observed using the InGaAs quantum well as a cap layer. Using of the InGaAs quantum well as the InGaP(As) quantum dots formation surface does not lead to the shift of the maximum photoluminescence spectrum wavelength. An increase of the InAs molar fraction in the InGaAs cap layer from 0.17 to 0.23 leads to a blue shift of the quantum dot array maximum photoluminescence spectrum by 108 nm.

Keywords: molecular-beam epitaxy, quantum dots, heterostructure, semiconductors.

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1. Introduction

The nanoscale semiconductor objects ensure significant improvement of characteristic if radiation sources due to quantization effect. One of the most developed disciplines of quantum dots (QD) application is use of arrays of semiconductor QDs as active areas for sources of optical radiation of near infrared (IR) band [1–5]. Previously in paper [6] we suggested the method of obtaining the semiconductor QDs InGaP(As) of spectral range 1 μm, obtained by substitution of phosphorus with arsenic in semiconductor layer InGaP during epitaxial growth by method of molecular-beam epitaxy (MBE).

In present paper we studied effect of molar fraction of InAs in InGaAs layer, used as deposition surface and cap layer, on optical properties of QD InGaP(As).

2. Materials and methods

The heterostructures for study were prepared by MBE method on semi-isolating substrates GaAs (100) using Riber49 production system (France). Five heterostructures (QD1−QD5) were prepared, they differ by the presence and location of quantum well (QW) in the heterostructure, and by molar fraction of InAs in QW composition. The base structure of heterostructure (QD1), that differs by QWs absence, indicating thicknesses and molar fraction of materials in triple solutions is shown in Figure 1, *a*. The transformed into QDs array the semiconductor layer InGaP, agreed by lattice parameter with substrate, has thickness 2 nm. The process of InGaP(As) QD formation by substitution of phosphorus with arsenic is described in details in previous paper [6].

The heterostructure studied here were prepared at growth temperature 580°C. Transformed layer InGaP, and cap layer 5 nm thick were deposited at temperature 520°C. Total time for substitution of stream of material of V group and heterostructure holding in arsenic stream was 5 min. Two Ga sources were used: first — to form InGaP layer (deposition rate 0.2 ML/s), second — for rest Ga-containing layers (deposition rate 0.6 ML/s). Ratio of streams of materials of III group to materials of V group is maintained at 1 : 10 during the entire growth process.

Series of heterostructures QD2−QD5 with QD1 InGaAs 5 nm addition to the base structure was prepared. For heterostructures QD2 and QD3 one layer with QW $In_{0.17}Ga_{0.83}As$, was used, it differs by its location in the heterostructure. For the heterostructures QD4 and QD5 the array layer InGaAs was used, it differs by molar fraction of InAs in its composition. The schematic representation of heterostructures QD2−QD5 is shown in Figure 1, *b*.

For analysis of surface and geometric size of QD by transmission electron microscopy (TEM) a separate heterostructure TEM1 was prepared, which was analog of QD1, but layer with QD InGaP(As) in it was practically on surface and was coated only by layer GaAs 25 nm thick.

The heterostructures were studied by photoluminescence (PL) method at room temperature in unit RPM2000 Nanometrics. PL excitation was ensured by Nd:YAG-laser with

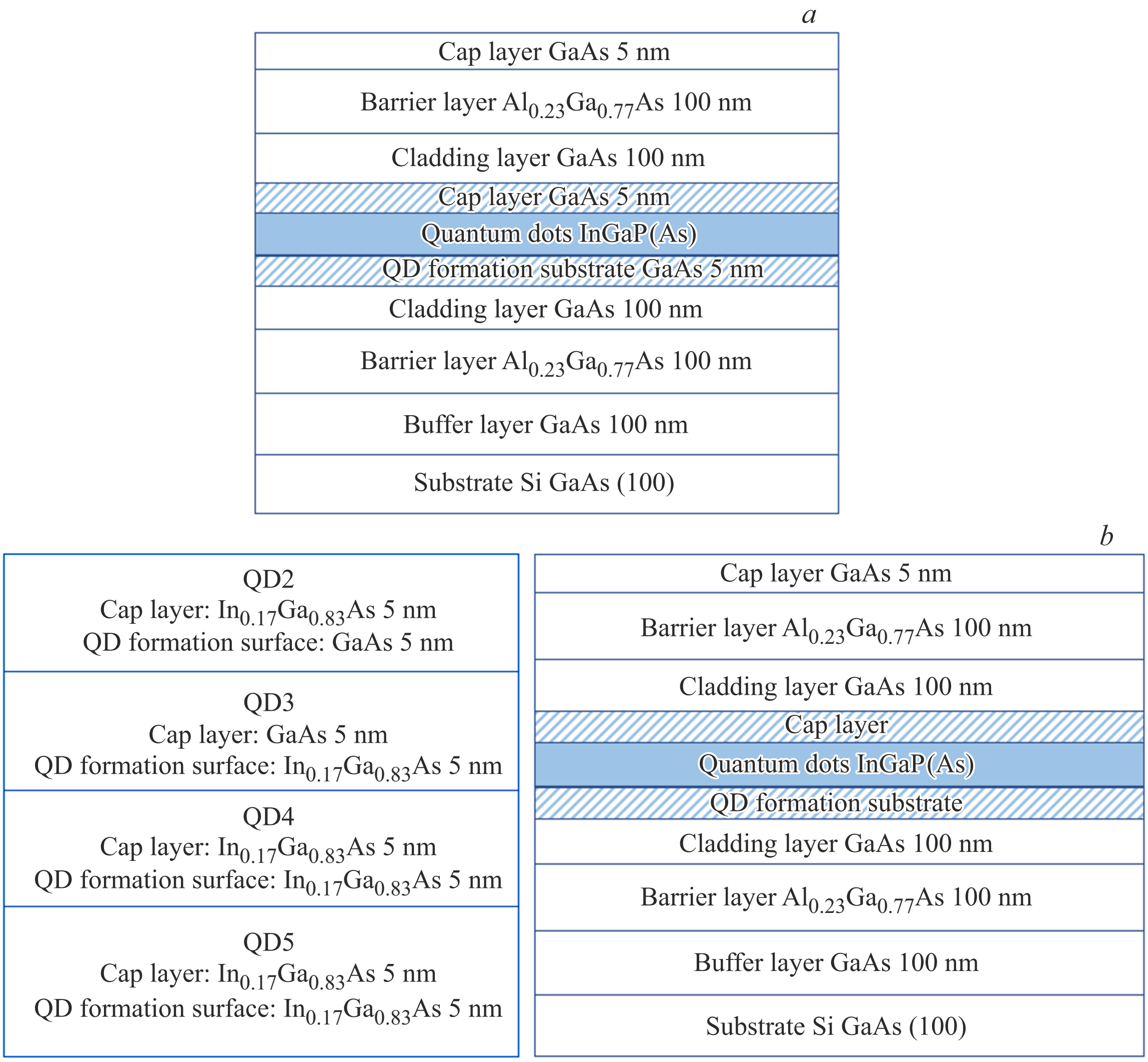

Figure 1. Schematic representation of structures of base heterostructure QD1 (*a*) and heterostructures with QWs InGaAs QD2–QD5 (*b*).

radiation wavelength 532 nm and radiation power 45 mW. Electronic and microscopy studies were performed using equipment of Core Shared Research facilities „Materials Science and Diagnostics in Advanced Technologies“ (Ioffe PTI, Saint-Petersburg) using microscope JEM-2100F in scanning mode.

3. Results and discussion

Studies by TEM of the heterostructure TEM1 (Figure 2) showed that Array of QDs InGaP(As), obtained under these growth conditions has surface density $1.3 \cdot 10^{12}\,\mathrm{cm}^{-2}$. At that QDs have high level of homogeneity in size, and their lateral dimensions are 5–7 nm.

Figure 3 presents PL spectra of heterostructures QD1–QD5 obtained at room temperature. PL spectra show three clear maximums at 860, 924, 978 nm. The first peak at 860 nm corresponds to GaAs, second peak at 923 nm corresponds to QW $In_{0.17}Ga_{0.83}As$, used as deposition surface for transformed layer InGaP, third peak at 979 nm corresponds to similar QW, used as QDs cap layer. Maximum shift of PL spectrum of QW into short-wave band indicates QW thickness decreasing, associated with partial conversion of QW top layers upon change in streams of materials of V group during formation of QD array. Maximum of PL spectra of QD InGaP(As) array or all heterostructures is in range 1027–1195 nm. PL spectra of QD arrays show that use of QW $In_{0.17}Ga_{0.83}As$ as QD cap layer leads to longwave shift of PL maximum by 56 nm. At same time QW use as deposition surface for InGaP layer has no effect on wavelength of PL spectrum maximum of QD array, which is presumably associated with partial conversion of QW top layers, see above, and with occurrence of two elastic compensated two-dimensional layers InGaAs and InGaAsP.

Comparison of heterostructures QD4 and QD5 showed that with increase in molar fraction of InAs from 0.17 to 0.23 the long-wavelength shift of PL spectrum maximum by 108 nm is observed, but at that decrease in PL intensity

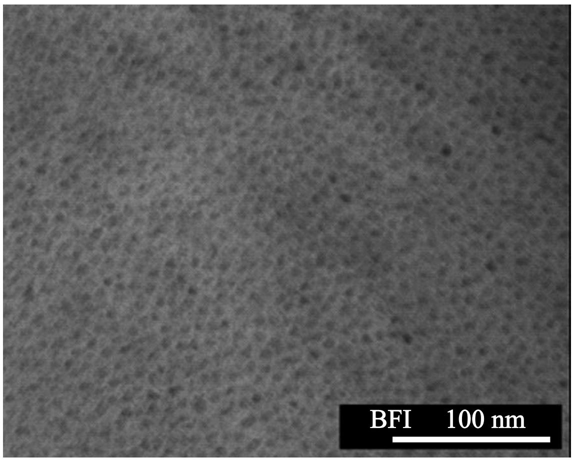

Figure 2. TEM image of planar surface of heterostructure TEM1 (001) in scanning mode.

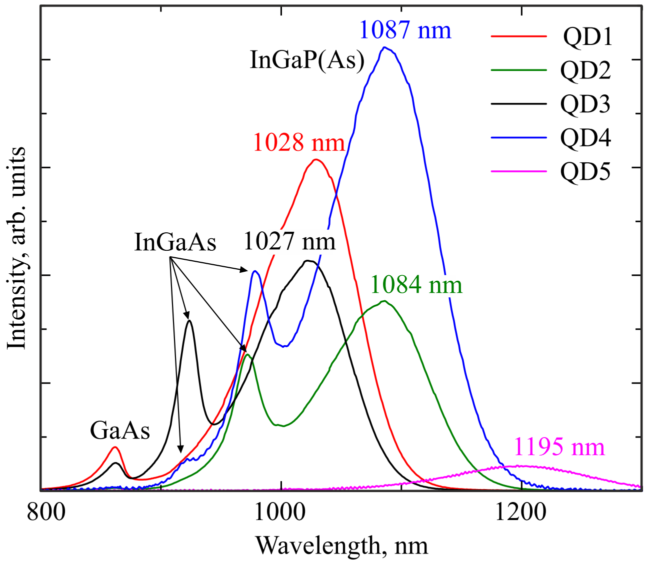

Figure 3. PL spectra of heterostructures QD1–QD5, obtained at room temperature.

by 18 times is observed due to increase in nonradiative recombination on structural defects. For the heterostructures QD1–QD4 number of surface defects with area of 0.6 to 250 μm^2 did not exceed 20 cm^{-2}, at same time for heterostructure QD5 this value is 71 cm^{-2}. We concluded that in the considered heterostructure with InGaP(As) QDs for the InGaAs array layer, the molar fraction of InAs 0.23 is the limit for formation of the defect-free heterostructure.

Mean-square deviation of such parameters as width of PL peak in QD arrays, measured at half maximum, wavelength and maximum intensity of PL spectrum, did not exceed 0.24, 2.80 and 7.9%, respectively. The data obtained ensure supposition on possibility of obtaining by this method of substitution of V group elements of heterostructures with several layers of InGaP(As) QDs with high homogeneity of optical parameters over the substrate area.

4. Conclusion

In paper we studied effect of InGaAs QW on optical properties of InGaP(As) QDs obtained by substitution of phosporous with arsenic in InGaP layer 2 nm thick during epitaxial growth by MBE method. It is shown the long-wavelength shit of P maximum off QD array is observed when QW is used as capping QD layer. For QW InGaAs 5 nm thick and with molar fraction of InAs 0.17 the long-wavelength shift o PL spectrum maximum is 56 nm. The increase in molar fraction of InAS in InGaAS array layer to 0.23 leads to long-wavelength shift of PL spectrum maximum of QD array by 108 nm relative to array layer with molar fraction of InAs 0.17, n to P intensity decreasing by 18 times, associated with nonradiative recombinltion of charge carriers on structurlal defects.

Surface density of InGaP(As) QD array is up to $1.3 \cdot 10^{12}$ cm^{-2} with lateral size of QD 5–7 nm. These QD arrays can be used to implement the heterostructure active areas of radiation sources of near UR band, including possibility to implement several QD layers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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