1 µm range InGaPAs three-dimensional islands grown by molecular beam epitaxy

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Abstract. A new technique allowing growing three-dimensional InGaPAs islands with reduced surface density by molecular beam epitaxy is proposed. The structural and optical properties of the islands have been studied depending on the InGaP layer thickness, the substrate temperature, and exposure time in the arsenic flow. The estimated island density was about 1.3 × 10¹⁰ cm⁻².

1. Introduction

Nowadays research in the field of single photon sources attracts a great interest all over the world [1-3]. For this application unique properties of semiconductor quantum dots (QDs) [4, 5] can be used. In a single QD a single electron can be excited from the valence band to the conductance band and drop back into the valence band releasing its energy by the emission of single photon. One of the main problems occurs is achieving QD arrays with relatively low QD surface density. For typical laser applications QD surface density is about 5 × 10¹⁰ cm⁻² or more [6-9] though for single photon source application desirable QD surface density should be lower than 1 × 10¹⁰ cm⁻² [10, 11], better – about 1 × 10⁹ cm⁻². Thus one of the main focuses in single photon sources research is finding new techniques of QD epitaxial growth in order to achieve QD arrays with low surface density keeping high structural and optical properties.

A new technique allowing growing three-dimensional InGaPAs islands with reduced surface density formed by elastic transformation of the InGaPAs layer grown on the GaAs surface by molecular beam epitaxy is proposed in this work. The structural and optical properties of the islands have been studied depending on the InGaP layer thickness, the substrate temperature, and exposure time in the arsenic flow.

2. Experiment

Four heterostructures (C1-C4) were grown on GaAs (100) substrates by molecular beam epitaxy (MBE) using Riber 49 machine. They were consisted of a GaAs buffer layer, a 200-nm-thick GaAs-based carrier collection region sandwiched by AlGaAs barrier layers of thickness 100 nm, and a 5 nm thick GaAs cap layer. The main feature of the new technique was that QDs were formed by replacement of phosphorus in the InGaP epitaxial layer by arsenic, upon exposure of InGaP layer in the As flow while the epitaxy process was stopped. This InGaP layer was placed at the center of the charge carrier collection layer. During the growth of InGaP layer through the 30 seconds the flow of
phosphorus was substituted by the flow of arsenic. Then, the growth surface was held in the flow of arsenic for 5–10 minutes, during which phosphorus atoms in the InGaP layer were replaced by arsenic atoms, followed by the formation of the InGaP(As) layer.

The differences between heterostructures C1-C4 can be found in Table 1. Note that design of heterostructure C4 was equal to the design of heterostructure C3, the only difference was that the InGaP(As) layer in heterostructure C4 was covered only with a GaAs layer (thickness 25 nm).

**Table 1. Differences between heterostructures C1-C4.**

| Sample name | InGaP thickness, nm | Holding time, min. | Substrate temperature during holding, °C |
|-------------|---------------------|---------------------|-----------------------------------------|
| C1          | 2                   | 5                   | 520                                     |
| C2          | 2                   | 5 (0.5 + 4.5)       | 535                                     |
| C3          | 3                   | 10 (0.5 + 9.5)      | 535                                     |
| C4          | 3                   | 10 (0.5 + 9.5)      | 535                                     |

Photoluminescence (PL) spectra of grown heterostructures were measured at room temperature. PL excitation was done by using YAG: Nd laser (\(\lambda = 532\) nm, optical excitation power 45 mW). TEM was used to estimate the QD surface density. Electron microscopy studies were carried out using the equipment of the Joint Research Center “Materials science and characterization in advanced technology” (Ioffe Institute, St. Petersburg) using a JEM-2100F microscope at an accelerating voltage of 200 kV. To analyze the structural properties X-ray diffraction technique was used. The analyses were made using PANalytical X’pert Pro diffractometer.

**3. Results**

As it can be seen from Figure 1 the PL spectra of the grown heterostructures have 2 main peaks. In addition to the GaAs peak each PL spectrum has an additional peak in the spectral range of 953-979 nm, which can be attributed to the InGaPAs islands emission. For heterostructure C1 (InGaP layer thickness 2 nm, layer transformation to QDs at 520 °C for 5 minutes) location of PL maximum was 973 nm. A significant scattering the InGaPAs islands in size and/or composition was proved by measuring FWHM of the PL spectrum maximum corresponding to emission from the islands. The obtained value was 95 meV. The redshift of peak PL wavelength corresponding to emission from the InGaPAs islands by 6 nm for heterostructure C2 is obtained and is caused by increasing the holding temperature by 15 °C. The uniformity of InGaPAs islands in for heterostructure C2 is slightly better in comparison with C1, which is proved by measuring FWHM (90 meV) for the peak corresponding to InGaPAs islands. For heterostructure C3 blueshift of the PL maximum corresponding to InGaPAs islands by 20 nm is obtained and is caused by increasing in the exposure time up to 10 minutes and InGaP layer thickness up to 3 nm. In the same time for heterostructure C3 sample PL intensity increased and also the broadening of the PL peak corresponding to InGaPAs islands also increased (FWHM = 97 meV).
The data obtained by x-ray diffraction experiments for heterostructure C3 showed the presence of a thin layer with a lattice constant corresponding to InGaP$_{0.9}$As$_{0.1}$ layer (Figure 2). Note that prior to the growth of heterostructures C1 – C4 the InGaP layer was calibrated by the composition by using X-ray diffraction technique and it can be stated that the In$_{0.49}$Ga$_{0.51}$P layer was deposited during the growth of heterostructures C1 – C4, while InGaP$_{0.9}$As$_{0.1}$ was observed on the X-ray curves. In Figure 2 for comparison also presented the rocking curve of sample C422 with an active region based on InAs / In$_{0.16}$Ga$_{0.84}$As QDs.

In Figure 3 it is shown the plan view TEM image of heterostructure C4 which was grown especially for these experiments. One can clearly see the three-dimensional islands elongated along the
direction [1-10] which have an oval shape. Based on the TEM analysis, the density of InGaPAs islands was estimated as $1.3 \times 10^{10} \text{cm}^{-2}$.

![TEM Image](image)

**Figure 3.** Plan view TEM image of heterostructure C4.

**4. Conclusions**

A new technique is proposed for the formation of three-dimensional InGaPAs islands, which consists of replacing phosphorus with arsenic in an InGaP layer deposited on GaAs directly during epitaxial growth. It was shown that InGaPAs islands emit in the spectral range of ~1 μm at room temperature and their estimated surface density was $1.3 \cdot 10^{10} \text{cm}^{-2}$.

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