Investigation of optical properties of QD-InAs/GaAs heterostructures obtained by ion-beam deposition

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Abstract. In this paper, we investigate heterostructures with an array of InAs quantum dots encapsulated by GaAs barrier layers obtained by ion-beam epitaxy. The thickness of the layers was less than 30 nm. It is shown that this technique allows to obtain quantum dots with lateral dimensions up to 50 nm with a height of 10 nm. The density of the obtained array of quantum dots was $10^9$ cm$^{-2}$. The studies performed using photoluminescence methods revealed the peaks of the main transitions for quantum dots at 1.1 eV (1150 nm) for samples with GaAs barrier, which corresponds to the near-infrared. The width of the main peak of the samples was about 0.2-0.25 eV, which is associated with the dispersion of quantum dots sizes. Dark current-voltage characteristics of the structures proved that the value of dark current density at 90 K is about $10^{-6}$ A/cm$^2$. The asymmetry of the dark current curves at positive and negative shifts is determined. The samples also showed that an increase of temperature leads to degradation of characteristics. When the operating temperature rises to 300 K, the density of the dark current changes in the range from 0.1 to 0.01 A/cm$^2$.

1. Introduction

Modern photodetectors are subject to a number of requirements, namely, speed, minimal internal noise, high operating temperatures, good detectability. At present, QDIP (with quantum dots) and QWIP (with quantum pits) photodetectors based on A3B5 multicomponent solid solutions are perspective and meet the requirements [1]. Localization of photogenerated electrons in a quantum dot in three directions contributes to the reduction of thermionic generation and dark current [1]. The creation of A3B5 nanoheterostructures with quantum dots gave rise to the development of high-efficiency injection lasers [2], solar cells [3], and photodiodes [4]. The growth of QDs occurs in the Stranski–Krastanov mode, when the substrate wetting layer is elastically stressed. An InAs/GaAs heteropair is ideal for such growth conditions. However, in terms of technology, it has limitations when used in photodetectors of infrared radiation. The most frequently used methods for growing photodetecting structures are molecular-beam epitaxy (MBE) and vapor-phase epitaxy (MOCVD) [2-8]. Disadvantages of these techniques are high cost and technological complexity of equipment. The subject of this paper is to obtain heterostructures with an array of InAs quantum dots by ion-beam deposition (IBD). This technique allows us to obtain epitaxial layers [9-10] and quantum dots [11-13] of complex semiconductors of high quality and density. The advantages of this technique include the hardware simplicity and the low-cost equipment compared to MBE and MOCVD. Additionally, the IBD technique allows ion-beam etching processes to be carried out before the crystallization of semiconductor heterostructures, which has a positive effect on their quality.
2. Experimental

Single crystal GaAs and InAs targets were used to obtain heterostructures with quantum dots. The targets of the bottom conductive material n+ contained an admixture of tellurium with a concentration of $3 \cdot 10^{17}$ cm$^{-3}$. For the top conductive layer, the targets were doped with zinc to a concentration of $3 \cdot 10^{17}$ cm$^{-3}$. Targets of closing layers and matrices for the quantum dots array did not contain doping impurities. The bottom conductive layer was 200 nm thick, the spacer layer was 180 nm, the top conductive layer was 200 nm, the barrier layer was 30 nm and 50 nm. The substrate temperature before cleaning was 450 °C. Annealing of the samples was carried out at the temperature of 550 °C. Growing heterointerfaces with quantum dots requires constant layer growth control, low growth rates and low sputtering ratio. The low sputtering ratio can be achieved by reducing the ion-beam energy. However, it is important to consider the change in the geometry of the ion-beam-target-substrate system. It was established that at the ion-beam energy $E_{Ar}$ of 180 eV (sputtering ratio was 0.4 for GaAs and 0.5 for InAs), the ion-beam current $I_{Ar}$ is 140 µA. At the given parameters of the ion-beam, the minimum loss factor was achieved at the incidence angle of 55° between the ion-beam and the target. The voltage of the cathode control unit was 190 V, voltage of the ion beam was 110 V. Parameters of the discharge control unit: $U = 60$ V, $I = 0.5$ A. These conditions allowed to reach the lower limit of growth rate control of 0.7 nm/s.

The substrate temperature was 500°C when the conductive and buffer layers were applied. The temperature was reduced to 480°C before the InAs layer was applied. At the selected growth rate, the InAs wetting layer was formed in 40 seconds (by the Stranski–Krastanov mode). The wetting layer usually contains early nucleation centers. According to Stranski-Krastanov growth mode, further sputtering of InAs during 125 s allows to form islands of quantum dots of necessary density. At the final stage of island formation, the resulting layer should be «covered» with a barrier layer to obtain a field of elastic deformations. Monocrystalline targets of unalloyed GaAs were used for barrier layer deposition. The barrier layer has been deposited at the following process parameters: ion beam energy $E_{Ar} = 280$ eV, ion beam current $I_{Ar} = 500$ µA, incidence angle between the ion-beam and the target - 65°, substrate temperature was 490 °C, growth rate was 2 nm/s.

Surface morphology and elemental composition of the grown heterostructures was investigated on a scanning high-vacuum atomic force microscope NT-MDT Solver HV (Russia) and a high-resolution two-beam scanning electron microscope with the Schottky cathode Zeiss CrossBeam 340 (Germany).

3. Results and Discussion

It was established that when InAs is deposited for 40 s (figure 1a), the first small nanoislands spread over the sample surface are observed. Further deposition of the active material (figure 1b) results in the formation of three-dimensional nanometer-sized islands (quantum dots). The formation of quantum dots occurs due to the appearance of the elastic deformation force field. The difference between the lattice constant of the active material and the lattice constant of the substrate material results in elastic stresses that increase the internal energy of the system. For achievement of equilibrium it is energetically advantageous to pass to the island growth mode with increase of wetting layer thickness.
Figure 1. Results obtained using an atomic-force microscope (AFM) at InAs deposition time a) 40 sec., b) 70 sec., c) 125 sec.

When InAs is deposited for 70 s, the density of quantum dots remains insufficient for technological applications. InAs deposition time was increased to achieve higher density of quantum dots (figure 1c). Two-minute deposition leads to the development of the dot shape and formation of an array with a density of \( \sim 10^{10} \text{ cm}^{-2} \). Further deposition of the active material leads to the development of dot shape and high size dispersion. The studies conducted using AFM show that the best conditions for the growth of InAs quantum dots are: substrate temperature 480 \( \degree \text{C} \), InAs deposition time 125 seconds.

Analysis of statistical data on the surface allowed us to determine that the majority of InAs nanoclusters are smaller than 50 nm, but there are also larger islands (more than 50 nm) on the surface, which indicates some heterogeneity. The graph of quantum dots density distribution by lateral sizes over the considered section of 10x10 microns is shown in figure 2. As shown in the histogram, the density of quantum dots within the study area was about \( 10^{3} \text{ pcs/\mu m}^{2} \), which corresponds to a density of about \( 10^{9} \text{ cm}^{-2} \).

Figure 2. Size distributions of InAs quantum dots

The obtained results of the surface morphology of the samples coincide with the works of third-party studies on this subject [18-20].

Figure 3 shows the photoluminescence spectra obtained for samples with GaAs barrier layers. The peak of the main transitions in QD is at 1.12 eV, which corresponds to \( \lambda = 1.2 \mu \text{m} \). The large width of the main peak is related to the dispersion of quantum dots sizes. With a barrier layer thickness of 30 nm, all quantum dots are in the electrostatic field of this barrier, which provides the emission of
excited electrons from QD levels into the heterostructure matrix by two main mechanisms: over-barrier thermal emission and tunneling. A decrease in the thickness of the barrier layer was accompanied by a red shift of the main peak. However, when applying a thin cover layer, the red shift disappears, which is probably due to the elastic deformation forces in the quantum dot array.

The secondary peak is shifted to the short-wave region of the spectrum (blue shift) of 1.3 eV ($\lambda = 953$ nm). This peak characterizes the emission transitions in the wetting layer. As the barrier layer is applied to an array of quantum dots, the wetting layer changes its composition and represents a Ga$_x$In$_{1-x}$As solution. This peak with a wavelength of 953 nm corresponds to 35% indium content in the solution.

![Figure 3](image3.png)

**Figure 3.** Photoluminescence of samples with InAs quantum dots and GaAs barrier layers in different technological modes

The last peak (1.5 eV, 890 nm) corresponds to the edge of self-absorption in the GaAs layer. This peak is a low-intensity peak because not much of the radiation reaches this area of the structure.

Figure 4 shows the dark current density dependencies for samples with GaAs barriers. Asymmetry of the dark current curves at positive and negative shift is typical. It is related to the asymmetry of quantum dots sizes.

![Figure 4](image4.png)

**Figure 4.** Dark current density of samples with GaAs barrier layer
The number of electron-filled states in quantum dots increases with a small shift. When most of the states are occupied, no increase in dark current is observed. A further shift increase leads to a reduction in the barrier and an exponential increase in dark current. At zero shift the density of dark current structure with GaAs barrier is $10^{-6}$ A/cm$^2$ (at 90 K). If the shift is increased to 0.8 V, the dark current increases by three orders of magnitude ($10^{-3}$ A/cm$^2$). Further shift leads to an increase in dark current up to $100$ A/cm$^2$, whereupon external voltage does not affect the characteristic. At 90 K, only the tunnel effect contributes to the dark current. As the temperature increases, the dark current increases due to the contribution of thermionic emission. The graph shows that the dark current value at room temperature (300 K) is about $10^{-7}$ A/cm$^2$.

4. Conclusion
The paper demonstrates the possibility of obtaining photodetecting InAs/GaAs heterostructures with quantum dots via ion-beam deposition. The investigations of the surface morphology of the samples performed using an atomic-force microscope (AFM) and a scanning electron microscope (SEM) showed the presence of InAs quantum dots with lateral sizes up to 50 nm, height of about 10 nm and density of $10^9$ cm$^{-2}$.

According to the studies of of dark current-voltage characteristics, it is established that the dark current density in structures with GaAs barrier layer is $10^{-6}$ A/cm$^2$ at the temperature of 90 K. A sharp increase in the density of the dark current to $10^{-3}$ A/cm$^2$ at 300 K was observed. Photoluminescence peaks for the main transitions in the array of InAs quantum dot of 1.1 eV (for the GaAs barrier) were found. It was established that the usage of thinner barriers leads to a red-shift. The obtained results of photoluminescence and dark current density dependences demonstrate the possibility of applying the used heterostructures for near-infrared photodetectors.

It was revealed that it is necessary to increase the number of InAs QD layers and reduce the thickness of barrier and cover layers of the grown heterostructures in order to achieve dark current densities of less than $10^{-6}$ A/cm$^2$.

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