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Study of the photoluminescence properties of subcritical InAs/GaAs quantum dots formed onto structured substrates

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Abstract. In this work we study the optical properties of InAs quantum dots grown on the GaAs(001) nanostructured surfaces at sub-critical thickness of deposition. For substrate nanostructuring we used technique based on two-stage thermal desorption of native GaAs oxide under molecular arsenic flux. The results of experimental studies showed the possibility of quantum dots formation on structured surfaces at equivalent deposition thicknesses in the range of 0.5–1.5 ML. In this case, quantum dots are formed predominantly in nanoholes on the surface and are high inhomogeneous in size. At the same time measurements by photoluminescence spectroscopy showed broad (900–1100 nm) emission spectrum for quantum dot only for sample with 1.5 ML of InAs. We hypothesize that at smaller thicknesses, the formed quantum dots become smaller than the minimum acceptable sizes due to segregation effects during overgrowth. The use of a structured surface also makes it possible to suppress the wetting layer formation – in the photoluminescence spectra there are only lines of platelets, apparently formed on morphological inhomogeneities outside the holes.

Keywords: native oxide, quantum dots, A3B5, molecular beam epitaxy, nanopatterning

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Исследование фотолюминесцентных свойств докритических квантовых точек InAs/GaAs, сформированных на структурированных подложках

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Аннотация. В данной работе проведены исследования оптических свойств квантовых точек InAs, полученных путем осаждения докритических толщин на наноструктурированную поверхность GaAs(001). Для наноструктурирования подложки была использована методика, основанная на двухстадийной термодесорбции собственного оксида GaAs в потоке молекулярного мышьяка. Результаты экспериментальных исследований показали возможность формирования квантовых точек на структурированных поверхностях при эквивалентных толщинах осаждения в диапазоне 0,5—1,5 МС. В этом случае квантовые точки формируются преимущественно в сформированных на поверхности углублениях и имеют высокую неоднородность размеров. Измерения методом фотолюминесцентной спектроскопии показали наличие квантовых точек, излучающих в широком диапазоне длин волн (900—1100 нм), только для образца с эквивалентной толщиной осаждения 1,5 МС InAs. Мы предполагаем, что при меньших толщинах образующиеся квантовые точки становятся меньше минимально допустимых размеров, в т.ч. из-за эффектов сегрегации при заращивании. Результаты исследования также показали, что использование структурированной поверхности позволяет подавить образование смачивающего слоя — в спектрах фотолюминесценции присутствуют только пик, отвечающий излучению локальных двумерных структур, по-видимому, образовавшихся на морфологических неоднородностях вне отверстий.

Ключевые слова: собственный оксид, квантовые точки, A3B5, молекулярно-лучевая эпитаксия, наноструктурирование

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Introduction

The production of low-density quantum dots (QD) is becoming increasingly popular since they underlie the sources of single and entangled photons that act as the elemental basis for quantum communications and computing [1, 2]. One of the directions for obtaining low density quantum dots is the use of preliminary structuring of the growth surface with subsequent deposition of the quantum dot material [3—5]. In this case, the nanoholes formed on the surface subsequently act as nucleation centers for self-organizing nanostructures [6—8]. Today, surface structuring methods have a number of limitations that affect the optical qualities of subsequently formed quantum structures, mainly due to contamination of the growth surface. Therefore, the search for alternative methods of surface nanostructuring and growth technique for subsequent localized formation of quantum dots remains relevant. One of the candidate for this role can be controlled decomposition of the substrate surface at the stage of thermal removal of GaAs native oxide [3].

In this work we experimentally demonstrate the possibility of obtaining relatively low-density self-organizing InAs/GaAs quantum dots obtained on the GaAs(001) nanostructured surfaces at sub-critical thickness of deposition with an emission range of up to 1100 nm.

Materials and Methods

For experimental studies, we used GaAs(001) substrates with a pre-grown GaAs/AlGaAs structure, on the surface of which native oxide film was then formed in air. To form nano-sized holes, we used the original technique based on two-stage thermal desorption of native GaAs oxide under molecular arsenic flux. As a result, an array of inhomogeneous symmetrical holes was formed on the surface. The average values of the diameter and depth of which were 60 and 4 nm, respectively. Control of oxide removal was carried out in-situ using an integrated

RHEED system. At the next stage, an InAs layer with an equivalent thickness in the range of 0.5–1.5 ML was deposited. To study the optical properties, a GaAs/AlGaAs heterostructure was grown on top of the structures prepared in this way. In addition, we repeated the same heterostructure, where the active region was a 1.5 ML InAs wetting layer on an atomically flat surface without nanostructuring which we used as a reference sample. Uncapped structures were analyzed using scanning electron (SEM) and atomic force (AFM) microscopy. The optical properties were analyzed using photoluminescence spectroscopy (PL).

Results and Discussion

SEM-analysis (Fig. 1, *a*, *b*, *c*) of the surface of the uncapped samples showed that for all samples deposited material accumulates in the nano-sized holes formed at the nanopatterning stage, thereby forming an array of inhomogeneous QDs. In this case, decreasing the amount of InAs from 1.5 ML to 1.0 ML leads to a pronounced decrease in their size. And it was found that the structures do not assemble into obvious 3D objects after deposition of 0.5 ML. However, according to AFM data (Fig. 1, *d*), a decrease in the hole depth was observed, which indicates their filling with deposited material and the localization of nanostructures within them. However, relevant assessment of the size of such structures is difficult using AFM or SEM.

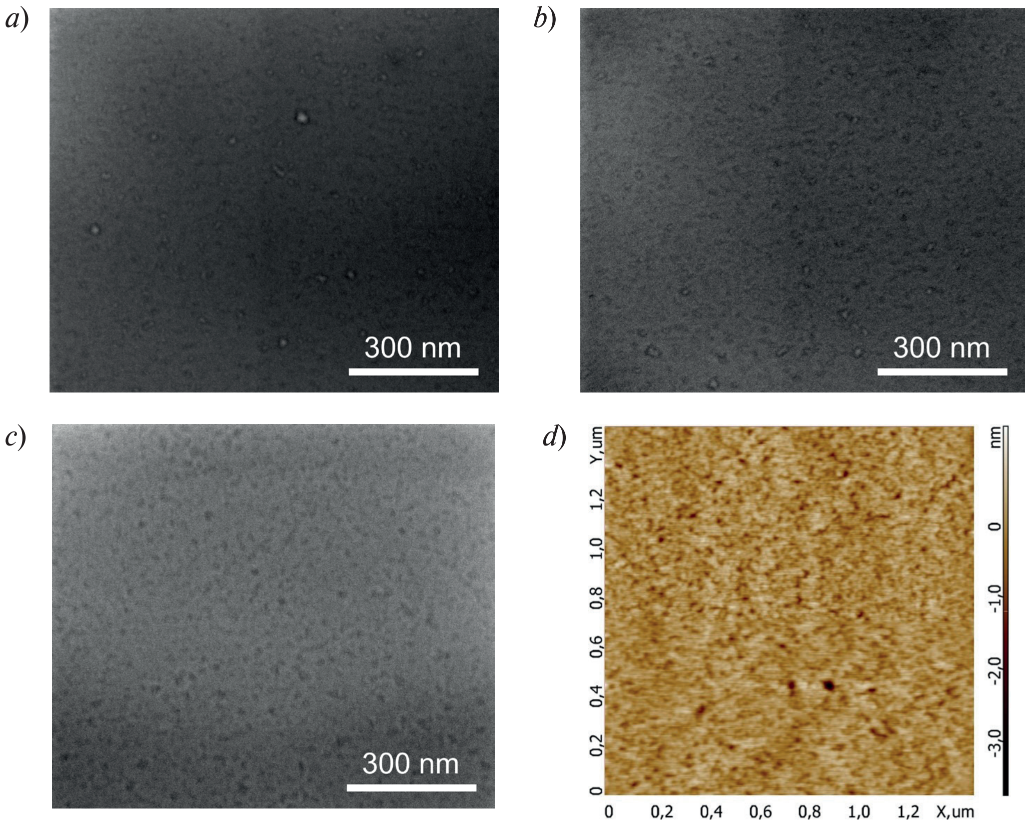

Fig. 1. SEM images of the nanostructured GaAs surface after deposition of (*a*) 1.5 ML, (*b*) 1.0 ML and (*c*) 0.5 ML InAs; (*d*) AFM images of the surface of (*c*)

PL spectra for samples with different equivalent layer thicknesses InAs are shown in Figure 2, *a*. The signal from the QDs (broad band in the range of 870–1100 nm) is only present on the 1.5 ML InAs sample. In addition, there is no peak of the wetting layer in the spectrum, which indicates the suppression of its formation during deposition on a structured surface. On samples with smaller thicknesses (1.0 and 0.5 ML), the PL spectra do not have any features characteristic of QD. This may be due to the fact that during the overgrowth process, part of the QD material segregates, which leads to a decrease in their effective size below the limit at which an electronic level exists in a quantum-sized system.

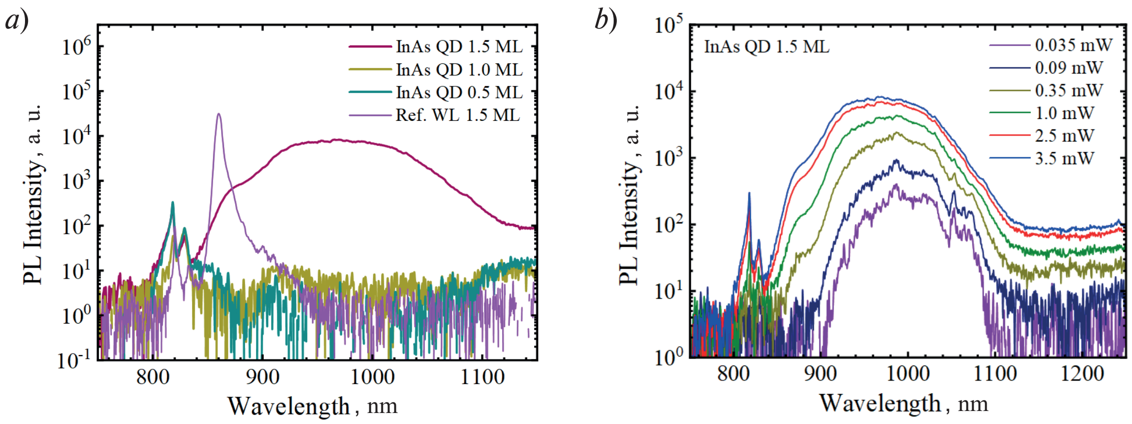

Fig. 2. PL spectra for the samples with different equivalent thickness of InAs deposition (*a*) and for the sample with 1.5 ML InAs deposition at different excitation powers (*b*)

Figure 2, *b* shows the photoluminescence spectra at different excitation powers for a sample with 1.5 ML of InAs. Analysis of the PL spectra of this sample shows that with increasing excitation power, in addition to the QD peaks (900–1100 nm), a low-intensity short-wavelength shoulder (850–900 nm) appears in the spectrum. The same type of structures is responsible for the formation of the long-wavelength shoulder in the spectrum of the reference sample in the Figure 2, *a*. We associate this feature with the emission of so-called platelets – two-dimensional structures formed on morphological inhomogeneities in the spaces between the hole with QDs.

Conclusion

Thus, studies have been carried out on the formation and optical properties of subcritical InAs/GaAs quantum dots on structured substrates. The possibility of obtaining subcritical QDs of low density, emitting in the range of 900–1100 nm, has been demonstrated. The emission wavelength of the obtained QDs is significantly longer compared to alternative methods for forming near-critical QDs (about 950 nm). The results obtained can be used to develop a technological process for the formation of low-density InAs QDs in the O- and, in the future, C-bands without a wetting layer.

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