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Quantum dots formation by InGaAs decomposition onto a patterned GaAs surface

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Abstract. In this work, we present the results of experimental studies of the formation processes and optical properties of ordered arrays of InGaAs nanostructures obtained by deposition of quantum well material layer on the nanopatterned GaAs surface. For GaAs nanopatterning we used our original technique based on the combination of focused ion beam treatment and local droplet etching which allows to create regular arrays of nanoholes with different morphology. Using room-temperature photoluminescence (PL) intensity mapping we have shown that quantum well material localizes inside the created holes but position of corresponding PL peak (960–970 nm) is independent of morphology and is determined only by the chemical composition of the deposited material. Based on low-temperature (5 K) PL measurements we conclude that inside the holes quantum well decomposes due to the difference in a mobility of Ga and In adatoms during its material deposition with formation a “quantum well + quantum dot” system. While the quantum well PL peak locates approximately at 920 nm, the quantum dot lines lie in the wavelength range of 930–950 nm.

Keywords: quantum dots, A3B5, decomposition, structuring, molecular beam epitaxy, nanostructures, nanopatterning

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Формирование квантовых точек путем осаждения InGaAs на структурированную поверхность GaAs

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Аннотация. В данной работе представлены результаты экспериментальных исследований процессов формирования и оптических свойств упорядоченных массивов наноструктур InGaAs, полученных методом осаждения слоя материала квантовой ямы на структурированную поверхность GaAs. Для структурирования GaAs использовалась оригинальная методика на основе комбинации технологий сфокусированного ионного пучка и локального капельного травления, которая позволяет формировать массивы углублений на поверхности с различной морфологией. Анализ карт распределения интенсивности фотолюминесценции (ФЛ) при комнатной температуре показал, что материал квантовой ямы локализуется внутри сформированных на поверхности углублений. Было показано, что положение пика ФЛ локализованных наноструктур (960–970 нм) не зависит от морфологии и определяется только химическим составом осажденного материала. Анализ спектров микрофотолюминесценции при 5 К показал, что внутри углублений квантовая яма распадается, предположительно, из-за разницы в подвижности адатомов Ga и In при осаждении материала с образованием системы «квантовая яма + квантовая точка». При этом спектре ФЛ квантовой яме соответствует пик на 920 нм, а линии квантовых точек лежат в диапазоне длин волн 930–950 нм.

Ключевые слова: квантовые точки, A3B5, распад, структурирование, молекулярно-лучевая эпитаксия, наноструктуры, модификация

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Introduction

Great interest in quantum dots (QD) is due not only to their unique electronic and optical properties, but also to the need to create highly efficient compact (micro- and nano-sized) light sources including non-classical sources of single [1] and entangled photons [2] based on them. Since the properties of QDs largely depend on their structural characteristics [3–5], the requirements for the accuracy of their control increase as the size of devices based on them decreases. And despite the long history of studying QDs, the development of effective methods for controlling their properties, including the position of individual dots in an array [6, 7], remains an urgent task. One of the most promising methods of QD control is the preliminary structuring of the surface by creating holes (or recesses) of various geometries [8, 9], which are the preferred sites for the nucleation and growth of self-organized nanostructures [10, 11]. This paper presents the results of studies on the possibility of forming InGaAs QDs and their ordered arrays by deposition of quantum well (QW) material onto a nanostructured GaAs surface.

Materials and Methods

Preliminary nanopatterning of GaAs surface was carried out on GaAs/AlGaAs heterostructure using a focused ion beam (FIB) etching. As a result, square arrays of holes with different geometric characteristics were formed. The ion beam accelerating voltage was 5 kV, and the distance L between the holes in the array was 0.5 and 1 μm. The number of ion beam passes N varied from 1 to 60. Then pre-growth treatment was carried out using the original local droplet etching technique [8], because of which pyramidal-shaped holes with lateral sizes varied from ~ 100 to ~ 300 nm were formed at every point of ion beam exposure. Then a 10 nm thick InGaAs layer with an indium content of 17% was deposited on the patterned surface. This layer was placed in the center of the optical cavity formed by the AlGaAs/GaAs/AlGaAs heterostructure. After formation sample were studied by photoluminescence spectroscopy at 5 and 300 K.

Results and Discussion

The results of experimental studies showed that when 10 nm InGaAs is deposited on the nanostructured surface, the epitaxial material is localized in the region of the holes (Fig. 1, *a*). PL intensity distribution maps (300 K) show the dependence of the PL signal intensity in the wavelength range 900–1050 nm on the initial morphology specified by the parameters of nanopatterning. PL measurements at different points of the signal maximum showed that the position of the long-wavelength peak corresponding to InGaAs is unchanged for all points and locates in the spectral region of 960–970 nm, regardless of the initial morphology. Such wavelength corresponds to the emission of InGaAs/GaAs QWs with the same composition on non-patterned surfaces.

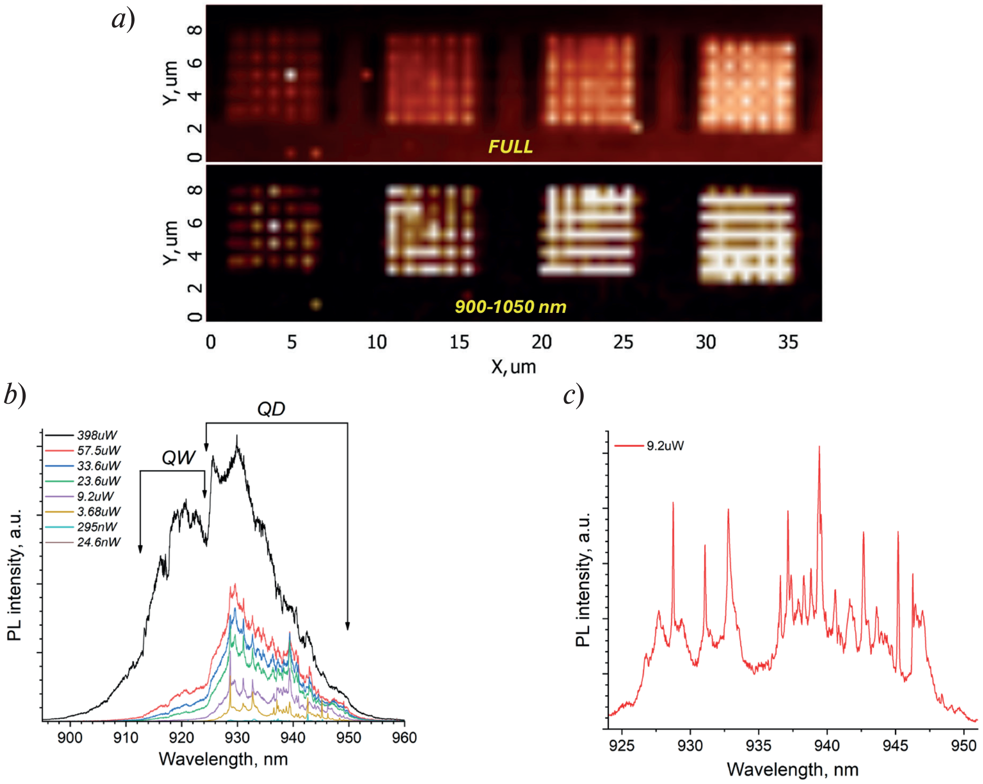

Fig. 1. PL spectra in patterned areas: PL intensity distribution map at 300 K for arrays with $L = 1.0$ μm and N varied from 20 (left array) to 60 (right array) passes (upper panel – full spectra; lower panel – spectra in the wavelength range 900 – 1050 nm) (*a*); spectra at different excitation powers for an array with $L = 0.5$ μm and $N = 40$ passes; *c*) high resolution PL spectra of the same arrays with individual QDs lines (*b*)

Analysis of the PL spectra at 5 K (Fig. 1, *b*) showed that localized InGaAs nanostructures emit in the broad wavelength range of 900–950 nm. At low temperature as the excitation power decreases, the peak splits into short- (900–925 nm) and long-wavelength (930–950 nm) components. Moreover from Fig. 1, *b* we can clearly see that as the pump power decreases, the maximum intensity shifts to the long-wavelength region due to the rapid decay of the short-wavelength shoulder. At the same time, the long-wavelength part of the spectrum breaks up into separate lines corresponding to the radiation of individual quantum dots. This is especially clearly visible in the high-resolution spectrum shown in the Fig. 1, *c*.

Analysis of the presented data allows us to assume that two types of nanostructures are formed in the nanoholes – a quantum well and a quantum dot, forming a coupled quantum-size system. In this case, the position of the emission lines of quantum wells and quantum dots does not depend on geometric characteristics of nanoholes. At the same time, the overall emission intensity of the InGaAs nanostructures shows a positive correlation with the sizes of the corresponding holes (Fig. 1). We associate this with the redistribution of QW and QD contributions to the PL spectrum when the morphological parameters of growth surface are changed. Based on this we conclude that inside the holes QW decomposes due to the difference in a mobility of Ga and In adatoms during its material deposition with formation a “quantum well + quantum dot” system.

Conclusion

Thus, we conducted studies on the possibility of forming In(Ga)As QDs on a structured GaAs surface by filling the nanoholes with InGaAs quantum well material. The results of studying the obtained samples using the PL method showed a high degree of localization of the quantum well material in the holes. We found that the PL intensity of the structures is directly proportional to the size of the initial nanoholes. Analysis of PL at low temperatures showed the formation of QDs emitting in the longer wavelength range in the holes. This suggests that the QDs are enriched in indium, which leads to the formation of a dot-in-well type structure inside the nanoholes. We attribute this to the decomposition of the quantum well material at the initial stage of epitaxial growth, caused by different diffusion lengths of the metal (Ga and In) components. Since the QD wavelength does not depend on the morphology, we can assume that the process is self-regulating and is determined by the balance of elastic strains in the “quantum dot + quantum well” system.

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