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Submonolayer InAs Quantum Dots in Silicon grown by Molecular Beam Epitaxy

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Abstract. The fabrication of composite material with embedded III-V quantum dots is of great interest due to promising silicon-based light emitting devices. In this work, the growth of self-assembled InAs quantum dots on Si substrates as well as subsequent capping layer formation by molecular beam epitaxy is presented. The evolution of size, density and shape of QDs are characterized by atomic-force microscopy. Bimodal size distribution of QDs at the submonolayer InAs coverage was observed. Full embedding into silicon matrix and dislocation free crystal structure of InAs QDs were confirmed by transmission electronic microscopy.

Keywords: quantum dots, semiconductors, molecular beam epitaxy

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Субмонослойные InAs квантовые точки в кремнии, выращенные методом молекулярно-пучковой эпитаксии

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Аннотация. Создание композитного материала с встроенными квантовыми точками A_3B_5 представляет интерес для разработки светоизлучающих устройств на кремнии. В данной работе представлены результаты по синтезу методом молекулярно-пучковой эпитаксии самоиндуцированных квантовых точек InAs на подложках Si и их последующему заращиванию слоем кремния. Эволюция размеров, плотности и формы КТ исследовалась методом атомно-силовой микроскопии. Обнаружено, что при субмонослойном покрытии InAs наблюдается бимодальное распределение КТ по размерам. Полное внедрение в кремниевую матрицу и бездислокационная кристаллическая структура КТ InAs подтверждены данными просвечивающей электронной микроскопии.

Ключевые слова: квантовые точки, полупроводники, молекулярно-пучковая эпитаксия

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Introduction

Monolithic integration of III–V compound materials on silicon (Si) platform attracts intense research interest over years because it opens up new opportunities for the fabricating of photonic integrated circuits with optical data transmission systems [1]. Unfortunately, direct epitaxial growth of planar layer on Si suffers from large lattice mismatch and different expansion coefficients. In order to overcome this issue, a various methods have been proposed, such as the growth of the thick graded buffer layers [2], the insertion of several filter layers [3], migration-enhanced epitaxy growth of GaP [4].Other interesting epitaxial approaches is based on the utilizing of Si substrates with special surface preparations, including the fabrication of V–grooved and 4 – 6° offcutted towards the [110] direction substrates [5], the patterning of substrate surfaces for confined lateral overgrowth [6]. Despite the great efforts and demonstration of several successful realizations, above mentioned methods still remain rather complex from the technological point of view. In turn, the growth of nanocomposite material consisting of III–V quantum dots (QDs) fully embedded in Si can be applied since they can can be processed like Si. Several studied have been published on the fabrication of Si nanocomposite containing InAs QDs. Unfortunately, in spite of growth reports and morphological characterization [7–9], the photoluminescence emission, to our knowledge, was demonstrated only one-time [7]. One key point was to growth of 2 – 6 monolayer thickness QDs and the formation of dislocations in QDs was commonly observed [8]. In contrast, QDs with smaller size, which formation was found to occur at a smaller InAs coverage [9], may be more tolerant to dislocations.

Thus, the study of the mechanism of InAs dot formation on Si is of great interest. Here we report on the growth of submonolayer InAs QDs on Si by molecular beam epitaxy and fabrication of light emitting nanocomposite material.

Materials and Methods

Growth experiments were carried out on Si(100)4° using 21EB200 Riber MBE system equipped with solid-state As, In effusion cells and e-beam evaporator for deposition of Si. Prior to growth wet chemical processing followed with degasing and annealing step at 950°C were performed to achieved atomically-clean Si(100) 2×1 surface. Afterwards, temperature was decreased to 600°C

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and 50 nm Si buffer layer was formed. Then, self-assembled growth of InAs QDs was carried out at 400°C. The amount of InAs being deposited onto Si surface corresponded to equivalent film thickness of 0.3 – 3 monolayer (ML).). It should be noted, that the growth rate of 0.01 nm/s was calibrated using standard procedure based on the measurements of reflection high-energy electron diffraction (RHEED) oscillation. The V/III was kept constant for all growth experiments and corresponded to ~20.

Topography investigation of the samples grown was performed on an Ntegra Aura (NT-MDT, Russia) scanning probe microscope in semi-contact mode using Si probes (HANC, TipsNano) with resonant frequency $f_0 \approx 140$ kHz, spring constant $k \approx 3.5 \mathrm{N \cdot m^{-1}}$ and tip curvature radius < 10 nm.

Structural characterization of InAs QDs fully embedded in Si matrix was performed using Zeiss Libra 200FE transmission electron microscope (TEM) operated at 200 kV. Samples were prepared using conventional thinning processes including mechanical polishing and Ar-ion milling.

Results and Discussion

We first probed the growth of InAs QDs using RHEED. One of the most important parameters that controls the size of the QDs is the amount of InAs. Under growth condition used in our experiments, the formation of QDs was clearly observed after 20s (0.8 ML) InAs deposition by transition appearing of 3D spots on streaky (2x1) RHEED pattern.

In order to gain information on the growth start of InAs on Si(001) a series of the samples with a various InAs coverage was grown. Figure 1 demonstrate the AFM images of the samples grown. The self-assembled InAs QDs are clearly can be identified on the bare Si surface in all cases. The InAs QDs size distribution was found to be inhomogeneous in all cases, as it can be seen in (Fig. 1, *d*, *e*, *f*). In detail, two types of QDs, which had irregular circular shape, were formed after the 0.3 ML growth. Relatively small InAs QDs were about 87 nm in the diameter and height of 5 nm. The bigger size QDs have 162 nm diameter and 14 nm height. The density of small and big QDs corresponded to 4 and 1 μm^{-2}.

The increasing of InAs coverage led to formation of QDs with bigger sizes, wherein the bimodal size distribution remained the same. It should be noted also, the dependence of QD densities on the coverage turned out to be different for two size types of QDs. In detail, density of small dots increases up to at 0.7 ML coverage and then decreases. At the same time, growth density of bigger size dots increases with the growth time, as well as the broadening of dot size occur. The reason for the peculiar behavior remains open. Nonetheless, it apparently can be connected with the coalescence of dots.

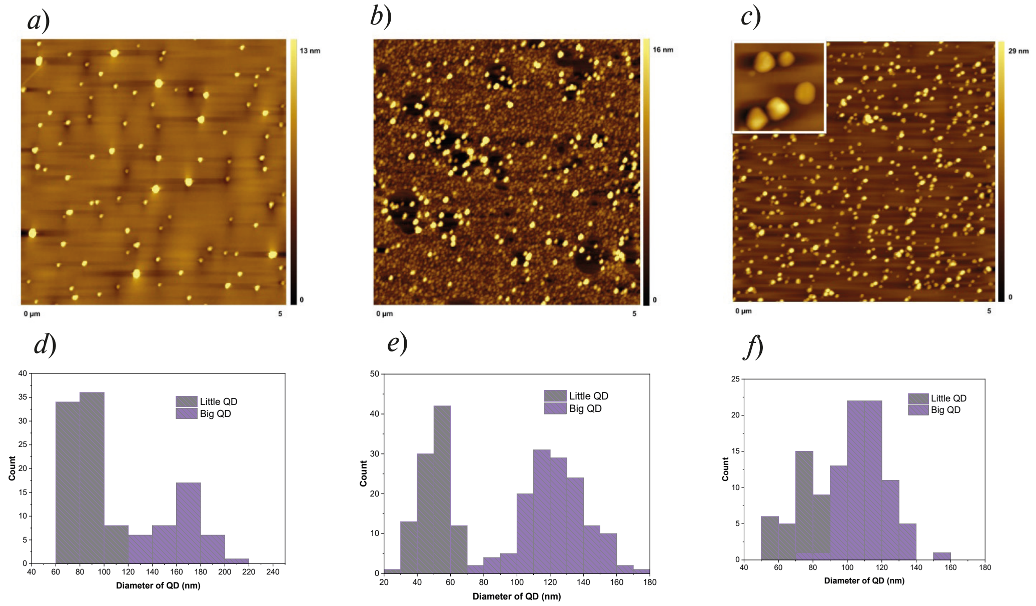

Fig. 1. The AFM images of s QDs with 0.3, 0.9, 1 ML InAs coverages (*a*, *b*, *c*); the size distribution of InAs QDs formed (*d*, *e*, *f*)

As it was mention above, one of the main tasks was the fabrication of Si nanocomposite with embedded InAs QDs. For this purpose, *in-situ* formation of Si capping layer was performed after the 0.3ML InAs QDs growth. At first, thin 10 nm Si layer was grown at the QDs growth temperature followed with the increasing substrate temperature to 500°C and growth of 20 nm Si. The evolution of RHEED patter during the capping layer growth revealed the formation of amorphous Si layer at the first stage. More pronounced Si crystallization was achieved during subsequent overgrowth at higher substrate temperature. Investigation of the sample by TEM revealed that InAs QDs fully embedded inside Si matrix (Fig. 2). The size of InAs QDs measured by TEM corresponded to those measured with AFM. High-resolution TEM analysis confirmed the dislocation free crystal structure of InAs QDs.

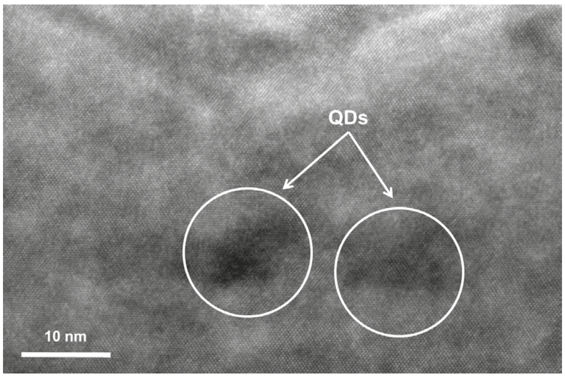

Fig. 2. TEM image of InAs QDs after the Si capping layer formation

Conclusion

In summary, the growth of InAs QDs on the Si was demonstrated. The size distribution of submonolayer InAs QDs was found to be bimodal. The increasing in InAs coverage led to the increasing average dot diameters and to the broadening in size distribution. Capping of dots with Si opens up possibilities for the fabrication of composite materials with embedded QDs inside the Si matrix. Such material can be used for the realization of new light sources on Si platform.

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