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Features of MBE growth of AlGaAs nanowires with InAs quantum dots on the silicon surface

R.R. Reznik [1,2,3]✉, V.O. Gridchin [1,2,3], K.P. Kotlyar [1],
A.S. Dragunova [2,4], N.V. Kryzhanovskaya [4], Yu.B. Samsonenko [2,3],
I.P. Soshnikov [2], A.I. Khrebtov [1], G.E. Cirlin [1,2,3]

[1] Saint-Petersburg State University, St. Petersburg, Russia;
[2] Alferov University, St. Petersburg, Russia;
[3] IAI RAS, St Petersburg, Russia;
[4] HSE University, St. Petersburg, Russia
✉r.reznik@spbu.ru

Abstract. AlGaAs nanowires with InAs quantum dots on the silicon surface were synthesized by molecular-beam epitaxy. Morphological and optical properties of grown nanostructures were studied. It is important to note, that emission from quantum dots is observed in the wavelength range from 780 to 970 nm. Assumptions about the nature of short-wave radiation from quantum dots were formulated. In particular, one of the reasons may be the significant desorption of indium atoms and the presence of gallium atoms in the catalyst droplets during growth at the substrate temperature of 510 °C. Our work, therefore, opens new prospects for integration of direct bandgap semiconductors with silicon platform.

Keywords: III-V semiconductors, nanowires, quantum dots, molecular-beam epitaxy, silicon

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Особенности роста нитевидных нанокристаллов AlGaAs с квантовыми точками InAs на поверхности кремния методом роста МПЭ

Р.Р. Резник [1,2,3]✉, В.О. Гридчин [1,2,3], К.П. Котляр [1],
А.С. Драгунова [2,4], Н.В. Крыжановская [4], Ю.Б. Самсоненко [2,3],
И.П. Сошников [2], А.И. Хребтов [1], Г.Э. Цырлин [1,2,3]

[1] Санкт-Петербургский государственный университет, Санкт-Петербург, Россия;
[2] Академический университет им. Ж.И. Алферова РАН, Санкт-Петербург, Россия;
[3] Институт аналитического приборостроения РАН, Санкт-Петербург, Россия;

[4] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербург, Россия
✉ r.reznik@spbu.ru

Аннотация. Методом молекулярно-пучковой эпитаксии были синтезированы AlGaAs нитевидные нанокристаллы с InAs квантовыми точками на поверхности кремния. Были исследованы морфологические и оптические свойства выращенных наноструктур. Важно отметить, что излучение из квантовых точек наблюдается в диапазоне длин волн от 780 до 970 нм. Сформулированы предположения о природе коротковолнового излучения квантовых точек. В частности, одной из причин может являться высокий уровень десорбции атомов индия и присутствие атомов галлия в каплях катализатора в процессе роста при температуре подложки 510 °С. Таким образом, наша работа открывает новые перспективы для интеграции прямозонных полупроводников с кремниевой пластиной.

Ключевые слова: III-V полупроводники, нитевидные нанокристаллы, квантовые точки, молекулярно-пучковая эпитаксия, кремний

Финансирование: Экспериментальные образцы были выращены при финансовой поддержке Санкт-Петербургского государственного университета в рамках исследовательского гранта № 93020138. Исследования морфологических свойств выращенных образцов были выполнены при поддержке Министерства науки и высшего образования Российской Федерации (госзадание № 0791-2020-0003). Исследования оптических свойств выращенных образцов были выполнены при финансовой поддержке гранта РНФ № 21-72-00099.

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Introduction

Nowadays semiconductor materials based on III-V compounds attract increased attention for optoelectronic applications due to their direct band gap nature [1]. With a decrease in the size of such materials below the de Broglie wavelength, they begin to exhibit quantum properties, which allow the creation of new generation devices [2]. Of particular interest are combinations of objects with different dimensionalities. For example, modern methods of creating nanostructures make it possible to form in the body of nanowires (NWs) narrow-gap nanoobjects – quantum dots (QDs) [3]. The size and density of such QDs can be strictly determined by the growth parameters and the NW itself can act as a waveguide for directional emission from the QDs [4]. It is important to note that, due to the unique morphology of the NWs, such structures can be synthesized on mismatched surfaces [5–7], which makes it possible to advance in solving the problem of integrating III-V direct-gap nanostructures with silicon technology [5, 6]. Our previous successes in the formation of such structures were associated with synthesis InAsP QDs in InP NWs [8, 9] and GaAs QDs in AlGaAs NWs [10–13] on the surfaces of a silicon wafers by molecular-beam epitaxy (MBE) technique. In particular, it was shown that nanostructures based on GaAs QDs in AlGaAs NW are efficient and directed sources of single photons in the wavelength range of 750–800 nm [14, 15], which indicates the promise of their application for quantum informatics. However, in this case, the change in the emission wavelength occurs due to the change in the size of the QDs and is strictly limited. Therefore, to increase the number of applications based on QDs in NWs, it is necessary to expand the range of QDs materials.

In this work, in order to shift quantum light sources emission to longer wavelengths, AlGaAs NWs with InAs QDs were synthesized by MBE.

Materials and Methods

Experimental samples were synthesized using Riber Compact 21 MBE setup equipped with Gallium (Ga), Indium (In), Arsenic (As) effusion sources and additional chamber for metallization. On the preliminary stage Si(111) wafers were cleaned in 10:1 aqueous solution of HF. Then silicon substrates were immediately loaded into the metallization chamber and were heated up to the 850 °C for 20 minutes. After thermal cleaning of the substrates their temperature was decreased to 550 °C. After stabilization of the substrates temperature a thin layer of Au was deposited on the wafers surface for following Au-droplets formation during 50 seconds. After that temperature of the wafer was cooled down to room temperature and substrates were transferred into the growth chamber without the violation of ultrahigh-vacuum conditions where they were heated to 510 °C. The growth of nanostructures was carried out in several stages. Firstly, Ga, Al and As sources were opened for AlGaAs NWs growth for 13 minutes. Then the Al and Ga sources were closed and the In source was opened at the same time for InAs QDs formation during 5 seconds. Finally, the In source was closed and Al and Ga sources were opened for following growth of AlGaAs NWs during 14 minutes. During the entire growth, the fluxes from the sources were constant and corresponded to the growth rates of the planar layers 0.7 monolayers per second (ML/s) for Ga, 0.3 ML/s for Al and 0.4 ML/s according previous calibrations in GaAs(100) surface. Reflection high-energy electron diffraction (RHEED) patterns dynamics observation showed wurzite crystallographic structure formed already after 1 minute of growth.

The morphological properties of grown experimental samples were studied by scanning electron microscopy (SEM) using Supra 25 Zeiss microscope. Optical properties of samples were studied with the use of the macro-photoluminescence (PL) technique at 77 K.

Results and Discussion

Figure 1 shows the typical SEM image of nanostructures grown on Si(111) substrate. It can be seen from the figure that the average AlGaAs NWs height is 1.6 μm. At the same time, the diameter of NWs is not inhomogeneous in height, since NWs have a pencil shape. The NWs diameter is 140 nm at the base and 15 nm at the top. It is important to note, that most of the AlGaAs NWs formed in the <111> direction. This fact indicates the epitaxial nature of NW growth on the silicon surface.

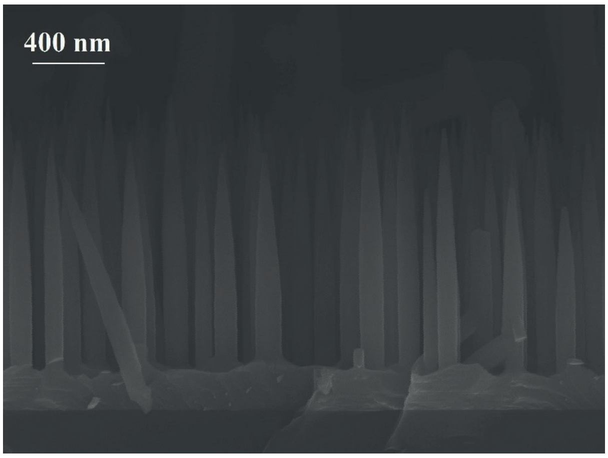

Fig.1. Typical SEM image of AlGaAs NWs with InAs QDs grown on Si(111) substrate

Typical PL spectrum corresponding to emission from InAs QDs is shown in Fig. 2. As can be seen from the figure, emission from QDs is observed in the wavelength range from 780 to 970 nm. However, it is well-known that bulk InAs emits in the longer wavelength range. One of the explanations for the shorter wavelength emission from the grown nanostructures can be a significant desorption of In atoms from the catalyst droplets at 510 °C and the presence of Ga atoms in this droplet. Thus, the chemical composition of QDs can correspond to InGaAs solid solution. Moreover, the presence of size quantization and mechanical stresses due to the mismatch of lattice parameters can also lead to a shift in the wavelengths of emission to the short-wavelength region. Detailed studies of this phenomenon nature will be carried out in subsequent works.

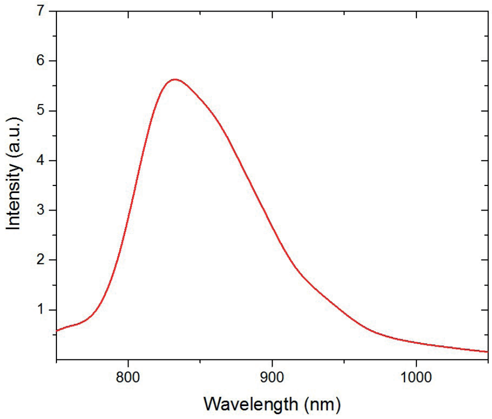

Fig. 2. Typical PL spectrum at room temperature corresponding to emission from InAs QDs

Conclusion

In conclusion, AlGaAs NWs with InAs QDs on the silicon surface were synthesized by MBE. Morphological and optical properties of grown nanostructures were studied. It is important to note, that emission from QDs is observed in the wavelength range from 780 to 970 nm. Assumptions about the nature of short-wave radiation from QDs were formulated. In particular, one of the reasons may be the significant desorption of indium atoms and the presence of gallium atoms in the catalyst droplets during growth at the substrate temperature of 510 °C. Our work, therefore, opens new prospects for integration of direct bandgap semiconductors with silicon platform.

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THE AUTHORS

REZNIK Rodion R.
moment92@mail.ru
ORCID: 0000-0003-1420-7515

GRIDCHIN Vladislav O.
gridchinvo@yandex.ru
ORCID: 0000-0002-6522-3673

KOTLYAR Konstantin P.
konstantin21kt@gmail.com
ORCID: 0000-0002-0305-0156

DRAGUNOVA Anna S.
anndra@list.ru
ORCID: 0000-0002-0181-0262

KRYZHANOVSKAYA Natalia V.
nataliakryzh@gmail.com
ORCID: 0000-0002-4945-9803

SAMSONENKO Yurii B.
yu_samsonenko@mail.ru
ORCID: 0000-0002-7119-3925

SOSHNIKOV Ilya P.
ipsosh@beam.ioffe.ru
ORCID: 0000-0002-9001-7599

KHREBTOV Artem I.
khrebtovart@mail.ru
ORCID: 0000-0001-5515-323X

CIRLIN George E.
george.cirlin@mail.ru
ORCID: 0000-0003-0476-3630

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