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Formation of site-controlled InAs quantum dots on nanopatterned GaAs(111)B surfaces

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Abstract. We study the processes of site-controlled growth of InAs quantum dots (QDs) on GaAs(111)B surfaces patterned by focused ion beams (FIB). The QDs tend to occupy vertexes of the pyramidal holes formed after annealing of the FIB-treated surfaces. The average degree of localization of QDs is found to strongly depend on the number of FIB passes and has a maximum value of 0.84, 0.7 and 0.92 for arrays with a distance of 2, 1 and 0.5 μm between holes, respectively. The average size and surface density of QDs also depends on the number of FIB passes, mainly with a non-monotonic nature. Photoluminescence emission of InAs QDs grown on the GaAs(111)B surface is observed in the spectral range of 950–1150 nm at a measurement temperature of 77 K.

Keywords: GaAs(111)B, focused ion beams, molecular beam epitaxy, quantum dots

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Формирование упорядоченных квантовых точек InAs на структурированных поверхностях GaAs(111)B

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Аннотация. Проведено исследование процессов селективно-позиционированного роста квантовых точек (КТ) InAs на поверхностях GaAs(111)B, структурированных методом фокусированных ионных пучков (ФИП). Установлено, что КТ стремятся зарождаться в вершинах пирамидальных углублений, образующихся после отжига ФИП-модифицированных поверхностей. Средняя степень локализации КТ в значительной степени зависит от числа проходов ФИП и имеет максимальное значение 0,84, 0,7 и 0,92 для массивов с расстояниями между углублениями 2, 1 и 0,5 мкм соответственно. Средний размер и поверхностная плотность КТ также зависят от числа проходов ФИП, имея преимущественно немонотонный характер. Показано, что фотолюминесцентное излучение КТ InAs, выращенных на поверхности GaAs(111)B, находится в спектральном диапазоне 950–1150 нм при температуре измерения 77 K.

Ключевые слова: GaAs(111)B, фокусированные ионные пучки, молекулярно-лучевая эпитаксия, квантовые точки

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Introduction

Quantum computing and communications are taking an increasingly firm place in the modern scientific and technical environment, providing the potential for the implementation of quantum internet [1]. For this purpose, photonic systems emerge as a particularly promising solution owing to their ability to propagate quantum states over long distances, exploit multiple degrees of freedom and maintain compatibility with traditional photonic infrastructure [2]. InAs/GaAs quantum dots (QDs) are regarded as one of the most advanced quantum emitters, offering key advantages such as telecom-wavelength operation, broad spectral tunability, on-demand photon generation, high indistinguishability and exceptional single-photon purity [3]. QDs grown on GaAs(111) patterned substrates exhibit enhanced properties due to their inherent C_{3v} symmetry enabling vanishing fine structure splitting – a critical requirement for high-fidelity quantum entanglement [4, 5]. Additionally, the formation of pyramidal holes on GaAs(111) surfaces facilitates the precise localization of triple QDs, making them highly suitable for applications in cellular automata, spin blockade devices, magnetoconductance studies, spin buses and related quantum phenomena [6].

In this paper, we investigate the epitaxial growth of InAs QDs on GaAs(111)B surfaces patterned with pyramidal holes. A systematic analysis of the QD size, surface density and spatial localization within nucleation centers is conducted to optimize the substrate patterning parameters and subsequent epitaxial growth conditions.

Materials and Methods

The GaAs(111)B surfaces were patterned by a focused ion beam (FIB) on a FEI Nova NanoLab 600 scanning electron microscope (SEM) equipped with a Ga^+ FIB column. FIB treatment point arrays of 5×5 μm in size with 0.5, 1 and 2 μm spacing between the points (L) and the number of ion beam passes (N) from 1 to 60 were used. Then, the substrates were placed in a SemiTEq STE 35 MBE equipment for annealing and transformation of rounded nanoholes into pyramidal ones. In the next step, InAs QDs were deposited on the surface with a thickness of 2.5 monolayers at a temperature of 500 °C. The samples obtained were examined using a FEI Nova NanoLab 600 SEM and an NT-MDT Ntegra atomic force microscope in a semi-contact mode.

Results and Discussion

SEM images of the FIB-treated arrays demonstrate that the FIB points transform into tetrahedral holes with three (111) facets for various spacings and number of passes (Fig. 1). Depending

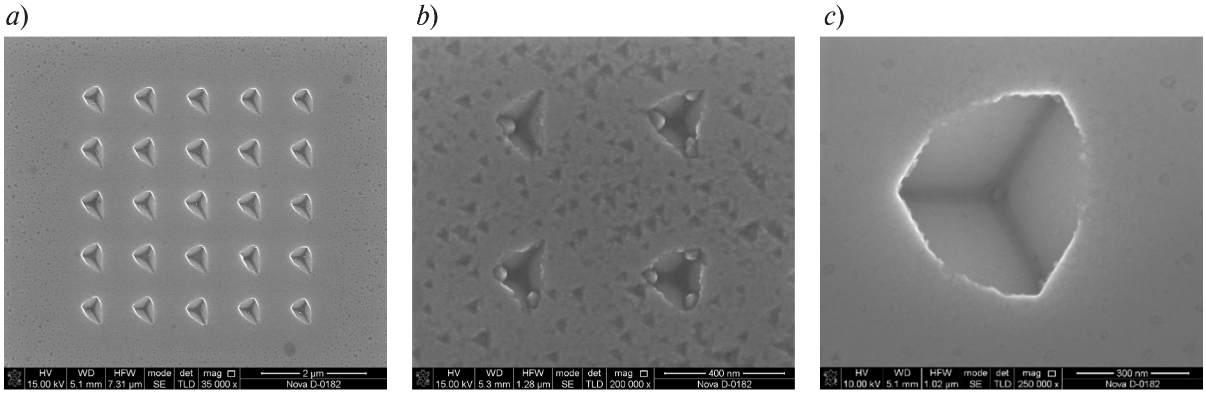

Fig. 1. SEM images of the hole arrays with InAs QDs: $L = 1$ μm, $N = 60$ (*a*), $L = 0.5$ μm, $N = 5$ (*b*), $L = 2$ μm, $N = 40$ (*c*)

on the treatment conditions, the surface between the holes can be smooth (Fig. 1, *a*, *c*) or rough (Fig. 1, *b*), which is governed by the intensity of ion resputtering. However, in both cases, InAs QDs are preferably localized within the pyramidal holes rather than outside the treated areas. When the period between holes is 1 μm, the holes contain approximately 1 QD located near the hole center (Fig. 1, *a*). In the case of a period reduced to 0.5 μm, QDs tend to occupy vertexes of the lateral triangle of the hole (triangular vertexes) (Fig. 1, *b*). An increase in the treatment period leads to the formation of large holes which have pronounced surface edges overhanging the hole walls (Fig. 1, *c*). In this case, QDs tend to occupy all vertexes of the hole pyramid.

An analysis of the degree of localization of QDs over the triangular vertexes of the 1-μm array shows that QDs are formed randomly in different holes within the same array with the localization varying from 0 (no QDs in required positions) to 1 (exactly 3 QDs in 3 vertexes) (Fig. 2, *a*). The average degree of localization depends on the initial parameters of the FIB treatment and has a maximum of 0.7 for $L = 1$ μm and $N = 5$ with decreasing to 0.26 at $N = 60$ (Fig. 2, *b*). The average size of QDs decreases from 42 to 23 nm with increasing N from 1 to 30 and then rises to 30 nm at $N = 60$.

A similar investigation for the 2-μm array of holes demonstrates that the average localization of QDs has a value ranging from 0.55 to 0.61 at 1–30 FIB passes and reaches 0.84 at 60 passes. However, the surface density of QDs monotonically decreases from 1.5 (1 pass) to 0.6 μm^{-2} (60 passes) in this case. A maximum average degree of localization of QDs is reached for the 0.5-μm array of holes and has a value of 0.92 for 20 FIB passes, with a 81% fraction of holes containing exactly three QDs at triangular vertexes.

It should be noted that the average localization of QDs changes non-monotonically with increasing N for all three interhole distances (L). This behavior may be associated with the complicated dynamics of the hole formation during annealing of samples after the FIB treatment.

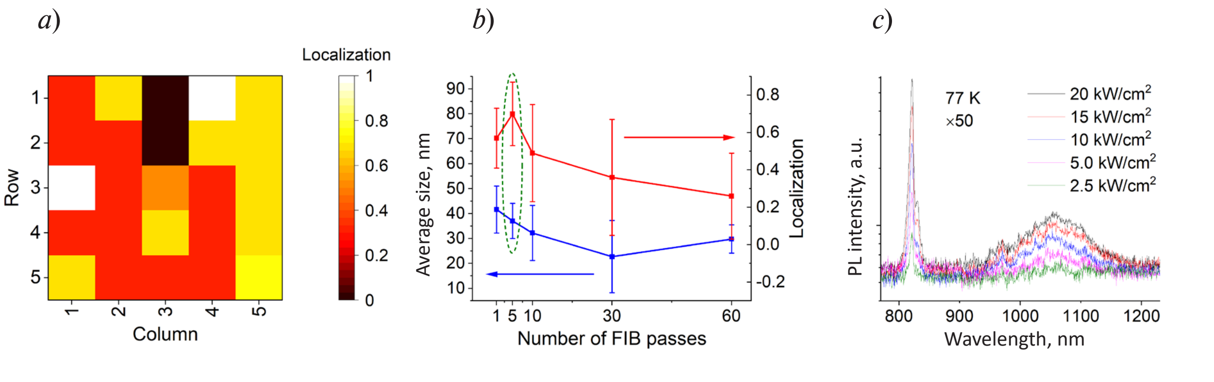

Fig. 2. Map of localization of QDs over the hole arrays with $L = 1$ μm and $N = 10$ (*a*), average size and degree of localization of QDs vs. number of FIB passes for $L = 1$ μm (*b*), PL spectra of InAs QDs formed on the GaAs(111)B surface (*c*)

Depending on the ion dose, the complex oxide above the FIB points can be in a more or less stable phase, inducing various intensities of the local droplet etching [7]. As a result, the holes have a wide size and shape distribution and serve as centers with various nucleation probability.

The photoluminescence (PL) spectra of InAs QDs grown on the GaAs(111)B were also measured at 77 K. It was found that they emit in a range of 950–1150 nm (Fig. 2, *c*), implying that they have a wide size distribution. However, the positive side of these spectra is that the emission wavelength of such QDs can be tuned over a wide range. Therefore, they have a great potential of a further use in site-controlled quantum emitters.

Conclusion

Thus, InAs QDs tend to occupy vertexes of the pyramidal holes obtained after FIB treatment of the GaAs(111)B surfaces. The average degree of localization of QDs for the 1-μm array has a maximum of 0.7 at 5 FIB passes, whereas their average size has a minimum of 23 nm at 30 FIB passes. For the 2-μm array, the localization of QDs reaches 0.84 at 60 FIB passes. A maximum localization of 0.92 is observed for the 0.5-μm array of holes at 20 FIB passes.

REFERENCES

1. **Ramakrishnan R.K., Ravichandran A.B., Kaushik I., et al.,** The Quantum Internet: A Hardware Review, Journal of the Indian Institute of Science. 103 (2023) 547–567.

2. **Luo W., Cao L., Shi Y., et al.,** Recent progress in quantum photonic chips for quantum communication and internet, Light Science & Applications. 12 (2023) 175.

3. **Katsumi R., Ota Ya., Benyousef M.**, Telecom-band QDs compatible with Si photonics for photonic quantum applications, Advanced Quantum Technologies. 8 (2) (2025) 2300423.

4. **Tuktamyshev A., Fedorov A., Bietti S., et al.,** Telecom-wavelength InAs QDs with low fine structure splitting grown by droplet epitaxy on GaAs(111)A vicinal substrates, Applied Physics Letters. 118 (13) (2021).

5. **Mano T., Ohtake A., Kuroda T.,** Lattice-Mismatched Epitaxy of InAs on (111)A-Oriented Substrate: Metamorphic Layer Growth and Self-Assembly of Quantum Dots, Physica Status Solidi. (2024) 2300767.

6. **Gaudreau L., Kam A., Granger G., et al.,** A tunable few electron triple quantum dot, Applied Physics Letters. 95 (2009) 193101.

7. **Balakirev S.V., Chernenko N.E., Lakhina E.A., et al.,** Influence of local droplet etching modes on the transformation of nanoholes formed by focused ion beams on a GaAs(111) surface, Nanobiotechnology Reports. 19 (S1) (2024) S37.

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