Study of the initial stage of GaAs growth on FIB-modified silicon substrates

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Abstract. In this work, we studied the effect of the deposition thickness, growth rate, arsenic flux, and implantation dose on the morphology of the GaAs nanostructures grown on modified Si areas. It is shown that an increase in the growth rate at the initial stages of the growth process leads to the transition of the growth regime from layered-like to one-dimensional with the formation of nanowires. Studies of the effect of As₄ pressure have shown that a change in the equivalent As₄ flux in the range of 3.7 - 5.0 ML/s does not lead to any significant change in the structure of the GaAs layer in the modified areas. An increase in the implantation dose during processing with a focused ion beam led to disordering of the directions of the grown nanowires due to the degradation of the substrate crystal structure.

1. Introduction
In recent years, more and more attention has been attracted to the epitaxial growth of III-V semiconductor compounds on silicon substrates, in particular, the monolithic integration method, which is supposed to allow combining light emission sources with high-speed information processing devices on one chip [1-3]. Therefore, the formation of high-quality III-V light sources on silicon remains one of the important modern problems of optoelectronics and nanophotonics [1-8].

However, there are a number of problems in the monolithic integration of III-V on Si: the growth of a polar III-V semiconductor on a non-polar Si substrate leads to the formation of antiphase domains [7, 8], the difference in the lattice constants of substrate and growth layer contributes to the formation of misfit dislocations and, as a result, threading dislocations [7-11], and the difference in thermal expansion coefficients of materials leads to the formation of thermal cracks [12]. Despite the fact that a wide range of techniques is used to improve the structural and functional characteristics of the III-V optical components on Si, completely new approaches are required to reduce the defectiveness of the resulting structures.

In this work, we investigated the effect of the implantation dose during Si substrate modification by focused ion beams, growth rate, and arsenic flux on the morphology of the grown GaAs structures.
2. Experimental procedure
The GaAs epitaxial materials were fabricated using a SemiTEq STE 35 molecular beam epitaxy system with solid-state sources. The studies were carried out on on-axis Si(100) substrates with local modification areas. The surface modification was carried out by local implantation of Ga ions into the Si substrate by the method of focused ion beams. The implantation dose varied from 1 to 21 pC/μm² and the current was 1 pA. The growth rate varied from 0.1 ML/s to 1 ML/s. The removal of native oxide from the Si surface was carried out at 900°C in vacuum for 30 minutes [13]. Then, a high temperature (600°C) GaAs buffer layer was deposited.

3. Results and discussion
Studies have shown that an increase in the GaAs deposition rate from 0.1 to 1.0 ML/s with a constant As₄ flux leads to an intensification of the nucleation and growth processes of GaAs nanowires (Figure 1), regardless of the implantation dose. This behaviour is due to the local accumulation of uncompensated Ga.

We believe that this may be due to, on the one hand, the presence of an excess of Ga atoms in the modified areas of Si, which arose as a result of the introduction of ions into the substrate, and, on the other hand, to the possible delay of GaAs nucleation processes on the Si surface, which can also lead to a local change in the ratio of the Ga and As₄ fluxes towards the metal component even under conditions of the initial excess of As₄. It should also be noted that such a local shift of the flux ratio

Figure 1. SEM images of modified Si areas after deposition of $H = 200$ nm GaAs at $T = 600°C$ with different deposition rates: (a), (d) $v = 1$ ML/s, (b) $v = 0.25$ ML/s, (c) $v = 0.1$ ML/s. The implantation dose and current were 7 pC/μm² and 1 pA for (a)-(c), and 21 pC/μm² and 1 pA for (d) respectively.
towards excess Ga was maintained throughout the entire growth period - the total length of GaAs nanowires reaches 15 – 20 μm.

It is important to note that with an increase in the implantation dose and, as a consequence, the degree of amorphization of the Si crystal lattice, the degree of influence of the crystal lattice of the substrate on the growth of GaAs nanocrystals decreases: from those oriented in accordance with the structure of the substrate in the directions [110], [1-10], [-110] and [-1-10] (the case of actually inheriting the structure of the substrate) to randomly oriented - the case of the absence of the influence of the structure of the substrate.

At the same time outside of the modification areas, an increase in the GaAs deposition rate leads to a sharp increase in the density and size of GaAs crystallites, reducing the selectivity of nucleation and growth processes, which, nevertheless, does not lead to the formation of a continuous film. Separate GaAs crystallites are formed on unmodified Si areas, the density of which is expected to increase from $3.8 \times 10^6$ cm$^{-2}$ to $5.38 \times 10^8$ cm$^{-2}$ as the GaAs deposition rate increases from 0.1 to 1.0 ML/s, which is due to a decrease in the diffusion length of adatoms.

An increase in the equivalent thickness of GaAs deposition while keeping the remaining parameters unchanged leads to an increase in the degree of filling of the modified areas (up to the formation of a continuous polycrystalline film) and the total height of the GaAs structure (Figure 2). Moreover, the analysis shows that the increase in the filling of the modified areas occurs both due to the growth of GaAs crystallites and due to an increase in their total number. In this case, an increase in the GaAs deposition thickness on unmodified areas of the Si surface did not lead to the formation of continuous films in the entire range of growth conditions under consideration.

![Figure 2. SEM images of modified Si areas after GaAs deposition at $T = 600^\circ$C and $v = 0.25$ ML/s with different deposition thicknesses: (a) 50 nm, (b) 200 nm. The implantation dose and current were 7 pC/μm² and 1 pA, respectively.](image)

Studies of the effect of As$_4$ pressure have shown (Figure 3) that a change in the equivalent As$_4$ flux in the range of 3.7 - 5.0 ML/s does not lead to any significant change in the structure of the GaAs layer in the modified areas, but leads to a sharp increase in the density and size of crystallites GaAs outside of the modified areas. Analysis of the set of experimental data shows that this effect is similar to an increase in the rate of Ga entry to the surface. Thus, the assumption of a local displacement of the flow ratios towards Ga is valid not only for modified, but also unmodified areas. Hence, it can be concluded that, at the initial stage of GaAs growth, the pressure of the Group V component is an important parameter from the point of view of not only the selectivity of epitaxial synthesis processes, but also the suppression, in our case, of the unwanted growth of nanowire nanocrystals.
Figure 3. SEM images of modified Si areas after deposition of 200 nm GaAs at $T = 600^\circ$C and $v = 0.1$ ML/s with various equivalent As$_4$ fluxes: (a) 3.7 ML/s, (b) 5 ML/s. The implantation dose and current were 7 pC/$\mu$m$^2$ and 1 pA, respectively.

4. Conclusions
Thus, the performed experimental studies show that the formation of GaAs structures on modified Si areas by Ga$^+$ ions makes it possible to localize the growth of the grown structure. The regularities of the influence are established and it is shown that a change in the main control parameters of the growth of GaAs on Si, such as the arsenic flux, the equivalent deposition rate and thickness, critically changes not only the type of growth, but also the morphology of the resulting nanostructures.

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