Application of the Atomic Layer Etching technique to remove broken layers after plasma-etched GaAs surface treatment

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Abstract. The work considers the application of focused ion beam techniques for the formation of nanoscale structures, as well as the atomic layer etching method for removing layers with surface defects. Also in the work, modeling of the formation of structures by the FIB method on the GaAs surface was used to determine the depth of penetration of atoms into the structure under certain experimental conditions. This method of forming defect-free structures was developed for the formation of a nanoscale surface relief for the subsequent growth of quantum dots by the method of drop molecular beam epitaxial.

1. Introduction
The task of controlled synthesis of semiconductor self-organizing nanostructures - quantum dots, filamentous nanocrystals, metallic nanodroplets - is extremely important, first of all, to create effective sources of single and entangled photons - the basis of quantum cryptography systems, as well as functional elements based on filamentary nanocrystals, single quantum dots and / or their complexes with a given topology, on the basis of which cellular automata, memory elements, integrated photonics and functional blocks quantum computing systems [1-12].

At the same time, drip epitaxy, based on separate deposition of components of groups III and V, allows not only to significantly expand the range of structures formed (quantum dots, rings, disks and complex, hybrid structures based on them), but also to realize independent control of the density and size of quantum dots, as well as to use for their creation virtually any A3B5 system, which is inaccessible to techniques based on the Stranski – Krastanov mechanism [13-21].

The use of structured GaAs and Si substrates and the features of droplet epitaxial techniques will effectively localize epitaxial growth at given points on the surface, thereby ensuring precise positioning and control of the parameters of synthesized nanostructures — metal nanoscale droplets (catalytic centers) and quantum dots based on them (in the case of GaAs) [22-30].

The structuring of the substrates was carried out by a combination of methods of focused ion beams and plasma-chemical etching. However, after obtaining substrates with nanoscale relief, a broken layer was formed on the surface in the depressions caused by plasma and penetration of Ga ions after exposure...
to focused beams. To remove damaged layers, the best method is layer-by-layer etching of the GaAs surface [31-37].

2. Materials and Methods
To achieve the goal of this work, experimental studies were conducted on the surface of standard GaAs plates. For the subsequent growth of quantum dots by the method of drop molecular beam epitaxial on the surface of the substrate, it is necessary to form structures in the form of a depression. The best method for forming such structures is the focused ion beam technique. Such formed structures are shown in Figure 1.

![Figure 1](image.png)

**Figure 1.** AFM-scan of experimental structures for studying defect formation after plasma exposure.

However, structures formed by a similar technique in the surface layers form a large number of defects. Various methods are used to eliminate this problem, for example, buffer layer build-up, however, the relief of the initial structures changes significantly and this has to be taken into account when forming the initial structures by the focused ion beam method. We also applied the method of removing surface layers by the method of plasma-chemical atomic layer etching (ALE). The essence of this multi-stage technique is as follows. At the first stage, a small concentration of chlorine-containing gas is introduced into the reactor, which reacts on the surface with the extreme atomic layers of the Ga and as structures, as well as with embedded Ga+ ions after surface treatment with focused gallium beams. At the second stage, combined plasma of inductively coupled and capacitive discharge in the atmosphere of a neutral gas Ar is ignited in the reactor. At the third stage, the removal of surface layers that interacted with chlorine atoms occurs. At the fourth stage, the reactor is cleaned and a similar cycle is repeated until all surface features created during the formation of the relief are removed.

3. Results
To determine the penetration depth of gallium ions and, accordingly, the occurrence of defective
layers, we simulated the process of formation of structures on the surface of an GaAs substrate using focused ion beam Ga+ methods. Under the processing conditions used on these structures, modeling showed that Ga+ ions penetrate to a depth of 12 atomic layers. Using the atomic layer etching technique, it was possible to remove surface defective layers, while in subsequent experimental studies by scanning microscopy of the spreading resistance (SSRM), no defects were detected on the surface (Figure 2 (a)).

![Figure 2(a, b) AFM-scan of the structure after passing through several cycles of plasma ALE: (a) general view of the array of structures; (b) the relief of an individual structure.](image)

The relief of the original structures practically did not change its shape (Figure 2 (b)). When using the “soft” regime of plasma-chemical etching, the angle of inclination of nanoscale structures usually changed and quantum dots did not grow, or a large buffer layer was required to be grown.

4. Discussion and Conclusions

As a result of experimental studies, experimental samples were obtained with nanoscale surface profiling, which will be further applied to the growth of quantum dots by the method of drop molecular beam epitaxial. These structures were formed by a combination of focused ion beam methods and plasma atomic layer etching. Using the model of structure formation by focused ion beams, it was revealed that gallium ions affecting the feds penetrated to a depth of 12 atomic layers. It was possible to establish that the nanoscale structures obtained by this technique did not change their configuration, as well as the number of defects on the surface is much smaller than when defects were removed by the “soft” plasma-chemical etching method.

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