Masking coating formation by the focused ion beams method for plasma chemical treatment

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Abstract. The application of the focused ion beams method makes it possible to obtain modified surfaces serving as a masking layer for subsequent processing of semiconductor materials. The use of plasma chemical etching as a method for profiling modified surfaces makes it possible to obtain cleaner surfaces than for liquid etching. In this paper, experimental studies of a masking coating formation were carried out using a focused ion beams method on a scanning electron microscope, followed by a relief formation by the plasma chemical etching method. The effect of local surface treatment of silicon by the focused ion beams method on the etching rate of the treated regions by the method of plasma chemical etching was examined. Samples with the formed regions were obtained, which demonstrated masking and stimulating properties during plasma chemical etching. The structures height after plasma chemical etching varied from 10 to 266 nm.

1. Introduction
Currently, there is an active development of nanoelectronics due to the reduction in the size of functional elements, accompanied by a decrease in their energy consumption and an increase in performance. Optical lithography is the most common method for the micro- and nanoscale structures formation in connection with the simplicity of this method and its wide possibilities [1]. However, at present, this method reaches its technological limit in the possibility of obtaining nanoscale structures in the hard ultraviolet region. In this regard, exploration of new methods of nanoscale profiling, which in the future will reduce the resulting structures geometric parameters is an urgent task [2-5]. One of such methods is the methods of focused ion beams and plasma chemical etching [6-9]. The combination of these methods will solve the problems that arise when using liquid etching and obtaining masking coatings using optical lithography. The application of the focused ion beams method makes it possible to obtain modified surfaces serving as a masking layer for subsequent processing of semiconductor materials [10-21]. The use of plasma chemical etching as a method for profiling modified surfaces makes it possible to obtain purer surfaces, does not require processing after the etching process, has high resolution, has a minimal lateral undercut effect and has high productivity [22-27]. With this technique, there are two types of interaction. In the first case, the working gas ions enter into a chemical reaction with the surface being treated, forming volatile compounds at low temperatures, followed by the removal of the reaction products from the reaction chamber through a pumping system [28-33]. In the other case, the ions are accelerated by an external field and the atoms are knocked out from the surface of the sample being processed, and a reactive ion-etching regime is realized [34-38]. With the help of the focused ion beams method, it is possible to
form modified regions with nanometric lateral dimensions, and by means of plasma chemical etching it is possible to form structures over modified regions with nanometer vertical dimensions. Based on the above study, a combination of these methods is an urgent task.

2. Description of the experiment and research methods
In this paper, we conducted experimental studies of the mask coating formation by the focused ion beams method on a scanning electron microscope (SEM) with an ion column Nova NanoLab 600 (FEI company, Netherlands), etching the modified regions by the method of plasma chemical treatment in a combined fluoride plasma of a capacitive and inductive discharge in a plasma chemical etching unit in an inductively coupled plasma STE ICP E68 (NTO, Russia), study of the obtained morphology on a scanning probe microscope (SPM) Ntegra Vita (NT-MDT, Russia).

For experimental studies, n-type silicon was used, with a resistivity of 0.001-0.005 ohm/cm, with an orientation of 100. The modification of the silicon substrates surface was carried out on 5x5 microns with minimal parameters of the ion beam diameter, accelerated ions energy 30 keV and with a different number of its passes, which varied from 10 up to 100.

In the next step, the samples were processed in a fluorine-containing plasma at different etching times. With constant processing parameters such as: the flux of fluorine-containing gas N$_{SF_6}$ is 15 cm$^3$/min, the N$_{Ar}$ flow is 100 cm$^3$/min, the pressure in the chamber during the process was about 2 Pa and the fixed powers of the sources of inductively coupled and capacitive plasma.

3. Results and discussions
After modification of the silicon surface ions by gallium ions, the samples were etched in plasma. In Fig. 1 there is an image from a scanning electron microscope of the modified region after plasma chemical etching at 100 passes of ion beam exposure and 120 seconds of etching in plasma. The image shows that the modified region after plasma chemical etching has a more developed relief than the rest region. This can be explained by the modification of Ga$^+$ ions by the focused ion beam region. Ga in the fluorine-containing plasma is etched worse than silicon, so the part of the surface which contained the silicon was removed, and the part where gallium predominated remained. The samples obtained during the experiments were investigated by scanning electron microscopy and atomic force microscopy (Fig. 1).

![Figure 1 (a, b). a) SEM image, b) SPM image of the modified region at 100 passes of the ion beam and etching time in plasma 120 seconds](image-url)

As a result, the rate of plasma chemical etching of regions modified by the method of focused ion beams turns out to be lower than the etching rate of the untreated region (Fig. 2).
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Figure 2 (a, b). a) a structure profile, b) a histogram from the image of an atomic force microscope of a modified region after plasma chemical etching for 120 seconds

With an increase of the ion beam passes number from 10 to 100, at a plasma etching time of 120 seconds, the height of the obtained structures ranged from 7 to 266 nm. This is due to the greater exposure to the sample surface and, as a consequence, to the different etching rates of the modified regions. Also, when the plasma etching time is increased from 30 to 120 seconds with the same number of ion beam passes, the structures height after plasma chemical etching increases from 10 to 266 nm. This is explained by the fact that, with a shorter etching time, the etching depth in the plasma becomes smaller, due to which the difference in height between the modified and the rest of the area decreases. Fig. 3 shows the dependence of the height of the obtained structures on the ion beam passes number at different etching times in a plasma on a silicon substrate.

Figure 3. Dependence of height on the ion beam passes number

The graph shows that when etched for 120 seconds with an increase in the number of passes from 10 to 100, the structures height increases from 7 to 266 nm. (Figure 3). With plasma etching time for 30 seconds at 10 ion beam passes, stimulation of etching is observed, the modified regions are obtained deeper by 6 nm than the rest of the substrate. This is due to the surface layer violation, which in the process of plasma chemical etching is removed faster than the rest surface. However, at 100 ion beam passes during plasma etching for 30 seconds, the modified regions exhibit a masking effect. The
structures height was 10 nm. This is explained by the fact that the region of action is saturated with gallium ions, which in turn form a masking effect.

4. Conclusion
In accordance with the results obtained, it can be seen that when the region is modified by the focused ion beams method, gallium ions are introduced into the semiconductor structure. A layer with embedded gallium ions, in turn, is a masking layer for plasma chemical etching in a fluorine-containing plasma. With an increase of the ion beam passes number, the modified regions exhibit large masking properties. In the course of the work, the structure height as a passes number function and the etching time in the plasma were obtained. With an increase in the etching time from 30 to 120 seconds, the height of the resulting structures increases from 10 to 266 nm. The number of passes also affects the height of the structures, but with a longer etching time in the plasma, the difference in height is greater. So with an etching time of 120 seconds, with an increase in the number of passes 10 to 100, the height of the structures increases from 10 to 266 nm. With a short etching time in the plasma, with a small ion beam passes number over the surface, etching is stimulated.

This technology can be used to form the structures and functional layers of quantum and optical nanoelectronics devices that require high resolution.

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