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# Studying the Resolving Power of Nanosized Profiling Using Focused Ion Beams

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**Abstract**—The results of experimental studies of the resolving power and accuracy of nanosized profiling using focused ion beams (FIBs) are presented. Dependences of the resolving power on the ion beam current were obtained for the boron-doped (10 ohm cm (100)) silicon substrate during FIB etching. It has been established that the best resolution upon silicon etching determined by the average thickness of the etched line is 15–52 nm and corresponds to ion beam currents of 1–30 nA. It has been shown that the precision in the formation of a topological pattern on the substrate surface increases with the decreasing magnitude of the ion beam current in the range of 0.5 pA to 1 nA, and the relative error in the formation of the nanostructure decreases from 5.10 to 0.07. The results of our research can be used to develop manufacturing processes when creating submicron structures and elements of nanoelectronics and nanosystem technology by using FIB.

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## INTRODUCTION

The method of focused ion beams (FIBs) is widely used in analyzing materials and structures in microelectronic devices, as well as in preparing specimens for the transparency electron microscopy (TEM) [1, 2]. However, the FIB technique can also be used for the nanosized surface profiling of solids and the formation of micro- and nanoscale structures in the production of prototypes of devices for micro- (nanosystem) technique and nanoelectronics [3]. As an analysis of the literature shows, the FIB technique allows one to create the elements of integral optics, nanoelectronics, micro- and nanoelectromechanical systems (MEMS, NEMS), and structures for the metrological maintenance of nanotechnology [4–7].

During the FIB etching of substrates, the material is locally atomized upon the action of the focused beam of gallium ions at an energy of 2–30 keV. When etching the substrate, the focused ion beam is moved step by step with a certain overlap, which is determined by the parameter "overlap" (in percentage). The beam exposure time at each point of the impact is set by an operator and lies in the range from $1.0 \times 10^{-7}$ to $4.5 \times 10^{-3}$ s [8]. The trajectory of the beam movement is determined by the digital pattern loaded with the help of system-management software, which represents a bitmap image file or an ASCII stream file containing coordinates of the points of impact.

The main limitations of the FIB method are associated with the complexity of the mode selection to provide the required geometry of structures. This is due to the lack of estimation techniques of resolution and accuracy upon forming a topological figure, which make it possible to predict characteristics of nanostructures depending on the ion-beam parameters.

The aim of this work is the development and studying of methods for determining the resolution and accuracy of topological pattern formation on the substrate by using local FIB etching method.

## EXPERIMENTAL PROCEDURE

Experimental studies were carried out using à Nova NanoLab 600 (FEI Company) ion–electron scanning microscope and an Ntegra Vita (ZAO NT-MDT, Russia) scanning probe nalolaboratory. As the substrate for experimental studies, we used silicon wafers KDB-10 (100).

For determining lateral resolution during FIB etching, we developed a technique whereby the array is formed of 15 lines 2 mm long and with a spacing of 5 to 700 nm between the lines. A raster pattern for etching is formed so that the lines consist of one row of pixels, with the resultant thickness of the line determined by the diameter of the ion beam instead of the parameters of scanning system. When etching according to the pattern, arrays of lines are successively formed at various magnitudes of the FIB current. The ion-beam current varies stepwise in the range of 1 pA to 3 nA at an accelerating voltage of 30 keV and overlap = 50%,

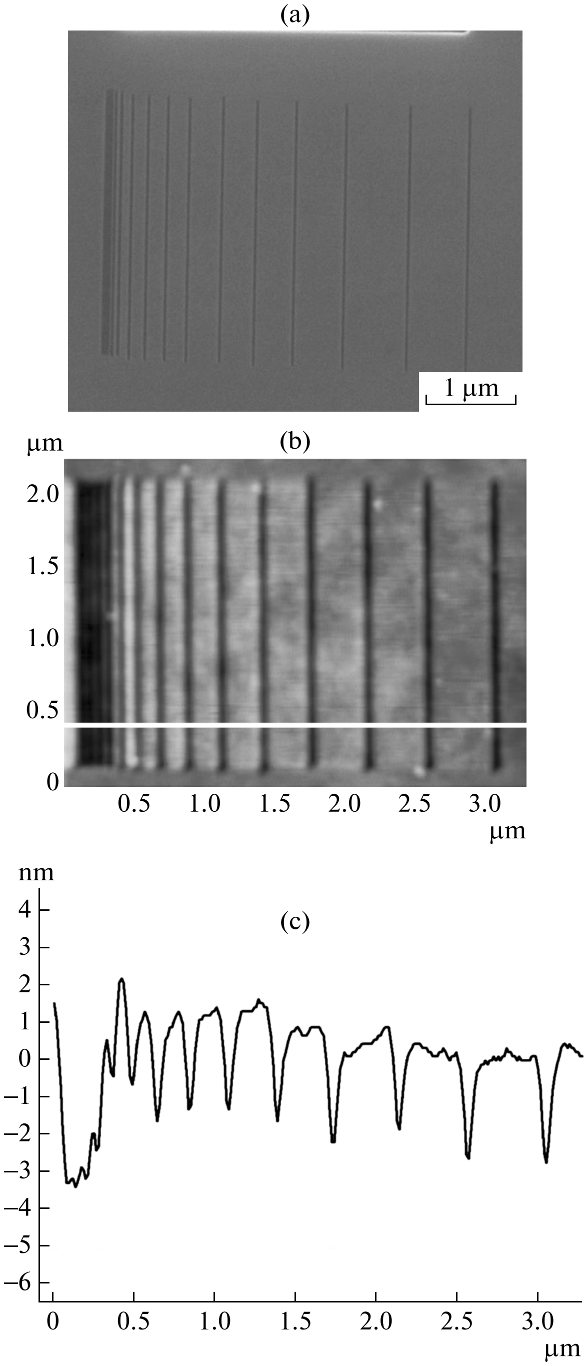


**Fig. 1.** The structure to determine resolution in the FIB method (ion beam current is 10 pA): (a) SEM image; (b) AFM image, (c) profilogram along the line.

and the number of the ion beam passages along the pattern is 1. After FIB etching, the surface of substrate was investigated by SEM and AFM (Fig. 1).

Two main geometrical parameters of the array of lines were measured according to the obtained images: the thickness of each line and the distance between the adjacent lines. The line thickness was measured using profilograms obtained from the AFM images (Fig. 1c),

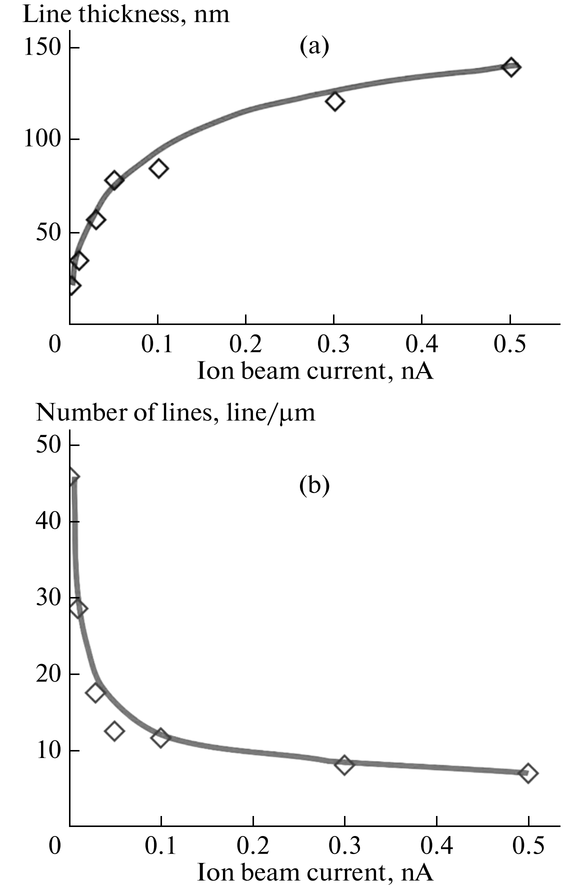


**Fig. 2.** Dependence of the FIB resolution on the ion-beam current: (a) thickness of an etched line; (b) number of distinguishable lines per unit length.

being determined as the width at a half-depth of the etched groove without the influence of redeposition of material on the substrate surface.

Resolution power during FIB etching was determined in two ways: by the minimum line width and the maximum number of distinct lines per unit length at a constant ion-beam current. Based on an analysis of experimental data, we obtained dependences of the FIB resolution on the beam current (Fig. 2).

Also, we performed experimental studies to determine the accuracy of formation of the topological pattern on the substrate using FIB etching. For this purpose, a technique was developed according to which a bitmap graphic template was formed that contains an array of 20 square structures with sizes ranging from $10 \times 10$ to $200 \times 200$ nm.

FIB etching for each predetermined pattern was carried out at an acceleration voltage of 30 keV; an exposure time of 10 ms; and a FIB current magnitude of 1, 10, and 30 pA. After etching, the substrate surface was investigated by scanning electron microscopy (Fig. 3).

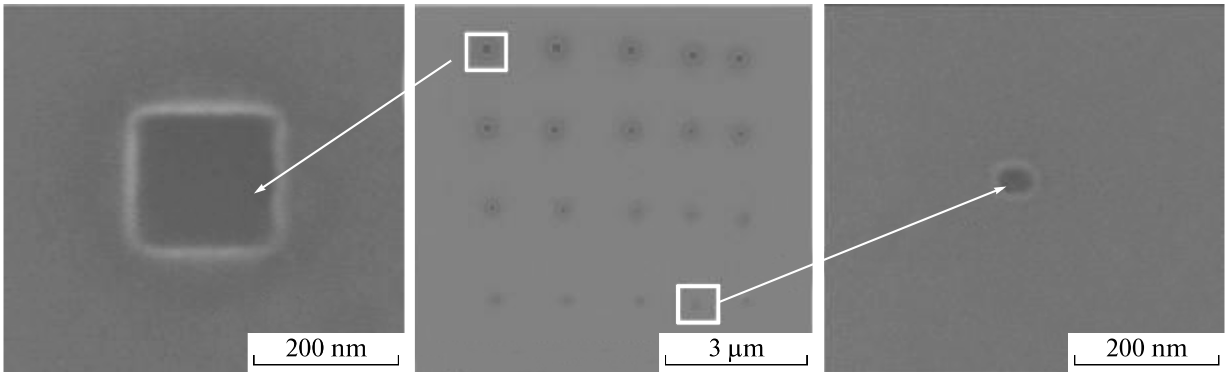


**Fig. 3.** SEM image of the structure to determine the accuracy upon the formation of a topological figure (ion-beam current is 10 pA).

Having measured the geometrical sizes of the structures, dependences of the length of a square side on the size of the specified raster pattern were plotted for different FIBs currents (Fig. 4). Moreover, we used digital image-processing techniques for SEM Nova NanoLab 600. A theoretical dependence is also shown on this graph, for which the mismatch between the specified and measured sizes is absent.

## RESULTS AND DISCUSSION

As an analysis of the dependences shows, the best resolution in technological FIB operations when forming topological patterns on the surface of silicon is achieved at ion beam currents from 1 to 30 pA. In particular, at a current of 1 pA, the line thickness equals 15 nm and the maximum number of lines per unit length is 47 lines/μm.

Results of a comparison of experimental and theoretical curves (Fig. 4) characterize the topological accuracy of the pattern on the substrate obtained by FIB etching. To determine the effect of structure size and FIB current on the accuracy of nanosized profiling, dependences of the relative error on the specified size upon nanostructure formation were plotted at FIB currents of 1 pA, 10 pA, and 30 pA (Fig. 5). It has been shown that the magnitude of the error is reduced as the size of the structures increases. In the range of currents under consideration, a significant impact of the FIB

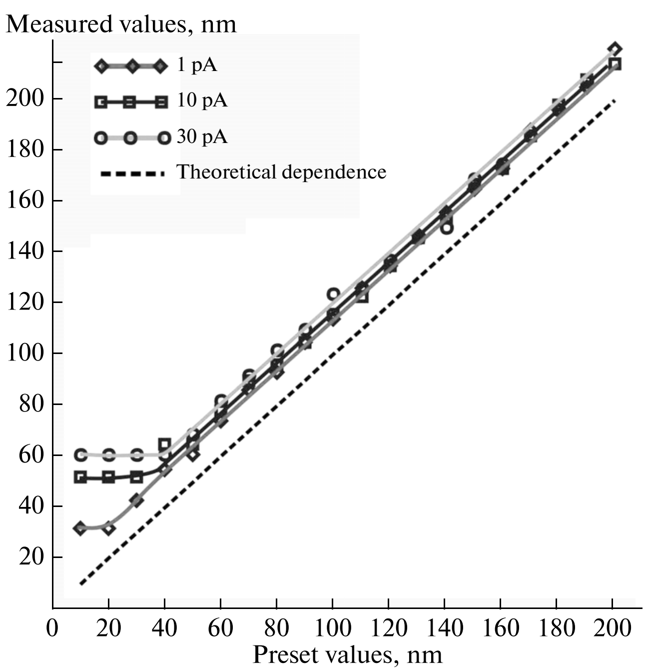


**Fig. 4.** The measured sizes of test structures depending on the specified sizes which are preset by the raster pattern at different ion beam currents.

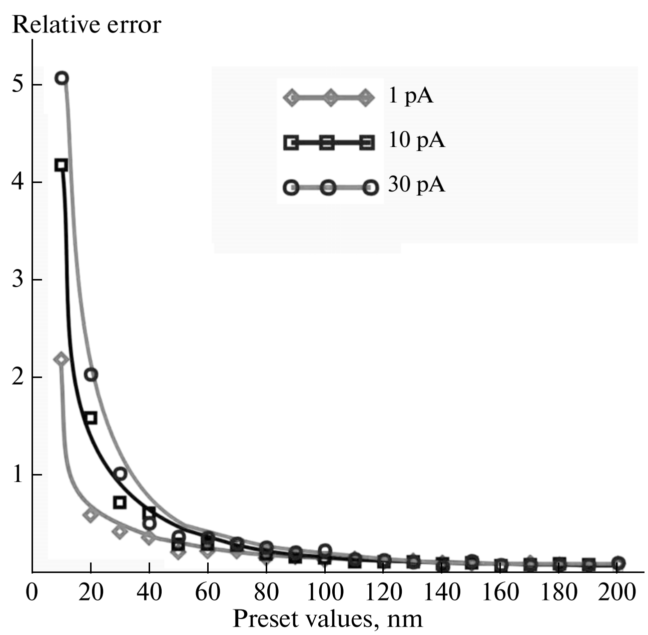


**Fig. 5.** Dependences of the relative error of the test structure sizes on the values preset by the raster pattern at different ion-beam currents.

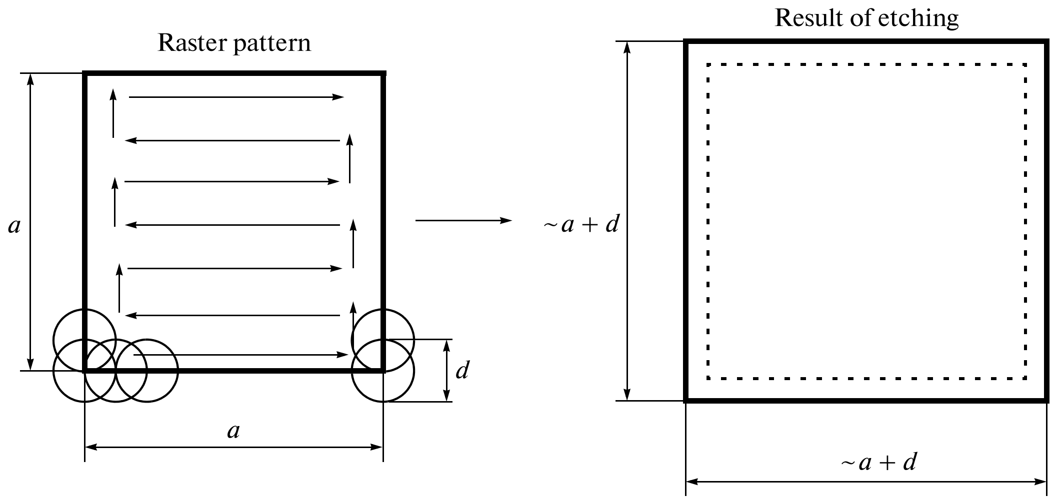


**Fig. 6.** Schematic view of the contribution of peripheral regions of the ion beam into the increase in the size of the test structure upon FIB etching.

current on the relative error of nanostructure formation is observed for structures up to 85 nm in size.

Dependency analysis (Figs. 4, 5) shows that, for the fixed values of a current, there are threshold values for the minimum size of the element below which there is a mismatch of preset and measured values. It is worth noting that the threshold values for the minimum size of the element increase with an increase in ion beam current.

Thus, when the predetermined size of an element is 10 nm, we obtain a difference of 20 nm at a current of 1 nA (threshold of 20 nm), 40 nm at 10 pA (the threshold value is 30 nm) and 50 nm at 30 pA (the threshold value of length is 40 nm). This means that an increase in the ion-beam current gives rise to a blurring of the borders of the elements of the pattern.

This effect can be explained by two factors: an increase in the physical diameter of the ion beam when the current rises and an increase in the size of peripheral regions of the beam (which are described by a Gaussian distribution [9]), in which the energy of ions is below the maximum energy in the beam. Peripheral regions of the beam are generally not considered in theoretical studies of the processes of etching, but they contribute to an extra etching of the boundary element of the pattern that leads to an increase in the size of the forming structures. Moreover, based on an analysis of experimental results, the presence of a mismatch between experimental and theoretical dependences in the entire range of the values measured above the threshold has been noted (Fig. 4). The value of the error is about 10–15 nm, which is comparable to the diameter of the ion beam used for the FIB current. The observed effect can be caused by extra etching of the pattern borders due to the influence of peripheral regions of the ion beam, as is shown in Fig. 6.

## CONCLUSIONS

Thus, in this work we have developed a technique for determining the lateral resolving power of nanosized profiling by using FIBs. It has been shown that the values of the average line thickness and the number of lines resolved per unit length characterize the resolving power of the method at certain values of the ion beam parameters. It should be noted that we must monitor the time of etching in the course of the study since the line thickness is considerably influenced by the depth of etching due to the geometrical shape of the FIB. It is shown that the best resolution during the etching of silicon is 15–52 nm and it is reached at magnitudes of the ion-beam current of 1–30 nA.

In addition, we have established that accuracy in the formation of a topological pattern on the substrate is worsened with an increasing ion-beam current. We have found the effect of the increasing size of elements relative to the specified size due to the action of peripheral regions of the beam. To eliminate this effect at the design stage, it is necessary to adjust the preset parameters of patterns by taking into account experimental values of the mismatch, material parameters, and the magnitude of the ion-beam current. The results of our research can be used to develop manufacturing processes when producing submicron structures and elements of nanoelectronics and in the technology of nanosystems by using the FIB method.

## ACKNOWLEDGMENTS

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