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GaAs microdisk formation by mechanical scanning probe lithography

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The present study investigates the features of formation of a lithographic pattern on a (100) GaAs substrate by mechanical scanning probe lithography using single-crystal diamond probes. It has been demonstrated that when the probe is pressed onto the surface and subsequently moves relative to the substrate, trenches are formed in the substrate. The depth and width of these trenches are found to be depending on the direction of movement and the shape of the probe tip. It is demonstrated that the greatest depth is achieved when the probe moves in the direction perpendicular to the plane of the edge of the tip with the largest area. Consequently, when the probe moves in a circular manner, the formed nanotrenches exhibit azimuthal inhomogeneity in their depth. This can be mitigated by tilting the substrate plane.

Keywords: scanning probe lithography, atomic force microscopy, GaAs, microdisks.

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The methods of scanning probe lithography make it possible to perform maskless lithography of modern materials using a probe of a scanning probe microscope with nanometer lateral resolution. One of such methods is mechanical scanning probe lithography (m-SPL), which consists in cutting or removing the surface material using a probe, the hardness of which exceeds the surface hardness [1]. The method advantage consists in its versatility and the possibility of lithography for the advanced semiconductor materials (dichalcogenides of transition metals [2], Van-der-Waals materials, halide perovskites [3] etc. [4]), for which no technology of mask lithography using etching has been developed yet.

Recently the detailed research was conducted on the formation of a nanogroove by lithography GaAs [5] and Si [6] using diamond probes. The effect of the probe pyramid shape and orientation of its faces, crystal-lattice orientation of the surface, pressing force and other factors on the groove depth and shape, and the thickness of the disordered layer in the source material was found. Besides, apart from the linear nanoobjects, the circular objects also are in demand. For example, microdisks from the modern semiconductor materials may be used as optical resonant cavities with optical quality factor (Q-factor) that considerably exceeds the Q-factor of stripe-type optical cavities [7]. The purpose of this paper is to study the features of microdisc formation on GaAs with the help of diamond probes using m-SPL method.

A (100) GaAs substrate with surface roughness level below ~ 1 nm was used. The studies were carried out on scanning probe microscope Ntegra AURA (NT-MDT) using cantilevers DRP_IN (Tipsnano). For comparison, two probes were selected from the same batch, and their stiffness was 180 N/m (probe 1) and 120 N/m (probe 2). These probes had a tip of single-crystal diamond with a curvature radius declared by the manufacturer, 25 nm. In the beginning of the m-SPL procedure against the relatively hard materials, usually the very tip of the probe would spontaneously break off. After breaking off the shape of the tip was determined using test lattice TGT1 (NT-MDT), which is an array of vertical needles with tip curvature radius of less than 10 nm.

Prior to the carving of microdisks, test grooves were made along with the probe movement in various directions. Fig. 1, *a* shows the images of the grooves obtained by the method of atomic-force microscopy (AFM) using probe 1 (left) and probe 2 (right). The probe moved in the numbered sequence indicated with the arrows. The pressing force was 50 μN, the movement speed - 10 μm/s. To assess the depth and width of the created grooves, fig. 1, *b* and *c* shows the profiles obtained perpendicularly to the cutting direction. The analysis of the images showed that probe 2 left 1.5 times deeper and wider grooves vs. probe 1. It is important to note that the depth and width of the grooves depend substantially on the movement direction. Besides, if for probe 1 the deepest groove was obtained when moving in direction *7*, for probe 2 the highest depth was obtained in directions *3* and *6*. Also note the difference in the depth and pile-up (light features on the AFM-images) as the probe moves vertically, but towards a different side (directions *1* and *6*). Since the substrate was oriented in the same manner, and the pressing force and motion speed of the probes were also the same, the differences in the dependence of the groove shape for two probes are probably explained by the difference in the shape of their tips.

Fig. 2, *a* and *b* presents AFM-images of the tips of probes 1 and 2 accordingly. For more convenient perception, the images produced using the test lattice are reflected along the vertical and horizontal lines. Indeed, the shapes of the probe tips differ significantly and may not be described

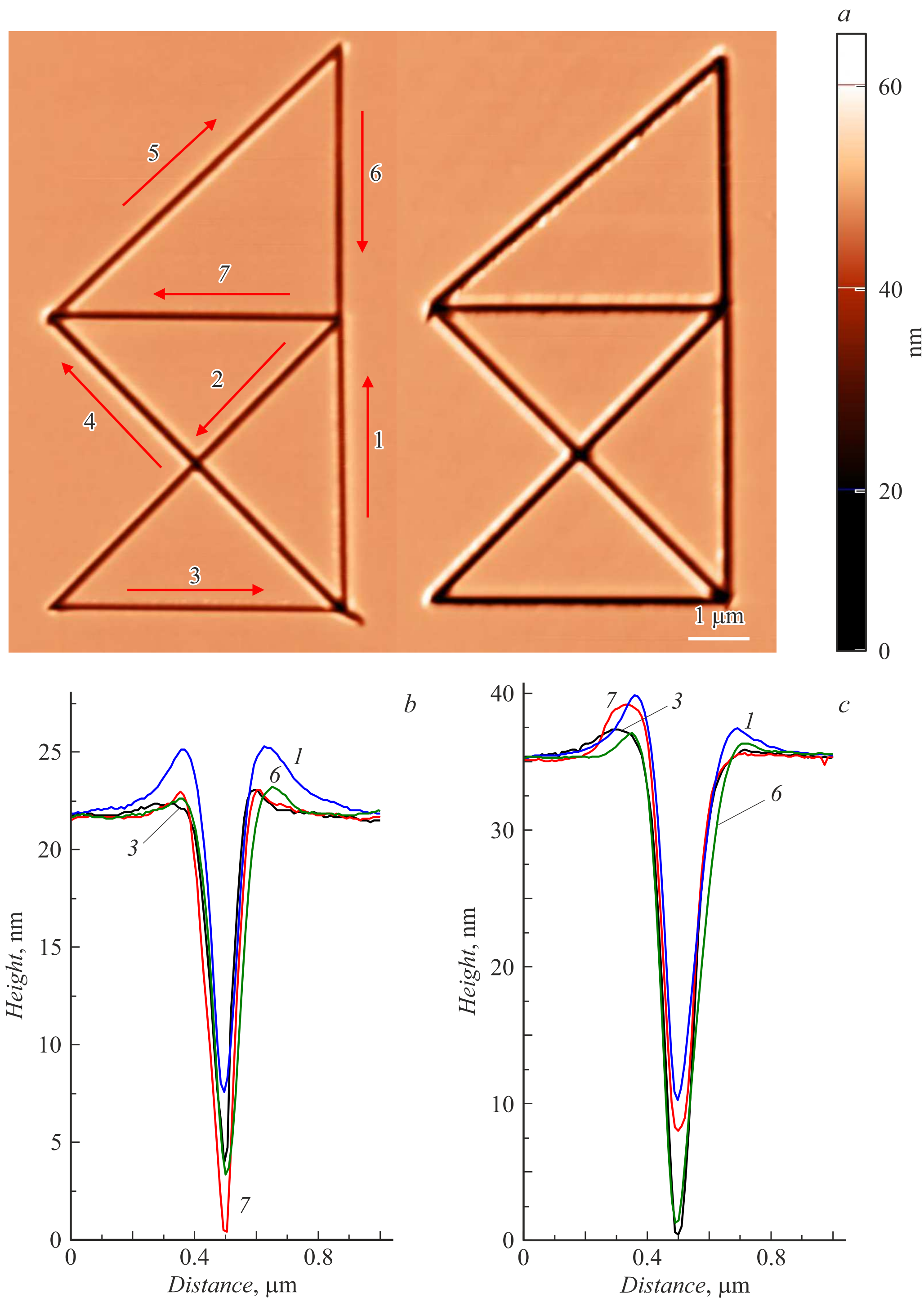

Figure 1. AFM-image (a) and corresponding profiles (b, c), obtained after m-SPL from the probe movement 1 (a, left) and 2 (a, right) in the sequence indicated by the arrows. The profiles were obtained in the directions perpendicular to the probe movement direction.

with a semi-sphere, since they are pyramids with different number and area of the faces.

Fig. 3 shows AFM-images and corresponding profiles of the microdisks made by the probe 1 (a) and probe 2 (b, c). When microdisks were made, the probe moved along circular trajectories counterclockwise (shown with the arrow in fig. 3, a). Besides, in the very beginning the probe moved from the center of the disk, and transition to the next circular trajectory of larger radius happened when the probe moved right. Therefore, you can see a horizontal line that starts in the disk center on AFM-images.

The analysis of the images shows that the material removal around the disk is non-uniform. And deeper (darker) and elevated (light) areas correlate with the data

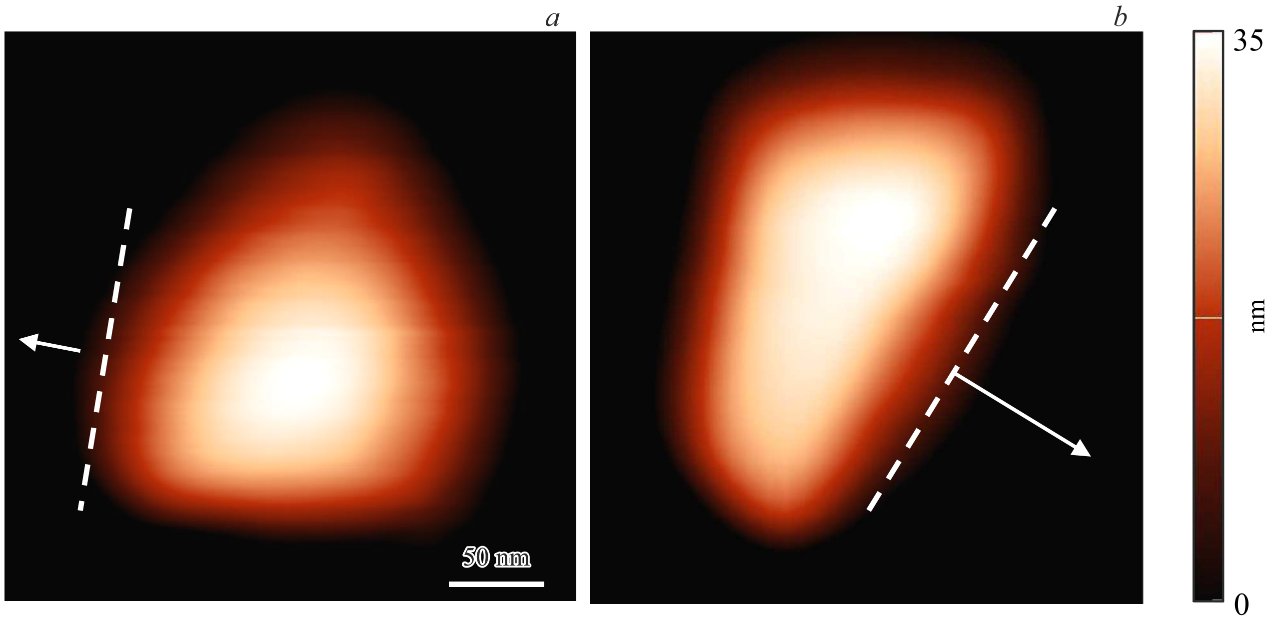

Figure 2. AFM-images of probe 1 tip (a) and probe 2 tip (b). The dashed line shows the face of the highest surface area.

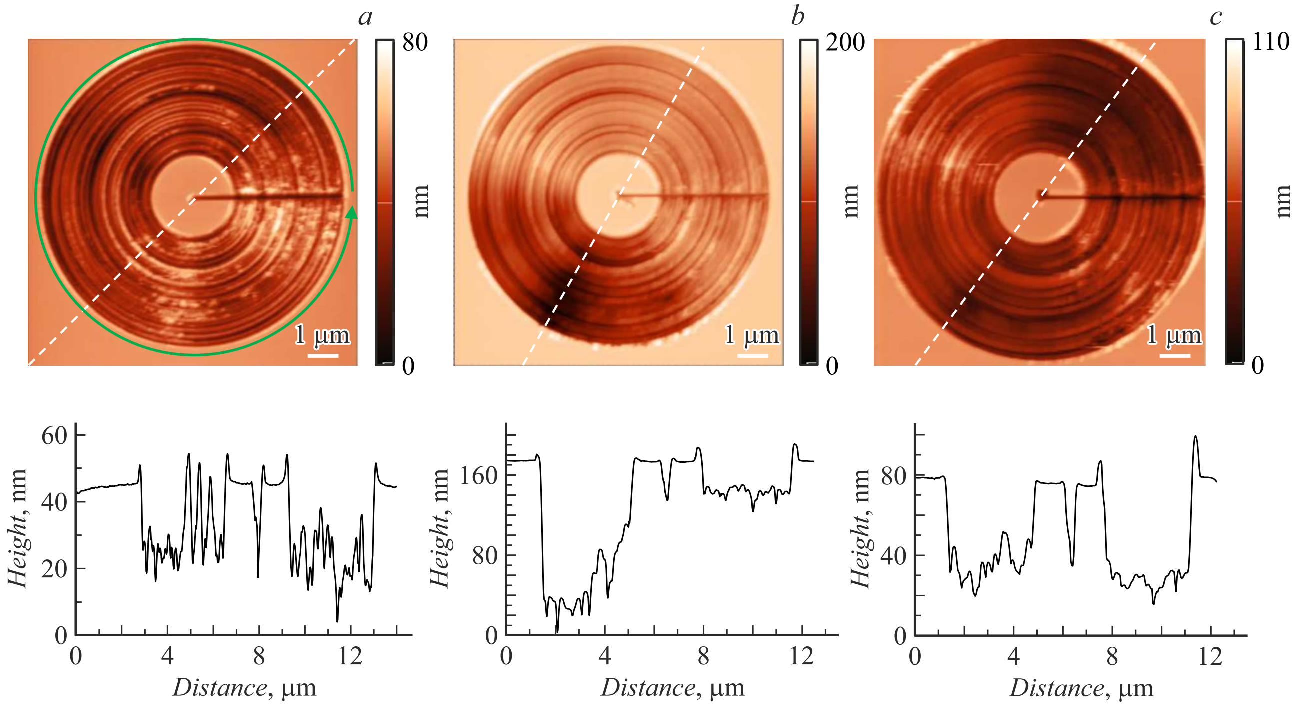

Figure 3. AFM-images ($a-c$) and corresponding profiles of microdisks formed by probe 1 (a) and probe 2 (b, c). The profiles were obtained along the dashed lines. The microdisk on fragment c is formed at another inclination of the substrate plane selected to reduce the non-uniformity of material removal.

in fig. 1. Indeed, in fig. 3, *a* the highest depth is observed in the upper and left parts of the image, which corresponds to directions *7* and *6* in fig. 1, *a*. Fig. 3, *b* has the largest depth in the lower left corner between directions *3* and *6* (right part of fig. 1, *a*). One should note strong azimuthal non-uniformity in material removal by probe 2, which is probably explained by the substantial difference in the planes that form the top of this probe (fig. 2, *b*). Paper [8] shows that the groove of the highest width and depth is formed when the probe moves forward with its face in the direction perpendicular to the face. The smallest depth is obtained when the pyramid edge moves forward.

Images in fig. 1 and 3 agree with this observation. Indeed, for probe 1 direction *1* with the pyramid edge forward movement creates a groove of the smallest depth, when moving in direction *7* the face of the highest area moves along the normal line and forms a groove of the largest depth. For probe 2 the longest face (dashed line in fig. 2, *b*) creates the maximum depth in the direction (light arrow), perpendicular to the face plane (see fig. 3, *b*, the darkest area).

For uniform removal of the material in the azimuthal direction by the probe 2, the substrate plane was tilted. The plane inclination effect in different directions was studied (not shown here), however, the most uniform removal of the material was obtained when the inclination was changed along the dashed line in fig. 2, *b* so that the lower end of such line was lifted up (towards the observer) by 2°. Fig. 3, *c* shows AFM-image of the microdisk with relatively uniform azimuthal removal of the material. The disk is formed when pressed by $40\,\mu$N and with the changed substrate inclination.

Therefore, the formation of microdisks on the GaAs surface with m-SPL method was studied. It was shown that the material removal as the probe moves under pressure on its surface depends on the direction of the probe movement and shape of the probe tip. The example used included two diamond probes of the same batch, with substantial differences in the tip faceting. It was shown that the removal of the material is most effective (depth and width) happens with the forward movement in the direction perpendicular to the probe's face with the largest surface area. Substantial difference in the area of the facets forming the probe's pyramid causes significant azimuthal non-uniformity in the material removal by the circular probe movement. Such non-uniformity may be reduced by inclination of the sample plane.

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Conflict of interest

The authors declare that they have no conflict of interest.

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