Physics of the Solid State, 2023, Vol. 65, No. 12

Fabrication of aperture cantilevers for scanning near-field optical microscopy using focused ion beam induced deposition method

© A.S. Kolomiytsev, A.V. Saenko, A.V. Kotosonova

Southern Federal University,
Taganrog, Russia

E-mail: askolomiytsev@sfedu.ru

Received May 16, 2023
Revised August 17, 2023
Accepted October 30, 2023

The paper presents a new technique for the formation of probe tips for scanning near-field optical microscopy using the method of local ion-induced carbon deposition. Experimental studies on tip formation have been carried out, with the establishment of optimal technological parameters to ensure high accuracy and repeatability of the process results. The parameters of the probe were investigated in atomic force microscopy mode, and the transmission of optical radiation through the probe aperture was also studied.

Keywords: cantilever, ion-induced deposition, scanning near-field optical microscopy, deposition, etching.

DOI: 10.61011/PSS.2023.12.57669.5157k

Currently, to create elements and structures of micro- and nanomechanics the methods and technological processes of traditional microelectronics are used, which make it possible to achieve high economic efficiency in serial production. However, a significant drawback of this approach is the limited range of parameters of structures that can be formed, and for manufacturability often the possibility of achieving better characteristics of devices is sacrificed. A promising approach to this problem solution is the integration of traditional microelectronic technologies and methods for the local formation of micro- and nanoscale structures. One of these methods is the method of local ion-stimulated deposition of materials from the gas phase [1,2]. The structures are formed by local decomposition of the process carrier gas under the action of a focused ion beam (FIB) with a diameter of 7 nm and energy up to 30−50 keV. Most often, when implementing such processes, either ions Ga^+ or ions of inert gases are used, which make it possible to achieve a slightly higher radiation dose and deposition rate with a slight decrease in resolution. The minimum sizes of structures that can be formed by this method are determined by the diameter of the ion beam and are 10 nm and more[3]. One of the promising areas of application of this approach is the formation and modification of the tip of probe sensors for scanning probe microscopy [4].

This paper presents the results of experimental studies on the tip formation of aperture cantilevers for scanning near-field optical microscopy (SNOM) using the method of local deposition of carbon by ion beam Ga^+. The aperture cantilevers are a micromechanical console, at the end of which there is a hollow tip, which has an input and subwavelength output apertures, designed to transmit optical radiation and detect a signal in the near field region [5]. The diameter of the exit hole of the aperture cantilever tip is 100−200 nm, and its walls are opaque to the radiation of the wavelength used. An important advantage of cantilevers of this type is the possibility of their operation both in the dynamic atomic force microscopy mode and in the SNOM mode in same measurement cycle.

To form the aperture probe tip at the initial stage on the beam of a standard tipless silicon cantilever FMG01 by FIB local etching at a beam current 7 nA, a through hole with a diameter of $10\,\mu$m was formed, through which the optical radiation of the near-field microscope is introduced. After this, by the method of local ion-stimulated deposition at ion current of 0.3 nA using the carrier gas of the deposited carbon $C_{10}H_8$, the probe tip was formed in the form of a hollow cone, the diameter of its base was about $10.5\,\mu$m, which is larger than the diameter of the input aperture. The tip of the SNOM probe is formed sequentially using a set of templates in the form of concentric circles with continuously-decreasing diameter. As a result, a hollow conical tip with an apex angle of 30° and a height of $27.99\,\mu$m was formed at the end of the cantilever console, at the base of which the input aperture hole is located. The stages of the manufacturing process of aperture SNOM probe are presented in Figure 1. The output aperture was also formed by local etching with a focused ion beam at beam current of 10 pA. Figure 1, *d* shows SEM image of aperture SNOM probe with the hollow tip, the insert shows image of the cross-section of such tip obtained by etching with a focused ion beam Ga^+ with an energy 30 keV and beam current 0.3 nA. To reduce the likelihood of parasitic transmission of optical radiation by the side walls of the probe and increase its temperature stability, a thin metal film of aluminum or gold is deposited on the surface of the tip. During the experimental part of the paper, aperture cantilevers for SNOM were manufactured with input aperture diameter of $10\,\mu$m, a probe tip angle of 30, 70 and 100° and outlet diameter of 80 to 150 nm. One of the tasks solved in this paper was to develop process modes to ensure high reproducibility and repeatability of the probe

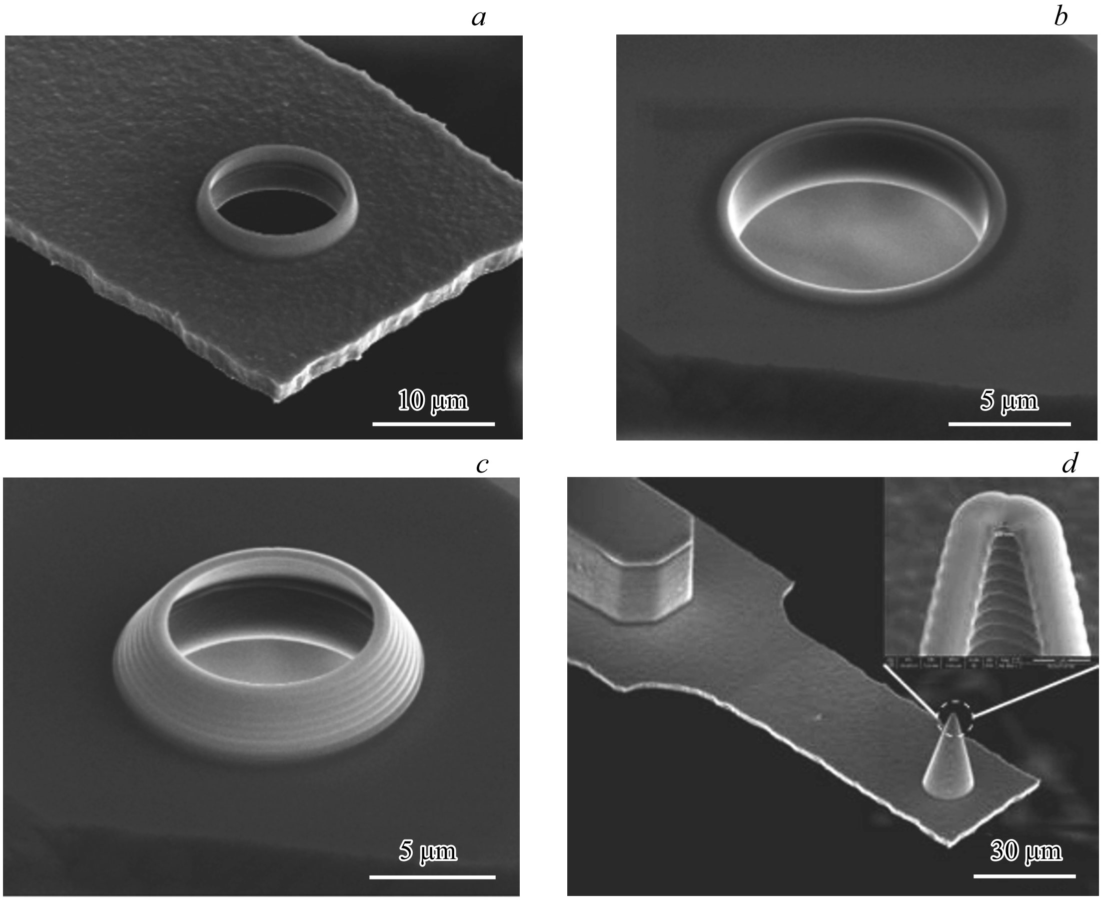

Figure 1. SEM images illustrating the process of tip formation of SNOM probe by the ion-stimulated deposition method: (*a*) — formation of the input aperture, (*b, c*) — layer-by-layer growth of carbon and formation of the tip shape, (*d*) — formation of the exit aperture. Insert to Figure, *d* — cross section of a tip with an aperture with a diameter of 100 nm.

tip parameters. During studies it was found that by ensuring a constant ion current (with values in the range from 0.3 to 3 nA) and a fixed time of exposure to the ion beam at a point, equal to 500 ns, to achieve high repeatability of probe parameters (size deviation is maximum 1%), the key parameters are maintaining a constant pressure of the carrier gas of the deposited material while maintaining the pressure in the chamber within 10^{-3}–10^{-4} Pa, as well as ensuring a minimum time interval between passes of the ion beam, during which the gas could be renewed in the deposition area. It was experimentally established that the optimal value of this time interval is 200 ns, since at lower value the gas molecules do not have time to be renewed and the deposition efficiency begins to fall, and the deposition process is gradually replaced by ion etching. For parameter values greater than 200 ns, the dynamics of the deposition process does not change, but the total process time increases.

The manufactured probes were tested in two stages: first by scanning TGZ02 test calibration lattice in the semi-contact atomic force microscopy (AFM) mode to assess the quality of surface topography measurements, and then in the transmission mode of blue laser radiation with a wavelength of 473 nm and measuring the power of transmitted radiation. Test results showed that in atomic force microscopy mode, each of the probes allows one to obtain AFM images of topography, as shown in Figure 2. Thus, at the passport value of the TGZ02 lattice period $3 \pm 0.01\,\mu$m the measured values of the period using probes with tip angles of 30, 70 and 100° were 3.01, 3.08 and $3.04\,\mu$m respectively. The measured height values of TGZ02 lattice elements (passport value 110 ± 10 nm) were 86, 99 and 107 nm, respectively, deviations from the actual height values do not exceed 23%. Since AFM mode for such probes is additional and is intended only to simplify the positioning of the probe on the sample, the test results can be called acceptable. The results of cantilevers testing for the transmission of optical radiation showed that for probes with a tip apex angle 100° and output aperture diameters from 82 to 200 nm, the transmittance factor ranged from $2 \cdot 10^{-4}$ to $1.5 \cdot 10^{-1}$, which allows their use when implementing aperture SNOM. When studying some of the probes not coated with aluminum, parasitic transmission of radiation by the walls of the tip or the

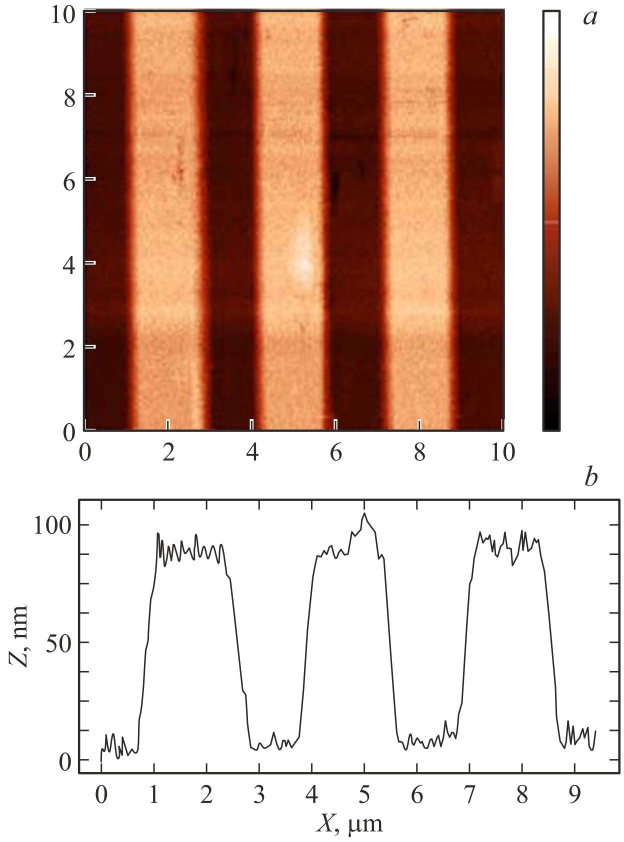

Figure 2. AFM image (*a*) and profilogram (*b*) of the TGZ02 calibration lattice.

cantilever beam was observed. Such transmission can be eliminated by applying an additional thin coating of aluminum up to 100 nm thick to all probes.

Thus, the paper presents an original technology for forming cantilever tips for scanning near-field optical microscopy using the method of local ion-stimulated carbon deposition. The values of technological parameters of ion-beam exposure were determined to ensure high accuracy and reproducibility of structure parameters (ion beam current, beam exposure time at point, residual vacuum value in the working chamber). It is shown that one of the key parameters of the process is the delay time between passes of the ion beam along the template, which is at least 200 ns. The results of testing the probes with various geometric parameters are presented.

Funding

The study was supported by a grant from the Russian Science Foundation No. 22-29-01239 at the Southern Federal University.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S. Reyntjens, R. Puers. J. Micromech. Microeng. **11**, 287 (2001). DOI: 10.1088/0960-1317/11/4/301.

[2] J. Gierak. Semicond. Sci. Technol. **24**, 043001 (2009). DOI: 10.1088/0268-1242/24/4/043001.

[3] A.S. Kolomiytsev, A.L. Gromov, O.I. Il'in, I.V. Panchenko, A.V. Kotosonova, A. Ballouk, D. Rodriguez, O.A. Ageev. Ultramic. **234**, 113481 (2022).
DOI: 10.1016/j.ultramic.2022.113481.

[4] B.G. Konoplev, O.A. Ageev, V.A. Smirnov, A.S. Kolomiitsev, N.I. Serbu. Russ. Microelectron. **41**, 41 (2012).
DOI: 10.1134/S1063739712010052.

[5] N.F. van Hulst, M.H.P. Moers, O.F.J. Noordman, R.G. Tack, F.B. Segerink, B. Bölger. Appl. Phys. Lett. **62**, 461 (1993). DOI: 10.1063/1.108933.

Translated by I.Mazurov