Fabrication of probes for scanning near-field optical microscopy using focused ion beam

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Abstract. The results of an experimental study of the fabrication of probe tips for scanning near-field optical microscopy (SNOM) using the focused ion beam (FIB) milling and ion beam induced deposition are presented. Methods of the FIB local milling and FIB-induced deposition of tungsten and carbon onto the tip of an atomic force microscope (AFM) probe are studied. In this work, a technique for the formation of AFM probes based on the use of a combination of ion-beam etching and ion-induced carbon deposition was developed. Based on the developed technique, several aperture probes for SNOM with an aperture diameter of 50, 150, and 200 nm, an apex height of about 20 nm, and a cone angle of about 35° were fabricated. The paper presents that the formation of SNOM probes by FIB-induced deposition allows creating a high efficiency tool for nanodiagnostics. The obtained results can be used to develop technological processes for the fabrication of specialized AFM probes and procedures for the express monitoring of technological process parameters in the manufacturing of the elements for micro- and nanoelectronics.

1. Introduction

Modern methods of producing structures and elements of nanoelectronics, sensorics, and nanomechanics are impossible without the high-resolution microscopy methods used to control the production process at all the stages. In nanotechnology, microscopy often appears not only as a method for assessing the topography of a surface, but also as a method for determining local surface properties. The resolving power of traditional methods of optical microscopy is limited by the diffraction limit of the light used, so a near field microscopy method is used to obtain images of nanoscale structures [1,2]. The main feature of the method is that the light source and the sample under study are smaller than the wavelength of light.

At the present stage of nanotechnology development, one of the most promising methods of surface diagnostics is scanning probe microscopy (SPM) [3-5]. The use of SPM methods makes it possible to study the local geometric, electrical, and mechanical properties of the substrate surface, as well as to form nanoscale structures on the surface of solids [1]. The perspective direction of microscopy at nanoscale is scanning near-field optical microscopy (SNOM), which significantly allows increasing the optical microscopy resolution and providing reliable control of the distance between the tip and the sample. SNOM is a microscopy technique for nanostructure investigation that breaks the far field resolution limit by exploiting the properties of evanescent waves. In SNOM (Fig. 1a), the excitation laser light is focused through an aperture with a diameter smaller than the excitation wavelength, resulting in an evanescent field (or near-field) on the far side of the aperture [2]. When the sample is
scanned at a small distance below the aperture, the optical resolution of transmitted or reflected light is limited only by the diameter of the aperture. One of the main problems in SNOM technology is the creation of probes with a controlled aperture size. The use of traditional technological processes does not allow varying the aperture diameter and creating probes for SNOM of the required shape.

The application of new methods of local nanostructuring makes it possible to form probes of various geometric shapes for specialized methods of SPM and SNOM [3]. Using local methods of nanoscale structuring, it is possible to create SNOM aperture probes with parameters that differ significantly from standard ones, which will allow minimizing artifacts, reducing costs, and increasing the accuracy and resolution of microscopy. One of the promising methods for forming the SNOM probe tips with high accuracy and resolving power is the use of focused ion beams (FIB) [6-14]. The FIB method allows performing technological operations of local ion beam etching and ion-induced deposition of materials from the gas phase without the needs of resists, masks, and chemical etchants. The essence of the FIB method lies in the local ion-beam sputtering of the material by a flow of gallium ions focused to a diameter of about 7 nm. Combining the FIB and highly selective gas chemistry, allows realizing operations of local ion-induced deposition of materials (carbon, tungsten, platinum, etc.). The combination of precision ion beam milling and ion-induced deposition of materials makes it possible to form the SPM probe tips with parameters that are unattainable when using traditional manufacturing processes.

A wide range of materials deposited by this method allows using FIB in formation of nanoscale structures probes for nanodiagnostics. The aim of this work is to create advanced apertured probes for SNOM using the FIB method and their experimental study [7].

2. Experimental

Traditionally, FIB technology is used to etch the tip of the probe through, thus forming an aperture probe. However, this approach has several disadvantages: the small diameter of the aperture inlet, the complexity of aligning the aperture with the axis of the probe tip, and the negative effect of the redeposited material. To eliminate these drawbacks, it is proposed to use the ion-induced deposition method to form a hollow tip of a probe with a controlled aperture diameter.

Experimental studies were carried out using a FEI Company DualBeam system Nova NanoLab 600, combining a Ga+ FIB and a field emission scanning electron microscope (SEM) and the Ntegra Vita scanning probe microscope (NT-MDT, Russia). The standard atomic force microscope (AFM) cantilevers NSG-10 (NT-MDT, Russia) with broken probes due to operation were used as a substrate.

The scheme of the process of forming a cantilever with an aperture is shown in Figure 1b. At the initial stage of the study, part of the cantilever beam containing the probe was removed. This operation was carried out by ion-beam etching with current of 20 nA.

![Figure 1](image_url)

**Figure 1.** Principle of SNOM with an aperture AFM probe (a) and the process of formation of the SNOM probe tip.
Figure 2. SEM images of 6 stages of forming the tip of an aperture cantilever.

At the next stage of work, a through hole with a diameter of 5 to 10 μm was formed in the remaining part of the beam using FIB etching at maximum current. The resulting hole of 5-10 μm in diameter is the input for optical radiation in the SNOM method. Figure 2 shows SEM images of 6 stages of forming the tip of an aperture cantilever.

After forming the hole through the beam, gas C6H14 was supplied to the area of the formed hole through the gas injector, which, when interacting with the gallium ion beam with an energy of 30 keV, decomposed into volatile components (which were immediately removed by the vacuum system of the microscope) and solid carbon, which was deposited on the surface. The trajectory of the ion beam was determined by digital patterns, so that the deposition of carbon occurred in an orderly manner from the base of the cone (about 5.5 μm in diameter) to its tip. The result was a conical tip formed by the edge height of about 5-6 μm (Fig. 3a).

At the final stage of the work, at the top of the cone, a hole of the required diameter is formed. For this purpose, a focused ion beam is used at ion current values from 1 to 25 pA at an accelerating voltage of 30 keV.

3. Results and discussion
The main advantage of the proposed technology is the ability to form probe tips of different shapes and sizes. The probe shown in Figure 3a has a tip radius of about 200 nm, which also allows using it to obtain AFM images.

The presented technique allows restoring the functionality of worn-out and broken AFM probes and improving their properties and parameters. Restoring the functionality of broken probes by FIB is cost-effective, because the standard probes are not maintainable.

The developed technique for forming probes can be quite simply automated. For example, in the software of the Nova Nanolab 600 system, you can repeat the sequence of actions specified by the operator with the help of simple programs written in a high-level language. Process control is also performed automatically using SEM. Thus, the time taken to produce 1 aperture probe is about 15 minutes.
Figure 3. (a) SEM images of the conical probe of aperture cantilever fabricated be FIB-induced deposition. (b) The diameter of the aperture is 112 nm.

The fabricated probes have been tested and found to have a longer service life as an AFM measurement tool. In addition, the ability to vary the diameter of the aperture makes it possible to form optimized probes for the desired wavelengths. The ability to form aperture SNOM probes based on the broken cantilevers makes it possible to significantly improve the economic efficiency of the proposed technology.

4. Conclusion
The experimental study of methods used to modify probes for AFM by the deposition of materials onto the tip of a worn probe using FIB has been carried out. Application of the technology of ion-induced deposition makes it possible to form probe tips in a wide range of shapes and sizes for different AFM applications. We have illustrated the procedure, based on FIB milling and deposition, to create probes with specific tip shape, starting from commercial ones. It is shown that the FIB method provides the formation of the aperture probes for SNOM method with the aperture diameter of about 112 nm and tip height 20 μm. Unlike many commercial probes for SNOM, manufactured probes can also be used to obtain images of the surface of solids in AFM mode. It is shown that the use of combination of FIB induced etching and deposition allows forming probes with an aperture diameter less than 50 nm.

The results obtained in the study can be used in the development of technological processes for the fabrication and modification of special aperture probes for SNOM, and in the development of procedures for the express monitoring of parameters of the technological process for manufacturing elements for micro- and nanoelectronics and micro- and nanosystems engineering.

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References
[1] Bhushan B 2010 Springer Handbook of Nanotechnology (3rd edn) (New York: Springer) 1964
[2] Yao N and Wang Z 2005 Handbook of Microscopy for Nanotechnology (Kluwer Acad. Publ.: New York) 743
[3] Chang W S, Bauerdick S and Jeong M S 2008 *Ultramicroscopy* 108 1070-5
[4] Avilov V I, Polupanov N V, Tominov R V, Smirnov V A and Ageev O A 2017 *IOP Conf. Ser.: Mat. Sci. Eng.* 256 012001
[5] Smirnov V A, Tominov R V, Alyab’eva N I, Il’ina M V, Polyakova V V, Bykov Al V and Ageev O A 2018 *Tech. Phys.* 63 1236-41
[6] Savenko A, Yildiz I and Petersen D H 2013 *Nanotechnology* 24 465701
[7] Ageev O A, Alekseev A M, Vnukova A V, Gromov A L, Kolomiitsev A S, Konoplev B G and Lisitsyn S A 2014 *Nanotechnologies in Russia* 9 26-30
[8] Giannuzzi L A and Stevie F A 2004 *Introduction to Focused Ion Beams: Instrumentation, Theory, Techniques and Practice* (New York: Springer) 357
[9] Lisitsyn S A, Kolomiitsev A S, Ilyin O I, Ilyina M V, Konoplev B G, Bykov A V and Ageev O A 2017 *Russ. Microelectron.* 46 1-6
[10] Soliman M, Ding Y and Tetard L 2017 *J. Phys.: Condens. Matter* 29 173001
[11] Wu X-Y, Sun L, Tan Q-F and Wang J 2015 *Chinese Phys. B* 24 054204
[12] Ageev O A, Konoplev B G and Smirnov V A 2012 *Russ. Microelectron.* 41 41
[13] Ageev O A, Bykov Al V, Kolomitiitsev A S, Konoplev B G, Rubashkina M V, Smirnov V A and Tsukanova O G 2015 *Semiconductors* 49 1743-8
[14] Ageev O A, Kolomitiitsev A S and Bykov A V 2015 *Microelectron. Reliab.* 55 2131-4