Application of focused ion beam for the fabrication of AFM probes

A S Kolomiytsev*, S A Lisitsyn, V A Smirnov, A A Fedotov and Yu N Varzarev
Southern Federal University, Institute of Nanotechnologies, Electronics, and Electronic Equipment Engineering, Taganrog, 347922, Russia
*askolomiytsev@sfedu.ru

Abstract. The results of an experimental study of the probe tips fabrication for critical-dimension atomic force microscopy (CD-AFM) using the focused ion beam (FIB) induced deposition are presented. Methods of the FIB-induced deposition of tungsten and carbon onto the tip of an AFM probe are studied. Based on the results obtained in the study, probes for the CD-AFM technique with a tip height about 1 μm and radius of 20 nm were created. The formation of CD-AFM probes by FIB-induced deposition allows creating a high efficiency tool for nanotechnology and nanodiagnostics. The use of modified cantilevers allows minimizing the artefacts of AFM images and increasing the accuracy of the relief measurement. The obtained results can be used for fabrication of AFM probes for express monitoring of the technological process in the manufacturing of the elements for micro- and nanoelectronics.

1. Introduction
An important stage in the development and production of integrated circuits is the implementation of operational control of geometric parameters of structures at various stages of the technological process. With modern topological norms of the production of very-large-scale integration (VLSI) devices (less than 30 nm), the microrelief of the surface both in the horizontal and in the vertical planes often plays a decisive role in obtaining a positive result [1]. Thus, an important task is the development of procedures and tools for determining the geometric parameters and the roughness of the vertical walls in high-aspect nanostructures.

At present, atomic force microscopy (AFM) is one of the most promising methods for studying the structure and properties of the solids surface with nanometer spatial resolution [2, 3]. Critical-dimension atomic-force microscopy (CD-AFM) is a promising method that can effectively solve problems of measuring the roughness of vertical walls by examining the morphology and local surface properties of high-aspect structures with a high spatial resolution [4-7]. The resolving power of an AFM is determined by the shape and radius of curvature of the used probe, which are limited by the technological processes, which entails the appearance of artifacts in AFM studies [8]. CD-AFM is based on the principle of detecting the force interaction of the lateral surface of the probe tip with the vertical planes of the structure under study (Fig. 1). For this purpose, protrusions of about 20 nm in length are axially symmetrically formed on the lateral surface of the probe.

The main problem of the CD-AFM method is the complexity and high cost of the probes manufacturing. Using local methods of nanoscale structuring, it is possible to create tips of CD-AFM probes with improved parameters, which allow minimizing artifacts, reducing costs, and increasing the accuracy and resolution of microscopy. One of the promising methods for forming the CD-AFM probe.
2. Experimental

The fabrication of the probe tips was performed with a FEI Company DualBeam system Nova NanoLab 600, combining a Ga⁺ FIB and a field emission scanning electron microscope. AFM experiments were performed using a Ntegra Vita AFM system by NT-MDT.

At the initial stage, the experimental studies of the ion-induced deposition of carbon and tungsten on the silicon surface were carried out. It was found that for accelerating voltage of 30 keV and ion beam current of 1 nA, the deposition rate of carbon was 7.8 nm/sec and of tungsten – 3.5 nm/sec. The minimum diameters of the formed structures were 22 nm and 35 nm, respectively.

The tips of the CD-AFM probes were formed on the basis of the standard AFM cantilevers NSG-10 (resonant frequency: 290 kHz, force constant: 44 N/m) with the damaged tip after intensive use. At the first stage of the experiment, the old tip of the probe was removed by FIB milling, and a basis for building up the new tip was formed. The following FIB parameters were used: the accelerating voltage of the ion beam – 30 keV; the ion beam current – 1 nA; and the dwell time of the ion beam – 1.0 μs. After that, the probe tip was formed by the method of FIB-induced carbon deposition. A probe with a tip height of about 1.2 μm and a diameter of about 150 nm was formed. The following parameters of ion-stimulated deposition of carbon were used: the ion beam current – 0.1 nA, the time of action at the point – 100 μs, the accelerating voltage – 30 keV. The chamber pressure after introducing C₁₄H₁₀ gas was 1×10⁻⁴ Pa. A bitmap of the desired probe structure was created using Unigen 3.2 software, and then uploaded into the FIB software [9]. At the next stage of research, rounded protrusions of about 120 nm in length and a radius of 20 nm were formed perpendicularly to the probe tip (Fig. 2). With these parameters, the process of a probe tip formation takes about 5 min, including the milling and deposition operations.

We tested a performance, resolution, and reliability of the FIB-fabricated probe by taking CD-AFM images of the 500 nm step of PMMA photoresist on the silicon surface. The AFM study of the lateral surface roughness was carried out at the Ntegra Vita probe laboratory using a standard NSG-10 probe and a FIB-fabricated CD-AFM probe. A semicontact AFM image of the PMMA step was obtained with the FIB-fabricated probe, demonstrating its capability for high spatial resolution imaging of the sidewalls. The resonance frequency of the new cantilever was 281,900 Hz, being not much different from that of the commercial cantilever. Figure 3 shows the AFM images of the PMMA step surface and profile obtained by FIB-fabricated probe.
3. Results and discussion

The analysis of AFM images shows that the sidewall roughness of the PMMA structures, obtained using standard cantilevers, contains artefacts and cannot be analyzed and measured. The artefacts were absent (Fig. 3) on the AFM image of the PMMA step scanned by the FIB-modified cantilever. As shown in Figure 3c, the use of a modified probe allows measuring the relief and roughness of the PMMA sidewall. The software package Image Analysis 3.0 (NT-MDT Co) allowed measuring the arithmetic mean roughness of the relief of the lateral wall, which was 9.44±1.96 nm.

It was also found that in order to achieve a high rate of ion-induced deposition the high current values (0.1-1 nA) should be used, but in this case it is impossible to achieve high resolution of deposition. To form structures with dimensions less than 50 nm, it is recommended to use small currents of the focused ion beam (30-50 pA).

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. To automate the process of AFM probe fabrication by FIB, Unigen 3.2 software is used, which was developed in the Southern Federal University [9]. The software allows to generate patterns for FIB milling and deposition as BMP files or ASCII based stream files based on designed 3D profile (as a mathematical formula, a curve, or a standard figure).

The results clearly demonstrate that the FIB-fabricated probes work well as AFM probes for high resolution sidewall roughness imaging (the study of the surface of the ICs, MEMS devices, etc.).

![Figure 2. SEM-image of the FIB-fabricated CD AFM probes.](image)

![Figure 3. (a, b) AFM images and (c) profile of 500 nm PMMA step obtained using FIB-fabricated CD AFM probe.](image)
4. Conclusion
The experimental study of methods used to modify probes for atomic-force microscopy by the deposition of materials onto the tip of a worn probe using focused ion beam was carried out. Application of the ion-induced deposition allowed creating the probe tips in a wide range of shapes and sizes for different AFM applications. We illustrated the procedure, based on FIB milling and deposition, to create probes with specific tip shape, starting from commercial ones. It was shown that the FIB method provided the formation of the CD-AFM probes with the radius of tip flare rounding 20 nm, tip height 1.2 μm, diameter of about 150 nm, and aspect ratio 1:20. It was shown that the use of modified cantilevers for the diagnostics of sidewall roughness allowed minimizing the artefacts of AFM images, as well as increasing the resolution and reliability of the obtained results.

The obtained results can be used in the development of technological processes for the fabrication and modification of special probes for atomic-force microscopy, including CD-AFM probes, 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.

Acknowledgments
This work was supported by The Grant of the President of the Russian Federation for State Support of Young Russian Scientists, Candidates of Sciences (project no. MK-6163.2016.8), with the use of the equipment of the Scientific-Educational Center and the Center for Shared Use “Nanotechnologies” of the Southern Federal University (Taganrog).

References
[1] Bhushan B 2010 Springer Handbook of Nanotechnology (3rd edn) (New York: Springer) p 1964.
[2] Ageev O A, Konoplev B G and Smirnov V A 2007 Russ. Microelectron. 36 53.
[3] Yao N and Wang Z 2005 Handbook of Microscopy for Nanotechnology (Kluwer Acad. Publ.: New York), p 743.
[4] Orji N G, Dixson R G 2007 Meas. Sci. Technol. 18 448.
[5] Ageev O A, Konoplev B G and Smirnov V A 2012 Russ. Microelectron. 41 41.
[6] Ageev O A, Bykov A V, Kolomiitsev A S, Konoplev B G, Rubashkina M V, Smirnov V A and Tsukanova O G 2015 Semiconductors 49 1743–8.
[7] Savenko A, Yildiz I and Petersen D H 2013 Nanotechnology 24 465701.
[8] Ageev O A, Kolomiitsev A S and Bykov A V 2015 Microelectron. Reliab. 55 2131–4.
[9] Ageev O A, Alekseev A M, Vnukova A V, Gromov A L, Kolomiitsev A S, Konoplev B G and Lisitsyn S A 2014 Nanotechnol. Russia 9 26–30.
[10] Giannuzzi L A and Stevie F A 2004 Introduction to Focused Ion Beams: Instrumentation, Theory, Techniques and Practice (New York: Springer) 357.
[11] 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.