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Fabrication of advanced probes for atomic force microscopy using focused ion beam

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ABSTRACT

In this work the results of experimental studies of a fabrication of advanced probes for Atomic Force Microscopy (AFM) using Focused Ion Beam (FIB) and nanolithography are reported. Ability to restore the functionality of broken AFM probe tips is shown. The superior performance of FIB-fabricated probes by observing AFM images of the nanostructures is demonstrated. It is shown that the formation of multiprobe AFM cantilevers by FIB-induced deposition of tungsten allows creating an electrical measurement tool for nanotechnology and high-performance instrument for probe nanolithography. It is shown that the use of modified cantilevers for the diagnostics of submicron structures allows one to minimize the artefacts of AFM images, as well as to increase the accuracy of the obtained results.

1. Introduction

The method of Atomic Force Microscopy (AFM) holds the greatest promise for surface diagnostics and analysis. The use of AFM allows one to study the local geometric, electrical, and mechanical properties of the substrate surface and form nanoscale structures on the surface of solids [1]. The resolution of AFM is defined by many factors, most of which are related to the shape and quality of the preparation of probes.

In the recent years, an important task is to fabricate probes with advanced parameters, in particular with the help of focused ion beam technology [2,3]. FIB enables reproducible and precise material processing with high accuracy. Material removal by ion beam milling and FIB-induced chemical vapour material deposition can be used for the fabrication of structures with micro- and nanoscale dimensions. The key feature of FIB is the high spatial resolution which is provided by the application of a gallium ion beam 7 nm in diameter, as well as by the possibility of varying the impact of the parameters over wide limits [4]. In contrast to conventional fabrication techniques based on optical lithography with the application of photoresist and material processing a direct writing mode by FIB allows precise nanopatterning even on sample with advanced topography [5].

In this work we describe the fabrication of advanced probes for AFM and nanolithography by the FIB local milling and their applications.

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2. Experimental

2.1. Experimental setup

The fabrication of 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 an Ntegra Vita AFM system by NT-MDT Co.

2.2. Fabrication of probes

At the first stage of research, the probe was built by FIB-induced deposition of tungsten on a commercial Si cantilever NSG 10 with broken tip (resonant frequency: 290 kHz, force constant: 44 N/md) and then sharpening it using a focused ion beam milling. The following FIB parameters were used: the accelerating voltage of the ion beam – 30 keV; the ion beam current – 30 pA; and the dwell time of the ion beam — 1.0 μs. The chamber pressure after introducing $W(CO)_6$ gas was 1×10^{-4} Pa. A bitmap of the desired probe structure was created by using Unigen 3.2 software, and then uploaded into the FIB software [6]. With these parameters, the process of a probe tip formation takes about 5 min, including the milling and deposition operations.

Fig. 1 shows secondary electron image of the FIB-fabricated AFM probe after two bitmap-based deposition and milling steps. The analysis of SEM image shows that a probe with a tip radius of about 50 nm, cone angle 1° and aspect ratio 1:30 was obtained after fabrication. FIB-fabricated probe tips can be sharpened less than 10 nm radius using further ion beam milling (see Fig. 2).

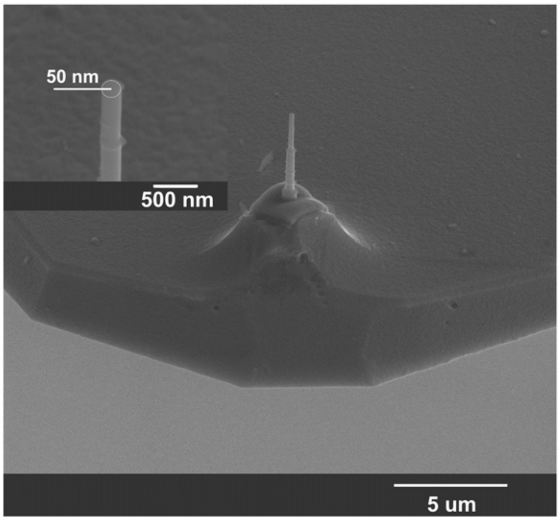

Fig. 1. SEM-image of the FIB-fabricated AFM probe.

At the second stage of research, FIB-induced deposition of tungsten was used for fabrication of 16 probes on NSG 10 cantilever (see Fig. 3). Exactly the same parameters of the FIB treatment were used. Multiprobe cantilevers based on FIB technology are expected to become powerful tools for improving the efficiency of probe nanolithography by local anodic oxidation. The formation of the cantilever with four precisely positioned and electrically isolated probes allows measuring electrical properties of IC components in high resolution.

2.3. AFM studying

We tested a performance, resolution and reliability of the FIB-fabricated probe by taking AFM images of the TGQ1 calibration grating (NT MDT Co). A semicontact AFM image of the TGQ1 taken with the FIB-fabricated probe, demonstrating its capability for high spatial resolution imaging. The resonance frequency of the new cantilever was 281,900 Hz, not much different from that of the commercial cantilever.

Fig. 4 shows the AFM images of the surfaces and profiles of the TGQ1 grating obtained by commercial NSG 10 probe (see Fig. 4a) and FIB-fabricated probe (see Fig. 4b).

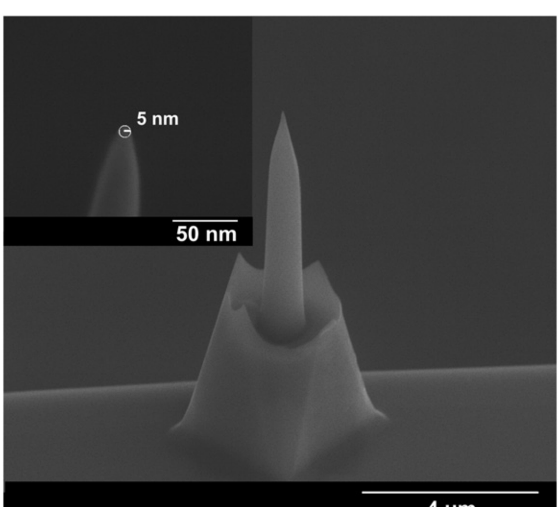

Fig. 2. SEM-image of the FIB-sharpened probe with 5 nm tip radius.

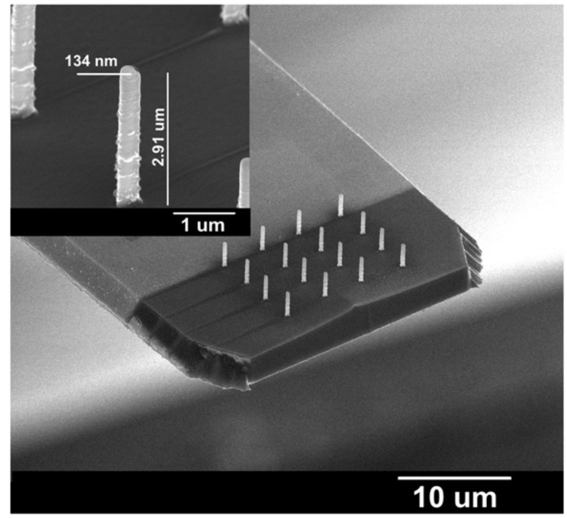

Fig. 3. SEM-image of the FIB-fabricated multiprobe cantilever.

3. Results and discussion

The analysis of AFM images (Fig. 4) shows that the shape of the structures of TGQ1 grating of the height, obtained using standard cantilevers, contains artefacts. The distortion of the shape and the deviation of the geometric dimension from the nominal value, are probably introduced by the contribution of the cosine angle of the tip (~22°). The artefacts were absent on the AFM image in scanning the TGQ1 grating by the modified cantilever.

AFM studies of the test gratings show that FIB-fabricated probes have increased lifetime compared to the standard cantilevers. This is because the standard crystalline Si probe tip is more fragile (especially in the study of hard materials) and after 50–60 scans breaks. At the same time the FIB-fabricated is gradually erased, and leads to the approximately 100–150 cycles of measurements. Example of studying the HOPG surface is presented in Fig. 5.

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 is used Unigen 3.2 software which was developed in the Southern Federal University [6]. 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). In the process of generating a pattern in the Unigen the technological parameters of the beam, the resolution of the pattern, and ion-solid interactions (the angular dependence of the sputtering yield, redeposition and amorphization) are taken into account.

The results clearly demonstrate that the FIB-fabricated probe works well as a probe of AFM for high aspect ratio nanostructures imaging (the study of the surface of the ICs, quantum dots, carbon nanotubes, etc.). Sufficiently low contact resistance of the FIB-fabricated probe (~100 Ω) enables using it as an electrical measurement tool. To achieve this goal it is necessary to solve the three problems. The first is the formation of isolated tracks on the cantilever beam. This problem can be simply solved by coating the surface of the beam by dielectric layer and the formation conductive tracks thereon using FIB-induced deposition. The second problem is the formation of several pads on the chip of the cantilever and modification of the universal probe holder, which will apply the electrical signals on the tips separately. This problem can be solved using well established method of optical lithography and design modification of the universal probe holder [7]. The third task is providing the accuracy of the probe positioning. This problem can be solved by using of the SEM and AFM in a single instrument or a precision system for moving and positioning of the samples (eg. laser

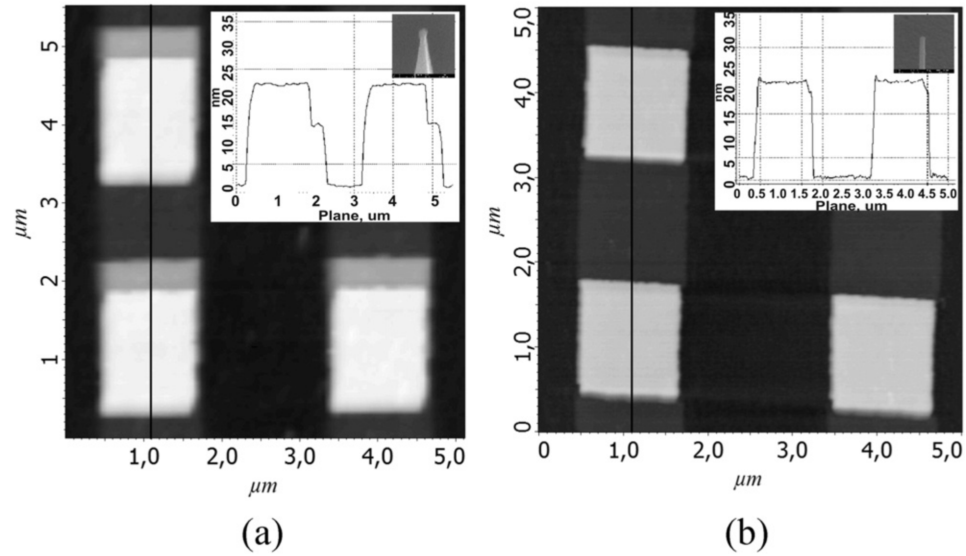

Fig. 4. AFM images and profiles of submicron features of TGQ1 calibration grating, which obtained using NSG10 commercial probe (a) and FIB-fabricated probe (b).

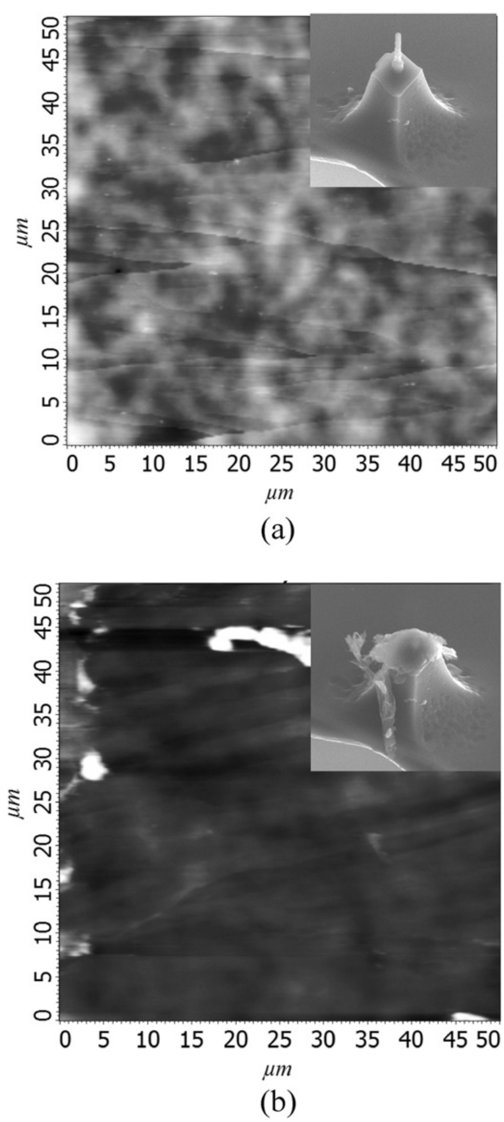

Fig. 5. AFM images of HOPG surface after 10 (a) and 173 (b) cycles of AFM measurements using FIB-fabricated cantilever.

interferometer stage). The combination of SEM and AFM offers an exact positioning of the AFM tip. An example of such a system is a SEM-AFM integration built by DME Company (Danish Micro Engineering). The system is realized as an integration of the DME developed UHV SPM into a Carl Zeiss AURIGA® Crossbeam Workstation. With a free field of view for the SEM, the SPM tip can be positioned to the area of interest under total observation by SEM with nm precision. Similar system is also described in [8].

4. Conclusions

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 probes with the radius of tip rounding less than 10 nm and aspect ratio 1:30 (see Fig. 2). It is shown that the use of modified cantilevers for the diagnostics of submicron structures allows one to minimize the artefacts of AFM images, as well as to increase the reliability of the obtained results. The proposed method will enable multiprobes fabricated using FIB-induced deposition techniques to be realized as an electrical measurement tool for nanotechnology and high-performance instrument for probe nanolithography.

Combining scanning probe technology and bitmap-based FIB technology will open a new direction of development of MEMS and NEMS. The obtained results can be used to develop the technological processes of the production and modification of probes for AFM and the methods of nanodiagnostics.

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