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Test structure for SPM tip shape deconvolution

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Abstract. A test structure for SPM cantilever tip shape deconvolution is described. It consists of a silicon mono-crystalline wafer and an array of silicon sharp tips on its surface. Different types of tip shapes are observed with this structure. Images of the cantilever tip before and after contact-mode scanning are compared. Experimental studies of the developed test structure containing an array of sharp tips indicate that it allows three-dimensional images of the scanning tip to be obtained.

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Any scanning probe microscope (SPM) image represents not only the sample itself but also the shape of a cantilever tip used to obtain that image [1–4]. Moreover, the shape of the tip can be changed during scanning [5], thus causing different distortions of the image. For the correct interpretation of the image data, it is useful to determine the tip shape before scanning and check afterwards if it has been changed.

Different nanometer-size simple objects on the surface of mono-crystalline substrates, steps, anisotropically etched surfaces and others [6], “special tip characterizers” [5, 7–11], and spherical objects [12–14], have been used to solve the problem of tip shape deconvolution. In [6] it is demonstrated that a stepped (305) surface of a $SrTiO_2$ crystal can be routinely used to evaluate the probing profile of scanning-force-microscopy probes. In [5, 7–11] there is a method of accurately measuring the shape of a probe by scanning special test structures (probe tip characterizers). The test structures consist of large lithographically patterned arrays of pillars or holes etched in a silicon substrate, or in a polysilicon layer deposited on an oxidized silicon substrate. Pillars and holes have vertical sidewalls. In [12–14] isolated spheres or two-dimensional close-packed lattices of spheres and cosinusoidal corrugations are used. But all these objects and structures either require rather complex calculations to restore the tip shape [12–14], or give information only about the cross section of the tip and its apex radius of curvature [5, 7–11].

It was shown in [15] that a tip mounted on the substrate or traditional metallic tip can be used to characterize STM and AFM tips. The apexes of mounted diamond fragments and of traditional metallic tips were investigated by the same diamond probe. This method indicated an efficient way of inspecting STM and AFM tips.

1 Description of the new tip characterizer

The test structure consists of a high-resistivity silicon mono-crystalline wafer (100) and an array of silicon sharp tips on its surface. It was fabricated by means of microelectronics (lithography, anisotropic etching of silicon, oxidation of silicon, and other).The structure was fabricated by production schemes described elsewhere [16, 17].

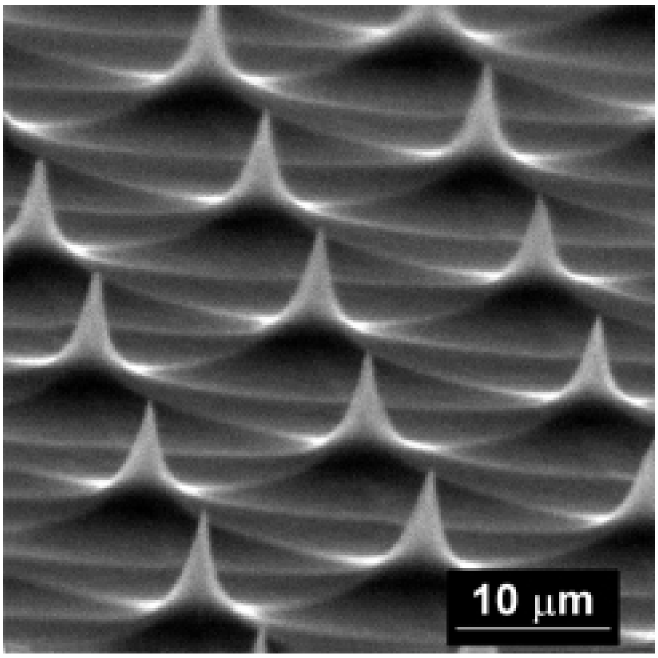

Fig. 1. SEM photograph of developed test structure

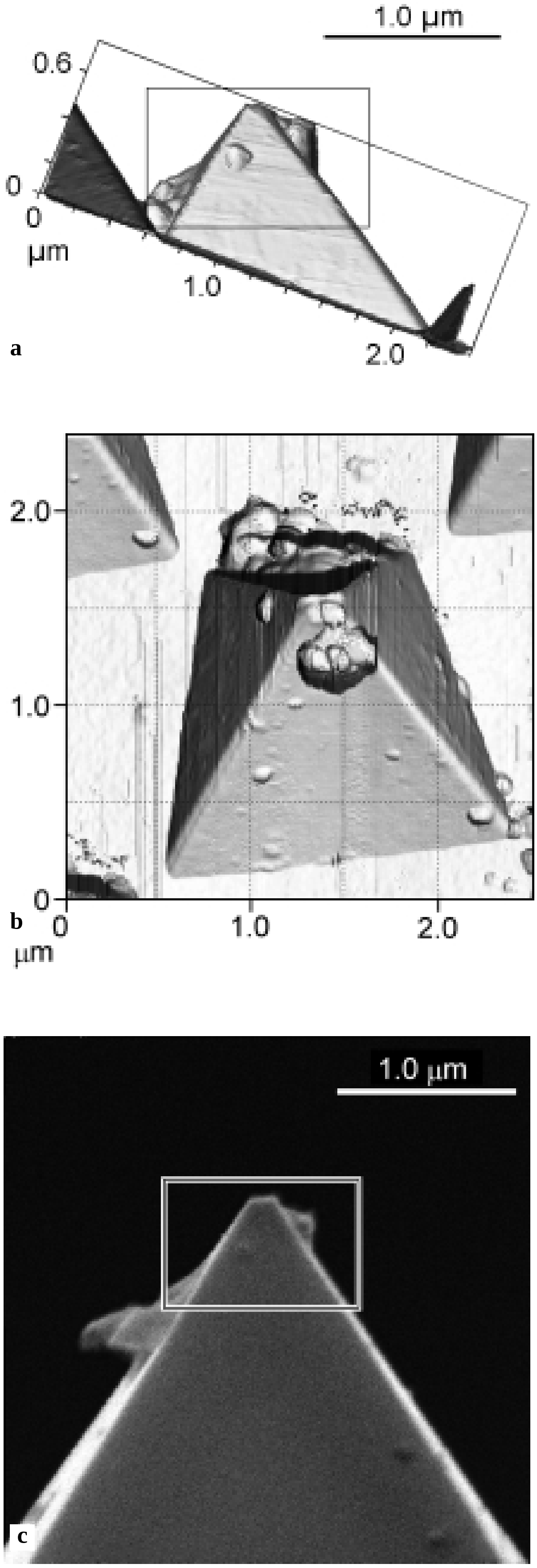

Fig. 2a–c. SPM (**a**,**b**) and SEM (**c**) images of Si_3N_4 pyramid tip. **a** side view; **b** top view

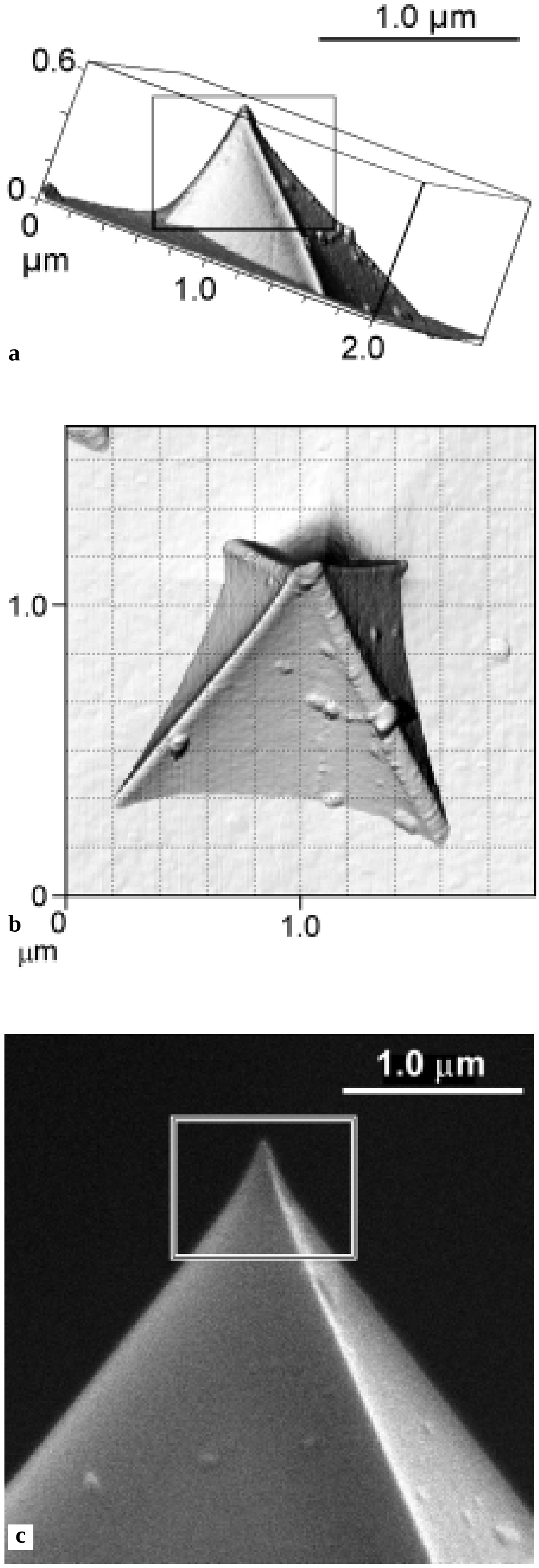

Fig. 3a–c. SPM (**a**,**b**) and SEM (**c**) images of sharpened Si_3N_4 pyramid tip. **a** side view; **b** top view

A sharp tip with high aspect ratio can be used as a sample for fast and accurate imaging of the cantilever tip intended for scanning. We produced an array of tips with full cone angles of less than 20° and radii of curvature less than 10 nm (Fig. 1). The tips are arranged into a square grating with 2.12-µm pitch (3-µm diagonal length). The tip height is about 0.6–0.8 µm. At least one tip has to be found for a scan size of about 3 µm. There are about 400 000 tips on the individual crystal. The sample area of crystal is 4 mm^2.

2 Experimental results and discussion

We used this structure to inspect common SPM cantilever tips: Si_3N_4 pyramid, sharpened Si_3N_4 pyramid, and sharpened Si cone tips. Corresponding scanned images are presented in Figs. 2–4. The scans have been obtained with a scanning probe microscope, Solver P4-SPM-MDT, in semi-contact mode. It should be noted that the scanning tip gives an inverted image of itself, and therefore it is a mirror transformation of the real tip shape (compare SPM images and SEM photos of the same tips in Figs. 2 and 3). But, for the same reason, the object distortion caused by the tip shape is also a mirror transformation of the tip features.

The images of the commercial Si_3N_4 cantilever with pyramid tip are presented in Fig. 2. The images in Fig. 2a,b have been obtained by scanning over our tip characterizer and the one in Fig. 2c with SEM. The SPM image reveals the characteristic features of the tip: flat top area with size of about 0.1 µm, and surface roughness. In [3] it was also demonstrated that Si_3N_4 microfabricated tips have the shape of truncated pyramids with a flat top of $\sim$ 600 nm.

The images of the commercial Si_3N_4 cantilever with a sharpened pyramid tip (sharpened Microlever PSI) are presented in Fig. 3. SPM images allow us to measure the sum of the cantilever tip radius of curvature and that of the characterizer tip. It is equal to about 250 Å, i.e. the nominal sharpened tip radius (200 Å) plus the characterizer tip radius (less than 100 Å).

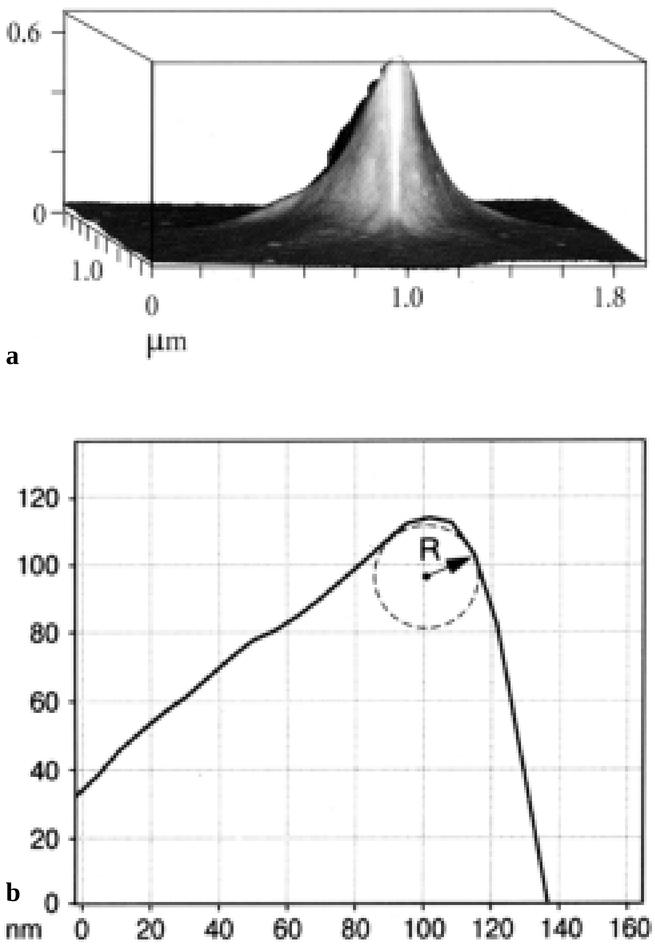

Fig. 4a,b. SPM image (**a**) and cross section (**b**) of Ultrasharp Si cone tip

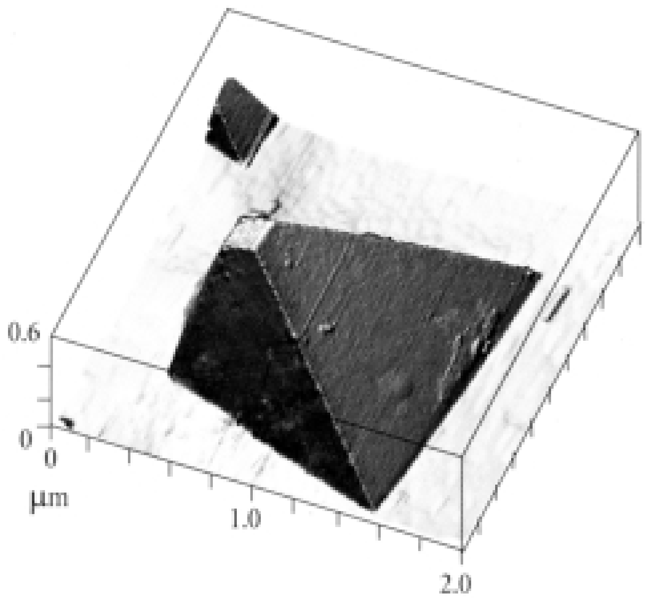

Fig. 5. SPM image of the cantilever tip before contact-mode scanning the sample with *E-coli* deposit

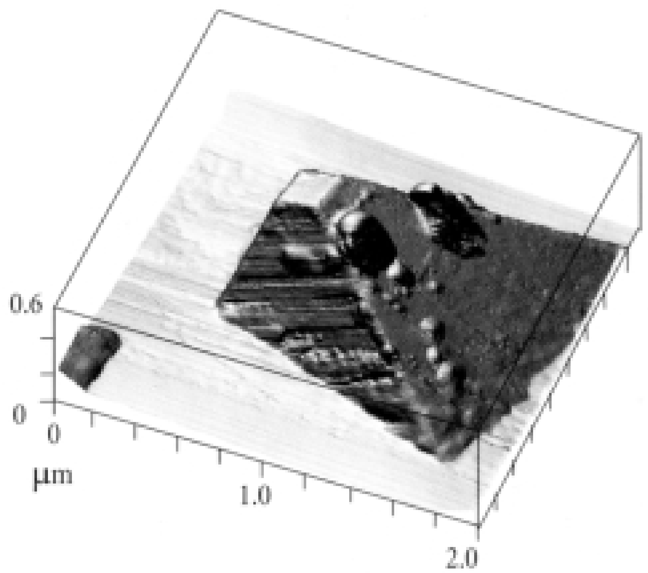

Fig. 6. SPM image of the cantilever tip after contact-mode scanning the sample with *E-coli* deposit

The image of the silicon cone tip of an Ultrasharp cantilever produced by NT-MDT is presented in Fig. 4. The sum of the radii of the cantilever grating tips is equal to 150 Å, which corresponds to nominal radii of both tips of less than 100 Å.

When studying some biological objects *(E-coli)*, we observed a dramatic decrease in image quality after scanning in contact mode. We used the test array to compare the tip shape before and after the scanning of biological objects. Corresponding images are presented in Figs. 5 and 6.

The image in Fig. 6 reveals strong contamination of the tip, which can cause substantial distortion of the shape of scanned objects.

3 Conclusion

Experimental studies of the developed test structure containing a grating of sharp tips indicate that it allows us to obtain three-dimensional images of the scanning tip if the radii of curvature of its characteristic features exceed those of the developed test structure tips (less than 10 nm). The image of the scanning tip is a mirror transformation of its real shape. The curvature radius of the image is the sum of the radii of the cantilever and the tip.

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