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Applications of atomic force microscope manipulator operating in hybrid mode

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Abstract. The topography images by atomic force microscope (AFM) operating in a new hybrid mode with nanometre scale noise are obtained. Using the improved feedback of the AFM hybrid mode, the possibility of the manipulations of the microdrops by microscope tip is shown. Additionally, we introduce a method of an extra gentle movement of nanowires by liquid flow organized by the AFM tip.

1. Introduction

Since introducing the atomic force microscopy (AFM) [1], numerous modes of operations of the microscopes have been developed [2]. Three basic modes such as static contact tapping [3], dynamic tapping [4,5], and non-contact [6] modes are the standard ones realized in most of AFM devices on the market. Each of the basic modes allows obtaining topography image of the solid sample with atomic resolution at certain conditions [7-9].

Essential improvement of the AFM electronics allowed assembling a huge amount of data during scanning. A number of more advanced AFM modes were introduced, such as peak-force mode, where the force curve is measured, stored and analysed for each point of the scan. Peak-force mode, as well as the multi-frequencies modes not only allow the easy extraction of an additional information about mechanical properties of the surface under investigation such as viscosity, elasticity etc., but they are also essential important in investigations of the biological objects [2].

AFM probes are widely applied to manipulate both solid objects [10] and drops of the liquids [11]. Usually standard static contact mode is successfully used for this purpose [12,13], but the dynamic tapping mode may be applied for nanodrops deposition as well [14].

Current report is dedicated to improvement and application of the new hybrid mode introduced in Ref. [15]. We demonstrate the essential improvement in topography mapping as well as application of the AFM tip for microdrops manipulations. Finally, we introduce the novel method to replace the InAs nanowires without touching the wire by the tip, but using the liquid flow organized by the AFM tip only.

2. Topography mapping using AFM in hybrid mode

All manipulations and scanning presented in this report were done by home-made two-probe manipulator. Detailed description of this manipulator can be found elsewhere [15]. It is worth noting that both AFMs of this manipulator are operated in so called hybrid mode. The main idea of this mode is to unite the permanent pressing of the tip probe to the sample surface of the contact mode and the amplitude oscillating of the tuning fork as the feed-back signal similar to dynamic modes. The schematic of realization of this mode is shown in Figure 1. The tip is mounted not vertically but with a slope of 20
to 30 degrees to the sample surface. So, the tip of the probe stays on the sample surface due to the bending of the tip, while the base of the probe mounted on the tuning fork prong oscillates (Fig. 1).

Several examples of this mode application, such as measurements of adhesive force and electronic transport can be found in Ref. [15]. Tungsten tips for manipulations and PtIr for electronic transport measurements were used. Due to bulk PtIr tips, the current up to 1 μA can be safely applied during the measurement of electronic transport with ohmic contact resistance (less than 6 kOhm) and 100% of duty ratio [15]. But the first attempts of the topography mapping had too large noise in vertical direction to apply the obtained image for allocation of the nano-objects on the substrate [15]. So, the scanning electron microscopy image has to be used instead of AFM mapping to get the final result of the nanowires manipulations in case when optical microscopy has insufficient resolution [15].

Figure 1. The sketch of the hybrid mode. 1 - substrate, 2 - tip in the topmost position, 3 - tip in the bottommost position. The tip of the probe attached to the oscillating tuning fork touches the surface even at the topmost position. Two-arrows vertical line – direction of oscillations of the tuning fork prong.

Figure 2. (a) AFM topography image of InAs nanowire obtained using hybrid mode with artificially damped to quality factor equal to 22 of the tuning fork assembly. (b) cross-section at black line of (a). Vertical noise of less than 10 nm is clearly visible. The length of the scale bar is 0.5 μm.
The main problem to obtain the better AFM image, besides the lack of resolution in direction parallel to the tip, was the overregulation of the AFM feedback. The standard AFM electronics was used, while the response from the piezo-actuator was more than an order of magnitude larger than the typical value [15]. One of the solutions for such kind of problem is the decreasing of the quality factor of the tuning fork and the tip assembly. It can be done both electronically [16] and mechanically. The second method was chosen. Length of the tip was increased to 3 mm and the thin stripe of Varnish glue on the top of the prong was added, if necessary, to damp the quality factor of the tuning fork assembly to 20. It was found that the optimal quality factor for topography mapping was from 20 to 30. Overdamping results in the unacceptable signal to noise ratio, so the noise in the detecting amplitude of the tuning fork oscillations determines the topography mapping quality.

The example of the topography image in optimally tuned system is shown in Figure 2a. The quality factor was of 22 and resonance frequency of $f_0=16800$ Hz. The cross section of the image (Fig. 2b) demonstrates the vertical noise of essentially less than 10 nm. This more than an order of magnitude improvement of the noise level allows using AFM mapping images gathered in hybrid mode to allocate nanoobjects, such as nanowires on the substrate with precision of nanometre scale.

It is worth noting that an additional wire glued to the side of the prong to contact PtIr tip for electronic transport measurements additionally damping the quality factor serves not only for galvanic isolation of the tip, but works additionally toward more stable feed-back, so more reliable and stable ohmic contact between the AFM tip and measured object can be achieved.

3. Manipulations of microdrops

Essential improvement of the feed-back control allows extending the manipulator application to liquid microdrops replacements. This is again quite similar to applications of the standard static contact AFM mode, additionally to conductance measurements and measurements of the adhesive forces.

![Figure 3](image-url)

**Figure 3.** (a)-(c) Replacement of the drop beneath the tip. (d) Initial lake, (e) the lake shrunk by the landing tip and (f) the lake released by the tip jumped slightly up. (g)-(i) Step by step the process of the division of the large lake in two parts: (g) initial large lake, (h) the lake rearranged using the landing tip sweeping over the surface, (i) the landing tip assembling the part of the lake liquid, the division of the initial lake is completed. The length of the scale bar is 10 µm the same for all figures.
For demonstration, a Si wafer with 100 nm SiO₂ thermally grown surface layer was used as a substrate. The liquid was the heavy fractions remained after the evaporation of the isopropanol (Component reaktiv, TU 6-09-07-1718-91). Detailed chemical composition of such fractions are not important in the current investigation, because we are not interested in the resulted drops shapes, but the main issue is the demonstration of the potential of the hybrid AFM mode only.

Figures 3a-c show the replacement of the drop beneath the tip. There is no visible trace of the liquid remained after the AFM tip movement, so the volume of the moved drops presumably keeps almost constant. Figures 3d-f show the initial lake, the lake shrunk by the landing tip, and the lake released by the jumped up tip, correspondently. The shape and the size of the lake is similar before tip landing and after tip taking off. Figures 3h-i demonstrate the division of the large lake into two parts. Figure 3g shows the initial large lake assembled from the several smaller drops. Then, the lake is rearranged using the landing tip sweeping over the surface, wetting the substrate and, so, defining new oblong shape of the lake. The lake with a new shape is shown in Figure 3h. Landing tip assembling the part of the lake liquid is shown in Figure 3i. So, the division of the initial lake is completed.

All the images are obtained using direct short focus optical microscope, which allows adequate and comfort live checking the manipulations results. For drops manipulations, standard tungsten tips were used. Wetting of the tip was enough to perform all presented manipulations with drops. Additionally, we checked that the size of the drop with diameter approximately of 7 µm (Figs. 3d-f) had no visible changes of size, shape and, presumably, the volume after landing and taking off of the tip performed ten times. So, it is possible to conclude that the wetting of the tip still does not change the size of the drop after the single manipulation for more than 5%.

Let us discuss in detail the landing of the tip, assembling of the drop and taking off of the AFM tip (Figs. 3a-c as illustrations from the top view). Figure 4a shows the drop on the substrate surface with initial shape and the tip placed over it. Figure 4b shows the position, when the tip just touches the surface. Drop starts to wet the tip. Bended tip shown in Figure 4c assembles the liquid drop beneath itself. Bending of the tip essentially helps to replace the drop. When the tip is taking off, it initially gets straight, this returns the drop to its initial shape. Finally tip lefts the substrate surface. It is worth noting that the size of tip surface touches the liquid in drop could be approximately an order of magnitude larger, while tip is bending comparing to the straight one. This helps to relocate drops keeping their volumes almost constant.

Realization of the hybrid mode in liquid environment, which is of the essential importance for biological applications, is still under construction.

4. Application of the liquid flow for nanowire replacing

Easy and well-controlled manipulation of the liquid drops with AFM tip allows realizing a new extremely gentle nanowire replacement method without touching the nanowire with the AFM tip at all. Replacement is performed by liquid flow arranged by the tip.

Experimental measurements of the adhesion forces of the nanowires demonstrate quite a large error of measured values, namely more than an order of magnitude [10]. Presented method is applicable to nanowires, which stick to the substrate not too strong.

![Figure 4.](image-url) (a) The drop on the substrate surface with initial shape tip placed over it. (b) The tip just touches the surface. (c) Bended tip assembling the liquid drop beneath the tip.
Figure 5. Replacing of the InAs nanowire by a liquid flow. (a), (c), (f) AFM tip assembling the large lake of liquid. (b), (d), (e) Lake released by the AFM tip. Ovals mark the InAs nanowire replaced by the liquid flow. The length of the scale bar is 10 μm same for all figures.

Figure 5 shows replacing of the InAs nanowire by a liquid flow. AFM tip assembles (Figs. 5a,c,f) and releases (Figs. 5b,d,e) the large lake resulting in InAs nanowire (marked by oval) replacement over the SiO₂ substrate. The replacement of the wire is not well controlled by now. The direction of the movement is generally defined by the flowing of the liquid only. Additional efforts must be made to improve this "nanoflood" or "nanorafing" method.

The improved realization of this method should be performed provisionally in the following way and might include several steps. The first step is to pick up the drop and to drive the tip along the path of the future channel wetting the SiO₂ substrate, similar to lake reshaping mentioned in the previous section. The nanowire needed to be moved must be on the way of the channel. The second step is the formation of the large lake of the liquid (Fig. 5). The third step is to connect the lake to the channel. Some tilt of the substrate for 4 to 5 degree might help nanowire movement by the liquid flow. The fourth step (if necessary) is liquid transferring drop-by-drop with AFM tip to add the volume of the liquid to the top (source) lake. It is worth noting that the design of the AFM manipulator we use fits well to work on the tilted surfaces, because the working range in all directions including vertical is 50 microns.

5. Conclusion
In this report, we demonstrate an order of magnitude improvement of decreasing the vertical (z-directional) noise in topography mapping in hybrid AFM mode. The resulting images are acceptable for allocation of the nanoobjects with nanometre lateral resolution. Examples of microdrops manipulations using AFM tip operating in hybrid mode are presented. Finally, the new method of extreme gentle manipulations of the nanowire with the liquid flow organized by AFM tip is introduced.

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