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Fiber-top atomic force microscope

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We present the implementation of an atomic force microscope (AFM) based on fiber-top design. Our results demonstrate that the performances of fiber-top AFMs in contact mode are comparable to those of similar commercially available instruments. Our device thus represents an interesting alternative to existing AFMs, particularly for applications outside specialized research laboratories, where a compact, user-friendly, and versatile tool might often be preferred. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2358710]

Atomic force microscopes[1] (AFMs) are currently used in a wide variety of research areas, including fundamental physics,[2] micro- and nanotechnology,[3] chemistry,[4] biology,[5] soft condensed matter,[6] pharmacology,[7] dental medicine,[8] etc. Because of the versatility and the capabilities of these instruments, scientists with very different backgrounds and skills have been continuously proposing new ideas for the utilization of AFMs in very diverse contexts. This trend has increased the demand for user-friendly AFMs that could be routinely handled by untrained personnel even outside research laboratories (see, for example, Ref. 9). In a recent paper, our group has introduced an optomechanical micromachined device that might represent an important step in this direction: the fiber-top cantilever (FTC).[10] FTCs are obtained by carving a cantilever directly at the center of the cleaved edge of a single mode optical fiber (see Fig. 1).[10,11] Deflections of the cantilever can be measured by coupling light into the fiber and monitoring the interference of the light reflected at the fiber edge with that reflected by the cantilever itself,[10] as in common optical fiber interferometers.[12–14] The monolithic structure of the device eliminates any problem associated with the alignment of optical components, a relevant advantage with respect to other optical readout techniques. The absence of electronic contacts on the sensing head facilitates utilization in harsh conditions (e.g., conductive liquids, cryogenic and high temperatures, explosive gases, high electronic noise environments), where most micromachined sensors with electronic readout would not operate properly. Therefore, FTCs represent an interesting alternative to existing cantilever-based instruments, as they preserve the flexibility of an optical device in a compact, plug-and-play design.

The possibilities offered by FTCs were emphasized, so far, in a series of proof-of-concept experiments, where it was shown that these devices can operate as bimorph sensors,[10] optomechanical transducers,[10,11] and chemical sensors.[15] However, no attempt to test FTCs in more traditional AFM applications was reported. In this article, we demonstrate that FTCs can be used for contact mode AFM imaging purposes. The performances of our prototype are comparable to those of commercially available instruments, suggesting that fiber-top AFMs could replace conventional AFMs whenever a user-friendly, compact, and versatile scanning probe microscope is needed.

In Fig. 1 we report a scanning-electron-microscopy image of the FTC used for the experiment. The device was fabricated following the procedure described in Ref. 11. The cleaved edge of a single mode optical fiber (core diameter $=9\ \mu$m, cladding diameter$=125\ \mu$m), stripped of its jacket, was cut by means of focused ion beam milling in the form of a thin rectangular beam, suspended along one diameter of the fiber, with a sharp pyramidal tip at the top of its free hanging end.[11] Before moving the FTC out of the focused ion beam chamber, part of the top side of the cantilever was covered

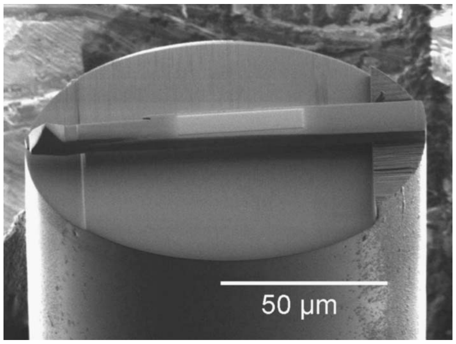

FIG. 1. A scanning-electron-microscopy image of the fiber-top cantilever (before the evaporation of the silver layer). The brighter area at the center of the cantilever indicates the presence of a thin platinum layer, which was deposited immediately after the fabrication.

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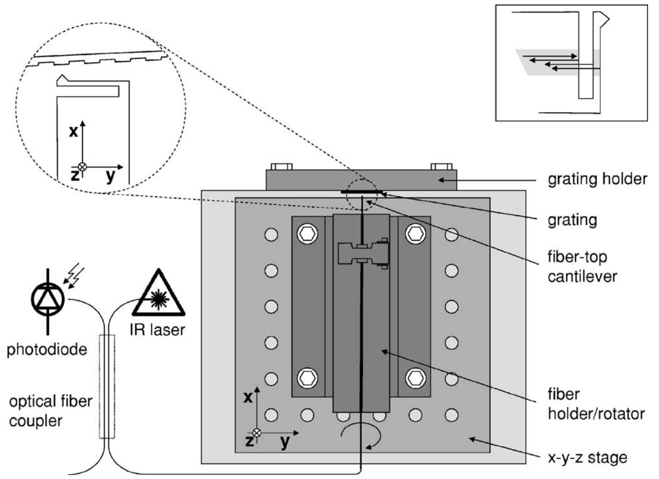

FIG. 2. Sketch of the experimental apparatus for contact-mode fiber-top atomic force microscopy (top view, not to scale). The drawing inside the dotted circle represents a close view of the cantilever as it is approaching the grating. Note that the grating is not perfectly parallel to the cantilever. Inset: a schematic view of the light path that allows interferometric measurements of the deflection of the cantilever. The shaded area represents the core of the fiber (not to scale).

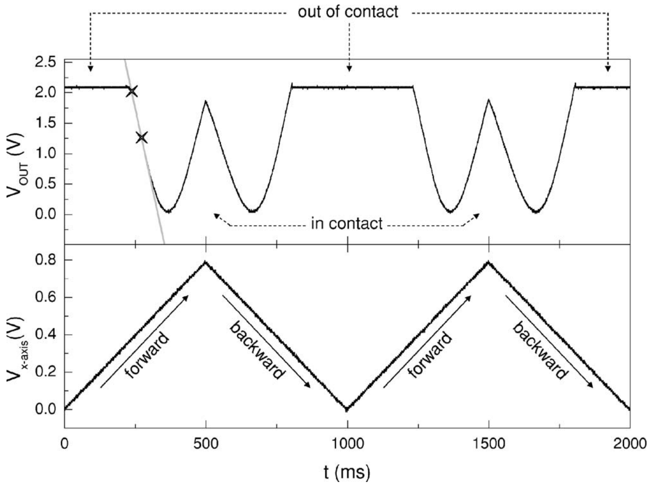

FIG. 3. Calibration data as a function of time. Top graph: output signal of the readout system of the fiber-top cantilever. Bottom graph: voltage signal applied to the x-axis piezoelectric stage. The two crosses indicate the extreme points used for the calibration. The light gray line represents the best linear fit of the data between the two crosses.

with a thin layer of platinum (which corresponds to the brighter area of the image reported in Fig. 1).[11] The purpose of this layer is not relevant to the aim of this experiment, and will not be discussed any further. The FTC was then mounted vertically inside a dual deposition system, where it was coated with a thin sputtered layer of chromium (thickness$\simeq$5 nm) followed by a thicker thermally evaporated silver film (thickness$\simeq$100 nm).

In order to measure vertical displacements of the cantilever, the fiber was coupled to the optical fiber interferometer readout system sketched in Fig. 2.[10] We refer the reader to Ref. 10 for further details.

The FTC was clamped on a fiber holder that could be rotated manually along the axis of the fiber (see Fig. 2). The holder was screwed on top of a triaxial translational stage equipped with three differential adjusters and three piezoelectric actuators for coarse and fine movements along the x, y, and z directions. While looking at the FTC with an optical microscope, the holder was rotated until the cantilever appeared to be parallel to the ground. In front of the FTC, we then mounted a commercial 23 nm height, 3 μm pitch grating for AFM calibrations (NT-MDT TGZ01), fixed to an aluminum plate anchored to the base of the translational stage, as indicated in Fig. 2. Note that the grating was not perfectly parallel with respect to the cantilever. The importance of this detail will become evident later in the text.

To calibrate the readout system, we brought the tip of the FTC close to the grating. We then applied a 1 Hz triangular voltage signal to the x-axis piezoelectric stage (bottom curve of Fig. 3). According to the specifications supplied by the manufacturer, the stage was linearly moving back and forth for 1.6 μm, at a speed of 3.2 μm/s. The top curve of Fig. 3 represents the output signal of the FTC readout apparatus (V_{OUT}) as a function of time for two consecutive cycles. The flat parts of the curve correspond to out-of-contact movements. After contact, the signal follows a sinusoidal curve, as expected for this type of readout system.[10,12–14] The shape of the curve also shows that the interference signal in out-of-contact positions is close to quadrature. Part of the sinusoid close to the jump-to-contact point (from $\simeq$2 ms after contact to $\simeq$90 ms before reaching the minimum of the interference signal, as indicated in Fig. 3) was fitted with a linear function, whose slope resulted to be equal to -21.6 V/s. For output signals that do not deviate much from quadrature (i.e., small deformations with respect to the out-of-contact position), one can thus assume that the vertical displacement of the free end of the cantilever is given by $\delta = aV_{\mathrm{OUT}}$, where $a = -148$ nm/V.

To demonstrate the capabilities of fiber-top AFMs, we switched off the motion in the x direction and brought the tip of the FTC in contact with the grating. We then applied a 1 Hz triangular voltage signal to the y-axis piezoelectric stage (bottom curve of Fig. 4). In the top part of Fig. 4 we plot V_{OUT} as a function of time. Note that (i) there are still flat parts of the signal, and (ii) wherever the signal is not flat,

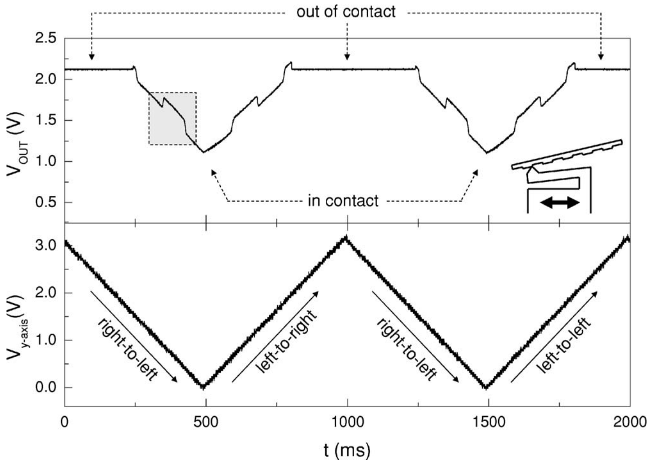

FIG. 4. Demonstration of the scanning capability of a fiber-top atomic force microscope in contact mode. Top graph: output signal of the readout system of the fiber-top cantilever as a function of time. Bottom graph: voltage signal applied to the y-axis piezoelectric stage as a function of time. The shaded area indicates the data reported in Fig. 5 after the elaboration explained in the text.

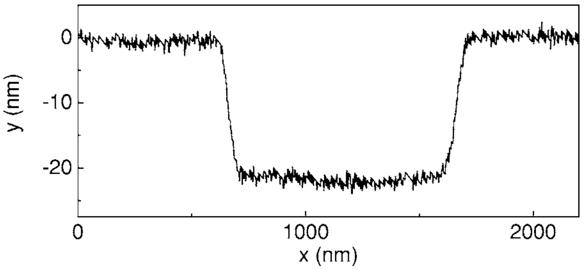

FIG. 5. Elaboration of the data enclosed in the shaded area of Fig. 4. The curve represents the profile of a valley of the grating.

the trace follows a tilted square wave profile. Because of a small angle between the cantilever and the sample, right-to-left (left-to-right) translations were accompanied by a decrease (increase) of the separation between the edge of the fiber and the grating. The flat parts of the signal correspond to the right side of the scan, where the probe and the sample were not in contact. The tilted parts correspond to contact mode scans. The trace follows the profile of the grating (square wave profile), which is tilted because of the nonparallelism of the cantilever and the juxtaposed surface. The presence of a flat signal before contact is important to rule out the possibility of a wrong interpretation of the data. For example, one could argue that part of the laser beam is somehow transmitted beyond the cantilever, and that the tilted squarelike signal is due to the interference of the light reflected at the fiber edge with that reflected by the sample itself. In that case, however, the trace would follow the profile of the grating before contact, too.

In Fig. 5 we show an elaboration of the data contained in the shaded area of Fig. 4. Raw data were corrected for tilting and converted to surface profile using the calibration parameters extracted from the x scan (Fig. 3). Note that, since a is negative, raw data are the mirror images of the real profile (i.e., the square peak contained in the shaded area of Fig. 4 corresponds to a valley of the real sample). According to our measurement, the depth of the valley is $\simeq 22.5$ nm, and its width is $\simeq 1.1\ \mu$m, in perfect agreement with the data sheet provided by the manufacturer. The noise (a few nanometers) is mostly due to vibrations of the setup. We noted, in fact, that its level was significantly lower when the FTC was kept out of contact. In that case, the standard deviation of the output signal acquired on a digital oscilloscope over a 0.2 s sample time was equal to $\simeq 550\ \mu$V, corresponding to $\simeq 80$ pm over the $\simeq 30$ kHz bandwidth of the photodiode's amplifier.

In conclusion, we have developed a fiber-top AFM for contact mode scanning microscopy. The performances of our prototype are similar to those achievable with commercially available AFMs. The monolithic structure of the device and the possibilities offered by an all-optical, user-friendly readout system represent significant advantages with respect to existing instruments, and may soon stimulate the implementation of fiber-top AFMs for applications outside specialized research laboratories, where they could be easily used even by untrained operators.

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