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Piezoresistive cantilevers as optical sensors for scanning near-field microscopy

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Abstract

To combine the high lateral resolution of AFM with near-field optical measurements, we propose the use of microfabricated piezoresistive cantilevers as miniaturized photosensitive elements. The silicon-based sensors consist of a *p*-doped piezoresistive path, which also includes the tip. The resistance of this path can *be changed either by pressure on the lever or by light*. For combined optical and topographical measurements, an evanescent field is created. Because the AFM tip is the only part of the cantilever that is exposed to the evanescent field, the tip can be used as a near-field optical probe. It is possible to extract the exponential decay of the evanescent field from combined force/optical measurements. To decouple optical and topographical information, the intensity of the evanescent field is modulated and the optical signal is measured with the lock-in technique.

1. Introduction

Scanning near-field optical microscopy (SNOM) [1] has proved to be a very promising technique, especially for biological applications. Several methods have been presented to merge the optical information of the SNOM with the surface topography as measured, for example, by scanning probe microscopy (SPM) (for an overview see for example [2–4]). Recently, it was shown by Mertz et al. [5] that standard atomic force microscopy (AFM) probes can be used for near-field light imaging as an alternative to tapered optical fibers and photo-multipliers. As demonstrated by Akamine et al. [6] it is also

possible to prepare a small photodiode at the end of the cantilever, which can be used directly to measure the optical signal as well as the topography with a lateral resolution of about 20 nm.

In this paper we propose the use of microfabricated piezoresistive AFM cantilevers as miniaturized photosensitive elements. As in the case of the photodiode-based cantilevers [6], this provides two major advantages. First, the light intensity can be detected directly in the near field and, second, it allows the high lateral resolution of AFM to be combined with near-field optical measurements in a very convenient way.

2. Sensors

We used microfabricated silicon cantilevers produced by Tortenese et al. [7] for our experiments.

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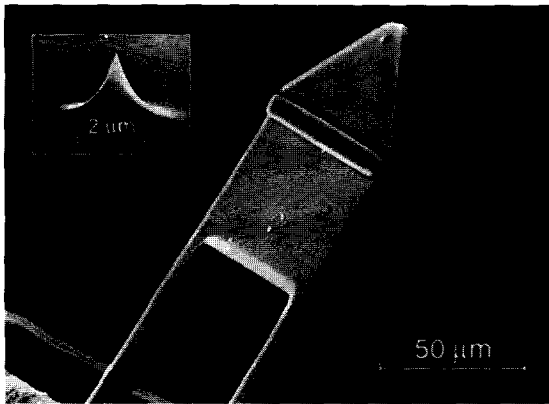


Fig. 1. SEM micrograph of a piezoresistive cantilever (Park Scientific Instruments). For the experiments a geometrically slightly different design was used where the tip is included in the piezoresistive path. Inset: image of the integrated tip for AFM.

The sensors contain an integrated piezoresistive path along the V-shaped cantilever for sensing its deflection in the AFM mode. The spring constant of the beam is 7 N/m and, having a sensitivity (relative change of resistance $\Delta R/R$ per angstrom of deflection) of $\sim 2 \times 10^{-7} \text{ \AA}^{-1}$, the minimum detectable deflection is about 0.6 Å. A typical scanning electron microscopy (SEM) image of a piezoresistive cantilever is shown in Fig. 1. The advantage of these cantilevers is that the piezoresistive path consists of highly *p*-doped (80 keV B⁺, 10^{15} – 10^{16} ions/cm²) silicon <110>, which also includes the tip. Owing to the high doping, the resistance of this path can be changed either by pressure on the lever or by light at constant temperature. In the first case, pressure applied on the lever leads to a geometrical change in the crystal structure, which modifies the specific electrical resistance of the semiconducting material. In the second case, incident light falling on the surface of the cantilever produces carriers, generated either by band-to-band transitions or by transitions involving forbidden-gap energy levels, resulting in an increase in conductivity (photoconductivity).

The optical sensitivity profile of the sensors was checked by scanning the cantilever at a constant distance of a few microns over a well defined laser beam. The beam was produced by a semiconductor laser chip ($\lambda \approx 688 \text{ nm}$) [8] having a spot size of about 5 μm. The sensitivity map (Fig. 2) represents a convolution of the Gaussian intensity profile of the

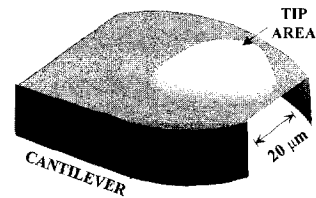


Fig. 2. Sensitivity map of the cantilever obtained by scanning over a laser beam of 5 μm diameter. It shows that the tip area is the most sensitive part.

laser and the optical sensitivity of the piezoresistive path including the AFM tip. The *p*-doping is the same over the entire sensor area but the tip appears more sensitive than the surrounding lever, which is probably due to a geometrical effect.

3. Experimental setup

The concept for combined optical and topographical measurements is shown in Fig. 3. An evanescent field is created at a prism surface by total internal reflection of a 7.6 mW HeNe laser beam fed into the prism by an optical fiber. In the AFM mode the tip is brought into contact with the surface of the prism. The piezoresistive path of the sensor is connected with a DC-biased Wheatstone bridge, which directly measures the deflection by sensing the change in the cantilever resistance. The output of the bridge is amplified by an instrumentation amplifier and connected to a feedback, which controls the force-induced change of the resistance while scanning over the prism surface. By increasing the sensitivity of the resistance measurement by a factor of 100, the tip

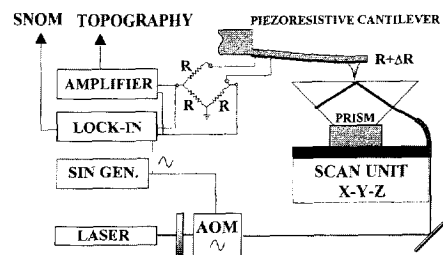


Fig. 3. Schematic drawing of the experimental setup. An evanescent field is created at the prism surface. The piezoresistive optical/force sensor is used to measure the topography and variations in the optical near field.

can be used as a near-field optical probe because it is the only part of the cantilever that is exposed to the evanescent wave. To decouple optical and topographical information, the intensity of the evanescent field is modulated at about 20 kHz and the optical signal is measured simultaneously with the force-induced change of the resistance using a lock-in amplifier parallel to the DC-biased Wheatstone bridge.

4. Results

Having a tip height of about 1.2 μm and an exponential decay length of the evanescent field of about 396 nm, the tip is the only part of the cantilever that is exposed to evanescent light. In order to measure the exponential decay of the evanescent field, the tip was moved towards the prism surface while the change in resistance of the cantilever was monitored using only the DC-biased Wheatstone bridge. The resulting piezoresistive signal depends naturally on the intensity of the evanescent light, but also on the tip–surface interaction. In order to eliminate the latter contribution, the displacement curve measured without light (laser beam off) was subtracted from the curve taken with the laser beam on. The corrected data gives the exponential decay of the evanescent light shown in Fig. 4 (bottom curve). This curve is still a convolution of the increasing effective sensitivity of the tip with the exponential

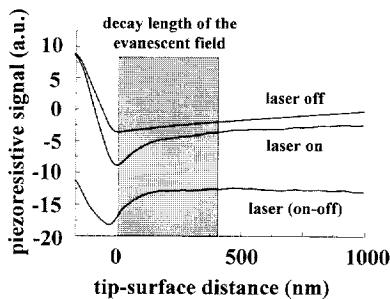


Fig. 4. Piezoresistive signal versus tip–surface distance. Top: force–distance curve with the laser beam off. Middle: combined optical/force signal with the laser beam on. Bottom: corrected displacement curve (laser on minus laser off) used to extract the exponential decay of the evanescent field.

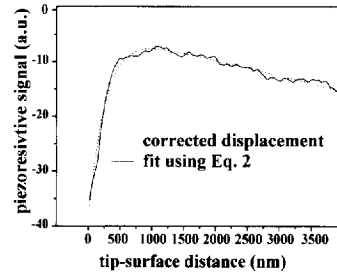


Fig. 5. Piezoresistive signal versus tip–surface distance. Solid line: corrected displacement curves (laser on minus laser off). Dashed line: fit of the distance dependence using Eq. (2) ($C_1 = -0.0026 \text{ nm}^{-1}$, $C_2 = 5.820$, $C_3 = -0.0049 \text{ nm}^{-1}$).

increase of the light intensity when the tip is pushed towards the prism surface.

While the *p*-doped layer has an average thickness of about 0.5 μm [7] and every photon will be absorbed by only one impurity atom or not at all, the light-sensitive part of the tip can be described by an effective area exposed to the evanescent field. Assuming a cone geometry for the tip, this effective light-sensitive area is

$$F = x^2 \pi \frac{\tan \alpha}{\cos \alpha} = Cx^2, \quad (1)$$

where C is the constant defined by the tip geometry, x the effective height of the cone, and α the fixed opening angle of the cone.

Owing to the exponential increase of the evanescent light intensity, the piezoresistive signal versus the tip–surface distance can be described by

$$\frac{\Delta R}{R} = C_1 x + C_2 \int_0^{x_{\max}} \exp(C_3 x) x^2 dx, \quad (2)$$

where $C_{1,2,3}$ are fitting parameters and the integration limits are the points at which the tip starts to dip into the evanescent field (0) and the prism surface (x_{\max}), respectively.

The first term in Eq. (2) describes a linearly decreasing background induced by scattered light during the tip approach, and the second term is the convolution of the evanescent field with the tip geometry. As shown in Fig. 5, the calculated displacement signal fits well with the measured signal, and the fitting parameter C_3 yields an acceptable decay length of 408 nm.

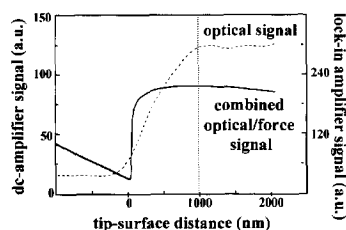


Fig. 6. Piezoresistive signal versus tip-surface distance. Solid line: force curve with the laser beam on. Dashed line: optical signal measured with the lock-in technique. Dotted marker: onset of the evanescent field.

The optical signal can be measured independently of the combined optical/force curve. In that case the laser beam is modulated and the piezoresistive signal analyzed by a lock-in technique in parallel to the DC-biased Wheatstone bridge, as shown in Fig. 3. One particular example is shown in Fig. 6. In the pure optical signal the onset (dotted line in Fig. 6) of the evanescent field with a decay length of 396 nm occurs at about 1000 nm, as expected, whereas the onset of the less sensitive combined optical/force signal depends on the intensity of the evanescent wave, as evident from the difference between Fig. 4 (laser intensity before the fiber: $I = 2.5$ mW) and Fig. 5 ($I = 7.6$ mW).

The method was also used to study locally transparent samples mounted on top of the prism. Surface topography and lateral variation of the optical near field were measured simultaneously in order to estimate the lateral resolution of the sensors. No convincing optical image has yet been taken. It seems that the intensity of the light field on partially coated samples is too low for the present sensor configuration. Therefore the output signal of the lock-in is too noisy to observe lateral variations of the optical near field clearly.

For a different kind of photodetection cantilever, the reader is referred to Ref. [9].

5. Conclusions

In conclusion we showed that microfabricated piezoresistive cantilevers can be used as combined AFM and near-field optical probes. It was possible to extract the exponential decay of an evanescent field created at a prism surface from combined force/optical measurements. To decouple optical and topographical information the light intensity was modulated and measured by the lock-in technique.

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