Novel micromachined cantilever sensors for scanning near-field optical microscopy*

S. MÜNSTER, S. WERNER, C. MIHALCEA, W. SCHOLZ & E. OESTERSCHULZE
University of Kassel, Institute of Technical Physics, Heinrich-Plettstr. 40, 34109 Kassel, Germany
(E-mail: oester@physik.uni-kassel.de)

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Summary
The reproducible micromachining of hollow metal tips on Si cantilevers and their applicability to scanning near-field optical microscopy (SNOM) is described. This sensor is fabricated using semiconductor compatible technologies. A hollow metal pyramid is employed as an optical aperture sensor for SNOM and simultaneously as a force sensor for scanning force microscopy applications. Apertures down to 120 nm were realized. To confirm the feasibility of the sensor we present measurements on microstructured chromium films as well as on hot filament chemical vapour deposition grown (111) diamond membranes. The SNOM images show a resolution of about 100 nm, demonstrating the usefulness of these probes.

Introduction
Scanning near-field optical microscopy (SNOM) has become a widely used technique for optical imaging of materials in the subwavelength region (Dürrig et al., 1986; Betzig et al., 1987; Fischer et al., 1988; Danzebrink et al., 1995). In most cases optical fibres are employed as near-field sensors; these are produced by thermal pulling or etching of macroscopic optical fibres to yield sharp tips. The tip performance suffers from the insufficient reproducibility of the tip fabrication process that leads to difficulties in reliable optical imaging. A shear-force mode is necessary to control the distance between tip and sample to get additional topographical information and to avoid damaging of the fragile tip which limits the lateral resolution (Betzig & Trautman, 1992; Froehlich & Milster, 1995). Therefore, it is desirable to introduce a sensor design which avoids the above-mentioned disadvantages. In recent years a sensor based on a cantilever design which is well known from scanning force microscopy (SFM), was employed (van Hulst et al., 1993; Akamine et al., 1994; Radmacher et al., 1994; Bauer et al., 1995; Danzebrink et al., 1995; Ruiter et al., 1996). A SiN cantilever was used directly for photon scanning tunnelling microscopy (PSTM) to collect the evanescent field caused by total internal reflection at the sample surface (Fig. 1a). To use the transparent cantilever as an aperture probe it is necessary to metallize the tip, forming a small aperture at the apex, which is again a technique of insufficient reproducibility (Fig. 1b).

In this paper we introduce a novel optical aperture sensor based on a cantilever design for combined scanning near-field optical and scanning force microscopy that is fabricated using semiconductor-compatible technologies. A hollow metal pyramid with an aperture at its apex is integrated at the very end of a silicon cantilever (Fig. 1c). The aperture works as a confined light source in the scanning near-field optical mode if it is illuminated from the back. Additionally, the sensor is employed as a conventional force sensor for SFM and can be operated in the static as well as in the dynamic mode.

In comparison with other sensor fabrication technologies the advantages of this technology are the high accuracy and reproducibility, which are important to fabricate sensors with identical properties.

Sensor technology
The combined SNOM/SFM sensor consists of two parts: the cantilever including the tip and a holder necessary for easy mechanical handling of the complete sensor. The most important steps of the fabrication processes of sensor and holder are shown in Fig. 2. In both cases p-doped (100) Si wafers with a boron doping concentration of about $10^{16} \text{cm}^{-3}$ are used as base material. For the cantilever fabrication a membrane is anisotropically etched with alkaline solutions from the back side of the silicon wafer (step (a), Fig. 2). Varying the
thickness of the membrane between 2 and 10 \( \mu m \) allows us to adjust the spring constant of the desired cantilever as well as the tip height. An additional etching process with KOH is employed in step (b) (Fig. 2) to define the geometry of a 600-\( \mu m \)-long and 150-\( \mu m \)-wide cantilever as well as to get an inverse pyramid with (111) side walls. This results in an opening angle of 70.5° between opposite side walls of the inverse pyramid. An SEM image of the inverse pyramid is shown in Fig. 3(a). Isotropic reactive ion etching (SF \(_6\)) from the back side of the membrane opens the inverse pyramid in step (c) (Fig. 2) and thus defines the aperture at its apex. Deposition of a 100–120-nm thin metal layer (chromium, aluminium, etc.) on top and subsequent plasma etching from the back side of the membrane in step (d) (Fig. 2) results in a hollow metal pyramid with an optical aperture at the apex. Aperture sizes of about 120 nm have been determined from SEM images shown in Figs. 3(b) and 3(c). The aperture size is controllable by the dry etching plasma process (step (c) Fig. 2). The top view of the sensor in step (e) (Fig. 2) depicts the cantilever including the tip connected via a thin membrane to an outer Si frame.

For the holder fabrication a silicon wafer is oxidized (step (f), Fig. 2) and an optical lithography process defines the holder geometry (step (g), Fig. 2). Opening the uncovered parts of the oxide layer by wet chemical etching with BHF the complete holder is subsequently fabricated by an anisotropic etching process. The cross-section and top view of the holder are shown in Figs. 2(h) and 2(i), respectively.

In the following step (j) (Fig. 2) both wafers are fixed to each other by Si/Si fusion bonding. Figure 3(d) depicts a light microscope image of the bonded holder (left) and sensor (right). Finally, the sensors can be freed by an RIE process from the tip side in step (k) (Fig. 2).

**Experimental set-up**

The set-up of the combined SNOM/SFM microscope is shown schematically in Fig. 4. It consists of three main parts: a scanning near-field optical microscope, a conventional scanning force microscope and a classical microscope. The position of the cantilever is fixed during operation while the sample is scanned by piezoelectric actuators (scan range: 20 \( \mu m \) \( \times \) 20 \( \mu m \)).
For the optical near-field microscope the beam of a polarized He/Ne laser (optical output power 3 mW, wavelength 633 nm) is focused with an objective (OB1) (NA 0.5 magnification 40×) into the hollow tip on the cantilever (C). The light passing the aperture is partly transmitted through the sample (SA), collected by a second objective (OB2) and detected by a photomultiplier (PMT) (Hamamatsu R928).

To operate the sensor in the static or dynamic SFM mode a conventional triangulation (beam deflection) technique is used to detect the cantilever deflection. In this case an infrared laser diode (LD) (optical power 1 mW, wavelength 780 nm) and a quadrant photodiode are used. This technique allows us to detect both torsion and vertical deflection. Thus topography and friction properties of the sample surface can be determined (Meyer & Amer, 1988).

To view the sample, the position of the tip and the laser spot simultaneously, a beam splitter (BS2) and a CCD

Fig. 3. Scanning electron microscopy images of different parts of the near-field sensor: (a) back side of the metal pyramid; (b) hollow metal pyramid with an optical aperture at the apex; (c) chromium pyramid with an aperture of about 120 nm at the apex; (d) Si/Si bonded holder (left side) and cantilever (right side) before releasing the sensor by a reactive ion etching process.

Fig. 4. Schematic set-up of the scanning near-field microscope employing the combined SNOM/SFM probes. MI: mirror; BS: beam splitter; PH: pinhole; FL: focus lens; C: cantilever; LS: light source; OB: objective; SA: sample; PF: polarizer; QD: quadrant diode; FLT: filter; LD: laser diode; PMT: photomultiplier.
camera are inserted into the optical path forming an inverted optical microscope. This allows us to adjust the position of the laser spot into the hollow tip.

The vertical and friction force signal as well as the output of the photomultiplier are simultaneously recorded by a digital signal processor system (DSP) (Stopka et al., 1995). The DSP is also used in the feedback loop of the microscope to keep the force between probe and sample constant.

Results

For the characterization of the mechanical sensor behaviour the resonance frequency of the cantilever was measured to be 15.2 kHz. This is in good agreement with the theoretical value of 15.4 kHz calculated for a 8-μm-thick and 600-μm-long cantilever. The same measurement leads to an evaluated spring constant of 1.87 N m⁻¹.

To demonstrate the suitability of the novel sensor, measurements were performed on microstructured 80-nm-thick chromium layers on flat glass substrates. The chromium layer was patterned by e-beam lithography to yield several 100-nm line-shaped grooves with a periodicity of about 180 and 300 nm, respectively. Measurements were performed in the constant-force mode where both the near-field optical data in the transmission mode and the topographical data have been recorded simultaneously. From the near-field optical image in Fig. 5(a) five (four) white trenches are resolved in case of the 300-nm (180 nm) periodic line structure whereas the trenches are revealed as dark lines in the topography image (Fig. 5(b)). Comparing both images, a small shift in the horizontal direction is apparent: this is caused by tilting the tip with respect to the sample. Hence the force image is generated by one corner of the quadratic aperture at the tip apex whereas the optical image is determined by the centre of the aperture. From the cross-section of the optical image in Fig. 5(c) taken at the marked position in Fig. 5(A) a lateral resolution of about 80 nm was obtained, which underlines the suitability of the novel sensor.

The same sensor was used for the investigation of diamond materials. A diamond layer with an average thickness of about 6 μm was deposited on a (100) Si substrate by the hot filament chemical vapour deposition (HFCVD) method. Etching the Si substrate from the back side releases the diamond membrane. Single diamond crystals are observed in the topography image on top of the membrane surface (Fig. 6(a)). The measurement was performed in the constant-force mode. The vertical force image (Fig. 6(b)) and the friction force image (Fig. 6(c)) which corresponds to the vertical deflection and the torsion of the cantilever during scanning shows an improved contrast with respect to the edges of the diamond crystals and material inhomogeneity. Figure 6(d) shows the simultaneously recorded near-field optical image. The optical contrast is influenced by the local membrane thickness and the orientation of the single crystallite surfaces with respect to the aperture plane. Although combined scanning tunnelling and scanning thermal microscopy measurements reveal laminar structures on the side walls of similar diamond crystals (Stopka et al., 1995; Oesterschulze et al., 1996; Ackermann et al., 1996), the optical signal remains almost constant, owing to the finite size of the aperture. Nevertheless, 100–120-nm line-shaped structures are observed by scanning across the edges of the crystals which corresponds to the aperture size.

Conclusion

In this paper we introduce a novel sensor which consists of a hollow metal tip with a miniaturized optical aperture of 120 nm at its apex. The tip is integrated at the very end of a cantilever which allows us to perform SNOM and SFM measurements simultaneously. This avoids the disadvantages of the shear force detection mode necessary in the case of conventional optical fibre sensors. Furthermore, the high opening angle of about 70.5° shifts the optical cutoff position closer to the aperture, increasing the sensor transmission in comparison to optical fibres. The application of semiconductor-compatible sensor fabrication
technologies results in high accuracy and reproducibility of the sensor geometry which is necessary for both reproducible properties as well as convenient theoretical modelling of the sensor. We emphasize that, owing to the fabrication technologies employed, it is also feasible to design tips sensitive for, for example, thermal, optical, magnetic and mechanical sample properties.

The suitability of the sensor was demonstrated by investigating structured thin chromium layers on flat glass substrates in the transmission mode. A lateral resolution of about 100 nm in the SNOM/SFM mode was achieved. The same sensors were applied to study the topography and optical behaviour of (111) diamond membranes.

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**Fig. 6.** Investigation of a 6-μm-thick (111) diamond membrane deposited by a HFCVD process on a (100) Si wafer. The silicon substrate was etched with KOH from the back side to release the diamond membrane. (a) SFM topography image taken in the constant-force mode; (b) vertical force image; (c) friction force image; (d) SNOM image of the transmitted light intensity.
References


