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Hybrid optical fiber-apertured cantilever near-field probe

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In this letter, we propose a hybrid optical fiber-apertured cantilever probe for optical near-field applications. A thermal SiO_2 cantilever beam with a SiO_2 pyramidal tip was formed by Si micromachining technique and bonded with an optical fiber using a polyimide adhesive layer. A subwavelength aperture at the apex of the SiO_2 tip was formed by etching the SiO_2 in a buffered-HF solution. Optical near-field imaging in contact mode was observed with the fabricated probe. The probe could work in contact mode because the cantilever at the end of the fiber can flexibly move on the sample surface. By detecting the far-field light which is reflected-back by the tip of the cantilever, the vibration of the cantilever was observed using the probe itself. With the proposed structure, a hybrid fiber bundle-apertured cantilever array is feasible for application in parallel near-field processing or data storage.
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A near-field scanning optical microscopy (NSOM) probe is the most crucial tool for near-field, nano-optics.[1] Normally, a tapered, metalized optical fiber having a small optical aperture is utilized as the NSOM probe.[2] An optical fiber based probe is advantageous in coupling and guiding light from the light source to the aperture or vice versa from the aperture to the detector. However, the conventional optical fiber based NSOM probes have several disadvantages as the following: (i) fabrication process is not suited for mass production, (ii) aperture size and tip shape is difficult to control, (iii) optical throughput (i.e., the ratio of near-field and corresponding far-field intensities) is low, (iv) mechanical property of the fiber tip is poor, (v) control of tip–sample distance is quite complicated, and (vi) difficult to utilize fiber probe for applications that require an array of nanolight sources.

Presently, Si micromachined cantilevers have been developing for NSOM applications by several groups to overcome drawbacks of the optical fiber based probes.[3–11] Recently, Si micromachined probes having a small aperture at the apex of a SiO_2 tip were proposed. The fabrication process was batch processed and the reproducibility was very high.[9,10] Measurement and simulation results proved that optical throughput of the SiO_2 aperture tip was very high. For instance, a 100 nm SiO_2 aperture tip yields an approximately 10^{-2} optical throughput.[11] Other hybrid structures of the optical fiber and apertured tip were proposed.[12,13] In this letter, we report on a type of NSOM probe we developed: hybrid optical-fiber and apertured cantilever to take advantage of both optical fiber and apertured cantilever for parallel near-field imaging, processing, photolithography, or data storage.

Structure of the probe is schematically shown in Fig. 1. Far-field light is guided by the core of the fiber and illuminates the apertured tip. Since the opening angle of the SiO_2 tip is very large, the cutoff effect is minimized and the optical throughput of the probe is improved. Moreover, the far-field light which is reflected back by the tip of the cantilever can be utilized to monitor the deflection or vibration of the cantilever, i.e., to monitor the tip–sample distance by the probe itself.

The fabrication process is drawn in Fig. 2 (dimensions are not to scale). Briefly, an pyramidal etch pit or etch pit array is formed on a Si wafer [*n* type, resistivity 0.01–0.1 Ω cm, 200-μm-thick (100) orientation] by etching the Si in a tetramethyl ammonium hydroxide (step 1). Next, the wafer is oxidized in wet oxygen at 950 °C for 10 h (approximately 1-μm-thick) and followed by a Cr sputtering (about 100-nm-thick) (step 2). Next, the structure of the cantilevers on the wafer is patterned by photolithography, Cr and SiO_2 etching (step 3). For bonding with the optical fiber, a polyimide col-

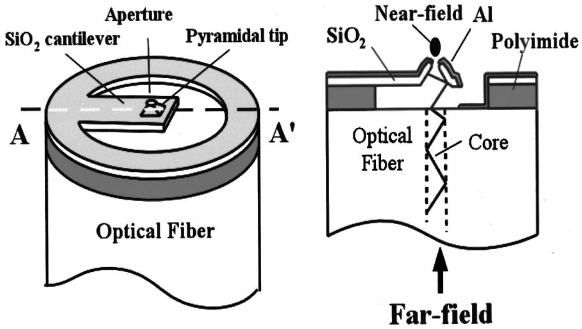

FIG. 1. Schematic diagram of the hybrid optical fiber-apertured cantilever probe.

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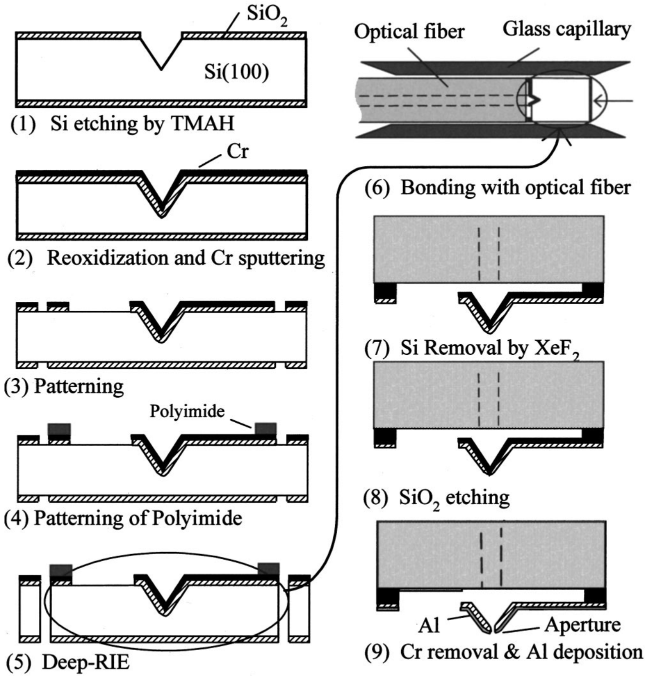

FIG. 2. Fabrication process of the hybrid optical fiber-apertured cantilever.

umn (5-μm-thick) is formed by photolithography (step 4).[14] Next, the wafer is etched through with a deep-reactive ion etching (step 5). At this step, more than 3000 Si columns are obtained on a 2×2 cm^2 Si wafer. Next the Si column (125-μm-diameter) is bonded with the optical fiber (125-μm-diameter) in a glass capillary (127-μm-diameter) at 360 °C (step 6). After bonding, the fiber-Si column combination is taken away from the capillary and the Si base is then completely etched in a XeF_2 dry etching until forming a SiO_2 cantilever having a SiO_2 tip at the end of the fiber. XeF_2 was chosen because of its outstanding selectivity of etching of the Si and the SiO_2. The aperture at the apex of the tip is created by etching the SiO_2 in a buffered-HF (50% HF:40% NH_4F, 9 cc:100 cc) (step 8). As reported in Ref. 9, since the thickness of the low temperature grown SiO_2 tip at its apex is thinnest, as small as 25-nm aperture can be created by the etching technique. Finally, the Cr film is removed and an approximately 100-nm-thick opaque layer (Al) is entirely coated on the lower side of the probe (step 9).

A scanning electron microscopy (SEM) image of the fabricated probe is shown in Fig. 3(a). A typical SEM image of the fabricated aperture with approximately 250-nm-diameter is shown in Fig. 3(b). The diameter of the cladding and the core of the single mode optical fiber are 125-μm and 5-μm, respectively. The width and the length of the cantilever beam are 35 μm and 60 μm, respectively. The size of the tip is $20\times20\,\mu$m^2. It is seen that the accuracy of the alignment between the core and the aperture tip is very essential. In this fabrication process, a misalignment of several μm was found.

To concentrate more light at the aperture, a glass ball lens was put on the upper side of the SiO_2 tip before the assembling step. Figure 3(c) shows the SiO_2 cantilever probe on a Si column, where a glass ball lens of 14 μm was inserted by manipulation using a sharp metal tip under a microscope. The ball is attached to the metal tip by an electrostatic force and then inserted into the tip.

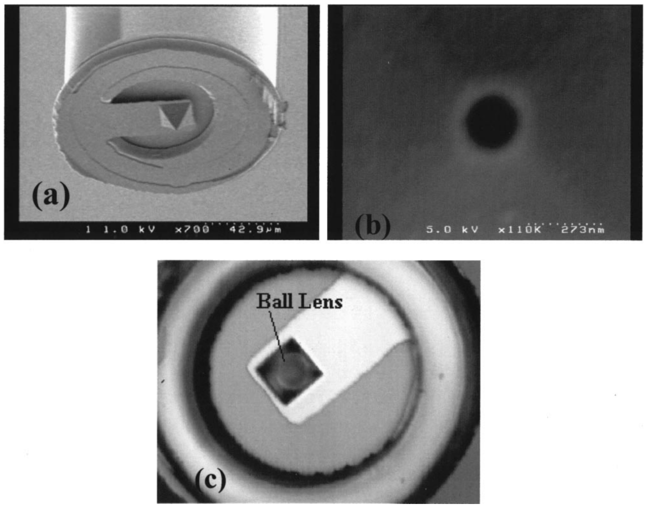

FIG. 3. (a) SEM image of the fabricated probes, (b) SEM image of the typical aperture with approximately 250-nm-diameter, and (c) optical image of the SiO_2 cantilever structure on the Si column with glass ball lens before bonding with the fiber. The ball lens was manipulated with a sharp metal tip under an optical microscope.

Using the fabricated probe of hybrid optical fiber-apertured cantilever, a near-field image was observed in contact mode. A schematic diagram of the measurement setup is shown in Fig. 4(a). The probe is mounted on a holder. A charge coupled device camera is used to observe the approaching of the probe on the sample. A pulsed laser diode beam (wavelength: 670-nm and power: few mW) was

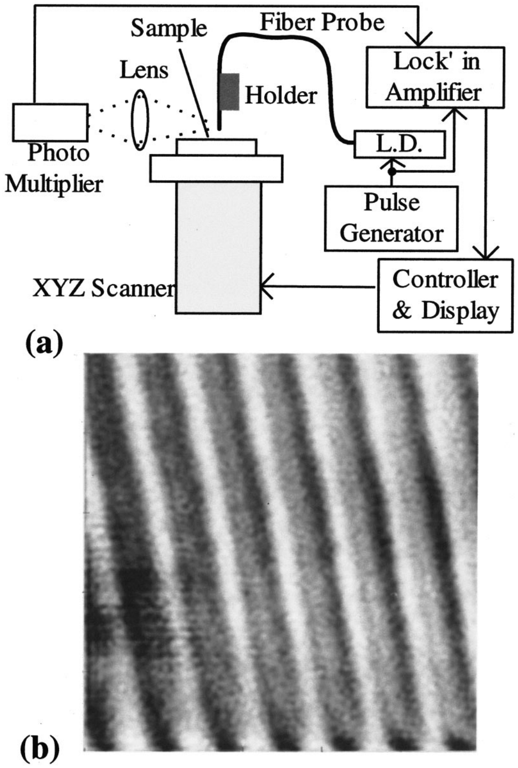

FIG. 4. (a) Experimental setup for optical near-field imaging in contact mode and (b) the optical near-field image of the resist patterns on a Si substrate using the fabricated probe with approximately 400-nm aperture (image size $5\times5\ \mu$m^2).

coupled into the other end of the fiber probe, and illuminates the tip to form near-field light at the aperture. Scattered light with the sample was collected by an objective, detected by a photomultiplier tube (PMT) and the photon signal was lock-in amplified. The sample is raster scanned under the probe by applying a driving signal to an XYZ piezoscanner without any *z*-feedback control. The recorded optical near-field image of the resist patterns on a Si substrate with the fabricated probe is shown in Fig. 4(b). A resolution of 250-nm was obtained from the cross section of the image. The resolution of the image is not very high since the aperture of the probe was large in this experiment (around 400 nm). However, the possibility of the optical near-field applications of the proposed probe is optimistic. The probe can also be operated in a collection mode where an evanescent field light on the sample is collected by the aperture.

As previously mentioned, since the probe consists of a flexible cantilever at the end, it can operate in contact mode without any *z*-feedback control. This should be advantageous for utilizing the structure for data storage. Moreover, with this structure, a simplified setup for monitoring of the tip–sample distance using the probe itself can be expected. To confirm this principle, the following experiment was performed as shown in Fig. 5(a). The probe is mounted in a piezoelement in a vacuum chamber with pressure of 3×10^{-2} Torr. The probe (cantilever) is vertically vibrated by applying a driving voltage to the piezo. The vibration amplitude of the cantilever is monitored by a displacement sensor connected with a network analyzer. The far-field light that is reflected back by the tip of the cantilever and passed through the core of the fiber is detected by a PMT through a photocoupler. The optical signal of the PMT is recorded by the network analyzer. Figures 5(b) and 5(c) show the amplitude of the vibration measured by the displacement sensor and the optical signal detected by the PMT, respectively. It is shown that the peaks in both Figs. 5(b) and 5(c) show the mechanical resonant peak of the cantilever. It is seen that a very small mechanical oscillation of 3.5-nm could be detected with this measurement. Comparing Figs. 5(b) and 5(c), a detectable minimum deflection of the cantilever of 0.5-nm can be addressed with reflected far-field signal. This means that the hybrid optical fiber-apertured cantilever can serve as a self-distance modulation probe. By keeping the reflected light intensity at a constant value, one may keep the tip–sample distance constant using a feedback loop. It should be noted, however, that the mechanical quality factor of the cantilever was very low, about 8–10 in atmosphere because of the air damping and the mechanical energy loss of the cantilever. After the etching of the Si base, the SiO_2 cantilever was slightly bent due to the internal stress. However, the bending of the SiO_2 cantilever can be balanced with the metallic opaque layer.

What we want to address in this letter is that a combination of optical fiber and micromachined cantilever can be utilized as a NSOM probe to take the advantages and eliminate the disadvantages of the fiber and the cantilever. The fabrication process is quite simple. A hybrid lensed fiber bundle and apertured cantilever array is under development for high speed optical near-field imaging, processing, or data storage.

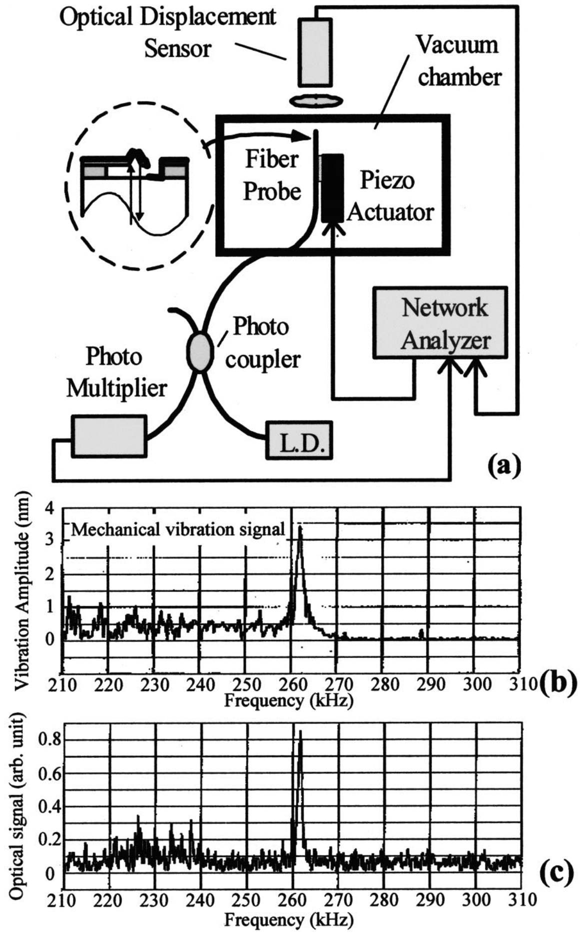

FIG. 5. (a) Experimental setup for evaluation of the vibration detection, (b) vibration amplitude of the cantilever detected by the displacement sensor, (c) and by the PMT.

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[1] *Near-field Optics*, NATO ASI Series, edited by D. W. Pohl and D. Courjon (Kluwer, Dordrecht, 1993), Vol. 242.
[2] E. Betzig and J. K. Trautman, Science **257**, 189 (1992).
[3] N. F. van Hulst, M. H. P. Moers, O. F. J. Noordman, R. G. Tack, F. B. Segerink, and B. Boelger, Appl. Phys. Lett. **62**, 461 (1993).
[4] C. Mihalcea, W. Scholz, S. Werner, S. Munster, E. Oesterschulze, and R. Kassing, Appl. Phys. Lett. **68**, 3531 (1996).
[5] H. Zhou, A. Midha, G. Mills, L. Donaldson, and J. M. R. Weaver, Appl. Phys. Lett. **75**, 1824 (1999).
[6] C. Mihalcea, A. Vollkopf, and E. Oesterschulze, J. Electrochem. Soc. **147**, 1970 (2000).
[7] R. Eckert, J. M. Freyland, H. Gersen, H. Heinzelmann, G. Schurmann, W. Noell, U. Staufer, and N. F. de Rooij, Appl. Phys. Lett. **77**, 3695 (2000).
[8] M. Sasaki, K. Tanaka, and K. Hane, Jpn. J. Appl. Phys., Part 1 **39**, 7150 (2000).
[9] P. N. Minh, T. Ono, and M. Esashi, Appl. Phys. Lett. **75**, 4076 (1999).
[10] P. N. Minh, T. Ono, S. Tanaka, and M. Esashi, J. Microsc. **202**, 28 (2001).
[11] P. N. Minh, T. Ono, S. Tanaka, M. Esashi, Appl. Opt. **40**, 2479 (2001).
[12] W. Noell, M. Abraham, K. Mayr, and A. Ruf, J. Barenz, O. Hollricher, O. Marti, and P. Guthner, Appl. Phys. Lett. **70**, 1236 (1997).
[13] B. J. Kim, J. W. Flamma, E. S. Ten Have, M. F. Garcia-Parajo, N. F. van Hulst, and J. Brugger, J. Microsc. **202**, 16 (2001).
[14] T. Katsumata, Y. Haga, K. Minami, and M. Esashi, Trans. Inst. Electr. Eng. Jpn., Sect. E **120**, 58 (2000).