MINIATURE FIBER FACET ATOMIC FORCE MICROSCOPE USING PHOTONIC CRYSTAL SENSORS

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ABSTRACT

A miniaturized Atomic Force Microscope is fabricated on the facet of an optical fiber. Photonic crystal mirrors are integrated into the fabrication creating a Fabry Perot sensor for sensitive force measurements that verify the probe's ability to resolve forces down to 8 pN/Hz$^{0.5}$. This AFM form factor enables a path towards in-vivo, high-bandwidth and non-contact AFM imaging.

INTRODUCTION

Atomic Force Microscopy (AFM) uses a force-sensing probe with a sharp tip to map a surface with nanometer spatial resolution. In tapping mode AFM (TM-AFM), the probe and sharp tip follow the surface topography by oscillating near the probe's fundamental resonance while maintaining a constant oscillation amplitude by feedback control. As the probe indents the surface it experiences an interaction force with frequency components well beyond the bandwidth of the probe. Consequently these frequency components of the interaction force are strongly attenuated. This problem can be overcome by reducing the measurement noise such that the attenuated frequency components can be detected [1,2]. A different approach is to equip the AFM with additional high bandwidth force sensors that has the temporal resolution to measure the high-frequency interaction forces [3]. In this paper we present fiber AFM probes with integrated high-bandwidth force sensors fabricated entirely in silicon. The force sensors leverage photonic crystal (PC) mirrors for high sensitivity.

DEVICE CONCEPT

The device operates by measuring the tip-sample interaction force, F_{ts}, by detecting the relative displacement of two photonic crystal (PC) mirrors in a Fabry-Perot (FP) configuration on an optical fiber [Fig. 1]. One PC mirror is fixed to the fiber facet (reference mirror) and the other mirror holds the AFM tip, and it is connected through mechanical springs that allows it to move in the direction of the fiber axis (measurement mirror). As a force acts on the tip, the measurement mirror is displaced. The displacement (x) is determined by the reflection from the FP cavity and the force is given by $F_{ts} = kx$, where k is the spring constant.

FABRICATION

Beginning with a silicon on insulator wafer (SOI), PCs and springs were defined using reactive ion etching (RIE) with a SiO_2 hard mask [Fig. 2 (a)]. Release tabs that allow the device to be transferred to an optical fiber, were patterned and etched to the buried insulator.

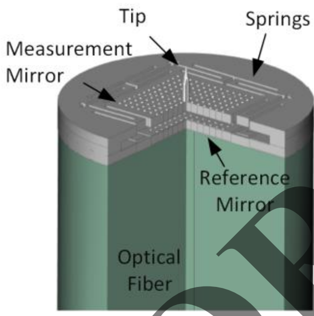

Figure 1 Drawing of the fiber probe

The device was encapsulated in low-stress thermal oxide followed by a blanket RIE [Fig. 2 (b)]. The measurement mirror was then released by a timed isotropic silicon etch [Fig. 2 (c)]. The reference mirror was patterned by RIE using the original SiO_2 hard mask [Fig. 2 (d)]. The device was then released by etching a backside hole and removing all SiO_2 in vapor hydrofluoric acid [Fig. 2 (e)]. A $15\mu m$ AFM tip was made separately by potassium hydroxide etch and RIE. To complete the AFM, the tip was transferred onto the probe and the probe was transferred onto the optical fiber using a focused ion beam [Fig. 2 (f)].

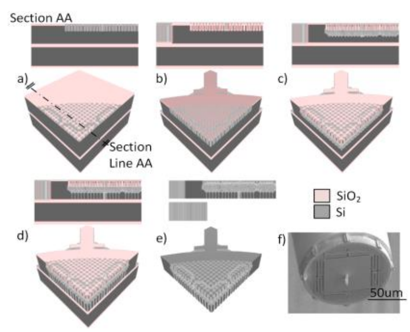

Figure 2 Probe fabrication. a) Patterning of the measurement mirror. b) Patterning of the supporting tabs. c) Release of the measurement mirror. d) Patterning of the reference mirror. e) Release of device. f) Scanning Electron Microscope (SEM) image of the final device.

MEASUREMENTS

To measure the tip sample interaction force, the fiber probe was brought close to a silicon surface using the stepper motor of a commercial AFM (TT-AFM, AFM Workshop). Light from a tunable laser set to 1537 nm was incident on the device cavity and both the incident and the reflected light were measured with photodiodes through a 3dB coupler [Fig. 3 (a)] and acquired at 1 MHz. This setup allowed calculation of the device's reflectivity and provided the measurement mirror's displacement. The mass of the measurement mirror was 4ng from SEM cross-sections and the dominant frequency found in the oscillations of the probe was measured as 22 kHz. This gave a flexural stiffness (k) of 0.06 N/m. The tip sample interaction force (F_{ts}) was then directly given from the displacement of the measurement mirror from its neutral position (x).

The sample was set into a 2 kHz sinusoidal motion by an acoustic buzzer. As the tip of the fiber probe interacted with the sample's surface, the measurement mirror was displaced and the reflectance changed. With calibration, both the surface's topography and the tip sample interaction force could be calculated from the reflectance. Figure 3b shows the force signal of one oscillation cycle. At the beginning of this curve, the probe sensed no force until an attractive force pulled the tip into contact. The surface continued to rise so that the force became repulsive and pushed the measurement mirror towards the reference mirror. As the sample pulled away from the probe, attractive forces kept the tip in contact past its neutral position until the force in the springs overcame the adhesive forces. The device then snapped back to its neutral position.

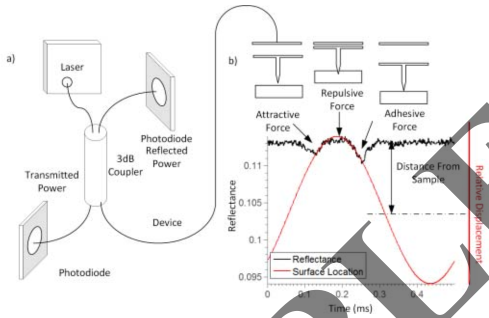

Figure 3 Force-sensing experiment. a) Measurement setup b) Raw data with the surface position and the tip-sample interaction force.

Maintaining a constant Fts while scanning a surface provides topography, but is limited to the accuracy and bandwidth of the feedback. The deflection of the probe however provides both the position of the sample's surface and the tip's indentation into the sample at each tap. To acquire deflection, the measured reflectance signal was converted to tip displacement from a FP model that provides a deflection signal with no calibration or reference needed. The sample's oscillation is sinusoidal with a known frequency and constant amplitude. Fitting this sinusoid to the parts of F_{ts} where the indentation of the probe was zero, provided the sample's position while the difference between the sample's position and the deflection provided indentation.

RESULTS

To demonstrate the ability of the probe to measure topography and the tip sample interaction force simultaneously, measurements of a bare silicon wafer were taken. The oscillating sample sat on the TT-AFM's z piezoelectric actuator which was used to pull the sample away from the tip while measuring the reflectance at 1MHz. The position of the sample and the resulting force curves were calculated from reflectivity measurements of the fiber AFM probe [Fig. 4]. The resolution was 8pN/Hz$^{0.5}$ with a sensitivity of 15% reflectivity change per μN. This was sufficient for the probe to track the position of the surface and simultaneously extract the full tip sample interaction force at each individual tap. The silicon surface had a peak attractive force of 2nN. Though the sample was retracted such that the probe was no longer in contact, this peak attractive force was still clearly seen. Instead of applying feedback to the piezo actuator to maintain the oscillation amplitude, it could be set to maintain this peak attractive force. The piezo actuator position then provides the topography without contact.

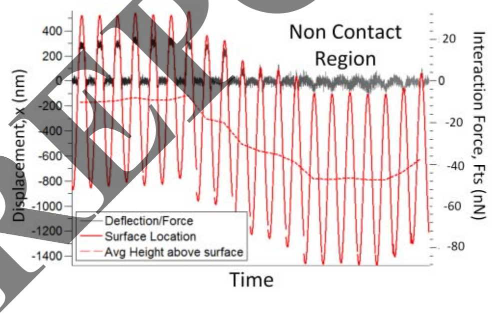

Figure 4 Surface location and tip-sample interaction force for a retracting sample.

CONCLUSION

We have presented a miniaturized AFM system utilizing PC mirrors and optical fiber sensing for high force resolution and demonstrated that it can resolve attractive forces for non-contact imaging.

REFERENCES

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