MICROMECHANICAL DATA STORAGE WITH ULTRA LOW-MASS CANTILEVERS

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Abstract

We describe a micromechanical approach to data storage based on the atomic force microscope. For this purpose, we have fabricated Si_3N_4 cantilevers which have 30 times less mass than the smallest commercially available cantilevers. With these cantilevers, we have demonstrated reading real data at rates exceeding 1 Mbit/s.

Introduction

Scanning probe microscopy has long been seen as a possible basis for an ultrahigh density data storage device.[1] Both the scanning tunneling microscope (STM) and the atomic force microscope (AFM) have demonstrated the ability to write and detect surface features on the nanometer scale.[2] One of the keys difficulties in making this approach practical is the extremely low data rates typically achieved with these techniques. Recently, however, we have developed a new micromechanical approach based on the AFM that combines high density with more reasonable data rates.[3] Using commercially available cantilevers,[4] we demonstrated reading and writing at frequencies up to 100 kHz.

In this technique, the tip of an AFM cantilever is placed in contact with a rotating surface, as shown in Fig. 1. The substrate material is polycarbonate, and the writing is done by heating the tip with a pulsed infrared laser. With the tip in contact, the heated tip softens the polymer surface, and the pressure from the tip creates a small pit. Typical pulse parameters are 20 mW and 1 µs pulses, with a loading force on the tip of roughly 10^{-7} N. Pits as small as 100 nm across and 10 nm deep have been written in this way.[3]

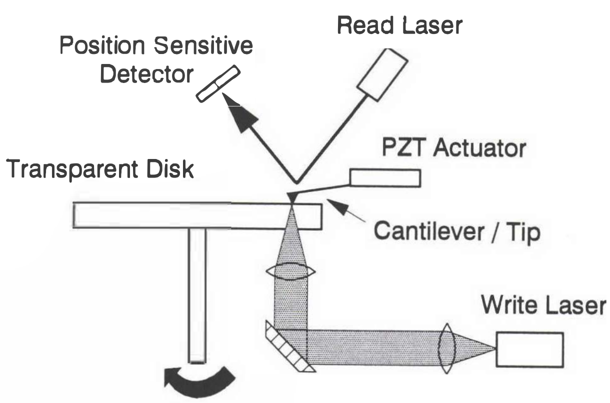

Fig. 1. Experimental setup. Focused laser beam propagates through transparent polycarbonate sample and heats the optically absorbing AFM tip. The heated tip softens the substrate, and the local tip pressure creates an indentation. The sample is placed on a precision air-bearing spindle to allow for sample rotation. The PZT actuator is used to maintain generally constant loading force.

In Fig. 2. we show an AFM micrograph of a pattern written into a test sample in this manner. The sample, which was a section of a grooved optical disk, was raster-scanned under the tip using piezoelectric scanners, and pits were written by pulsing the laser at the desired locations. This pattern represents a density of about 25 Gbit/in^2, a more than 20× increase in areal density compared to conventional optical recording.

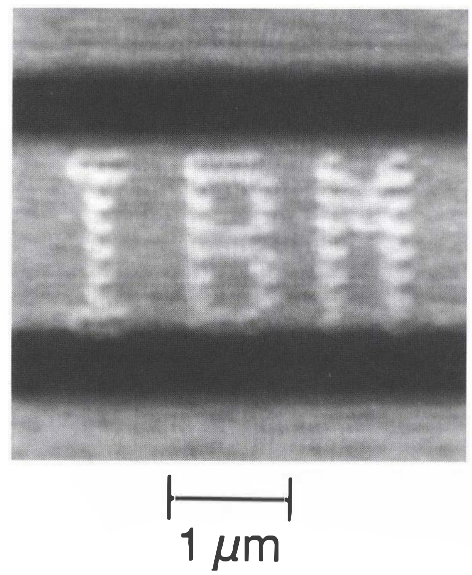

Fig. 2. "IBM" written between the grooves of an optical disk. Each letter would nearly fit inside a typical CD ROM mark.

We detect the marks on the rotating sample with mechanical readback. As the tip rides over the surface of the sample, a topographic feature such as a pit causes a deflection of the cantilever. This deflection is then detected using a standard optical sensor, as shown in Fig. 1. The data rate in this mechanical scheme is related to f_{max}, the maximum frequency at which the tip can track the surface. For a rectangular beam, a simple model which neglects higher order modes gives

$$f_{max} = f_0\left(\frac{2z_L}{h}\right)^{1/2} = 0.46\left(\frac{F_L}{mh}\right)^{1/2}$$

where f_0 is the resonant frequency, h is the pit depth, z_L is the load displacement of the cantilever, F_L is the loading force, and m is the mass of the cantilever.[3] Because of wear and signal-to-noise considerations, the loading force and pit depth cannot be varied arbitrarily. Thus the primary means to improve performance is to reduce the cantilever mass. This is easily understood, as it is the

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acceleration imparted to the tip that determines the response. Our efforts have therefore been to fabricate smaller cantilevers as a means to improve data rate.

Fabrication

Our cantilevers were made from silicon nitride and had integrated pyramidal tips, following the process of Albrecht *etal.*[5] We made both triangular and rectangular levers. The lateral dimensions were chosen so as to make the cantilevers straightforward to fabricate and reasonable to work with in our setup. The thickness was then chosen to give spring constants on the order of 1 N/m. Using these criteria, we chose to make a series of cantilevers with lengths 20-30 μm and thickness 0.35 μm. The resulting mass ranged from 0.3-0.6 ng, depending on geometry. For comparison, commercial silicon nitride cantilevers have a mass of at least 10 ng. Figure 3 shows an optical micrograph of our cantilevers. A rectangular and an open triangular cantilever are shown; closed triangular levers were also fabricated. A scanning electron micrograph is also shown of the pyramidal tip on a triangular cantilever. Tip radii well under 100 nm have been obtained.

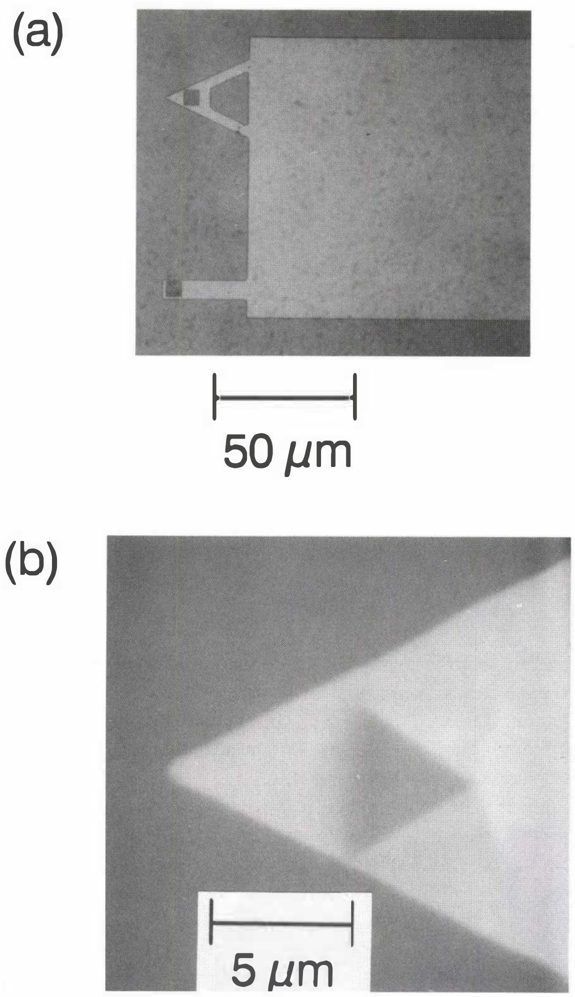

Fig.3.(a) Optical micrograph of cantilevers on the plated Cu support. (b) Scanning electron micrograph of pyramidal tip.

One of the difficulties in making cantilevers with pyramidal tips is that the tips end up on the wrong side; that is, they point toward the silicon support, which interferes with sample access. In commercial cantilevers, this problem is solved by anodically bonding the nitride layer to a glass substrate, then etching away the silicon support.[5] We have used a fairly straightforward alternative, in which we plated a thick film of copper onto the nitride at the base of the cantilevers, as shown in Fig. 4. This film then provided a suitably rigid support after the removal of the silicon.

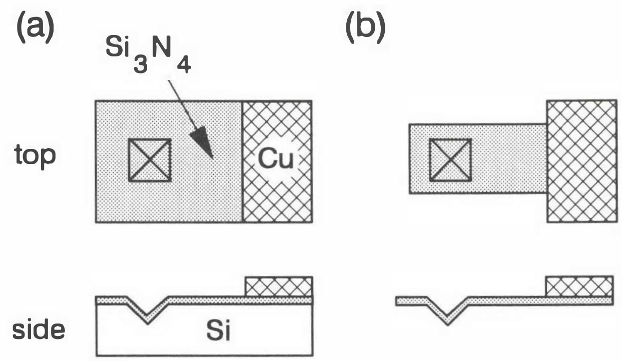

Fig. 4. (a) Formation of Si_3N_4 structure. The tip is formed by depositing onto a (111) etch pit in Si(100). A Cu backing layer is plated before removal of the Si. (b) A freestanding cantilever is formed upon removal of the Si. The 12 μm thick Cu film provides rigid support over its 0.5mm dimensions.

The vibrational noise spectrum of a weak cantilever shows a distinct peak at its resonant frequency due to its thermally-driven noise.[6, 7] On a closed triangular cantilever, we observed this peak at 1.3 MHz, in excellent agreement with the value of 1.35 MHz calculated for a cantilever without a tip. (We took the modulus E to be 1.6×10^{11}N/m^2 and density ρ to be 3300 kg/m^3.[5]) The spring constant k was calculated from the geometry to be 2 N/m. This can also be estimated from the amplitude and width of the thermal noise peak, using the fact that the integrated noise energy is of order k_BT.[6] With this method we obtained 3 N/m, in reasonable agreement. The rectangular cantilevers had calculated spring constants closer to the design point of 1 N/m, with frequencies at about 600 kHz. For comparison, the resonant frequency of a commercial cantilever is typically about 90 kHz with a spring constant of roughly 0.4 N/m.

Results and Discussion

The new cantilevers gave significantly enhanced performance, as shown in Fig. 5. A grooved glass disk was used as a test sample, where the groove width was 0.8 μm. In the upper trace, taken with the commercial cantilever, the basic groove periodicity was seen, along with some unwanted ringing, corresponding to higher order cantilever modes. With the new cantilevers, however, the tip cleanly tracked the surface without ringing, as shown in the lower trace.

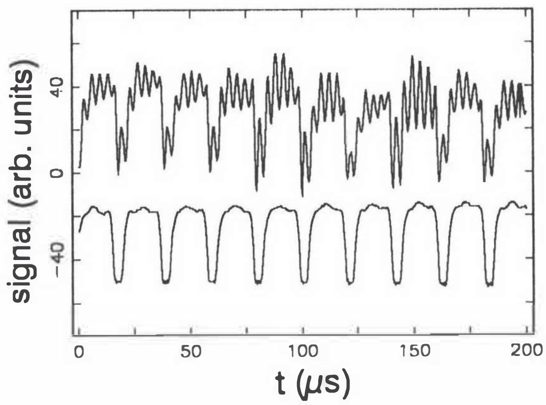

Fig. 5. Readback signal on a grooved glass test structure. Upper curve, obtained using a commercial cantilever, shows unwanted ringing, degrading signal-to-noise. Lower curve was obtained with a new low-mass cantilever, and gives an accurate representation of the surface topography.

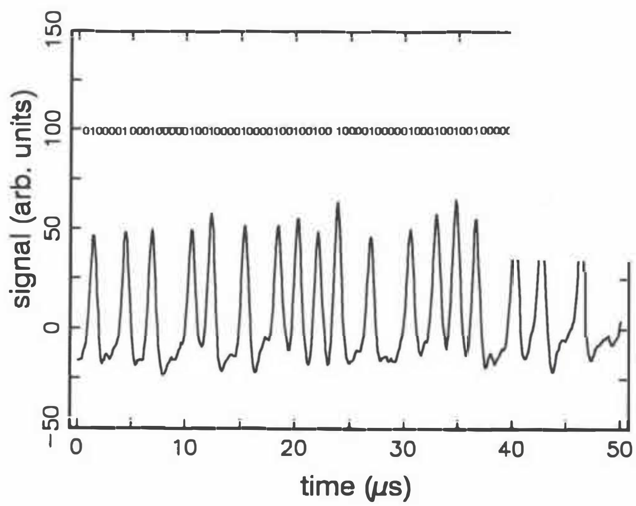

Fig. 7. Readback signal on data tracks shown above. The corresponding data pattern is shown above the waveform. The clock period is 0.6 μs, which with a rate 1/2 (2,7) code corresponds to a data rate of 830 kbit/s (Ref. 8) This data rate is nearly an order of magnitude higher than achieved with conventional cantilevers.

To measure the data rate, we first wrote a series of tracks containing known data patterns. The data are represented by the spacing between the pits, which varies as shown in Fig. 6. This data pattern was a pseudorandom 127 bit sequence of 1's and 0's which repeated. The writing was performed at a rate of about 200 kbit/s; its speed was limited by the thermal response time of the tip, currently about 5 μs.

The readback signal from a triangular cantilever on such a track is shown in Fig. 7, along with the corresponding data pattern. A 1 is seen above every peak in the waveform. The data rate from this waveform corresponds to 830 kbit/s. This is nearly an order of magnitude higher rate than was previously possible.

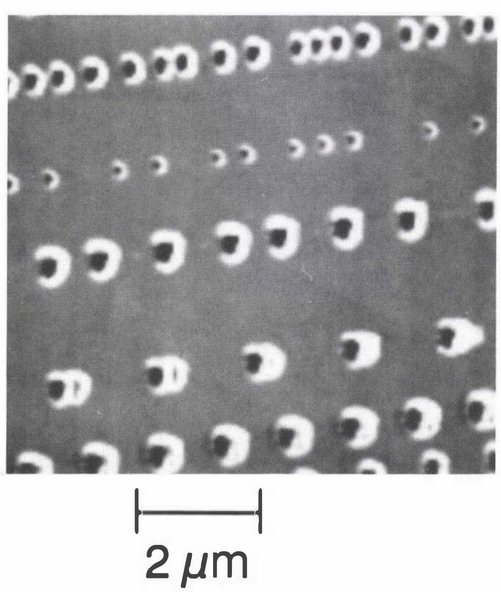

Fig. 6. AFM micrograph of tracks written thermomechanically on the rotating sample. Data are encoded by the spacing between the pits. Data are encoded using a (2,7) run-length limited code, meaning that there are between 2 and 7 0's between every 1.

We can use standard algorithms to detect the location of the peaks, and then characterize the readback in a number of ways. First, we can simply decode the peaks to get back to our original data, and compare to look for errors. We found that we typically got about 1-3 errors per 1000 bits, for a raw error rate of the order of 10^{-3}. This value is high by data storage standards, but is excellent for a scanning probe technique, and can be brought lower using standard error correction correction schemes.[8] We can also analyze how accurately the peaks are located in time or space to determine the jitter. Figure 8 shows a histogram of peak spacings for data read at 1.2 Mbit/s. Distinct histograms are observed at the expected spacings, with quite narrow widths, suggesting that somewhat higher density recording is possible. We note that the above data rate is equivalent to original CD-ROM rates.

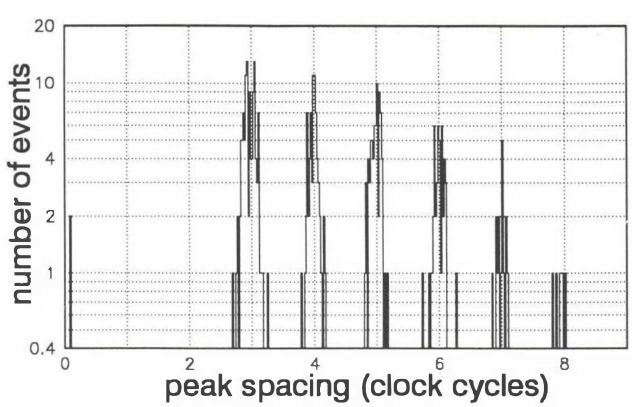

Fig. 8. Histogram of peak spacings for data read at 1.2 Mbit/s. The histograms are non-overlapping, indicating low timing jitter. One clock cycle corresponds to 0.6 μs.

Conclusion

We have shown that megahertz operation of a scanning-probe-based device is possible. We have furthermore used our device to store kilobytes of real data with few errors. Reducing the mass of the cantilevers was key to achieving these data rates, and further reduction in size will be needed to reach even higher data rates. Because we have not pushed the limits of micromachining, we expect that improvements of another order of magnitude may be possible. Beyond that, it is also possible in principle to fabricate arrays of levers to operate in parallel for higher data rate.

Acknowledgement

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