The “Millipede”–More than 1000 Tips for Parallel and Dense Data Storage

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SUMMARY

A MEMS-based AFM-array concept (“Millipede”) for data storage of potentially ultrahigh density, terabit capacity, and high data rate is presented. Thermomechanical writing and reading in very thin polymer films is used to store and sense 30-40-nm-sized bits with similar pitch size, resulting in 400-500 Gbit/in^2 storage densities. We have successfully batch-fabricated first all-silicon 32×32 AFM cantilever array chips. In addition, we have recently demonstrated time multiplexed parallel read/write operation with the array chip. Our 32×32 array chip is the first VLSI-NEMS (Nano ElectroMechanical System) for nano-technological applications.

Keywords: Scanning probe data storage, AFM array chips, thermomechanical write/read/erase.

INTRODUCTION

Atomic force microscopy (AFM)-based data storage is a promising alternative to conventional magnetic data storage because it offers great potential for considerable storage density improvements [1]. We have recently demonstrated storage densities of up to 500 Gbit/in^2 by thermomechanical writing and thermal readout in thin polymer films with bit sizes and pitches of 30-40 nm each [2]. This is about 10 times more than today's best research demonstrations for longitudinal magnetic recording [3]. The highest data rate achieved for AFM data storage with fast single levers is 6 Mbit/s [4], which cannot compete with existing technologies. However, with arrays of several hundreds to thousands of levers operating in parallel, the data rate for AFM data storage can be improved substantially. We have recently designed, developed, and fabricated a 32×32 (1024) two-dimensional (2D) cantilever array chip for parallel AFM applications. This chip, in conjunction with the 500 Gbit/in^2 storage density in a thin polymer medium, may be the basis of future high-data-rate, terabit storage devices.

Thermomechanical AFM Data Storage

Thermomechanical data storage [1,2,4–6] constitutes a particularly elegant implementation of an AFM storage scheme. Here a resistive cantilever tip is heated by current pulses. As a result, indentations representing data bits are formed by a combination of applying a local force to the polymer layer and softening it by local heating. Several issues are involved in this operation, including the spatial and temporal localization of the heat deposition as well as the melting and displacement of media to form data bits. We discovered that the heat transfer from the tip to the polymer through the small contact area is poor. Consequently, the tip must be heated to a relatively high temperature (≃400 °C, well above the melting temperature of the polymer) to initiate the indentation process.

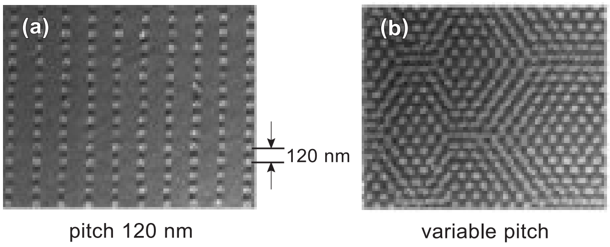

FIG. 1. *Series of 40-nm data bits formed in a uniform array with (a) 120 nm and (b) 40 nm pitch, resulting in bit areal densities of ≃400 Gbit/in^2. All images obtained with the thermal read-back technique. Adapted from [2].*

Using this technique, data bits 40 nm in diameter have been successfully written, as shown in Fig. 1, into a layered storage medium consisting of a Si substrate covered by a 70-nm-thick, crosslinked, hard-baked photoresist buffer layer and a 40-nm-thick PMMA film. The writing was performed using a 1-μm-thick, 70-μm-long, two-legged Si cantilever. The resistive heater region at the tip is formed by heavy-ion implantation of the cantilever legs with the lightly doped tip region masked off. The patterns were written by applying electrical pulses of 2 μs duration to the cantilever tip and repeating the process every 50 μs.
Imaging, viz. reading back of the data, is done using the heater of the cantilever as thermal sensor by exploiting its temperature-dependent resistance. The resistance increases roughly linearly with temperature by a factor of 3 from room temperature to 500 °C. Above 500°C the resistance drops as the number

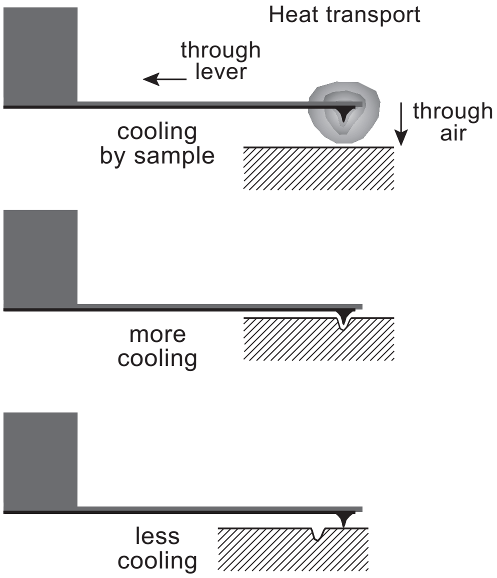

FIG. 2. *Principle of AFM thermal sensing. The tip of the heater cantilever is continuously heated by a DC power supply. From [8], © 1999 IEEE.*

of intrinsic carriers increases due to thermal excitation. For sensing, the resistor is operated at ≃350 °C. The principle of thermal sensing is based on the fact that the thermal conductance between the resistor and the storage substrate changes according to the spacing between them (Fig. 2).

In addition to ultra-dense thermo-mechanical writing and reading, erasing and rewriting capabilities of the polymer storage media have also been demonstrated. Thermal reflow of a storage field is achieved by heating the media to 150 °C for a few seconds. The smoothness of the reflown media allowed multiple rewriting of the same storage field [2].

Millipede Storage Concept

The 2D cantilever array concept [7], called Millipede, is illustrated in Fig. 3. It is based on an "en bloc" x/y scanning of either the array chip or storage media. In addition, a feedback-controlled z-approaching scheme brings the entire cantilever array into contact with the storage media. This contact is maintained and controlled while x/y scanning is performed for read/writing.

The Millipede concept does not employ individual height control for each lever, but instead relies on global feedback for the entire chip, which greatly simplifies the system. However, this requires excellent uniformity of tip height and accurate control of lever bending.

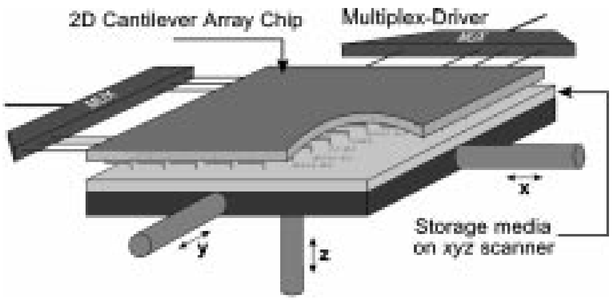

FIG. 3. *Millipede concept. From [8], © 1999 IEEE.*

The basic Millipede concept entails a time multiplexing scheme for addressing the array in a row-by-row fashion, similar as for DRAMs. Furthermore, the storage media is divided into 32×32 storage subfields with the size of the pitch between two cantilevers, and each cantilever reads and writes only in its own subfield. Hence, for operation of the Millipede, position tolerances of the tips relative to each other are insignificant.

MEMS-Based AFM Array Chip

The Millipede chip consists of 32×32 sensor cells (Fig. 4) arranged in a square pattern and interconnected in a crossbar architecture. The cell area and x/y cantilever pitch is 92×92 μm^2, which results in a total array size of less than 3×3 mm^2 for the 1024 cantilevers. The cantilevers are made entirely of silicon for good thermal and mechanical stability. They consist of a heater platform with a tip on top, and legs acting as a mechanical spring and electrical connections (made of highly doped Si) to the heater.

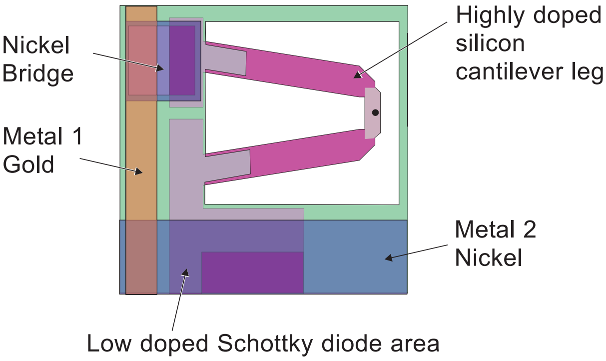

FIG. 4. *Cantilever cell layout. From [8], © 1999 IEEE.*

On the lever, no metal wiring was used in order to eliminate electromigration and parasitic z-actuation of the lever due to a bimorph effect. The resistive ratio between the heater and the silicon interconnect sections should be as high as possible; currently the highly doped interconnections are 400 Ω and the heater platform is 6 kΩ. Sensor dimensions are: 50-μm-long, 10-μm-wide and 0.5-μm-thick legs, and a 5-μm-wide, 10-μm-long and 0.5-μm-thick platform. Such a cantilever has a stiffness of 1 N/m and a resonant frequency of 200 kHz. The heater time constant is about 1 μs, which should allow a multiplexing rate of 100 kHz. Figure 5 shows the fabricated chip with the 32×32 array in the center and the electrical wiring connecting the array with the bonding pads. Details of the chip fabrication are described in [8].

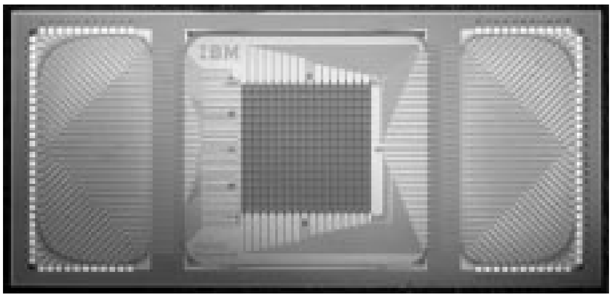

FIG. 5. *Photograph of the fabricated chip (14×7 mm^2). The 32×32 cantilever array is located at the center and the bond pads are distributed on either side. From [8], © 1999 IEEE.*

First Write/Read Results with the 32×32 Array Chip

The experimental system is based on the basic concept as shown in Fig. 3. A 3×3 mm^2 silicon substrate is spin-coated with the SU-8/PMMA polymer medium structure described above. This storage medium is attached to a small magnetic $x/y/z$ scanner and approaching device. The three magnetic z-approaching actuators bring the medium into contact with the tips of the array chip. The z-distance between the medium and the Millipede chip is controlled by the approaching sensors (additional cantilevers) in the corners of the array. The signals from these cantilevers are used to determine the forces on the z-actuators and, hence, also the forces of the cantilever while it is in contact with the medium. This sensing/actuation feedback loop continues to operate during x/y scanning of the medium. The PC-controlled write/read scheme addresses the 32 cantilevers of one row in parallel.

The results of writing and reading in this fashion can be seen in Fig. 6, which shows 1024 images written by the levers then read back. Of the 1024 levers, 834 were able to write and read back data, which is more than 80%. The sequence is as follows. First a bit pattern is written to each of the levers in row 1 simultaneously then read back simultaneously, followed by row 2 etc. until row 32. The images sent to the levers are different, each lever writing its own row and column number in the array. The bit pattern is 64×64 bits, but odd bits are always 0. In this case the area used is 6.5×6.5 μm^2. The image read back is a gray-scale bit map of 128×128 pixels. The interlever distance is 92 μm so the images in Fig. 6 are also 92 μm apart. A working storage system would fill the entire space between levers with data.

Those levers that did not read back failed for one of four reasons: (i) a defective chip connector like that in column 25 made that column unusable, (ii) a point defect occurred, meaning that a single lever or tip is broken, (iii) nonuniformity of the tip contact due to tip/lever variability or storage substrate bowing due to mounting, (iv) thermal drifts, with the latter two being the most likely and major sources.

At present, there is clearly a tradeoff between the number of working levers and the density, which will most likely be resolved by a better substrate/chip mounting technique and lower thermal drifts.

The writing and readback rates achieved with this system are 1 Kb/s per lever, thus the total data rate is about 32 Kb/s. This rate is limited by the rate at which data can be transferred over the PC ISA bus, not by a fundamental part of the read/write process. For more details on the system, fabrication, and operating aspects, see [8–10].

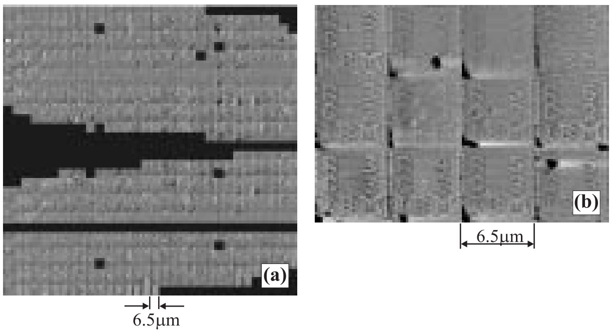

FIG. 6. *(a) 1024 images, one from each lever at 15–30 Gb/in^2. (b) Enlarged view of typical images from (a). The numbers in the images indicate the row and column of each lever. From [10].*

CONCLUSION AND OUTLOOK

In conclusion, a very large 2D array of local probes have been operated for the first time in a semi-parallel fashion, and write/read storage operation in a thin polymer medium has been successfully demonstrated at densities at or significantly higher than those achieved with magnetic storage systems. Densities and yield of operation achieved with this first demo are very encouraging, although considerable improvements are possible in both areas. Storage densities comparable to or higher than the 400 Gb/in^2 demonstrated with single levers [2] will be possible, whereas the high operating yield confirms the concept of global array approaching. Faster electronics will allow the levers to be operated at higher rates. The system needs to reach 60 Mb/s to be useful for video applications, for example, which with 32 levers working in parallel would mean 2 Mb/s per lever. With integrated electronics beside each lever all 1024 could be operated in true parallel fashion, allowing the rate per lever to drop to 60 Kb/s.
Although we have demonstrated the first high-density storage operations with the largest 2D AFM array chip ever built, there are a number of issues to be addressed before the Millipede can be considered for commercial applications, just a few of which are mentioned here:

- Overall system reliability, including bit stability, tip and medium wear, erasing/rewriting.
- Limits of data rate (S/N ratio), areal density, array and cantilever size.
- CMOS integration.
- Optimization of write/read multiplexing scheme.
- Array-chip tracking.

Our near-term future activities are focused on these important aspects.

SUMMARY

The Millipede AFM storage concept provides a possible roadmap towards future terabit storage systems. Storage densities of up to 500 Gbit/in^2 have been realized by thermo-mechanical writing and readback in thin polymer (PMMA) film media. We have fabricated the densest and largest 2D AFM cantilever array chip with 32×32 (1024) cantilevers on only 3×3 mm^2. This constitutes a major step towards future ultrahigh density, high-data-rate storage systems with a potential capacity far beyond that of today's magnetic recording approaches. The Millipede concept presented here focuses on a polymer storage media, but the concept may be expanded to other media, provided suitable read/write functionality can be integrated into cantilevers and tips.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge R. Beyeler, G. Genolet, R. Germann, and P.F. Seidler for their technical contributions, stimulating discussions, and encouraging support.

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