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The Millipede, a MEMS-based Scanning-Probe Data-Storage System

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"Millipede": a MEMS-based Scanning-Probe Data-Storage System

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***Abstract*—Ultrahigh storage densities of up to 1 Tbit/in.^{2} or more can be achieved by local-probe techniques to write, read back, and erase data in very thin polymer films. The thermo-mechanical scanning-probe-based data-storage concept called Millipede combines ultrahigh density, small form factor, and high data rate. After illustrating the principles of operation of the Millipede, we introduce system aspects related to the read-back process, multiplexing, and position-error-signal generation for tracking.**

I. INTRODUCTION

Techniques that use nanometer-sharp tips for imaging and investigating the structure of materials down to the atomic scale, such as the atomic force microscope (AFM) and the scanning tunneling microscope (STM) [1,2], are suitable for the development of ultrahigh density storage devices [3–9]. As the simple tip is a very reliable tool for the ultimate local confinement of interaction, tip-based storage technologies appear as natural candidates for extending the physical limits that are being approached by conventional magnetic storage. Areal densities achievable by today's magnetic recording technologies are limited to about 150 ~ 200 Gbit/in.^{2} by the well-known superparamagnetic effects. On the other hand, data rates well above 800 Mbit/s are achieved by magnetic recording, whereas the mechanical resonant frequencies of the AFM cantilevers limit the data rates of a single cantilever to a few Mbit/s for AFM data storage. The solution for substantially increasing the data rates achieved by tip-based storage devices is to employ arrays of cantilevers operating in parallel, with each cantilever performing read/write/erase operations over an individual storage field [6–9].

The "Millipede" concept, as described in [6–9], for the realization of highly parallel scanning-probe data storage, has demonstrated areal densities up to 1 Tbit/in.^{2} with a single cantilever, and parallel operation of very large two-dimensional (32×32) AFM cantilever arrays with integrated tips and write/read functionality. The Millipede device shown in Fig. 1 is a highly parallel scanning-probe data-storage system, in which information is stored as sequences of "indentations" and "no indentations" written into approx. 50-nm-thick polymer films using an array of AFM cantilevers. Each cantilever performs write/read operations over an individual storage field with size of the order of 100×100 μm^2. Thermomechanical writing is obtained by applying a local force by the cantilever/tip to the polymer layer, and simultaneously softening the polymer layer by local heating. Fig. 2a shows data bits of 40 nm in diameter that have been written using a 1-μm thick, 70-μm long, two-legged Si cantilever, whose legs are made highly conducting by high-ion implantation, while the heater region remains low-doped. Fig. 2b shows that 40-nm bits can be written very close to each other without merging, implying a potential storage areal density of the order of 400 Gbit/in.^{2}. More recently single-cantilever areal densities up to 1 Tbit/in.^{2} have been demonstrated, although currently at a somewhat degraded write/read quality, as illustrated in Fig. 2c.

To read the written information, the heater cantilever originally used for writing is given the additional function of a thermal readback sensor by exploiting its temperature-dependent resistance. The principle of thermal sensing is based on the fact that the thermal conductance between heater platform and storage substrate changes according to the distance between them. Therefore, during the read process, the cantilever resistance reaches different values depending on whether it moves over an *indentation* ("1") or a *no indentation* ("0").

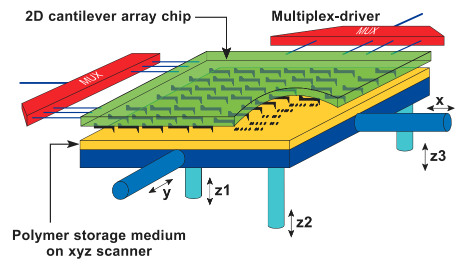

Fig. 1. Illustration of the Millipede concept. From [9].

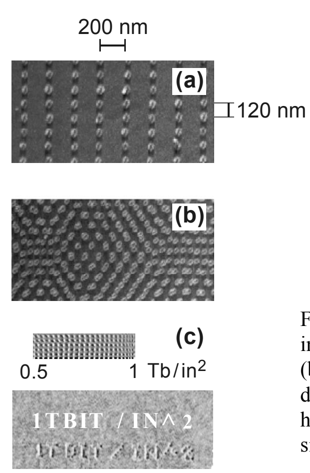

Fig. 2. Series of 40-nm data bits formed in a uniform array with (a) 120-nm and (b) variable pitch, resulting in bit areal densities of up to 400 Gb/in.^{2}. (c) Ultra-high-density bit writing with areal densities approaching 1 Tb/in.^{2}. From [7].

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II. System Aspects

The thermomechanical cantilever sensor, which transforms temperature into an electrical signal that carries information, is electrically equivalent, to a first degree of approximation, to a variable resistance [8]. The detection circuit must therefore sense a voltage that depends on the cantilever resistance value to decide whether a "1" or a "0" is written. The relative variation of thermal resistance is of the order of 10^{-5}/nm: a written bit "1" typically produces a relative change of the cantilever thermal resistance $\Delta R^{\Theta}/R^{\Theta}$ of about $10^{-4} \sim 5{\times}10^{-4}$. Note that the relative change of the cantilever electrical resistance is of the same order of magnitude. Thus, one of the most critical issues in detecting the presence or absence of an "indentation" is the high resolution required to extract the signal that contains the information about the bit being "1" or "0". The signal carrying the information can be viewed as a small signal superimposed to a very large offset signal [8].

Each cantilever can write data to and read data from a dedicated area of the polymer substrate, called a *storage field*. In each storage field, the presence (absence) of an indentation corresponds to a logical "1" ("0"). All indentations, also called *pits*, are nominally of equal depth and size, and placed at a fixed horizontal distance from each other along a data track. We refer to this distance, measured from pit center to pit center, as the *bit pitch*. The vertical (cross-track) distance between pit centers, the *track pitch*, is also fixed. To read and write data the polymer medium is moved under the (stationary) cantilever array at a constant velocity. Efficient parallel operation of large two-dimensional arrays can be achieved by a row/column time-multiplexed addressing scheme similar to that implemented in DRAMs. In the Millipede, the multiplexing scheme is used to address the array column by column with full parallel write/read operation within one column [6–9]. In particular, readback signal samples are obtained by applying a read pulse to the cantilevers in a column of the array, low-pass filtering the cantilever response signals, and sampling the filter output signals. Alternatively, maximum data rate can be achieved by full parallel operation, in which all cantilevers are accessed simultaneously. This maximum rate depends on the duration of the applied pulse and the scanner velocity.

With bits as closely spaced as in the Millipede, accurate tracking becomes a critical issue. Tracking amounts to controlling the position of each tip such that it is always positioned over the center of each written track during reading. During writing, the tip position should be such that the written bits are aligned with each other in a predefined way. In electro-mechanical systems, tracking is performed through a servo loop driven by an appropriate error signal. Ideally, the magnitude of this error signal is a direct estimate of the vertical (cross-track) distance of the tip from the track centerline, and its polarity indicates the direction of this offset. As in magnetic and optical storage, the position-error signal (PES) in AFM-based storage indicates the deviation of the sensing element from its ideal position on a track. PES generation is a process that strongly depends on the storage system under consideration, especially on how information readout is performed. Reliable tracking in AFM-based storage is achieved by dedicated storage fields for storing servo information, called servo fields to differentiate them from data fields storing user information. Fig. 3 shows an image with A, B, C, and D servo bursts written by a single cantilever.

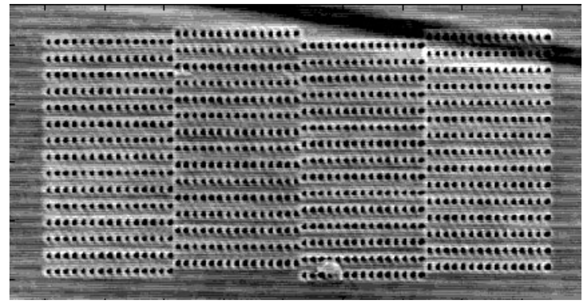

Fig. 3. A, B, C, D servo bursts. Track pitch and bit pitch set to 84 nm.

III. Conclusion

The Millipede has the potential to achieve ultrahigh storage areal densities of the order of 1 Tbit/in.^{2}. The high areal storage density, small form factor, and low power consumption make Millipede very attractive as a candidate future storage technology for mobile applications, offering several Gigabyte capacity at data rates of several Megabytes per second. Dedicated servo fields allow reliable system operation with a very small overhead.

IV. Acknowledgments

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