THERMOMECHANICAL DATA STORAGE

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ABSTRACT

In the future, the current method of magnetically storing data may reach its limit of maximum achievable density. Hence we need a data storage technology which has high storage capacity and is small in size. The solution is Thermomechanical data storage. Thermomechanical Data Storage is a data storage scheme in which nanometer sized pits on a plastic disc represent digital data. This data storage concept combines ultrahigh density, terabit capacity, small form factor and high data rates. By using this concept, we will be able to store the equivalent of 25 DVDs on a surface the size of a postage stamp. IBM scientists have demonstrated a data storage density of a trillion bits per square inch - 20 times higher than the densest magnetic storage available today. IBM achieved this remarkable density -- enough to store 25 million printed textbook pages on a surface the size of a postage stamp -- in a research project code-named "Millipede". Millipede uses thousands of nano-sharp tips to punch indentations representing individual bits into a thin plastic film. The result is akin to a nanotech version of the venerable data processing 'punch card' developed more than 110 years ago, but with two crucial differences: the 'Millipede' technology is re-writeable, and may be able to store more than 3 billion bits its of data in the space occupied by just one hole in a standard punch card.
LIST OF SYMBOLS AND ABBREVIATIONS

PMMA- POLY METHYLENE METHACRYLATE
SI- SILICON
AFM- ATOMIC FORCE MICROSCOPY
IBM- INTERNATIONAL BUSINESS MACHINE
SOE- SCHOOL OF ENGINEERING
CUSAT- COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
1. INTRODUCTION

In the 21st century, the nanometer will very likely play a role similar to the one played by the micrometer in the 20th century. The nanometer scale will presumably pervade the field of data storage. In magnetic storage today, there is no clear-cut way to achieve the nanometer scale in all three dimensions. The basis for storage in the 21st century might still be magnetism. Within a few years, however, magnetic storage technology will arrive at a stage of its exciting and successful evolution at which fundamental changes are likely to occur when current storage technology hits the well-known superparamagnetic limit. Several ideas have been proposed on how to overcome this limit. One such proposal involves the use of patterned magnetic media. Other proposals call for totally different media and techniques such as local probes or holographic methods. Similarly, consider Optical lithography. Although still the predominant technology, it will soon reach its fundamental limits and be replaced by a technology yet unknown. In general, if an existing technology reaches its limits in the course of its evolution and new alternatives are emerging in parallel, two things usually happen: First, the existing and well-established technology will be explored further and everything possible done to push its limits to take maximum advantage of the considerable investments made. Then, when the possibilities for improvements have been exhausted, the technology may still survive for certain niche applications, but the emerging technology will take over, opening up new perspectives and new directions.

Today we are witnessing in many fields the transition from structures of the micrometer scale to those of the nanometer scale, a dimension at which nature has long been building the finest devices with a high degree of local functionality. Many of the technologies we use today are not suitable for the
coming nanometer age; some will require minor or major modifications, and others will be partially or entirely replaced. It is certainly difficult to predict which techniques will fall into which category. For key areas in information-technology hardware it is not yet obvious which technology and materials will be used for nanoelectronics and data storage.

In any case, an emerging technology being considered as a serious candidate to replace an existing but limited technology must offer long-term perspectives. For instance, the silicon microelectronics and storage industries are huge and require correspondingly enormous investments, which makes them long-term oriented by nature. The consequence for storage is that any new technique with better areal storage density than today’s magnetic recording should have long term potential for further scaling, desirably down to the nanometer or even atomic scale.

The only available tool known today that is simple and yet provides these very long term perspectives is a nanometer sharp tip. Such tips are now being used in every atomic force microscope (AFM) and scanning tunneling microscope (STM) for imaging and structuring down to the atomic scale. The simple tip is a very reliable tool that concentrates on one functionality: the ultimate local confinement of interaction.

In the early 90's, Mamin and Rugar at the IBM Almaden Research Center pioneered the possibility of using an AFM tip for read back and writing of topographic features for the purposes of data storage. In one scheme developed by them, reading and writing were demonstrated with a single AFM tip in contact with a rotating polycarbonate substrate. The writing was done thermomechanically via heating of the tip. In this way, storage densities of up to 30Gb/in$^2$ were achieved, representing a significant advance compared to the densities of that day. Later refinements included increasing readback speeds up to a data rate of 10 Mb/s, and implementation of track servoing.
In making use of single tips in AFM or STM operation for storage, one has to deal with their fundamental limits for high data rates. The mechanical resonant frequencies of the AFM cantilevers limit the data rates of a single cantilever to a few Mb/s for AFM data storage, and the feedback speed and low tunneling currents limit STM-based storage & approaches to even lower data rates. Currently a single AFM operates at best on the microsecond time scale. Conventional magnetic storage, however, operates at best on the nanosecond time scale, making it clear that AFM data rates have to be improved by at least three orders of magnitudes to be competitive with current and future magnetic recording. Later, it was found that by operating the AFM tips in parallel, data storage with areal storage densities far beyond the expected superparamagnetic limit (~100 Gb/in$^2$) and data rates comparable to those of today's magnetic recording can be achieved.

The "Millipede" concept which will be discussed here is a new approach for storing data at high speed and with an ultrahigh density. It is not a modification of an existing storage technology, although the use of magnetic materials as storage medium is not excluded. The ultimate locality is given by a tip, and high data rates are a result of massive parallel operation of such tips. Using this Millipede concept areal densities up to 0.5-1 Tb/in$^2$ can be achieved by the parallel operation of very large 2D (32 x 32) AFM cantilever arrays with integrated tips and write/read storage functionality.

The fabrication and integration of such a large number of mechanical devices (cantilever beams) will lead to what we envision as the VLSI age of micro/nanomechanics. It is our conviction that VLSI micro/nanomechanics will greatly complement future micro and nanoelectronics (integrated or hybrid) and may generate applications of VLSI-MEMS (VLSI-MicroElectroMechanical Systems) not conceived of today.
2. THERMOMECHANICAL AFM DATA STORAGE

In recent years, AFM thermomechanical recording in polymer storage media has undergone extensive modifications mainly with respect to the integration of sensors and heaters designed to enhance simplicity and to increase data rate and storage density. Using these heater cantilevers, high storage density and data rates have been achieved. Let us now describe the storage operations in detail.

2.1. DATA WRITING

Thermomechanical writing is a combination of applying a local force by the cantilever-tip to the polymer layer, and softening it by local heating. Initially, the heat transfer from the tip to the polymer through the small contact area is very poor and improves as the contact area increases. This means the tip must be heated to a relatively high temperature (about 400°C) to initiate the softening. Once softening has commenced, the tip is pressed into the polymer, which increases the heat transfer to the polymer, increases the volume of softened polymer, and hence increases the bit size. Our rough estimates indicate that at the beginning of the writing process only about 0.2% of the heating power is used in the very small contact zone (10-40 nm²) to soften the polymer locally, whereas about 80% is lost through the cantilever legs to the chip body and about 20% is radiated from the heater platform through the air gap to the medium/substrate. After softening has started and the contact area has increased, the heating power available for generating the indentations increases by at least ten times to become 2% or more of the total heating power.
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With this highly nonlinear heat transfer mechanism it is very difficult to achieve small tip penetration and hence small bit sizes as well as to control and reproduce the thermomechanical writing process. This situation can be improved if the thermal conductivity of the substrate is increased, and if the depth of tip penetration is limited. These characteristics can be improved by the use of very thin polymer layers deposited on Si substrates as shown in figure 1. The hard Si substrate prevents the tip from penetrating farther than the film thickness, and it enables more rapid transport of heat away from the heated region, as Si is a much better conductor of heat than the polymer. By coating Si substrates with a 40-nm film of polymethylmethacrylate (PMMA) bit sizes ranging between 10 and 50 nm is achieved. However, this causes increased tip wear, probably caused by the contact between Si tip and Si substrate during writing. Therefore a 70-nm layer of cross linked photoresist (SU-8) was introduced between the Si substrate and the PMMA film to act as a softer penetration stop that avoids tip wear, but remains thermally stable.

Fig.1: Principle of data writing. A combination of tip heating to soften the polymer and the pressure exerted by the tip to sink into the polymer, and write a bit.
Using this layered storage medium, data bits 40 nm in diameter have been written as shown in Fig. 2. These results were performed using a 1-µm-thick, 70-µm-long, two-legged Si cantilever. The cantilever legs are made highly conducting by high-dose ion implantation, whereas the heater region remains low-doped. Electrical pulses 2 µs in duration were applied to the cantilever with a period of 50 µs. Figure 2a demonstrates that 40-nm bits can be written with 120-nm pitch or very close to each other without merging (Fig. 2b), implying a potential bit areal density of 400 Gb/in². By using a single cantilever areal densities up to 1 Tb/in² has been achieved as illustrated in Fig. 2c.
2.2 DATA READING

Imaging and reading are done using a new thermomechanical sensing concept. The heater cantilever originally used only for writing was given the additional function of a thermal readback sensor by exploiting its temperature-dependent resistance. The resistance (R) increases nonlinearly with heating power/temperature from room temperature to a peak value of 500-7000°C. The peak temperature is determined by the doping concentration of the heater platform, which ranges from $1 \times 10^{17}$ to $2 \times 10^{18}$. Above the peak temperature, the resistance drops as the number of intrinsic carriers increases because of thermal excitation. For sensing, the resistor is operated at about 350°C, a temperature that is not high enough to soften the polymer as is the case for writing. The principle of thermal sensing is based on the fact that the thermal conductance between the heater platform and the storage substrate changes according to the distance between them. The medium between a cantilever and the storage substrate—in our case air—transports heat from one side to the other. When the distance between heater and sample is reduced as the tip moves into a bit indentation, the heat transport through air will be more efficient, and the heater's temperature and hence its resistance will decrease. Thus, changes in temperature of the continuously heated resistor are monitored while the cantilever is scanned over data bits, providing a means of detecting the bits. Figure 3 illustrates this concept.
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Fig. 3: Principle of AFM thermal sensing. The tip of the heater cantilever is continuously heated by a dc power supply while the cantilever is being scanned and the heater resistivity measured.

Under typical operating conditions, the sensitivity of thermomechanical sensing is even better than that of piezoresistive-strain sensing, which is not surprising because thermal effects in semiconductors are stronger than strain effects. The good $\Delta R/R \sim 10^{-5}$/nm is demonstrated by tile images of the 40 nm size bit indentations in Fig. 2 which have been obtained using the described thermal-sensing technique.

The data erasing operation will be discussed while explaining the polymer material used as the storage medium.
3. THE MILLIPEDE CONCEPT

The 2D AFM cantilever array storage technique called "Millipede" is illustrated in Fig. 4.

Millipede uses thousands of nano-sharp tips to punch indentations representing individual bits into a thin plastic film.

![Millipede Concept Diagram](image)

Millipede is comprised of two postage stamp sized chips – a stationary chip and a movable chip as shown in figure 5. The stationary chip is an array of read/write probes. From above, each probe looks like a rounded “v”, is attached by its arms, and has a point at the end like a phonograph needle. The chip also contains read and write circuits for probe tips, position sensors, permanent magnets, and coils. The sensors, magnets, and coils are part of the electromagnetic actuator circuits that move the second chip in the x,y,z and tilt directions.
Fig. 5: A section of IBM Millipede MEMS based storage chips

The movable chip is the storage medium. The electromagnetic actuators move the storage medium over the stationary medium, which contains the cantilevers for write/read operations, in x and y directions. The storage area looks like a 32x32 checkerboard where a square in the checkerboard contains a million bits. Each probe reads and writes only in its square.

Millipede is based on a mechanical parallel x/y scanning of either the entire cantilever array chip or the storage medium. In addition, a feedback-controlled z-approaching and
leveling scheme brings the entire cantilever array chip into contact with the storage medium. This tip-medium contact is maintained and controlled while x/y scanning is performed for write/read. It is important to note that the Millipede approach is not based on individual z-feedback for each cantilever; rather, it uses a feedback control for the entire chip, which greatly simplifies the system. However, this requires very good control and uniformity of tip height and cantilever bending. Chip approach/leveling makes use of additionally integrated approaching cantilever sensors in the corners of the array chip to control the approach of the chip to the storage medium. Signals from these sensors provide feedback signals to adjust the z-actuators until contact with the medium is established. The system operates similarly to an antivibration table. Feedback loops maintain the chip leveled and in contact with the surface while x/y scanning is performed for write/read operations. This basic concept of the entire chip approach/leveling has been tested and demonstrated for the first time by parallel imaging with a 5x5 array chip. These parallel imaging results have shown that all 25 cantilever tips have approached the substrate within less than 1 µm of z-activation. This promising result convinced us that chips tip-apex height control of less than 500 nm is feasible. This stringent requirement for tip-apex uniformity over the entire chip is determined by the uniform force required to minimize/eliminate tip and medium wear due to large force variations resulting from large tip-height nonuniformities.

During the storage operation, the chip is raster-scanned over an area called the storage field by a magnetic x/y scanner. The scanning distance is equivalent to the cantilever x/y pitch, which is currently 92 pm. Each cantilever/tip of the array writes and reads data only in its own storage field. This eliminates the need for lateral positioning adjustments of the tip to offset lateral position tolerances in tip fabrication. Consequently, a 32x32 array chip will generate 32x32 (1024) storage fields on an area of less than 3x3 mm². Assuming an areal density of 500 Gb/in², one storage field of 92x92 µm² has a capacity of 0.875 MB and the entire 32x32 array with 1024 storage fields has a capacity
of 0.9 GB 3 x 3 mm$^2$. The storage capacity of the system scales with the areal density, the cantilever pitch (storage-field size), and the number of cantilevers in the array. Although not yet investigated in detail, lateral tracking will also be performed for the entire chip with integrated tracking sensors at the chip periphery. This assumes and requires very good temperature control of the array chip and the medium substrate between write and read cycles. For this reason the array chip and medium substrate should be held within about 1°C operating temperature for bit sizes of 30 to 40 nm and array chip sizes of a few millimeters. This will be achieved by using the same material (silicon) for both the array chip and the medium substrate in conjunction with four integrated heat sensors that control four heaters on the chip to maintain a constant array chip temperature during operation. True parallel operation of large 2D arrays results in very large chip sizes because of the space required for the individual write/read wiring to each cantilever and the many I/O pads. The row/column time-multiplexing addressing scheme implemented successfully in every DRAM is a very elegant solution to this issue. In the case of Millipede, the time-multiplexed addressing scheme is used to address the array row by row with full parallel write/read operation within one row.

The current Millipede storage approach is based on a new thermomechanical write/read process in nanometer thick polymer films, but thermomechanical writing in polycarbonate films and optical readback was first investigated and demonstrated by Mamin and Rugar. Although the storage density of 30 Gb/in.2 obtained originally was not overwhelming, the results encouraged us to use polymer films as well to achieve density improvements.
4. CANTILEVER DESIGN AND FABRICATION

The cantilever chip (see Fig. 6) consists of a chip body with large metal pads for electrical contact, thick and mechanically stiff cantilever legs, and the thin cantilever itself, which corresponds to a cantilever as found in a Millipede array. The main part that influences power consumption and data rate of the cantilever is the heater / tip area. For this study, the heater dimensions as well as those of the two thermal constrictions on both heater sides will be varied. The thick legs allow some clearance to the chip body to facilitate the approaching procedure as well as a well-defined cantilever anchor position. Their stiffness is 30 times that of the cantilever, thus they are considered a perfect anchor.

The entire cantilever structure consists of monocrystalline silicon, ensuring thermal and mechanical stability, which is crucial for a cantilever used for thermomechanical writing / reading.
Fig. 6 (a) Schema of the thermomechanical lever chip showing the various device parts as well as the border between the regions patterned with optical and e-beam lithography. (b) SEM image of a typical cantilever.

The border between the two types of lithography is between the thick legs and the thin cantilever, as shown in Fig. 6 a: the thick lever parts, the metal pads and chip delineation were made using optical lithography, whereas the tip, the thin cantilever and the heater were made using e-beam lithography. A scanning electron microscope (SEM) image of a finished chip is shown in Fig. 6 b. For the alignment between heater and tip, a strategy of local alignment at each cantilever cell has been used. Note that the small size of the lever structure allows its fabrication in one e-beam writing field (200 µm), eliminating the stitching issue. Heaters with dimensions ranging from 200 nm to 3 mm with different constriction lengths have been designed. Because the structures made with e-beam represent only a small fraction of the wafer area, negative-tone ma-N 2410 resist from Microresist Technology has been used. Achievable resist thicknesses range from 0.8 to 1.5 µm, which is suitable for pattern transfer with dry etching as well as masking for dopant implantation, and still allows fine structuring. The e-beam lithography was carried out at 10 kV.
Fig. 7. Process flow chart showing a cross section of the basic cantilever processing steps.

Fig. 7 describes the process used for the cantilever fabrication. The starting substrate is a 4-inch silicon on insulator (SOI) wafer with a 1.5-μm thick epitaxial grown n-doped silicon membrane and a 0.4-μm thick buried oxide (BOX). The membrane is doped with phosphorous at a concentration of 5x10^{17} at/cm^3, which is the doping required for the heater platform. The first step consists of thermally growing a 700-nm layer of oxide (Fig. 7a), which is later used as mask material when etching the thick legs and the tip. Then an optical lithography step is performed, and the pattern transferred into half of the oxide thickness by CHF–O–based reactive ion etching (RIE) to delineate the thick lever part (Fig. 7b) and the alignment marks needed for the optical and e-beam lithography steps. Next, the first e-beam lithography is performed (Fig. 7c) to delineate the 2-μm diameter tip mask, and the mask is transferred into the remaining half of the oxide thickness using the same RIE process as before. Note that this also thins the oxide film on the thick lever part, and that, at this stage, the masks for both the tip and the thick legs consist of a 350-nm thick oxide film. Alignment is done by first using the global and then the local alignment marks at each cantilever writing field with structures made in Step 7b.
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The silicon tip is etched by an isotropic SF₆–Ar RIE process (Fig. 7d). An oxidation sharpening technique is used to finalize the tip shape (Fig. 7e). With this technique, tip apex radii can be achieved that are well below 20 nm. Then the lever part is patterned by e-beam lithography and transferred into the remaining silicon membrane using an anisotropic SF₆–C₄F₈ based RIE process (Fig. 7f). A 50-nm thick capping oxide layer is thermally grown, and the implantation mask is patterned using e-beam lithography. The resist mask protects the heater zone during the 80-keV, 1x10¹⁶ ions/cm² phosphorous implantation (Fig. 7g). Dopant activation is performed with a 1150°C, 20 s heating pulse, using a rapid thermal annealing system. Such a high-temperature, short-time pulse provides good dopant activation without significantly broadening the implantation zone by lateral dopant diffusion, which is crucial to prevent heater-length shortening. Once the thin capping oxide has been wet-etched, the metal pads are structured using a lift-off technique (Fig. 7h). Prior to etching the back side of the chip body, the front side is protected with resist. A deep reactive-ion-etching (DRIE) system is used to etch through the wafer thickness with the BOX as etch stop. Next the BOX is wet-etched (Fig. 7i). Finally the protection of the resist front side is removed using a solvent-based stripper (Fig. 7j). Fabricated cantilevers are 50 µm long and 100 nm thick, corresponding to a resonant frequency of 86 kHz and a spring constant of 10 mN/ m. Fig. 8 shows close-ups of the heater / tip area of different design as well as a high magnification view of a tip. The heater / constriction width ranges from 180 nm to 3 mm, and the tip–heater alignment accuracy is about 50 nm.
Fig. 8: SEM close up views of the cantilever tip/heater zone (a to e). Heater width and thermal constriction length have been varied. A detail view of the tip is also shown (f).

5. ARRAY DESIGN, TECHNOLOGY, FABRICATION.

After the cantilevers have been fabricated, they have to be arranged in an array for parallel operation. This process is explained here: Cantilevers are released from the crystalline Si substrate by surface micromachining using either plasma or wet chemical etching to form a cavity underneath the cantilever. Compared to a bulk-micromachined through wafer cantilever-release process as done for our 5 x 5 array, the surface micromachining technique allows an even higher array density and yields better mechanical chip stability and heat sinking. As the Millipede tracks the entire array without individual lateral cantilever positioning, thermal expansion of the array chip
Thermomechanical data storage has to be small or well controlled. Because of thermal chip expansion, the lateral tip position must be controlled with better precision than the bit size, which requires array dimensions as small as possible and a well-controlled chip temperature. For a 3x3 mm$^2$ silicon array area and 10-nm tip-position accuracy, the chip temperature has to be controlled to about 1°C. This is ensured by four temperature sensors in the corners of the array and heater elements on each side of the array. Thermal expansion considerations were a strong argument for the 2D array arrangement instead of 1D, which would have made the chip 32 times longer for the same number of cantilevers.

The photograph in Fig. 9 shows a fabricated chip with the 32 x 32 array located in the center (3x 3 mm$^2$) and the electrical wiring interconnecting the array with the bonding pads at the chip periphery.

Fig.9.a. Photograph of a fabricated chip.(14x7 mm$^2$) The 32x32 cantilever array is located at the center, with bond pads distributed on either side.

Figure 10 shows the 32x32 array section of the chip with the independent approach/heat sensors in the four corners and the heaters on each side of the array as
well as zoomed scanning electron micrographs (SEMs) of an array section, a single cantilever, and a tip apex. The tip height is 1.7 µm and the apex radius is smaller than 20 nm, which is achieved by oxidation sharpening. The cantilevers are connected to the column and row address lines using integrated Schottky diodes in series with the cantilevers. The diode is operated in reverse bias (high resistance) if the cantilever is not addressed, thereby greatly reducing crosstalk between cantilevers.

![SEM images of the cantilever array section with approaching and thermal sensors in the corners, array and single cantilever details and tip apex.](image)

Fig.10.a. SEM images of the cantilever array section with approaching and thermal sensors in the corners, array and single cantilever details and tip apex.

6. ARRAY CHARACTERIZATION

The array's independent cantilevers, which are located in the four corners of the array and used for approaching and leveling of chip and storage medium, are used to initially characterize the interconnected array cantilevers. Additional cantilever test structures are distributed over the wafer; they are equivalent to but independent of the array cantilevers.

The cantilevers within the array are electrically isolated from one another by integrated Schottky diodes. As every parasitic path in the array to the cantilever addressed contains a reverse biased diode, the crosstalk current is drastically reduced.
Thus, the current response to an addressed cantilever in an array is nearly independent of the size of the array. Hence, the power applied to address a cantilever is not shunted by other cantilevers, and the reading sensitivity is not degraded—not even for very large arrays (32 x32). The introduction electrical isolation using integrated Schottky diodes turned out to be crucial for the successful operation of interconnected cantilever arrays with a simple time-multiplexed addressing scheme.

The tip-apex height uniformity within an array is very important, because it determines the force of each cantilever while in contact with the medium and hence influences write/read performance as well as medium and tip wear. Wear investigations suggest that a tip apex height uniformity across the chip of less than 500 nm is required with the exact number depending on the spring constant of the cantilever. In the case of the Millipede, the tip-apex height is determined by the tip height and the cantilever bending.

7. THE POLYMER MEDIUM

The polymer storage medium plays a crucial role in Millipede like thermomechanical storage systems. The thin-film-sandwich structure with PMMA as active layer (see Fig. 1) is not the only choice possible, considering the almost unlimited range of polymer materials available. The ideal medium should be easily deformable for bit writing, yet written bits should be stable against tip wear and thermal degradation. Finally, one would also like to be able to repeatedly erase and rewrite bits. In order to be able to scientifically address all important aspects, some understanding of the basic physical mechanism of thermomechanical bit writing and erasing is required.
In a gedanken experiment we visualize bit writing as the motion of a rigid body, the tip, in a viscous medium, the polymer melt. For the time being, the polymer, i.e. PMMA, is assumed to behave like a simple liquid after it has been treated above the glass-transition temperature in a small volume around the tip. As viscous drag forces must not exceed the loading force applied to the tip during indentation, we can estimate an upper bound for the viscosity of the polymer melt using Stokes' equation

\[ F = 6\pi \eta R \nu \]  

(1)

In actual Millipede bit writing, the tip loading force is on the order \( F = 50 \) nN, and the radius of curvature at the apex of the tip is typically \( R = 20 \) nm. Assuming a depth of the indentation of, say, \( h = 50 \) nm and a heat pulse of \( \tau_h = 10 \) \( \mu \)s duration, the mean velocity during indentation is on the order of \( \nu = h / \tau_h = 5 \) \( \text{mms}^{-1} \) (note that thermal relaxation times are of the order of microseconds, and hence the heating time can be equated to the time it takes to

form an indentation). With these parameters we obtain \( \eta < 25 \) Pa s, whereas typical values for the shear viscosity of PMMA are at least 7 orders of magnitude larger even at temperatures well above the glass-transition point.

This apparent contradiction can be resolved by considering that polymer properties are strongly dependent on the time scale of observation. At time scales of the order of 1 ms and below, entanglement motion is in effect frozen in and the PMMA molecules form a relatively static network. Deformation of the PMMA flow proceeds by means of uncorrelated deformations of short molecular segments rather than by a flow mechanism involving the coordinated motion of entire molecular chains. The price one has to pay is that elastic stress builds up in the molecular network as a result of the deformation (the polymer is in a so-called rubbery state). On the other hand, corresponding relaxation times are orders of magnitude smaller giving rise to an
effective viscosity at millipede time scales of the order of 10 Pa s as required by our simple argument. [See Eq. (1)]. Note that, unlike the normal viscosity, this high-frequency viscosity is basically independent of the detailed molecular structure of the PMMA, i.e. chain length, tacticity, poly dispersity, etc. In fact, we can even expect that similar high-frequency viscous properties are found in a large class of other polymer materials, which makes thermomechanical writing a rather robust process in terms of material selection.

We have argued above that elastic stress builds up in the polymer film during indentation, creating a corresponding reaction force on the tip of the order of \( F_r = 2\pi GR^2 \), where \( G \) denotes the elastic shear modulus of the polymer. An important property for Millipede operation is that the shear modulus drops by orders of magnitude in the glass-transition regime, i.e. for PMMA from \( \sim 1 \) GPa below \( T_g \) to \( \sim 0.5...1 \) MPa above \( T_g \). (The bulk modulus, on the other hand, retains its low-temperature value of several GPa. Hence, in this elastic regime, formation of an indentation above \( 1 \); constitutes a volume preserving deformation.) For proper bit writing, the tip load must be balanced between the extremes of the elastic reaction force \( F_r \) for temperatures below and above \( T_g \). i.e. for PMMA \( F \ll 2.5 \) 1µN to prevent indentation of the polymer in the cold state and \( F \gg 2.5 \) nN to overcome the elastic reaction force in the hot state. Unlike the deformation of a simple liquid, the indentation represents a metastable state of the entire deformed volume, which is under elastic tension. Recovery of the unstressed initial state is prevented by rapid quenching of the indentation below the glass temperature with the tip in place. As a result, the deformation is frozen in because below \( T_g \) motion of molecular-chain segments is effectively inhibited (see Figure 11).
This mechanism also allows local erasing of bits. It suffices to locally heat the deformed volume above $T_g$ where upon the indented volume reverts to its unstressed flat state driven by internal elastic stress. In addition, erasing is promoted by surface tension forces, which give rise to a restoring surface pressure on the order of $\gamma (\pi/R)^2 h \approx 25 \text{ MPa}$, where $\gamma \approx 0.02 \text{ Nm}^{-1}$ denotes the polymer-air surface tension.

One question immediately arises from these speculations: If the polymer behavior can be determined from the macroscopic characteristics of the shear modulus as a function of time, temperature, and pressure, can then the time-temperature...
superposition principle also be applied in our case? The time temperature superposition principle is a very successful concept of polymer physics. It basically says that the time scale and the temperature are interdependent variables that determine the polymer behavior such as the shear modulus. A simple transformation can be used to translate time-dependent into temperature dependent data and vice versa. It is not clear, however, whether this principle can be applied in our case, i.e. under such extreme conditions (high pressures, short time scales and nanometer-sized volumes, which are clearly below the radius of gyration of individual polymer molecules).

One of the most striking conclusions of our model of the bit-writing process is that it should in principle work for most polymer materials. The general behavior of the mechanical properties as a function of temperature and frequency is similar for all polymers. The glass-transition temperature $T_g$ would then be one of the main parameters determining the threshold writing temperature.

A verification of this was found experimentally by comparing various polymer films. The samples were prepared in the same way as the PMMA samples discussed earlier by spin casting thin films (10-30 nm) onto a silicon wafer with a photo-resist buffer. Then threshold measurements were done by applying heat pulses with increasing current (or temperature) to the tip while the load and the heating time were held constant (load about 10 nN and heating time 10 $\mu$s). Examples of such measurements are shown in Fig. 12, where the increasing size and depth of bits can be seen for different heater temperatures. A threshold can be defined based on such data and compared with the glass-transition temperature of these materials. The results show a clear correlation between the threshold heater temperature and the glass-transition temperature (see Fig. 13).
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Fig. 12. Written bits for different polymer materials.

Fig. 13. The heater temperature threshold for writing bits with the same parameters as in fig. 10 is plotted against the glass transition temperature for these polymers including poly-α- methyl –styrene.

It is worth looking at the detailed shapes of the written bits. The polymer material around an indentation appears piled-up as can be seen, in Fig. 14. This is not only material that was pushed aside during indentation formation as a result of volume conservation. Rather, the flask heating by the tip and subsequent rapid cooling result in an increase of the specific volume of the polymer. This phenomenon that the specific volume of a polymer can be increased by rapidly cooling a sample through the glass transition is well known. Our system allows a cooling time of the order of microseconds, which is much faster than the fastest rates that can be achieved with
standard polymer-analysis tools. However, a quantitative measurement of the specific volume change cannot be easily done in our type of experiments. On the other hand, the pile-up effect serves as a convenient threshold thermometer. The outer perimeter of the donuts surrounding the indentations corresponds to the $T_g$ isotherm, and the temperature in the enclosed area has certainly reached values larger than $T_g$ during the indentation process. Based on our visco-elastic model, one would thus conclude that previously written bits that overlap with the piled up region of a subsequently written bit should be erased.

Fig. 14. Topographic image of individual bits. (a) The region around the actual indentations clearly shows the three fold symmetry of the tip, here a three sided pyramid. (b) The indentations themselves exhibit sharp edges, as can be seen from the inverted 3D image. Image size is 2μm.

With our simple visco-elastic model of bit writing we are able to formulate a set of requirements that potential candidate materials for Millipede data storage have to fulfill. First, the material should ideally exhibit a well-defined glass-transition point with a large drop of the shear modulus at $T_g$. Second, a rather high value of $T_g$ on the order of 1500 °C is preferred to facilitate thermal read-back of the data without destroying the information. We have investigated a number of materials to explore the $T_g$ parameter space. The fact that all polymer types tested are suitable for writing small
bits allows us to exercise the freedom of choice of polymer type to optimize in terms or the technical requirements for a device, such as lifetime of bits, polymer endurance of the read and write process, power consumption, etc. These are fields of ongoing, research.

Based upon the pile-up effect, erasing of data bits may be explained.

8. DATA ERASING
The pile-up phenomenon turns out to be particularly beneficial for data-storage applications. The following example demonstrates the effect. If we look at the sequence of images in Fig. 15 taken on a standard PMMA sample, we find that the piled-up regions can overlap each other without disturbing the indentation. If tile piled-up region of an individual bit-writing event, however, extends over the indented area of a
previously written hit, tire depth of the corresponding indentation decreases markedly (Fig. 15d).

This can he used for erasing written bits. However; if the pitch between two successive bits is decreased even further, this erasing process will no longer work. Instead a broader indentation is formed (Fig. 15d). Hence, to exclude mutual interference, the minimum pitch between successive bits must be larger than the radius of the piled-up area around an indentation.

Fig.15. Indentations in a PMMA film at several distances. The depth of the indentations is ~15 nm, about the thickness of the PMMA layer. The indentations on the left hand side were written first, then a second series of indentations were made decreasing distance to the first series in going from a to e.

In the example shown in Fig. 15 the temperature was chosen so high that the ring around the indentations was very large, whereas the depth of the bit was limited by the stop layer underneath the PMMA material. Clearly, here the temperature was too high to form small bits, the minimum pitch being around 250 nm. However, by carefully optimizing all parameters it is possible to achieve areal densities of up to 1Tb/in² as demonstrated in Fig. 2c.
The new erasing scheme based on this volume effect switches from writing to erasing merely by decreasing the pitch of writing indentations. This can be done in a very controlled fashion as shown in Fig. 16, where individual lines or predefined sub-areas are erased. Hence, this new erasing scheme can be made to work in a way that is controlled on the scale of individual bits. Compared with earlier global erasing schemes, this simplifies erasing significantly.

![Figure 16](image)

Fig.16. Demonstration of the new erasing scheme. (a) A bit pattern with variable pitch in the vertical axis (fast scan axis) and constant pitch in the horizontal direction (slow scan axis) was prepared. (b) Then two of the lines were erased by decreasing the pitch in the vertical direction by a factor of three, showing that the erasing scheme works for individual lines. One can also erase entire fields of bits without destroying bits at the edges of the fields. This is demonstrated in (c), where a field has been erased from a bit field similar to the one shown in (a)0. The distance between the lines is 70nm.

9. ADVANTAGES

The Advantages of this technology are:

1. Ultrahigh Density.
2. Terabit Capacity.

3. Small Form Factor.

4. High Data Rates.

5. Not affected by electric or magnetic fields.

10. CONCLUSION

Day by day, the need for more storage capacity is going on increasing. Six or seven years back, the maximum hard disk capacity available was about 2GB. But today hard disks of 80 GB and 100GB are very common. The external size of the hard disk is almost the same seven years back and today. It is the storage density that is being
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increased. After some years, the current method of magnetically storing data may reach its limit of maximum achievable density. Beyond this super paramagnetic limit, the capacity of magnetic storage cannot be increased. Hence there is a strong need for a new storage technique. The Thermomechanical storage concept described above may be considered as a good alternative. The millipede concept, which operates thousands of cantilevers for write/read operation can provide ultra high storage capacity at very high data rates. The Millipede project could bring tremendous data capacity to mobile devices such as personal digital assistants, cellular phones, digital cameras and multifunctional watches. In addition, the use of this concept may be explored in a variety of other applications, such as large-area microscopic imaging, nanoscale lithography or atomic and molecular manipulation. Research is going on to find new storage mediums and to construct yet smaller cantilever tips, so that the storage capacity can be increased further. In future we can expect a storage device of the size of a button with storage capacity of trillions of bits.

11. REFERENCES


4. www.ieee.org

5. www.research.ibm.com

6. www.zurich.ibm.com

7. www-snf.stanford.edu

8. www.almaden.ibm.com

9. www.physicsfinder.org

10. www.materialstoday.com

11. www.asrm.archivi.beniculturali.it/CFLR/Dobbiaco/Atti/Slides

12. www.me.gatech.edu/me/people/academic.faculty/King_William.html


15. www.nanoelectronicsplanet.com

16. www.sigmaxi.nsu.ru

17. www.moah.org