A

Seminar report

On

# Millipede

Submitted in partial fulfillment of the requirement for the award of degree
Of ECE

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# Preface

I have made this report file on the topic **Millipede;** I have tried my best to elucidate all the relevant detail to the topic to be included in the report. While in the beginning I have tried to give a general view about this topic.

My efforts and wholehearted co-corporation of each and everyone has ended on a successful note. I express my sincere gratitude to ………….who assisting me throughout the preparation of this topic. I thank him for providing me the reinforcement, confidence and most importantly the track for the topic whenever I needed it.

# Acknowledgement

I would like to thank respected Mr…….. and Mr. ……..for giving me such a wonderful opportunity to expand my knowledge for my own branch and giving me guidelines to present a seminar report. It helped me a lot to realize of what we study for.

Secondly, I would like to thank my parents who patiently helped me as i went through my work and helped to modify and eliminate some of the irrelevant or un-necessary stuffs.

Thirdly, I would like to thank my friends who helped me to make my work more organized and well-stacked till the end.

Next, I would thank Microsoft for developing such a wonderful tool like MS Word. It helped my work a lot to remain error-free.

Last but clearly not the least, I would thank The Almighty for giving me strength to complete my report on time.

## ABSTRACT

"Millipede" is a new (AFM)-based data storage concept that has a potentially ultrahigh density, terabit capacity, small form factor, and high data rate. Its potential for ultrahigh storage density has been demonstrated by a new thermomechanical local-probe technique to store and read back data in very thin polymer films. With this new technique, 3040-nm-sized bit indentations of similar pitch size have been made by a single cantilever/tip in a thin (50-nm) polymethylmethacrylate (PMMA) layer, resulting in a data storage density of 400500 Gb/in.$^2$

High data rates are achieved by parallel operation of large two-dimensional (2D) AFM arrays that have been batch-fabricated by silicon surface-nMcromachining techniques. The very large scale integration (VLSI) of micro/nanomechanical devices (cantilevers/tips) on a single chip leads to the largest and densest 2D array of 32 x 32 (1024) AFM cantilevers with integrated write/read storage functionality ever built. Initial areal densities of 100200 Gb/in.$^2$ have been achieved with the 32 x 32 array chip, which has potential for further improvements.

In addition to data storage in polymers or other media, and not excluding magnetics, we envision areas in nanoscale science and technology such as lithography, high-speed/large-scale imaging, molecular and atomic manipulation, and many others in which Millipede may open up new perspectives and opportunities.

## 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. 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 superparamagnetic limit.

In any case, an emerging technology being considered as a serious candidate to replace an existing but the technology must offer long-term perspectives.

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 used in every atomic force microscope (AFM) and scanning tunneling microscope (STM) for imaging and structuring down to the atomic scale.

The objectives of our research activities within the Micro- and Nanomechanics Project at the IBM Zurich Research Laboratory are to explore highly parallel AFM data storage with areal storage densities far beyond the expected superparamagnetic limit (60100 Gb/in.$^2$) and data rates comparable to those of today's magnetic recording. The "Millipede" concept presented here is a new approach for storing data at high speed and with an ultrahigh density. Our current effort is focused on demonstrating the Millipede concept with areal densities up to 500 Gb/in.$^2$ and parallel operation of very large 2D (32 x 32) AFM cantilever arrays with integrated tips and write/read storage functionality.

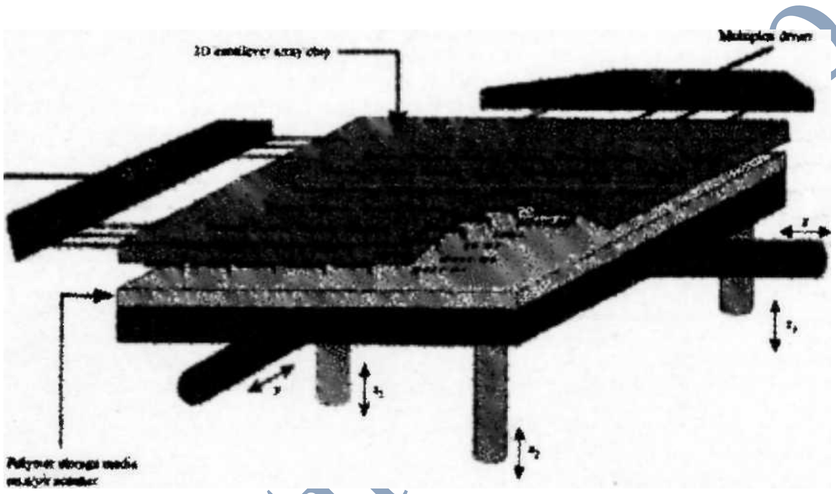
## 2. MILLIPEDE CONCEPT

"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 stringent control and uniformity of tip height and cantilever bending. Chip approach and leveling make use of four integrated approaching cantilever sensors in the corners of the array chip to control the approach of the chip to the storage medium. Signals from three sensors (the fourth being a spare) provide feedback signals to adjust three magnetic z-actuators until the three approaching sensors are in contact with the medium. The three sensors with the individual feedback loop maintain the chip leveled and in contact with the surface while x/y scanning is performed for write/read operations. The system is thus leveled in a manner similar to an antivibration air table. This basic concept of the entire chip approach/leveling has been tested and demonstrated for the first time by parallel imaging with a 5 * 5 array chip. These parallel imaging results have shown that all 25 cantilever tips have approached the substrate within less than 1 um of z-activation. This promising result has led us to believe that chips with a tip-apex height control of less than 500 nm are feasible. This stringent requirement for tip-apex uniformity over the entire chip is a consequence of the uniform force needed to minimize or 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 urn. 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 32 * 32 array chip will generate 32 x 32 (1024) storage fields on an area of less than 3 mm x 3 mm. Assuming an areal density of 500 Gb/in.$^2$, one storage field of 92 um x 92 um has a capacity of about 10 Mb, and the entire 32 x 32 array with 1024 storage fields has a capacity of about 10 Gb on 3 mm x 3 mm. As shown in Section 7, the storage capacity scales with the number of elements in the array, cantilever pitch (storage-field size) and areal density, and depends on the application requirements. Although not yet investigated in detail, lateral tracking will also be performed for die 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 tun 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 and 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. As previously noted, thermomechanical writing in polycarbonate films and optical readback were first investigated and demonstrated with a single cantilever 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.

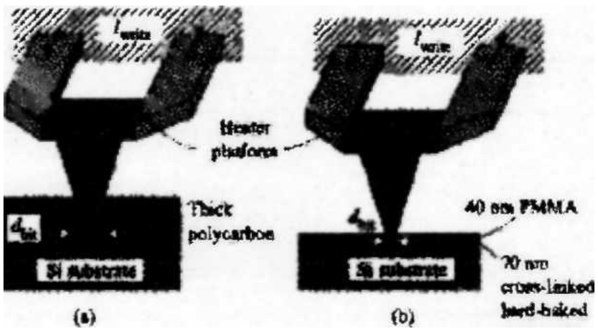
Millipede Conceptual Model



## 3. THERMOMECHANICAL AFM DATA STORAGE

In recent years, AFM thermomechanical recording in polymer storage media has undergone extensive modifications, primarily with respect to the integration of sensors and heaters designed to enhance simplicity and to increase data rate and storage density. Using cantilevers with heaters, mermomechanical recording at 30 Gb/in.$^2$ storage density and data rates of a few Mb/s for reading and 100 Kb/s for writing have been demonstrated. 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, improving as the contact area increases. This means that the tip must be heated to a relatively high temperature (about 400°C) to initiate the melting process. Once melting has commenced, the tip is pressed into the polymer, which increases the heat transfer to the polymer, increases the volume of melted 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 (1040 ran$^{2}$) to melt 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 melting 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. With this highly nonlinear heat-transfer mechanism, it is very difficult to achieve small tip penetration and thus 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. We have explored the use of very thin polymer layers deposited on Si substrates to improve these characteristics. The hard Si substrate prevents the tip from penetrating farther than the film thickness allows, and it enables more rapid transport of heat away from the heated region because Si is a much better conductor of heat than the polymer. We have coated Si substrates with a 40-nm film of polymethylmethacrylate (PMMA) and achieved bit sizes ranging between 10 and 50 nm. However, we noticed increased tip wear, probably caused by the contact between Si tip and Si substrate during writing. We therefore introduced a 70-nm layer of cross-linked photoresist (SU-8) between the Si substrate and the PMMA film to act as a softer penetration stop that avoids tip wear but remains thermally stable. Using this layered storage medium, data bits 40 nm in diameter have been written, as shown in. These results were obtained using a 1-urn-thick, 70-um-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 us in duration were applied to the cantilever with a period of 50 ps.



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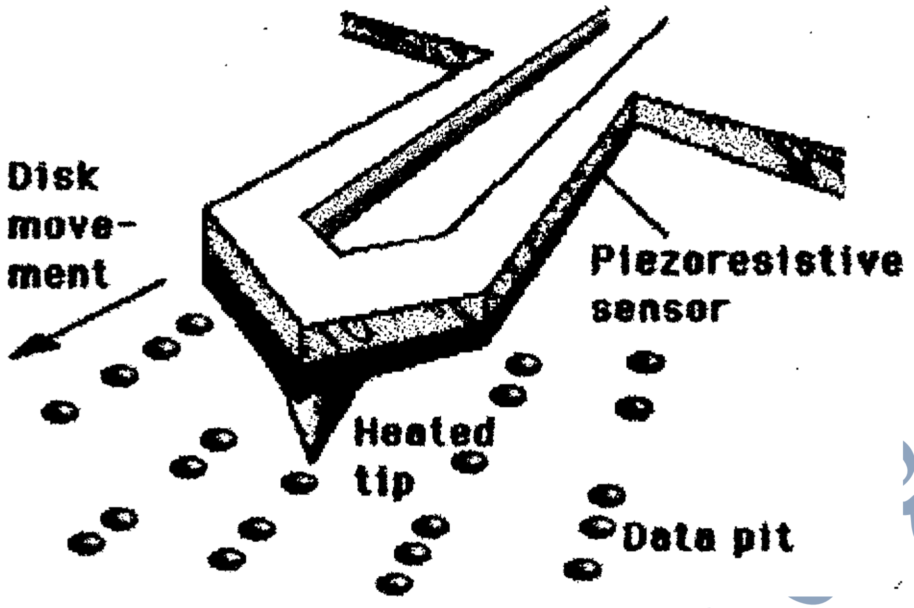
Imaging and reading are done using a new thermomechanical-sensing concept. The heater cantilever originally used only for writing was given the additional function of a thermal readback sensor by exploiting its temperature-dependent resistance. The resistance (R) increases nonlinearly with heating power/temperature from room temperature to a peak value of 500700°C. The peak temperature is determined by the doping concentration of the heater platform, which ranges from 1 x $10^{17}$ to 2 x $10^{18}$. 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 necessary 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. 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.

In addition to ultra dense thermomechanical write/read, we have also demonshated for the first time the erasing and rewriting capabilities of polymer storage media. Thermal reflow of storage fields is achieved by heating the medium to about 150°C for a few seconds. The smoothness of the reflowed medium allowed multiple rewriting of the same storage field. This erasing process does not allow bit-level erasing; it will erase larger storage areas. However, in most applications single-bit erasing is not required anyway, because files or records are usually erased as a whole. The erasing and multiple rewriting processes, as well as bit-stability investigations, are topics of ongoing research.

**Typical Cantilever Tip**



## 4. MILLIPEDE STORAGE TECHNIQUES

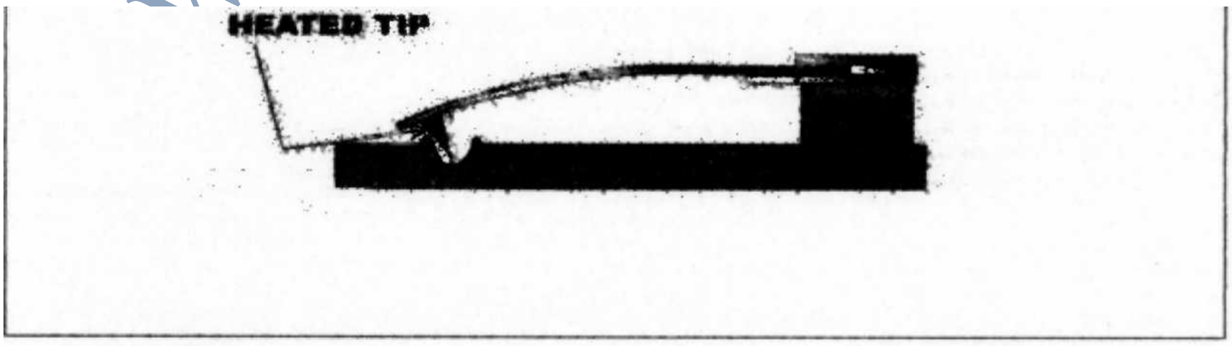
Three major storage aspects have to be dealt with which are:

### Data Writing

The tip of a cantilever is positioned over a spinning polycarbonate disk, which has a glass transition point of about 120-140 degrees Celsius. When the tip is heated, with an integrated resistive heater, it melts the polycarbonate upon contact, creating a tiny indentation representing the encoded digital data. The tip of the cantilever is kept in contact with the spinning disk by means of a very small loading force applied to the base of the cantilever. Using this type of heater, data has been written at the rate of 100 kbit/s. Voltage pulses 0.2 microseconds in duration and 30 volts in amplitude were used.

WRITING DATA

(THERMOMECHANICAL METHOD)



## Data Reading

Information encoded in the medium can be read back by any of the two methods described below:

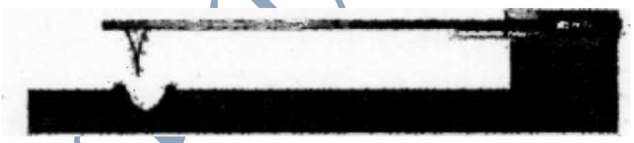
### a) *Thermomechanical method*

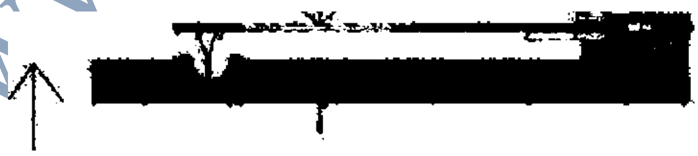
Reading can be done using a new thermomechanical-sensing concept, by exploiting its temperature-dependent resistance. For sensing, the resistor (cantilever) is operated at about 350°C, a temperature that is not high enough to soften the polymer, as is necessary for writing. The medium between a cantilever 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.

READING DATA

(THERMOMECHANICAL METHOD)





### b) *Piezoresistivity method*

Piezoresistivity of the silicon cantilever changes resistance slightly under stress. Heavily doped silicon exhibits piezoresistivity. Therefore a heavily doped cantilever can be used to sense indentations on a disk. Whenever the tip rides over an indentation, the cantilever flexes one way or the other. The stress in the cantilever varies accordingly, and so does the resistance. These slight changes in resistance can be converted to voltage signals, amplified and processed to regenerate digital data.

## Comparisons of methods used

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

# 5. ARRAY DESIGN AND FABRICATION

As a first step, a 5 x 5 array chip was designed and fabricated to test the basic Millipede concept. All 25 cantilevers had integrated tip heating for thermomechanical writing and piezoresistive deflection sensing for read-back. No time-multiplexing addressing scheme was used for this test vehicle; rather, each cantilever was individually addressable for both thermomechanical writing and piezoresistive deflection sensing. A complete resistive bridge for integrated detection has also been incorporated for each cantilever.

The chip has been used to demonstrate x/y/z scanning and approaching of the entire array, as well as parallel operation for imaging. This was the first parallel imaging by 2D AFM array chip with integrated piezoresistive deflection sensing. The imaging results also confirmed the global chip-approaching and -leveling scheme, since all 25 tips approached the medium within less than 1 pm of z-actuation. Unfortunately, the chip was not able to demonstrate parallel writing because of electromigration problems due to temperature and current density in the Al wiring of the heater. However, we learned from this 5 x 5 test vehicle that 1) global chip approaching and leveling is possible and promising, and 2) metal (Al) wiring on the cantilevers should be avoided to eliminate electromigration and cantilever deflection due to bimorph effects while heating.

Encouraged by the results of the 5 x 5 cantilever array, we designed and fabricated a 32 x 32 array chip. With the findings from the fabrication and operation of the 5 x 5 array and the very dense thermomechanical writing/reading in thin polymers with single cantilevers, we made some important changes in the chip functionality and fabrication processes.

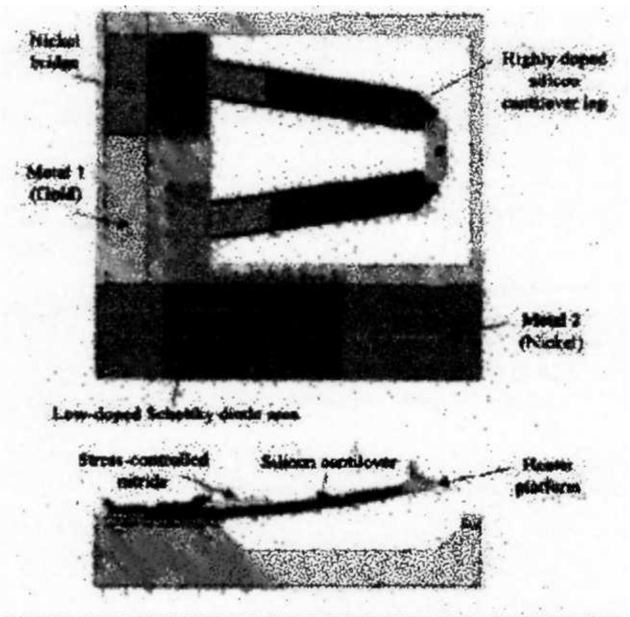
The major differences are: 1) Surface rnicromachining to form cantilevers at the wafer surface

2) All-silicon cantilevers
3) Thermal instead of piezoresistive sensing
4) First- and second-level wiring with an insulating layer for a multiplexed row/column- addressing scheme.

Since the heater platform functions, as a write/read element and no individual cantilever actuation are required, the basic array cantilever cell becomes a simple two-terminal device addressed by multiplexed x/y wiring. The cell area and x/y cantilever pitch is 92-um x 92 um, which results in a total array size of less than 3 mm x 3 nun for the 1024 cantilevers. The cantilever is fabricated entirely of silicon for good thermal and mechanical stability. It consists of the heater platform with the tip on top, the legs acting as a soft mechanical spring and an electrical connection to the heater. They are highly doped to minimize interconnection resistance and replace the metal wiring on the cantilever to eliminate electromigration and parasitic z-actuation of the cantilever due to the bimorph effect. The resistive ratio between the heater and the silicon interconnection sections should be as high as possible; currently the highly doped interconnections are 400 and the heater platform is 11 k (at 4 V reading bias).

## 6. CANTILEVER PROPERTIES

The cantilever mass must be minimized to obtain soft (flexible), high-resonant-frequency cantilevers. Soft cantilevers are required for a low loading force in order to eliminate or reduce tip and medium wear, whereas a high resonant frequency allows high-speed scanning. In addition, sufficiently wide cantilever legs are required for a small thermal time constant, which is partly determined by cooling via the cantilever legs . These design considerations led to an array cantilever with 50-u.m-long, 10-u.m-wide, 0.5-um-thick legs, and a 5-um-wide, 10-um-long, 0.5-um-thick platform. Such a cantilever has a stiffness of 1 N/m and a resonant frequency of 200 kHz. The heater time constant is a few microseconds, which should allow a multiplexing rate of 100 kHz.



Layout and cross section of one cantilever cell.

The tip height should be as small as possible because the heater platform sensitivity depends strongly on the distance between the platform and the medium. This contradicts the requirement of a large gap between the chip surface and the storage medium to ensure that only the tips, and not the chip surface, are making contact with the medium. Instead of making the tips longer, we purposely bent the cantilevers a few micrometers out of the chip plane by depositing a stress-controlled plasma-enhanced chemical vapor deposition (PECVD) silicon-nitride layer at the base of the cantilever . This bending as well as the tip height must be well controlled in order to maintain an equal loading force for all cantilevers of an array. 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 performed for our 5 x 5 array [10], the surface-micromachining technique allows an even higher array density and yields better mechanical chip stability and heat sinking. Because the Millipede tracks the entire array without individual lateral cantilever positioning, thermal expansion of the array chip must be either 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 3 mm x 3 mm 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 ID, which would have made the chip 32 times longer for the same number of cantilevers.

Integrating Schottky diodes in series with the cantilevers interconnects the cantilevers. The diode is operated in reverse bias (high resistance) if the cantilever is not addressed, thereby greatly reducing crosstalk between cantilevers.

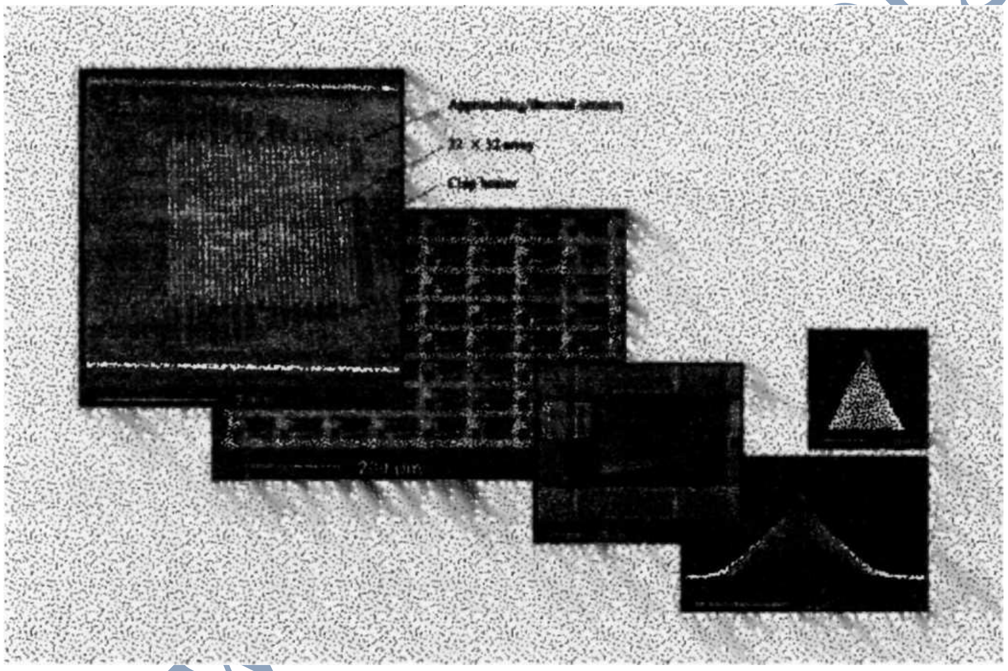
## 7. ARRAY CHARACTERIZATION

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. In the low-power part of the curve, the resistance increases as a function of heating power, whereas in the high-power regime, it decreases.

In the low-power, low-temperature regime, silicon mobility is affected by phonon scattering, which depends on temperature, whereas at higher power the intrinsic temperature of the semiconductor is reached, resulting in a resistivity drop due to the increasing number of carriers. Depending on the heater-platform doping concentration of 1 x 1017 to 2 x 1018 at./cm3, our calculations estimate a resistance maximum at temperatures of 500°C and 700°C, respectively.

The cantilevers within the array are electrically isolated from one another by integrated Schottky diodes. Because every parasitic path in the array to the addressed cantilever of interest 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, as demonstrated by the I/V curves. 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 x 32). The introduction of the 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 height and the cantilever bending determine the tip-apex height. The figure below shows the tip-apex height uniformity of one row of the array (32 tips) due to tip height and cantilever bending. It demonstrates that our uniformity is of the order of 100 ran, thus meeting requirements.

SEM images of the cantilever array section with approaching and thermal sensors in the corners, array and single cantilever details, and microscopic view of a single Tip.



[The tip shown above is less than 2 micrometers high and the radius at its apex smaller than 20 nanometers (millionths of a millimeter)].

## 8. FIRST WRITE/READ RESULTS WITH THE 32 X 32 ARRAY CHIP

We have explored two x/y/z scanning approaching schemes to operate the array for writing/reading. The first one is based closely on the Millipede basic concept. A 3 mm x 3 mm silicon substrate is spin-coated with the SU-8/PMMA polymer medium structure. 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 force of the cantilever while it is in contact with the medium. This sensing and 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. Writing is performed by connecting the addressed row for 20 us to a high, negative voltage and simultaneously applying data inputs ("0" or "1") to the 32 column lines. The data input is a high, positive voltage for a "1" and ground for a "0." This row-enabling and column-addressing scheme supplies a heater current to all cantilevers, but only those cantilevers with high, positive voltage generate an indentation ("1"). Those with ground are not hot enough to make an indentation, and thus write a "0." When the scan stage has moved to the next bit position, the process is repeated, and this is continued until the line scan is finished. In the read process, the selected row line is connected to a moderate negative voltage, and the column lines are grounded via a protection resistor of about 10 k, which keeps the cantilevers warm. During scanning, the voltages across the resistors are measured. If one of the cantilevers falls into a "1" indentation, it cools, thus changing the resistance and voltage across the series resistor. The written data bit is sensed in this manner.

The second x/y/z scanning and approaching system illustrated in make use of a modified magnetic hard-disk drive. The array chip replaced the magnetic write/read head slider and was mechanically leveled and fixed on the suspension arm. A piezoelectric actuator mounted on top of the suspension, which brought the array chip into contact with the medium and maintained it there, performed the z-approaching and -contacting procedure. The standard voice-coil actuator of the suspension arm achieved the 92-um scanning in x, whereas the slowly moving disk performed the y-scanning. The row/column-addressing scheme is very similar to the one used for the x/y/z scanner.

# 9. MILLIPEDE APPLICATIONS

The current 32 x 32 array chip is just one example of the many possible designs of a data-storage system; the design and concept depend strongly on the intended It is important to note that the same data capacity can be achieved, for example, using large arrays with small cantilever pitch/scan range or, conversely, using small arrays with a larger scan range. In addition, terabit data capacity can be achieved by one large array, by many identical small ones operating in parallel, or by displacing a small array on a large medium.

Out of this wide range of design and application scenarios, we would like to explain two cases of particular interest. *ah Small-form-factor storage system (Nanodrive)*

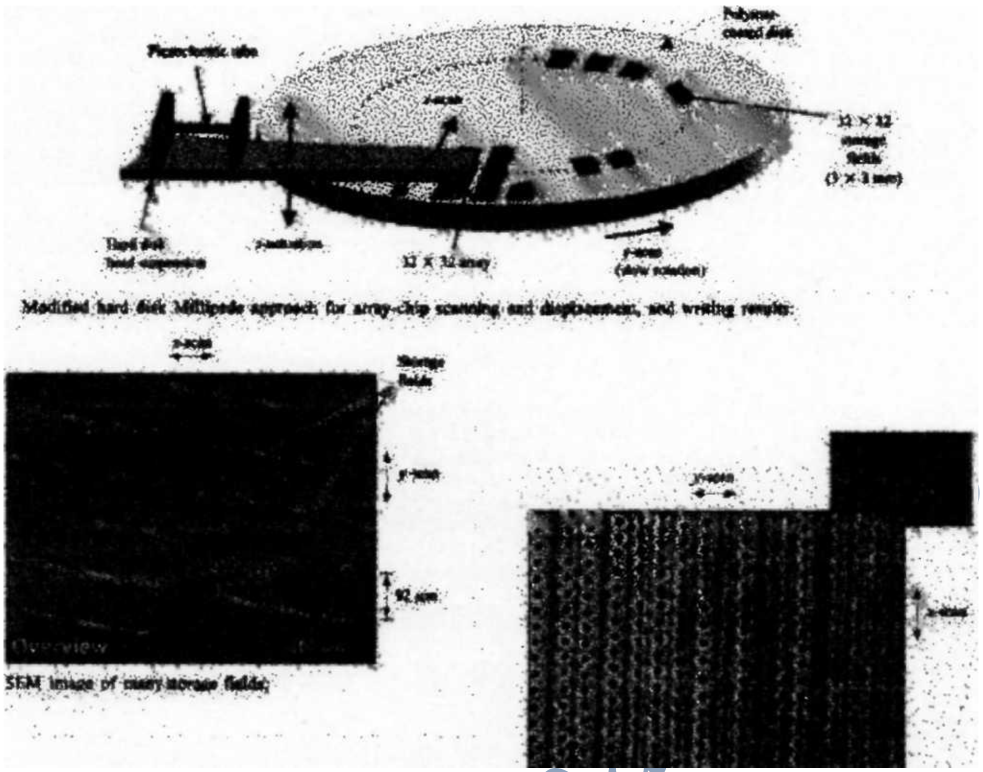
IBM's recent product announcement of the Microdrive represents a first successful step into miniaturized storage systems. As we enter the age of pervasive computing we can assume that computer power is available virtually everywhere. Miniaturized and low-power storage systems will become crucial, particularly for mobile applications. The availability of storage devices with gigabyte capacity having a very small form factor (in the range of centimeters or even millimeters) will open up new possibilities to integrate such "Nanodrives" into watches, cellular telephones, laptops, etc., provided such devices have low power consumption.

The array chip with integrated or hybrid electronics and the micromagnetic scanner are key elements demonstrated for a Millipede-based device called Nanodrive, which is of course also very interesting for audio and video consumer applications. AU-silicon, batch fabrication, low-cost polymer media, and low power consumption make Millipede very attractive as a centimeter- or even millimeter-sized gigabyte storage system.

*b). Terabit drive*

The potential for very high areal density renders the Millipede also very attractive for high-end terabit storage systems. As mentioned above, terabit capacity can be achieved with three Millipede-based approaches:

1) Very large arrays
2) Many smaller arrays operating in parallel
3) Displacement of small/medium-sized arrays over large media.



Modified hard disk Millipede approach for array-chip scanning and displacement, and writing results:

SEM image of many storage fields;

Although the fabrication of considerably larger arrays (105 to 106 cantilevers) appears to be possible, control of the thermal linear expansion will pose a considerable challenge as the array chip becomes significantly larger. The second approach is appealing because the storage system can be upgraded to fulfill application requirements in a modular fashion by operating many smaller Millipede units in parallel. The operation of the third approach was described above with the example of a modified hard disk. This approach combines the advantage of smaller arrays with the displacement of the entire array chip, as well as repositioning of the polymer-coated disk to a new storage location on the disk. A storage capacity of several terabits appears to be achievable on 2.5- and 3.5-in. disks.

## 10. ADVANTAGES

- High storage capacity (1 Tb/in$^2$).
- Very small form factor.
- Low power consumption (100 milliwatts).
- It is re-writeable.
- High data rate (high as 1 - 2 MB/s).
- Long-term perspectives.

# Reference

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