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PROBE-BASED DATA STORAGE TECHNOLOGY: THERMOMECHANICAL STORAGE –STATE OF THE ART

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Abstract

Ultra high density data storage imposes an ever increasing demand on the capacity and speed of data storage systems becoming an essential issue in this digital age. Secondary storage has been indispensable constituent of any computer system for storing data at high speed with ultra-high density. AFM (Atomic Force Microscopy) based data storage is a promising alternative to conventional magnetic data storage because it offers great potential for considerable storage density improvements, which has become very popular. Significant challenges, salient features and associated benefits of the nano tip based data storage devices were discussed briefly in this case study. This study addresses the following: (i) a brief discussion on emerging research directions broadly in the areas of thermomechanical data storage and storage intersecting low-dimensional polymer materials; (ii) advancing experimental methods to fabricate microcantilever with nano tip that can sustain with pulse gradient, thermo mechanically stable under large thermal cycles which can be electrically interrogated with negligible parasitic loss.

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1. INTRODUCTION:

Secondary storage is an indispensable constituent of any computer system, from the mobile PC to the server system. For several decades hard disks have been serving the secondary storage. The information storage imposes an ever increasing demand on the capacity and speed of data storage systems and has been becoming an issue in this digital age and in order to meet this demand, nanotechnology offers an alternative for present magnetic storage. In Magnetic storage, bit is represented by magnetized part on the recording medium. Magnetized part is represented as 1 and the Non-Magnetized part is represented as 0. But when the size of magnetic domain decreases below a certain value, the probability of the bit undergoing thermal demagnetization at room temperature becomes unacceptably large, and effects the magnetic domain and hence storage. The size of magnetic domain has a limiting value where it is not affected by thermal demagnetization at room temperature (i.e. magnetic domains become small to be stable at room temperature, called Paramagnetic Limits) (E.Grochowski et al., IBM). Within the paramagnetic limits, areal densities are 100Gbit/inch² (E.Grochowski et al., IBM). The searches for digital storage technologies which have to meet the demand for data storage with more storage capacity offered ever increasing data densities. Several ideas have been proposed on how to overcome this limit such as holographic storage, electron beam based storage, optical storage, and the tip based storage. One of such a proposal is AFM (Atomic Force Microscopy) tip method. AFM method employs a microcantilever with a sharp tip to image a nonconductive surface on the atomic scale.

The available tool known that is simple and providing long term perspectives is cantilever with nano tip. AFM based data storage is a promising alternative to conventional magnetic data storage. With the invention of STM it became possible to image atoms and a few years later manipulation at atomic scale was demonstrated by Eigler and Schweizer (1990) (D.M.Eigler et al., 1990). Probe storage resembles AFM. The main difference between AFM based data storage and Probe based data storage is the number of probes used. It offers great potential for considerable storage density improvements, which has become very popular.

THERMO MECHANICAL DATA STORAGE is a method that uses AFM tip heated by electric pulses, which in contact with a storage medium is used to store data. The MILLIPEDE concept introduced by IBM is a new approach for storing data at high speed and with ultra-high density. Locality of a bit is given by a tip, and results in high data rates due to parallel operation of such tips. Areal densities of 4 Tbit/inch² (G.Schmid et al., 2008) have been achieved by parallel operation of large 2D (32x32) AFM cantilever arrays with tips and write/read storage functionality. It is very attractive since bit size is not determined by maximum resolution of lithography processes. Cantilever probes are chemically etched and have the potential to be automatically sharp without expensive manufacturing step.

THERMO MECHANICAL DATA STORAGE:

This method uses a cantilever to write, read and erase of data bits (or simply bits). This is a probe based storage mechanism. In 1994 Gimzewski et al. Constructed first micro cantilever which was used as a chemical reaction sensor. A cantilever with a tip is used to indent bits on polymer medium. Writing is done by heating of the cantilever tip with a laser beam, and reading was achieved by measuring deflection of another laser beam. Piezo-resistive cantilevers were used in this recording type. A major disadvantage of this method is that lasers are bulky and require precise alignment. So, cantilevers with integrated heaters or writing elements that do not rely on lasers can be a solution to make it simple (Benjamin W.Chui, 1999).

AFM thermo mechanical recording in polymer storage medium has undergone many modifications mainly with respect to integration of sensors and heaters designed to increase simplicity and to increase data rate and storage density. Using these heater cantilevers instead of piezo-resistive cantilevers, high storage density and data rates have been achieved (Seongssoo Jang et al., 2006).

It is developed by IBM under a project named MILLIPEDE (Vettiger et al., 2000). In this method, topographical changes are created on a polymer medium by making indentations representing 1. Absence of indentations is used both as spacer between neighboring 1’s and also for 0’s.
DATA WRITING:
Data writing is a combination of applying a small force by cantilever to the polymer layer and softening it by heating (Seongsoo Jang et al., 2006). In the figure shown, cantilever has heater with a tip at its end. Data writing is done via heating of tip attached to heater region of the cantilever. Electrical pulses were applied to the cantilever due to which a small force and heat is induced at the tip of cantilever. Tip must be heated to a relatively high temperature (about 400) by electrical pulses. Once softening has started, tip is pressed into polymer which increases heat transfer to polymer, increases the volume of polymer, and hence also increases bit size (Jungchul Lee et al., 2006).

Fig 1: Data Writing Principle: Electric pulses are sent to heater by electrical connections through cantilever attached to base. Tip which is attached to heater also heats along with heater and this heat is utilised to soften the polymer medium (G.Schmid et al., 2008).

This Thermo mechanical Cantilever (or heater cantilever) is made of silicon (semiconductor). The hard Si substrate prevents farther penetration of tip into the film, and enables transport of heat from heater region away from the polymer, since Si is better conductor of heat than the polymer. Bit sizes ranging between 10 and 50 nm are achieved on polymer Polymethylmethacrylate (PMMA), which when coated on Si substrate with 40 nm film thickness. This causes increased tip wear because of contact between Si tip and Si substrate during writing (P. Vettiger et al., 2002). So as to decrease this wear, a 70-nm layer of cross linked photo resist (SU-8) was introduced between the Si substrate and the PMMA film which acts as a penetration stopper (M. Hopcraft et al., 2004). The cantilever legs are highly doped by high-dose ion implantation and have low resistance to electric pulses, whereas the heater region is low-doped and has high resistance for heat dissipation to take place.

DATA READING:
Data bit reading by cantilever can be done in mainly in 3 ways. They are piezoresistive strain sensing, thermo mechanical sensing and optical readout technique.
High speed and throughput can be achieved, along with the possibility to give each cantilever a different task (reading, writing and erasing).
Piezoresistive Strain sensing: These are also called as strain sensing or strain gauge. The sensing is based on the principle that electrical resistance of a material changes as a result of applied strains. Mathematically,

\[ \frac{\Delta R}{R} = G \cdot \frac{\Delta L}{L} \]

Where,
- \( \Delta R \rightarrow \) change in resistance
- \( R \rightarrow \) initial resistance
- \( G \rightarrow \) gauge factor of piezoresistor.

Electric pulse is passed through the piezoresistive cantilever that doesn’t provide enough temperature for writing
and that pulse is capable of applying force to the cantilever so that tip gets into the polymer medium. The indentation in the recording medium has some depth due to tip penetration. If there is an indentation, there is little strain since cantilever gets into the polymer and change in resistance is read as 1. If no indentation is present in a place on the storage medium, there will be stress since tip cannot be penetrated into the polymer and resistance changes and this change in resistance is more and read as 0 (Seongsoo et al., 2006).

Fig 2: Two step dopant implantation of thermal microcantilever (Benjamin W.Chui, 1999).

**Thermo Mechanical sensing:** This sensing concept, also called as thermal sensing is used for imaging and reading of data bits. The principle of thermal sensing is that the thermal conductance between the tip and the storage medium changes according to the distance between them. The gap present between them varies heat transfer and cooling takes place. If the distance is large then there is slow cooling and if the distance is small, heat transfer rate is a higher and cooling rate increase (U.ADurig et al., 2000).

Fig 3: Data reading principle: The tip of the heater cantilever is continuously heated and data is being read based on the heater resistivity measured (G.Schmid et al., 2008).

The heater has the additional function of a thermal read back sensor by exploiting its temperature-dependent resistance. The resistance (R) increases nonlinearly with tip heating power/temperature. 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 medium between a cantilever and the storage substrate as 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 will be more efficient, and cooling is provided by substrate by transport of heat from tip (Mark A. Lantz et al., 2003). Due to this cooling, tip temperature decreases thereby decreasing its resistance. Temperature changes of the continuously heated resistor tip are monitored providing a means of detecting the bits, while the cantilever is scanned over data bits. Thermomechanical sensing is better than that of piezoresistive strain sensing because thermal effects in semiconductors are stronger than that of strain effects.
Optical Readout:

Several optical readout techniques for cantilever arrays have been proposed. The use of additional hardware leads to a very challenging design. The cantilever displacement is measured by detecting the deflection of a laser beam reflected from the backside of the cantilever and the deflection is detected by a position sensitive detector (split detector or photo diode) (A.J. Putman et al., 1992) or (Konrad Neiradka et al., 2012). The light from the laser strikes the cantilever at its end and the propagation direction and displacement of the cantilever is determined by the deflected angle of the cantilever. The angular deflection of the reflected laser beam is two times that of the angular deflection of the cantilever. A major drawback of collimated laser beams is that large reflective surfaces are required to direct the reflected laser beam towards the detector. The reflective surfaces can be made on the cantilever by attaching a mirror. Micro fabricated cantilevers which have a reflective gold coating on the backside have become commercially available. This optical waveguide deflection technique is easily adoptable to arrays by guiding the light. Another major disadvantage is the implementation of light wave guides on cantilevers is a considerable expansion of fabrication process. A time multiplexer switches ON/OFF of the sequentially to address the cantilevers. Recent application involves use of single light source for an entire array. Disadvantages are loss of bandwidth, need for one light source for each cantilever and timing issues that have to addressed to avoid overlapping of the reflected beams.
CANTILEVER:

Cantilever is fixed at one end and the other end is free to move when it experiences stress. A key enabler is its ability to sense with high resolution. For an ideal integrated cantilever, it must satisfy the following conditions. It should be with low stiffness of order of 1 N/m or even less suitable to operate at very low loading forces, which is necessary to avoid tip wear. Resonant frequency should be as high as possible and the combination of low stiffness and high frequency makes the cantilever to have low mass (Eric Finot et al., 2008) or (William P. King et al., 2002).

For writing, cantilever with integrated element for heating the tip is required. Integrated heater is made by doping the silicon cantilever. A semiconductor cantilever is lightly doped all along its length. Heater region is doped with high ion implantation, making heater region of high resistance for power dissipation and rest of cantilever of low resistance. When electric current flows through the cantilever, power is dissipated mainly within the high-resistivity heater region, leading to localized temperature rise at tip. Writing and reading are done by bringing tip in contact with storage medium. Design of heater region mainly depends on first ion implant step.

Actuation of motion for the cantilever is given in different ways. Some of them are electrothermal actuation, piezoelectric actuation. Electrothermal actuation is based on thermal expansion of materials. It consists of a bilayer structure having different thermoelastic coefficients. When the structure is heated, different internal stresses will develop inside the material causing the structure to bend. The power is delivered to the structure by applying a current due to which joule heating takes place and the cantilever is bent (William P. King et al., 2004). Piezoelectric actuation of cantilever uses piezo materials for actuating purpose. Piezoelectric effect can be used as sensing and its inverse effect (electric potential through a piezoelectric causes deformation) in actuating applications. Through piezoelectric actuator, we can convert electrical signal into precisely controlled physical displacement. In thin films of piezoelectric, piezoelectric coefficient is reduced because of the limited crystallographic orientation and difficulty in depositing without deteriorating its properties. When piezolayer is strained, it causes a bending moment in the cantilever structure causing the beam to bend up and down. If we cancel the electric field, the piezoelectric crystal is suddenly released from strained position moving the cantilever structure up. Piezoelectric method offers the advantage of low power consumption, high bandwidth and linear actuation. This offers great potential for even high
frequency applications. Piezoresistive is a potential candidate. It is fully integrable, broadband, and offers the highest transduction gain.

Important consideration in the design of heater cantilever is time constant (cooling rate i.e. how fast it is heated and cooled), which determines maximum data writing rate and its frequency. Heater fabrication is based on selective doping of different parts of cantilever. In the second implant step, high doping concentration leads to self heating of cantilever. This is because of decreasing resistance on increasing doping concentration i.e. when a pulse is given, due to low resistance current is very high which emits heat during its passage. So, doping concentration also plays important role in design of heater-cantilever.

Cooling rate mainly depends on the type and geometry of the cantilever. The rate at which heater region cools is determined in terms of thermal time constant ($t_\text{c}$). For the operation of the heater, a current pulse is passed through the cantilever to the cantilever to cause heat dissipation in the heater region resulting in temperature rise. After the pulse has ended, heat is carried away mainly by conduction to the base. Heat is carried away by convection (air is the medium) and radiation to a small extent. So, cooling rate is dependent on material of cantilever. Presence of impurities in silicon lowers its thermal conductivity. So, before doping, it must be made sure that it is pure. The shorter the thermal time constant, more frequently heating pulses can be applied and higher data rates. Cantilever should have higher thermal conductivity also.

![Fig 6: Cantilever Description (Benjamin W. Chui, 1999).](image)

![Fig 7: Heat paths relevant for experiment using heated probes (Pozidis et al., 2004).](image)
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) (Benjamin W. Chui, 1999).

Time constant decreases with decreasing constriction length, decreasing leg length, increasing leg width and decreasing constriction width. Trends (a) and (c) in Fig. 3.7 can be explained by the fact that a smaller thermal resistance from the heat source (the cantilever tip) to the heat sink (the cantilever base) is present when the constriction is shorter and the legs are shorter as well. Trend (d) is most likely due to the fact that the smaller thermal mass associated with a narrower constriction can be heated and cooled more efficiently—this effect apparently more than offsets the reduced thermal conductivity of the constriction itself. Heater should not be made too small as resistance would be overwhelmed by that of the resistance of the cantilever.

In this way cooling rate depends on the geometry also. Tip is very small on heater region. It is estimated that at the beginning of the writing process about 0.2% of the heating power is used in the very small contact zone to soften the polymer locally. Nearly 80% of heat is lost through the cantilever legs to the chip body and about 20% is radiated through the air gap to medium/substrate. During softening, the contact area increases and the heating power for generating the indentations increase by ten times and becomes more than 2% of the total heating power.

With this highly nonlinear heat transfer mechanism it is difficult to achieve small tip penetration and to maintain bit sizes small as well as to control and reproduce the thermomechanical writing process. This thermal mechanism can be improved by increasing thermal conductivity of the substrate, and if the depth of tip penetration is limited. These can be by the use of very thin polymer layers to be deposited on Si substrates.

**THE MILLIPEDE CONCEPT:**

Thermomechanical data storage has led to a first prototype in 2005 (Millipede, 2005) with certainly for that time, revolutionary areal densities around 1Tb/inch$^2$. The 2D AFM cantilever array storage technique is called Millipede. It uses thousands of nano-sharp tips to punch indentations that represent individual bits into a thin plastic film (Vettiger et al., 2000) or (M. Despont et al., 2004). Probe storage is very attractive because bit size is not determined by maximum resolution of lithographical processes that become increasingly costly. Probes can be chemically etched and have the potential to be automatically sharp without any manufacturing step.
When the numbers of probes are increasing, the accuracy of nano positioning has to be maintained even under the application of impact loads. Deviations in array probes have to be minimized for proper functioning and reliability working throughout device lifetime. As the number of cantilevers increases, its complexity increases (Suhas Somnath et al., 2013). A schematic of such an architecture that makes a storage device based on probe technology is proposed by IBM and is as shown in fig 9.

Fig 9: Measured (●) and simulated (-----) thermal time constants for under repeated-pulse conditions. In general it is seen that shorter, wider legs and smaller heater constrictions give rise to shorter time constants. (Benjamin W.Chui, 1999).

Fig 10: Millipede Arrangement (P.Vettiger et al.,2002)
It consists of two chips - a stationary and a movable chip. Array of read/write probes are present on the stationary chip. Read and write circuitry for probe tips, position sensors are also present on the stationary chip. The second chip (movable chip) moves in x, y, z and tilt directions. Electromagnetic actuation circuits moves the storage medium(movable chip) over the stationary medium, which contains the cantilevers for write/read operations. Millipede is based on mechanical parallel scanning of entire cantilever chip on storage medium.

Z-approaching with feedback-control and levelling scheme brings the entire cantilever array chip in contact with the polymer storage medium. During this, the tip-medium contact is maintained and controlled and x/y scanning is performed for write/read operations (Indermuhle et al., 1995). Millipede is not based on individual z-feedback for each cantilever, it uses a feedback control for the entire chip, which simplifies the system and this requires very good control and cantilever bending and uniformity of tip height. Chip approach/levelling is achieved making use of additional integrated cantilever sensors in the corners of the array chip so as to control the approach of the chip to the storage medium. These cantilever sensors provide feedback signals to adjust the z-actuators until uniform contact with the medium is achieved. Feedback loops for z-approach, maintains the chip levelled and contact with the storage surface while x/y scanning is being performed for write/read operations. Chips tip-apex height control should be maintained uniform and height less than 500 nm is feasible. Requirement for tip-apex uniformity over the entire chip is determined by the force applied to minimize/eliminate tip wear and medium wear due to force variations that results from large tip-height non uniformities. Each cantilever/tip of the entire cantilever array writes and reads data only in its storage field and thereby eliminating the need for lateral positioning adjustments of the tip. The storage capacity of the system changes with the areal density, bit size, and the number of cantilevers in the array. Lateral tracking will also be performed for the entire chip by tracking sensors integrated at the chip periphery. This requires good temperature control of the array chip and the medium (Suhas Somnath et al., 2013). Temperature uniformity can be maintained by using the same material (silicon) for both the array chip and the medium substrate in combination with four integrated heat sensors that control four heaters on the chip to maintain a constant array chip temperature during operation (Suhas Somnath et al., 2013). The sensors are hard wired to the rest of the storage channel and failure of any part of system leads to data loss. Even break-down of probes, sensors or read electronics is tolerated up to a certain threshold without any loss of data. The integrated sensing of the probes could be replaced by external readout. This reasoning leads us to an architecture in which laser light is used to read the data. Photo detectors collect the reflected light, which contains the desired information.

Parallel operation of large 2D arrays results in large chip sizes since space required for the individual write/read wiring to each cantilever and the I/O pads is large (Kenneth E. Goodson et al., 1999). The row/column time-multiplexing addressing scheme implemented successfully in every DRAM is a solution to this issue. For Millipede, the time-multiplexed addressing scheme is used to address the array with parallel write/read operation. The Millipede storage approach is based on a new thermomechanical write/read process in nano thick polymer layers. Thermomechanical writing on polycarbonate films and optical read back was investigated and demonstrated first by Mamin and Rugar.

As writing and reading are done by heating of tip, temperature must be controlled. Cooling must be given to cantilevers which can be determined by thermal time constant. If cooling rate is slower, it takes more time to cool and to use that cantilever again, pulse has to be given without bothering about the temperature which leads to thermal degradation of polymer. If pulse is not sent, temperature may or may not be sufficient to do the particular operation. If cooling is not provided, temperature sensors are to be used in much number and pulse duration calculations becomes complex. Pulse duration calculations are totally based on thermal time constant. Cantilever is made of semiconductor material and its intrinsic carrier density varies with temperature. As temperature increases, resistance increases up to certain level of temperature. When temperature reaches a certain value, intrinsic carrier density exceeds dopant carrier density. As heater region is lightly doped, its resistance is determined to a large extent by intrinsic carrier concentration but not dopant impurity concentration. Extra carriers that become available cause heater region to decrease in resistance, which allows more current to flow and generate more heat, leading to further drop in resistance. So cooling is important not to happen this type of situation and to achieve higher data rates.

**THE POLYMER MEDIUM:**

Polymer medium plays an important role in thermomechanical data storage. Long term reliability is achieved by a
very robust medium. The ideal medium should be easily deformable for bit writing; bits written should be stable against tip wear and thermal degradation. It must have high impact strength. It must be capable for repeatedly erase and rewrite of bits. It must be highly cross linked to limit bit size.

Mechanism involved in bit writing and erasing is that the tip is moving in polymer with greater temperature making it a viscous medium. Polymer 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. Force applied should be greater than viscous drag forces of that polymer to make an indentation. Polymer properties are dependent on the time scale of observation. The medium must exhibit high viscosity values since after the removal of tip indentation must remain. Heat is carried away by the Si substrate which is the movable chip. Additional polymer which is highly cross linked and photo resist can be placed between polymer and Si substrate to absorb heat from the indent quickly after removal of tip and also reduces wear of tip between tip and Si substrate. In viscous elastic region of polymer during writing, indent formation constitutes high viscosity and Si substrate carries heat from it makes indent cool quickly.

During read operation the read resistor is heated below glass transition temperature, during write operation the write resistor is heated above glass transition temperature and the change in polymer medium is created. The change is in the most straight-forward implementation, an indentation that represents a 1. The absence of the indentation is used both as a space between neighboring 0’s, as well as for a 1’s.

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