Design of Atomic Force Microscope Cantilevers for Combined Thermomechanical Writing and Thermal Reading in Array Operation

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Abstract*—In thermomechanical data writing, a resistively-heated atomic force microscope (AFM) cantilever tip forms indentations in a thin polymer film. The same cantilever operates as a thermal proximity sensor to detect the presence of previously written data bits. This paper uses recent progress in thermal analysis of the writing and reading modes to develop new cantilever designs for increased speed, sensitivity, and reduced power consumption in both writing and reading operation. Measurements of cantilever electrical resistance during heating reveals physical limits of cantilever writing and reading, and verifies a finite-difference thermal and electrical simulation of cantilever operation. This work proposes two new cantilever designs that correspond to fabrication technology benchmarks. Simulations predict that the proposed cantilevers have a higher data rate and are more sensitive than the present cantilever. The various cantilever designs offer single-bit writing times of 0.2 μs–25 μs for driving voltages of 2–25 V. The thermal reading $\Delta R/R$ sensitivity is as high as 4×10^{-4} per vertical nm in near steady-state operation. Analysis of the adaptable operation of a single cantilever bounds the operation of a cantilever array. The present cantilever operates with an array data rate as high as 35 Mbit sec^{-1} at a power of 330 mW and can operate at less than 100 mW. Proposed cantilevers offer a factor of 10 improvements in both data rate and power consumption. By considering their thermal, mechanical and electrical design, and by optimizing cantilevers for both writing and reading, this work aims to guide the future development of AFM cantilevers for thermomechanical data storage systems. [774]

***Index Terms*—Atomic force microscope (AFM), data storage, microscale heat transfer, thermal engineering.**

I. Introduction

THE VARIETY of applications of atomic force microscopy for the measurement of small features [1], [2] and for highly local surface modification [3]–[5] have brought atomic force microscopy (AFM) to the forefront as a next-generation data storage technology [6]–[8]. This paper describes the design of a MEMS-based data storage system that employs AFM for the thermomechanical formation and thermal detection of small data bit indentations in polymer. A review of thermomechanical data storage technology describes the development of the design, fabrication, and operation of the cantilevers. This paper employs improved understanding of cantilever thermal operation to drive further cantilever design and operation improvements. Measurement, modeling, and simulation investigate the thermal, electrical, and mechanical response of the AFM cantilever-based data storage device, with the goal of improving device design. The present work approaches the AFM cantilever design with a comprehensive view of device operation that accounts for individual AFM cantilever writing and reading operation, the cantilever fabrication and design requirements, and for system-level operation of a cantilever array.

The rapid advancement of magnetic data storage can be measured by continuous increases in the area density of data bits in commercial disk drives, currently growing at an annual rate of 100% [9]. The superparamagnetic effect, which governs the thermal stability of a magnetic data bit, will likely limit data density in current magnetic data storage technology near 100 Gbit/in^2 [10]. Several ingenious efforts show promise for expanding this limit even further, for example patterned magnetic media for perpendicular recording [11] and thermally assisted magnetic recording [12]. However, it remains unclear which technology will permit data storage devices capable of 1 Tb/in^2 and beyond.

Several AFM-based data storage technologies that employ surface modification can produce feature sizes that are significantly smaller than magnetic recording data bit sizes [3]–[8]. The various AFM surface modification research includes AFM cantilevers designed for guiding electromagnetic radiation into photoreactive polymer [13], cantilever tips which direct electrostatic discharge to locally oxidize a reactive surface [3], local chemical delivery with the AFM tip [14], direct indentation of soft materials [5], and the present approach of thermally-assisted indentation of soft materials. Mamin *et al.* [7] have written a review of AFM for data storage. Lithographic patterning of extremely small features also drives progress in technology surface modification, and in general many of the probe-based data storage approaches offer promise for lithography.

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Despite the progress and promise of these many AFM data storage technologies, there remain pervasive challenges to transferring this technology to a commercial product platform. These challenges include:

• **Speed.** Typical single-cantilever mechanical time constants are close to 100 kHz [15], which is small compared to a system-level data rate of 200 Mbit $\sec^{-1}$ for a commercially available disk drive [16]. Scanning probe data storage with competitive data rates are accomplished through single-cantilever optimization [17] and more recently the development of cantilever arrays [18], [19].

• **Ability to "close the loop"** and detect the presence of or even the size and shape of the modified feature. The first design work for AFM cantilevers used in thermomechanical data storage wrote and read data bits with separate, individually optimized cantilevers [20]. Lithographic patterning that uses an AFM cantilever tip or scanning tunneling microscope (STM) tip as a waveguide requires wet chemistry to realize the features [13]. In general, the best AFM cantilever for patterning features or writing data bits is not necessarily the best cantilever for sensing the features written.

• **Reversibility,** as in erasing data or mending a lithographic mistake. While there exist successful data storage approaches, such as digital video disk-read only memory (DVD-ROM), the magnetic-type recording scheme that offers many rewrites is often preferred.

• **Robustness.** Several approaches for probe-based surface modification and feature detection require high voltage [4], sophisticated feedback electronics, or careful alignment and preparation of a tunneling tip or a carbon nanotube [6]. The realization of a commercial product must overcome or avoid components that require laboratory equipment or high vacuum to operate reliably.

Thermomechanical data storage offers attractive solutions to each of these challenges. The present approach [8] aims to provide a large, functional array of AFM cantilevers, each capable of high data rates and high sensitivity. Elsewhere our group has reported data erasing [21], thus satisfying the reversibility requirement. Continuous contact between the AFM cantilever and the polymer surface, the sharp onset of bit formation [22], and the reliable stability of the data bits at temperatures below the bit writing temperature [23] make thermomechanical data storage very robust. This paper addresses the remaining issues of writing speed and reading sensitivity.

II. Thermomechanical Writing and Reading

In thermomechanical data writing, a resistively heated AFM cantilever is in contact with and scans over a substrate coated with a thin polymer film. Heat generated in the cantilever flows along the cantilever tip into the thin polymer film, locally raising the polymer film temperature and causing the polymer to soften. Force applied to the softened polymer from the heated cantilever tip causes the polymer to deform, thus forming an indentation, with a radius of curvature as small as 20 nm [21], [22]. Fig. 1 illustrates thermomechanical data writing.

Several realizations of thermomechanical modification of polymer surfaces preceded the current approach. Mamin [24] first demonstrated thermomechanical data writing with the AFM by using an infrared laser to heat the cantilever. Further work used a commercial piezoresistive silicon cantilever that self-heated during brief electrical pulses [25]. While these resistively heated piezoresistive cantilevers could thermally write without the optical access of the first design, the entire cantilever was heated during an electrical heating pulse, resulting in cantilever thermal time constants as long as 0.45 ms. In order to reduce the thermal time constant for heating, Chui *et al.* [20] designed and optimized AFM cantilevers with a heating time of less than 1 μs, and a cooling time of near 10 μs. The design improvement consisted of preparing the silicon cantilever with regions of differential impurity doping, such that only a small region of the cantilever near the tip was highly resistive, therefore creating a small heater region with significantly reduced heat capacitance.

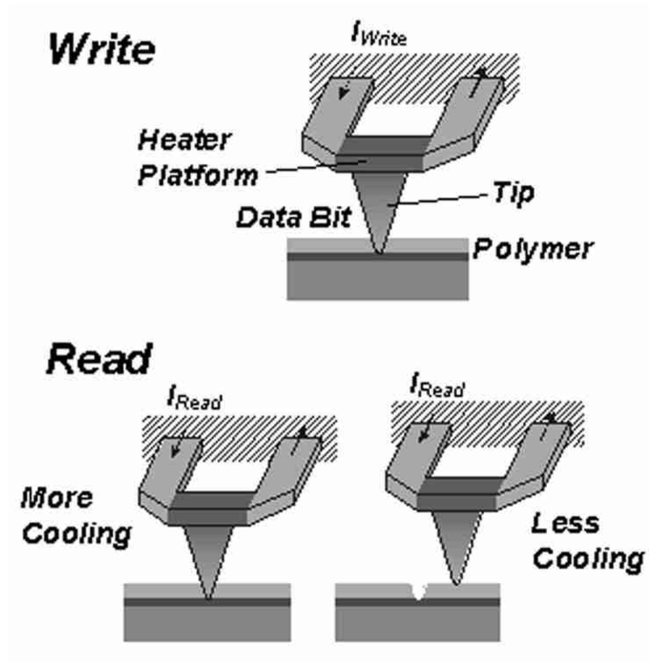


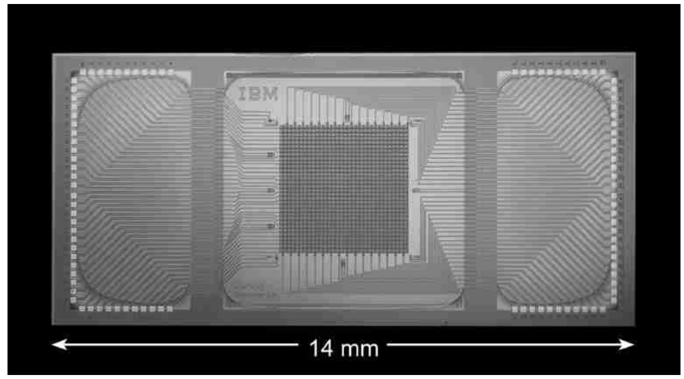
Fig. 1. Schematic of thermomechanical data writing and thermal data reading. The same cantilever can be used for both writing and reading. The heat transport mechanism for writing is distinctly different from that for reading, motivating concurrent optimization of the cantilever for both.

A resistively heated silicon cantilever can be used to thermally detect the presence of a previously written data bit, allowing data reading. In reading operation, the cantilever is heated to a temperature that is below the threshold temperature for bit formation. As the warm cantilever follows the contour of a previously written data bit, the change in the thermal impedance between the cantilever and the substrate produces a measurable change in the temperature of the cantilever. By recording the dynamic temperature signal as the cantilever tip moves over the polymer surface, a surface contour map can be made. Fig. 1 illustrates thermomechanical data reading. Binnig *et al.* [21] measured the vertical sensitivity of thermal data reading to be between 10^{-4} and 10^{-5} per vertical nanometer for a cantilever that had not been optimized for thermal data reading. This thermal data reading technique is distinct from that scanning of thermal microscopy [26], where a small thermocouple scans over a sample to measure a local temperature field. Scanning thermal microscopy is significantly better than our present implementation for high-resolution thermometry, while our thermal proximity sensing yields extremely high vertical sensitivity for topographic imaging.

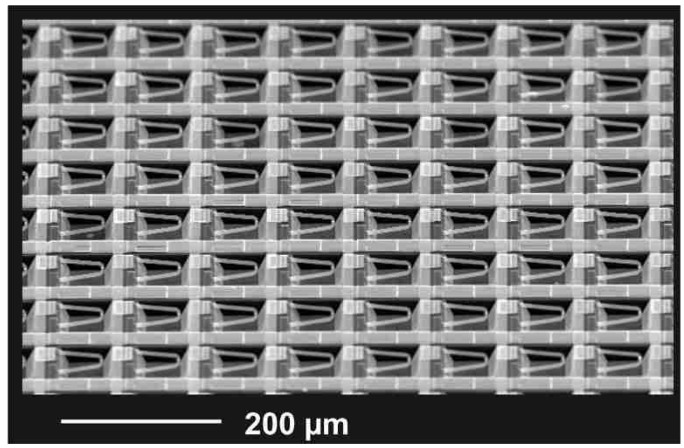
A crucial stage in the development of thermomechanical data storage technology was the development of fabrication techniques to reliably make AFM cantilevers with uniform mechanical and electrical properties [8], [20], [27]. Fig. 2 shows the latest cantilever, which is 50 μm in length and has a tip height of 500 nm. More recent versions of this cantilever have a smaller tip height and are thinner for improved reading sensitivity [29]. This cantilever is intended for use in an array of many cantilevers, such as the array of Fig. 2. Fig. 2 shows an array of 1024 cantilevers in a 32 $\times$ 32 square array. The fabrication of this array device is detailed in Refs. [8], [27].

A cantilever array can write and read data bits with higher speed than a single cantilever operating alone. Fig. 3 shows a concept of the operation of a cantilever array for thermomechanical data storage. While much work has been done to design and optimize individual AFM cantilevers (for example [17]), only recently has there been significant progress in the development of cantilever arrays. Lutwyche [28] report the fabrication and operation of a 5 $\times$ 5 cantilever array, which measured features of characteristic size 2 μm. A larger device with 1024 cantilevers in a 32 $\times$ 32 square array, known as the "Millipede" [8], demonstrated successful thermomechanical and thermal data reading at a data density of 100–200 Gb/in^2 [29]. The present study targets the design of a cantilever for operation in a cantilever array similar to the Millipede.

Analysis of heat transport in the cantilever has yielded a more thorough understanding of thermomechanical writing and thermal reading. King *et al.* [30], [31] performed analysis of heat transport in the AFM cantilever during thermal data reading and thermal data writing with the goal of understanding and improving cantilever operation. This work showed that for a typical cantilever tip height of 300 nm, there is a temperature difference of approximately 50 °C along the length of the cantilever tip for typical heater temperatures of near 350 °C. This temperature drop along the length of the cantilever tip is primarily due to sub-continuum heat transport effects in the cantilever tip [30]. Significant rise in the polymer data layer temperature is limited to regions experiencing direct heating from contact with the tip, and does not occur through any other transport mechanism such as conduction through the air. Thus, data bit writing occurs only due to the presence of the cantilever tip. These authors additionally showed that the thermal reading does not occur due to the change in contact area between the tip and sample as the tip enters and exits a bit formation. Rather, the thermal reading occurs through the following process: as the cantilever tip follows the contour of the written bits, the distance between the cantilever legs and the substrate changes. This change in the cantilever–substrate air gap thickness modifies the thermal impedance of the cantilever heater region, thus resulting in a varying temperature of the cantilever heater region for a constant heating power [31], [32]. Thermal analyzes have concluded that it is the presence of the tip that induces data bit writing, and the heat flux from the



(a)



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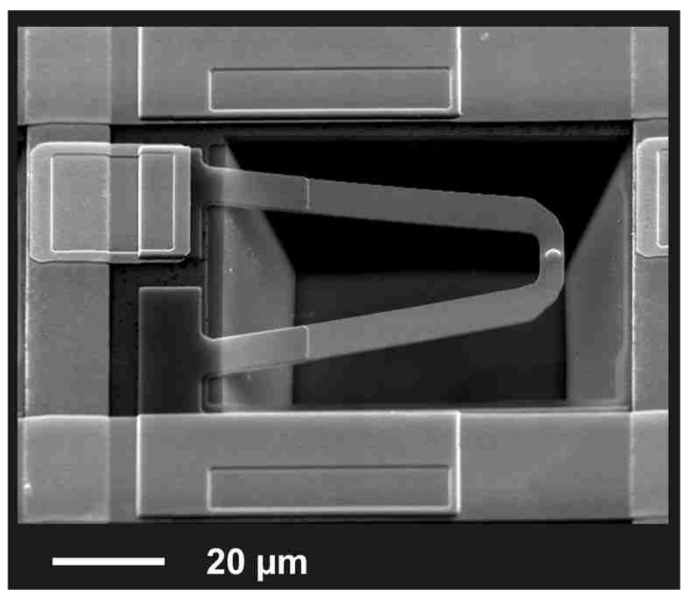


(c)

Fig. 2. Picture of the Millipede cantilever array data storage chip and scanning electron microscope images of individual cantilevers in the array. Fabrication details can be found in [8] and [27] and successful operation of the array is reported in [29].

cantilever heater and legs into the data substrate that permits thermal data reading.

The use of individual cantilevers for both writing and reading motivates improved cantilever design, which is made possible by the recent progress in understanding cantilever thermal operation. Previous published work on cantilever design [20] for thermomechanical data storage focused on optimizing the operation of single cantilevers for serial bit writing, and did not account for thermal reading with the same cantilever or for the cantilever operating in an array. As the heat transport mechanisms for reading and writing are separate for the current Millipede cantilever design are separate, there exists an opportunity to optimize the cantilever thermal operation for both thermomechanical writing and thermal reading [33], [34]. The ultimate cantilever design must not only consider thermal operation, but also electrical and mechanical operation, all of which are interrelated, thus complicating the design analysis.

This paper reports progress in the detailed measurement and simulation of cantilever electrical and thermal operation, with the goal of improving future designs. Electrical measurement of single-cantilever operation compares well with a finite-difference simulation of cantilever electrical and thermal operation. The validated simulation is then used to predict the operation of two future cantilever designs. Finally, an analysis of cantilever array operation predicts system operation requirements.

III. Measurement and Simulation Approach

The measurement of the cantilever electrical response to brief electrical pulses is an effective technique for characterizing cantilever thermal and electrical operation. The general measurement approach described here has previously been used to characterize the thermal and electrical operation of cantilevers during single heating events [20], [24]. This paper uses the same approach, and additionally uses it to characterize cantilever thermal reading behavior. Fig. 4 shows a circuit that was built to electrically drive the cantilever with short voltage pulses and to measure the cantilever electrical response. By monitoring the voltage across both the sense resistor–cantilever system and the sense resistor alone, it is possible to monitor both the current flow through and voltage across the cantilever. A continuous dc offset of 1 V allowed for observation of the cantilever cooling time. Voltage pulses between 1 1 μs and 25 μs in length and between 1 V and 20 V in amplitude above the offset voltage excited the cantilever–sense resistor circuit. These pulse lengths are comparable to those used to write data bits in both single cantilever bit writing [21] and array bit writing [29] operation. A storage oscilloscope captured the transient voltage across the circuit and across the sense resistor. The threshold temperature for bit writing with this cantilever type was previously determined to be $350\,^{\circ}$C, which corresponds to a cantilever resistance of 5.1 kΩ. The parameters for cantilever bit-writing operation were determined as the time required and energy used by the cantilever to reach this electrical resistance.

Combined force and thermal detection of the cantilever–substrate gap thickness calibrate the cantilever thermal data reading sensitivity. For typical thermal data reading operation of the Millipede cantilever, a constant dc offset voltage of between 1 V and 3 V monitors the voltage across the cantilever. As the cantilever scans over the contours of the data surface, the change in voltage across the sense resistor detects the change in current flowing through the cantilever, which corresponds to the change in cantilever resistance. The most sensitive thermal data reading operation is for a sense resistance close to the resistance of the cantilever, which is approximately 2.5 kΩ. A smaller sense resistor could be used to reduce the total power consumed by the circuit, but would result in reduced sensitivity. In this measurement, a calibrated piezoelectric actuator holds the data media. Varying the voltage across the piezoelectric actuator changes the cantilever–substrate distance. A laser is directed at the cantilever, and a differential optical detector captures the laser signal reflected off of the cantilever. Measuring the change in reflected angle of the laser off the cantilever allows detection of cantilever deflection. This mimics a common technique for optical AFM [1]. An oscilloscope monitors the voltage across the sense resistor as the cantilever–substrate gap narrows. The cantilever begins to deflect at cantilever-substrate contact, and this is then determined to be the baseline signal for thermal data reading. The cantilever is withdrawn from the sample, and the cantilever electrical resistance is measured at a cantilever–substrate gap distance of 100 nm. This 100 nm retraction is sufficient to remove any hysteresis observed between the approach and withdraw of the cantilever [22]. These two resistances then yield the cantilever thermal data reading sensitivity as

$$S = \frac{\frac{R_{\mathrm{Surface}} - R_{100\ \mathrm{nm}}}{R_{\mathrm{Surface}}}}{\Delta}. \qquad (1)$$

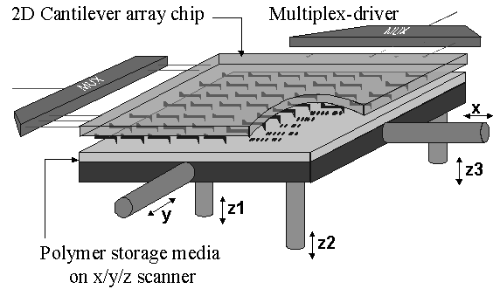


Fig. 3. The concept for a data storage device is to operate the cantilever array such that each of the cantilevers is in contact with a polymer data substrate. By scanning the cantilever array relative to the substrate and electrically selecting individual cantilevers from the array, high data rates and data capacity is possible.

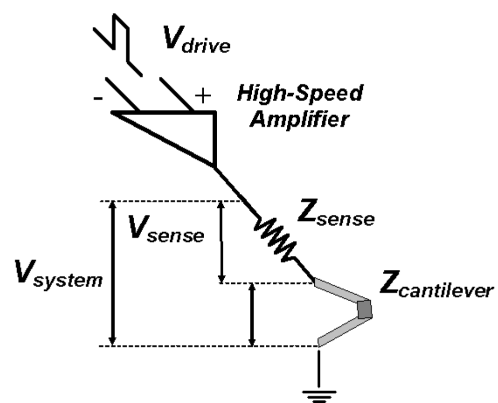


Fig. 4. High-speed electronics electrically drive and monitor the electrical response of the cantilever. The sense resistor is not needed in data writing, as data writing is accomplished in open-loop operation, but is required for thermal date reading.

Where S is sensitivity in m^{-1}, $R_{Surface}$ is the electrical resistance of the cantilever in contact with the sample surface in Ω, and $R_{100\ nm}$ is the cantilever electrical resistance at a distance of 100 nm from the sample surface in Ω. The absolute value of S can be positive or negative, as the temperature coefficient of electrical resistance changes sign as the doped silicon cantilever enters a thermal runaway regime. Chui [35] provides a detailed study of thermal runaway in doped silicon microcantilevers.

A finite-difference simulation predicts the transient cantilever temperature distribution and electrical properties for the duration of the electrical heating pulse. The simulation divides the cantilever and nearby air into finite elements with dimensions of 50 nm on a side. Fig. 5 shows a schematic of the simulation domain. By including the presence of the polymer-coated silicon substrate, the simulation can predict the operation of the cantilever during thermal data reading. Solution of the heat equation calculates the temperature at each of the temperature nodes at each time step. The heat equation is given as

$$\nabla^2 T + \frac{q}{k} = \frac{\rho C_p}{k}\frac{dT}{dt}. \qquad (2)$$

Where T is the temperature at each temperature node in K, q is the heat generated at each node in W, k is the local thermal conductivity in W/mK, ρ is the material density in kg/m^3, C_p is the material heat capacity in J/KgK, and t is time in sec. Equation (2) is solved through a second order discretization in space. Explicit time advancement employs steps of 1 ns in length. Circuit design models [36] calculate the temperature-dependent intrinsic carrier generation and the temperature-dependent electrical resistivity of the doped silicon at every time step. The thermal conductivity of the heavily doped thin silicon cantilever is assumed to be 50 W/mK, and to vary as the inverse of temperature. The simulation operates in the following manner: for each simulation time step, the simulation calculates the total cantilever electrical resistance, which determines the cantilever current at fixed driving voltage. The cantilever current determines the heating power at each position along the length of the cantilever. The simulation agrees with analytical solutions for one-dimensional transient thermal conduction in the cantilever to within 2% for the present geometry and simulation parameters. Further discrepancy between the simulation and measurement results beyond the simulation error is due to noise and parasitic capacitance in the cantilever.

IV. Cantilever Designs

This work predicts the operation of three separate cantilever designs. The first cantilever is identical in its mechanical and electrical properties to the Millipede cantilever shown in Fig. 1, and it is with this cantilever that measurements are made. The good agreement between measurement and simulation verifies the simulation predictive ability for operation of the improved cantilevers. The design of the second cantilever corresponds to the fastest and most sensitive cantilever that could be made with no changes to the fabrication process that produces the present Millipede cantilever. Finally, the third cantilever is the fastest

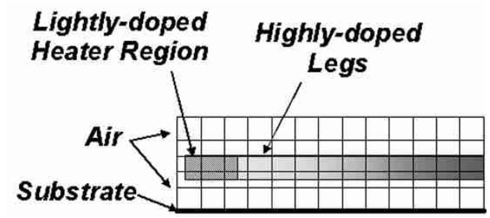


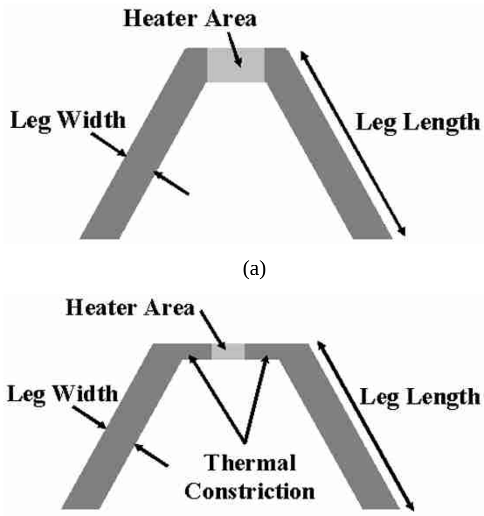
Fig. 5. The finite-difference simulation regime contains temperature nodes in and around the cantilever. The substrate can be added to the simulation as a boundary condition in order to predict cantilever operation during thermal data reading.

and most sensitive that could be produced with CMOS-like manufacturing processes known today. The present paper refers to the present cantilever, the improved cantilever, and the advanced technology cantilever as cantilever Type A, B, and C, respectively. Fig. 6 shows the basic schematics of the present and proposed cantilevers: Fig. 6(a) represents cantilever Types A and B, Fig. 6(b) shows Type C. Table I lists the geometric parameters of heater region area, cantilever length, width, thickness, and cantilever tip height. Table I additionally gives the electrical and mechanical properties of the three cantilever types.

This work assumes that for data bit writing in thin poly methyl methacrylate (PMMA) films, the cantilever must reach the previously-reported bit-writing temperature of 350 °C [21], [22], [29] and the cantilever tip must be in good contact with the polymer film. While the overall writing time will be governed also by loading force and tip shape, the previously published data [21], [22], [29] has shown that a cantilever spring constant as high as 3 N/m [21] and as low as 0.01 N/m [21] writes data bits at a threshold writing temperature of 350 °C. In general, the cantilevers with the smallest volume in which resistive heating takes place will be the fastest for heating. The presence of a thermal constriction near the heater, as in Fig. 6(b), will shorten heating time. Chui [20] designed cantilevers with similar thermal constrictions, but noted that the longer thermal relaxation time associated with the thermal constriction adversely affected the time between serial writing events with a single cantilever. Increased time between heating events is not necessarily a disadvantage in the design of cantilevers for parallel operation.

The electrical resistance of the cantilever, which is given primarily by the electrical resistance of the small heater at the cantilever end, should be as small as possible, to reduce the voltage and power requirements for device operation. However, the smallest practical value of the cantilever electrical resistance is near 1.5 kΩ, as the resistance of the heater region must be large compared to the electrical resistance of the cantilever legs and the on-chip interconnects.

In general the thinnest cantilevers with the shortest tips will be the most sensitive for thermal data reading [32]. Several generations of Millipede cantilevers have been fabrication, each thinner than the last. The original Millipede type cantilevers were 500 nm thick [27] and had cantilever tips 500 nm in height. The Millipede cantilevers have more recently been made thinner at 300 nm, and with shorter tips also at 300 nm [29] for improved reading sensitivity and lower stiffness. The cantilever measured in the present work is the thinnest we have fabricated to date,



(a)

(b)

Fig. 6. Schematic of the basic cantilever "footprint." Cantilever Type A and Type B have the footprint of (a), and cantilever Type C has the footprint of (b). The thermal constrictions reduce the quantity of heat that flows along the legs of the cantilever, thus increasing writing speed and thermal reading sensitivity.

TABLE I
MECHANICAL AND ELECTRICAL DESIGN PARAMETERS OF THE CANTILEVERS CONSIDERED IN THE PRESENT STUDY

Cantilever	A Present Cantilever "Millipede"	B Next Generation	C Advanced Technology
Heater	5 μm x 7 μm	2 μm x 5 μm	0.2 μm X 0.3 μm
Thermal Constriction	-	-	0.2 μm X 0.3 μm
Leg Length	50 μm	20 μm	10 μm
Leg Width	10 μm	5 μm	1 μm
Thickness	0.2 μm	0.2 μm	0.2 μm
Tip Height	0.5 μm	0.2 μm	0.2 μm
Spring Constant	1.8 N m^{-1}	0.11 N m^{-1}	0.18 N m^{-1}
Mechanical Resonant Frequency	189 kHz	236 kHz	980 kHz
Heater Doping	10^{18} cm^{-3}	10^{18} cm^{-3}	5 X 10^{17} cm^{-3}
Electrical Resistance at 25 °C	2.66 kΩ	2.01 kΩ	1.55 kΩ

at 200 nm. Shortening the cantilever tips below approximately 200 nm will have a reduced improvement on cantilever reading sensitivity, as the mean free path of air molecules at room temperature and pressure is near 60 nm [37]. Therefore, at a gap distance of several mean free path lengths and below, fewer air molecules will exchange thermal energy with the cantilever and data substrate, thus reducing the effective thermal conductance of the air gap below the conductance predicted by continuum theory [38]. The reduced thermal conductance between the cantilever and the substrate reduces improvements in thermal reading sensitivity accordingly.

The presence of the thermal constriction increases the thermal resistance of the cantilever legs. This increased thermal resistance is intended not only to improve the writing speed, but also to improve thermal reading sensitivity of the cantilever. The thermal impedance of the thermal constriction causes a higher fraction of the heat generated in the cantilever across the air gap, and into the data substrate below the cantilever. The temperature of the cantilever heater region therefore depends more strongly

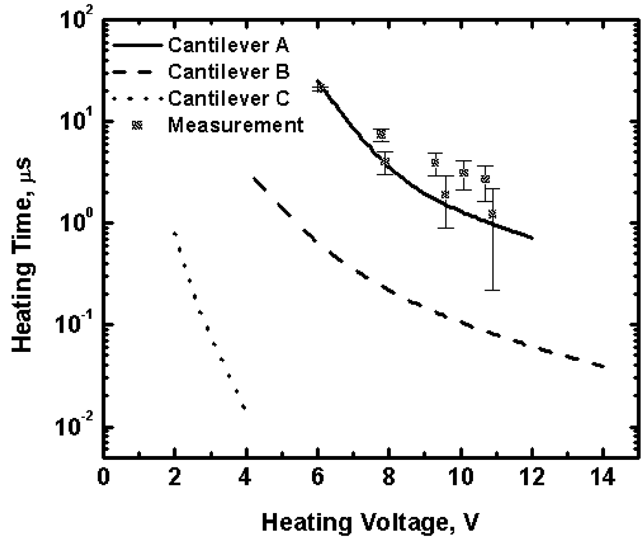


Fig. 7. Time required to reach the bit writing temperature as a function of voltage applied to the cantilever.

upon heat transfer across the air gap, and is more sensitive to changes in the heat transfer across the air gap.

V. RESULTS AND DISCUSSION

Key parameters that affect the design and operation of a data storage system are data writing and reading rates, the energy consumed during data writing, and the sensitivity during data reading. Measurement results for the Type A cantilever compare well with predictions made using the finite-difference simulation. Predictions are also made for the operation of the Type B over its entire operational range and for Type C for a nominal operation point.

A. Thermomechanical Data Writing

The time required for the cantilever to reach the bit writing temperature defines a key parameter in the single-cantilever writing rate. Higher voltages allow the cantilever to reach the bit writing temperature in shorter time, but can place more strenuous power supply requirements on the data storage system. The power requirement is particularly important for mobile data storage applications. Fig. 7 shows the time required for the cantilever to reach the bit writing temperature as a function of voltage applied to the cantilever. There exists a threshold voltage below which the cantilever will never become hot enough to write a data bit. This threshold voltage is measured as near 6 V for the present cantilever, with improvement to 4 V for the Type B cantilever. Bit writing is possible with the type C cantilever at 2 V at near 1 μs heating time. The threshold writing voltage defines the longest bit writing time and lowest power at which the cantilever could operate.

A second parameter which influences system level design and operation is the energy required to write a single data bit. The very small size of the MEMS chip shown in Fig. 2 motivates targeting an interface with mobile electronics for commercial realization. Such a mobile device will operate at least some of the time on a battery power supply, for which the energy drawn from a battery is an important constraint. Fig. 8 shows the energy required for the cantilever to write a single bit as a function of heating time. For all three cantilever types, the bit writing energy decreases with decreased heating time. This is because for shorter cantilever heating times, heat has less time to diffuse into the nearby air and along the cantilever legs. Therefore, a higher fraction of the heat remains in the heater region, increasing the heating efficiency. The minimum amount of energy required for bit formation is defined by the product of the heat capacity of the heater platform and the temperature rise in the platform. For cantilever A, B, and C, the minimum possible energy required is 3.8 nJ, 1.1 nJ, and 6.5 pJ. In Fig. 8, cantilevers A and B approach their minimum energy operating point. The minimum energy operating point for cantilever C is beyond the chart boundary. Considering only the single-cantilever energy requirement, the data storage system operates most efficiently if the cantilever heats fast enough for the minimum energy limit, but no faster.

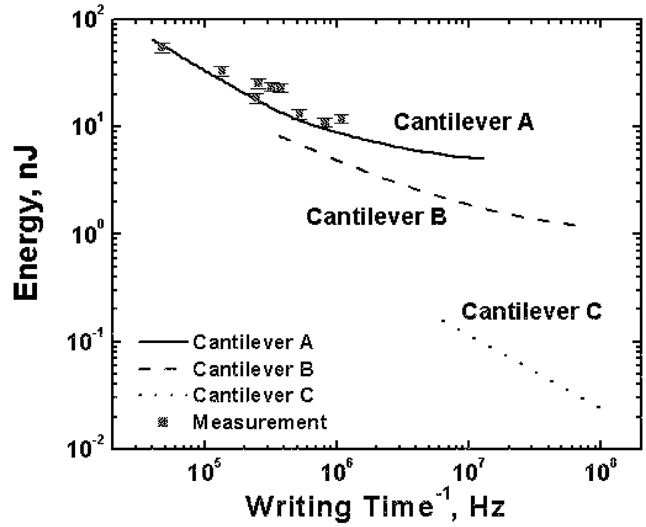


Fig. 8. Energy required to heat the cantilever to bit writing temperature as a function of the inverse of writing time. The inverse of writing time is close to the data writing rate. The electrical time constant of the measurement cantilever bond pad metal, limits measurement of Cantilever A.

B. Thermal Data Reading

A cantilever optimized for thermal data writing is not necessarily also optimized for thermal data reading. The present work aims to optimize cantilevers concurrently for data writing and thermal data reading. Fig. 9 shows the thermal data reading sensitivity as a function of cantilever heating power for a 100 nm vertical cantilever displacement. Thus, Fig. 9 shows the approximate cantilever sensitivity for reading a data bit of depth of 100 nm. The general double-hump shape of the curves is because the temperature coefficient of electrical resistivity changes from negative to positive at a temperature of near 100 °C. A higher cantilever heating power corresponds to a larger difference between the temperatures of the cantilever heater region and the data substrate, resulting in a higher thermal data reading sensitivity. The nonlinear shapes of the curves for sensitivity as a function of temperature indicate both the heat transfer rate from the cantilever into the substrate and the temperature dependence of the cantilever electrical resistance.

Cantilevers are preferred to have higher sensitivity and lower power consumption. There is a general trend of improvement in thermal reading sensitivity for the successive cantilever designs at given power operation points. The Type B cantilever is predicted to have improvement in thermal data reading sensitivity over the Type A Millipede cantilever, due to the shorter cantilever tip and the more narrow cantilever legs. Type C cantilever offers an improvement in thermal data reading sensitivity due to the presence of the thermal constrictions as well as narrower legs, but the overall improvement is on the power axis, not the sensitivity axis.

The nonlinear shapes of the curves for sensitivity as a function of temperature indicate the coupling of the heat transfer rate from the cantilever into the substrate and the temperature dependence of the cantilever electrical resistance. The shift of the doping concentration for the Type C cantilever, which was required to achieve a reasonable room-temperature electrical resistance, causes the cantilever to have different temperature-resistance characteristics. For the measurements reported in Fig. 9 the signal to noise ratio was always better than 10 : 1 for operation at near steady state conditions, with the best signal to noise ratios found for the highest reading

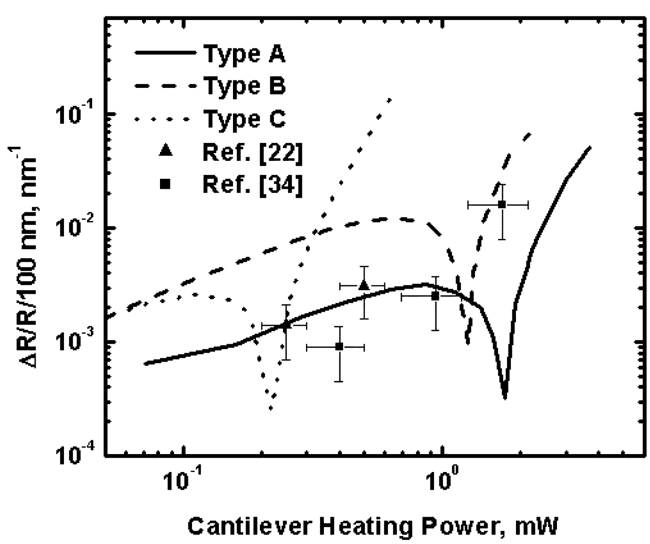


Fig. 9. Thermal data reading sensitivity as a function of cantilever heating power. The previously reported reading sensitivity was estimated in [21] and [29] for cantilevers with designs similar, but not identical to the Type A cantilever.

temperatures. The cantilever should operate at temperatures as high as possible for high sensitivity and good signal to noise characteristics but not so hot that previously formed data bits are erased or modified, and that new data bits are not formed. Cantilevers with extremely small heater-thermometers, such as the Type C cantilever will benefit from detailed analysis and measurement of noise sources, as well as a study of the time constants associated with dynamic reading. Our experience is that the cantilever time constants associated with dynamic thermal reading are close to the time constants for data writing. While the measurements and simulations reported here are steady-state measurements, the thermal data reading sensitivity reported here is much higher than the sensitivity reported for commercial piezoresistive cantilevers [15].

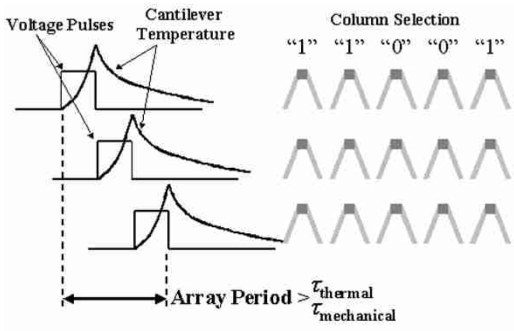


Fig. 10. The array operates with multiplexed row-by-row writing and reading [29]. Power is delivered for each row in a serial manner, and each cantilever will be selected for bit formation by connection of the electrical path along the column. A "1" refers to electrically switching the cantilever "on" for heating and bit formation; a "0" refers to keeping the cantilever switched "off" for no heating and no bit formation.

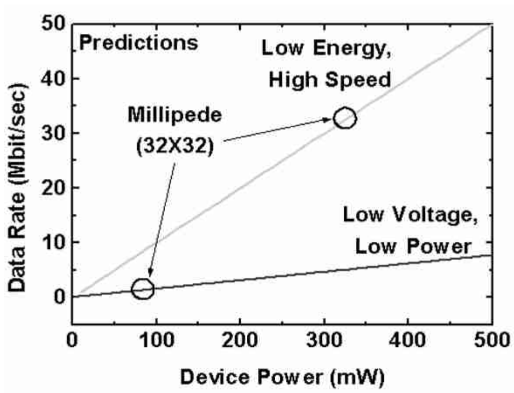


Fig. 11. Predictions for array operation of the Millipede Type A cantilever. The data rate can be varied by varying the cantilever driving voltage, which will correspond to a change in the power requirement. The circles represent operation of all 1024 cantilevers of the Millipede array shown in Fig. 2.

C. Cantilever Array Operation

Previous published work that focused on improving AFM cantilever design for data storage applications primarily focused upon serial cantilever writing and reading, and therefore took the single cantilever mechanical, electrical, and thermal time constants as the fundamental limits of data rate. Array operation imposes different limits on the data rate. In practice, the Millipede array writes line-by-line, as shown in Fig. 10. A multiplexing scheme selects columns for "1" or "0" to be written by pulling up the source of an external transistor, and the rows are selected one at a time [29]. Thus, in the operation of n^2 cantilevers in a square n by n cantilever array, n^2 bits can be written in the time required to select n rows. If n rows can be selected for at a rate equivalent to the single-cantilever serial writing rate, then n^2 bits can be written at the single-cantilever serial writing rate.

The single-cantilever serial writing time is not a fixed number but rather a function of heating voltage, as shown in Fig. 7. Therefore, the array data rate will also be a function of heating voltage. The practical limit of array operation speeds will not be heating voltage, but heating power. Fig. 11 shows predictions for data rates possible with the Millipede Type A cantilever in array operation as a function of available heating power. The two lines represent two separate operating conditions: one at the lowest power and speed, the other at a high speed, energy-efficient operation point. The cantilever array could operate at any position between the two lines with changes only in the electrical signals delivered to the cantilever array. The possibility to dynamically change the operation point of a thermomechanical data storage device is a feature not previously anticipated, but with possible advantages over magnetic data storage devices which must operate at near constant power during write/read operation, due to the mechanical spinning of the magnetic disk.

VI. Summary and Conclusions

This paper reports progress on the design of cantilevers, concurrently optimized for data writing and reading, which are targeted for use in array operation. Measurements and simulations are made for the operation of the present generation Millipede cantilever. Good agreement between measurement and simulation indicate progress in the basic understanding of how the cantilever accomplishes data writing and reading. Two additional cantilever designs improve on both the single-cantilever writing time and the thermal data reading sensitivity over previous cantilever designs. High data rates are possible with parallel cantilever operation in an array, and combined analysis of single cantilever and array operation shows the system-level adaptability in a power and speed tradeoff.

There remain several open opportunities to improve the technology discussed in this paper. While the present cantilever array is square, it is not clear that the best array will be square. A data storage product requirement could impose power and data rate requirements on that the optimal array is rectangular. Technology applications beyond data storage, such as lithography or micro-manipulation could drive completely different device requirements. The very high thermal data reading sensitivity offers exciting opportunities for future metrology applications.

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