MEMS Memory Elements

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Abstract— This paper presents a design example that illustrates the potential of microelectromechanical systems (MEMS) to perform the mechanical positioning required for addressing stored data and to enable an entirely new mechanism for reading and writing magnetic data. Specifically, MEMS sensors and actuators can be used to achieve active servo control of the separation between magnetic probe tips and a media surface with sub-nanometer accuracy. This allows mechanical position to be used to selectively write magnetic marks in a continuous thin-film magnetic media. In addition, MEMS sensors can be used to measure the separation between a magnetic probe tip and the media with a noise floor of roughly 22 picometers, allowing them to be used as position sensors in a magnetic force microscope (MFM) style data detection system.

TABLE OF CONTENTS

1. INTRODUCTION

Mass data storage devices in which data is addressed by positioning some form of storage media with respect to an array of sharp probe tips using microelectromechanical systems (MEMS) have the potential to create a whole new storage technology capable of achieving a quantum decrease in entry cost, access time, volume, mass, power dissipation, failure rate, and shock sensitivity when compared with today's hard disk drives. At the same time, MEMS-based mass storage devices have the potential to achieve a cost / bit stored that is one to two orders of magnitude cheaper than that of patterned nonvolatile storage technologies; e.g., EEPROM, MRAM, FeRAM, etc. This is because they do not rely on lithography to precisely define a data storage cell – they rely on mechanical positioning for addressing.

MEMS-based mass storage devices could enable many new applications capable of exploiting the low entry cost and extremely small size of these new hybrid devices; e.g., "intelligent" appliances, sophisticated teaching toys, biomedical monitoring devices, civil infrastructure monitoring devices, micro- and nano-satellites, highly-integrated archival storage systems, highly-secure storage systems, etc.. For many of these applications the needed computing power is already available at low cost. What has kept many of them from becoming a reality is the lack of low cost mass data storage device storing a few gigabytes of data and costing only $10-$20.

The technologies needed to build these hybrid devices are already emerging, making it likely that a broad market for MEMS-positioned nonvolatile rewritable **mass** storage devices will develop within the next five years. This paper examines one approach to creating a MEMS-based data storage technology being developed in the Center for Highly Integrated Information Processing and Storage Systems (CHIPS) at Carnegie Mellon University.

In this paper, we will first describe the design of a MEMS media positioning system. Next, we will describe a MEMS probe tip positioning system that can control the spacing between the probe tip and the media. We will discuss the feasibility and performance of using electrostatic actuation and capacitive sensing to actively control the height of each probe tip with respect to the media. Then, we will describe an approach to creating a large array of permanent magnet nanometer size probe tips. Finally, we will describe results of computer simulation of both the writing and reading processes for this type of MEMS-positioned permanent magnet probe based mass storage device.

2. MEDIA POSITIONING

Microelectromechanical systems (MEMS) are being developed as actuators for positioning the media in new mass-manufactured silicon-based non-volatile storage devices at a number of companies and research universities; e.g., IBM [1], HP [2][3], Kionix [4][5] and CMU [6]. In general, all of these approaches include

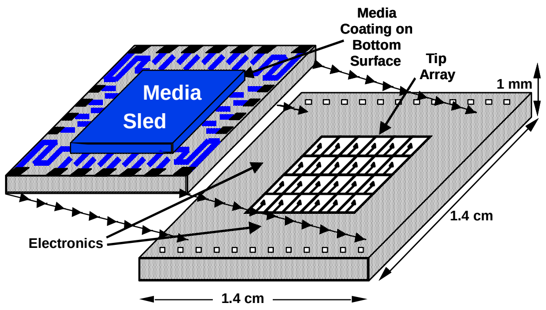

Fig. 1: Conceptual diagram MEMS-Actuated data storage devices with X-Y motion of the media and Z motion of the Probe Tip for a 4x5 array of Probe Tips with electrostatic actuators.

some form of storage media on the surface of a large nearly flat micromachined plate that is suspended by springs and moved in X and Y as a result of the force generated by electrostatic, piezoelectric, or magnetic actuators. The micromachined plate has the potential to move with nanometer resolution because there are no rubbing mechanical contacts between components and hence, there are no stiction problems. For structures with micrometer dimensions, the surface area to volume ratio is high; therefore, stiction forces between any two surfaces that touch (e.g., the surfaces in any mechanical bearing) are extremely large and make precise positioning nearly impossible.

Unfortunately, most MEMS spring suspension systems exhibit repeatable linear motion only for deflections that are a small fraction of their length (typically 10%). In order to scan data stored on the entire media plate, a large array of probe tip read / write heads is necessary. As long as the pitch of the array in X and Y is smaller than the peak motion of the media plate in X and Y, then the complete media area can be used for data storage. Fig. 1 illustrates a simplified diagram of a MEMS-actuated probe-based storage device constructed from two silicon wafers that are bonded together.

Because the cost to manufacture devices using a VLSIC photolithographic fabrication process is roughly proportional to the total area of the device, one important figure of merit for MEMS-actuated data storage devices is the percentage swept area, which we define to be the fraction of the total area of the die containing the probe tip array that can be addressed by all of the tips. For a fixed minimum line width used to define the springs, the maximum deflection achievable in an electrostatically actuated media positioning system rises roughly as the square of the X or Y dimension of the overall structure. Therefore, bigger actuators and bigger media plates result in higher percentage swept areas.

A simplified conceptual layout of one proposed media actuator is shown in Fig. 2. The anchors (black squares) in the four corners are all connected to the media sled. They are held near electrical ground and a high-frequency excitation signal is applied in order to allow capacitance measurements to be made. The comb-like structures on the four sides are the actuator stators. Both the media anchors and the actuator stators are bonded to the underlying silicon wafer that holds the probe tip array and the CMOS electronics in a wafer-to-wafer bonding process. This avoids hand assembly of individual devices. X and Y positioning will be performed by a closed-loop control system that senses the position of the stage by measuring the capacitance of each actuator using high frequencies and controlling the force of each actuator by applying a low frequency signal.

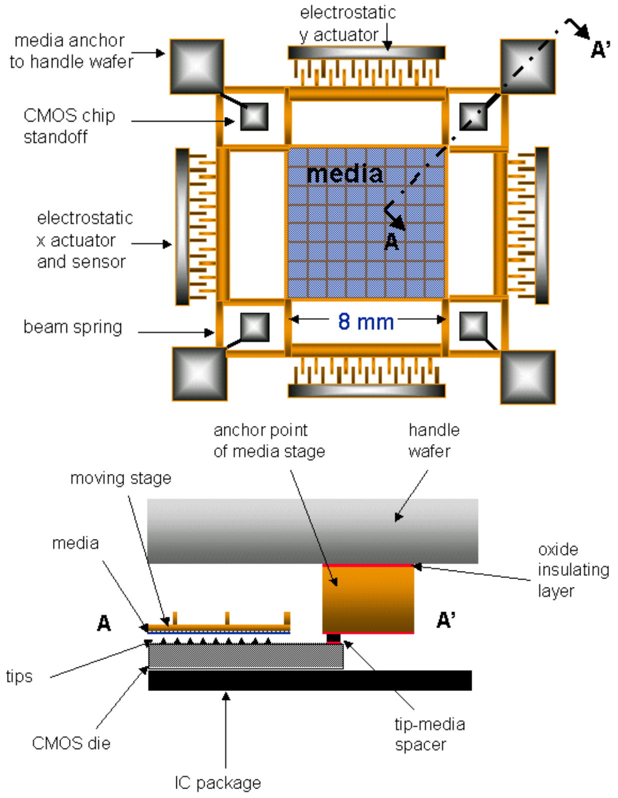

Fig. 2: Simplified pictorial diagram of the MEMS media actuator. Below is a cross-section illustrating how the single crystal silicon actuator wafer can be assembled onto an IC with an array of probe tips.

This design for the media actuator is based on a decoupled-mode X-Y microstage originally conceived for use as a vibratory-rate gyroscope [12]. A box-spring suspension is used to decouple the two in-plane directions of actuation so that comb fingers can be used for X and Y actuation without mechanical interference. High-aspect-ratio silicon structures allow the actuator to remain extremely flat even though it is a large structure. In addition, in order to decrease the mass of the media plate, much of the mass is etched away leaving only stiffening beams to maintain flatness. The high aspect ratio also greatly diminishes the vertical motion resulting from external accelerations of the device. Note that the fabrication and operation of the media actuator have been described further by Carley et al [6].

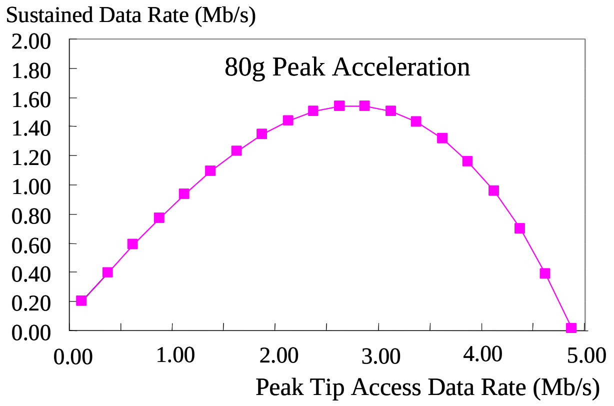

Fig. 3: Overall sustained data rate as a function of the actual probe tip reading and writing data rate (assumes probe makes no limit on data rate).

Because there is a maximum voltage that can be applied to the actuator, there is also a maximum acceleration that can be imparted to the media plate. In this design, peak operating voltages for the actuators are 120V which generates a peak acceleration of roughly 80g's. It is important to realize that there is an optimum individual probe tip data rate for any Cartesian storage device subject to a maximum acceleration limit (see Fig. 3). For a 100µm-stroke Cartesian media plate and an 80g acceleration limit, probe tip data rates above 3Mb/s actually result in a lower average data rate. This is because the media plate spends a disproportionate time decelerating and turning around after reading an individual track, and, because higher probe tip data rates require higher linear velocity for a given data bit size (see [13]).

3. PROBE HEAD POSITIONING

Most mechanisms for reading and writing data bits require the probe tip to be extremely close to the media (typically much closer than the mark size). Therefore, some mechanism must be provided to allow all of the large array of probe tips to come into near contact with the media simultaneously. Most approaches to this problem place each probe tip on the end of a mechanical beam that can move in the Z direction. Passive schemes simply bring the array of probe tips and the media together until there is contact between all of the probe tips and the media [1]. Wear of the probe tips and the media is minimized by keeping the spring constant of the cantilevers low and keeping the difference between tip heights small.

One major advantage of magnetic recording as a storage mechanism is that physical contact between the probe tip and the media is not required – a soft or hard magnetic probe tip need only be brought to within a fraction of the recorded mark size to allow reading and writing [7]. In this section we describe a methodology for precisely controlling the probe-tip to media spacing with sub-nanometer accuracy.

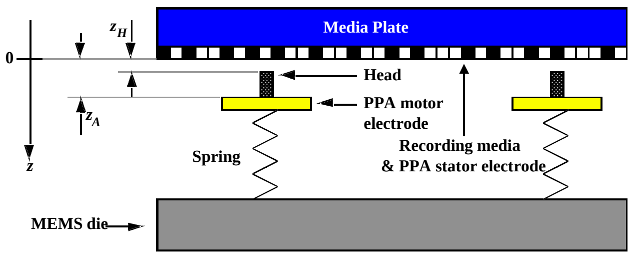

Fig. 4: General approach of using a parallel plate capacitor for both Z position sensing and Z actuation.

Our approach to MEMS-based probe-tip height control is shown conceptually in Fig. 4. Each permanent magnetic probe recording head is carried by an independent Z actuator which controls its head-to-media spacing. Each actuator consists of a spring and an electrostatic parallel-plate electrostatic actuator (PPA) [10]. The recording media acts as the PPA's stator electrode. It is common to all head actuators. The PPA electrodes can also be used to capacitively sense the distance from the media to the motor electrode. This is an extremely nonlinear feedback control system, and providing stable feedback control can be difficult. See [11] and [14] for a discussion of the control system design.

One implementation of a simple head actuator structure is shown in Fig. 5. This figure also shows an SEM of such a device fabricated using the "poly-release" CMOS MEMS process developed at Carnegie Mellon University [8]. The PPA motor electrode is 40µm by 40µm, and the feedback loop is designed to hold the plate to media spacing at a value of approximately 230nm. In this head actuator design, the spring is implemented by a pair of cantilever beams in order to provide sufficient stiffness against lateral and rotational motion. Each beam is 200µm long, 1.8µm across, and 4.1µm high. Note that the laminated structural material fabricated in the CMU CMOS MEMS process [9] has an intrinsic vertical stress gradient which cause the spring to curl out of plane by several microns (curl is visible in Fig. 5).

Writing with a permanent magnetic probe tip at the end of this cantilever can be achieved by simply modulating the spacing between the magnetic probe tip and the media. This suggests that we want a Z suspension that has a high resonant frequency in order to allow writing at a high data rate. In our initial prototype device (see Section 5), we find that a probe-tip to media spacing of 2nm results in highly reliable written marks while a height of 11nm results in good reading resolution with an extremely low probability of causing any change in the stored pattern in the media. Note, one disadvantage of this scheme is that a separate permanent magnetic probe tip of slightly larger diameter must be used to erase a given track before it can be rewritten. Therefore, two separate Z mechanical suspensions must be able to access the same data area – one for reading/writing and one for erasing. In essence, a stripe of data on this devices (approximately 1000 bit positions long) is like a sector on a hard disk drive. It must all be read or written at once.

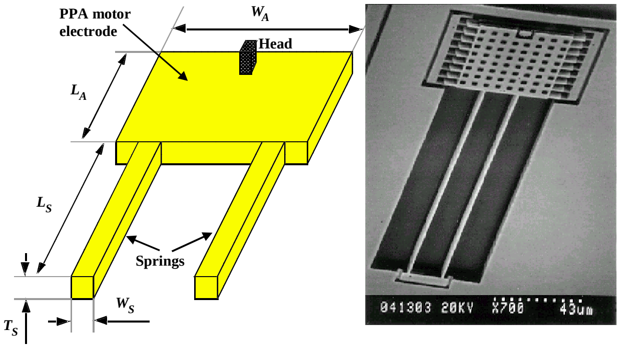

Fig. 5: MEMS implementation of parallel plate capacitor for both Z position sensing and Z actuation. Note, an SEM of such a structure is shown at right without a head in place.

When we are reading the data, we create what amounts to a magnetic force microscope. The RMS equivalent disturbance force noise due to the front end electronics noise is approximately 38 fN/sqrt(Hz), which gives an RMS input referred force noise floor that is about 12pN assuming a 50KHz bandwidth. For more details on the noise floor for this sensor, see [14]. Since the interaction force between a permanent magnetic tip and a thin-film magnetic media can be hundreds of pN, this means that we can actually read the magnetic state of the media by simply sensing the force the media exerts on the permanent magnet read/write head. Note, one other source of disturbance is the Brownian noise associated with the air between the actuator plate and the media. In this case, we are assuming that we are operating in a near vacuum and can neglect the Brownian noise contribution.

4. MAGNETIC PROBE RECORDING HEADS

Optimization of the design of permanent magnetic probe heads interacting with a thin-film magnetic media would leads to an extremely high aspect ratio cylinder of permanent magnetic material. Fortunately, dropping the aspect ratio down to 4:1 causes only a small drop in the magnetic field at the tip of the probe.

In manufacturing, deposition of an array of permanent magnet probe tips could be done using the Spindt tip process [15] widely used in making field emission displays with minimum effect on the other parts of the structure. In this case we would have probe tips in the shape of a cone. Alternatively, a combination of wide area optical lithography with small area e-beam lithography can be used to cost effectively manufacture an array of photoresist dots where tips are desired down to 50nm in diameter [16]. By using this combination of optical lithography and e-beam lithography to pattern a magnetic thin film, 50nm diameter cylinders of a permanent magnetic material with a height of 100nm can be created cost effectively [11].

5. SYSTEM PERFORMANCE SIMULATION

In order to assess the viability of the proposed storage system, we created a detailed simulation that includes the effects of media noise, electronics noise, Brownian noise, and manufacturing variations. We generate a distribution of magnetic grain size, and orientation to match that of today's commercial vertically oriented magnetic media. Optimizing the selection of the magnetic probe tip geometry for the best signal-to-noise ratio (SNR) resulted in a cylindrical magnetic probe tip 40nm in diameter and 100nm in height. The track pitch was 68nm and the bit length (with run length coding) was 100nm. For these parameters, the simulation of 4000 recorded bits, including the up and down movement of the probe tip during writing and then a second pass scan for reading, resulted in an RMS-to-RMS SNR of 13 dB which is quite sufficient for reliable signal detection.

6. CONCLUSIONS

Assuming a 20% overhead for error correction coding, the track pitch and bit pitch determined for the initial demonstration system results in approximately 1.5 million user bits being addressed by an individual magnetic probe tip that scans over a 100µm by 100µm media area. The overall system would consists of 6,400 of these individual probe tip elements, resulting in a total storage capacity of approximately 1Gbyte of user data on a 1.4cm x 1.4cm x 1mm 2 wafer silicon sandwich. The density of the magnetic data stored on this media is limited by thermal decay of the smaller magnetic grains over time. In our simulations, we are assuming that a 10 year lifetime is required when we set the grain size. Fortunately, researchers at companies that manufacture hard disk drives are working hard to develop thermally stable media with smaller grain sizes and as these developments become available, we would expect the be able to increase the density of data stored on MEMS-positioned magnetic-probe-based mass storage devices.

7. ACKNOWLEDGEMENTS

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