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13. ABSTRACT *(Maximum 200 words)*

We envision arrays of silicon "disk drives" which are completely manufactured by planar lithographic techniques that can vastly decrease the *size, weight, power* requirements, *cost, latency* of access, and *failure rate*, of data storage systems. In this project we have demonstrated MEMS actuators that achieve $\geq 1\%$ swept area. To achieve this goal, we have developed a custom MEMS process that starts with a standard CMOS foundry. We have achieved multiconductor movable beams that are 1.2μ wide and 5μ tall with 1.2μ spaces between beams. In addition, our MEMS process allows the creation of upward facing platinum Spindt field-emission tips used for reading and writing data. Using a commercial STM system, we have demonstrated the writing of 3nm – 25nm diameter pits in a carbon thin film media. Finally, we have used the MEMS positioner to demonstrate STM operation with the platinum tips fabricated on the MEMS actuators. We project that these MEMS actuators and platinum STM tips, combined with our designs for cabon thin film media, could be used to create a 10GB WORM data storage array that requires only 1cm x 1cm x 2mm of physical space.

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SILICON MICRO-DISK ARRAYS FOR DATA STORAGE

FINAL REPORT

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Abstract

We desire a revolutionary leap forward in volumetric density and power requirements of data storage systems for portable applications. Our proposed solution is to apply the planar lithographic manufacturing techniques which revolutionized electronic circuit fabrication to the manufacture of data storage systems. We envision arrays of silicon "disk drives" which are completely manufactured by planar lithographic techniques. By constructing arrays of silicon micro-disks, integrated with signal processing electronics, we can vastly decrease the *size, weight, power* requirements, *cost, latency* of access, and *failure rate*, of data storage systems. To achieve these goals, we need a MEMS fabrication process that is tightly integrated with MOS device fabrication as we envision thousands of independent MEMS devices on a single IC that must all be controlled by electronics.

In addition, the MEMS actuators that we envision would have a high percentage swept area (area over which tip can be positioned as a percentage of the area required for entire structure and control electronics). Our goal in this project is to achieve $\geq 1\%$ swept area. To achieve these goals, we have developed a MEMS process that starts with a standard CMOS foundry to define MOS devices and the metallization for the MEMS devices. We have characterized the mechanical properties of beams fabricated in this process. We have achieved multiconductor movable beams that are 1.2μ wide and 5μ tall with 1.2μ spaces between beams. In addition, our MEMS process allows the creation of upward facing platinum Spindt field-emission tips which will be used for reading and writing data on carbon thin-film media. We have demonstrated the ability of our three degree-of-freedom MEMS actuators to achieve a swept area of over 1%. In addition, using a commercial STM system, we have demonstrated the writing of pits in a carbon thin film media that varied in diameter from 3nm up to 25nm. Finally, we have used the MEMS positioner to demonstrate STM operation with the platinum tips fabricated on the MEMS actuators. We project that these MEMS actuators and platinum STM tips, combined with our designs for carbon thin film media, could be used to

create a 10GB WORM data storage array that requires only 1cm x 1cm x 2mm of physical space.

Introduction

A substantial improvement in *size* and *weight* results from shrinking down the height of the disk drive components. In a silicon micro-disk array, the height is only the thickness of two silicon wafers. Fabrication using parallel lithographic techniques makes the additional cost of using three actuators (one for "x", one for "y", and one for "z" (height)), instead of one actuator, negligible. Therefore, we choose to abandon the standard magnetic recording disk drive approach of a single actuator (for radius) a rotating disk (for theta), and an air-bearing slider (for height), resulting in dramatically lower power requirements. In scenarios where a powered down mode is used, the silicon micro-disk array would be ready for immediate operation with no need to wait while a disk spins up to speed.

Just as for VLSI electronic circuits, the parallel lithographic fabrication paradigm enables us to economically manufacture large arrays of such silicon micro-disks, which should ultimately result in dramatically lower data storage system *cost* as almost no manual mechanical assembly is required. In fact, rather than manufacture one large micro-disk on a silicon die, we choose to exploit the parallel nature of the fabrication process to create arrays of small micro-disks on a single die. In an array of small micro-disks, each disk has a smaller actuator which must be moved a shorter distance, requiring less power. Another benefit of smaller actuator movements is that less time is required to reach any particular stored record, which, in addition to the fact that there is no rotational latency, results in a dramatic decrease in overall *latency* of access. And finally, by appropriate coding of user data across a large array of micro-disks, the likelihood of unrecoverable data loss, i.e., the *failure rate*, can be made dramatically lower. More specifically, due to manufacturing defects, a few micro-disks may fail initially. During operation, one or more micro-disks may fail. However, the ability of the system to continue to deliver data can be assured as long as an appropriate coding methodology is applied to the array of silicon micro-disks; e.g., a code patterned after the redundant array of independent disks (RAID) work.

There are two main research challenges which must be tackled in order to create the proposed silicon micro-disk array. The first one is defining the physical mechanism by which data bits are stored, and the processes for reading and writing bits. The second one is developing the necessary microelectromechanical structures to implement these reading and writing processes. We will now discuss each of these in more detail.

Having chosen to fabricate arrays of silicon micro-disks, we must select a method for storing information that is compatible. Our initial designs of microelectromechanical actuators indicated that a total change in length of 10% was about all we could expect from an electrostatically deflected spring composed of aluminum beams. Assuming that only 10% of the area is swept by actuator in both x and y directions, then only 1% of the area of the silicon substrate will be used for data storage. We concluded that an extremely high areal density storage mecha-

nism was required in order to achieve reasonable overall system storage density. After comparing many possible approaches, we selected data storage based on STM for two reasons. First, it offered the extremely high areal density required. And second, standard methods exist for fabricating the STM tips using integrated circuit processing steps.

After careful review of many possible approaches for applying STMs to data storage, we have chosen to use a thin carbon film for data storage. By applying a pulse of voltage to a tip in proximity to a carbon film a pit can be created. The exact mechanism for the change in the carbon thin film has not been discovered. One possibility is that local ohmic heating caused by the STM current flow raises the carbon film to a temperature at which the crystalline structure changes. Another alternative is that the strong electric field directly changes the energy states in the carbon film making an alternate crystalline structure more favorable. Whether mediated directly by the electric fields, or by localized ohmic heating, small (about 3nm diameter) spots with a high contrast appear. During the read process, the difference between the conductivity and/or the height of unwritten regions versus written regions appears as variations in the current through the STM tip.

Because of the stored spot size is small, roughly 3nm diameter, and because we will use field-emission currents rather than tunneling currents, the STM tip does not need to have atomic resolution. In addition, we can allow the STM tip to be removed from the media by a substantial spacing, on the order of 3-5nm. We can take advantage of this spacing to improve the data rate of our system by employing fixed-height scanning of the STM tip where the mechanical limits of the system in the z dimension are not as important. In this mode, the data is read out as high frequency variations in the tip current to which the feedback loop cannot respond. More gradual variations in the media to tip spacing are controlled by the feedback loop.

The MEMS Process

The first phase of this research project was the development of the necessary microelectromechanical structures to implement the reading and writing processes. Specifically, we need to position in x, y, and z (height), an STM tip over a thin carbon film. Because we expect to have a large (> 1000) number of parallel storage units, we must have the sensing and control electronics integrated with the MEMS devices. To that end, we developed a MEMS fabrication process that is a series of post-processing steps following standard CMOS foundry fabrication.

All of the details describing the process and a number of example devices are included in [1][2][3]. However, a few highlights are worth mentioning in this report. First, we can now create beams that are only 4 λ wide with spaces between beams of only 4 λ. For the HP 0.5μ process, $\lambda = 0.3\mu$ so we can make 1.2μ wide beams with 1.2μ spacing. In addition, as can be seen in [1], [2] and [3], the oxide etch is almost perfectly vertical therefore the beams are nearly rectangular and their shape is controlled only by the accuracy of the metal 3 lithography which we have found to be quite good. Studies of these structures have determined an effec-

tive Young's modulus of 61 GPa. Cantilevered structures curl up with a radius of curvature of about 4.2 mm.

Actuator Design

We have spent considerable effort developing 3-DOF actuators that can achieve the largest possible swept area. Recently we have developed the following approaches to achieve higher swept areas: (1) actuators with position sensing and feedback, and (2) single beam X and Y actuators with multiple tips each with its own Z actuator. One example of such an actuator structure is shown in Fig. 1. This structure has exhibited motion of +/- 3μm in X, +/- 1μm in Y, and 1μm of downward Z motion with applied voltages up to 24V.

The data storage system we are currently developing incorporates absolute and relative position sensors to locate data on the recording media, and to provide the necessary observability of all mechanical structures. The sensor and readout subsystem must achieve a position error on the order of a nanometer, while rejecting off-axis and out-of-plane motion, so the main design goal was to maximize in-axis sensitivity while achieving very low cross-axis sensitivity. These conflicting specifications can be met by taking advantage of the design freedom allowed by the laminated structures fabricated in the CMU MEMS process.
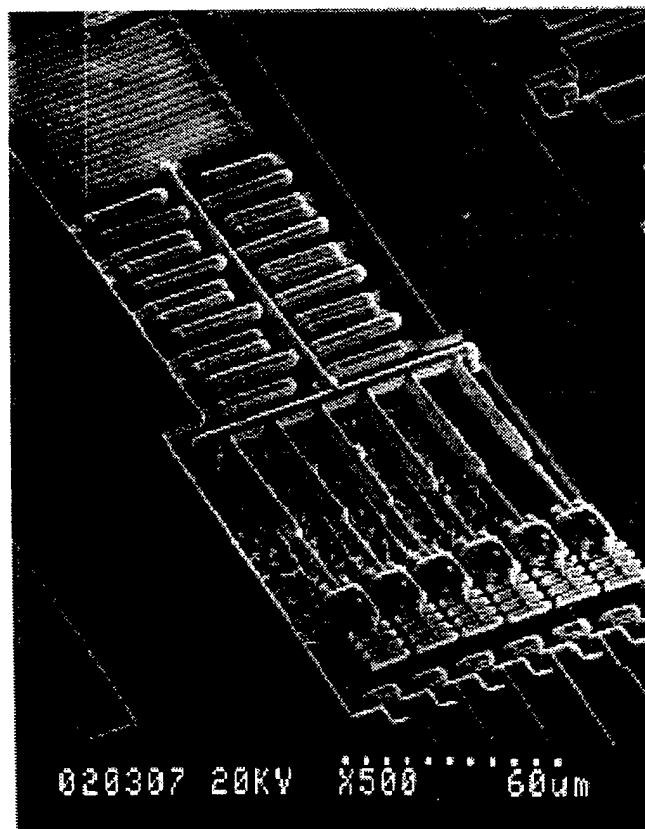

Fig. 1: Illustration of single beam 3-DOF actuator with 6 independent tips.

STM Tip Deposition

We have spent considerable effort developing a process flow for making STM tips that is compatible with our overall fabrication approach. We have completed a basic process flow for making Aluminum and Platinum Spindt tips that is compatible with the standard CMOS foundry and our new post-processing steps (see Fig. 2).
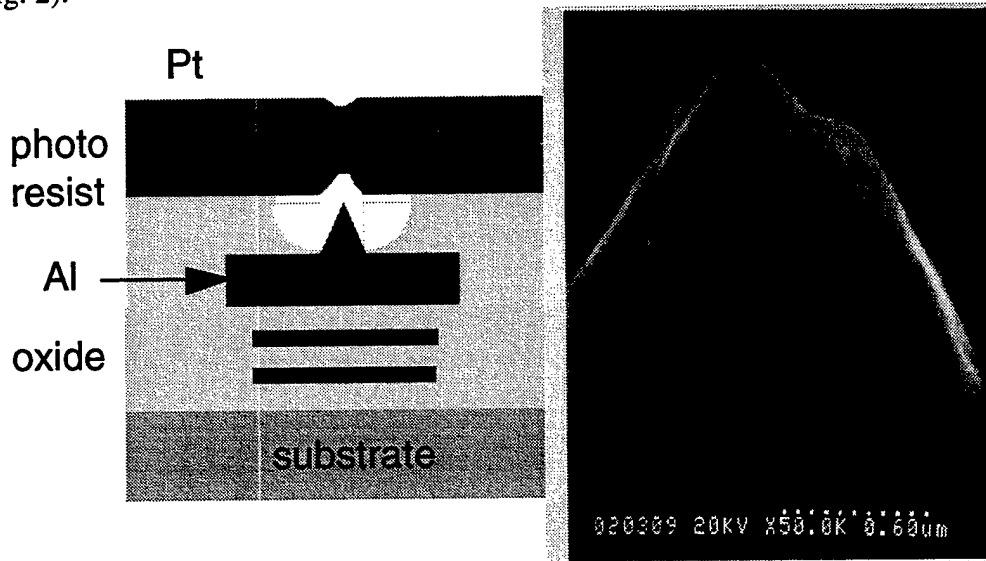

Fig. 2: Deposition of a Spindt Platinum STM tip.

Carbon-Film Storage Media

The last component of a storage system which must be addressed is the media. In this case, we have just begun to explore carbon thin films deposited on silicon wafers as our media. Using a commercial STM system, we have demonstrated the writing of 3nm – 25nm diameter pits in a carbon thin film media by varying the pulse amplitude and duration as shown in Fig. 3.

Conclusions

In conclusion, we are continuing to refine and develop the CMU MEMS device fabrication post–processing flow. In addition, the repeatability and manufacturability of the new process is vastly better than that of our original MEMS process flow. We have redesigned our 3-DOF actuators to exploit this new process, have developed a first pass STM tip deposition process, and have a preliminary media deposition process. We project that these MEMS actuators and platinum STM tips, combined with our designs for carbon thin film media, could be used to create a 10GB WORM data storage array that requires only 1cm x 1cm x 2mm of physical space.
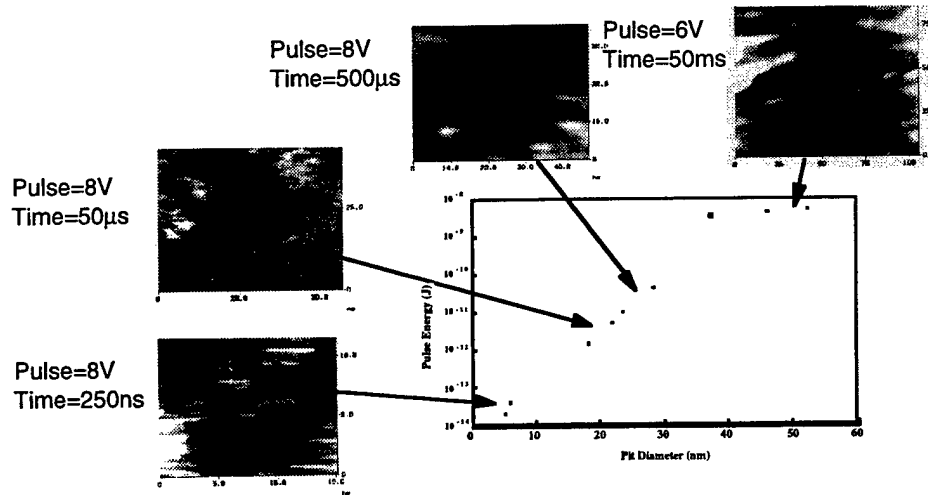
Fig. 3: Carbon Thin Film Media on Si substrate, pit size versus pulse duration.

Acknowledgment/Disclaimer

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