Actuation for Probe-Based Mass Data Storage

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ABSTRACT

This paper describes the development of a micro media actuator (MMA) for probe-based mass data storage. The process is based on dry etching and incorporates a thinned silicon media sled to increase the frequency response of the system. The suspended micro-mechanical media sled moves in *x-y* (±50 µm) using electrostatic actuation. The system design specification requires actuation of an 8x8 mm^2 magnetic media over an array of 80x80 probe tips.

The main advantage of our design is lower access time (1 ms – 0.1 ms), and an optimized design for specified maximum space allowed. The multiple competing design goals in the media actuator led to the development of an optimization-based media-actuator design tool, which was used to identify and characterize the parameters needed to scale the media. The tradeoff between access time and capacity is invariant of media size. The MMA is to be integrated with other MEMS components and CMOS electronics to achieve the data storage system [1].

Keywords: CMOS, Data Storage, Electrostatic Actuator, MEMS, Optimization.

1 INTRODUCTION

The development of technology that requires electronics and data storage with low power consumption, small packaging and reliability has been the focus of industry in the last years. In this context, the area of MicroElectro-Mechanical Systems (MEMS) provides a feasible way to build key elements that enable these devices to be manufactured.

Different groups have explored the development of MEMS actuators for probe-based mass data storage. Instead of storing information on a conventional rotational disk, all probe storage research efforts, including ours, propose a 2-D translational media sled that is accessed by an array of tip actuators. Micromechanical sled motions (*x-y*) approaching 100µm have been demonstrated using comb-drive actuators in the SCREAM process [2][3]. An electromagnetic micro *x-y* stage for probe-based data storage was presented recently [4]. Storrs Hoen and his colleagues at HP Labs have demonstrated micro-machined actuators using an electrostatic surface drive to achieve 8µm displacement at 4 V applied bias in a 3mm by 3mm structure [9]. The main advantage of our design is lower access time (1 ms – 0.1 ms), and an optimized design for specified maximum space allowed.

The objective of this project is to create and demonstrate the feasibility of MEMS technology for a rewritable data storage cache capable of recording densities greater than 10 GB/cm^2, utilizing an array of CMOS micromachined tip actuators, a single MEMS-based media actuator, and perpendicular magnetic probe recording technology [1]. This report describes the methodology for design of the micro media actuator.

2 MECHANICAL DESIGN AND ANALYSIS

2.1 Design specifications & Topology choice.

A suspended micromechanical media sled moves in *x* and *y* using electrostatic actuation (Figure 1). A box spring suspension is used to decouple the two lateral directions (x-y) of actuation, so that comb fingers can be used for x-y actuation without mechanical interference. This topology has been used successfully in the construction of gyros [5] and other electromagnetic micro x-y stage for probe-based data storage from Samsung [4]. The beams that support the structure are modeled as springs to determine the actuation voltage needed to move the sled up to 50 µm. The design specifications for the MMA are focused on the area availability and the normal parameters that are considered in the performance of a conventional HDD (Table 1).

Area = 8x8 mm^2 magnetic media sled
Access time < 10 ms
Voltage < 120 V
Active power < 1 W, limited by CMOS electronics
Swept area = 100 µm x 100 µm (stroke+-50 µm *x-y* axis)
Stability in z < 10 nm
Thickness to gap ratio ~ 20:1

Table 1: Design specifications for the micro media actuator.

The symmetry of the design provides simplicity for the fabrication process and the layout generation. It is compact and can be built in a single layer structure. These features are key elements in a manufacturing process. It is also relatively easy to make updates in the design since the layout is generated systematically through parameterized cells (Pcells™ [6]).

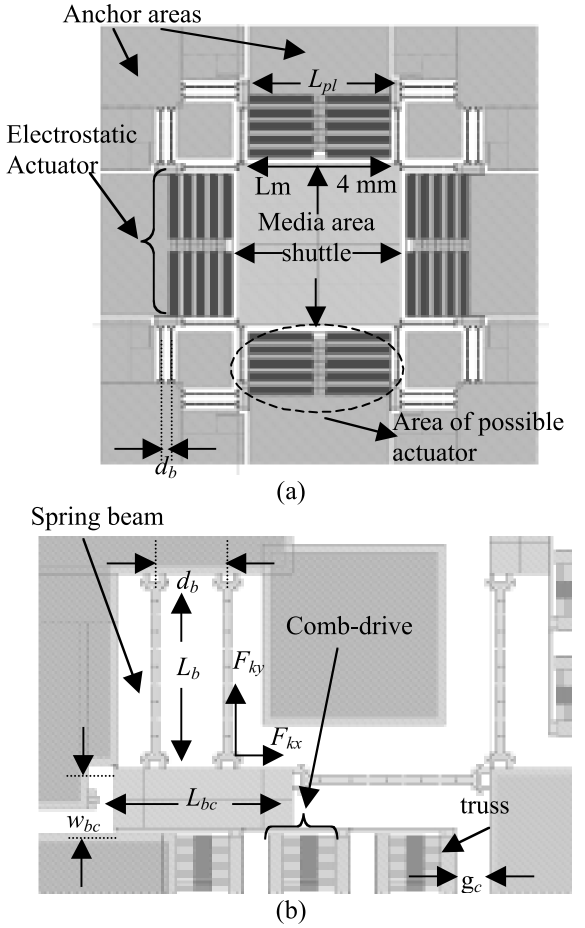


Figure 1: Layout of a 4 x 4 mm^2 media actuator. (a) Complete schematic of the media actuator, 12 beams support the media on x and y. (b) Detail of the box spring suspension.

2.2 Lumped parameter system

The layout in Figure 1 shows the mechanical elements of the system. Design parameters for the fabrication of this structure are summarized in Table 2.

The suspension consists of 12 guided-end flexures in each lateral axis (*x-y*). Therefore the spring constant of the system is twelve times that of a guided-end beam.

Capacitance, $C \propto N$ since $\frac{dC}{dx} = \frac{N\varepsilon_0 h}{g}$, given that g and h are constant (process dependent) and L_o is fixed (dependent on desired stroke). With $N = \frac{A_{comb}}{A_{finger}} = \frac{L^2}{L_{finger} P_f} \propto L^2$ and $k_x \propto 1/L^3$ from $F_e = k_x x$ we obtain a relation for the stroke $x \propto L^5$.

Design parameters	
Thickness of the spring beams	h
Width of the spring beams	w_b
Length of the spring beams	L_b
Number of fingers in a comb-drive	N
Gap between the fingers	g
Finger overlap	L_o
Pitch between fingers	P_f
Mass of the media sled	m
Voltage applied between rotor / stator	V
Displacement	x

Table 2: Definition of the design parameters for the MMA.

Substituting basic equations of electrostatic actuation and mechanical force, we find family of designs that will depend on the width, thickness, length of the beams, number of fingers and gap between the fingers. The maximum operation voltage and the required maximum displacement are set by the design specifications. The last factor to take into account is the access time of the media actuator, which is related to the resonant frequency:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_x}{m_{eff}}} \qquad (1)$$

where the effective mass is calculated from density ρ = 2.330 x10^3 kg/m^3, thickness of the media sled, and target dimensions (i.e. 8x8 mm^2). For the mass of the media sled we consider a silicon thickness of 20µm.

2.3 Optimization tool

Design optimization was performed with the International Mathematical and Statistical Library (IMSL) [7]. The method, based on the iterative formulation and solution of quadratic programming (QP) sub problems, obtains these sub problems by using a quadratic approximation of the Lagrangian and by linearizing the constraints [8]. The optimization formulation takes into account parametric constraints such as length and width of the beams, number of fingers, gap between fingers, thickness of plate and beams, displacement, operating voltage, and tries to minimize an objective function. The chosen objective function is total area:

$$A_{mma} = L_m^{\ 2} + 4(L_m L_b + L_b^{\ 2}) \qquad (2)$$

A smaller device footprint allows a greater number of designs in a single wafer and also is important in terms of packaging and manufacturing robustness. Smaller designs provide lower-cost integration with a CMOS chip. Using IMSL, it was possible to consider several designs that meet the constraints.

2.4 Constraints

1. Static force balance relates the mechanical spring force in the system to the electrostatic force given by the comb drives.

$$g[0]=\frac{N\varepsilon_0 hV^2}{g}-12\frac{Ehw_b^{\ 3}}{L_b^{\ 3}}x=0 \tag{3}$$

3. This inequality in the analysis states that the area available for the actuator has to be greater than the real area of the comb drives in the system.

The area available for the actuator is:

$$A_p=L_m(L_b+d_b)-A_{beam}-L_m g_c \tag{4}$$

The area, A_p, of the actual actuator is

$$A_r=N\cdot A_{finger}-(L_b-g_c)w_{bc} \tag{5}$$

and must be less than the available area:

$$g[2]=A_p-A_r \tag{6}$$

4. Comb drives placed next to each other in an array can create an attractive force when the rotor is too close to the stator. Our conservative design approach dictates that the desired electrostatic force be at least five times the attractive force between adjacent combs.

$$\frac{N\varepsilon_0 hV^2}{g}\geq 5\left[\frac{\varepsilon_0 hL_{tr}V^2}{g_c^{\ 2}}\right] \tag{7}$$

This constraint sets the minimum spacing between combs. Where the electrostatic force between adjacent combs is approximated as a parallel plate separated by a distance g_c, and L_{tr} is the length of the truss and is dependent on the number of fingers on the comb drive.

5. In order to prevent the fingers of the comb drives from snapping together, their electrostatic force has to be less than the force exerted by the spring beams that hold the comb drives in a stable position. The moment that results from the spring beams is:

$$4M_b=4F_{kx}\frac{L_{pl}}{2}+4F_{ky}\frac{d_b}{2} \tag{8}$$

Where F_{kx} and F_{ky} are the components of the forces due to the restoring moment of the spring beams (Figure 1b).

The moment given by the electrostatic force in the fingers is:

$$M_e=\sum_{i=1}^{N_{cd}}F_{ei}l_i \tag{9}$$

where F_{ei} is the electrostatic force exerted by the fingers on a comb drive. l_i corresponds to distance from the center of mass to the axis where the comb drive i generates the force F_{ei}, and N_{cd} is the number of comb drives in one actuator.

This results in the inequality $M_e<4M_b$

$$d_b>\frac{M_e-4F_{kx}\frac{L_{pl}}{2}}{2F_{ky}} \tag{10}$$

6. The resonant frequency is constrained to prevent other structures of the system to resonate at a lower frequency than five times the fundamental shuttle resonance ($f_{tr}>5f_r$). The resonant frequency of the rotors on each comb drive must be considered.

The resonant frequency of the rotor in the comb drive is:

$$f_{tr}=\left(\frac{1}{2\pi}\right)\left(\frac{k_{truss}}{M_{truss}+NM_{finger}}\right)^{1/2} \tag{11}$$

7. The resonant frequency of a single actuator is also calculated to satisfy $f_{act}>3f_r$. The analysis affects sizing of the beams that hold the comb drives. The spring constant of the frame that holds the comb drives is:

$$k_{bc}=2Eh\left(\frac{w_{bc}}{L_{bc}}\right)^3 \tag{12}$$

Other constraints such as media sag from gravitational force, and thickness to gap ratio of structures were also considered in the analysis.

2.5 Simulation Results with IMSL.

The key results of this study (Figure 2) show the Pareto curve of access time versus capacity given fixed fabrication process limits. Analyses of several media dimensions for the MMA were explored. The area above these curves represent the access time that are feasible according to the constraints that were defined in the previous section, and to the specific target specification design. Final values for the 8x8 mm^2 design are frequency response 1.270 kHz, finger gap 3 μm, length, width and thickness of beam 0.595 mm, 5 μm, and 60 μm respectively. Different topologies, processes and materials could be used, which means that the areal density could possibly be improved thereby increasing the capacity of the current designs.

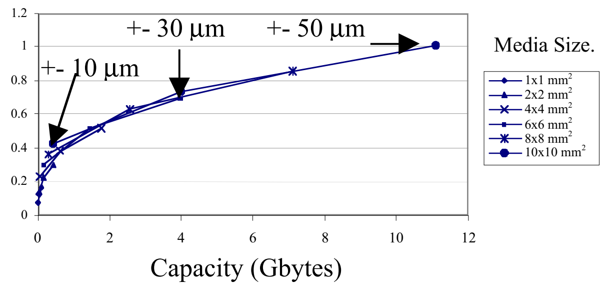


Figure 2: The tradeoff between access time and capacity is invariant of Media size. It is dependent on the fabrication technology.

3 PROCESSING

The process is shown in Figure 3. Four masks are required for the complete fabrication of the MMA. The first mask is used to set the alignment marks on the oxide, plus a slight over etch of 5 µm is required for future alignment. The second mask defines the stiffening ribs of the MMA and the third mask defines the anchors. The fourth mask is used for defining the beams and comb drives on the front side.

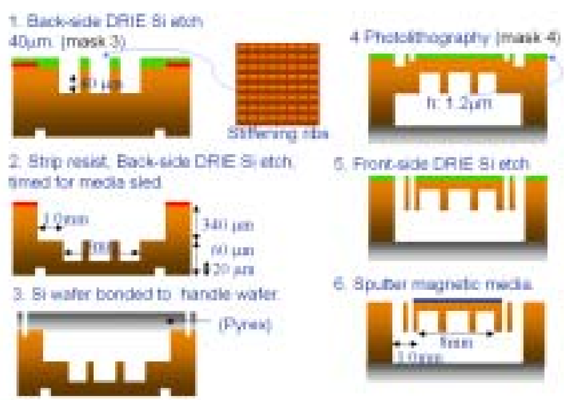


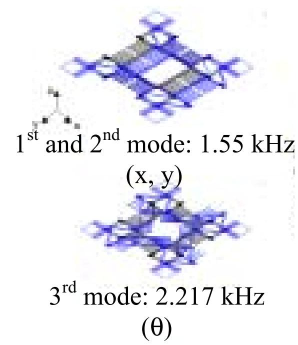
Figure 3: Abbreviated MMA process flow.

4 SYSTEM SIMULATION

Once the optimal designs are obtained from the IMSL program, a finite element analysis of the media actuator was performed for the characterization of the mechanics of the system. The simulations performed were run on ABAQUS incorporating a thinned Si media sled. Since the thickness of the sled is 20 µm, the addition of stiffening ribs, 60 µm thick, prevented unwanted modes in the MMA. Figure 4 shows the results in a 4x4mm^2 MMA.

5 CONCLUSIONS

An optimal design for a micro media actuator intended for a data storage system has been proposed and simulated. The use of IMSL helped us to understand the scaling capabilities of our system, and to conclude that the tradeoff between access time and capacity is invariant of media size. The mechanics of the systems were characterized through finite element analysis using ABAQUS. The FEA results are consistent with the initial calculations obtained through the optimization tool. Given that the tradeoff is dependent on the fabrication technology, the methodology can be imported to other processes to obtain an optimal design for a specific application.



4x4 mm^2 Media

Plate thickness:	20 µm
Comb gap:	4.5 µm
Beam thickness:	90 µm
Beam length:	1.28 mm
Beam width:	8 µm

Figure 4: MMA modes for a 4x4 mm^2 MMA. Frequency response is improved with a thinner media sled..

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