A MEMS-BASED ACTIVE-HEAD SLIDER FOR FLYING HEIGHT CONTROL IN MAGNETIC RECORDING

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This paper describes design and fabrication of a MEMS-based active-head slider using a PZT thin film for flying height control in hard disk drives. A piezoelectric cantilever integrated in an air bearing slider is used to adjust the flying height individually. A novel air bearing surface (ABS) geometry that minimizes the aerodynamic lift force generated beneath the head has been designed based on the molecular gas film lubrication (MGL) theory. The sliders with PZT actuators were fabricated monolithically by silicon micromachining process. Performance of the actuator was tested by using an optical surface profiler. The fabricated slider was then mounted on a suspension and flying height of the slider above a spinning disk has been measured by multiple wavelength interferometry. Change in the head-disk spacing has been successfully confirmed by applying voltage to the PZT actuator.

Keywords: Hard disk drive, Air bearing surface, PZT thin film, Flying height, MEMS

INTRODUCTION

Air bearing sliders in hard disk drives (HDD) are flying above the spinning magnetic disks by aerodynamic pressure generated in the air film. The flying height is becoming smaller with the continuous increase in the recording density and will fall below 10 nm in the near future. The flying height is determined by the balance of loading force given by the suspension and the lift force generated by the air bearing slider. Variation of the flying height is caused by many factors, such as environmental change, waviness, and vibration of the disk surface, and seeking operation. In particular, static variation due to air pressure change comprises a large proportion of the total variation. Furthermore, individual deviation in the flying height due to manufacturing tolerance is also a big issue in such low spacing sliders. Therefore, margin for the flying height variation must be taken into account when the nominal flying height is designed.

In this study, an active-head slider, which allows the flying height to be adjusted individually by using a microactuator integrated in a slider, is proposed to compensate the flying height variation and to keep a constant ultra-low spacing during the read and write operation. An active slider with an actuator was first developed by Yeack-Scranton et al.[1] in 1990 for contact recording. Since then, various kinds of active sliders using a bulk PZT[2], thin film PZT [3] and thermal actuators [4] have been reported. However they have not been in practical use.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>width of the cantilever</td>
<td>m</td>
</tr>
<tr>
<td>D</td>
<td>inverse Knudsen number</td>
<td></td>
</tr>
<tr>
<td>d33</td>
<td>piezoelectric strain constant</td>
<td>m/V</td>
</tr>
<tr>
<td>Ei</td>
<td>Young’s modulus</td>
<td>N/m²</td>
</tr>
<tr>
<td>EI</td>
<td>equivalent bending stiffness of the cantilever</td>
<td>N/m²</td>
</tr>
<tr>
<td>f</td>
<td>natural frequency of the cantilever</td>
<td>Hz</td>
</tr>
<tr>
<td>h1</td>
<td>thickness</td>
<td>m</td>
</tr>
<tr>
<td>H</td>
<td>dimensionless bearing clearance</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>length of the cantilever</td>
<td>m</td>
</tr>
<tr>
<td>l</td>
<td>length of the slider</td>
<td>m</td>
</tr>
<tr>
<td>M</td>
<td>mass of cantilever end</td>
<td>kg</td>
</tr>
<tr>
<td>p</td>
<td>dimensionless air pressure</td>
<td></td>
</tr>
<tr>
<td>Qr</td>
<td>Poiseille flow rate</td>
<td></td>
</tr>
<tr>
<td>Qr*</td>
<td>relative Poiseille flow rate (= 6 Qr/D)</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>circumferential disk speed</td>
<td>m/s</td>
</tr>
<tr>
<td>V</td>
<td>drive voltage of the cantilever</td>
<td>V</td>
</tr>
<tr>
<td>W</td>
<td>loading force of the slider</td>
<td>N</td>
</tr>
<tr>
<td>w</td>
<td>width of the slider</td>
<td>m</td>
</tr>
<tr>
<td>X, Y</td>
<td>coordinates of the air bearing surface</td>
<td></td>
</tr>
<tr>
<td>δ</td>
<td>displacement of the cantilever tip</td>
<td>m</td>
</tr>
<tr>
<td>A</td>
<td>bearing number</td>
<td></td>
</tr>
<tr>
<td>ρ1</td>
<td>density of the cantilever and PZT</td>
<td>kg/m³</td>
</tr>
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</table>
DESIGN AND NUMERICAL ANALYSIS

Actuation schemes
There are two possible actuation schemes for the flying height control: direct actuation and indirect actuation. In the direct actuation scheme, a dual-slider structure that consists of a primary air-bearing slider as a stable reference platform and a small secondary slider carrying a head is used. These sliders are interconnected by a deformable actuator that drives the head directly. Yeeck-Scranton et al. [1] developed an active slider in this scheme by mounting a bulk piezoelectric material in the slider. Kurita et al. [2] and Tagawa et al. [3] have also studied the direct head actuation using a PZT actuator.

On the other hand, in the indirect actuation scheme, whole or partial air bearing surface (ABS) is deformed by an actuator integrated in a slider, which results in the change of the head-disk spacing indirectly. Khanna et al. [5] proposed a deformable slider using a bulk PZT in 1990. Recently, a partially deformable ABS using a thermal actuator [4] has been proposed.

In this study, the direct actuation scheme is adopted because of the low power consumption, which is suitable for MEMS-based thin film actuators, and a novel ABS design for the direct actuation is presented.

Structural Design
A schematic diagram of the newly designed active-head slider is shown in Fig.1. The slider has a standard "pico-slider" size (1 by 1.25 by 0.3mm) and a cantilever with a PZT thin film coated on its surface is integrated in the central rear part of the slider. Figure 2 shows the structure of the piezoelectric cantilever. The PZT layer is sandwiched by two metal electrodes and expands or shrinks laterally by applying voltage between the electrodes, which causes the vertical motion at the free end of the cantilever. This structure is called the piezoelectric unimorph cantilever.

Dimensions of the cantilever were determined so as to meet following conditions: the displacement of the cantilever is more than 30nm and the resonant frequency is more than 100kHz. The thickness of the PZT thin film is restricted by crack formation during the deposition process, and was determined to be 2 μm. The displacement of the free end of the cantilever δ is expressed as:

$$\delta = \frac{3mn}{1+4mn+6m^2+n^2} \frac{d_{33}L^2V}{h_1^2}$$  (1)

$$m = \frac{E_1}{E_2}, \quad n = \frac{h_2}{h_1}$$  (2)

Natural frequency of the cantilever is approximately given by

$$f = \frac{1}{2\pi L^2} \sqrt{\frac{3EI}{M}}$$

$$\overline{EI} = \frac{1+4mn+6m^2+4m^3+4n^3}{1+mn} \left( \frac{E_1 \delta h_1^4}{12} \right)$$  (4)

The natural frequency f and the displacement δ as a function of the cantilever length are plotted in Fig. 3, based on the following assumptions: $h_1=2 \, \mu m$, $h_2=50 \, \mu m$, $E_1=130GPa$, $E_2=63GPa$, $V=5V$ and $d_{33}=-50 \times 10^{-12}m/V$. From these calculations, the length and the thickness of the cantilever were determined to be 450-650 μm and 40-70 μm ranges, respectively.
Air bearing surface (ABS) design

A novel air bearing surface geometry for the active-head slider has been designed based on the molecular gas film lubrication (MGL) theory [6] so as to meet following conditions:

a) The slider body always flies at a safe and constant distance above a disk. The flying height is about 20 nm at the trailing edge, and 90-95 nm at the leading edge.
b) The head motion has little effect on the flying height of the slider body.

In order to meet these conditions, it is necessary to reduce the aerodynamic force generated beneath the head. Large aerodynamic force causes lift of the slider body or upward deflection of the cantilever, which counteracts the head motion.

Numerical analysis based on the MGL theory has been carried out to determine the ABS profile. The generalized static Reynolds' equation for ultra-thin gas film is expressed as

\[
\frac{\partial}{\partial X} \left( \frac{Q_{P}X H_{x}}{\partial X} \right) + \left( \frac{1}{w} \right)^{2} \frac{\partial}{\partial Y} \left( Q_{P}X H_{y} \frac{\partial P}{\partial Y} \right) = \lambda \frac{\partial (PH)}{\partial X} \tag{5}
\]

The values of the Poiseuille flow rate \( Q_{P} \) is approximated using power series representation [7], assuming the accommodation coefficient to be 0.9.

\[
Q_{P} = \frac{D}{6} + 0.11993 \quad (D \geq 100)
\]

\[
Q_{P} = 0.15114D + 1.7220D \quad \frac{10^{11}}{\text{nm}^3} \quad (5 \leq D < 100)
\]

\[
Q_{P} = 0.12679D + 1.45927 + \frac{0.016800}{D} + \frac{0.000969}{D^2} \quad (0.15 \leq D < 5)
\]

\[
Q_{P} = -2.64827D + 2.42846 + \frac{0.01947}{D} - \frac{0.000079}{D^2} \quad (0.01 \leq D < 0.15)
\]

Rectangular unequal spacing meshes were used for the numerical calculation. The control volume method was applied for discretization of the Reynolds' equation including discontinuous bearing clearance. The discretized equation is then linearized with respect to \( P \) using the Newton-Raphson method and solved by the column method [8]. The aerodynamic lift force is obtained by integrating the air film pressure \( P \) over the air bearing surface. Loading force \( W \) and the circumferential speed of the disk \( U \) are assumed to be 2.7 gf and 9.61 m/sec, respectively, and flying height of the slider was evaluated by balancing the forces and moments acting on the slider.

Figure 4 shows a newly designed ABS profile with five pads. Four of them located in each corner support the load and maintain a stable flying attitude of the slider. The pad beneath the head has a small area and no shallow step to minimize the air bearing lift force.

Figure 5 shows the static pressure distribution for a half width of the ABS. When no deflection is given to the cantilever (\( \delta = 0 \)), the flying height of the slider is calculated to be 20 nm, as shown in Fig. 5 (a). When the deflection of 15 nm is given to the end of the cantilever, the flying heights of the slider and the head become 20.3 nm and 5.3 nm, respectively, as shown in Fig. 5 (b), which indicates the lift of the slider body due to the head motion is only 0.3 nm. The aerodynamic lift force beneath the head is evaluated to be 14.5 mgf, which is 0.5% of the loading force.

Figure 6 shows the results of the
calculation with and without air bearing lift beneath the head. The flying height of the head without the air bearing lift (broken line) decreases linearly with increasing applied voltage, whereas the flying height with air bearing lift (solid line with filled circles) exhibits nonlinear behavior because of the upward deflection of the cantilever due to the aerodynamic lift force. The difference between these two curves indicates the amount of the upward deflection. The slider body maintains almost constant flying height regardless of the applied voltage. The voltage required to lower the head from 20 nm to 5 nm is evaluated to be 2.23 V.

FABRICATION

The active-head sliders with a PZT unimorph cantilevers have been fabricated monolithically by silicon micromachining process. By using MEMS technology, hundreds of sliders with cantilevers of various lengths were fabricated simultaneously without assembly process. Figure 7 shows the fabrication process. First, a 300-μm-thick silicon wafer is etched from the backside by KOH solution to form the 0.1-μm-deep steps and 1-μm-deep recesses for the air bearing surface. Then the wafer is thermally oxidized to deposit 0.1-μm-thick insulating layer. After that, a 0.45-μm-thick bottom electrode (Pt/Ti), a 2μm-thick PZT film, and a 0.25-μm-thick top electrode (Au/Cr) are deposited sequentially. The metal electrodes and the PZT film are coated by sputtering and sol-gel method, respectively. It has been confirmed that the 2-μm-thick crack-free PZT film is successfully deposited by multiple spin coating and heat treatment. The top electrode and the PZT film are then patterned by ECR (electron cyclotron resonance) etching. Subsequently, the bottom electrode and the upper part of the silicon slider are patterned by ECR etching and deep-RIE (reactive ion etching), respectively. Lastly, the 50-μm-thick cantilever and the sidewall of the slider are formed simultaneously by deep-RIE and the sliders are separated individually from the wafer.

Figure 8 shows SEM micrographs of the fabricated sliders. The 250-μm-deep perpendicular walls at the end of the cantilevers are successfully etched.

TESTING AND RESULTS

Figure 9 shows surface profiles of the 550-μm-long and 70-μm-thick cantilever with and without drive voltage, measured by an optical surface profiler. The height of the top surface of the cantilever from the top surface of the slider body is plotted as a function of the longitudinal distance from the fixed end of the cantilever. The results indicate that the cantilever without drive voltage is warped upward because of the residual stress during the deposition process. The cantilever is additionally deflected by applying voltage to the top electrode. The warp at the free end of the 70-μm-thick cantilever without drive voltage is about 350 nm and it tends to increase with decreasing the cantilever thickness. The thermal warp is one of the most critical issues for developing the active-head slider using PZT thin film. Change in materials and the thickness ratio of the unimorph cantiler, and/or modification of the deposition process and heat treatment may be effective to solve the
problem.
The displacement of cantilever tip as a function of applied voltage is shown in Fig. 10 (a). Two 70-μm-thick cantilevers of 450 μm and 550 μm lengths are tested. When positive voltage is applied to the top electrode, the displacement of the cantilevers increases monotonously with increasing applied voltage. On the contrary, when negative voltage is applied, the cantilevers are lowered down to -5 V and then begin to rise up. This is considered to be due to the hysteresis of the piezoelectric materials.
The displacement curves in the -5 to +5 volt range are enlarged in Fig. 10 (b). The displacement is almost proportional to the applied voltage within ±5V. When the voltage of 5V is applied, the displacement of the 550-μm-long cantilever tip reaches more than 60 nm, which is large enough to control the flying height. Piezoelectric constant $d_{31}$ is estimated as $182 \times 10^{-12}$ m/V from Eq. (1).
The frequency response of the 650-μm-long and 40-μm-thick cantilever measured by a Laser Doppler vibrometer is shown in Fig. 11. The resonant frequency is 78 kHz and the Q value is estimated approximately to be 250. The cantilevers of 550 μm and 450 μm lengths exhibit resonant frequencies over 100 kHz.
The fabricated slider was then mounted on a suspension. The bottom electrode was bonded to an electrical lead on the flexure at the end of the load beam and the top electrode was connected to the flexure itself by solder balls of 100 μm in diameter, as shown in Fig. 12. The flying height above a spinning glass disk was measured by means of multiple wavelength interferometry. The rotational speed of the disk is 4200 rpm, which is corresponding to the circumferential speed of 9.6 m/s at the slider.
The results of the flying height measurements are shown in Fig. 13. The slider maintains a constant flying attitude above a spinning disk although it rolled. The minimum flying height was found to be 30 nm at the left trailing edge of the slider. On the other hand, the flying height of the head could not be measured quantitatively because of the large warp of the cantilever. However, shift of the interference fringes was observed on the pad at the cantilever tip by changing the voltage from 0 to 15V. Hatched areas shown in Fig. 14 indicate the positions of a red interference band on the pad with the drive voltage of (a)0 V and (b)15 V. The results demonstrate the flying height of the head can be adjusted using a PZT thin film actuator.

**CONCLUSION**

An active-head slider for adjusting the flying height individually using a piezoelectric cantilever integrated in the slider has been proposed. This slider makes it possible to eliminate the margin for the flying height variation due to the manufacturing tolerance and environmental change, and to realize an ultra-low spacing with high reliability.
The structure of a piezoelectric unimorph cantilever and a
PZT coating and bulk micromachining by deep RIE. Performance of the actuator was tested by using an optical surface profiler. Displacement of more than 60 nm was obtained at the cantilever tip with drive voltage of 5 volts. Furthermore, the flying height measurement above a spinning disk was carried out. Vertical displacement of the head was successfully confirmed while the slider is flying stably above a disk. The experimental results demonstrate the possibility of controlling flying height using a PZT thin film.

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REFERENCES


Fig. 12 Mounting on a suspension

Fig. 13 Results of the flying height measurements

Fig. 14 Shift of the interference fringes. The hatched areas show a red interference band.