Fast electrothermally activated micro-positioner using a high-aspect-ratio micro-machined polymeric composite

Lau, Gih Keong; Yang, Jiaping; Thubthimthong, Borriboon; Chong, Nyok-Boon; Tan, Cheng Peng; He, Zhimin

2012

Lau, G. K., Yang, J., Thubthimthong, B., Chong, N.- B., Tan, C. P., & He, Z. (2012). Fast electrothermally activated micro-positioner using a high-aspect-ratio micro-machined polymeric composite. *Applied Physics Letters*, 101(3), 033108-.

<https://hdl.handle.net/10356/94794>

<https://doi.org/10.1063/1.4737644>

© 2012 American Institute of Physics. This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of American Institute of Physics. The paper can be found at the following official DOI: [doi:<http://dx.doi.org/10.1063/1.4737644>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Fast electrothermally activated micro-positioner using a high-aspect-ratio micro-machined polymeric composite

Gih-Keong Lau, Jiaping Yang, Borriboon Thubthimthong, Nyok-Boon Chong, Cheng Peng Tan et al.

Citation: *Appl. Phys. Lett.* **101**, 033108 (2012); doi: 10.1063/1.4737644

View online: <http://dx.doi.org/10.1063/1.4737644>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v101/i3>

Published by the [American Institute of Physics](#).

Related Articles

Discuss on using Jiles-Atherton theory for characterizing magnetic memory effect

J. Appl. Phys. **112**, 093902 (2012)

Hard HfB₂ tip-coatings for ultrahigh density probe-based storage

Appl. Phys. Lett. **101**, 091909 (2012)

On the lifetime of plasmonic transducers in heat assisted magnetic recording

J. Appl. Phys. **112**, 034512 (2012)

Application of Landau-Lifshitz-Bloch dynamics to grain switching in heat-assisted magnetic recording

J. Appl. Phys. **112**, 013914 (2012)

Mechanisms of heat transport across a nano-scale gap in heat assisted magnetic recording

J. Appl. Phys. **111**, 124508 (2012)

Additional information on *Appl. Phys. Lett.*

Journal Homepage: <http://apl.aip.org/>

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: <http://apl.aip.org/authors>

ADVERTISEMENT

AIP | Applied Physics
Letters

**EXPLORE WHAT'S
NEW IN APL**

SUBMIT YOUR PAPER NOW!

**SURFACES AND
INTERFACES**

Focusing on physical, chemical, biological, structural, optical, magnetic and electrical properties of surfaces and interfaces, and more...

**ENERGY CONVERSION
AND STORAGE**

Focusing on all aspects of static and dynamic energy conversion, energy storage, photovoltaics, solar fuels, batteries, capacitors, thermoelectrics, and more...

Fast electrothermally activated micro-positioner using a high-aspect-ratio micro-machined polymeric composite

Gih-Keong Lau,¹ Jiaping Yang,² Borriboon Thubthimthong,¹ Nyok-Boon Chong,² Cheng Peng Tan,² and Zhimin He²

¹Nanyang Technological University, Singapore 639798

²Data Storage Institute, A*STAR, Singapore 117608

(Received 26 January 2012; accepted 3 July 2012; published online 18 July 2012)

Recently, silicon electrothermal micro-actuators have been developed for dual-stage micropositioning in hard disk drive. But, silicon with a low coefficient of thermal expansion (CTE) has a shortcoming of requiring a large temperature change ($>300^{\circ}\text{C}$) to expand adequately. This letter presented a high-CTE polymer composite to solve the shortcoming of silicon. The polymer composite consists of high-aspect-ratio micro-machined SU-8 thermal expander and silicon thermal conductor. A micro-positioner which embodies the proposed polymer composite can drive a slider to travel fast ($>1\text{ kHz}$) more than a 17 nm-pitch data track under a moderate temperature rise ($<100^{\circ}\text{C}$). © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4737644>]

Recently, magnetic bit patterned media has been demonstrated to be capable of storing data at a 2.5 terabit-per-square-inch (Tb/in^2) areal density and a 17-nm track pitch.¹ To have data access in the Tb/in^2 magnetic media in a hard disk drive (HDD), a magnetic recording head needs to be positioned very accurately over a targeted circular data track.² A solution to this requirement is by using a micro-actuator, which moves the head carrier, i.e., a slider, relative to the tip of a primary rotary actuator.³ This dual-stage micro-actuator is required to generate a fast dynamic displacement and a sufficient force to move the slider. There are various dual-stage micro-actuators developed, namely piezoelectric,^{4–6} electrostatic,^{3,7} and electromagnetic.^{8,9} Among them, both piezoelectric and electrostatic micro-actuators are compact and lightweight ($<3\text{ mg}$).^{3,5} However, they require a high driving voltage (20–30 V) and are subjected to reliability issues for long-term operation.^{10,11}

Recently, electrothermal micro-actuators have been proposed and developed as an alternative solution for dual-stage micropositioning.^{12,13} As compared to piezoelectric and electro-static micro-actuators, the silicon electrothermal micro-actuators are capable of generating a large force at a low driving voltage ($<5\text{ V}$) and adequately fast response ($>1\text{ kHz}$).^{14–16} In addition, they have a high stiffness and consequently can achieve a high mechanical resonant frequency for precise positioning.¹³ Shortcoming of the silicon micro-actuators, which have a low coefficient of thermal expansion (CTE), is the large operating temperature change (greater than 300°C),^{13,14} which may affect their long-term structural integrity of head gimbal assembly. In this Letter, we designed a high-CTE polymer composite to solve the shortcoming of silicon in building the electrothermal micro-actuator.

The designed polymer composite consists of highly expandable SU-8 and high-aspect-ratio silicon (Si) microstructure.¹⁷ It is capable of achieving a large thermal expansion with fast response at a temperature rise less than 100°C . The large thermal expansion is attributed to high CTE of SU-8 ($>50 \times 10^{-6}/^{\circ}\text{C}$ (Ref. 18)). With the integrated heat conduc-

tor of silicon microstructure (with a thermal conductivity of $148\text{ W/m/}^{\circ}\text{C}$), fast heating and response of SU-8 expander can be achieved even though SU-8 itself is an thermal insulator (with a low thermal conductivity of $0.2\text{ W/m/}^{\circ}\text{C}$ (Ref. 19)).

Figs. 1(a) and 1(b) shows the micro-positioner design, which embodies the above mentioned polymer composite in two thermal unimorphs. This micro-positioner is housed in a small silicon die, which has a frame and three electrical contact pads. The die has a footprint of $0.86\text{ mm} \times 1.15\text{ mm}$, a

FIG. 1. An electrothermally activated micro-positioner using high-aspect-ratio micromachined polymer composite of silicon and SU-8 epoxy: (a) a scanning electron micrograph (SEM) of a micromachined chip of the micro-positioner with two thermal unimorphs (on the contact pad are residues of carbon adhesive for attaching the device on a sample holder of SEM); (b) a schematic drawing showing that activation of a thermal unimorph in the micro-positioner moves a slider on a flexural stage by a lateral stroke $u(t)$; (c) photograph of a thermal unimorph, which consists of a comb-like silicon skeleton, a U-shape platinum heater, and transparent SU-8 polymer filling.

thickness of 0.07 mm, and a mass of 0.13 mg. The two thermal unimorphs are 530 μm apart. Each thermal unimorph can produce a lateral in-plane bending when the polymer composite in it expands under local heating by a platinum thin-film heater. Alternate activation of the two unimorphs can move a femto slider (0.6 mg), which is mounted on a flexural stage, laterally to and fro.

Detailed embodiment of the polymer composite in the thermal unimorph is shown in Fig. 1(c). In the thermal unimorph, there is a high-aspect-ratio silicon comb micro-structure, which has 6 fins extended from a backbone (25 μm wide, 70 μm thick, and 120 μm long). Each fin is 30 μm long, 10 μm wide, and 70 μm thick, and the trench between the fins is 10 μm wide. Solid SU-8 polymer fills the trenches between the fins. The SU-8 filling and the silicon fins effectively form a layered composite, which stands perpendicular to the wafer plane. As the SU-8 filling is sandwiched between the silicon fin plates with a narrow spacing (10 μm wide), it can be heated up or cooled down by the fins instantaneously (with a time constant for heat diffusion being less than 1 μs (Ref. 20)).

The flexural stage of the micro-positioner are designed to be stiff, so that it can achieve high resonant frequencies (>10 kHz) in both in-plane and out-of-plane directions when loaded by the slider. The present design of the flexural stage is supported by three flexural beams, namely a central beam and two side beams, which are extended from the tip of each thermal unimorph. These flexural beams are designed to have a high aspect ratio (70 μm thick to 20–25 μm wide) such that it has a high out-of-plane stiffness.

Fabrication of the micro-positioner involves deep reactive ion etching (DRIE) of silicon and modified photolithography of SU-8, which is a high-aspect ratio negative-tone photoresist.²¹ In the modified photolithography process, extra steps need to be developed to ensure complete filling of SU-8 photoresist into the trenches. First, the liquid SU-8 photoresist is modified in terms of the solid-resin-to-solvent ratio such that the liquid photoresist has a low viscosity to flow and seeps into the trenches by capillary effect and a sufficient amount of solid resin remains as a structural and expansion material in the trenches after prebaking. Second, the liquid photoresist is poured over a trenched wafer. The trenches act as a mold to contain the liquid photoresist. The excess coating of photoresist over the wafer surface is spun off to a minimal thickness using a spin coater. Afterwards, the liquid SU-8 is subjected to vacuum and pre-baking. Vacuum helps remove the trapped air bubbles from the liquid SU-8 filling in the trenches. Pre-baking removes solvent of the liquid SU-8 filling and leaves solid SU-8, which fills partially the trenches. Repeating the processes for liquid photoresist filling and prebaking eventually fills up the trenches with SU-8 solid. Completion of photolithography processes results in a Si/SU-8 composite block, which is released from the substrate afterwards, as shown in Figs. 1(a) and 1(c). Two pads of 7 μm thick SU-8 are coated on the flexural stage and they serve to contain liquid adhesive for slider attachment in the subsequent assembly.

The proposed polymeric composite embodied in the thermal unimorph is designed for fast thermoelastic expansion. To measure how fast the thermoelastic actuation is, a

single thermal unimorph out of the two in the micro-positioner is activated by pulsed resistive heating; whereas the other unimorph is left inactivated. The unimorph, under activation by a square voltage pulse with a 50% duty cycle, oscillates laterally and in turn moves the flexural stage and the slider. Displacement of the moved slider is measured by a laser doppler vibrometer (Polytec OFV-534), which has the sensing laser pointed on the slider sidewall.

Fig. 2 shows that the actuated slider responds fast to the pulse heating at pulsewidths of 0.5 ms and 1.0 ms. The peak-to-peak stroke (u_{p-p}) increases at an decreasing rate with the pulsewidth. This exponential trend leads to the determination of thermomechanical time constant of close to 1.0 ms. As the driving voltage increases, the peak-to-peak stroke generally increases. Under activation by a 4 V pulse with a pulsewidth of 3 ms, the slider travels a large peak-to-peak stroke of close to 50.0 nm. A shorter pulsewidth results in a decrease in the magnitude of peak-to-peak stroke, e.g., 18.8 nm induced by a 4 V pulse with a 0.5 ms pulsewidth. This is attributed to a smaller temperature rise in a shorter pulse of heating. Yet, the generated stroke of 18.8 nm under activation by the square voltage pulse is enough to travel a 17 nm-pitch data track on a 2.5 Tb/in² magnetic media.

Bi-directional actuation of the flexural stage and slider using the pair of thermal unimorphs depends on the relative

FIG. 2. Displacement of the slider, when driven by the micro-positioner, which has one of the two thermal unimorph activated by pulsed heating at a 50% duty cycle: (a) activation by a square voltage pulse with 4 V magnitude and 0.5 ms pulsewidth; (b) activation by a square voltage pulse with 4 V magnitude and 1 ms pulsewidth. (c) peak-to-peak stroke of the actuated slider as a function of pulsewidth and magnitude of a square voltage pulse. The time constants of the thermomechanical response are obtained by least-square fitting the experimental data using the exponential equations of time, as indicated besides the curve-fit lines.

temperatures of the unimorphs. Hence, the net stroke $u(t)$ to actuate the slider is governed by the relationships below

$$u(t) = b(T_L(t) - T_0) - b(T_R(t) - T_0), \quad (1)$$

in which $T_L(t)$ and $T_R(t)$ is the average temperatures of the left and right unimorphs, respectively, T_0 is the initial reference temperature, and b is a proportionality constant, which depends on the design of the unimorphs^{21,22} and flexural beams. During alternate activation, resistive heating is localized at the activated unimorph. The left activated unimorph bends towards the left, whereas the right activated one bends towards the right. If both unimorphs are activated simultaneously, the two will oppose each other.

Besides self heating, resistive heating of the activated unimorph causes a gradual temperature rise to the silicon die, which is mounted on a printed circuit board (PCB) and traps heat. In turn, the inactivated unimorph is heated by the silicon die. The temperature rise in the inactivated unimorph is termed as the thermal crosstalk, and it causes the inactivated unimorph oppose the stroke of the activated unimorph. Hence, it is undesirable.

To study the extent of the thermal crosstalk in the silicon die on PCB, temperatures in the activated unimorph and the inactivated one are measured using a Agilent source meter (B2902A) with two channels. Heaters of the two unimorphs are measured with an initial resistance of 53.3Ω at the room temperature (20°C) and a temperature coefficient of resistance (TCR) ($\beta = 1.89 \times 10^{-3}/^\circ\text{C}$). Hence, average temperature changes in the unimorphs can be estimated from the measured heater resistances.

Fig. 3(a) shows that, under a pulsed heating at 4 V and a 6 ms pulsewidth, the activated unimorph is subjected to fast temperature change ($T_L - T_0$) less than 100°C with a time constant of less than 1 ms, whereas the inactivated unimorph is subjected to a gradual temperature rise ($T_R - T_0$) less than 25°C , with minor perturbations following that of the die. The peak-to-peak temperature difference $((T_L - T_R)_{p-p})$ between the activated and in-activated unimorphs remains rather constant, e.g., 72.0°C at 4 V, over cycles of a pulsed heating. In general, the peak-to-peak temperature difference is an exponential function of pulsewidth (t_p) as shown in Fig. 3(b). It depends also on the driving voltage (V) as shown in Fig. 3(c). These findings suggested that resistive heating is rather localized at the activated unimorph, and the thermal crosstalk can be reduced with a shorter pulsewidth (<1 ms) of heating. In short, the thermal crosstalk does not affect operation of the micropositioner, but it causes a higher operating temperature, at which the activated unimorph needs to produce a stroke.

The die temperature rise can be minimized if the silicon die is mounted on a perfect heat sink, such as that available surrounding the slider, which is subjected to strong cooling by air bearing over a spinning disk. In this case, the crosstalk is minimized and the actuation depends solely on the temperature rise of the activated thermal unimorph ($T(t) - T_0$). A lumped-parameter model is developed for the activated unimorph by accounting for heat capacity, heat conduction, and heat generation in or out of it as follow:

FIG. 3. Temperatures of the two unimorphs, one activated under pulsed resistive heating and one inactivated. The temperatures are estimated from the resistance change of each heater: (a) temperature change of left heater (T_L), right heater (T_R), and their difference ($T_L - T_R$) over time under a 4 V and 6.1 ms voltage pulse; dependences of peak-to-peak temperature difference ($T_L - T_R$) on (b) pulsewidth and (c) voltage.

$$mc_p \frac{\partial(T(t) - T_0)}{\partial t} + \frac{kA_c}{L}(T(t) - T_0) = \frac{V^2}{R_0(1 + \beta(T(t) - T_0))}, \quad (2)$$

in which m is the effective thermal mass, c_p is the specific thermal capacitance, k is the thermal conductivity of the unimorph, L is the characteristic path length for heat transfer between the unimorph and the heat sink, A_c is the cross-section area for the heat flux, i.e., that of the silicon backbone, R_0 is the heater resistance at the initial temperature T_0 , β is TCR of the heater, and V is the driving voltage across the heater.

Solution to the linearized Eq. (2) is an exponential function of time

$$T(t) - T_0 = \frac{1}{\frac{R_0 k A_c}{V^2 L} + \beta} (1 - e^{-t/\tau}), \quad (3)$$

in which the time constant τ is

$$\tau = \frac{mc_p L}{kA_c + \beta V^2 L / R_0}. \quad (4)$$

The analytical solution shows that the temperature rise of the activated unimorph depends on the pulsewidth and driving voltage and these trends agree well with the experimental observations. In addition, the solution shows the influences of design parameters on time constant. It predicts that the unimorph design can achieve a shorter time constant, below 1 ms for the current design, by sizing down both the thermal mass and path length for heat conduction.

FIG. 4. Frequency response of the slider, which is actuated by two thermal unimorphs under alternate activation with a half-sine pulse. The in-plane motion of the slider is measured by a laser doppler vibrometer.

So far, only a single thermal unimorph out of the two is activated using a square voltage pulse in the tests to determine time constants. In the application to move a slider for track following, both thermal unimorphs are alternatively activated by a half-sine voltage pulse. Alternate activation of both unimorphs produces bi-directional actuation, yet their response time is expected to be similar to that produced by the single activation. Under alternate activation by a half-sine pulse of 3.5 V, the actuated slider oscillates with an amplitude that decreased with the pulse frequency as shown in Fig. 4. The unimorphs are electrothermally activated faster than 1 kHz and can drive the flexural stage/slider into the in-plane mechanical resonance at 33.0 kHz. A smaller stroke amplitude is observed under activation by the half-sine pulse with the same voltage magnitude and pulsewidth, as compared to the square pulse. Yet, a larger stroke amplitude and faster heating is possible at a higher driving voltage according to Eqs. (3) and (4).

In summary, a high-aspect-ratio micro-machined polymeric composite of SU-8/Si is demonstrated to be capable of generating a fast thermal expansion (>1 kHz) under pulsed heating. A micro-positioner, which embodies such polymer composite in two thermal unimorphs, can generate a bi-directional stroke adequate to travel more than a 17 nm-pitch data track under activation by a moderate temperature rise ($<100^\circ\text{C}$). Hence, this electrothermally activated micro-actuator can be used for dual-stage micropositioning in a terabit-per-square-inch disk drive.

This work was funded by the Agency for Science, Technology and Research (A*STAR) in Singapore under the program of “Integrative Approach for 10 Tb/in² Magnetic Recording Research.”

- ¹Y. Kamata, A. Kikitsu, N. Kihara, S. Morita, K. Kimura, and H. Izumi, *IEEE Trans. Mag.* **47**, 51–54 (2011).
- ²R. Wood, J. Miles, and T. Olson, *IEEE Trans. Mag.* **38**, 1711–1718 (2002).
- ³T. Hirano, L. Fan, J. Gao, and W. Lee, *J. Microelectromech. Syst.* **7**, 149–155 (1998).
- ⁴Y. Soeno, S. Ichikawa, T. Tsuna, Y. Sato, and I. Sato, *IEEE Trans. Magn.* **35**, 983–987 (1999).
- ⁵Y. Jing, J. Luo, W. Yang, and G. Ju, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **51**, 1470–1476 (2004).
- ⁶Y. Nojima and S. Koganezawa, *J. Adv. Mech. Des., Syst. Manuf.* **5**, 45–53 (2011).
- ⁷D. A. Horsley, R. Horowitz, and A. P. Pisano, *IEEE/ASME Trans. Mechatron.* **3**, 175–183 (1998).
- ⁸R. Hipwell, K. Bartholomew, W. Bonin, Z. Boutaghou, and A. Lateef, *Solid State Technol.* **5**, 75–78 (2003). Available at <http://www.electroiq.com/articles/sst/print/volume-46/issue-5/features/mems/hard-disk-drive-performance-enhanced-by-mems-devices.html>.
- ⁹M. D. Bedillion, M. Karaman, and P. B. Chu, in *Proceedings of the American Control Conference, 2005* (IEEE, 2005), pp. 3216–3222.
- ¹⁰M. White, P. Hingwe, and T. Hirano, in *Proceedings of the American Control Conference, 2004* (IEEE, 2004), Vol. 1, pp. 541–546.
- ¹¹J. R. Heffelfinger and D. A. Boismier, in *MRS Proceedings* (Cambridge University Press, 1999), Vol. 604.
- ¹²S. L. Paalvast, H. T. M. Pham, P. M. Sarro, and R. H. Munnig Schmidt, *Proc. Chem.* **1**, 690–693 (2009).
- ¹³S.-H. Choe, H. Tomotsune, T. Eguchi, M. Kanamaru, T. Aono, S. Nakamura, and A. Koide, in *Digest of APMRC* (2010), pp. 1–2.
- ¹⁴L. Que, J. S. Park, and Y. B. Gianchandani, *J. Microelectromech. Syst.* **10**, 247–254 (2001).
- ¹⁵H. Sehr, I. S. Tomlin, B. Huang, S. P. Beeby, A. G. R. Evans, A. Brunnschweiler, G. J. Ensell, C. G. J. Schabmueller, and T. E. G. Niblock, *J. Micromech. Microeng.* **12**, 410 (2002).
- ¹⁶R. Hickey, D. Sameoto, T. Hubbard, and M. Kujath, *J. Micromech. Microeng.* **13**, 40 (2003).
- ¹⁷G. K. Lau, J. F. L. Goosen, F. Van Keulen, T. Duc, and P. M. Sarro, *Appl. Phys. Lett.* **90**, 214103 (2007).
- ¹⁸R. Feng and R. J. Farris, *J. Micromech. Microeng.* **13**, 80 (2003).
- ¹⁹D. R. Lide, “CRC Handbook of Chemistry and Physics, internet version,” (2007), Sec. 12, pp. 35, 77, 219.
- ²⁰G. K. Lau, J. F. L. Goosen, and F. van Keulen, *J. Microelectromech. Syst.* **19**, 992–1001 (2010).
- ²¹T. Chu Duc, G. K. Lau, and P. M. Sarro, *Appl. Phys. Lett.* **91**, 101902 (2007).
- ²²S. Timoshenko, *J. Opt. Soc. Am* **11**, 233–255 (1925).