Magnetic Head Protrusion Profiles and Wear Pattern of Thermal Flying-Height Control Sliders With Different Heater Designs

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Hard drives featuring sliders with thermal flying-height control (TFC) using thermal expansion of a heating element have been widely used in products for achieving lower magnetic spacing. This approach allows to actively compensate for static FH variations and achieves sub-1-nm clearance during read/write operation. However, the soft-error rate (SER) may not be minimized with an arbitrary heating element due to the nonuniform protrusion profile and the several micrometers of physical separation between reader and writer. Most published work mainly focused on actuation efficiency or reader spacing without detailed study of the relationship between balance of read/write spacing and the location of heating element. This paper uses an established numerical approach with head structure and pole-tip recession profile measured by scanning electron microscope and atomic force microscope to calculate the 3-D protrusion profiles, and to predict the head wear pattern created in TFC stress test, in which an excessive heating power is applied to the heating element so that part of the head is in contact with the spinning disk for a period of time. We also present novel experimental method for measuring wear pattern with angstrom-level resolution by Elastic Peak Maps. TFC sliders with three different heater elements are investigated numerically and experimentally. The numerical results compare well with the measurements in relative wear depths among various layers, and both show that the location and design of heating element have significant effect on the resulting FH profile as well as read and write magnetic spacings. As a result, one can reduce the SER by tailoring the heater design with the considerations of the magnetic requirement and reliability concerns.

***Index Terms*—Air-bearing surface (ABS), finite-element model, flying height (FH), hard disk drives (HDDs), head-disk interface (HDI), magnetic head slider, pole-tip protrusion, thermal flying-height control (TFC).**

I. Introduction

THERMAL FLYING-HEIGHT CONTROL (TFC) sliders using thermal actuation have been widely used to increase the area recording density by flying magnetic recording heads in close proximity of magnetic media in hard disk drive (HDD). TFC also serves as a new technique for compensating static flying-height (FH) variations due to manufacturing tolerance and environmental changes, and reducing the risk of harmful head-disk contact, which is essential for long-term reliability. In such a drive, a resistive heating element (heater element) is deposited near the read/write elements, and the gap FH is reduced by applying a current through the heater element to deliberately induce heater pole-tip protrusion (H-PTP).

Moreover, in order to further increase the areal density by minimizing the magnetic spacing in reading and writing, a “touchdown (TD) and pullback (PB)” scheme has recently been implemented in some of today’s hard disk drives. The operation of touchdown and pullback is performed by increasing the power applied to a TFC heater element in the magnetic head until head-disk contact, i.e., touchdown, is detected, and the protruded bulge is “pulled back” by reducing the power by a certain amount. One major advantage of this approach is the head-to-head FH variation can be minimized and a sub-1-nm FH can be achieved for read/write operation. However, due to physical separation between the TMR sensor (reader) and the write gap (writer), the pole-tip recession (PTR) profile created in the lapping process as well as other considerations, the heater element has to be properly designed to obtain a preferred protruded bulge for both reading and writing. The nonlinear thermal–structural coupled-field problem of the TFC sliders has been developed and thoroughly investigated under various operational conditions. Juang *et al.*, among others, proposed an iterative approach to numerically predict the TFC sliders’ flying performance, such as actuation efficiency and FH profiles [1]–[5]. Using similar approach, Zheng *et al.* [6] studied the effects of altitude on TFC actuation. Their numerical and experimental results both indicate an increase in the actuation efficiency. Liu *et al.* [7], [8] extended the model to analyze the TFC actuation in air-Helium gas mixtures. Zheng *et al.* [9] numerically investigated the flying characteristics of a TFC slider with two heaters and insulator elements. They found that for a constant heater power, the dual TFC heater with thermal insulators achieved a larger FH reduction than the case with a single heater. In previous studies, the numerical results were validated by experiments [6], [10], [11], but most of the comparisons were on the relationship between the heating power and the reader spacing change or temperature rises of the heater element and write coil. In [10], Juang *et al.* proposed an optical FH measurement apparatus capable of measuring the entire 3-D FH profile near the pole tip. This method allows us to compare the reader and writer protrusion among different heater designs, but it requires lengthy postprocessing of the raw data. An alternative and more direct approach is to deliberately create head wear by applying additional heating power to the TFC for an extended period of time after the TD is detected, known as TFC “overpush.” The wear is created due to the direct contact of slider carbon overcoat (COC) with the high-speed rotating disk, resulting in several Angstrom thinning of the COC.

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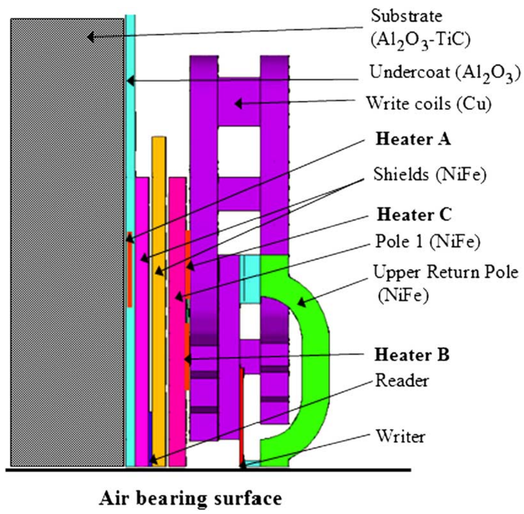

Fig. 1. Cross-sectional view of a magnetic head indicating the different layers and the three heater locations. The TMR sensor (reader) and write-gap (writer) are located at 1.9 and 8.55 μm from the slider substrate.

However, details of the 3-D protrusion profiles and the corresponding wear patterns as a function of heater design have not been adequately investigated yet. In this paper, we study the protrusion profiles created by three different TFC heater designs, and compare those with carbon overcoat wear measurement by Auger elastic mapping.

II. Head Structure and Numerical Modeling

Fig. 1 shows a cross-sectional view of the magnetic head slider studied in this paper. The magnetic head is fabricated on an Al_2O_3–TiC substrate. The head has a 3-turn helix coil and a bottom pole (P1) thickness of 1.2 μm. The top and bottom shields (S1, S2) are both 1 μm thick. The distance between the TMR sensor (reader) and the write gap (writer) is 6.5 μm. Three heater locations are studied: heater A is located between the substrate and S1; heater B and heater C are located between P1 and bottom coil, but the latter is several micrometers farther away from the air-bearing surface (ABS). The ABS is the same for all three sliders. The nominal dynamic pitch angle is 110 μrad in the flying condition of a linear velocity of 12.5 m/s and a zero skew angle.

The contact area between head and disk at touchdown is mainly determined by heater design, head structure, and PTR profile. PTR is the recess in height, typically ranging from several Angstroms to several nanometers, of the deposited layers with respect to the slider substrate at room temperature without heating power. In general, undercoat and overcoat are recessed more than the metallic layers due to the higher removal rate of alumina [12]. Fig. 2(a) shows a closeup view near the deposited region measured by atomic force microscope (AFM). The PTR profile is measured by line scan as shown in Fig. 2(b), which is then incorporated into the ABS for numerical analysis.

We use optical microscope, scanning electron microscopy (SEM), and AFM images to measure the fabricated geometry and to create a 3-D finite-element model of the entire slider.

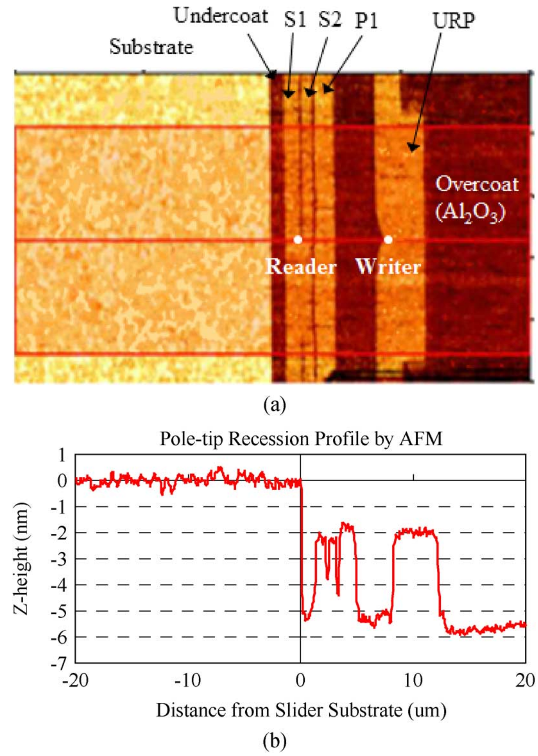

Fig. 2. (a) Two-dimensional AFM image scanned on the ABS. (b) Pole-tip recession profile measured by AFM line scan.

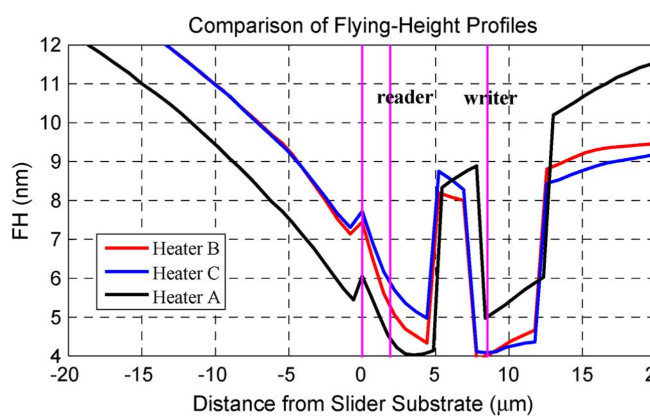

Fig. 3. Comparison of FH profiles along the center line of ABS with different heater designs. A proper heating power is applied to each design such that the minimum FH is 4 nm. The step at 0 μm is pole-tip recession. (Reader: TMR sensor; writer: write gap).

We then use an established numerical approach [10] to simulate the protrusion and FH profiles at touchdown and overpush conditions. The slider and disk deformations induced by the air-bearing pressure on the slider's ABS are included. Fig. 3 shows a comparison of the FH profiles of different heaters along the center line of ABS. A proper power is applied to each design such that the minimum FH is 4 nm. It is seen that the heater design and location effectively modify the profile. The touchdown region, reader, and writer FHs are altered accordingly. TFC heater element can then be designed to reduce soft-error rate (SER) by balancing the reader and writer magnetic spacings.

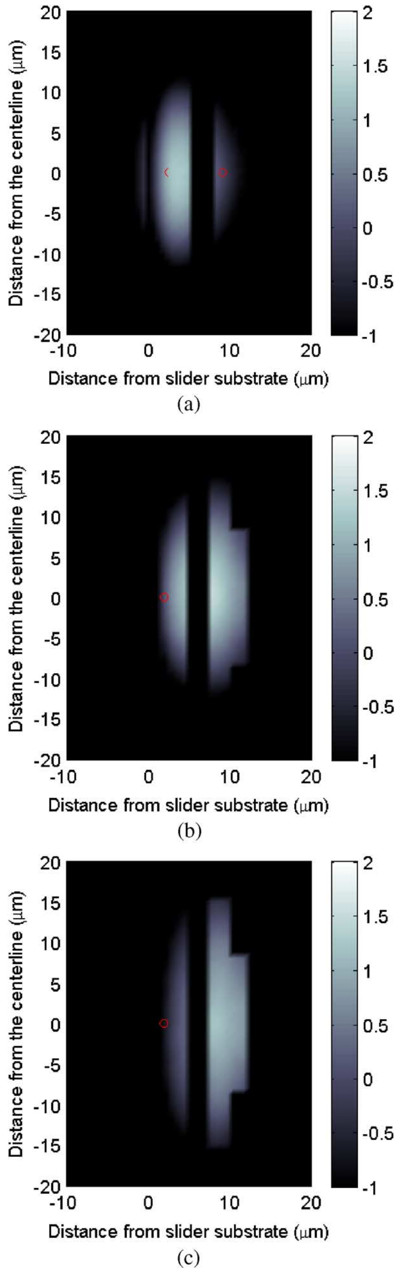

Fig. 4. Comparison of wear pattern predicted by simulation for magnetic head with different heater designs: (a) with heater A, (b) with heater B, (c) with heater C. A 20-mW additional power is applied after touchdown. The unit of the color bar is nanometer.

Fig. 4 shows a comparison of slider COC wear patterns predicted by simulation for the three heater elements. Carbon overcoat wear is estimated by applying an additional power of 20 mW after TD with an assumption that the material in contact with the disk was removed. The maximum wear amounts are 1.3, 1.5, and 1.2 nm for heater A, heater B, and heater C, respectively.

III. Experimental Methodology

A. Slider Wear by TFC Overpush

In order to measure the wear pattern, several head gimbal assemblies (HGAs) with magnetic heads with different heater elements were flown on a Guzik spin-stand with TFC "overpush" meaning that an excessive power ranging from 10 to 30 mW was applied after the touchdown was detected by an acoustic emission sensor. The touchdown powers are 97, 89, and 104 mW for heater A, heater B, and heater C, respectively. The power consumption of heater C is 17% higher than that of heater B since the former has a larger bulge and more air-bearing lift as a result of a longer heater-to-ABS distance.

B. Elastic Peak Maps

Auger elastic mapping method was then used to inspect the wear pattern by measuring the carbon overcoat thickness. The COC wear is typically less than 10 Å, which is not easily observable from a SEM image. However, elastic peak maps show variations in the intensity of the elastic peak due to thinning of the COC and can be used to detect Angstrom-level wear with very high contrast. A Physical Electronics SMART-200 Auger system [13] was used to acquire the elastic peak maps. Electrons from a surface include elastic (no energy loss) and inelastic (scattered) electrons. A secondary electron detector (SED) typically used on SEMs collects all of the electrons and cannot distinguish elastic from inelastic electrons. The energy analyzer in the Auger system allows one to isolate the signal due to elastic electrons and map any variations. Without an overcoat the elastic peak map shows differences in the backscatter factors, brighter for metals and darker for alumina. Adding an overcoat (no wear) attenuates the signal from all of the underlying structures. Wear of the overcoat reduces the thickness and lessens the attenuation resulting in an increased signal from the underlying material. Thus, mapping the elastic peak intensity shows where the overcoat has been thinned. A 1-KeV primary beam was used for these maps to provide adequate spatial resolution and has an attenuation length that is sensitive to the overcoat wear.

Fig. 5(a)–(c) shows the Auger images of three TFC heater elements after TFC overpush stress test with a burnished power of 14, 35, and 18 mW for heater A, heater B, and heater C, respectively. The burnish power is defined as the increase of TD power due to the COC thinning after the stress test. Area with thinner COC is lighter than that with no wear since any thinning of the COC will highlight the underlying region, which is typically of metallic material. Auger elastic mapping method provides a good way to inspect the wear pattern and the relative wear among different layers, but it does not give an absolute measurement of thickness, which may be measured by AFM scan. The measured wear patterns agree well with the simulation in terms of relative wear between reader and writer, and confirmed that TFC heater element can serve as a powerful design parameter to obtain desired protrusion profile and achieve more balanced magnetic spacing in read/write operation. Fig. 5(a) clearly shows that the S2/P1 area has maximum wear, which indicates that the reader is closer to the magnetic media than the writer at TD condition, while the main pole and the upper return pole area was worn out with heater C as shown in Fig. 5(c), which implies that the writer is closer to the media at TD condition. The wear pattern of heater B is more balanced as shown in Fig. 5(b), which is achieved by moving the heater element closer to the ABS. Compared with the dual-heater approach in which the SER can

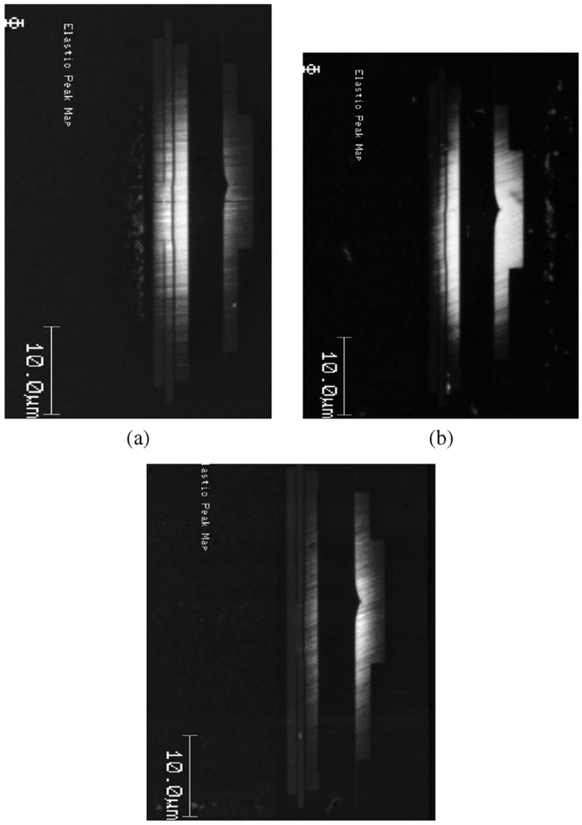

Fig. 5. Wear measurement by Auger elastic mapping. Wear pattern on magnetic head burnished by TFC touchdown: (a) with heater A, burnished 14 mW, (b) with heater B, burnished 35 mW, and (c) with heater C, burnished 18 mW.

potentially be minimized by activating each heater for read and write operation independently, optimized single heater design has the advantage of simplicity since it does not require additional electrical contact and can readily use existing firmware and channel technologies.

IV. Conclusion

This paper numerically and experimentally investigates the protrusion profiles and wear patterns of a TFC slider with three different heater designs. We use an established numerical approach with detailed head structure and PTR profile measured by SEM and AFM to calculate the 3-D protrusion profiles and predict the COC wear pattern created in the TFC "overpush" condition. We experimentally carry out overpush stress tests using a Guzik spin stand, and investigate the wear pattern by elastic peak mapping method. The numerical results compare well with the measurements in terms of relative wear depths among various layers, and show distinct features of the patterns created by different heater designs. For example, heater A produces more reader protrusion and results in a smaller reader magnetic spacing than the writer's. The maximum protrusion of heater C is near the write gap so that the write magnetic spacing can be minimized for write operation at the expense of lower resolution due to its higher read spacing. Heater B provides a more balanced profile by moving the heater element closer to the ABS so that neither the read magnetic spacing nor the write one is too large during read/write operation. It is seen that one can reduce the SER by tailoring the heater design with the considerations of the magnetic requirement and reliability concerns.

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