An Experimental Study of Head Instabilities in TMR Sensors for Magnetic Recording Heads with Adaptive Flying Height

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1. Introduction

The rapid growth of recording areal density in hard disk drives requires a reduction in the flying height at the read/write elements. Currently, the flying height is approximately around 5 nm. With such a low head-disk clearance, even variations and changes of the flying height for a few nanometers have an influential effect on the recording performance. A tolerance stack-up in manufacturing processes can generate the flying height variations. The head-disk clearance additionally depends on the ambient temperature. When the ambient temperature varies, the clearance changes because of temperature-induced head protrusion (T-IHP) induced by differences in the rate of thermal expansion of head materials [1]–[4]. In the writing process, the write current creates power dissipation consisting of Joule heating in the coil as well as eddy currents and hysteresis losses in the yoke. This additional heating generates extra head protrusion called write-induced head protrusion (W-IHP). Without AFH control, it is difficult to optimize the performance of the magnetic recording system at a high areal density. To achieve the target head-media clearance in writing and reading processes, sliders that consist of micro-actuators have been proposed for adjusting the flying height [5]–[7]. Among these approaches, the most practicable one is an adjustment of the head-media clearance at the read/write elements with thermal expansion by a heating element near the read/write elements [7]. The heating generated in the heater induces head deformation, called heater-induced head protrusion (H-IHP). This protrusion improves significantly the writability and readability of the perpendicular recording system. However, the thermal stress may impact the performance of the sensor element by inducing noise and instability in some weak heads.

In this study, we used a spin stand tester to measure head protrusion rate versus the applied heater power. The electrical performance of the heads with AFH were investigated through the measurement of track average amplitude (TAA), overwrite (OVW) and BER by enabling and disabling AFH. The performance comparison between weak heads and normal heads was made. Next, we used a quasistatic tester (QST) to investigate the effect of the thermal stress due to AFH on voltage fluctuations, noise and instability of TMR sensors, comparing between the unstable heads and normal heads. Finally, we examined the root cause of the failure based on the related theory and the experimental result.

2. Experiments

2.1 Apparatus

Both a spin stand tester and an ISI QST tester are used in this experiment. A schematic view of the experimental setup of the spin stand is presented in Fig. 1(a). The disk and head are set in the spin stand tester that consists of a spindle unit, a read/write unit, and a fly-height adjustment unit. A schematic view of QST setup is presented in Fig. 1(b). The head is set in the magnet air-gap of the QST tester consists of a digital multimeter, noise-detection circuit, and a heater power supply.
2.2 Samples

The heads in this experiment are perpendicular magnetoresistance (PMR) heads using for an areal density of 130 Gbit/in² and they are in a form of head gimbals assembly (HGA). The slider consists of a small planar heater near the read/write elements. The material of the heater is NiCr. The reader is a TMR sensor with IrMn as the antiferromagnetic (AFM) layer. The junction barrier is made of MgO. The pinned layer is made as SAF. SAF is a combination of two ferromagnetic layers, pinned layer (PL) and reference layer (RL), separated by a thin Ru layer. PL and RL are made of CoFe. The air-bearing surface (ABS) view of the TMR sensor and the schematic of TMR stack are shown in Fig. 2.

2.3 Experimental Methods

2.3.1 Spin Stand

All parameters at spin stand were measured at an inner diameter (ID) radius with skew angle of −11 degrees and the linear velocity of 15.84 m/s. First, the spin stand tester is used to measure a head-to-media spacing (HMS) versus applied heater power. The test result leads to the calculation of a head protrusion rate and the head-media clearance without AFH. The head protrusion or H-IHP is measured relied on Wallace spacing loss method with harmonic ratio technique given as [8]

\[ \Delta H_{MS} = -\frac{v}{109.2f_0}(\Delta dB_3 - \Delta dB_1) \]  

where \( f_0 \) is the fundamental frequency of the written signal, \( v \) is the velocity of the written track, \( \Delta dB_1 \) and \( \Delta dB_3 \) are the spectral amplitude of the 1st and 3rd harmonic, respectively.

The position error signal (PES) is used to determine close proximity of head and media. Positive \( \text{PES} \) and Negative \( \text{PES} \) are measured when the head is moved to the right and left of the center track for 25% of a track width, respectively. At a very small clearance between the head and media, \( \Delta PES (\Delta PES = \text{Positive}_\text{PES} - \text{Negative}_\text{PES} ) \) is significantly different because the head is off the track due to a sideways-contact force. If it is above the threshold, the head-media contact is defined. The flying height of each individual head at zero heater power is determined from \( \Delta H_{MS} \) when the head contacts to the media.

Then, the study in the effect of head protrusion on OVW, TAA, and BER is achieved by measuring these parameters with and without AFH where the head-media clearance during AFH is around 3 nm. TAA is measured using a write pattern of 490 kfci. OVW is measured using write patterns of 490 kfci and 70 kfci while BER is measured with a random pattern.

2.3.2 Quasi-Static Test

In the spin stand, the temperature distribution in the head
slider is under flying conditions while that of QST is under natural convection conditions [1]. Therefore, the heat transfer path due to heating from the heater in the head slider is different between in the spin stand and QST. To simulate an equal thermal stress as enabling AFH of the spin stand, we adjusted the heater power to obtain the same temperature at the read/write elements.

To investigate the effect of thermal stress on the sensor elements, the transfer curves and noise spikes of heads are measured at various head temperatures. Each individual head was biased to get a voltage drop across the sensor of 100 mV in equilibrium. The transfer curve of TMR sensor is determined from the measurements of a voltage drop across the sensor, while sweeping an external homogenous magnetic field parallel to the layers of TMR sensor from $-500$ Oe to $+500$ Oe and back. These measurements consider the switching of the magnetization in the soft-magnetic layer while the hard magnet remains nearly unaffected.

Noise spikes of TMR heads are observed in time domain by reading back through the preamp and a low pass filter of 80 MHz. Noise signal was sampled by a digitizer with a sampling rate of 160 M samples/sec [9]. The test setup is with the test cycle of 1000 cycles and the read duration of 20 $\mu$s in each cycle. In addition, the noise spikes are measured at various values of transverse field by sweeping from $-500$ Oe to 500 Oe with an increment step of 10 Oe. At each value of the transverse field, if the noise signal is sampled from $n$ cycles and it takes $k$ sample in each cycle, the peak of noise spikes can be represented by these following terms [9]

$$\begin{align*}
\text{Max Amp} &= \text{Max}(\text{SAmp}_1, \text{SAmp}_2, \ldots, \text{SAmp}_n) \\
\text{Noise Amp} &= \frac{1}{n} \sum_{i=1}^{n} \text{Max Amp}_i \\
\text{Max Noise Amp} &= \text{Max}(\text{Max Amp}_1, \text{Max Amp}_2, \ldots, \text{Max Amp}_n)
\end{align*}$$

where $\text{SAmp}$ is the amplitude of each sample, $\text{Max Amp}$ is the maximum noise amplitude in each cycle.

3. Results and Discussions

3.1 Spin Stand Result

The HMS reduction versus the applied heater power of three example heads is almost linear as shown in Fig. 3. Using a linear regression, the HMS reduction slopes of these heads are 0.150, 0.153 and 0.156 nm/mW, respectively. These heads show the flying height at zero heater power of 6.181, 6.301, and 6.155 nm, respectively. Controlling the flying height of these heads to reach the target of 3 nm in adaptive fly mode, the heater power of 21.2, 21.6, and 20.2 mW is required for each head, respectively. The head temperature rise with enabling AFH is around 38°C. The temperature rise inside the slider head is calculated by measuring the change of the writer-coil resistance when the heater power increases by using the following term

$$R = R_0[1 + \alpha(T - T_0)]$$

where $\alpha$ is the temperature coefficient of resistance of copper, $R_0$ is the writer-coil resistance at a reference temperature $T_0$, and $R$ is the writer-coil resistance at the temperature $T$ when the heater power is applied.

Figure 4 shows the on-track BER of good heads and weak heads at non-AFH (zero heater power) and AFH (clearance = 3 nm). In adaptive fly mode, BER of good heads improves for 1.35 decades because the lower fly enhances both writability and readability. This protrusion improves the write performance of the perpendicular recording system because the reduction of the gap between the main pole and soft-underlayer increases magnetic flux at the recording layer. In general, OVW is the parameter to represent the writability of head-media. Figure 5 shows that OVW improves for 5 dB when HMS decreases by 3 nm. This head protrusion additionally enhances the readability because the closer to the media the higher readback signal the sensor picks up. Figure 4 shows that High Frequency Amplitude increases by 7.2% when HMS decreases by 3 nm. However, the BER of weak heads does not improve where OVW and High Frequency Amplitude are comparable to those of good heads. The thermal stress from the AFH heater may induce instability on the TMR sensors of these weak heads resulting in poorer BER. Therefore, a further
3.2 Quasi-Static Test Result

Instabilities of TMR sensors can be observed from their transfer curves. It shows that weak heads indicate instabilities and nonlinearities in their transfer curves through the presence of voltage fluctuations and open loops between forward and backward curves when applying the electrical current to the heater. Without the thermal stress from the heater, the transfer curves of these heads show smooth transfer curves as shown in Fig. 6(a) and Fig. 6(c). The heating from the heater causes temperature rise in the area close to the read/write elements. This additional thermal stress develops instabilities on the TMR sensor by showing abrupt jumps of head voltage and a large open loop as shown in Fig. 6(b) and Fig. 6(d), respectively.

The abrupt jump of the TMR resistance also produces large noise spikes. Generally, the maximum amplitude of noise spike is preferred to represent the noise behavior of the sensor in QST. Figure 7 shows the maximum amplitude of noise spikes versus field plots at different temperatures for the worst of the good heads. Without applying the heater power, MaxNoiseAmp presents a maximum value in the order of 200 μV. MaxNoiseAmp becomes slightly larger as the increase of thermal stress and it reaches to 302 μV at temperature rise of 38°C. Figure 8 shows the noise behavior of head #1 that presents voltage fluctuations on the transfer curve when thermal stress was applied. It shows a noise peak in an order of 250 μV without applying heater power and it slightly increases to 300 μV at temperature rise of 8°C as shown in Fig. 8(a) and (b). At the temperature rise of 17°C, the higher thermal stress creates large noise spikes at the field of −130 Oe, −70 Oe, and 430 Oe as shown in Fig. 8(c). MaxNoiseAmp increases to the order of 500 μV at almost every magnetic field at temperature rise of 27°C and it increases to above 600 μV at every magnetic field at temperature rise of 38°C as shown in Figs. 8(d) and (e), respectively. Figure 9 shows noise behavior of head #2 that presents an open loop of the transfer curve. It is similar to...
head #1 except it creates a large noise spike earlier at temperature rise of 8°C with a noise peak in the order of 400 μV. In addition, NoiseAmp of these heads also increases significantly due to the thermal stress.

Figure 10 shows a comparison of noise behavior between good and weak heads with and without applying the thermal stress. Without the thermal stress, most of weak heads show a comparable MaxNoiseAmp to good heads. However, they are very sensitive to the applied thermal stress resulting in the increase of their MaxNoiseAmp dramatically while those of good heads slightly increase. Consequently, high noise spike in weak heads degrades the recording performance by reducing the signal-to-noise ratio (SNR) and raises BER.

3.3 Discussions

Initially, the source of these voltage fluctuations and large noise spikes may be located at any layers of the TMR sensor such as the permanent magnet (PM), free layer (FL), SAF layers or AFM layer as shown in Fig. 2. Generally, FL requires a proper stabilizing field from PM. A poor stabilization field or FL asymmetry can lead to head instability. FL edge magnetization being weakly pinned can be excited by the thermal stress. It switches back and forth and leads the sensor into unstable states. Normally, the nature of instability due to PM-FL shows a bending transfer curve rather than an open loop. Moreover, the instability due to low FL stabilizing field normally can be recoverable with the mag-
In this experiment, an external field of 8.5 kOe was applied in parallel to PM field to reset PM and FL before re-testing the transfer curve and noise spike. However, this field is unable to remove this instability permanently.

In this case, the mechanism of abrupt jumps of head voltage and a large open loop of the transfer curve is more likely because of the imperfectly fixed magnetizations of PL and RL due to SAF edge magnetization flipping [10]. SAF magnetization has bi-stable edge states and it can move between its stable states with either field or thermal activation. In the forward curve of Fig. 6(d), SAF edge magnetization flipped from a stable state “A” to a state “B” at point “1” due to magnetic activation while the thermal stress were kept constant. In the state “B,” an angle between the magnetizations of FL and RL becomes much smaller than that of the state “A” causing an abrupt reduction of TMR resistance. At the beginning of the reverse curve SAF magnetization is still in the state “B” and it changes back to the state “A” at point “2,” therefore, creating a hysteresis loop. SAF edge magnetization uncontrollably flips back and forth resulting in voltage fluctuations on the transfer curve as shown in Fig. 6(b).

The reduction of exchange bias field potentially creates these SAF instabilities. The dispersion and thermal stability of AFM may cause to lower the SAF/AFM exchange bias field. The AFM is made of individual grains and the crystalline anisotropy easy axes of the grains are randomly distributed. SAF energy minima are determined by misalignments between the AFM crystalline axes and the exchange direction as well as misalignments between the exchange direction and the PL magnetization. Larger AFM dispersion gives less net stabilizing field to the SAF that lowers the energy barrier to flop the SAF edge magnetization. The increase of AFM dispersion also lowers the energy barriers allowing AFM thermal fluctuation that causes a SAF flop because the local PL magnetization follows the AFM flip. In addition, the AFM grain size is the dominant variable affecting the thermal stability of exchange bias field. The exchange bias field decreases as the AFM grain size is reduced [11]. AFM layer has an inherent grain size distribution and shows a number of cut grains around the edges of the sensor from milling and lapping processes as shown in Fig. 11.

These truncated grains are much weaker than normal grains. The weak heads may have the higher AFM dispersion and/or a higher number of weak grains than good heads. Without the thermal stress from the AFH heater, the exchange bias field of the weak heads is sufficient to stabilize SAF layer. However, the thermal stress from the AFH heater decreases significantly the exchange bias field of these heads and their SAF layers become unstable while good heads are still stable at an equivalent thermal stress.

Figure 12 shows SEM images of the sensor elements. The SEM images of head #1 and head #2 show rougher ABS surfaces close to the sensor element than that of a good head. The mechanical stress that creates these shallow scratch lines may additionally contribute to SAF insta-
bility. It may impact to the stabilizing field of the SAF edge magnetization.

4. Conclusion

Adaptive flying height based on heater-induced head protrusion compensates for the impact of the process and environment variations and improves the writability and readability of the magnetic recording system. However, the thermal stress from the heater induces serious instabilities in some heads. With AFH, these heads become unstable by showing voltage fluctuation on the transfer curve and large noise spikes that degrade BER of the magnetic recording system. The thermally activated flipping of SAF edge magnetization potentially causes these instabilities where the switching of bi-stable edge states in SAF creates an open loop of the transfer curve. In some heads, SAF edge magnetization flips back and forth resulting in voltage fluctuations on the transfer curve.

The TMR sensor in the AFH slider head is required to improve the robustness. The dispersion and thermal stability of AFM potentially are the sources to create these SAF instabilities because the larger AFM dispersion in these heads and/or a higher number of weak grains due to a grain size distribution and cut grains reduce the SAF/AFM exchange bias field that lowers the energy barrier to flop the SAF edge magnetization. SAF and AFM annealing under the high temperature and high magnetic field in the wafer fabrication process, in principle, can reduce the AFM/SAF dispersion. The mechanical stress due to scratch lines close to the sensor element may additionally induce the flop of SAF edge magnetization. The lapping process in the slider fabrication can be one of the processes that create the rough surface and scratch lines.

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References


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