Journal of
INDUSTRIAL
TECHNOLOGY

Volume 22, Number 4 - October 2006 through December 2006

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Peer-Refereed Article

KEYWORD SEARCH

Computer Technology
Electricity
Electronics
Materials & Processing
Materials Testing
Research

The Official Electronic Publication of the National Association of Industrial Technology • www.nait.org

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A Study of Magneto-Resistive Read-Write Head Reliability Using Low-Frequency Noise Measurement Technique

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Abstract

Low-frequency noise measurement technique is applied to study reliability of magneto-resistive (MR) read-write head against failure conditions. The MR head sample is subjected to high electrical and thermal stress to induce failure conditions. The behavior of sample under these conditions is monitored using dynamic signal analyzer-based noise measurement system. The measurement system, samples used, and the experimental results obtained under stressing conditions are analyzed and reported in the paper. The reliability study serves as a useful tool for manufacturers to assess the operating conditions and life duration of MR head element.

Introduction

Many of the past improvements in disk-drive capacity have been a result of improvements in the read-write head, which records data by altering the magnetic polarities of tiny areas, called domains (each domain representing one bit), in the storage medium. Early products used read-write heads made of ferrite, but beginning in 1979, silicon chip design technology enabled the precise fabrication of thin-film inductive (TFI) heads (Daniel, Mee & Clark, 1996). The TFI read-write head consists of wired wrapped magnetic cores, which produce a voltage when moved past a magnetic hard disk platter. In TFI it became impractical to increase areal density of recorded data in the conventional way - by increasing the sensitivity of the head to magnetic flux changes by adding turns to the TFI head's coil. This method increases the head's inductance to levels that limited its ability to write data.

In 1991, IBM's work on anisotropic magneto-resistive (AMR) technology led to the development of magneto-resistive (MR) heads capable of the areal densities required to sustain the disk-drive industry's continued growth in capacity and performance (IBM; Mallinson, 1995). The physical characteristics of an MR read-write head are shown in Figure 1. In an MR read-write head, simply called as MR head, the write element is a conventional TFI head, while the read element is composed of a thin stripe of magnetic material (Ashar, 1997). Rather than reading the varying magnetic field in a disk directly, an MR head looks for minute changes in the electrical resistance of the overlying read element, which is influenced by that magnetic field. The greater sensitivity that results allows data-storing domains to be shrunk further.

The MR head element can be made smaller than the data track so that if the head were slightly off-track or misaligned, it would still remain over the track and able to read the written data on the track (IBM; Belleson & Grochowski, 1998). Its small element size also precludes the MR head element from picking up interference from outside the data track, which accounts for the desirable high signal-to-noise ratio. Although manufacturers continued to sell thin-film heads through 1996, MR heads have come to dominate the market. Manufacturing MR heads can present difficulties. The MR head elements are extremely sensitive to electrostatic discharge, which means special care and precautions must be taken when handling these heads. They are also sensitive to contamination and corrosion, because of the materials used in its design.

Figure 1: Magnetoresistive (MR) read-write head element.

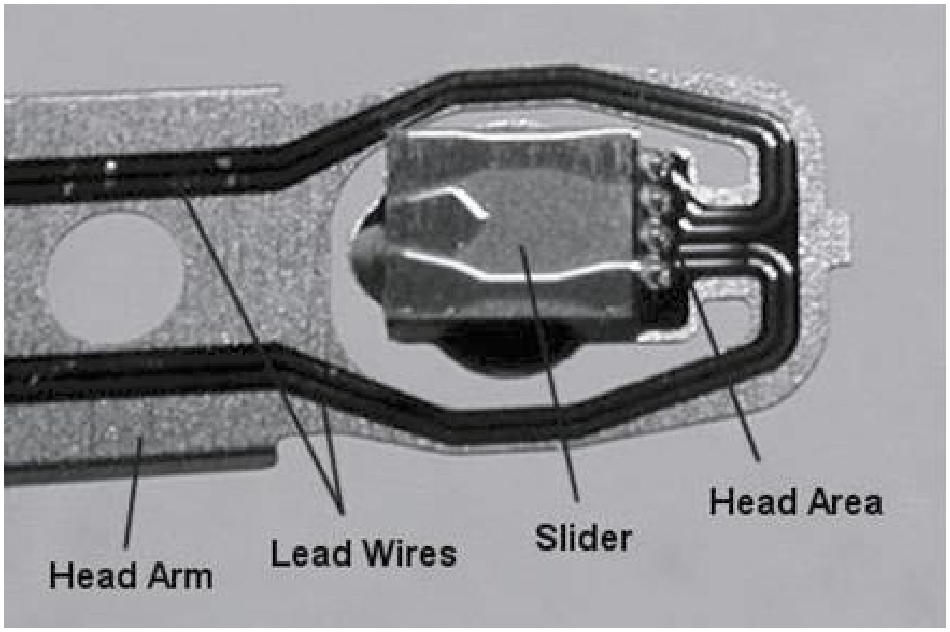
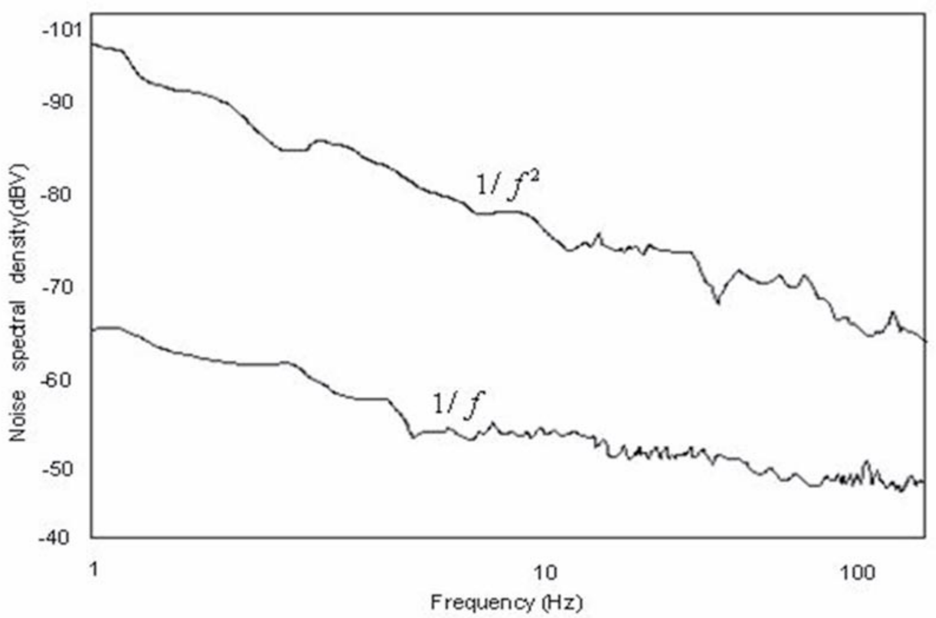


Figure 2: A typical 1/f and $1/f^2$ noise pattern.



The use of MR heads also introduced a new challenge not present with TFI heads: thermal asperities, the instantaneous temperature rise that causes the data signal to spike and momentarily disrupt the recovery of data from the drive (Tian, Cheung & Wang, 1997). Thermal asperities are transient electrical events, usually associated with a particle, and normally do not result in mechanical damage to the head, but can lead to misreading data in a large portion of a sector. Thermal asperities can be caused due to self-heating in MR heads due to writing currents (Iben, 2003). Head protrusion caused by the thermal expansion of its constituent films alters the head media, which may also lead to thermal asperities and mechanical damage (Wang, Wu, Weresin & Ju, 2001). Thermal crosstalk between read and write heads also has deleterious effects. Heat generated in the write head (due to writing currents) causes a temperature rise in the adjacent MR sensors, which are very susceptible to failures caused by thermally activated mechanisms, including interdiffusion, loss of magnetic coupling, and degradation of tunnel barriers (Jang, Wang, Cho & Lee, 2002; Ju, 2005).

Recently, the use of decreasingly thin films in MR heads and demands for a higher mean time-to-failure has created the need for rigorous investigation of the fundamental limits of reliability for MR head designs. A sizable body of knowledge exists concerning the tolerance of most MR head materials to degradation mechanisms such as galvanic corrosion and frictional damage (Pust, Rea & Gangopadhyay, 2002). Most of this knowledge has been gained through the industry's vast experience with TFI heads. However, the tolerance of MR head materials to damage caused by the flow of electrical current at elevated temperature has not been important until the emergence of MR heads for rigid disk drives.

Under normal operating conditions the changes in MR read-write head sensor (stripe) properties are undetectable. To estimate failure conditions, sensors need to be exposed to elevated temperatures and currents and changes in relevant physical parameters to be measured (Ju et al., 2001). In this study, we have made use of the low-frequency one-over-f (1/*f*) noise also known as excess noise measurement technique, which has been extensively used to study reliability in metal thin films, wafer level reliability issues and reliability of various other solid-state devices (Zeynep & Wiyi, 1990; Rawat & Massiha, 2004). Research has shown that low-frequency noise and resistance measurements can be used as a sensitive tool for detecting stress induced damage (Zeynep & Min, 1992). Also it is widely accepted that 1/*f* noise shows a significant increase during the process of failure due to heat induced stress, and that the noise magnitude is related to the time of failure of the sample (Zeynep & Wiyi, 1990; Fleetwood & Giordano, 1985).

The excess noise measurement technique is much faster than the conventional mean-time-to-failure (MTTF) method and is nondestructive in nature, which makes this technique an ideal tool to study failure issues in thin film-based materials (Ghate, 1982). In a noise measurement experiment it is necessary to monitor the excess noise produced by the sample while it is subjected to the electrical and thermal stress in order to make a correlation between the noise voltage spectral density or noise power and the sample failure conditions. This was made possible by using a dual channel dynamic signal analyzer-based low-frequency noise measurement system. Physical parameters such as stripe resistance and noise spectral density were measured as functions of temperature and current density. In this paper the results were obtained by applying low-frequency noise measurements on MR head samples subjected to electrical and thermal stress.

In the next section, a brief introduction to electrical noise theory and low-frequency noise measurement system is presented. The later part of the paper focuses on the experiments performed, experimental results and significance of the study conducted. Finally, the relevant conclusion is presented.

Electrical Noise Theory and Measurement System

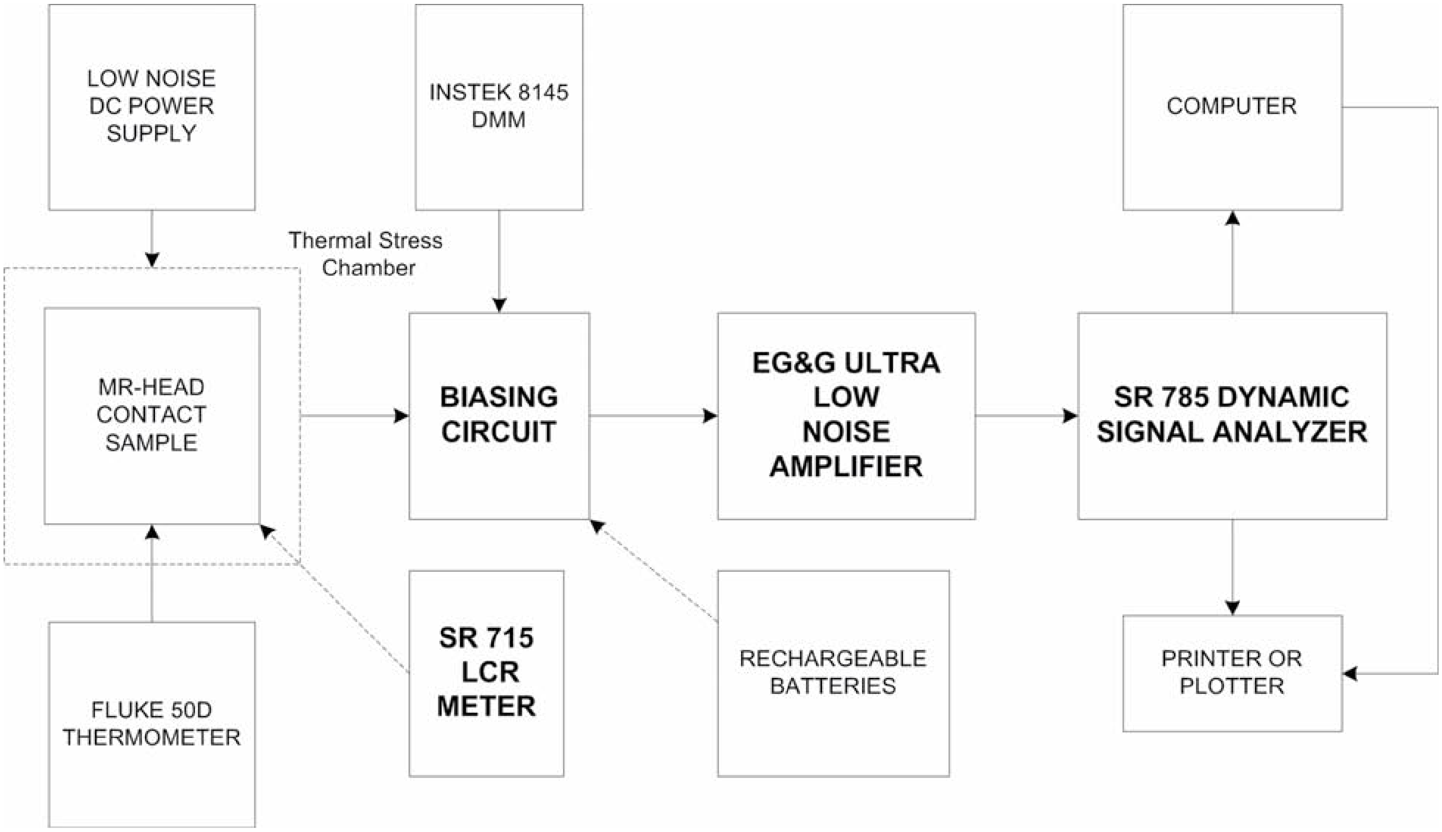
1. Electrical Noise Theory:

Noise in a broad sense can be defined as an unwanted signal or disturbance. Three main types of noise mechanisms are referred to as thermal noise, shot noise, and low-frequency excess noise. Thermal noise is caused by the random thermally excited vibration of the charge carriers in a conductor. Shot noise is found in tubes, transistors, and diodes. Shot noise is associated with current flow across a potential barrier. The low-frequency or excess noise was first observed in vacuum tubes; this noise was called flicker noise (Haus, 2000). Studies of low-frequency noise have shown that the major cause of this noise in semiconductor devices is traceable to the surface of the material (Ciofi & Neri, 2000). In general, depending on the spectral shape of the noise power spectrum, these studies can be divided into two groups: one that concentrates on $1/f$ noise and ones that deals with $1/f^2$ noise. At low frequencies, $1/f^{\alpha}$ noise with $0.7 \leq \alpha < 1.4$ is referred to low-frequency $1/f$ noise or simply $1/f$ noise. A typical $1/f$ noise and $1/f^2$ noise patterns are depicted in Figure 2 (Kogan, 1985).

The noise voltage spectral density of a DC biased metal thin film consists of the thermal and excess noise components. The thermal noise term can be measured without applying current or it can be easily estimated using,

$$S_v = 4k_B RT$$

Figure 3: Low-frequency noise measurement setup.



where k_B is the Boltzmann's constant, if temperature T and resistance R of the sample is known. The thermal noise exists in all devices with finite conductivity at temperatures above absolute zero, and it determines the minimum level of noise in the test sample. However, when the low-frequency noise measurement system is used, an additional noise can be generated through the preamplifier, biasing circuit, multimeters, power supplies, and connecting wires. This noise is called the system noise. The sum of the test sample thermal noise and the system noise determines the minimum level or background noise, denoted as $S_{v(bgn)}$. Hence, the total noise $S_{v(total)}$ can be written as:

$$S_{v(total)}(f) = 4k_B RT + S_{v(system)}(f) + \frac{KV^{\beta}}{f^{\alpha}}$$

$$= S_{v(bgn)}(f) + \frac{KV^{\beta}}{f^{\alpha}}. \qquad (1)$$

where K and β are constants, f is the frequency, α is termed as frequency exponent and V is the voltage across the conductor.

In this project $S_{v(bgn)}$ was measured when the entire system was operating with no DC current passing through the MR samples.

2. Low-Frequency Noise Measurement System:

The low-frequency electrical noise measurement system used in this research project consists of four important parts: SR785 Dynamic Signal Analyzer, EG&G 5184 Ultra Low Noise Voltage Preamplifier, SR715 LCR meter, and Biasing circuit. The function and characteristics of each part is described next. A block diagram of low-frequency noise measurement system used in the project is shown in Figure 3.

A. SR785 Dynamic Signal Analyzer: The SR785 is dual channel and makes use of Fast Fourier Transform (FFT) to obtain the frequency spectrum of an input voltage signal. One important feature of this is different types of averaging modes, which are necessary in a given frequency range to reduce the variance of the final plot. Furthermore, the trace storage, retrieval, capture buffer and the math function are used to store and subtract background noise from the final measurement.

B. EG&G Ultra Low-Noise Voltage Preamplifier: The excess noise generated by an MR sample under test is in the ρV to ηV range. The sensitivity of a SR785 signal analyzer is limited to detect input noise of about 10ηV/√Hz at 200 Hz. For this reason a very low-noise preamplifier is needed to amplify the noise signal in the amplitude large enough to drive an input of the dynamic signal analyzer. The gain provided by the preamplifier is 60 dB (fixed).

C. SR LCR Meter: The resistance of an MR sample (stripe) changes when an electric current flows through it. In the noise measurement experiments we have to keep track of the resistance of the MR stripe whilst the current is flowing through it. The LCR meter is capable of measuring the resistance, inductance and capacitance while the current flows through the sample.

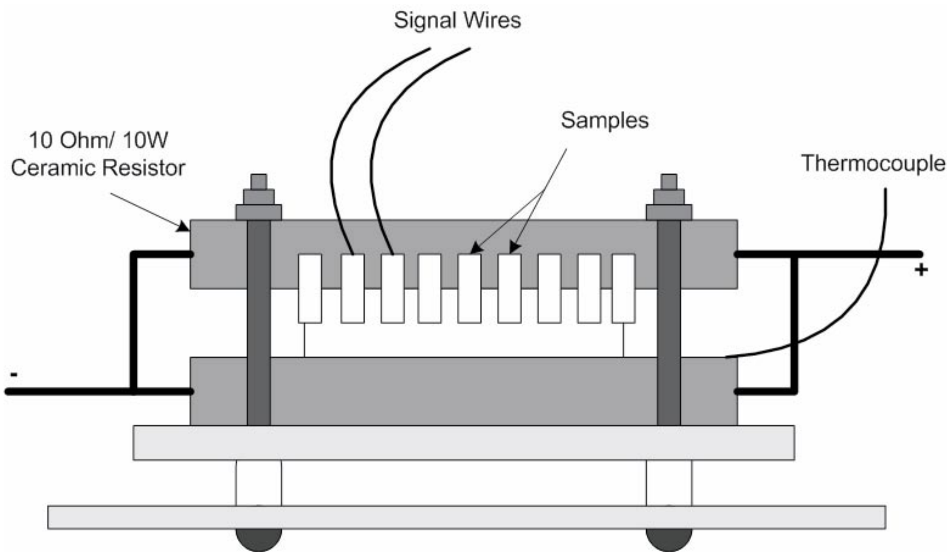
D. Biasing Circuit: To achieve a fixed range of current density across the sample, a biasing circuit is designed and fabricated. Connecting a few batteries in series with resistances provides the biasing voltage. The design of the biasing circuit is critical for the required current density across the MR stripe. The batteries are used instead of a power supply to avoid electrical noise, which adds to the 1/*f* noise to be measured. An ultra low-noise power supply can also be used, if available.

In addition to this measurement setup, a heating chamber shown in Figure 4 was also constructed to induce thermal stress to the MR samples. A thermocouple probe was used to keep track of the sample surface temperature.

Performing Low-Frequency Noise Measurements

In this research, the low-frequency noise measurements were carried out on five MR samples. The layout of the selected sample with MR contacts is shown in Figure 5. Each sample has a set of three MR contact stripes (Y-R1, R1-R2, and Y-R2). The material composition was Nickel-80% and Iron-20%. All of the metals in the stripe are ion-beam deposited. The selected samples were inspected using a Scanning Electron Microscope (SEM) for dimensions and any damage. The resistance of each strip is measured at regular intervals with aide of LCR meter used in the noise measurement

Figure 4: High temperature chamber.



system.

The MR head contacts were placed on a high temperature printed circuit board and mounted in a heating chamber specially built for the research experiments. The stress conditions were created through a combination of elevated temperature and excess current. The thermal and electrical stress was applied to all the MR contacts simultaneously. The MR contacts were subjected to current densities between 2.0×10^6 A/cm^2 and 2.4×10^7 A/cm^2 and the ambient temperature up to 400 °C. To capture 1/*f* noise spectra across the MR contact we first measured the $S_{v(bgn)}$ when the entire system was operating with no DC current passing through the MR contacts. This spectrum was captured and stored in the dynamic signal analyzer. Next the sample was kept under current density $J = 3.0 \times 10^6$ A/cm^2 and the ambient temperature was raised from 23 °C up to 400 °C. The MR samples were also subjected to higher current densities between 2.0×10^6 A/cm^2 and 2.4×10^7 A/cm^2 at a constant temperature. The noise spectrum corresponding to these conditions were also captured and stored in the dynamic signal analyzer. Using the math features of the dual channel dynamic signal analyzer, background noise was subtracted from the total noise with the remainder being the excess noise exhibited by the MR sample. The time period (stressing period) for each set of noise measurement was documented, so that the changes in the level and slope of the spectrum of excess noise could be traced as a function of test time duration.

Experimental Results

All the MR contacts were subjected to thermal and electrical stress simultaneously and showed similar responses under these conditions. All the three MR contacts exhibited a 1/*f* noise spectrum on being subjected to high current densities and higher temperatures. The error in the measured noise spectral density S_v was less than 4%, which was evaluated by repeating the measurements with other set of MR samples. In this paper the results for Y-R1 MR contact only are reported. The dimension of this MR contact was 4.0 micron × 0.25 micron × 0.1 micron.

The noise spectral density S_v versus current density J at 50 Hz for three different temperatures is shown in Figure 6. As observed in Figure 6, the current dependence of the noise magnitude shows that there seems to be a threshold below which the noise voltage has a lower degree of dependency on the bias current. Above this threshold value the noise magnitude (power) increases at a higher rate. In the experimental result shown in Figure 6 the MR contact exhibited higher noise power above 3.6×10^6 A/cm^2. The increase in noise power above this point is an indication that stress or failure conditions have started to set in. The current dependency of the spectral shape, namely the frequency exponent (α), was also investigated for all the MR samples. The frequency exponent was found by measuring the slope of the noise spectral density curve. The frequency exponent versus current density J for Y-R1 contact is shown in Figure 7. Under the subjected conditions there was no decomposition of the spectra leading to a frequency exponent below 1 for current densities

Figure 5: The MR contacts of the read-write head sample.

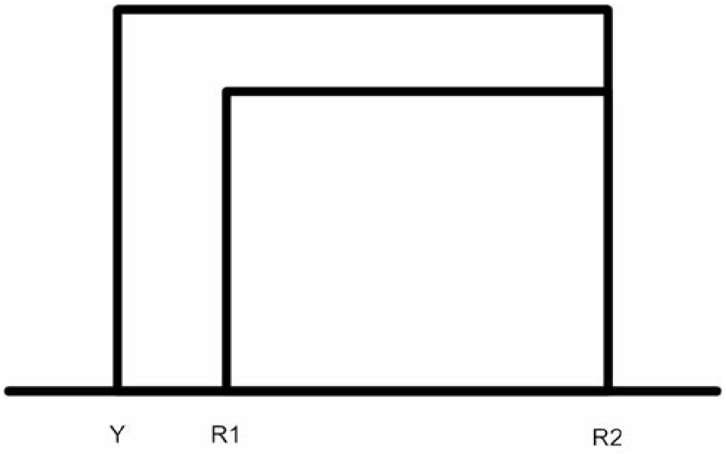
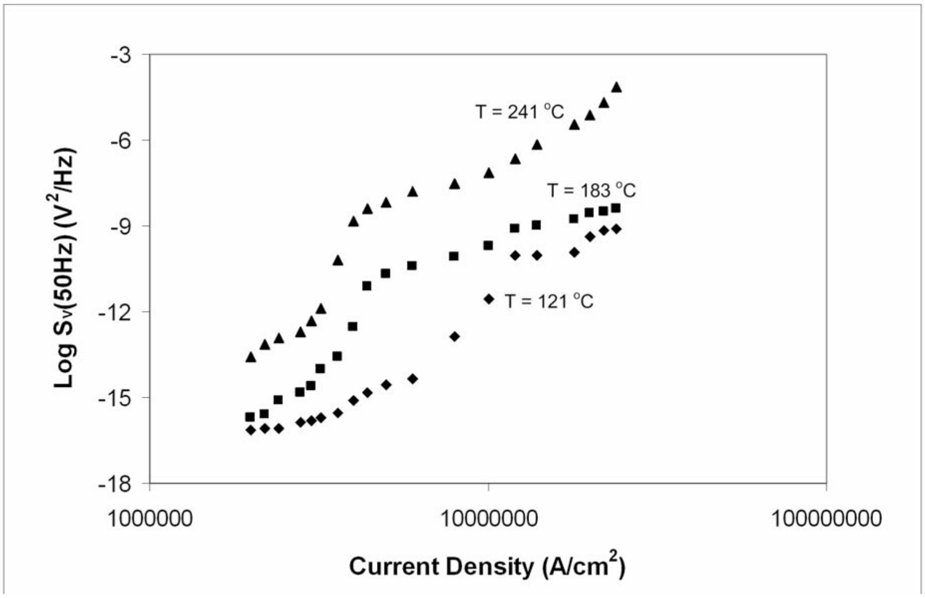


Figure 6: Dependence of the noise spectral density S_v (at 50Hz) on the current density J.



below 8×10^6 A/cm^2. Under high bias conditions non-stationary effects are introduced and the frequency exponent become higher than 1. The change in resistances was monitored throughout the experiment and the relative values (deltaR/R$_0$) were calculated for all the MR contacts. The change in resistance versus temperature at current density $J = 3.0 \times 10^6$ A/cm^2 and $J = 8.0 \times 10^6$ A/cm^2 is shown in Figure 8. In Figure 8 we observe that the resistance of the strip first increases gradually until ~248 °C. After this initial period the resistance of MR stripe increases rapidly as thermal runaway occurs. This could be caused due to electromigration-induced microsegregation of Ni and Fe atoms followed by oxidation of Fe which is due to elevated temperature and exposure to air. In Figure 8 we also observe that at a much higher current density, the resistance of MR stripe reaches a peak and then falls abruptly. This rapid resistance increase followed by an abrupt fall observed in this experiment is reflective of stress-induced damage that leads to the failure of the MR head contact.

Significance of the Research

The MR head sensor provides a higher output signal, which results in a higher signal-to-noise ratio, thereby permitting the reading of a higher areal density of recorded data on the magnetic disk surface. Such high data recording densities are possible because the MR head sensors are very small in size. Because of the small sizes involved, modern MR head sensor fabrication is accomplished using monolithic thin-film photolithographic fabrication technology (Ashar, 1997; IBM). The sensitivity of an MR head depends on many factors. One of the most significant factors is the bias current provided to the MR head. The ability to read a signal from the storage media is, in part, a function of the amount of bias current supplied to the MR head. Signal sensitivity can be increased by increasing the amount of bias current supplied to the MR head.

The increased bias current generally produces an improved signal-to-noise ratio and reduces bit error rates. However, simply increasing the bias current is not a complete solution because excessive current can significantly shorten the useful life span of the MR head due to overheating that can lead to burn out (Gibbons, Liu, Stoev, Shi, Yan & Saha, 2000). Catastrophic failure is often preceded by a decrease in performance as quantified by the bits per error rate (BER). Changes in the sensor response over time can result in degraded performance with lower BER values, and ultimately in failure. Catastrophic failure, however, is not the most common cause of MR head failure. The most common cause of MR head failure is a phenomenon known as electromigration and/or interlayer diffusion (Iben, 2003). Constant exposures to even normal operating levels of bias current will, over time, change the molecular structure of the MR head element, thereby degrading the magnetic sensing capability of the MR head.

The results from this study can help manufacturers in fabricating high performance MR head elements. During the manufacturing process, one can determine the range of their operating characteristics over temperature and bias current variations. The designers can select a MR stripe bias current that holds the stripe temperature below

Figure 7: Frequency Exponent (α) versus current density J (at 180 °C).

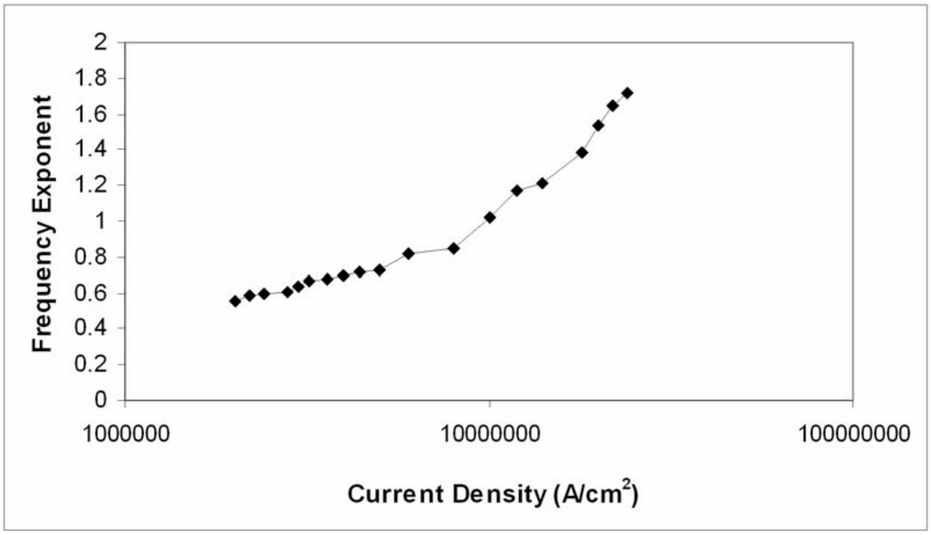
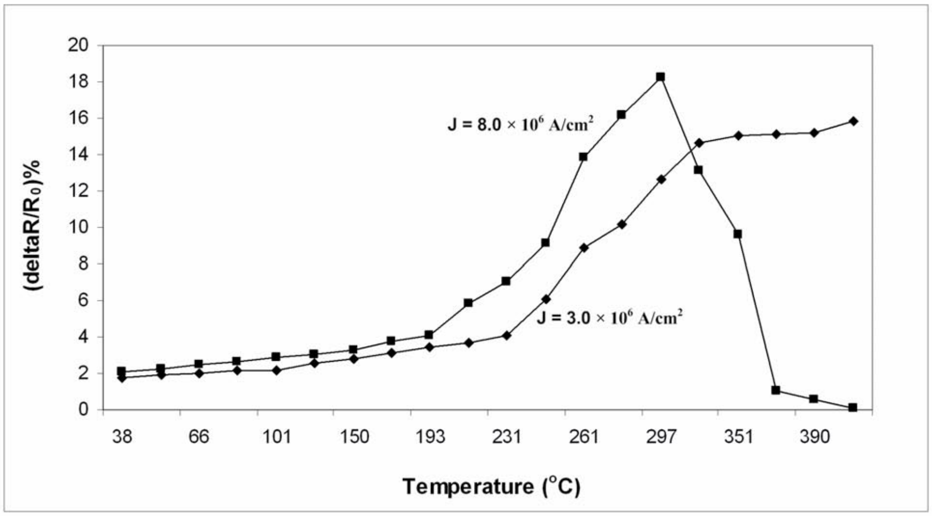


Figure 8: Change in resistance versus current density J.



a predetermined threshold, thereby providing the desired minimum lifetime for the storage unit. This study also helps us to understand how the MR head behaves when subjected to continuous stress for a longer period of time. The experimental results can help manufacturer to set the operating conditions and assess the life duration of the MR heads.

Conclusion and Further Work

A faster and nondestructive Low-frequency electrical noise technique was used to study reliability conditions in MR heads. Using a dual channel dynamic signal analyzer-based measurement systems low-frequency noise signals in MR head samples subjected to stress conditions were measured and the relevant results were reported in the paper. To this effect 5 sets of MR head samples were used. The low-frequency noise measurement system used for experiments in capturing the noise power spectrum was also discussed in the paper. The experimental results showed that the noise signal spectrums were found to be function of subjected heating temperatures and the higher current densities. The MR samples showed no sign of damage even when subjected to extreme current density up to 2.0×10^7 A/cm^2 and temperature up to 380 ^{o}C. Only when subjected to temperatures above this, the MR contact stripe started decaying and exhibited an increase in frequency exponent or higher noise power, thereby indicating its maximum reliability condition. Also the MR head contacts showed large resistance drift after being subjected to higher temperatures (>250 ^{o}C) and higher noise power above current density over 8.0×10^6 Amp/cm^2. From the results we can conclude that the damaged MR stripes are found to exhibit excess noise at low temperatures and currents.

The results showed that the noise measurement technique could be applied to study the reliability of MR heads, which are constantly introduced to thermal asperities due to the disk, read and write activities. We can also deduce the sustainability of the MR head against excess use due to frequent read and write operations and also under any other thermal conditions. The experiments conducted during the study were sufficient to analyze the conditions that can lead to MR head failure. The study can be further extended by using annealed samples. It would be interesting to know the results of annealing the samples before being subjected to stress conditions. The performance of MR heads fabricated on a given fabrication line may vary considerably because of process variations in the important geometric features on the heads, such as read-width (RW) and stripe-height (SH). A study could also be conducted to evaluate the impact of geometrical characteristics on MR head reliability. The authors would also like to emphasize that if several samples are made available then the computing or extrapolating time-to-failure described using Arrhenius model can be of greater significance.

Acknowledgment

The authors thank Dr. Mohammed Madani at the University of Louisiana, Lafayette for fabricating MR head samples used in the study.

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