Magnetic In-line Metrology for GMR Spin-Valve Sensors

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Introduction

Areal storage densities are increasing at an unprecedented rate owing to advances in the development of media[1] and read head materials. Increasing storage density necessitates increased signal output from the read sensor. For this reason, over the last few years thin film inductive heads have been replaced by heads based on the anisotropic magnetoresistance (AMR) effect. Recently, a class of metallic multilayer films exhibiting the giant magnetoresistive (GMR) effect have gained considerable attention for their application as read heads for hard disk (HD) and tape magnetic storage. GMR effect read sensors exhibit an MR ratio, $\Delta R/R$, which is typically 8% or higher as compared with 2% for AMR readers. Their increased sensitivity allows the read element track width to decrease, thus increasing track density and ultimately, storage density[2].

The exchange biased spin-valve is a multilayer GMR device and offers the most promise as a candidate for read head applications[3]. A spin-valve[4] (SV) consists of 4 layers: a free and pinned layer both comprised of a soft ferromagnet such as permalloy (NiFe) or a Co alloy. These layers reside on either side of a non-magnetic Cu spacer. An exchange layer of anti-ferromagnetic material (commonly comprised of a Mn alloy[5], e.g., NiMn) is deposited next to the pinned layer. The device structure is illustrated schematically in figure 1. The free layer is sufficiently thin to allow conduction electrons to frequently move back and forth between the free and pinned layers via the conducting spacer layer. The magnetic orientation of the pinned layer is fixed and held in place by the AFM layer, while the free layer magnetic orientation changes in response to the magnetic field from a bit on a hard disk.

The quantum nature of electrons, i.e., either spin up or spin down, is exploited in GMR sensors. Conduction electrons with spin parallel to the material's magnetization (spin "up") move freely, while the motion of those electrons with anti-parallel orientation (spin "down") is impeded via collisions with atoms in the material. When the free and pinned layer magnetizations are parallel, spin up electrons move freely in both magnetic layers, corresponding to a low resistance device configuration. Conversely, when the free and pinned layer magnetizations are anti-parallel, movement of spin up electrons is hampered by one layer, while the movement of spin down electrons is hampered by the other, leading to a high resistance. In the GMR sensor, a recorded bit rotates the free layer magnetization relative to that of the pinned layer, effectively switching the device between these two alternative configurations, i.e., either high or low resistance. These effects are illustrated in figure 2.

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[1] Magnetic Media: Measurements With a VSM
[2] D. Heim, et. al., IEEE Trans on Magnetics, v. 30, p. 316 (1994)
H. Kanai, et. al., IEEE Trans on Magnetics, v. 32, p. 3368 (1996)
K. Takano, et. al., IEEE Trans on Magnetics, v. 34, p. 1516 (1998)
[3] and for non-volatile magnetoresistive RAM (MRAM) devices (E. Chen, et. al., J. Appl. Phys. v. 81 (8), p. 3992 (1997))
[4] R. White, IEEE Trans on Magnetics, v. 28, p. 2482 (1992)
J. C. S. Kools, IEEE Trans on Magnetics, v. 32, p. 3165 (1996)
[5] M. Lederman, Performance of Metallic Antiferromagnets For Use In Spin-Valve Read Sensors

Significant challenges have been encountered in the development and manufacture of GMR multilayer film devices. One primary concern is the uniformity and thickness of the deposited layers (for example, the Cu space layer is typically less than 15 atoms in thickness). These film properties significantly impact physical properties of the device such as; magnetoresistance, resistivity, magnetization, and magnetostriction[6]. Further, film properties[7] (such as surface roughness) impact the coupling between layers, the coercivity of the free layer, and the effectiveness of the antiferromagnetic layer in pinning one of the magnetic layers[8]. In sum, there are a large number of critical process control parameters which will have an impact on the utility of the device. Further complicating matters is the fact that many of these parameters are interrelated. In order to fabricate devices compatible with use as read sensors (an output variation of less than 10%, for example), strict tolerances must be maintained, and the devices must be subject to tight quality control processes.

Similar challenges have been encountered in measuring their resultant physical properties, particularly magnetic properties. In addition to manifesting a GMR effect, the other defining characteristic of a spin valve is a hysteretic response that is shifted or asymmetric with respect to the magnetic field origin, unlike typical hard or soft magnetic materials. Furthermore, the parameters that are extracted from the resultant hysteresis loops (exchange field, pinning field, free layer coercivity, blocking temperature, etc.) are similarly novel. This article will discuss the utility of the Vibrating Sample Magnetometer (VSM) technique in characterizing these materials, and recent advancements and additional capabilities in VSM measurement methodology that have been developed to characterize the magnetic properties of these pivotal materials.

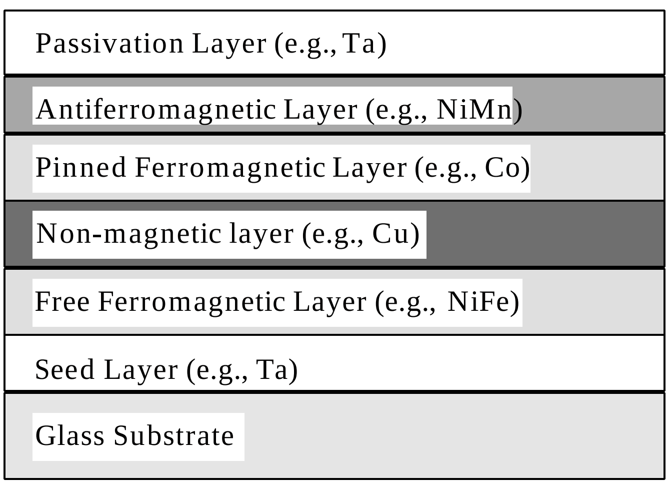

Figure 1: Schematic illustration of a spin-valve GMR sensor.

[6] B. Gurney, et. al., J. Appl. Phys. v. 81 (8), p. 3998 (1997)
[7] K. Krishnan, et. al., J. Appl. Phys. v. 83 (11), p. 6810 (1998)
[8] W. Egelhoff, et. al., J. Appl. Phys. v. 79 (11), p. 8603 (1996)

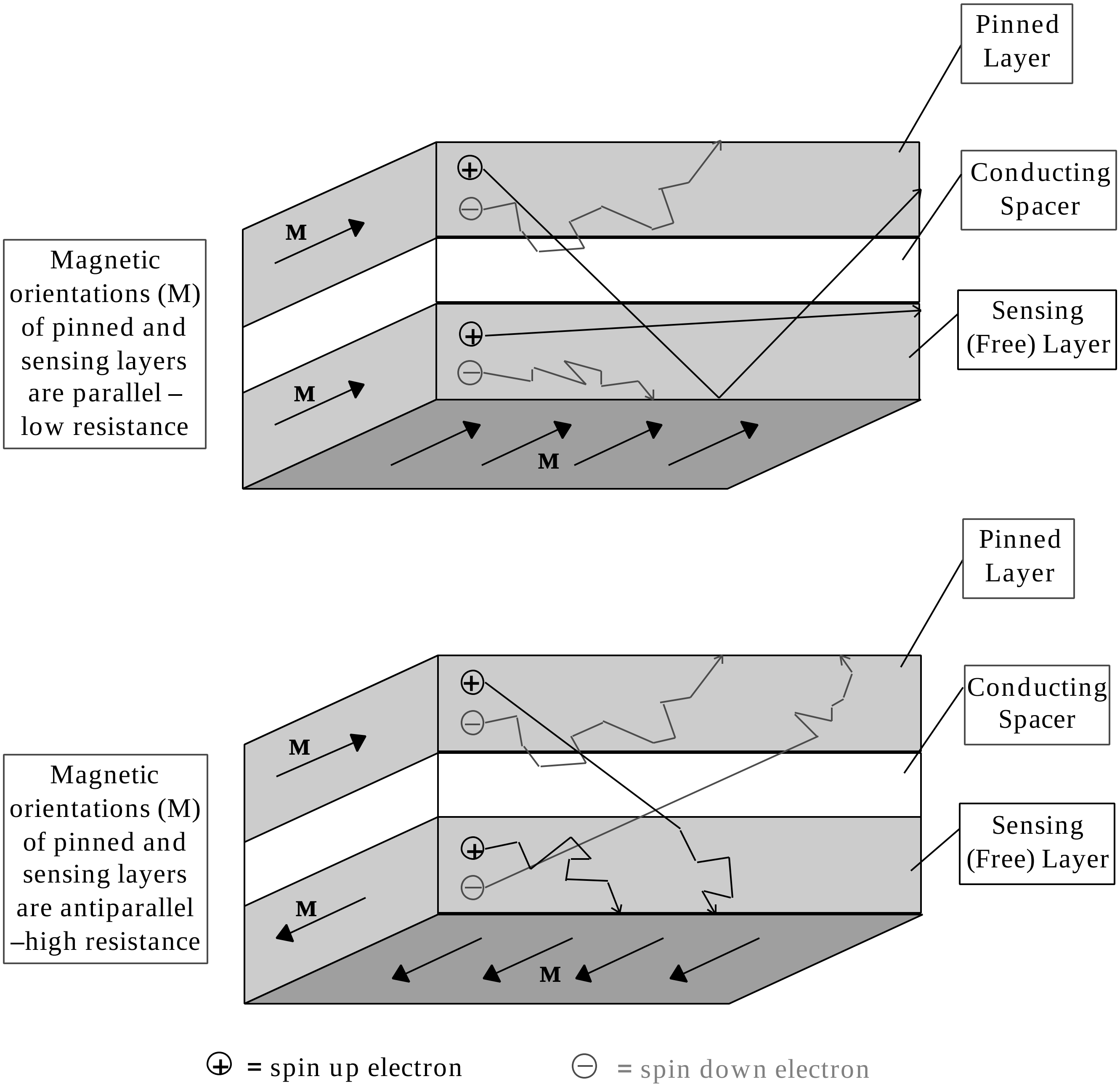

Figure 2: Illustration of quantum nature of electrons in a GMR sensor.

Advanced Read Heads – Changing Requirements For Magnetic Metrology

The vast majority of the cost in manufacturing read head sensors is incurred in processing the individual sensors, all of which occurs after the deposition process. Therefore a means for qualifying the post deposition product is critical. In light of the constraints imposed on the manufacturing processes utilized in fabricating GMR SV devices[9], a variety of *in-process* metrology is performed to provide the feedback required for process control. In-process measurement of magnetic and magneto-resistive properties is one method by which the film deposition process is qualified and controlled.

[9] e.g., surface roughness, layer thickness control, process control, etc.

Vibrating Sample Magnetometry (VSM) is the standard reference for measuring the magnetic properties of materials as a function of field and temperature, often serving as the standard by which other metrology test tools are calibrated. A VSM can quickly and accurately measure the magnetic hysteresis loop of a material, and is exceedingly easy to use, rendering it attractive not only for research and development applications but also making it conducive to the needs of a manufacturing environment.

GMR SVs have imposed a myriad of requirements on metrology tools, and on the VSM technique specifically, for example:

- Since GMR film thicknesses are on the order of nanometers, measured signals of the SV's intrinsic magnetic behavior are very small, requiring improvements in VSM sensitivity.
- A GMR hysteresis loop is asymmetric, unlike traditional symmetric hysteresis loops, and the parameters that are extracted from the resultant loop are also intrinsically different. This has necessitated changes in data acquisition methods and data analysis algorithms.
- Owing to the field dependence of some parameters, and low coercivity free layer properties, enhancements in field accuracy, control and resolution are required.
- In practice, recording heads operate at relatively high internal temperatures, typically as high as 200 °C. The temperature dependence of GMR SVs must therefore be quantified, particularly as new SV structures are developed. This has necessitated the development of a furnace option that does not incorporate magnetic materials or shielding, which tends to deleteriously effect VSM performance.
- Measurement of the magneto-resistive (MR) characteristics of SVs is also required. To eliminate the need for two separate metrology tools, the MR and VSM techniques have been married within a single system, thus reducing cost and space requirements.
- Typically, GMR films are deposited on 4 in to 6 in wafers. Many vendors deposit, in-situ, on smaller test coupons (<25 mm dia.) which are subjected to the quality control metrology. The relatively large size of these test coupons have in turn dictated the need for larger, higher uniformity, variable gap electromagnets that may readily accommodate samples of various sizes. Further, the aforementioned furnace and MR options also must be designed to accommodate large samples.
- Development of fast data acquisition and analysis routines, allowing the VSM sample characterization to be incorporated into process control and monitoring, while still maintaining adequate production throughput.
- Methodologies which allow for better than 2 % repeatability of extracted spin valve characterization quantities.
- Windows-based data acquisition/control and analysis software.

The remainder of this article will be devoted to presenting pertinent magnetic and magneto-resistive data for GMR SV samples, thus demonstrating the performance capabilities of the VSM technique for this demanding measurement application.

Magnetic Measurements with a VSM**

As mentioned previously, unlike *typical* hysteresis loops which are symmetric with respect to the field axis, SV's are highly *atypical* and exhibit asymmetric characteristics. Further, the parameters most commonly extracted from SV loops are completely different than those extracted from symmetric loops[10].

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[10] R. White, IEEE Trans on Magnetics, v. 28, p. 2482 (1992)
J. C. S. Kools, IEEE Trans on Magnetics, v. 32, p. 3165 (1996)

As an illustration, figure 3 shows a symmetric hysteresis loop for a hard disk sample (CoPt). Some of the parameters that are extracted from the loop and that are generally of interest in connection with magnetic media materials are also presented. Comparatively, figure 4 shows an asymmetric hysteresis loop for a SV sample[11].

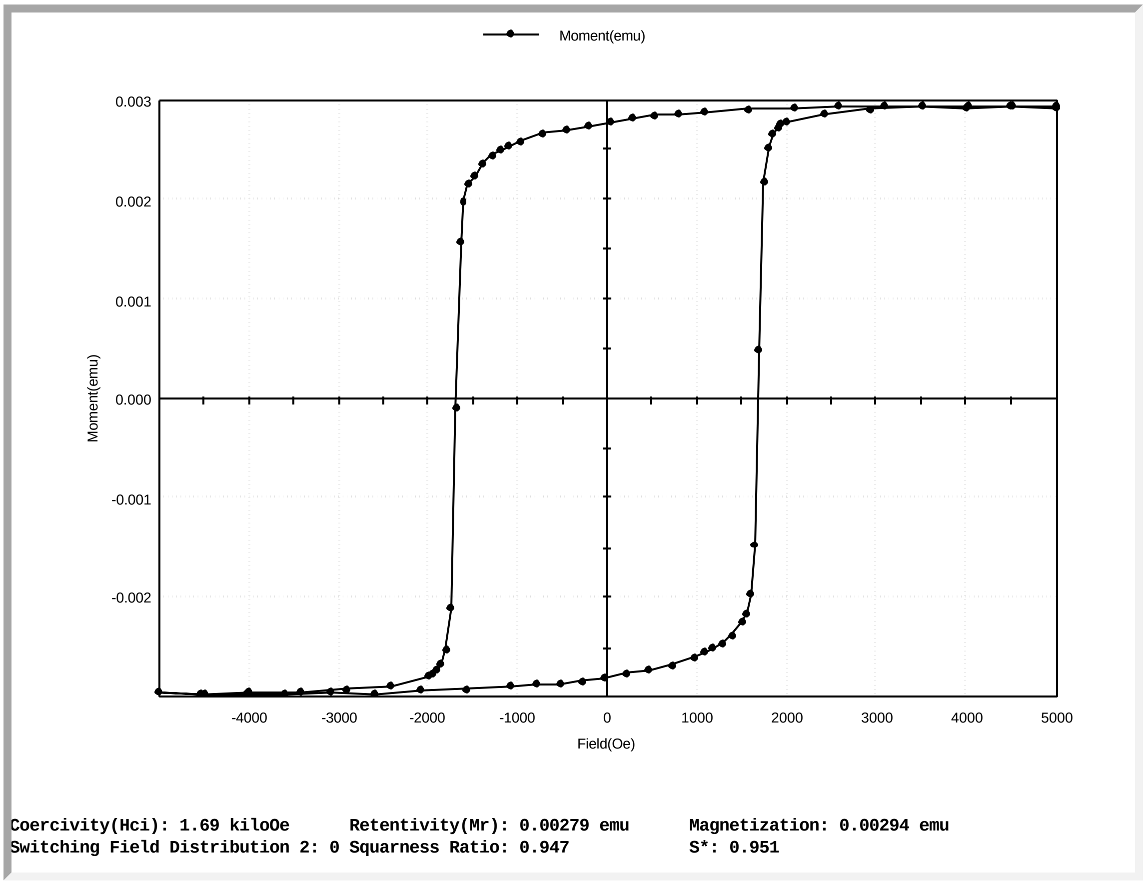

Figure 3: Symmetric M(H) hysteresis loop for a CoPt hard disk sample.

**** Lake Shore Cryotronics gratefully acknowledges Applied Magnetics Corp. for the spin-valve samples used in this study, and for many fruitful discussions.**

[11] applied field aligned with easy axis

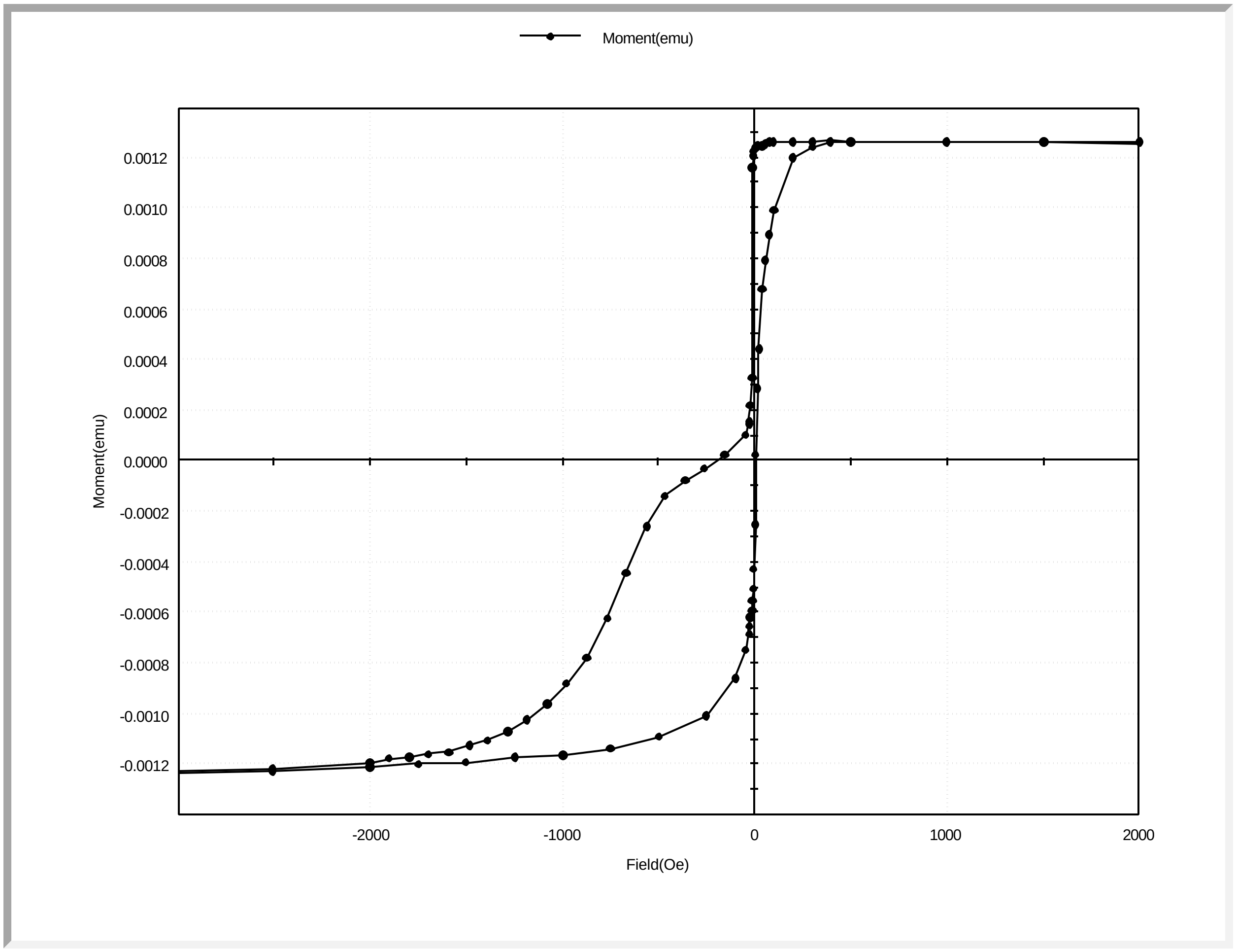

Figure 4: Asymmetric M(H) hysteresis loop for a NiMn SV sample.

The irreversible hysteretic portion of the loop located in the third quadrant is commonly referred to as the pinned layer loop, or the AFM loop. Three parameters that are commonly extracted from the pinned layer loop are:

M_{sp}: Pinned layer saturation moment.
H_{cp}: Pinned layer coercivity.
H_{ex}: Exchange field.

The pinned layer saturation moment provides information about the overall magnetization of the deposition product. The pinned layer coercivity is half the width, or the mid-point of the hysteretic loop.

The exchange field is a measure of the exchange anisotropy which occurs in ferromagnetic-antiferromagnetic (FM-AFM) bilayers, such as in the pinned layer portion of the SV structure. If such a bilayer is cooled through its' AFM Néel temperature in the presence of an applied magnetic field, the FM layer becomes single domain. If the applied field is removed, the FM layer continues to have its moments pinned by the AFM layer antiparallel to the direction of the previously applied field as if an internal "exchange field" were applied in this direction.

In terms of the SV multilayer device, for applied fields smaller than H_{ex} only the free layer moments reverse their direction with changing bias fields. For fields that exceed H_{ex} the applied field will overcome the internal field due to the AFM layer, and pinned FM layer moments will reverse their direction as well. In effect, the relative orientation of the magnetization directions of the two FM layers in the SV are antiparallel (high resistance) for $0 < H_{applied} < H_{ex}$, and parallel (low resistance) for $H_{applied} > H_{ex}$.

Different vendors commonly use different algorithms for extracting or deriving values for H_{ex}, H_{cp}, etc. One common method employed for exchange field determinations is to apply independent linear fits to two regions of the ascending portion of the M(H) loop (3rd quadrant in figs. 4 & 5), extrapolate to an intersection point, and then interpolate to the field axis. The VSM software includes linear fitting algorithms for automated extraction of such parameters. A graphical representation of one such linear fit procedure for exchange field determinations is illustrated in figure 5 which shows an expanded view of an SV pinned layer loop. Values for the linear fit slopes and intersects are also presented.

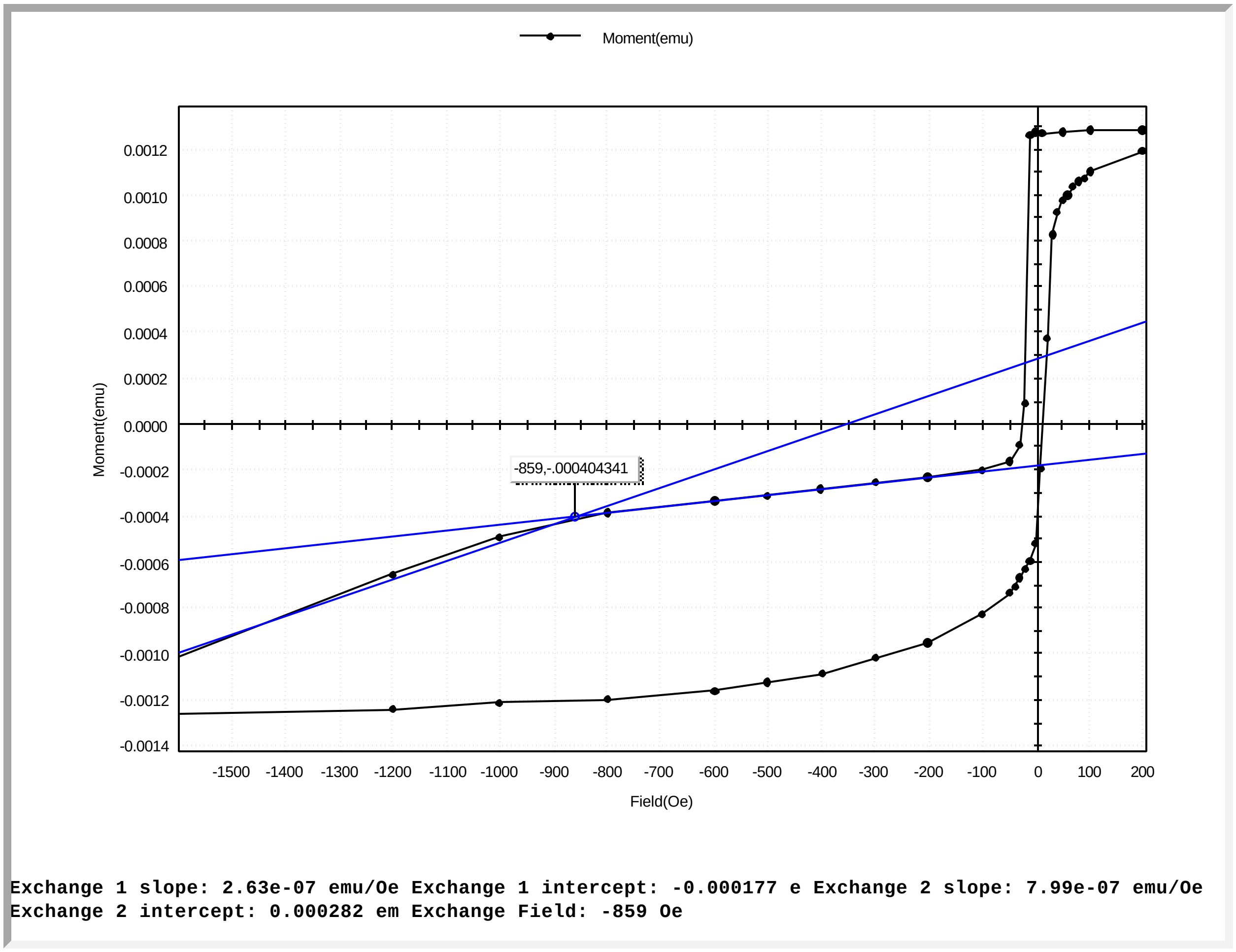

Figure 5: Illustration of a linear fit procedure that is commonly employed for exchange field determinations.

In addition to measurements of the major or pinned layer loop, the region near zero-field where the magnetization changes sign is often of interest as well. The low-field loop is called the SV free layer loop and figure 6 shows a low-field loop measurement for a NiMn SV sample. Note the exchange-biasing of the free layer loop. Three parameters that are commonly extracted from this portion of the loop are:

M_{sf}: Free layer saturation moment.
H_{cf}: Free layer coercivity.
H_{ilc}: Interlayer coupling field.

The free layer coercivity is the half-width of the free layer loop, and the interlayer coupling field is a measure of residual coupling of the free layer to the AFM/FM pinned bilayer through the non-magnetic spacer layer. As mentioned previously, accurate determinations of free layer loop properties require good field control and resolution, enhancements that have been incorporated in the VSM.

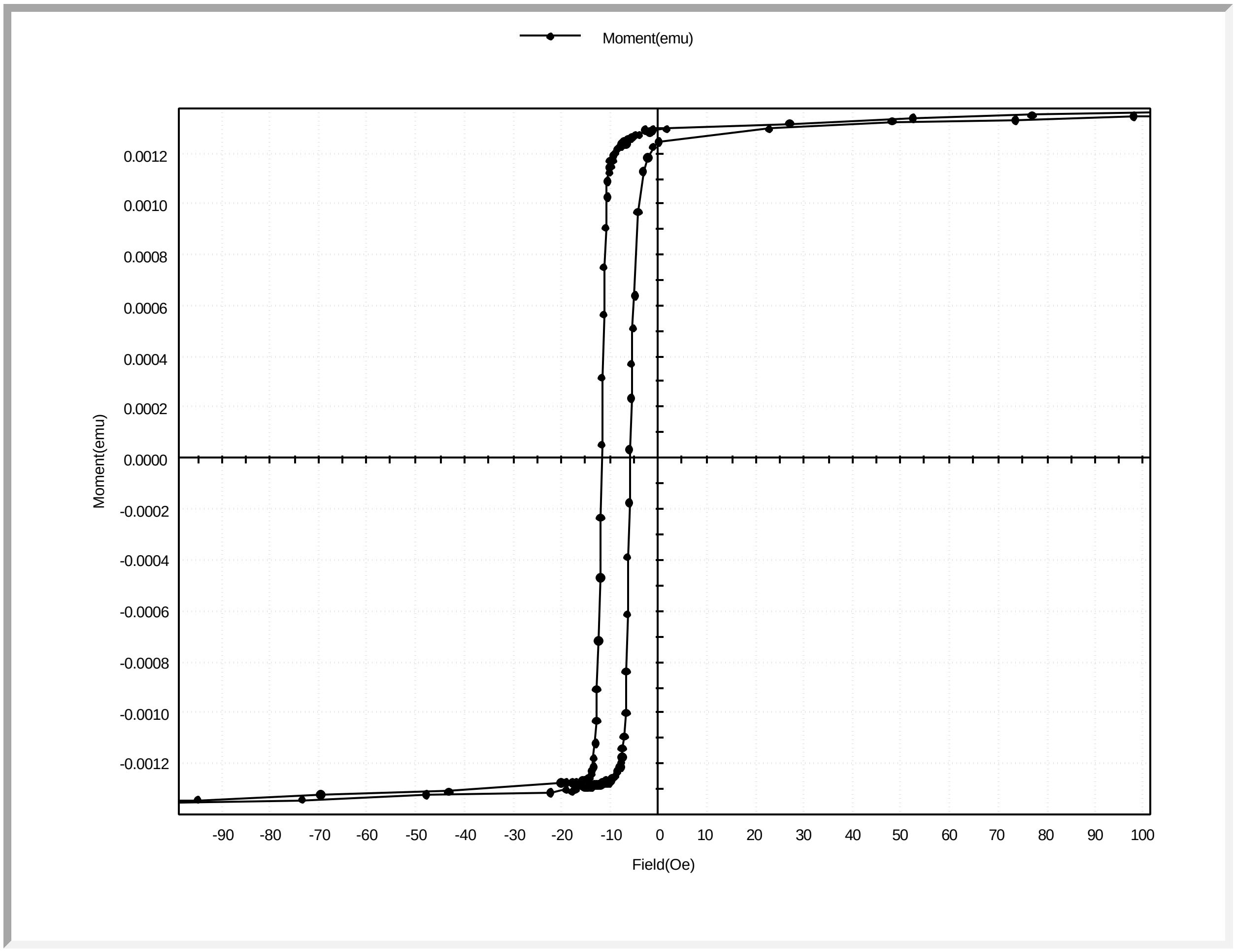

Figure 6: Expanded plot of free layer loop.

Temperature Dependence[12]

The structural and thermal stability of SVs is exceedingly important in connection with their application as read heads owing to the elevated temperatures at which a typical hard disk drive operates[13]. Further, post-deposition processing of SVs involves a high temperature anneal, which can lead to a degradation of the multi-layer structure due to mass transport by diffusion or to a disordering of the AFM layer. Either situation can lead to a decrease in the magnetoresistive response of the material. Measurement of the temperature dependence of the exchange field, $H_{ex}(T)$, the blocking temperature T_B, and the remanent blocking temperature T_{RB}, essentially measure the thermal range over which the AFM layer can effectively pin the adjacent FM layer, as well as the onset of structural degradation in the material. These are very important in determining the thermal stability of the material for read head applications, and for investigating novel SV structures. SVs with pinning AFM layers of FeMn, NiO, IrMn, and NiMn have blocking temperatures of 150, 200, 220, and 380 °C, respectively. Hence, for present generation SV materials variable temperature capability to at least 400 °C is required.

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[12] J. C. S. Kools, IEEE Trans on Magnetics, v. 32, p. 3165 (1996)
S. Mao et. al., J. Appl. Phys. v. 83 (11), p. 6807 (1998)

[13] typically as high as 200 °C

In response to this requirement, a large sample (to 1 in) non-magnetic furnace assembly option was developed for the VSM. A non-magnetic furnace is desirable since the moments that are measured for SV samples are typically small at ambient temperature, and decrease with increasing temperature. Additionally, fast thermal variation without sacrificing temperature accuracy or stability allows for rapid characterization in both research and QC/QA applications. The oven option is constructed of non-magnetic or weakly magnetic constituent parts including a quartz sample chamber, non-magnetic halogen lamp fixture for radiant heating of a sample, boron-nitride sample holders, and titanium radiation shields.

Figure 7 shows the temperature dependence of H_{ex} to 300 °C for a NiMn SV as determined from measurements of M(H) loops as a function of temperature.

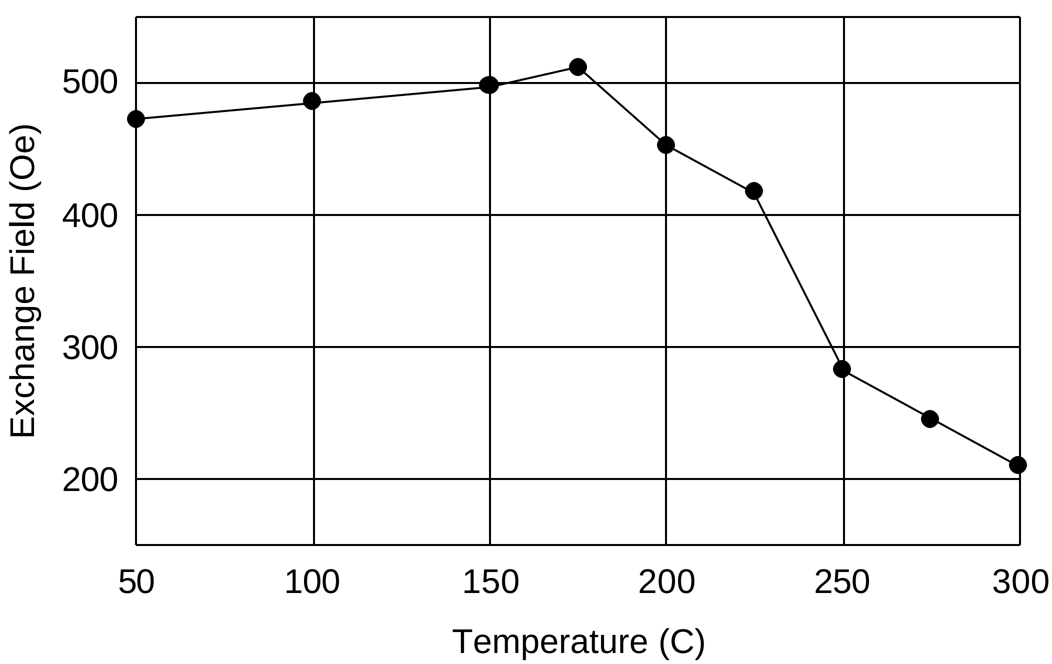

Figure 7: H_{ex}(T) for a NiMn SV.

Magneto-Resistance

Magnetoresistance, the measurement of resistance as a function of magnetic field, R(H), is also a SV metrology requirement. The GMR effect is typically expressed as the MR or magnetoresistive ratio $\Delta R/R = [\ R(H) - R(H_{sat})\ ]/R(H_{sat})$. As is obvious from figures 8 and 9, low-field resolution and precision are critical requirements for this measurement, and for the quantities typically extracted from the raw data. Since these have already been incorporated into the VSM for magnetic metrology requirements, it is a natural extension to incorporate a magnetoresistance measurement onto the VSM platform. Further, this has the effect of minimizing costs, both in terms of capital equipment purchases, and in terms of overhead costs associated with occupying manufacturing floor space. The magnetoresistance measurement option is configured with spring-loaded contacts for ease of sample handling, exchange, and contacting

In addition to determining the MR ratio, other parameters are also extracted from the MR measurement data, such as pinned layer loop properties (H_{ex}, H_{cp}) and free layer loop properties (H_{ilc}, H_{cf}). A high temperature MR probe has also been developed and provides for R(H) measurements to 400 °C, yielding another means for investigating SV thermal properties.

Figures 8 and 9 show typical pinned layer and free layer, respectively, ΔR/R vs. H curves for a NiMn SV sample[14]. Note the excellent field control and resolution that is obtainable and demonstrated in the free layer loop illustrated in figure 9.

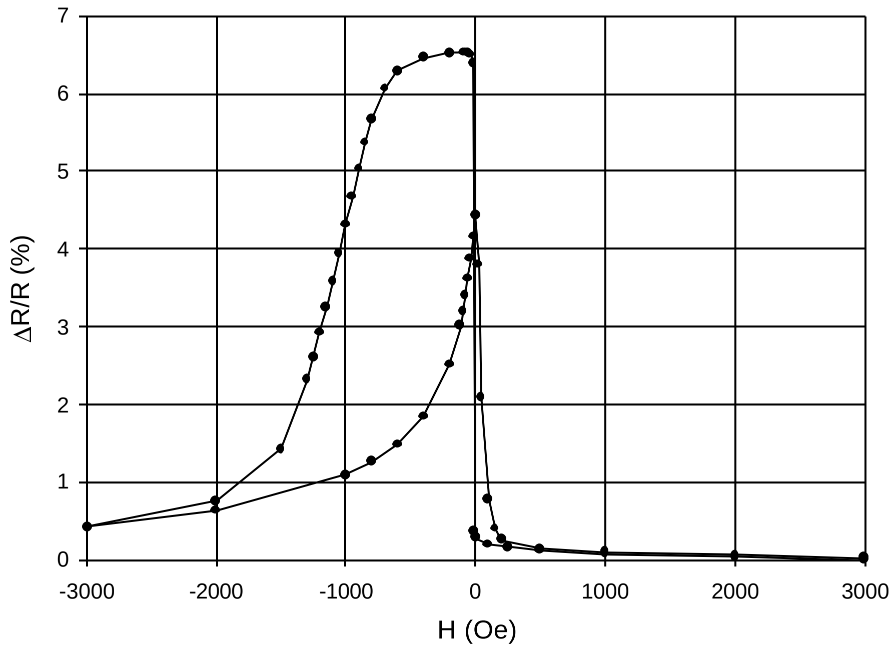

Figure 8: Pinned layer R(H) curve for a NiMn SV sample - H_{ex} = 620 Oe, H_{cp} = 528 Oe.

[14] magnetic field aligned with easy axis

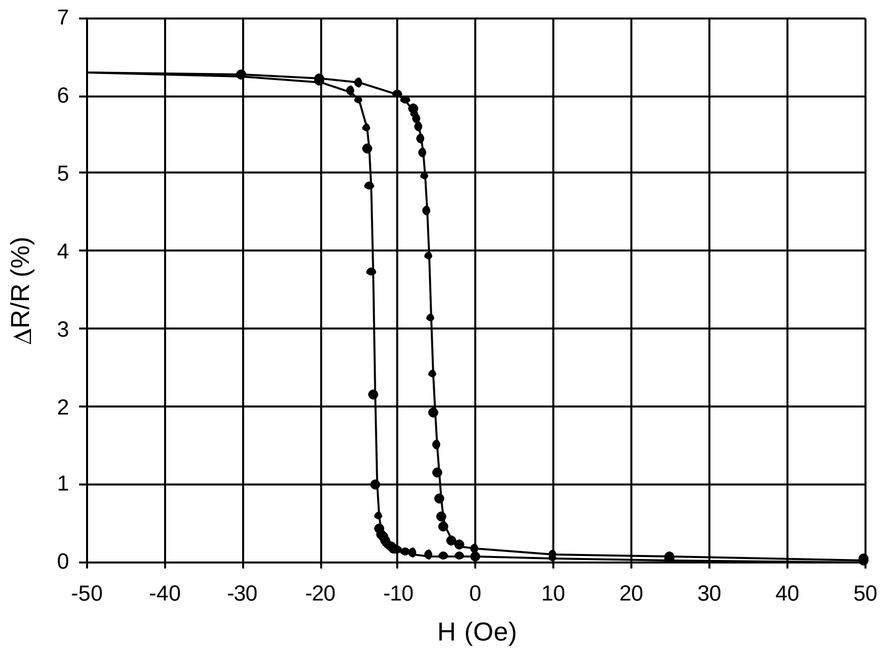

Figure 9: Free layer R(H) curve for a NiMn SV sample - H_{ilc} = 9.45 Oe, H_{cf} = 3.71 Oe.

Conclusion

The applicability of vibrating sample magnetometry to the characterization of GMR SV magnetic properties has been discussed. Only very small magnetic property variations can be tolerated in today's advanced read head materials, and magnetic metrology is being used to control and optimize the critical film deposition process. Using the VSM to provide in-process feedback leads to early detection of defective product, thus improving production yields and increasing profitability.

A tunnel junction device will likely represent the next generation read head[15]. SVs consist of two ferromagnetic (FM) layers separated by a conductive non-magnetic spacer layer (e.g., Cu), whereas tunnel junctions consist of two FM layers separated by a non-magnetic electrically insulating layer. Tunnel junctions (like spin valves) exhibit a two-state magnetoresistance dependent upon the relative orientation of the two ferromagnetic layers which lends itself to current data storage modalities[16]. Current tunnel junction devices exhibit MR ratios of > 25% vs. < 10% for SVs, and this increased sensitivity would allow further decreases in bit size, implying smaller track widths and still larger track densities. The hysteresis loops of tunnel junctions are even more complex than SVs, and it is likely tunnel junctions will require additional advancements in magnetic metrology tools such as the VSM.

[15] Machine Design v. 68, p. 32 (1996)
[16] S. Maekawa, U. Gafvert, IEEE Trans on Magnetics, v. MAG-18, p. 707 (1982)
J. Moodera, L. Kinder, J. Appl. Phys., v. 79 (8), p. 4724 (1996)
S. Gider, et. al., Science, v. 281 no. 7, p. 797 (1998)