JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 8 15 APRIL 2004

Exchange biased magnetoresistance based spin-transport sensor

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(Received 9 September 2003; accepted 22 January 2004)

A method for measuring processes that alter the degree of exchange bias (H_{EX}) for a thin film by monitoring H_{EX} indirectly through the magnetoresistance (MR) is described. In unbiased magnetic films and multilayers, the positive and negative magnetic field sweep MR spectra are symmetric about zero applied field. Introducing an exchange bias to the film shifts the intersection point of these two curves away from zero to H_{EX}. Taking the difference in the measured MR at zero field for a positive and negative field pulse (measuring ΔMR at zero field) gives a relative measure of H_{EX}. Any variations in the exchange bias field will result in a corresponding change in the ΔMR, which, unlike H_{EX}, can be measured with two points rather quickly, making it ideal for sensor applications. A method for selecting material parameters for increased sensitivity or operational range is given. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1669072]

Exchange bias is typically an interface phenomenon observed in magnetic systems composed of a ferromagnetic (F) layer in contact with an antiferromagnetic (AF) layer. The coupling between these layers results in a unidirectional shift of the hysteresis loop as the system is cooled below the magnetic ordering temperature of the AF layer in a static field. Observed in 1956 for cobalt particulates within cobalt oxide,[1] exchange bias is widely used in magnetic device engineering[2] and has prompted many studies.[2–10] There is no definitive microscopic description of exchange bias largely because it can be the result of so many interface phenomena including domain wall formation at the AF/F interface; compensated and uncompensated spin in the AF layer; and net noncollinear magnetization of the AF interfacial layer.[2–8] Results from these models do not always quantitatively agree with experimental results often because realistic atomic scale interfacial roughness must be included in the model.

Exchange bias is an essential aspect of many giant magnetoresistance (GMR) device structures including read heads, spin valves, spin tunnel junctions, and sensors.[2–5] For magnetic field based sensors, by biasing the hysteresis loop to an accessible region, slight magnetic field variations result in large conductivity changes. Since exchange bias is intimately connected to interfacial processes, it therefore seems reasonable that monitoring exchange bias is a sensitive way to monitor interfacial interactions. Any phenomena or process that modifies the F/AF interface (alloying, roughening, etc.) would modify the exchange bias and is therefore susceptible to monitoring by conductivity changes (often the basis of a sensor technology). Normally, the determination of H_{EX} would require continuous and stable control of a magnetic field. Developing a method that avoids the need for careful control of magnetic fields would be a tremendous advantage in utilization of this class of devices, particularly for sensor applications.

Our samples were prepared with UHV electron beam deposition in a static magnetic field. Exposing the freshly deposited cobalt layer to oxygen at ambient temperatures results in the formation of ~20 Å of an AF oxide layer. Cooling this AF/F system in the presence of a magnetic field below the Neél temperature (T_{N}) of the AF layer induces magnetic ordering and an exchange bias of the ferromagnetic layer. The Neél temperature of CoO is conveniently located at about 290 K (Ref. 3) making it a prototypical system for building this type of sensor.[2,3,6] The CoO/Co bilayer also presents an added advantage in that Co forms a flat interface, has a large coercive field, and has an exchange bias of about 9.5 kOe at 10 K.[10] The magnetoresistance measurements are done at room temperature with standard van der Pauw (four wire) configuration with a LABVIEW™ operated, very stable current source, a sensitive digital multimeter, and a computer-controlled magnet that can generate ±7.0 kgauss uniform field with a 2.5 in. pole face. The value of H_{EX} is usually extracted by performing a complete magnetization hysteresis loop or a magnetoresistance measurement. This requires a continuous control of the applied field at each data point measured and thus limits the application of direct exchange bias based sensors.

We are proposing a measurement approach where the need for a continuous field for determination of H_{EX} is set aside and relative changes in the value of exchange bias are employed in the sensing application. Besides eliminating the need of having fine and stable field control requirements, this technique takes magnetoresistance based sensing to a different level.

Typically the MR spectrum for a magnetic system is symmetric for the positive and negative going field sweeps, crossing each other at zero field.[11–13] Because the MR is double valued, we can define a difference spectrum, ΔMR, of the MR for the positive and negative going sweeps. In exchange biased magnetic films, the exchange field introduces

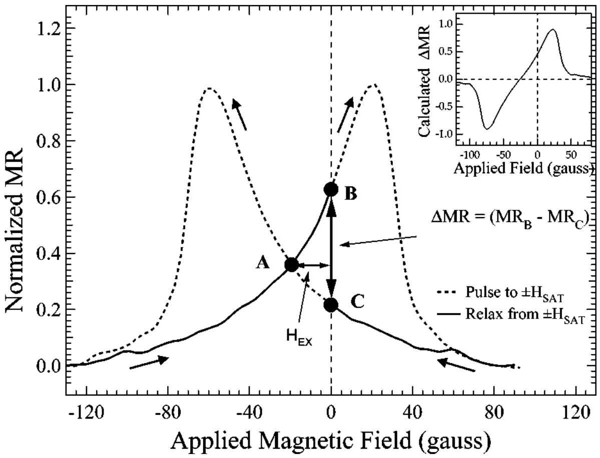

FIG. 1. The magnetoresistance is measured twice at zero field, after a pulse to negative and positive fields. The zero field MR difference is $\Delta MR = MR_B - MR_C$. Inset-The ΔMR as a function of applied field.

an offset in the intersection of the magnetoresistance spectra (point "A" of Fig. 1) between the positive going sweep (field varied from $-H_{SAT}$ to H_{SAT}) and the negative going sweep (field direction reversed). In the difference spectrum (ΔMR), this is the zero crossing point (Fig. 1 inset). An exchange biased system can have a nonzero ΔMR at zero field which depends on H_{EX} and the width of the MR curves. In fact, as demonstrated in Fig. 1, the ΔMR value at zero applied field can be used as a measure of H_{EX}.

The objective is then to use this direct relation between H_{EX} and ΔMR to monitor processes that alter H_{EX}. The measurement procedure is as follows. Pulse the applied field to a value beyond the saturation field, H_{SAT}, forcing the MR value to follow the dashed lines (see Fig. 1). When the applied field is removed, the MR relaxes tracing the solid lines to points C or B from $\pm H_{SAT}$, respectively. ΔMR is then calculated by taking the difference in the measured MR resistance values: $\Delta MR = MR_B - MR_C$.

This measurement process only requires the ability to pulse to high fields and make two subsequent conductivity measurements for the relative determination of H_{EX}. Any processes that alter H_{EX} would result in a variation in ΔMR. Unlike the measurement of H_{EX} from a magnetoresistance spectra, where locating the intersection point (A) is mandatory, determining ΔMR requires only two measurements of MR at zero field (points B and C) making this method a fast and easy way to monitor factors that change H_{EX}.

The success and sensitivity of this measurement depends on the detailed shape of the MR loops and the value of the exchange bias field. Only particular combinations of exchange bias, field position of the maxima in the MR response, and the width of the MR loops will be useful. Since these characteristics are determined by the materials, interfacial structures, and growth methods used, it would be useful to define the interrelationships between these fields which would be of the greatest utility.

From the example given in Fig. 1, there seem to be a large number of material parameters to be optimized, the exchange field H_{EX}, the field of maximum MR H_{MAX}, the saturation field H_{SAT}, and the width of the MR peak. If we focus on the difference spectra ΔMR, the parameters can be combined for a more universal description. To examine the effect of H_{EX} on the ΔMR spectra, the MR responses for the positive and negative field sweeps were modeled as two Gaussians centered at $\pm H_{MAX}$ as given by

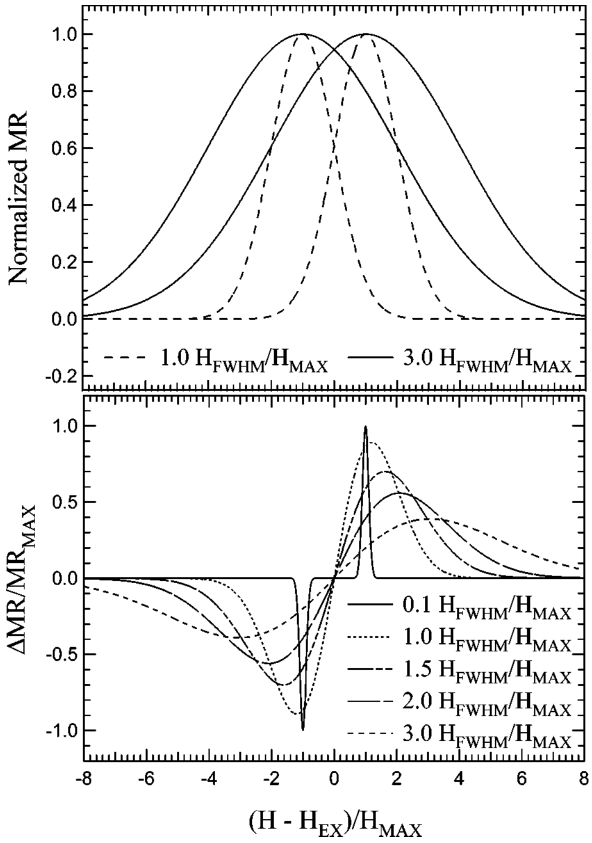

FIG. 2. Top—Gaussian modeling of the MR response for two values of the width. Bottom-calculated normalized ΔMR for different widths of the MR response.

$$MR_{\pm} = \exp\left[-4\ln 2\left(\frac{H_{APPLIED} \mp H_{MAX}}{H_{FWHM}}\right)^2\right], \quad (1)$$

where H_{MAX} is the field giving the maximum magnetoresistance, H_{FWHM} (full width at half maximum) is the width of the Gaussian MR response $[H_{SIGMA} = H_{FWHM}/2\,(2\ln 2)^{1/2}]$, and H_{EX} is the exchange bias field. For a more universal description, H_{MAX} can be considered a scaling field. Similarly, H_{EX} represents an offset field, shifting the spectra to a zero. Therefore, the important variable is not the applied field, but the scaled and offset field given by $H = (H_{APPLIED} - H_{EX})/H_{MAX}$. The remaining parameter is H_{FWHM}, the width of the MR loop given in terms of the full width at half maximum.[14]

Figure 2 shows the modeled MR response, using this scaled and offset field, with different full width at half maximum (FWHM) broadening (Fig. 2—top) as well as the calculated ΔMR for all fields, not just at zero field (Fig. 2—bottom). The field position of the two extremes of the ΔMR response determines the operational range whereas the slope in this range determines the sensitivity to changes in H_{EX}. Interestingly, although the MR peak field is indepen-

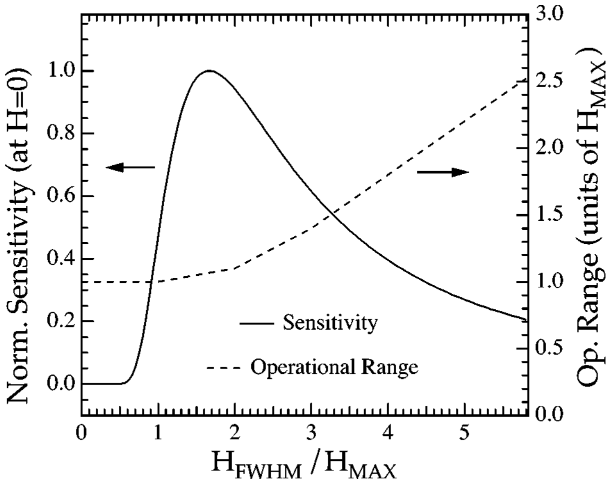

FIG. 3. Left-normalized sensitivity. Right-operational range.

dent of the width of the MR peak, the peak in ΔMR is not. The operational range of this sensor depends on both.

For a sharp MR response, a small relative H_{FWHM} (dashed lines in Fig. 2—top and Fig. 2—bottom, first solid lines), small variation in the exchange bias field results in large variations in ΔMR but over a narrow operational range. Similarly, a very broad MR response (a large relative H_{FWHM}) will result in a gradual change in ΔMR over a larger operational range.

Our described measurement procedure consists of determining ΔMR at zero applied field, ($H_{\mathrm{APPLIED}}=0$). In the absence of exchange bias ($H_{\mathrm{EX}}=0$), this corresponds to a scaled and offset field of $H=0$ and $\Delta\mathrm{MR}=0$ in Fig. 2. With exchange bias $H_{\mathrm{EX}}\neq 0$, our measurement process still demands no applied field ($H_{\mathrm{APPLIED}}=0$) corresponding to a scaled and offset field of $H=H_{\mathrm{EX}}/H_{\mathrm{MAX}}$ and $\Delta\mathrm{MR}\neq 0$. As H_{EX} changes, so does ΔMR.

There is a trade off between operational range and sensitivity (slope of the ΔMR curve). In Fig. 3 we have plotted the variation of the normalized sensitivity and the operational range as a function of the width of the MR response peak. The best case is for a material that has $H_{\mathrm{FWHM}}=2*H_{\mathrm{MAX}}$ and $H_{\mathrm{EX}}<H_{\mathrm{MAX}}$. These set of parameters provide an optimal operation region without loss in sensitivity.

We have developed a method for monitoring processes which modify interface magnetic structure through exchange bias by pulsing the applied field and evaluating the difference in magnetoresistances ΔMR at zero field. This approach of recording changes in ΔMR instead of directly measuring H_{EX} provides a fast and convenient method to monitor conditions or processes that affect the interfacial magnetic structure. Since H_{EX} can also strongly depend on operation temperature, we will use temperature control to test our devices and further demonstrate the viability of this approach.

This research was supported in part by the Office of Naval Research and DARPA under Grant No. N660001-02-C-8048.

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