

# Magnetoresistance monitoring of processes that affect thin film exchange bias

E. Negusse<sup>a)</sup> and Y. U. Idzerda

*Department of Physics, Montana State University, Bozeman, Montana 59717*

P. A. Suci

*Center for Biofilm Engineering and Department of Microbiology, Montana State University, Bozeman, Montana 59717*

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A simple method where the relative change in exchange bias, introduced by external process, is measured by taking only two magnetoresistance readings at a selected field value is presented. Modeling of this measurement process showed that optimal performance can be achieved by engineering the device parameters so that the maximum in the magnetoresistance occurs near the exchange bias field and the width of the magnetoresistance (MR) curve is twice the field value of this maximum MR. Our analysis further showed that the sensitivity can be enhanced by operating the sensor at an operation field close to the exchange bias field. © 2004 American Institute of Physics. [DOI: 10.1063/1.1688677]

## I. INTRODUCTION

Discovered in cobalt particulates by Meiklejohn and Bean,<sup>1</sup> exchange bias is an interface phenomenon observed in magnetic systems where an antiferromagnetic (AF) layer placed adjacent to a ferromagnetic layer introduces a coupling that results in a unidirectional shift of the hysteresis loop as the system is cooled below the Néel temperature ( $T_N$ ) of the AF layer in the presence of a magnetic field.<sup>1-4</sup> Although the AF layer is insensitive to an external field, cooling the system in an applied field indirectly affects the magnetic ordering of the AF through interfacial coupling with the ferromagnetic layer, promoting nucleation sites for the magnetic ordering of the antiferromagnetic layer. This usually results in a negative exchange bias (i.e., the hysteresis loop is shifted opposite to the applied field direction during cooling). Exchange biased systems show the following interesting properties: (i) unidirectional shift in the hysteresis loops, (ii) blocking temperature above which the exchange bias disappears, (iii) training effect (dependence of  $H_{EX}$  on the number of field reversals), and (iv) enhanced coercivity. This has made employing exchange bias a very useful approach in device engineering such as giant magnetoresistance read-heads, spin valves, and other spin-based devices.

Exchange bias is an interface phenomenon that depends on many factors such as interface quality, roughness, and intermixing. Normally, these factors are used to control the value of the exchange field,  $H_{EX}$ , but in this work the value of the exchange bias is used to monitor processes which affect these factors. The direct application of a method that relies on an absolute measurement of the degree of exchange bias entails the careful measurement of the hysteresis loop or the complete magnetoresistance curve<sup>5</sup> as the field is swept

beyond both saturation fields, requiring a stable and controllable magnetic field. Instead, by indirectly monitoring only relative changes in  $H_{EX}$  induced by external process, we can simplify these field requirements.

## II. MEASUREMENT PRINCIPLE

Rather than measuring the full hysteresis loop or the complete magnetoresistance curve, we are proposing a measurement approach where the direct recording or indirect extraction of  $H_{EX}$  is set aside and relative changes in the value of exchange bias are employed in the sensing application. Besides eliminating the requirement of having a fine and stable applied field control, this approach takes magnetoresistance based sensing to a higher level and facilitates the use of exchange bias for the investigation of surface and interface effects on magnetic heterostructures.

In unbiased systems, the positive sweep and the negative sweep magnetoresistance spectra are symmetric about zero field and, by symmetry, the intersection point of these two curves is located at zero field. In exchange biased systems, however, the intersection point is shifted from zero and the field value where the crossing occurs (point A) is a measure of the exchange bias,  $H_{EX}$  (see Fig. 1). Extracting  $H_{EX}$  from this type of measurement is a time consuming process making sensor applications that measure direct changes in exchange bias impractical if not impossible.

As described in Fig. 1, using the difference magnetoresistance ( $\Delta MR$ ) to measure relative changes in  $H_{EX}$  instead avoids the above-mentioned difficulty associated with measuring  $H_{EX}$  directly. The measurement procedure we are proposing is as follows. A static magnetic field,  $H_{OP}$ , is applied to establish the operational point. Applying an external magnetic field pulse greater than saturation field forces the magnetoresistance response to follow the dashed lines (Fig. 1). When this pulsing field is removed, the system relaxes (solid lines Fig. 1) back to  $H_{OP}$  (operational field) where the mag-

<sup>a)</sup>Author to whom correspondence should be addressed; electronic mail: ezana@physics.montana.edu

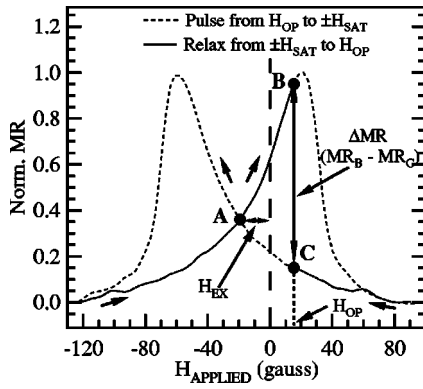


FIG. 1. The difference MR ( $\Delta MR$ ) at zero field is a measure of the shift in the crossing point (A) of the positive sweep (from  $-H_{SAT}$  to  $H_{SAT}$ ) and negative sweep (reverse direction) introduced by  $H_{EX}$ .  $\Delta MR$  could also be measured at a tunable operation field ( $H_{OP}$ ) where it is maximum.  $\Delta MR$  at  $H_{OP}$ , which is a measure of  $H_{EX} + H_{OP}$ , can be measured by pulsing to  $\pm H_{SAT}$  and letting the system relax to  $H_{OP}$  (points C and B, respectively).

netoresistance  $MR_B$  is determined. The field is then pulsed beyond the opposite saturation field, where the magnetoresistance is again measured after system relaxation back to  $H_{OP}$  giving  $MR_C$ . Taking the difference between the two consecutive measurements, gives the  $\Delta MR$  at  $H_{OP}$ . For appropriate systems, the  $\Delta MR$  determined at  $H_{OP}$  is proportional to the sum of  $H_{OP}$  and  $H_{EX}$  making it ideal for measuring relative changes in  $H_{EX}$  without doing a complete hysteresis or MR spectra. Moreover, this method can be accomplished by taking only two MR readings (at points B and C), making this method a fast and easy way to monitor factors that affect exchange bias in thin films.

From design and implementation point of view, conducting the  $\Delta MR$  measurement at zero field (with  $H_{OP}=0$ ) is more convenient. However, operating at a field other than zero can dramatically increase the sensitivity of the measurement. This way the device can be tuned to operate at a desired value.

### III. MODELING

To examine the effect of  $H_{EX}$  on the  $\Delta MR$  curve, identify the important system parameters and investigate the impact of measuring  $\Delta MR$  at  $H_{OP}$ , we modeled the MR response for the positive and negative field sweeps as two Gaussians centered at  $\pm H_{MAX}$  given by

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

where  $H_{MAX}$  is the field giving the maximum magnetoresistance,  $H_{FWHM}$  is the width of the Gaussian MR response, and  $H_{APPLIED}$  is the applied field. For a more universal description,  $H_{MAX}$  can be considered a scaling field and  $H_{EX}$  as an offset field that shifts the spectra to a new 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.<sup>6</sup>

Figure 2 (top) shows MR models with the same coercive field but different broadening or full width at half maximum

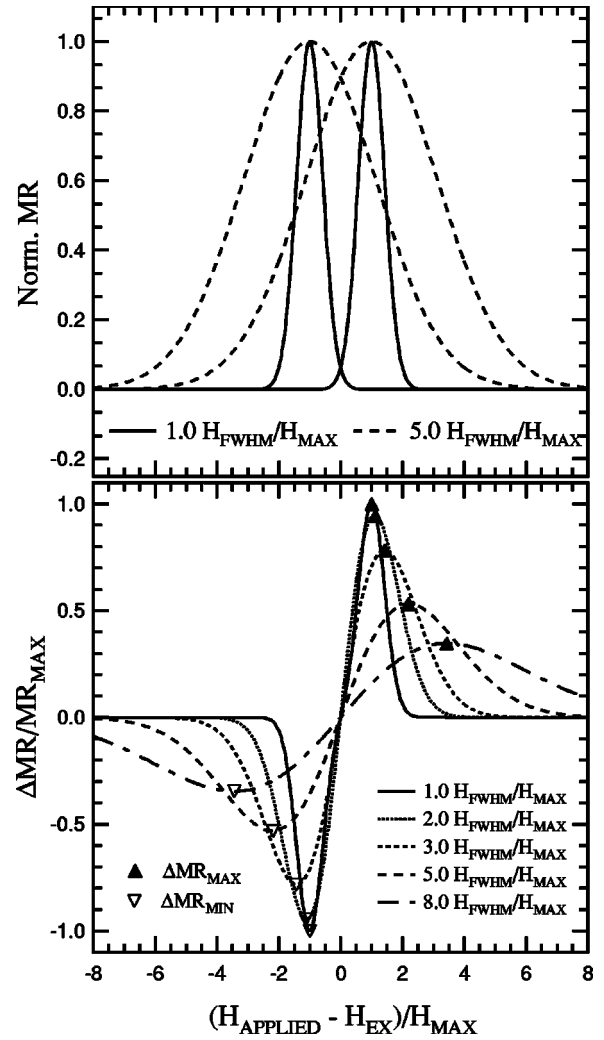


FIG. 2. (Top) MR spectra modeled with two Gaussians centered at  $\pm H_{MAX}$  with different FWHM. (Bottom) The  $\Delta MR$  response for different  $H_{FWHM}$  fields. Increased  $H_{FWHM}$  fields result in wider operation regions (position of the  $\Delta MR$  maxima) but reduce the sensitivity (slope at  $H_{OP}$ ) and  $\Delta MR_{MAX}$  intensity.

(FWHM). For an appropriately broad MR response, shown as solid lines, the  $\Delta MR$  is linear near the zero field region [solid line Fig. 2 (bottom)]. This is the ideal operational region. On the other hand, a sharp MR response (dashed lines in Fig. 2), the  $\Delta MR$  plot is not suitable for sensor operation. An extremely broad MR response will also decrease the sensitivity. In Fig. 2 are also plotted the points where the magnetoresistance is a maximum (or minimum). The field range between the maximum and minimum for a given curve represents the operational range of the device for that broadening and the field value for the maximum  $\Delta MR$  corresponds to a minimum in the sensitivity.

There is a tradeoff between operational range and sensitivity (slope of the  $\Delta MR$  curve). In Fig. 3 (middle) we have plotted the variation of the normalized sensitivity and the operational range as a function of the width of the MR response at zero field ( $H_{OP}=0$ ). The product of sensitivity and operational range gives a more generalized description, figure of merit (FoM), which illustrates the combined effect of these two important parameters. Figure 3 (bottom) shows the

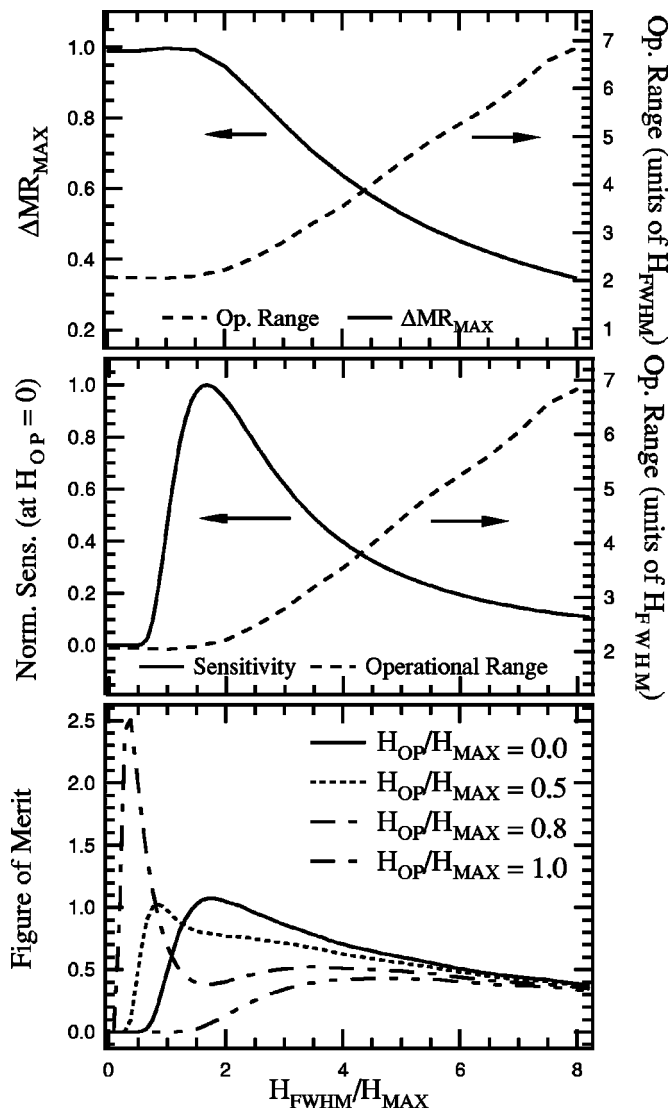


FIG. 3. (Top) Increasing  $H_{FWHM}$  increases the operational range (solid line) but reduces the  $\Delta MR_{MAX}$  intensity (dashed line). (Middle) Sensitivity and operational range at  $H_{OP}=0$ . (Bottom) FoM, sensitivity times operational range, of running the system at a given value of  $H_{OP}$ . The sensitivity values were normalized to that of  $H_{OP}=0$ .  $H_{OP}$  values slightly smaller than  $H_{MAX}$  do enhance sensitivity at reduced operation range.

FoM for different  $H_{OP}$  where the sensitivity was normalized to that of  $H_{OP}=0$ . A closer look at the FoM for  $H_{OP}=0$  indicates that best sensitivity with operational range equal to  $H_{MAX}$  can be achieved if the device is engineered to have  $H_{FWHM}$  almost twice  $H_{MAX}$ . MR width greater than twice

$H_{MAX}$  can increase the operational range but result in significantly reduced sensitivity and  $\Delta MR_{MAX}$  intensity [Fig. 3(top)]. The FoM plot for different  $H_{OP}$  values reveals a very remarkable fact that the sensitivity of the system can be dramatically enhanced either by adjusting the  $H_{EX}$  of the device closer to  $H_{MAX}$  or operating at  $H_{OP}$  closer to  $H_{MAX}$ . As expected, this significant increase in sensitivity results in notably diminished operable range indicated by the FoM peak shifting towards zero in Fig. 3 (bottom). The modeling showed running a device with  $H_{EX} < H_{MAX}$  and  $H_{FWHM} \approx 2 * H_{MAX}$  operated at zero field provides an optimal operation region without loss in sensitivity.

**IV. CONCLUSION AND FUTURE DIRECTION**

We have developed a convenient method for conducting MR measurements by pulsing the applied field and evaluating the  $\Delta MR$  at zero field or at a static offset field. This approach of recording changes in  $\Delta MR$  at a fixed field instead of directly measuring  $H_{EX}$  allows a fast and convenient method to monitor conditions or processes that affect  $H_{EX}$ . The modeling identified optimal values for the relevant material parameters that potential candidates for this application need to have. Optimal performance can be achieved by engineering the device parameters so that the maximum in the magnetoresistance ( $H_{MAX}$  in our model) occurs near the exchange bias field,  $H_{EX}$ , and the width of the MR curve is twice the field value of this maximum MR. An alternative approach is to operate the device at  $H_{OP}$  slightly smaller than  $H_{MAX}$ . This can greatly reduce problems associated with engineering a device with the above stated characteristics allowing operation at a tunable field value. However, it also introduces some degree of complexity to the device construction. The next step is to demonstrate the viability of this device by examining the strong dependence of  $H_{EX}$  on operation temperature and interface roughness.

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<sup>6</sup>We have used the FWHM because of its ease in determination. In this case,  $H_{SIGMA}$ , standard deviation is related to  $H_{FWHM}$  as  $H_{SIGMA} = H_{FWHM} / (2(2 \ln 2)^{1/2})$ .