APPLICATION NOTE

First-Order-Reversal-Curve Analysis of Exchange Bias Magnetic Multilayer Films

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Abstract

Exchange bias magnetic multilayer films are technologically important materials for applications such as spin-valve read heads for hard disk drives, and gigahertz range microwave devices. In these materials at least one anti-ferromagnetic (AFM) layer is intercalated between ferromagnetic (FM) layers. In addition to their technological applications, they are also useful for fundamental studies of magnetic interactions and magnetization reversal processes in magnetic nanostructures because both the number (n) of periodic arrays, and the thickness of the FM and AFM layers can be controlled.

Vibrating sample magnetometers (VSM) are commonly used to characterize the magnetic properties of exchange bias films. The magnetic characterization of such materials is usually made by measuring a hysteresis loop from which one can obtain the exchange bias (H_{ex}) and coercive field (H_c) values. It is not possible, however, to obtain information about magnetization reversal, including distributions of switching and reversal fields, from the hysteresis loop alone. For these investigations one needs to use more advanced measurement protocols and analysis such as first-order-reversal-curves (FORCs)[1,2,3].

In this paper we will discuss the FORC measurement and analysis technique and present results for two $(FeNi/IrMn)_n$ magnetic multilayer films where (n) is the number of layer repetitions. We will show that FORC analysis is needed to correlate exchange bias with in-homogeneities existing at the AFM/FM interface.

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Experimental

The samples are multilayer films of composition [FeNi (60 nm)/IrMn (20 nm)]$_5$, and [FeNi (80 nm)/IrMn (20 nm)]$_4$ where FeNi represents Ni (80%) Fe (20%)[4]. The hysteresis loop and FORC measurements were performed using a Lake Shore MicroMag™ VSM system. Measurements were performed at room temperature and with the applied field oriented in-plane, and either parallel to the easy axis (0° and 180°) or perpendicular to the easy axis (90°).

Figure 1 shows hysteresis loops for sample [FeNi (60 nm)/IrMn (20 nm)]$_5$ for three different in-plane orientations (0°, 90°, and 180°) of the applied magnetic field. The results are presented in terms of magnetic moment m (emu) versus magnetic field H (Oe). When the magnetic field is applied parallel (0°) to the exchange bias field the loop is shifted towards the left (negative field values), and when applied anti-parallel (180°) the loop is shifted to the right (positive field values). For magnetic fields oriented perpendicular to the exchange bias field (90°) the loop passes through the origin and has zero coercivity ($H_c = 0$). From the 180° hysteresis loop, the exchange bias and coercivity fields are: H_{ex} = 40 Oe and H_c = 3.5 Oe. The extra steps in the 0° and 180° curves between positive and negative saturation magnetization are related to microstructural defects/roughness of the AFM/FM interfaces. FORC analysis can give a more detailed account of the effect of in-homogeneities on the magnetization reversal of the AFM/FM interface.

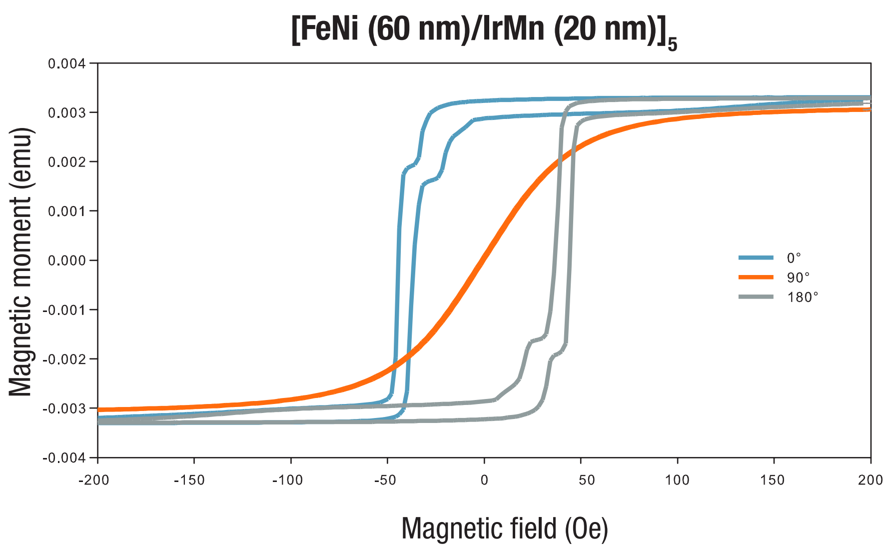

Figure 1 Hysteresis loop for three different in-plane orientations (0°, 90° and 180°).

First-Order-Reversal-Curves (FORCs)

More complex magnetization curves covering states with field and magnetization values located inside the major hysteresis loop, such as first-order-reversal-curves (FORCs), can give additional information that can be used for characterization of magnetic interactions. A FORC is measured by saturating a sample in a field H_{sat}, decreasing the field to a reversal field H_a, then sweeping the field back to H_{sat} in a series of regular field steps H_b. This process is repeated for many values of H_a, yielding a series of FORCs. The measured magnetization at each step as a function of H_a and H_b gives $M(H_a, H_b)$, which is then plotted as a function of H_a and H_b in field space. The FORC distribution $\rho(H_a, H_b)$ is the mixed second derivative, i.e., $\rho(H_a, H_b) = -\partial^2 M(H_a, H_b)/ \partial H_a \partial H_b$, and a FORC diagram is a contour plot of $\rho(H_a, H_b)$ with the axis rotated by changing coordinates from (H_a, H_b) to $H_c = (H_b - H_a)/2$ and $H_u = (H_b + H_a)/2$, where H_u represents the distribution of interaction fields, and H_c represents the distribution of switching fields.

Figure 2 shows a series of FORCs for the field oriented at 180° with respect to the exchange bias field. And, figure 3 shows the corresponding FORC diagram[5]. The figure 3 diagram shows there is a main FORC distribution that is centered around H_c (3.5 Oe); however, note that the distribution of switching fields extends over several Oe. The peak of the distribution in the H_u direction corresponds to the exchange bias field H_{ex} (40 Oe). The spread of the distribution in the H_u direction is related to interactions between the AFM and FM layers.

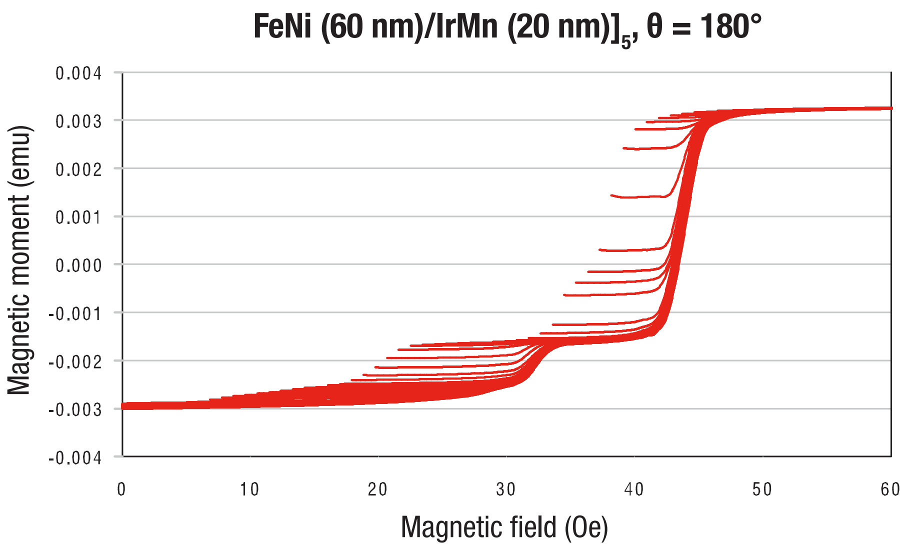

Figure 2: FORCs for [FeNi (60 nm)/IrMn (20 nm)]$_5$ at θ = 180°.

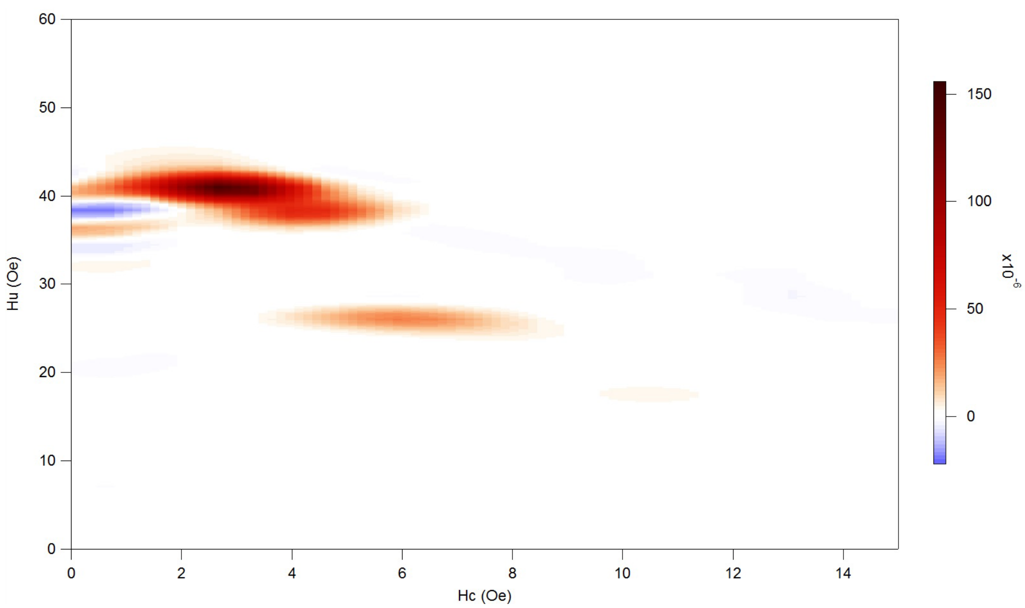

Figure 3: FORC diagram for [FeNi (60 nm)/IrMn (20 nm)]$_5$ at θ = 180°.

The satellite distribution centered at H_u = 25 Oe and H_c = 6 Oe is related to structural in-homegeneities at the AFM/FM interface and are more pronounced the higher the number of layer repetitions, or equivalently the higher the number of AFM/FM interface in-homogeneities. An an example, figures 4 and 5 show a series of FORCs and the corresponding FORC diagram[5] for the second sample. This sample has a thicker FeNi layer and one less layer repetition, i.e., [FeNi (80 nm)/IrMn (20 nm)]$_4$. The main FORC distribution is centered around H_c = 4.5 Oe and H_u = 28 Oe, which is consistent with coercivity and exchange bias fields determined from the hysteresis loop. There is a prominent satellite distribution centered around H_c = 7 Oe and H_u = 18 Oe. Note that the spread of the satellite H_c distributions for the sample with 5 layers is larger than that of the sample with 4 layers due to the increased number of AFM/FM interface in-homogeneities. The FORC measurement protocol and analysis provide additional information that cannot be obtained from the standard hysteresis loop measurement alone.

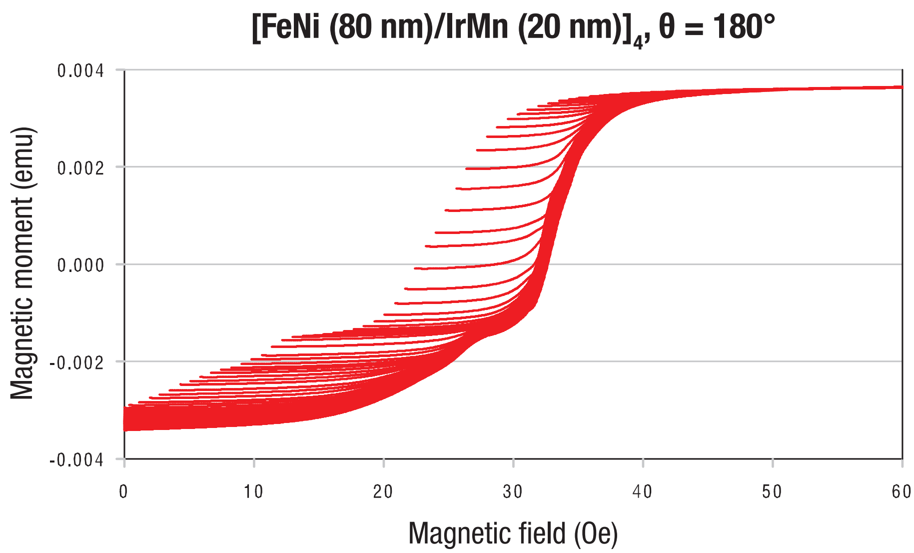

Figure 4: *FORCs for [FeNi (80 nm)/IrMn (20 nm)]$_4$ at θ = 180°.*

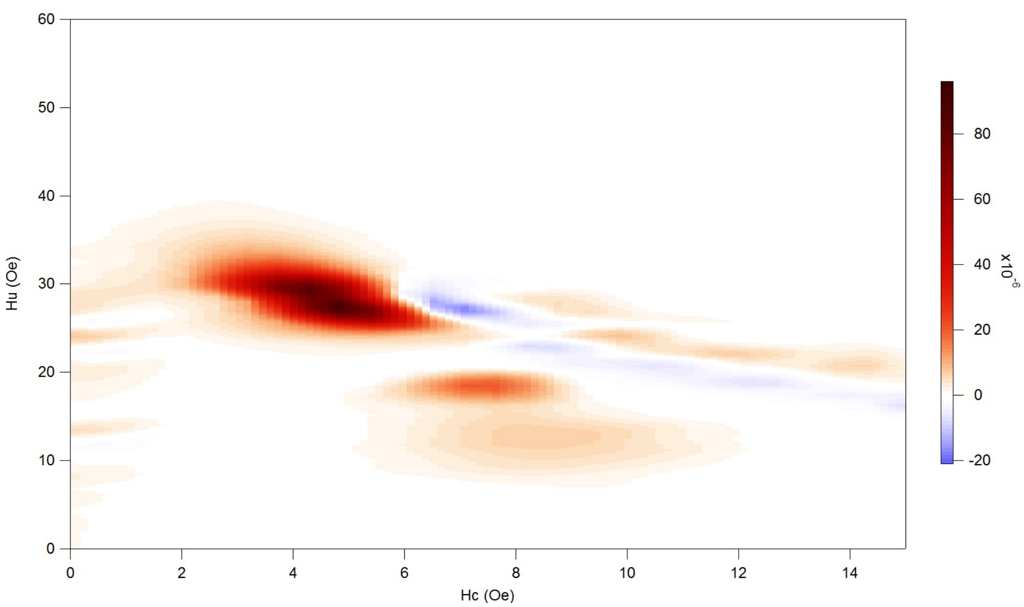

Figure 5: *FORC diagram for [FeNi (80 nm)/IrMn (20 nm)]$_4$ at θ = 180°.*

Conclusion

In this paper we have shown that FORC analysis provides more information than can be obtained from hysteresis loop measurements alone for exchange biased magnetic multilayer films. While the shift in the hysteresis loop provides a simple means for determining the exchange field, the FORC technique shows both main and satellite distributions, the former being related to the exchange biasing and the latter showing the effect of in-homogeneities at the AFM/FM interface.

References

1 S. Khanal, A. Diaconu, J. Vargas, D. Lenormand, C. Garcia, C. Ross, L. Spinu , "Exchange bias in (FeNi/IrMn)n multilayer films evaluated by static and dynamic techniques ", J. Phys. D: Appl. Phys., 47, 255002, 2014

2 J. Davies, D. Gilbert, M. Mohseni, R. Dumas, J. Akerman, K. Liu, "Reversal mode instability and magnetoresistance in perpendicular (Co/Pd)/Cu/(Co/Ni) pseudo-spin valves", Appl. Phys. Lett., 103, 132406, 2013

3 Y. Fang, C. Zha, S. Bonetti, J. Akerman, "FORC studies of exchange biased NiFe in L10 (111) FePt-based spin valves", J. of Phys. Conf. Series, 200, 2010

4 Samples courtesy of C. Garcia, Massachusetts Institute of Technology

5 R. J. Harrison and J. M. Feinberg, "FORCinel: An improved algorithm for calculating first-order reversal curve distributions using locally weighted regression smoothing", Geochemisty, Geophysics, Geosystems, 9, 11, 2008