Switching behavior of Fe-Pt/Ni-Fe exchange-spring films studied by resonant soft-x-ray magneto-optical Kerr effect

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(Received 1 June 2000)

We have studied the magnetic switching behavior of exchange-coupled $Fe_{55}Pt_{45}/Ni_{80}Fe_{20}$ films. On top of magnetically hard $Fe_{55}Pt_{45}$ films having coercive fields up to 10 kOe were deposited soft magnetic NiFe films of different thickness values to form exchange-spring magnet structures. Magnetometry measurements exhibit the loop shapes characteristic of the exchange coupling between hard and soft magnetic phases; a reversible switching of the soft layer at low fields and an irreversible switching of the hard layer at higher fields. To investigate the switching behavior in more detail we prepared samples with 20-Å Co layers either deposited on top of the soft magnetic NiFe film or at the NiFe-FePt interface. Soft-x-ray magneto-optical Kerr effect measurements performed at the Co *L*-edge resonance allows us to use the Co layer as a local probe of the reversal process. The element-specific Kerr loops reveal that the reversible twist in the soft layer is not pinned rigidly at the interface but rather propagates significantly into the hard magnetic layer. As a consequence the reversible magnetization is not only stored in the soft layer, as often assumed. Additionally the major loops do not exhibit any well-defined switching field of the hard layer. Instead the results indicate that the irreversible switching of the hard phase evolves continuously with increasing external field in this materials system.

I. INTRODUCTION

In order to create high performance permanent magnets for future applications in magnetic technology it is of great interest to optimize the maximum energy product $(BH)_{\mathrm{max}}$, twice the maximum magnetostatic energy available from a magnet of optimal shape. It is well known that $(BH)_{\mathrm{max}}$ increases with the coercive field H_c as well as with the saturation magnetization M_{sat}. However, for materials with high H_c values $(\mathbf{H_c>2\pi M_{sat}})$ the theoretical value for the energy product is limited only by M_{sat}. In this case one obtains $\mathbf{(BH)_{max}=(2\pi M_{sat})^2}$. Maximizing the energy product requires identifying materials with a high M_{sat} and sufficient anisotropy to maintain $H_c>2\pi M_{\mathrm{sat}}$. A high Curie temperature T_c is also required for most technical applications. Unfortunately these conditions are not easily met from single-phase materials. On the basis of these limitations, Kneller and Hawig[1] proposed an alternative approach to optimize $(BH)_{\mathrm{max}}$ by combining a hard magnetic phase with a high H_c with a soft magnetic phase with high M_{sat} in a nanocomposite geometry. Such exchange-coupled systems are called exchange-hardened or exchange-spring magnets. The hard-magnetic phase provides the high anisotropy and stabilizes the soft magnetic layer via exchange coupling at the interface. The term exchange-spring refers to the reversible demagnetization curves that are often observed in these structures. The soft phase is pinned at the interface, while the center of the soft phase can rotate with a reverse field. The angle of rotation increases with increasing distance from the hard layer, as in a Bloch wall, and will rotate back in alignment with the hard phase when the applied field is reduced. This is shown schematically in Fig. 1. Interest in such materials has led to research into exchange-coupled hard/soft magnetic bilayers and multilayers as model exchange-spring magnets.[2,3] Hard/soft magnetic bilayers have also been recently studied because they allow one to control and manipulate domain-wall structures in ferromagnetic films[4–6] and for potential applications in magnetic devices.[7,8]

In this paper we present the magnetic switching behavior of exchange-coupled $Fe_{55}Pt_{45}/Ni_{80}Fe_{20}$ bilayers. FePt in the $L1_0$ phase has been proposed as a hard-magnet material for high-energy product exchange-spring magnets.[9] First we briefly discuss the properties of the magnetically hard FePt films, which we optimized to obtain high coercive fields. Subsequently, we deposited soft NiFe films of different thicknesses on top of the FePt to form exchange-spring magnet structures. For a more detailed investigation of the switching behavior, we studied samples with 20-Å Co layers, either deposited on top of the soft NiFe film or at the FePt/NiFe interface. Resonant soft x-ray magneto-optical Kerr effect measurements performed at the Co *L* edge allow us to use the Co layer as a local probe of the reversal process, since these layers are reasonably assumed to be a small perturbation to the overall properties of the exchange spring system. We will discuss the switching mechanism of the system with respect to reversible and irreversible properties. Comparison with the recently studied SmCo/Fe system[3] highlights the individual variations in the exchange-spring behavior for different materials and microstructures.

II. EXPERIMENTAL PROCEDURES

The single FePt films as well as the FePt/NiFe bilayers were grown by magnetron sputtering onto glass substrates with a 15-Å Pt seed layer.[10,11] The hard-magnetic $Fe_{55}Pt_{45}$ films are cosputtered from elemental targets allowing the

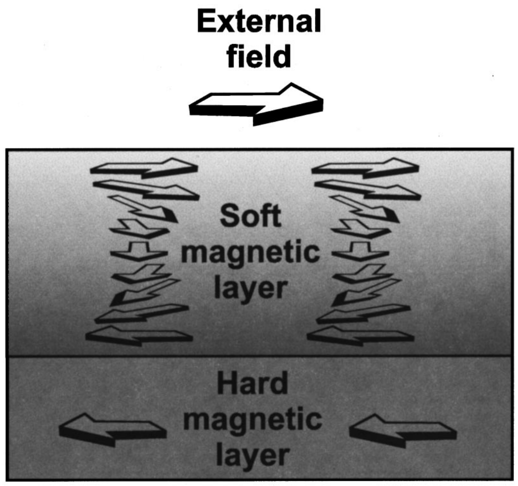

FIG. 1. The spin structure commonly associated with an exchange-spring magnet; a reversible twisting of the soft layer in a reverse field pinned at the interface of the hard layer.

composition to be controlled. The Ar sputtering pressure was 10 mTorr and the substrate temperature maintained at 420 °C. For this study the FePt layer thickness was kept constant at 200 Å. The samples were then cooled to 150 °C prior to the deposition of the $Ni_{80}Fe_{20}$ layers to avoid a chemical reaction with the hard layers. The NiFe layers were sputtered from an alloy target in 3 mTorr of Ar and range in thickness from 100 to 800 Å. 20-Å thick Co marker layers were deposited at different depths within the NiFe layer under the same conditions. Below we discuss the results for the Co layers either at the FePt-NiFe interface or on top of the NiFe layer. All films are capped with Pt to prevent oxidation.

We studied the magnetic properties by the visible magneto-optical Kerr effect (MOKE) and with a superconducting quantum interference device. Major and remanent magnetic hysteresis loops were measured to gain information about the reversible and irreversible magnetization parts of the exchange-spring system. The Co hysteresis loops were measured by resonant soft x-ray magneto-optical Kerr effect (XMOKE) at the Advanced Light Source at Lawrence Berkeley National Laboratory. Both the rotation and intensity of linearly polarized x rays incident at 7–8° from grazing were measured in a longitudinal field.[12–14] The XMOKE rotation signal measures changes in longitudinal magnetization, while the intensity signal measures changes in net transverse magnetization that may be present in certain reversal mechanisms, such as coherent rotation. Sensitivity to just the Co layers is obtained by tuning to the Co L_3 edge and using a tunable linear polarizer for rotation measurements. This element specificity allows selective probing of the magnetic response of both the top of the NiFe layer as well as the NiFe-FePt interface by measuring the Co response of marker layers located at these positions.

III. RESULTS AND DISCUSSION

For the FePt single layers we found that a ratio of 55 at. % Fe and 45 at. % Pt results in the highest H_C values. Typical 200-Å FePt films have 10-kOe coercive fields at room temperature, in agreement with the finding of Refs. 10 and 11.

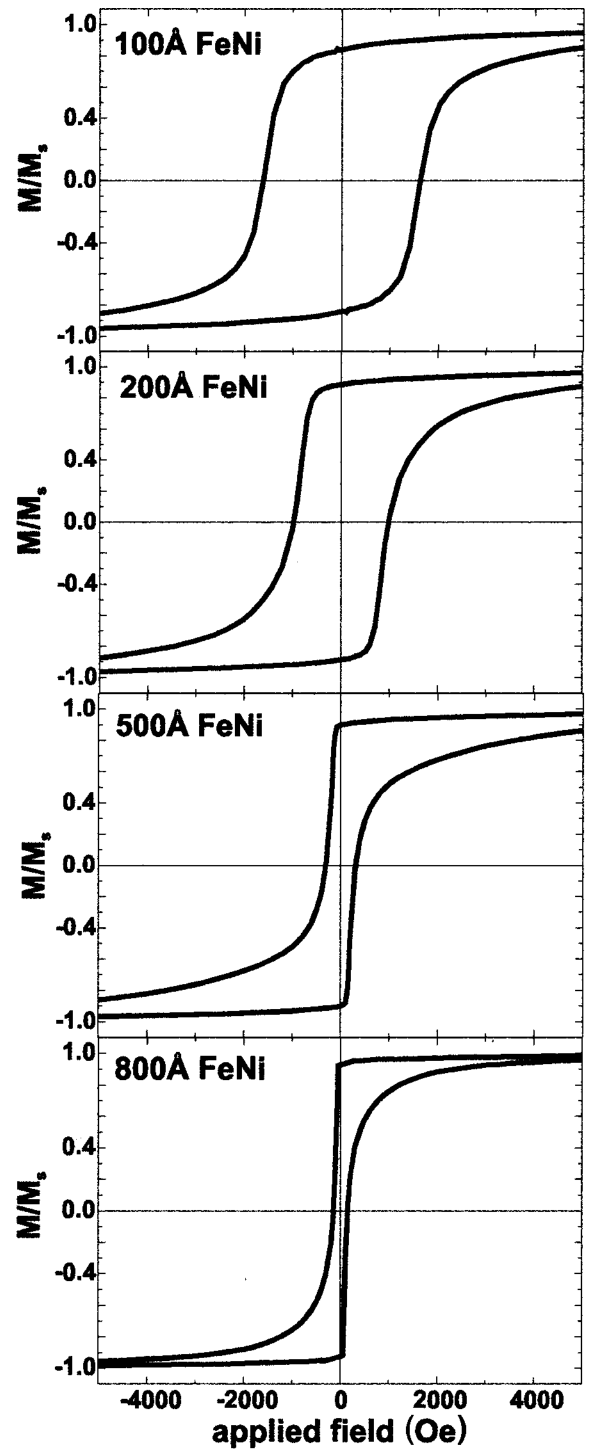

FIG. 2. Hysteresis loops for FePt/NiFe exchange-spring films with 200-Å FePt layers and increasing FeNi thickness values as given in each panel.

X-ray diffraction confirms a (111) texture of the high-anisotropy $L1_0$ phase of FePt.

Magnetization loops for selected FePt/NiFe(t) bilayer structures are shown in Fig. 2. The loops exhibit a continuous change with increasing t from a shape similar to the FePt film for $t = 100$ Å to loops typical of an exchange-coupled bilayer system.[15,16] The coercive fields of the composite films drop systematically with increasing t from about 1.8

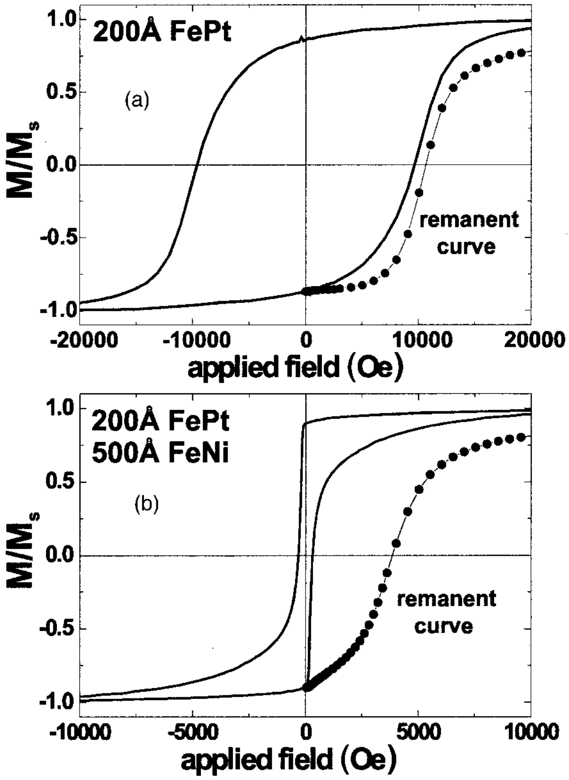

FIG. 3. Major loop (solid line) and remanent loop (filled circles) for an uncoupled FePt single layer (top panel) and for an exchange-coupled FePt/NiFe bilayer film (bottom panel).

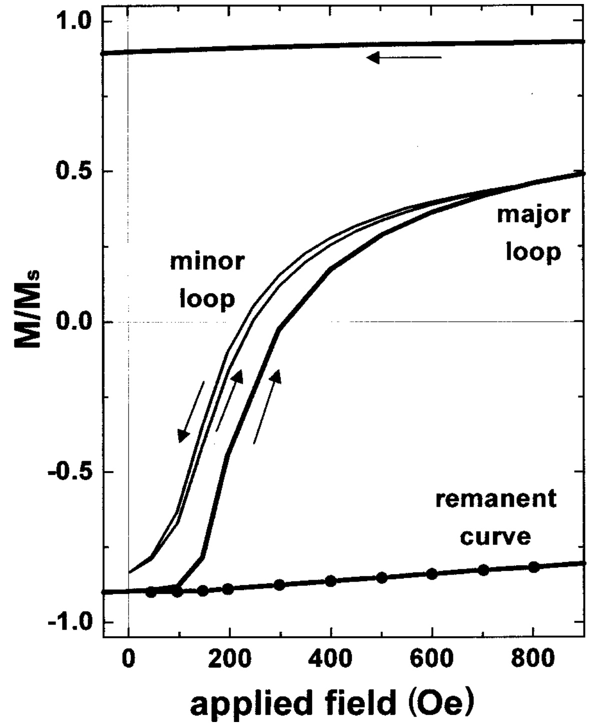

FIG. 4. Major loop (thick solid line), minor loop (thin solid line) and remanent loop (filled circles) for the exchange-coupled FePt/NiFe bilayer film shown in Fig. 4. The arrows indicate the direction of the field sweep for the major and minor loops.

kOe for the $t=100$ Å layer down to ~100 Oe for $t=800$ Å. For the thicker NiFe layers, the films nucleate reversal at low fields and then asymptotically approach saturation with increasing field. This behavior is associated with a twisting of the soft layer as shown in Fig. 1. The nucleation field H_N is the field that introduces the twist into the soft layer and corresponds to the sharp drop in magnetization during reversal. This field was determined analytically by Goto *et al.*[4] assuming an infinitely rigid hard layer as given by

$$H_N=\pi^2 A_S/2M_S t_S^2, \tag{1}$$

where A_S is the atomic exchange within the soft layer (of order 10^{-6} erg/cm) and M_S and t_S are the saturation magnetization and thickness of the soft layer, respectively. Micromagnetic calculations including finite anisotropy of the hard layer find that H_N scales as $t_S^{-1.75}$ for thicker soft layers.[17] This scaling with soft layer thickness gives a reasonable description of the nucleation fields for the present samples.

One characteristic of exchange-spring films is that the twisting behavior of the soft film should be reversible for fields below those required to switch the hard layer. We explored this in more detail for a 500-Å NiFe bilayer film. Shown in Fig. 3 are the major hysteresis loop and the remanent loop for the FePt films and the 500-Å NiFe sample from Fig. 2. We measured the remanent loop by first saturating in a negative field and then measuring the remanent magnetization after applying increasingly positive fields. The reversible change in magnetization $\Delta M_{\mathrm{rev}}(H)$ is given by the difference between the remanent loop and the major loop for a given reverse field. The irreversible magnetization change $\Delta M_{\mathrm{irr}}(H)$ is given by the difference between the remanent magnetization for a reverse field H and the remanent magnetization after saturating the sample. For a single FePt film, the remanent loop closely mimics the major loop with a 10% difference between the H_c and the remanent coercivity H_{cr} where the remnant loop crosses zero.

For the exchange-spring sample, the twisting behavior is reversible resulting in a large difference between the remanent curve and the major loop and between H_c and H_{cr}. The reversible properties of the NiFe layer are shown explicitly in Fig. 4 where we plot a minor loop for a field larger than the coercive field. As the field is removed the remanent magnetization is nearly completely regained. Irreversible switching occurs at higher fields and is characterized by the remament coervcitiy (H_{cr} is the field where half the sample has irreversibly switched). Irreversible switching is usually associated with the reversal of the hard magnetic layer. A feature of the FePt/NiFe system that differs from some other exchange-spring systems[15,16] is the smooth approach of the saturation magnetization rather than a sudden switching into the saturated state. It is not possible to define a switching field for the hard layer from the major loop but it can be estimated from the remanent coercivity H_{cr}. Thus, for thicker NiFe layers the coercivity H_c is dominated by the reversible behavior of the NiFe layer and H_{cr} is characteristic of the irreversible behavior of the FePt layer. There is, however, some irreversible magnetization loss for all fields above H_N.

In order to probe the magnetic switching behavior of the exchange-spring system and in particular to study the interfacial region between the hard and soft layers, we added Co

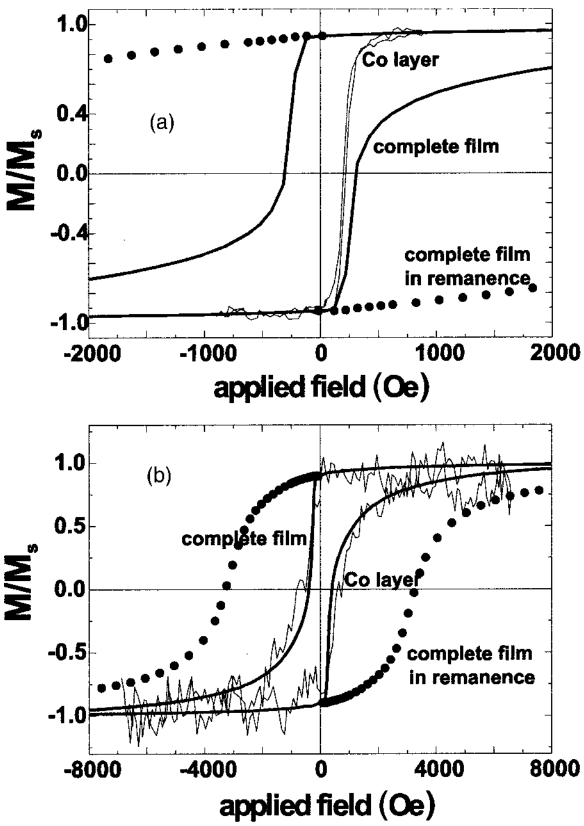

FIG. 5. (a) Top panel: Element-sensitive Kerr rotation loop for the 20-Å Co layer on top of the 500-Å NiFe (thin line) compared with the major (thick line) and remanent loop (circles) of the bilayer structure. (b) Bottom panel: Element-sensitive Kerr loop for the Co layer at the hard-soft magnetic interface (thin line) compared with the major (thick line) and remanent loop (circles) of the bilayer structure.

interlayers to a set of samples having a 500 Å thick NiFe layer. The Co layers act as marker layers to probe the local response of the system. A Co layer at the surface of the NiFe layer reflects the properties of the top part of the soft layer, while the Co layer at the NiFe-FePt interface determines the reversal behavior near the interface and provides insight into the hard layer. The element-specific Co hysteresis loops using the Kerr rotation signal are compared to the magnetometer loops in Fig. 5. We measured both major loops and minor loops. The top panel of Fig. 5 shows a minor loop for the structure with Co on top of the NiFe. The Co layer exhibits a square loop at the nucleation field for the total structure. Thus when the twist structure is introduced into the 500-Å NiFe layer, surface spins completely reverse and a domain wall forms within the bilayer. Additional information can be obtained from the Kerr intensity. For this sample the Kerr intensity signal (not shown) exhibits a feature in the reversal region indicating that a net transverse moment exists during reversal. This is also consistent with coherent rotation, but not with a mechanism involving randomly oriented domains. Hysteresis effects are small, so that the minor loop is nearly reversible (as long as the hard layer is not switched) resulting in a biased minor loop for the top Co layer. The loop bias is determined by the nucleation field for reversal and can be estimated from Eq. (1).

For the interface Co layer [Fig. 5(b) bottom] the noise in the x-ray MOKE measurement is higher since the x-ray intensity at the marker layer is reduced by roughly 20 times by absorption in the NiFe. Nevertheless, the statistics are sufficient to explore the reversal of the interfacial Co layer. It displays a loop that looks very similar to the major loop of the total bilayer system. The coercive field is slightly larger, but the nucleation field and the general shape are nearly identical. As the interfacial Co layer reflects the reversal properties of the top of the FePt layer,[18] these results show that the hard layer starts reversal at the nucleation field of the soft layer. This implies that reversible magnetization is stored not only in the soft layer but also in the hard layer. In fact, the interfacial layer is nearly completely switched in the reversible regime ($H<H_{cr}$). This behavior of the hard magnetic layer is contrary to simple models that suppose a twist primarily in the soft layer and a rigid structure in the hard layer as implied in Fig. 1 and explicitly assumed in deriving Eq. (1). The FePt/NiFe system shows significant deviation from this model. Such a reversible perturbation of the hard layer had been inferred from magnetization curves of SmCo/Fe and SmCo/NiFe bilayers.[15,16] In these cases, the magnetization is fitted to a one-dimensional model to separate the behavior of the hard and soft phases. In the present case, by exploiting the element specificity of the XMOKE technique we were able to observe directly the interfacial response. As can be seen, for low fields the exchange-spring propagates into the hard magnetic layer demonstrating that the hard phase possesses a significant portion of the reversible magnetization.

As mentioned above, the FePt/NiFe samples exhibit an asymptotic approach to saturation. In the SmCo/Fe system,[15] there was strong irreversible drop in magnetization at higher fields indicating the sudden switching of the hard layer. Such a feature is missing in the loop of the FeNi/FePt bilayer. The hard phase seems to switch continuously with increasing external field rather than at a defined value. The origin for this different switching behavior can be found by considering the microstructure of the hard magnetic layers. The SmCo hard layers were epitaxially grown onto single-crystalline MgO(110) substrates resulting in the SmCo films having a well-defined uniaxial in-plane anisotropy. The current FePt films are (111) textured. Since the FePt easy axis is along the (001) axis of the ordered FePt the local easy axis lies at an angle with the film normal with a random in-plane distribution. The magnetic properties of FePt films are nearly isotropic for the fields applied parallel or perpendicular to the surface. In the exchange-spring structure the soft layer nucleates reversal of the hard. The domain wall in the soft layer propagates into, and switches the hard layer with increasing field.[1,15] Since the hard layers are in general thicker than the domain-wall width within the hard layer, the hard layer reverses by propagation of the domain wall from the interface with the soft layer down through the film. In the case of SmCo hard layers, the epitaxial crystalline structure combined with the uniaxial in-plane anisotropy gives rise to little domain-wall pinning normal to the film. Modeling of the magnetization reversal suggests that once the domain wall is nucleated in the SmCo layer it propagates through the film and switches the hard layer. For FePt/NiFe, the films are textured with an isotropic magnetic structure. Once the NiFe layer nucleates a domain wall into the FePt layer, it is pinned within the FePt layer. Higher applied fields are then required to propagate the domain wall through the FePt film. Thus, the FePt/NiFe samples are not fully reversed until fields near the coercive field of the isolated FePt layers (~10 kOe) are applied and the domain walls are completely swept out of the FePt layer. This suggests that the one-dimensional modeling that was effective in understanding of the SmCo/Fe system will not be sufficient to describe an exchange spring films with a more complicated microstructure.

In conclusion, we have studied the magnetic switching behavior of exchange-coupled $Fe_{55}Pt_{45}/Ni_{80}Fe_{20}$ films. Magnetometry measurements exhibit the loop shapes characteristic of the exchange coupling between hard and soft magnetic phases; a reversible switching of the soft layer at low fields and an irreversible switching of the hard layer at higher fields. The resonant soft x-ray magneto-optical Kerr effect in conjunction with ultrathin Co marker layers provided an effective means to resolve reversal behavior in depth in these structures, and suggest that these techniques will be useful to study other layered magnetic structures. Co layers either deposited on top of the soft magnetic NiFe film determined that reversal is nucleated at the surface of the soft layer, as expected. Kerr loops from Co layers at the FePt-NiFe interface reveal that the reversible twist in the soft layer is not pinned rigidly at the interface but rather propagates significantly into the hard magnetic layer. As a consequence the reversible magnetization is not only stored in the soft layer, as often assumed.

ACKNOWLEDGMENTS

J.B.K. was supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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[18] Since the Co layer thickness value (20 Å) is significantly less than the exchange length of Co (~50 Å), the Co response will closely mimic the magnetic response of the FePt layer surface.