Interphase exchange coupling in Fe/Sm–Co bilayers with gradient Fe thickness

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We have fabricated Fe/Sm–Co bilayers with gradient Fe thicknesses in order to systematically study the dependence of exchange coupling on the thickness of the Fe layer. The Fe layer was deposited at two different temperatures (150 and 300 °C) to study the effect of deposition temperature on the exchange coupling. Magneto-optical Kerr effect and x-ray magnetic circular dichroism (XMCD) have been employed as nondestructive rapid characterization tools to map the magnetic properties of the gradient samples. Systematic enhancement in exchange coupling between the soft layer and the hard layer is observed as the soft layer thickness is decreased. Separate exchange couplings of the Fe layer with Co and Sm in the hard layer are revealed through measuring the element-specific hysteresis curves using XMCD. The single-phase-like magnetization reversal critical thickness increases from 12 nm for Fe deposited at 150 °C to 24 nm for Fe deposited at 300 °C, indicating an important role of the state of the interface in the exchange coupling. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2042529]

INTRODUCTION

Enhanced remanence and increased maximum energy product can be achieved in nanocomposite exchange-coupled soft/hard magnet systems by combining high magnetization in the soft magnet with high anisotropy in the hard magnet.[1] The exchange coupling beneficial to the maximum energy product takes place only if the dimension of the soft phase is smaller than a critical thickness. When the soft-phase dimension is larger than this length, the exchange coupling between the hard and soft phases can no longer fully control the reversal of the soft-phase moment, and the hysteresis loop displays a two-phase-like characteristic (with a step in the loop). Early theoretical calculations had predicted that the critical thickness is twice the domain wall thickness in the hard phase and is not related with the soft phase.[2] However, recent theoretical and experimental investigations have shown that the critical thickness is also strongly dependent on the soft-phase parameters,[3,4] including magnetization and anisotropy. Another unresolved aspect of exchange coupling is how the state of the interface influences the exchange coupling. Until very recently, not much attention was paid to the interface effect.[5] In order to gain clear understanding of the effect of various soft-phase parameters and the interface state on exchange coupling, many combinations of hard-soft composite systems need to be studied. The delicate nature of these effects requires such experiments to be performed under strictly the same conditions varying only one parameter at a time, because subtle run to run variation in conditions can lead to a significant deviation from the expected behavior. This problem can be circumvented by employing the high-throughput synthesis and measurement techniques, where many samples can be studied at a time to minimize the error from condition variation and drastically increase the experimental efficiency.[6]

In this work, combinatorial magnetron sputtering was used to synthesize exchange-coupled magnetic bilayers, where the natural thickness gradient in the deposition geom-

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etry was used to create a wedge thickness profile in the soft layer in order to systematically investigate the thickness dependence of exchange coupling.

EXPERIMENT

Fe/Sm–Co magnetic bilayers were deposited on Si (100) substrates in the high-vacuum magnetron sputtering chamber equipped with three parallel sputtering guns (with the base pressure in the 10^{-9}-Torr range).[7] $SmCo_5$ and Fe targets were dc sputtered with an Ar pressure of 5 mTorr. The sputtering power and the target-to-substrate distance were adjusted to optimize the saturation magnetization and coercivity of the Sm–Co layer and the thickness gradient of the Fe layer. The Sm–Co layer was found to be textured with *c* axis in the film plane. Wavelength dispersive x-ray spectroscopy (WDS) indicated that the composition of the deposited Sm–Co layer was $SmCo_{6.5}$. A uniform thickness of the Sm–Co layer with homogeneous magnetic properties was attained in a relatively large region ($\sim 9 \times 50$ mm^2) on the substrate when it was deposited at 550 °C. An Fe layer with a natural thickness gradient of ~0.55 nm/mm was formed in the same region of the substrate (inset of Fig. 1). The thickness gradient of the Fe layer was confirmed by secondary-ion-mass spectroscopy (SIMS).

RESULTS AND DISCUSSION

We have found that depending on the thermal treatment, Sm–Co films can display very different values of coercivity and saturation magnetization. We have used 130-nm-thick Sm–Co layers with the saturation magnetization of 530 emu/cc and the coercivity of 14 kOe. This value of saturation magnetization is comparable to that of epitaxial Sm–Co films grown at 600 °C on Cr-buffered MgO (100).[8] Subsequently, the Fe layer was deposited on top of the Sm–Co layer after the wafer is cooled to 300 or 150 °C. Afterwards, a Cr layer (7 nm) was deposited at room temperature as a capping layer to prevent oxidation of the bilayers.

We have used the magneto-optic Kerr effect (MOKE) and the x-ray magnetic circular dichroism (XMCD) for rapid characterization and mapping of magnetic properties of the thickness gradient bilayer samples. The longitudinal MOKE magnetization loops measured at different spots on the samples using a 633-nm wavelength laser are shown in Fig. 1 [Figs. 1(a) and 1(b) are from bilayers with Fe deposited at 150 and 300 °C, respectively]. Because the penetration depth of the laser is limited to ~20 nm, the MOKE signal is surface sensitive and mainly reveals the magnetic behavior of the upper soft layer in the magnetic bilayers. The field dependence of the Kerr effect represents the magnetization process of the soft layer due to the applied field.[9] Enhancement in the exchange coupling between the soft layer and the hard layer with the decreased soft layer thickness is clearly evident, as minor loops get smaller and it becomes harder to reverse the polarization of the soft layer when the Fe layer gets thinner. The maximum applied field for this measurement was 10 kOe, which is not large enough to saturate the Fe layer when it is strongly coupled to the hard Sm–Co layer.

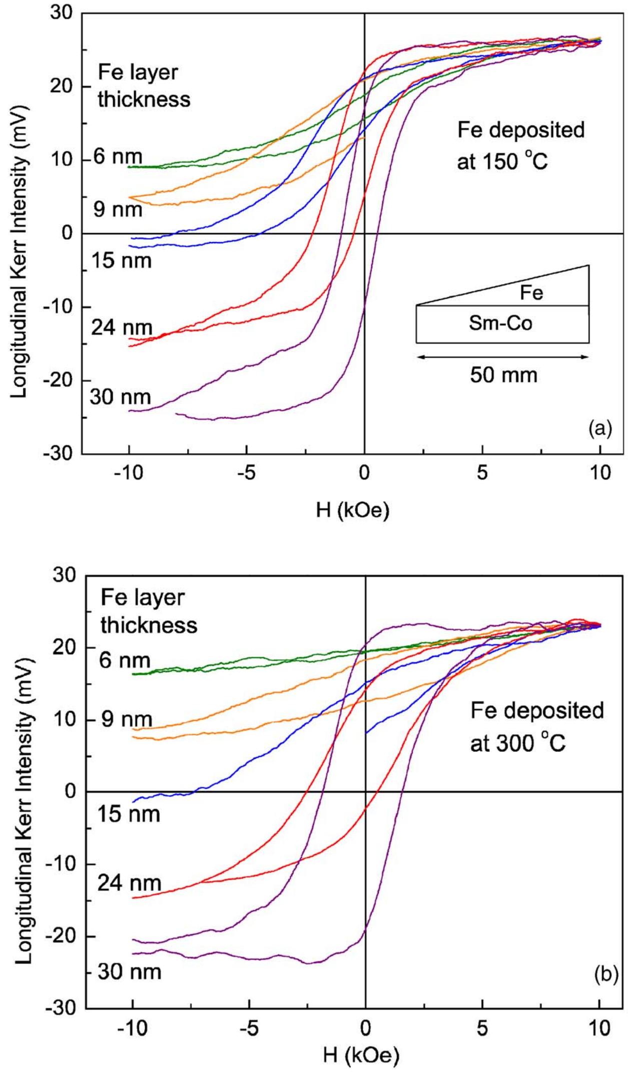

FIG. 1. (Color online) Longitudinal Kerr magnetization loops taken at different spots on Fe/Sm–Co bilayers with gradient Fe thickness deposited at 150 °C (a) and 300 °C (b). The inset of (a) shows the schematic of the samples.

Therefore, most of the loops we obtained are minor loops and asymmetric. Comparing Fig. 1(a) with Fig. 1(b), we conclude that it is harder to reverse the magnetization of the Fe layer deposited at 300 °C, indicating stronger coupling. The coercivity of the 30-nm Fe layer in Fig. 1(b) is larger than that in Fig. 1(a).

In order to probe the magnetic property of the buried hard layer, we have performed XMCD utilizing a synchrotron x-ray beam. Through the use of circularly polarized x rays tuned to an elemental absorption resonance, we can probe the individual magnetic behavior of soft and hard layers separately. The XMCD signal represents the difference between the absorption of left and right circularly polarized x rays, which effectively measures the populations of the up and down spin orientations.[10] XMCD measurements were performed at beamline 4-ID-C of Advanced Photon Source using a 7-T superconducting magnet.[11] The fluorescence yields at the Fe L_3, Co L_2, and Sm M_5 edges were used to record the element-specific hysteresis curves at 100 K at various spots on the samples (Fig. 2). Only half loops were

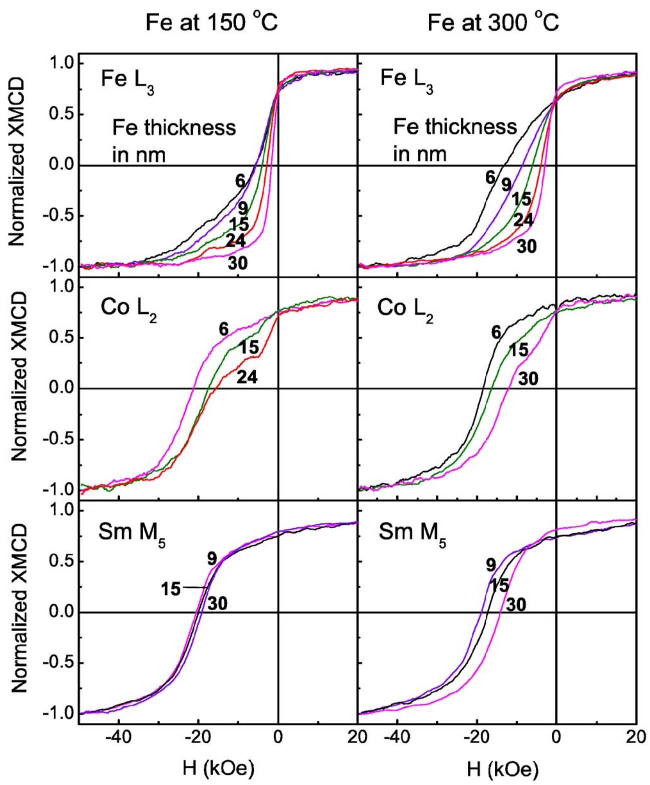

FIG. 2. (Color online) Fe L_3, Co L_2, and Sm M_5 edge XMCD hysteresis curves taken at different spots on Fe/Sm–Co bilayers with gradient Fe thickness deposited at 150 °C (left) and 300 °C (right). The number on the curve is the Fe thickness in the unit of nanometers.

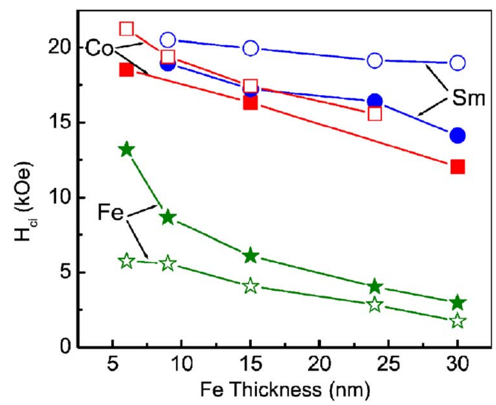

FIG. 3. (Color online) Fe thickness dependence of element-specific coercivity for Fe, Co, and Sm deduced from XMCD data for Fe deposited at 150 °C (open) and 300 °C (solid).

recorded to make efficient use of the beam time. It is interesting to note that the shape of the hysteresis curves and the coercivity are different for Co and Sm. This indicates that there is a field-induced noncollinear spin configuration between the Co and Sm magnetic moments. In some two-sublattice ferromagnets, the strong competition between the exchange interaction, magnetocrystalline anisotropies, and Zeeman energy could produce the field-induced noncollinear spin configurations.[12] In our case, we found that the noncollinear spin configuration is not present in a single Sm–Co layer sample (not shown here), which indicates that the noncollinear spin configuration is not a bulk effect and that it is closely related with the difference in interlayer Co–Fe and Sm–Fe exchange interactions. Because Sm 4f electrons are screened by the outer-shell electrons, they are subjected to stronger interaction with the crystal field, and weaker interaction with Fe atoms, compared to 3d electrons in Co atom. The stronger Fe thickness dependence of the Sm coercivity for 300 °C-deposited Fe indicates stronger exchange coupling between Sm and Fe atoms. It is worthwhile to note that the Co hysteresis curves show a knee when the soft layer is thicker than 15 and 30 nm for the Fe layer deposited at 150 and 300 °C, respectively. This might be due to the coexistence of multiphases in the Sm–Co layer or the presence of composition inhomogeneity in the film. Indeed, $SmCo_5$, rhombohedral Sm_2Co_{17}, and hexagonal $SmCo_{8.5}$ were observed in the film by high-resolution transmission electron microscopy (HRTEM).[13] It should be noted that the microscopic composition inhomogeneity observed in the nanometer region is not in conflict with the above-mentioned macroscopic magnetic property homogeneity observed on the millimeter scale in the Sm–Co layer. Different Sm–Co phases and compositions can have different magnetocrystalline anisotropies. They can also have different critical thicknesses with the Fe layer, which give rise to the knee when the Fe thickness is larger than the smallest critical thickness. The stronger exchange coupling with the higher-temperature deposited Fe seems to increase the smallest critical thickness. No obvious knee can be observed in the Sm hysteresis curves. This indicates that the exchange coupling between Sm and Fe is probably not sensitive to the phase and composition variations.

The Fe thickness dependence of the element-resolved coercivities as deduced from the XMCD result is plotted in Fig. 3. The coercivity of the Fe layer in the exchange-coupled bilayer can become much larger than that of an independently measured single Fe layer (~500 Oe), and it increases with the decreased Fe layer thickness. The larger Fe coercivity, the better squareness, and the stronger thickness dependence in the higher-temperature deposited Fe bilayer indicate the more favorable exchange coupling, which is consistent with the results obtained from MOKE.

In order to confirm the results, we have also performed M-H loop measurements using a superconducting quantum interface device (SQUID) magnetometer on selected regions of the samples by cutting the bilayer wafer into 5×5-mm^2-sized squares (Fig. 4). As the Fe thickness is increased, the hysteresis curves changes from the single-phase-like magnetization reversal to the two-phase magnetization reversal. The single-phase-like magnetization reversal can be sustained up to 24 nm for Fe deposited at 300 °C, but only 12 nm for Fe deposited at 150 °C.

We believe that the observed enhanced coupling for bilayers with Fe deposited at the higher temperature is due to the interdiffusion of the Fe atoms and concomitant formation of a coherent interface. SIMS analyses of the interfaces indicate that in comparison to Fe deposited at 150 °C, 300 °C deposition results in an interface region approximately 6 nm where Fe had interdiffused. It is interesting to note that a separate experiment performed with Co/Sm–Co bilayers did

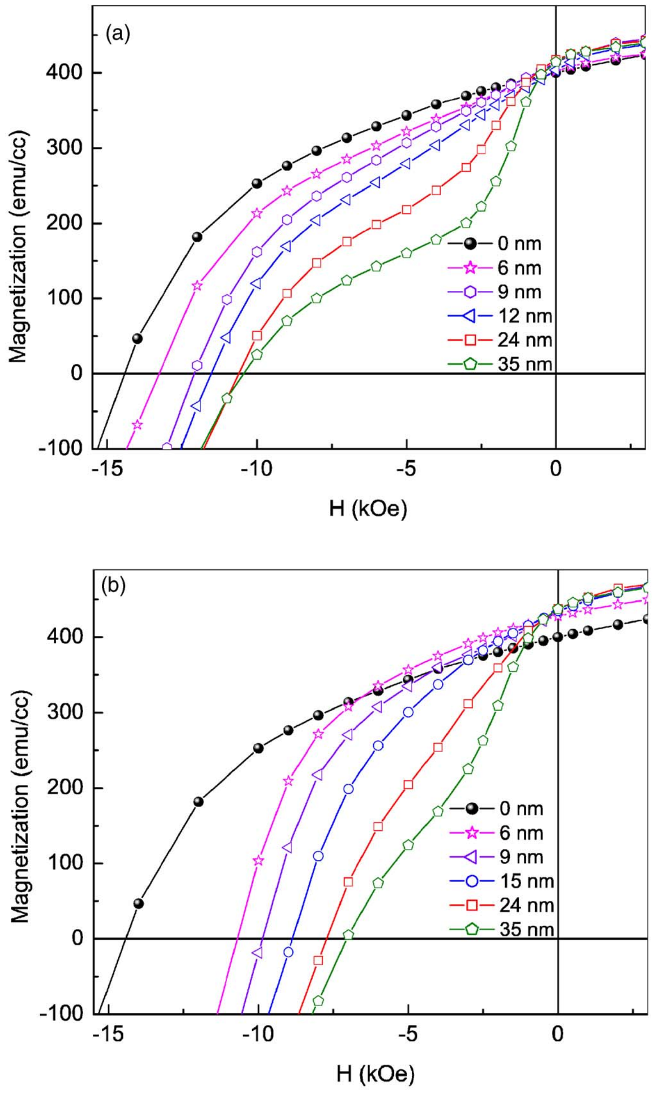

FIG. 4. (Color online) Room-temperature hysteresis curves for Fe/Sm–Co bilayers with different Fe thickness deposited at 150 °C (a) and 300 °C (b).

not exhibit any interdiffusion for the Co deposited at 300 °C indicating that the interdiffusion in the Fe/Sm–Co case is most likely between Fe and Co atoms.

Figure 5 is a HRTEM image of the Fe/Sm–Co bilayer with Fe deposited at 300 °C displaying an epitaxial coherent interface that had formed between the layers. Such an interface was not observed for the bilayer with Fe deposited at 150 °C, and therefore we directly associate the coherent interface as the cause of the enhanced exchange coupling. The formation of the coherent interface was likely facilitated by the interdiffusion of the Fe and Co at the higher temperature. Thus, the interface is perhaps best described as actually between Fe–Co/Sm–Fe–Co.[14] We believe that it is the combination of the interdiffused region with gradual composition change and the reduced density of defects (as evidenced by the lattice coherence) which has given rise to an enhanced interphase exchange coupling.

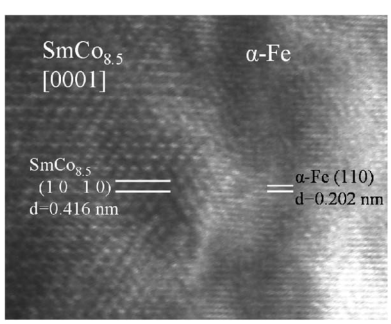

FIG. 5. HRTEM of the Fe(110)//$SmCo_{8.5}$ (10-10) interface (Fe deposited at 300 °C). A coherent interface was observed.

CONCLUSIONS

In conclusion, we have demonstrated the utility of high-throughput studies in investigation of exchange coupling in the gradient thickness Fe/Sm–Co bilayers. MOKE and XMCD have been employed to rapidly characterize the interlayer exchange coupling. The field-induced noncollinear configuration between the Co and Sm magnetic moments and the different Sm–Fe and Co–Fe exchange couplings were revealed by measuring the element-specific hysteresis curves using XMCD. Deposition of the soft layer at 300 °C was found to enhance the interphase exchange coupling due to the formation of an intermixing boundary with a lattice coherent interface.

ACKNOWLEDGMENTS

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[13]A detailed HRTEM structural characterization for the Fe/Sm–Co magnetic bilayer will be published separately.
[14]Further high-resolution interface studies using energy dispersive x-ray analysis (EDAX) and electron-energy-loss spectroscopy (EELS) are currently underway.