Layer resolved magnetization reversal study in $SmCo_5$/Fe nanocomposite bilayers*

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A hard/soft $SmCo_5$/ Fe nanocomposite magnetic bilayer system is fabricated on x-ray transparent 100–200 nm thin Si_3N_4 films by magnetron sputtering. The microscopic magnetic domain pattern and its behaviours during magnetization reversal in the hard and the soft magnetic phases are studied separately by element specific magnetic soft x-ray microscopy at a spatial resolution of better than 25 nm. We observe that the domain patterns for the soft and hard phases show coherent behaviours in varying magnetic fields. We derive local $M(H)$ curves from the images of Fe and $SmCo_5$ separately and find the switches for hard and soft phases to be the same.

Keywords: multilayers, x-ray microscopes, magnetic properties of nanostructures

PACC: 7570K, 7550

In 1991 Kneller and Hawig[1] proposed the concept of nanostructured two-phase magnets, named spring exchange magnets. These magnets are a combination of soft and hard magnetic phases which are strongly exchange-coupled. The exchange coupling between soft and hard phases occurs only if the dimension of the soft phase is less than a critical value, usually less than 10 nm. There are two main advantages of exchange spring magnets: enhancement of energy product due to strong exchange coupling between hard and soft phases and less use of costly and more reactive rare earth elements.[2]

It is predicted that an energy product up to 137 MGOe (1 MGOe $\approx$ 7.96 kJ/m^3) is achievable by optimizing SmFeN/FeCo nanocomposites.[3] Up to now, enhancements in magnetization and energy product have been observed, but experimentally observed energy products are not even half of the theoretical prediction. Research on the subject using different fabrication methods—mechanical milling,[4] melt spinning,[5] chemical synthesis[6] and sputtering[7−12] for example—and materials systems is active.[4−12]

We have prepared thin magnetic film consisting of hard/soft $SmCo_5$/Fe nanocomposites by using sputtering. This technique allows the layer thickness, a key parameter determining the properties of the coupled magnet, to be accurately controlled and a systematic study to be undertaken.

The role of the constituent phases in the collective magnetic behaviour of an exchange-coupled sample cannot be resolved by using a magnetometer. However, by using synchrotron radiation, we can spatially resolve the soft and hard phase behaviours separately. Up to now, most of the research on spring exchange magnets has focused on the magnetization response of the combined two-phase system and only a few studies have characterized the dynamics of individual phases. We imaged the bilayers using magnetic soft x-ray transmission microscopy (M-TXM) and utilizing element specificity to distinguish the individual layers. This M-TXM technique can achieve a spatial resolution down to 15 nm by advanced Fresnel zone plate elements used as x-ray optics.[13]

$SmCo_5$ and Fe were deposited on x-ray transparent 100–200 nm thin Si_3N_4 films by dc magnetron sputtering. In the deposition process the thickness of all the layers was monitored by using an acoustic crystal thickness monitor, mounted inside the cham-

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ber and calibrated by the weight method. The samples were capped with a 10 nm layer of Ti. All layers were deposited at a temperature of 500 °C. The nominal composition of the samples from the top layer to the thin Si_3N_4 substrate was as follows: Ti 10 nm/ Fe x nm/ $SmCo_5$ 40 nm/ Si_3N_4 thin films where $x = 0$, 5, 7.5 and 10 nm separately. The base pressure was kept below 1.33×10^{-5} Pa and the Ar pressures were 0.4 Pa for Fe and Ti and 1.066 Pa for $SmCo_5$.

To study the magnetic domain structure and the response of each individual layer, particularly the magnetic coupling mechanism, as a function of length on the microscopic scale, we used the high resolution magnetic soft x-ray transmission microscope located at beam line 6.1.2 at the Advanced Light Source, Berkeley, CA. The experimental setup of XM-1 is shown in Fig. 1. The details of magnetic soft x-ray microscopy and the optical functionality are described elsewhere.[14]

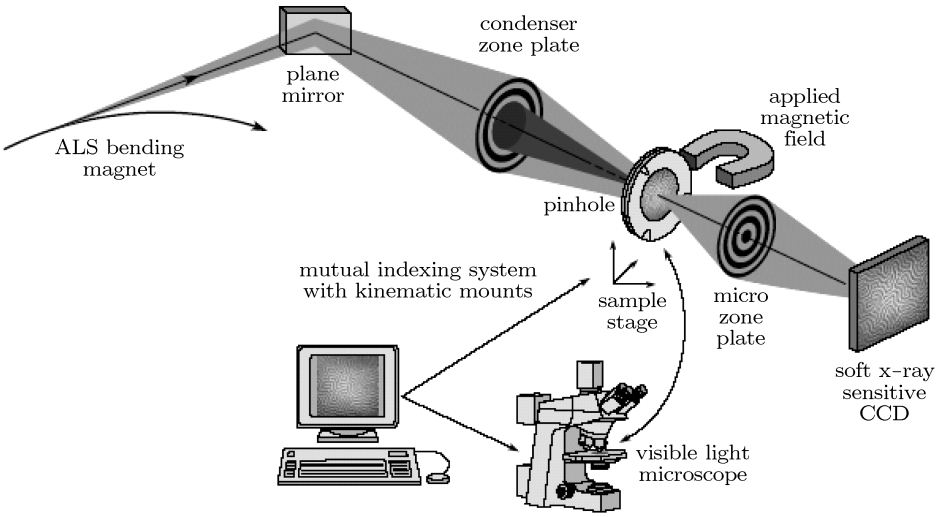


Fig. 1. Schematic diagram of XM-1 at the Advanced Light Source (ALS).[13]

The optical design follows the requirements for a conventional optical microscope, with Fresnel zone plates used as x-ray optical elements. Circularly polarized x-rays are emitted off-orbit from a bending magnet with a degree of circular polarization of about 60%–70%.[15] A condenser zone plate(CZP) together with a pinhole close to the samples acts as a linear monochromator to select an appropriate wavelength, such as Fe and Co L3 absorption edges at 706 eV and 778 eV, respectively. The CZP provides a hollow cone illumination on the specimen. A high resolution x-ray objective lens, the micro zone plate, forms a real space image onto a CCD detector covering a field of view of about 10 μm. Typical exposure time is in the second regime.[16] Both out-of-plane and in-plane magnetizations can be addressed by choosing an appropriate tilt angle of the sample's plane relative to the photon propagation direction. Magnetic fields up to 1–2 kOe (1 kOe=79.6 A/m) can be applied during the recording both perpendicular and parallel to the sample's plane, which allows a study of the domain structure throughout the full magnetization reversal of each layer.

Figure 2 shows the domain patterns of $SmCo_5$ and Fe in $SmCo_5$/Fe nanocomposite magnetic bilayers. In the present study we have achieved x-ray images with a spatial resolution of better than 25 nm. In combination with x-ray magnetic circular dichroism a large and component specific magnetic contrast mechanism is obtained by using circularly polarized x-rays from the synchrotron radiation source. In the transmission geometry the x-ray absorption coefficient in the vicinity of element specific absorption edges, such as the L edges in 3d transition metals, depends strongly on the relative orientation between the helicity of the photons and the local magnetization of the specimen.[17]

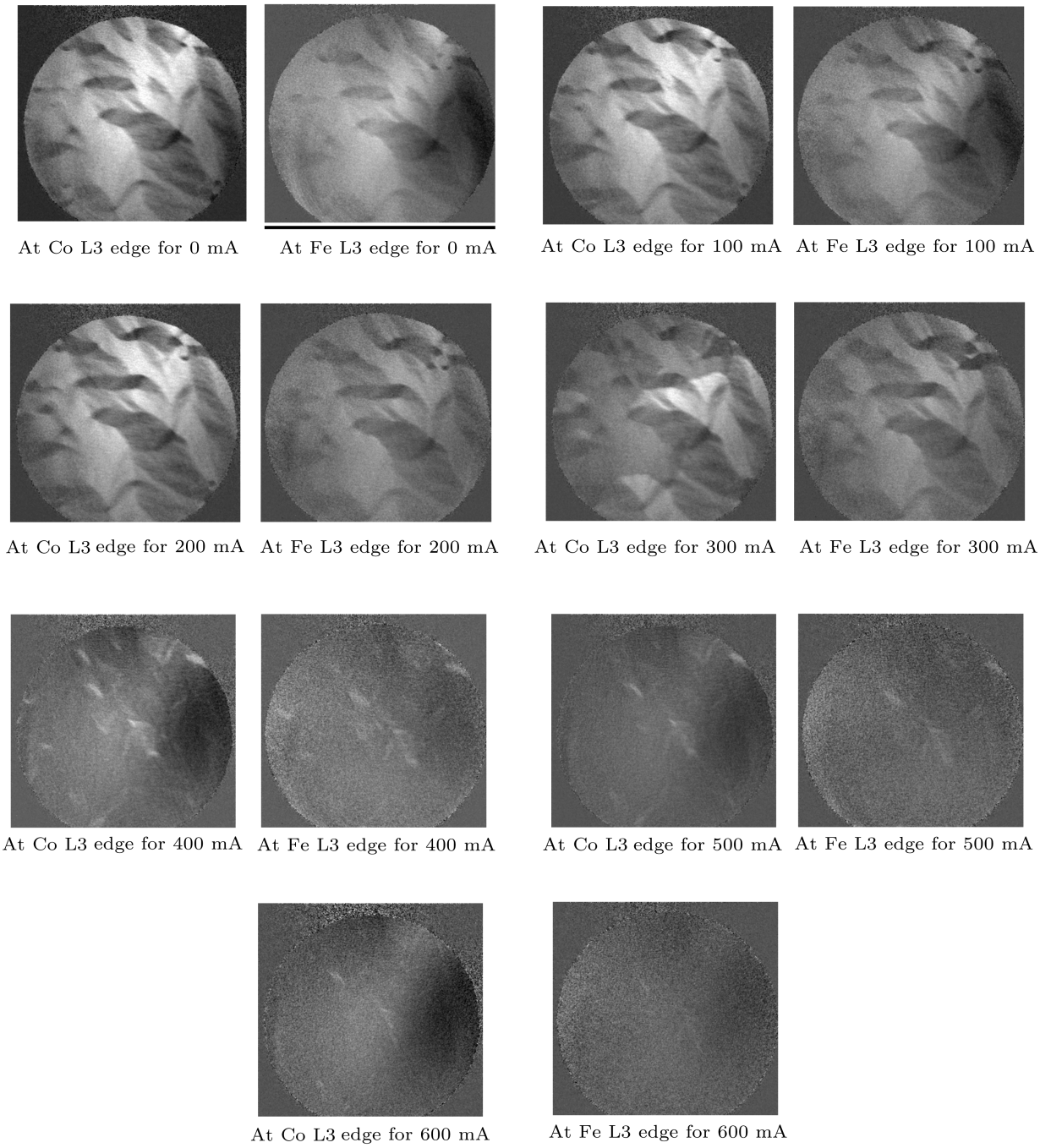


Fig. 2. Domain patterns of $SmCo_5$ and Fe taken by fixing the beam for Fe L3 and Co L3 edges, with $SmCo_5$ being 40 nm thick and Fe being 5 nm thick, capped with a 10 nm thick Ti layer and annealed at 500°C for 30 min. The value of current applied to the electromagnet is annotated for each image.

Layer resolved x-ray images have been taken at the Fe L3 edge (706 eV) and Co L3 edge (778 eV) separately. A magnetic field was applied in the direction perpendicular to the sample plane, and the corresponding value of the bias current in the field coil is indicated for each image. These Co images are representative of the hard phase $SmCo_5$. The images for soft phase and for Co demarcated hard phases are shown side by side for comparison. The field of view is typically 10 μm with a magnification of about 2500. For each set, two images were taken by changing the direction of circularly polarized radiation. The patterns for soft and for hard magnetic phases show that both domain patterns are identical. The set of domain patterns was taken by varying the applied magnetic field perpendicular to the film plane. The domain pat-

tern vanishes when the applied magnetic field is high enough to rotate the direction of the domain perpendicular to the film plane. It should be noted that with changing magnetic field, the soft and hard phases both vary with their domains synchronically. This is indicative of strong exchange coupling between the two phases.

At an applied magnetic field corresponding to a 600 mA bias current, the magnetization is being rotated in the perpendicular direction, which is indicated by the domain pattern of Fe and Co. This suggests that the c-axis of $SmCo_5$ is making an angle with the film plane as it is being rotated at a low applied magnetic field. It should be noted that for a 600 mA current, there are some white spots left, which implies that the applied magnetic field is not sufficient to rotate the magnetization completely.

It is possible to deduce from these images the local hysteresis curves which represent magnetization reversal in each layer.[18] The average intensity of a specific area was taken for each image and was assigned a point value. This process was repeated for each image taken during the variation of the applied magnetic field from a positive maximum value to a negative maximum value, i.e. in the opposite directions and then again to a positive maximum value, i.e. in the same directions. In this way we generated the local hysteresis loop.

The local hysteresis loops were taken for both Co and Fe, as shown in Figs. 3 and 4. The local hysteresis loops for different areas taken on images are almost the same for both Fe and Co i.e. for the soft phase Fe and hard phase $SmCo_5$. The images have been taken for the Fe layer with a thickness of 5 nm. The corresponding $SmCo_5$ layer thickness is 40 nm. The figures show the comparison value of average intensity with the change in bias current of applied magnetic field. The comparison value of average intensity shown on the y-axis of the figure is equivalent to the magnetization. In these local loops, their coercivities are almost the same for Fe and $SmCo_5$.

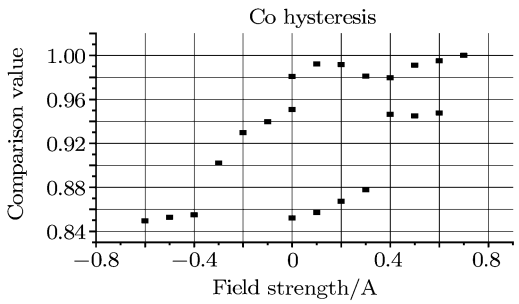


Fig. 3. Local hysteresis loop of $SmCo_5$ taken by adjusting the circularly polarized x-rays at the Co L3 edge. The loop was taken by comparing values of average intensity at different values of applied magnetic field.

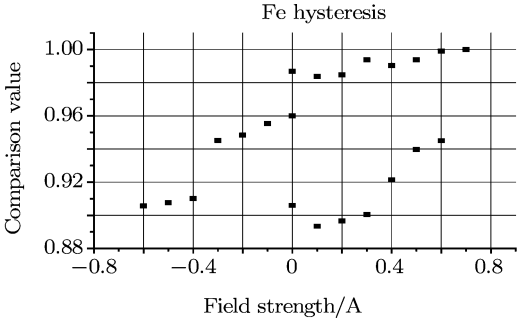


Fig. 4. Local hysteresis loop of Fe taken by adjusting the circularly polarized x-rays at the Fe L3 edge. The loop was taken by comparing the values of average intensity at different values of applied magnetic field.

In the previous study by Yu *et al.*,[19] magnetization reversals were observed for $SmCo_5$ and Fe. Although the paper reported a rise in coercivity for soft phases, there is a considerable difference in coercivity values between the soft and hard phases. In our work, the domain patterns are very similar for hard and soft phases; the changes in the images with applied magnetic field are almost coherent. The local hysteresis loops are also very similar to each other. The coercivity values of Fe in the work by Yu *et al.* are about 25%–30% less than that for the hard phase while in our work these values are almost the same, showing strong exchange coupling between the two phases.

In conclusion, we fabricate nanocomposite $SmCo_5$/ Fe bilayers on 100-to-200 nm thin Si_3N_4 films. The samples are studied with magnetic soft x-ray microscopy by obtaining element specific domain patterns for Fe and $SmCo_5$ hard phases. The formations of the domain patterns in the soft phase and in the hard phase are observed to be similar, showing their strong exchange coupling. We derive from the XMCD contrast local magnetic reversal loops indicating that on a microscopic length scale the soft Fe and hard $SmCo_5$ phases behave in the same way. We conclude that strong exchange coupling between soft and hard phases can be achieved in which the two phases switch simultaneously.

Acknowledgement

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