Pinpointing Chiral Structures with Front/Back Polarized Neutron Reflectometry

We have developed a new method of using polarized neutron reflectometry (PNR) to extract the structure of buried magnetic spirals in magnetic films. This technique improves upon earlier methods by being particularly sensitive to the presence of magnetic twists vis-à-vis structures in which the magnetization direction does not vary appreciably. Tracking the formation and growth of twists may solve a number of puzzles that hamper the development of magnetic thin film devices.

In collaboration with IBM scientists, we have applied the technique to a thin-film exchange-spring magnet and confirmed that the results may violate the current theory regarding the behavior of such magnets. It has been predicted that exchange-spring magnets, comprised of soft and hard ferromagnets in close proximity, are a composite that has a strong moment and does not readily demagnetize [1]. Therefore, exchange-spring magnets should give industry the ability to make much smaller permanent magnets for use in the magnetic recording devices, and elsewhere. As a side effect, when a small external magnetic field is opposed to that of the magnet, the portion of the soft ferromagnet farthest from the hard ferromagnet may twist into alignment with the field. When the field is removed, the soft ferromagnet untwists. The film provided by IBM consists of the hard ferromagnet $Fe_{55}Pt_{45}$ topped by the soft ferromagnet $Ni_{80}Fe_{20}$ [2].

Figure 1 shows a simplified diagram of the behavior predicted by current theories [1]. A magnetic field of 0.890 T, provided by an electromagnet, is sufficient to align both the soft and the hard layers of our exchange-spring magnet, as shown on the left. When a modest reverse field (on the order of 0.025 T) is applied to the exchange spring magnet, only the top of the soft layer will realign with the magnetic field. The hard layer remains pinned in the original direction, and a continuous twist is induced in the soft layer, as the direction of magnetization changes smoothly between the reverse field direction to the aligning field direction.

Although there are many alternatives to PNR to measure the magnetization, typically they measure only the average orientation of the magnetic spins, and cannot readily distinguish a spiral from a structure in which all the spins are canted with respect to an external field. PNR can extract the depth-dependence of the magnetic and chemical structure. We have studied the sample over a wide range of external magnetic fields, and can track the development of the spiral with field [3].

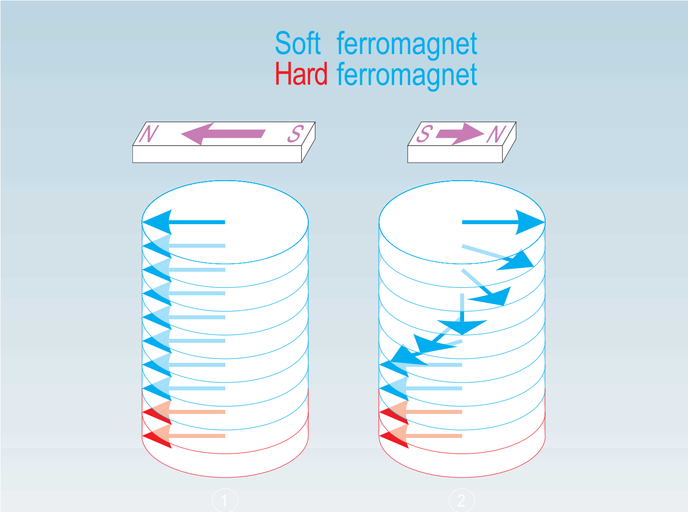

FIGURE 1. Model for field behavior of exchange-spring magnets. On the left the magnet has been aligned by a large external magnetic field. On the right a smaller field opposed to the first field causes a twist to form in the soft ferromagnet, while the hard ferromagnet remains aligned.

A PNR experiment begins with neutrons whose magnetic moments are aligned parallel (+) or opposite (−) to the external magnetic field. When the magnetization of the sample is perpendicular to this magnetic field, the neutron moment precesses as it interacts with the sample. When this happens the spin-flip (SF) reflectivities R^{+-} and R^{-+} are strong. If the magnetization of the sample is parallel to the external magnetic field, no precession occurs, but the non-spin-flip (NSF) reflectivities R^{++} and R^{--} will differ. The NSF reflectivities also provide information about the chemical structure of the film.

Our new modification of the PNR method greatly enhances the contrast between colinear and certain non-colinear magnetic structures [4]. We first measure the reflectivity with neutrons glancing off the front surface of the material, and then repeat with neutrons glancing off the back surface. The experiment is akin to holding the plane of the film up to a “magnetic mirror” to see whether the mirror image is the same as the original structure. In a colinear structure, all the spins are aligned along a common direction, and the mirror image is very much like the original structure.

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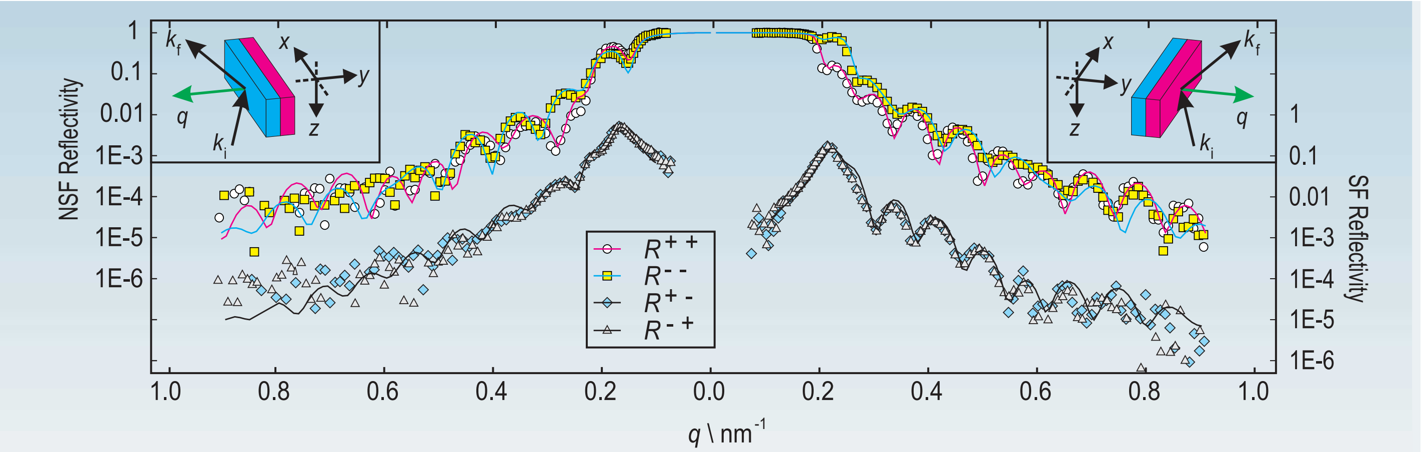

FIGURE 2. Reflectivity of a Ni$_{80}$Fe$_{20}$|Fe$_{55}$Pt$_{45}$ bilayer. The front reflectivity is plotted on the right while the back reflectivity is plotted on the left. The SF reflectivities R^{+-} and R^{-+} are plotted against the right ordinate axis. The NSF reflectivities R^{++} and R^{--} are plotted against the left ordinate axis.

But the mirror image of a magnetic twist to the right is a magnetic twist to the left. Therefore, if the front and back reflectivities are significantly different, we can deduce the presence of a spiral. Fitting the data confirms the spiral's existence.

Figure 2 shows data collected at 0.026 T after aligning in -0.89 T. Fits to the data are shown as solid lines. The data from the front reflectivity are shown on the right, and the data from the back reflectivity are shown on the left. The spin-flip (SF) reflectivities R^{+-} and R^{-+} are plotted against the right-hand axis, which have been shifted relative to the NSF reflectivities R^{++} and R^{--} plotted against the left axis. At $q = 0.2$ nm^{-1}, there is a splitting in the front NSF reflectivity that is much more pronounced than that of the back reflectivity at the same q. This is a hallmark of the spiral structure.

Figure 3 shows the magnetic structure that gives the excellent fit to the data plotted in Fig. 2. The location of the hard/soft interface is marked in Fig. 3. Surprisingly, we discover the spiral invades the hard ferromagnet even at extremely low fields. Current theory predicts that when this occurs, the soft ferromagnet will not be able to untwist fully. Yet, other magnetic studies show that our exchange-spring magnet does untwist when this field is removed. Thus, our PNR measurements have identified a shortcoming of current theory.

With this new technique, NIST is now able to better characterize the magnetic properties of thin films, which can improve the capability and reliability of industrial devices for magnetic recording and sensing.

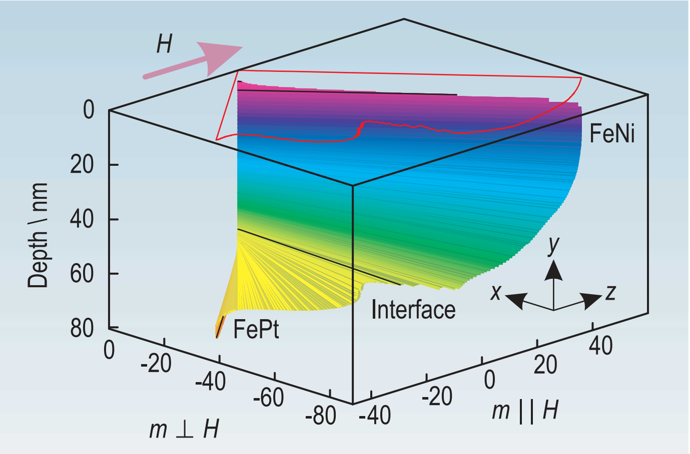

FIGURE 3. Fitted magnetization of the data presented in Fig. 2. The front of the sample is at a depth of 0 nm and the back is at a depth of 70 nm. The red curve is a projection of the magnetic structure into the plane of the front surface.

References

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