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# Magnetic structure variations during giant magnetoresistance training in spin valves with picoscale antiferromagnetic layers

S. Moyerman and J. C. Eckert
*Harvey Mudd College, Claremont, California*

J. A. Borchers[a)]
*NCNR, National Institute of Standards and Technology, Gaithersburg, Maryland*

K. L. Perdue
*Harvey Mudd College, Claremont, California*

M. Doucet
*NCNR, National Institute of Standards and Technology, Gaithersburg, Maryland and University of Maryland College Park, Maryland*

P. D. Sparks
*Harvey Mudd College, Claremont, California*

M. J. Carey
*San Jose Research Center, Hitachi Global Storage Technologies, San Jose, California*

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Microscopic models of exchange bias focus on the formation of domains in the antiferromagnet or the ferromagnet, or on a small induced moment in the antiferromagnet. Previous giant magnetoresistance (GMR) measurements, however, reveal exchange bias and training effects in CoFe-based spin valves with antiferromagnetic IrMn layers as thin as 0.4 nm. Polarized neutron reflectometry studies of a related spin valve with a 1.6 nm IrMn layer were carried out for several points along the GMR hysteresis curve to probe separately the free and pinned CoFe layers. These measurements confirm that the two ferromagnetic CoFe layers are aligned in parallel in saturating fields. During the first field cyle, regions of high resistance correspond to an antiparallel alignment of the CoFe layers as expected. Significant changes in this antiparallel structure are observed during the second field sweep, and a magnetic spiral forms and persists in the pinned CoFe layer. High-field saturation seems to reduce the effectiveness of the pinning and thus gives rise to training. These results have implications for the origin of exchange bias in spin valves with thin antiferromagnetic layers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165607]

The discovery of giant magnetoresistance[1] (GMR) has prompted the rapid development of spin valves (SVs) for commercial applications such as hard-drive read heads. A simple SV consists of a biasing antiferromagnetic (AFM) layer, a pinned ferromagnetic (FM) layer, a nonmagnetic spacer layer, and a ferromagnetic layer whose magnetization is free to rotate in an applied field. Exchange biasing is currently under investigation as its origins are not well understood. For example, GMR measurements at 5 K have verified exchange bias for AFM layers as thin as 0.4 nm,[2] indicating origins based in very small-scale interactions. To probe further the characteristics of such structures, an exchange-biased SV with an AFM 1.6 nm IrMn layer is investigated using GMR and polarized neutron reflectometry (PNR).

GMR measurements offer information regarding the switching properties of spin valves, and the exchange and coercive fields may be determined. However, microscopic models require information about the field-dependent switching and magnetization of the individual magnetic layers. PNR is thus an excellent tool as it provides measurements of the depth-dependent vector magnetization of individual layers at subnanometer length scales. Although most exchange-biased models focus on domains in the adjacent AFM and FM layers, a recent PNR study[3] suggests the existence of a net moment in the AFM and argues against the formation of a domain wall parallel to the interface. In contrast, PNR experiments on other exchange-coupled systems[4–6] have revealed smooth spirals in the magnetic layers persistent over a wide field range.

Our sample was grown using dc magnetron sputtering. Layers were deposited onto a 18 mm $\times$ 18 mm Si wafer yielding the nominal structure Si/5.0 nm Ta/3.0 nm $Ni_{86}Fe_{14}$/1.0 nm $Co_{84}Fe_{16}$/3.0 nm Cu/3.0 nm $Co_{84}Fe_{16}$/1.6 nm $Ir_{20}Mn_{80}$/1.0 nm Cu/5.0 nm Ta. The Ta seed layer induces strong (111) texturing. The NiFe/CoFe free magnetic layer gives a low coercivity with high GMR. At 3 nm, the Cu spacer is thick enough to minimize Neél coupling. CoFe in the pinned layer ensures high GMR and good pinning with the IrMn AFM. After pinning the top CoFe layer by cooling from 300 K in a field of −7000 G, the in-plane GMR was measured at 20 K, yielding the hysteresis loops in Fig. 1. We find an exchange field of 970 G, a coercive field of 680 G, and a GMR of approximately 20%. It is usually assumed that regions of low resistivity correspond to parallel alignment of

[a)]Electronic mail: julie.borchers@nist.gov

 

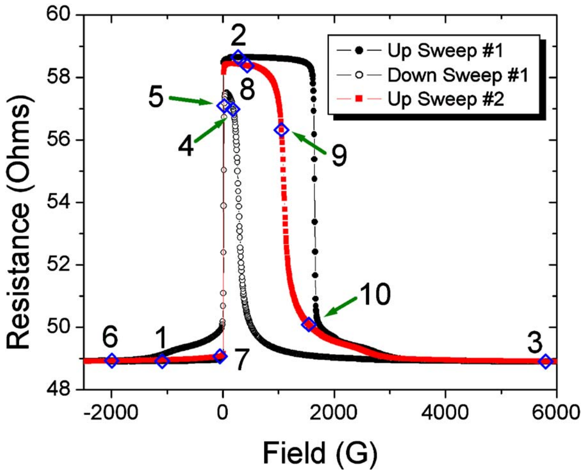


FIG. 1. (Color online) In-plane resistance measured on the CoFe-based SV after field cooling in −7000 G to 20 K. The field was cycled between −7000 and 7000 G.

the FM layers, while regions of high resistivity are associated with their antiparallel alignment. For our sample, this simple interpretation is naïve because the GMR clearly exhibits training effects. During the second field cycle, the resistivity maximum is reduced, extends over a smaller field range, and has rounded edges.

PNR measurements at the NIST Center for Neutron Research (NCNR) were carried out below 7000 G to identify the spin structures responsible for the changes in resistance. Neutrons with wavelength of 0.475 nm were polarized parallel to the applied field in the sample plane using Fe/Si supermirrors as described in Ref. 7. The reflectivity data were corrected for background, the efficiencies of the polarizing elements (typically >96%)[7] and the footprint of the beam. This yields four reflectivity cross sections: $R^{++}$ and $R^{--}$, designated non-spin-flip (NSF) as the neutron maintains its polarization, and $R^{+-}$ and $R^{-+}$, labeled spin flip (SF), where the neutron spin is rotated by 180°. NSF reflectivity is sensitive to the chemical structure of the film, and the difference between $R^{++}$ and $R^{--}$ arises from the component of the magnetization aligned along the field axis. The SF reflectivity yields nonzero values only when a component of the magnetization lies perpendicular to the field direction.

After field cooling from 300 to 20 K in −3250 G,[8] ten data sets were taken sequentially in fields of −1100, 270, 5800, 178, 18, −2000, −50, 440, 1050, and 1550 G, labeled as 1–10 on the hysteresis loop in Fig. 1. The sample was saturated in a field of 7000 G between points 3 and 4 and in a field of −7000 G between points 6 and 7. At points 8–10, reflectivities from the front and the back of the sample were collected to help detect magnetic twists or spirals.[5,6] To obtain a profile of the chemical and magnetic structures as a function of depth, the data were fitted to the reflectivity theoretical formalism[7] with the *REFLPAK* software[9] that utilizes least-squares optimization. Other fits were obtained using reflectivity software that utilizes a genetic algorithm optimization routine.[10] This program allows for simultaneous fitting of multiple PNR data sets with many correlated and uncorrelated parameters. Structural parameters from x-ray reflectivity measurements were held constant in the neutron fits to ensure self-consistency, but restricted freedom was given to the angles of the moments, spiral pitch, and magnetic densities between data sets. The neutron fits were most sensitive to changes in the magnetization of the CoFe layers, the magnetic roughness, and magnetization orientation of the pinned FM layer.

Figure 2 shows the reflectivity data obtained in 1050 G (point 9) during the second field sweep. The reflectivity data from the back surface are plotted on the left versus "negative" wave vector $Q$, and the reflectivity data from the front are plotted on the right as a function of "positive" wave vector. The "front" indicates the neutrons encountering the sample surface first, and the "back" requires initial passage through the substrate. As discussed in Refs. 5 and 6, subtle differences seen in the front and back SF reflectivities, along with significant SF scattering, are suggestive of canted moments or a magnetic spiral.

Comparable reflectivity data obtained in fields of −1100, 5800, −2000, and −50 G, corresponding, respectively, to the minimum resistance states 1, 3, 6, and 7 (Fig. 1), show no significant SF scattering. The fits are consistent with near saturation of both CoFe layers parallel to the field (Fig. 2). The reflectivity fits give magnetizations of 1380 G for both the top and bottom CoFe layers and 760 G for the NiFe layer. These values are within 5% of bulk, further indicating saturation and an absence of in-plane domains.

The data set taken in 270 G (point 2 in Fig. 1) reveals an antiparallel alignment of the two FM layers, where the magnetic moment of the free layer is slightly decreased from bulk. The weak SF scattering indicates that the free CoFe/NiFe and pinned CoFe layer moments are aligned parallel and antiparallel, respectively, to the field with almost no perpendicular component as expected from the high resistance.

During the downward sweep of the first hysteresis cycle (Fig. 1), reflectivity data were collected at two intermediate fields, 178 and 18 G (points 4 and 5). At point 4, fits reveal that twisted spins in the pinned CoFe layer span an angular range of 65°. The portion of the CoFe layer closest to the AFM-FM interface reorients antiparallel to the field, whereas the portion furthest from this interface is canted relative to the field. At point 5 (18 G), near-antiparallel alignment of the CoFe and CoFe/NiFe layers has been achieved once more (Fig. 2). These reflectivity results suggest that the section of the CoFe layer closest to the IrMn layer initially reverses back to the pinning direction upon reducing the field from saturation. The remainder of the layer then reverses more gradually via coherent rotation over a field range of approximately 150 G, giving rise to the rounded feature in the MR (Fig. 1). However, PNR fits indicate that the magnetic moment of the pinned CoFe layer is reduced by 10%–25% relative to the saturation value, suggesting the presence of in-plane domains.

Data collected during the upward sweep of the second hysteresis cycle provides insight into the training effect (Fig. 1). SF scattering is exhibited at 440, 1050, and 1550 G (points 8-10) and suggests that canted moments or spin twists exist within the FM layers. Fits to the data reveal that the CoFe/NiFe free layer is aligned parallel to the field, as

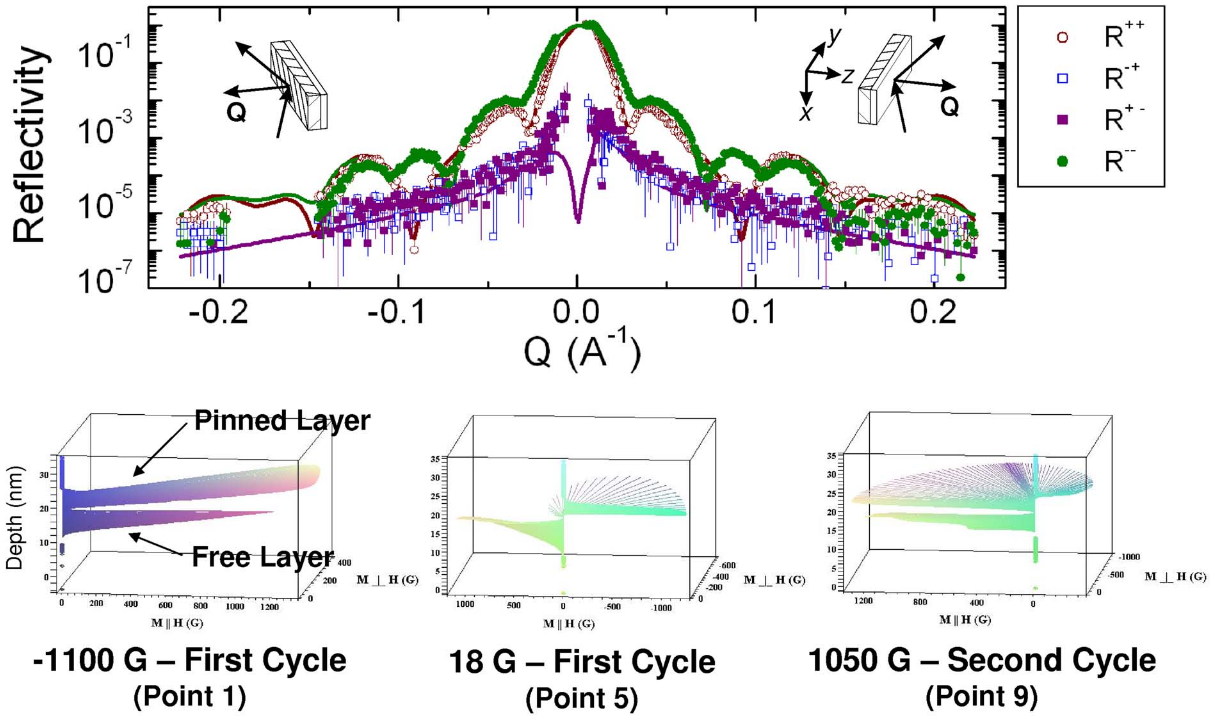


FIG. 2. (Color online) Top shows back/front polarized neutron reflectivity for the CoFe-based SV in 1050 G (point 9) at 20 K during the second field cycle. The lines correspond to fits. Insets show the scattering of the neutrons from the surface (right) and substrate (left). Bottom shows magnetization as a function of depth obtained from fits to the reflectivity data at the designated fields. The substrate/Ta interface corresponds to a depth of 10 nm.

expected, but a spin twist is present in the pinned CoFe layer with an angular span of up to 90°. The region of the CoFe layer nearest the AFM interface remains antiparallel to the field as before, while the region furthest from this interface is canted relative to the field. The extent of the spiral is greatest in 1050 G (Fig. 2), but the magnetic moment of the pinned CoFe layer near the CoFe/Cu interface is reduced, suggestive of in-plane domains. The span of the spiral decreases to 22° in 1550 G, consistent with the decreased resistance of this state. In the second upward sweep of the hysteresis loop, the spiral thus persists over a range of more than 600 G, indicating that the exchange anisotropy at the AFM-FM interface is not able to dictate the spin position of the entire FM layer.

The evolution of the magnetic structure of the SV is summarized at the bottom of Fig. 2, which shows plots of the depth dependence of the magnetization obtained from fits to the neutron reflectivity at three representative fields. This figure illustrates parallel alignment of the CoFe and CoFe/NiFe layers in saturation (point 1 in Fig. 1), antiparallel alignment as observed at 270 G and 18 G (point 5), and a spiral structure in the CoFe layer at the intermediate field of 1050 G (point 9). Small reductions in the magnetization are also evident for some of the intermediate fields, suggesting possible in-plane domain formation. Contrary to previous reports,[3] fits to the data do not require a net moment on the AF IrMn. However, the PNR measurement for our sample geometry is not sensitive to AF moments smaller than 10% of the CoFe moment.

Overall, PNR measurements of our CoFe-based SV can be explained in terms of weakened pinning of the FM layer from training. After field cooling, the first maximum in resistivity upon increasing the field arises from a simple antiparallel alignment of the free and pinned FM layers. After applying a saturating field opposite the pinning direction, a spiral domain wall develops in the pinned FM layer during subsequent reversal of its magnetization. While previous studies[3] discount the possibility of parallel domain-wall formation in exchange-biased layers, analogous spirals have been observed in systems with exchange-coupled layers.[4–6] In our case, the observed spiral in the pinned ferromagnet may account for the decreased GMR and biasing field in the second field cycle. Our results thus have strong implications for the theory of the origin of exchange bias and training effects.

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