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Domain overlap in antiferromagnetically coupled [Co/Pt]/NiO/ [Co/Pt] multilayers

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Domain overlap in antiferromagnetically coupled [Co/Pt]/NiO/[Co/Pt] multilayers

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Antiferromagnetically coupled magnetic thin films with perpendicular anisotropy exhibit domain overlap regions originating from magnetostatic stray fields localized in the vicinity of the domain walls. Using high resolution magnetic force microscopy, the authors investigate these overlap regions in [Co/Pt]/NiO/[Co/Pt] multilayers with various strengths of the interlayer exchange coupling. They develop a simple model that provides a quantitative explanation of the formation of these regions and the relationship between the domain overlap width and the coupling strength. Their results are important for application of magnetic layered structures with perpendicular anisotropy in advanced magnetoresistive devices. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2388892]

Magnetic thin-film layered structures exhibiting perpendicular magnetic anisotropy are promising candidates for the design of spintronic devices.[1] They are expected to improve density, stability, and reliability of spin valves and magnetic tunnel junctions.[2] The increasing interest in the systems with perpendicular anisotropy raises questions on the role of interlayer interactions, both exchange[3] and magnetostatic.[4,5]

It is known that magnetostatic stray fields play an important role in nonuniformly magnetized films. The interlayer magnetostatic coupling is responsible for a progressive reduction of the remnant magnetization of a hard ferromagnetic layer by repeated switching of a neighboring soft layer.[6] Even under moderate fields, mirrored domains may be formed in the hard and soft layers due to stray fields.[7] The stray fields in one magnetic layer lowers the nucleation field in the other layer due to domain walls[8] and may produce a biquadratic coupling due to film roughness.[9] Understanding the role of magnetostatic interactions in magnetic layered structures with perpendicular anisotropy is critical for the development of advanced magnetoresistive devices and recording media.[5]

In this letter, we elucidate the effect of magnetostatic interactions on the domain structure in [Co/Pt]/NiO/[Co/Pt] multilayers with perpendicular magnetic anisotropy. It has previously been shown that these multilayers exhibit oscillatory interlayer exchange coupling[3] (IEC) which occurs domain by domain[10] and is mediated by the canting of Ni spins in the NiO layer.[11,12] For antiferromagnetically (AFM) coupled samples it was found that there is a relative shift between the domains of the two magnetic layers originating from a competition between the magnetostatic interaction and the AFM IEC.[12] A similar behavior was also observed in [Co/Pt] multilayers separated either by Pt[4] or by Ru[5] layers. Here using high resolution magnetic force microscopy (MFM), we perform a detailed study of the domain overlap in [Co/Pt]/NiO/[Co/Pt] multilayers with various strengths of the IEC. We develop a simple model that explains the formation of these regions and predicts the relationship between the overlap width, the magnetization and thickness of the [Co/Pt] layers, and the magnitude of the IEC. Since this phenomenon is general for layered structures with perpendicular anisotropy, our results are important for application of these systems in industry.

Samples were sputtered on Si substrates from separate Pt, Co, and NiO targets and consisted of $\mathrm{Si}\langle 111\rangle/\mathrm{Pt}(100\ \text{Å})/[\mathrm{Pt}(6\ \text{Å})/\mathrm{Co}(4\ \text{Å})]_3/\mathrm{NiO}(t_{\mathrm{NiO}}\ \text{Å})/[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(6\ \text{Å})]_3/\mathrm{Cu}(20\ \text{Å})$, where t_{NiO} ranged from 7.5 to 12 Å. Details on sample growth and structure have been published.[3,10,12] These samples have shown the oscillatory IEC previously described.

The MFM images (Fig. 1) were made on virgin samples with different NiO thicknesses, corresponding to varying coupling strengths, in tapping/lift mode at a lift height of 5 nm under ambient conditions. The NiO thickness and the corresponding IEC strength J_{IEC} are both indicated on the individual figure panels. Note that positive (negative) J_{IEC} correspond to AFM (FM) coupling. The MFM tip, made by coating a 30 nm thick CoPt film on a cantilever, consists of a

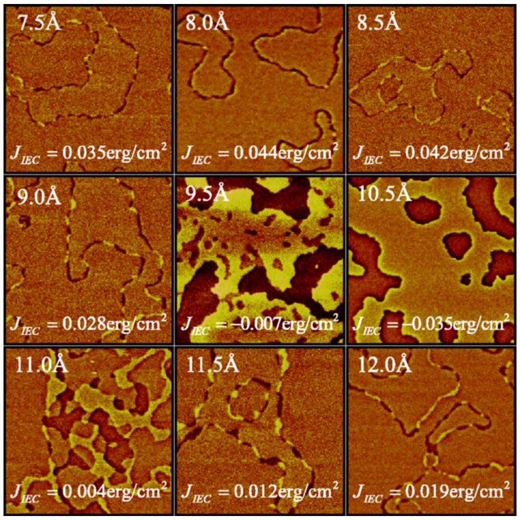

FIG. 1. (Color online) MFM images of coupled Co/Pt multilayers, with different thicknesses of the NiO interlayer corresponding to the IEC values listed. In the images, light colored areas indicate a magnetization out of the page. Each image is $5\times 5\ \mu\mathrm{m}^2$ in size.

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small magnetic CoPt particle (~30 nm) with a coercivity of about 15 kOe.[13] The MFM tips were magnetized so that the magnetization of the tip is perpendicular to the sample surface, pointing downward.

MFM measures the net magnetization through the depth of the sample, including both the top and bottom Co/Pt multilayers. There is a striking contrast between the FM and the AFM coupled samples. In FM coupled samples, the domain-by-domain coupling implies that an up (down) domain in the upper Co/Pt layer is in perfect alignment with an up (down) domain in the lower Co/Pt layer, leading to a net upward (downward) magnetization. In AFM coupled samples, an up (down) domain in the upper Co/Pt layer is in alignment with a down (up) domain in the lower Co/Pt layer, leading to a zero net magnetization. Hence in AFM coupled samples, the only contrast is seen in the regions of the domain walls where the magnetization changes from up to down, whereas in FM coupled samples, up and down domains are clearly visible. The rest of this work is devoted to the investigation of the domain wall regions in the AFM coupled samples.

Careful inspection of the images of AFM coupled samples reveals that rather than perfect alignment of domains, there is a slight shift between the domains in the upper and lower Co/Pt layers. The domain wall region possesses a net magnetic moment and is wider (>130 nm) than the expected domain wall width in these films (14–22 nm). This domain overlap region varies in width with J_{IEC}. Along the length of this overlap region, the magnetization switches from up to down. This is most clearly seen in the weaker coupled samples.

In order to investigate the width of the domain overlap region, regions that were fairly straight over a length scale of hundreds of nanometers were chosen. A representative set is shown in Fig. 2. Line scans were taken perpendicular to the length of these regions and averaged along the length to improve statistics. The final data were obtained from three different overlap regions for each thickness of NiO. The black boxes in Fig. 2 indicate one of the regions over which the width was averaged and the red lines indicate the average domain overlap width, obtained from the full width at half maximum (FWHM) of the line scans. Note that only regions where the magnetization was pointing downward (dark contrast) were analyzed to ensure uniformity in data across all domains of various samples of varying NiO thickness.

The origin of the overlap between antiparallel-aligned magnetic domains is the magnetostatic interaction. Magnetic stray fields which are produced by domains favor parallel alignment of the magnetic moments, competing with AFM IEC which aligns the magnetic moments antiparallel. For most samples, the IEC dominates the magnetostatic interaction and, if the magnetostatic coupling was homogeneous, the domains would align perfectly antiparallel with no overlap. The magnetostatic coupling, however, is strongly *inhomogeneous* over the surface due to the stray fields localized in the vicinity of the domain walls. This makes it energetically favorable to produce a shift δ between the antiparallel-aligned domains to reduce the magnetostatic energy which has the highest density in the vicinity of the domain walls.

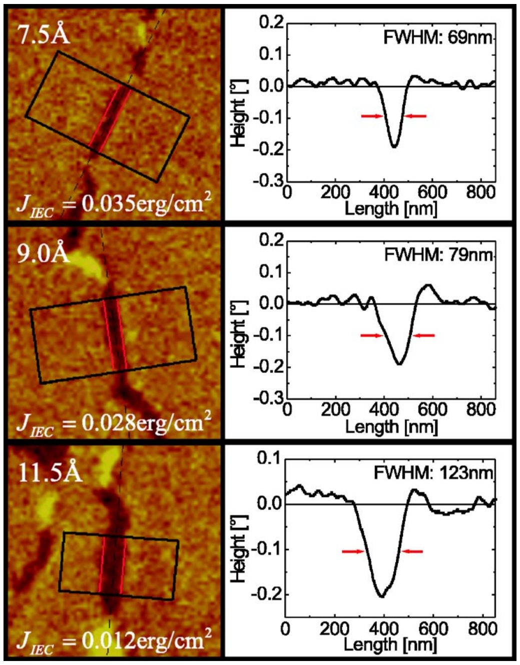

FIG. 2. (Color online) Representative line scans for the samples with NiO thicknesses of 7.5, 9, and 11.5 Å. The left panels show the region where the lines scans were performed, the black box indicates the region used for averaging and the red lines indicate the average domain overlap width. Each image is 1.25 × 1.25 μm^2 in size. The right panel shows the corresponding lines scans, averaged over the region enclosed in the black box. The y-axis indicates the MFM tip response. The red arrows indicate the location of the red lines in the left panel and represent the FWHM of the features.

The energetics of the domain overlap can be described as follows. Assuming an abrupt domain wall at $x=0$ separating two semi-infinite domains lying in the x-y plane, as shown in Fig. 3, we find that the x and z components of the field produced by the bottom Co/Pt film are

$$H_x(x,z) = 2M_{\mathrm{bot}} \ln\left(\frac{x^2+(z-t)^2}{x^2+z^2}\right), \tag{1}$$

$$H_z(x,z) = 4M_{\mathrm{bot}}\left(\arctan\left(\frac{z}{x}\right) - \arctan\left(\frac{z-t}{x}\right)\right), \tag{2}$$

where z is the distance above the film, t is the film thickness, and M_{bot} is the saturation magnetization of the bottom film. A similar field is produced by the upper Co/Pt film (separated by a spacer of thickness d from the bottom film) with a domain wall at $x=\delta$ and magnetization M_{top}. For perfectly antiparallel-aligned domains with no overlap ($\delta=0$), the magnetostatic energy density $U=H^2/8\pi$ is very large near the domain walls, as is evident from Fig. 3(a). The separation of the domain wall of the top and bottom films leads to a significant reduction in the magnetostatic energy, as seen

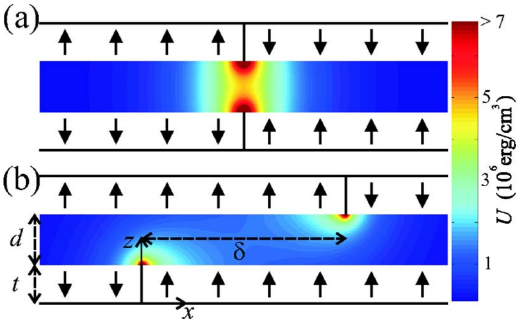

FIG. 3. (Color online) Magnetostatic energy density for antiparallel-aligned domains with no overlap (a) and with overlap δ (b) for t=3 nm, d=1 nm, and δ=4 nm.

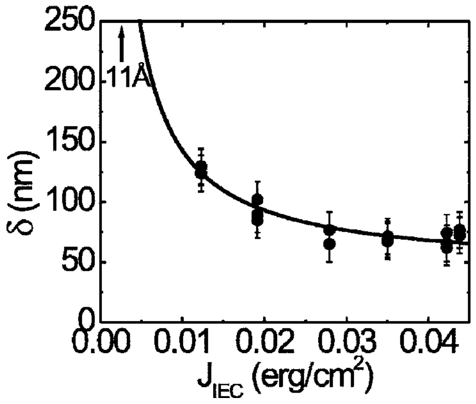

FIG. 4. Domain overlap width as a function of the coupling strength. Closed circles give the compiled line scan data for all samples. 15 nm error bars account for MFM resolution. The solid line indicates the best fit to Eq. (2). The fit parameters are discussed in the text. The arrow corresponds to the coupling strength for the 11 Å sample.

from the energy density plot shown in Fig. 3(b), even for a very small $\delta=4$ nm.

The reduction in the magnetostatic energy with increasing δ competes with the increase in the interlayer exchange energy per unit length, $J_{\mathrm{IEC}}\delta$. The total energy per unit length $E(\delta)$ relative to $\delta=0$ is

$$E(\delta)-E(0)=-2M_{\mathrm{top}}\int_{t+d}^{2t+d}\int_{0}^{\delta}H_z(x,z)dxdz+J_{\mathrm{IEC}}\delta. \quad (3)$$

To find the equilibrium overlap we minimize this energy with respect to δ which leads to

$$\frac{\partial E}{\partial \delta}=-2M_{\mathrm{top}}\int_{t+d}^{2t+d}H_z(\delta,z)dz+J_{\mathrm{IEC}}=0. \quad (4)$$

For $\delta \gg d$, as appears to be the case in Fig. 2, the magnetostatic field (2) is reduced to $H_z(\delta,z)\simeq 4M_{\mathrm{bot}}t/\delta$, so that Eq. (4) results in a finite overlap given by

$$\delta=\frac{8M_{\mathrm{top}}M_{\mathrm{bot}}t^2}{J_{\mathrm{IEC}}}. \quad (5)$$

Thus the domain overlap width is inversely proportional to the magnitude of AFM coupling.

This result is consistent with our experimental data. Figure 4 shows the average domain overlap width δ obtained from the MFM lines scans in three different regions as a function of J_{IEC}. Previous MFM experiments using similar tips under similar conditions indicate a spatial resolution of 15 nm;[14] hence we include error bars of ±15 nm. A best fit to the data gives

$$\delta=\frac{a}{J_{\mathrm{IEC}}}+b, \quad (6)$$

where $a=(1.0\pm0.1)\times10^{-7}$ erg/cm and $b=(43.5\pm3.7)\times10^{-7}$ cm. From Eq. (5), a is a measure of the magnetization of the Co/Pt multilayer. Assuming a Co thickness t of 1.2 nm for each layer and assuming an $M_{\mathrm{top}}=1.43M_{\mathrm{bot}}$ ratio (from magneto-optic Kerr effect, superconducting quantum interference device (SQUID), and alternating-gradient force magnetometer measurements[12]), we obtain $M_{\mathrm{top}}=1109.7\ \mathrm{emu/cm}^3$ and $M_{\mathrm{bot}}=776.0\ \mathrm{emu/cm}^3$, in excellent agreement with previous SQUID measurements that give values of $M_{\mathrm{top}}=1087.7$ and $M_{\mathrm{bot}}=760.6\ \mathrm{emu/cm}^3$. This is well within the range of previous measurements on Co/Pt multilayers, which have shown M_s values ranging from 600 to 2300 emu/cm^3.[15] The offset of 43 nm is explained from a combination of the finite thickness of domain walls (an effect that is ignored in the model which assumes abrupt transitions between domains) and the resolution of the MFM tip. A convolution of a Gaussian stray field with a FWHM of 15 nm (from the MFM tip) with a domain wall of 20 nm increases the width for each of the overlap features by 25–30 nm, nearly accounting for our offset within error bars. For the weakest coupled sample ($t_{\mathrm{NiO}}=11$ Å), there is a wide variation in the width of the overlap region. From the fit, we obtain an overlap width of 300 nm (as indicated in Fig. 4 by the arrow), which agrees reasonably well with that in Fig. 1.

In conclusion, we have shown that magnetic thin films with perpendicular anisotropy exhibiting AFM exchange coupling have domain overlap regions which can be quantitatively described by consideration of the stray fields that arise due to the domain walls, leading to a $1/J_{\mathrm{IEC}}$ dependence of the domain overlap width. Our results are important for application of magnetic layered structures with perpendicular anisotropy in advanced magnetoresistive devices.

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