# Domain-Wall Induced Coupling between Ferromagnetic Layers

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The remanent magnetization of a hard ferromagnetic CoPtCr layer is progressively decreased by repeated switching of a neighboring soft magnetic layer. We show that this effect depends strongly on the thickness of the CoPtCr layer and the spacing between the hard and soft layers. We propose a model that accounts for these results: An interlayer magnetostatic coupling is induced by large stray fields from domain walls that form within the soft layer during its magnetization reversal.

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Since the discovery of giant magnetoresistance in magnetic multilayers [1] and the emergence of magnetoelectronic devices, the study of indirect coupling between magnetic layers through a nonmagnetic spacer material has become an especially important issue. For metallic spacer layers, oscillatory interlayer exchange coupling has been observed experimentally for a wide range of materials [2] and addressed theoretically ([3], and references therein). For insulating spacer materials, a weak interlayer exchange interaction has been reported for only a few special cases [4]. However, in general, for both metallic and insulating spacers, magnetic layers may be coupled through magnetostatic interactions.

In this Letter, we address the influence of an unusual magnetostatic coupling, associated with the presence of domain walls (DW), on the stability of magnetic tunnel junctions (MTJ). The simplest structure of a MTJ involves two ferromagnetic (FM) layers separated by a thin insulating barrier. Depending on the relative orientation of the magnetization of the two FM layers, the tunneling probability of the electrons is either high (parallel orientation) or low (antiparallel orientation). This gives rise to low or high resistance values, respectively. In order to obtain magnetically stable MTJs, the magnetization of one FM layer must remain unchanged when the moment of the second layer is changed. This can be achieved by using a high coercivity or "hard" FM material.

The predominant interactions between the magnetic layers of a MTJ are magnetostatic, assuming the tunnel barrier is pinhole free. For devices of submicron lateral dimensions, the stray fields at the edges of the device give rise to significant coupling [5]. Roughness of the FM/spacer interfaces also results in magnetostatic coupling [6]. In the case of uniformly magnetized films, only these two mechanisms are present. However, nonuniform magnetization distribution in one of the layers (such as a domain wall or a vortex) also induces local stray fields which could give rise to a coupling between the layers. Indeed, the effect of stray fields from a domain wall in one FM film lowering the nucleation field in a second film was noted much earlier [7].

In a previous study of MTJs [8] it was found that repeated switching of the soft layer's magnetization by field cycling could demagnetize the hard magnetic layer, even though the cycling field was much too small to have any direct effect. This phenomenon was not observed if the magnetization was reversed in a rotating field, suggesting an important role of domain walls nucleated in the soft layer during its switching. Here we show, first, that this phenomenon is observed in magnetic trilayers with either metallic or insulating spacer layers, and second, that the stability of the hard layer is sensitive, in particular, to the thickness of the hard layer, and to the spacing between these magnetic layers. These results can be explained by a model in which stray fields are generated by Néel-like domain walls sweeping through the free layer during reversal of its moment.

Magnetic trilayers, comprised of a hard magnetic layer of CoPtCr ($Co_{75}Pt_{12}Cr_{13}$), a nonmagnetic spacer, and a soft layer of Co or FeNi ($Fe_{60}Ni_{40}$) were grown by dc magnetron sputtering in $10^{-3}$ Torr Ar on $Si/SiO_2$ wafers [8]. These latter FM materials were chosen because they have similar saturation magnetization values, while their anisotropy and exchange stiffness are significantly different. The spacer was either made of Al or $Al_2O_3$ (obtained by plasma oxidation of an Al layer). In all cases, the spacer was thick enough to avoid the possibility of electronic coupling and/or direct coupling through pinholes. Since the $Al_2O_3$ thickness is not precisely known, the spacer thickness is always given as the Al thickness (actual alumina thickness is about 30% larger than this nominal value).

The hysteresis loop of a typical sample is shown in the inset of Fig. 1. The hard CoPtCr and soft Co layers have very different switching fields, namely about 1.5 kOe and <100 Oe, respectively. Thus, by cycling the applied field through about $\pm 200$ Oe, the magnetization of the Co layer can be switched back and forth, but these fields are too small to themselves modify the magnetic state of the hard layer. However, as shown in Fig. 1, and as previously found for similar MTJ structures [8], the remanent magnetization of the hard layer decreases progressively with increasing numbers of cycles of the soft layer moment. The demagnetization curve is well described (see Fig. 1)

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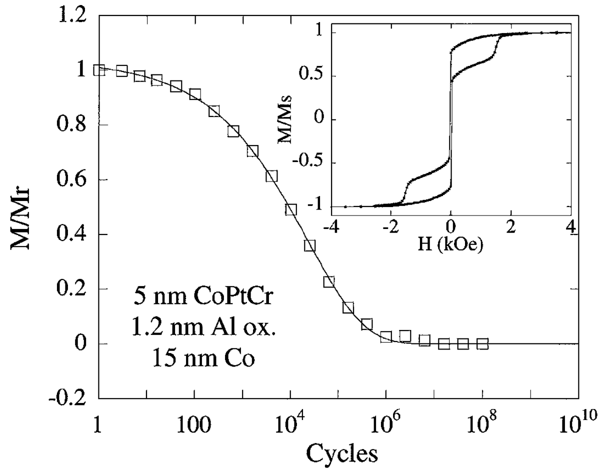


FIG. 1. Remanent magnetization of the hard CoPtCr layer in a CoPtCr/$Al_2O_3$/Co trilayer as a function of the number of times the free layer moment is cycled in a field of $\pm 200$ Oe. The curve through the data is a fit to a stretched exponential law. The inset shows the hysteresis loop of a typical trilayer.

by a stretched exponential law, $M/M_r = \exp[-(N/N_0)^{\beta}]$, where $M_r$ is the initial remanent magnetization and $N_0$ is a characteristic number of cycles and the exponent $\beta$ ranges between 0.2 and 0.4. Interestingly, this variation is typical of the slow relaxation of disordered systems such as spin glasses [9]. It has also been found recently to describe the creep of domain walls in a perpendicularly magnetized Co film [10].

The decay rate depends strongly on the thicknesses of the hard FM layer and the spacer layer. This decay may be characterized by the parameter $N_{1/2}$, defined such that $M = \frac{1}{2} M_r$. Figure 2(a) shows that $N_{1/2}$ increases exponentially with the thickness of CoPtCr for free layers of both Co and FeNi. Indeed, increasing the thickness of the hard layer from 5 to 40 nm improves its stability by $\sim$6 orders of magnitude. The variation is greater for free layers of FeNi than for Co. A similar exponential dependence of $N_{1/2}$ on the Al spacer thickness is also found as shown in Fig. 2(b).

Magnetic stray fields from a DW can be calculated from the gradient of the magnetic potential $\psi(\vec{r})$. For the thin Co films considered here, domain walls are likely to be of the Néel type in which the magnetization rotates within the plane of the film. Thus, there is no surface charge and $\psi(\vec{r})$ depends only on the divergence of the magnetization $\vec{M}(\vec{r})$ [11]. Following the model of Dietze and Thomas described in [12], we consider a linear domain wall with a single segment, which is infinitely long in the $y$ direction. The magnetization varies only along the $x$ direction perpendicular to the wall (see the inset to Fig. 3 for a schematic view of the geometry used in the model) and the only contribution to the magnetic potential is given by the component $M_x$ perpendicular to the DW. $M_x$ is approximated by a Lorentzian curve, $M_x(x)/M_s = q^2/(x^2 + q^2)$, where $q$ is a wall width parameter and $M_S$ is the saturation magnetization. The DW width parameter $q$ is calculated by minimizing the total energy including exchange, anisotropy, and magnetostatic terms [12]. For cobalt, the saturation magnetization $M_S = 1414$ emu/cm$^3$, the anisotropy constant $K = 4.0 \times 10^6$ ergs/cm$^3$, and the exchange stiffness $A = 1.55 \times 10^{-6}$ ergs/cm. For a film thickness of 15 nm, the DW parameter is $q = 6.7$ nm. This width is thickness dependent, and it increases with the film's

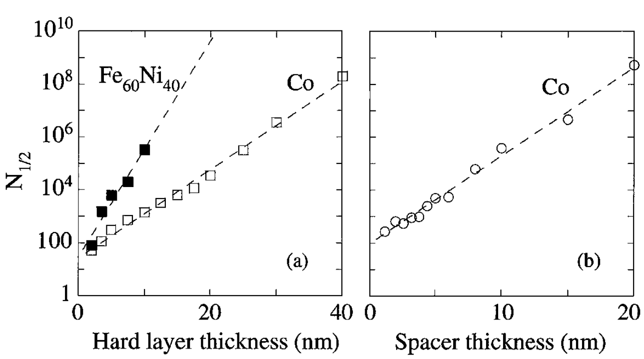


FIG. 2. Stability of the CoPtCr layer in a CoPtCr/spacer/FM trilayer as a function of (a) the CoPtCr thickness for samples with 1.2 nm thick $Al_2O_3$ spacer layers and (b) the Al spacer layer thickness for samples with 5 nm thick CoPtCr layers. The free layer is 15 nm thick in all cases. Dashed lines are fits to an exponential law.

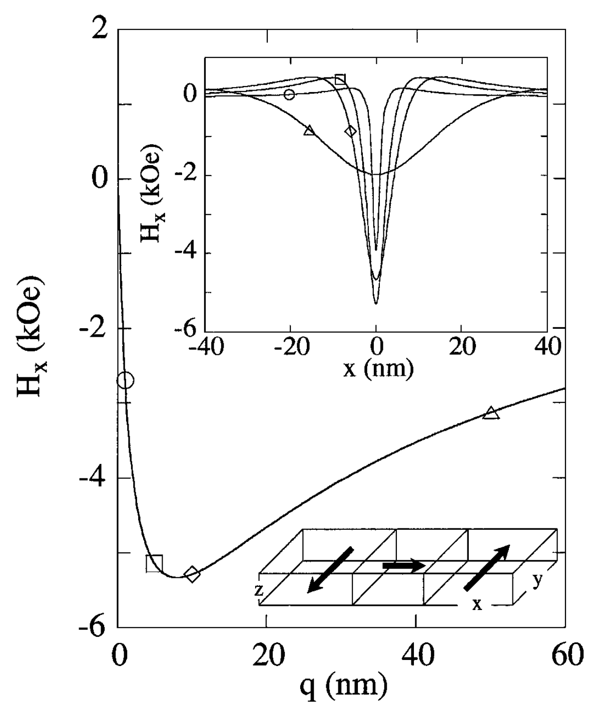


FIG. 3. Dependence of the maximum in-plane domain-wall stray field as a function of the wall-width parameter $q$. The top inset shows the variation in the direction perpendicular to the wall, for different values of $q$: $q = 1$ (○), 5 (□), 10 (◇), and 50 nm (△). The bottom inset shows a cartoon of the geometry used in the calculations.

thickness. Note that even though the Co films are polycrystalline, their grain size is larger than the DW width, so that bulk anisotropy and exchange constants used in these calculations are a reasonable approximation.

For a Néel wall with a single segment, the stray field has only two components, $H_x$ (in-plane perpendicular to the DW) and $H_z$ (out of plane). However, for the thin film geometry considered here, the magnetization lies in-plane due to the shape anisotropy so that out-of-plane fields should be less important. Thus we consider only the in-plane component here. The stray fields reach high values; $H_x$ is as large as 6 kOe at the surface of the film. Although $H_x$ decreases rapidly with increasing height above the film, it is still about 1 kOe as far as 20 nm above the DW. The stray fields are very sensitive to the DW width as shown in Fig. 3 for stray fields calculated 1 nm above the surface of a 15 nm thick film with $M_S = 1414\ \mathrm{emu/cm^3}$. $H_x$ increases with wall width to a maximum for $q \sim 7$ nm, and then decreases slowly for broader walls. The inset to Fig. 3 shows how $H_x$ decreases in the direction perpendicular to the wall, for different values of the wall width parameter ($q = 1$, 5, 10, and 20 nm). Note that the DW stray field strength is proportional to the saturation magnetization of the FM layer, and, for a given wall width, the field increases as a function of the thickness of the film.

It should be emphasized that this model is probably too simple to account for the details of the local demagnetization processes in the CoPtCr film. For example, the DW structure is likely much more complex than the simple Néel wall considered above. However, this model does give a good description of the main features of the demagnetization mechanism. The magnitudes of the DW stray fields calculated above are much larger than the coercive fields of the CoPtCr layers, thus confirming the proposal that they may be important with regard to the demagnetization of the CoPtCr layer on cycling the soft layer moment. Moreover, the stray fields are found to decrease rapidly with increasing distance from the DW. Thus, when the spacer thickness is increased, the average field acting on the hard layer will decrease so improving its stability as observed. The same explanation accounts for the improved stability of thicker hard layers. The model also accounts for the effect of different soft layers. In particular, although the saturation magnetization of $Fe_{60}Ni_{40}$ ($M_S = 1360\ \mathrm{ergs/cm^3}$) is only slightly smaller than that of Co its anisotropy is significantly smaller ($10^4\ \mathrm{ergs/cm^3}$). Depending on the exchange stiffness of FeNi, the calculated wall half-width $q$ ranges between ~30 and ~60 nm, much larger than that in Co. As shown in Fig. 3, the wall stray fields are thus reduced compared to that of Co, implying a greater stability for the hard layer as observed.

Quantitative comparison between the experimental results and the model requires the structure of the CoPtCr layer to be considered in more detail. Indeed, sputtered CoPtCr has a granular structure, with a grain size of about 10–20 nm [13], in which each grain behaves as a single magnetic domain. Thus, the DW stray fields acting on the CoPtCr layer must be averaged over the volume of these grains. As an approximation we consider an effective DW field $H_{DW}$ by averaging over a prismatic volume 20 nm wide and as thick as the CoPtCr layer (averaging over 10 nm grain size leads to similar conclusions). Since the stray fields decrease over a length scale comparable to the wall width (see Fig. 3), $H_{DW}$ is significantly reduced compared to the maximum value reached locally. In Fig. 4, $H_{DW}$ is calculated for the parameters corresponding to the two sets of samples shown in Fig. 2 with Co free layers. The $x$ axis represents either the hard layer (□) or the spacer layer thickness (○). $H_{DW}$ ranges between 0.6 and 3.7 kOe. These values are only about 60% of the maximum local field calculated for the same set of parameters, because of the averaging over the grain size.

It is interesting to plot the stability parameter $N_{1/2}$ as a function of a reduced field, $H_{DW}/H_c$, the ratio of the effective field acting on the hard layer magnetic grains scaled by the coercive field of the hard layer $H_c$, as shown in the inset to Fig. 4. The data for both sets of samples of Fig. 2 with Co free layers rescale to a single master curve. Moreover, the master curve exhibits two asymptotic regimes, with a crossover at $H_{DW} \sim H_c$. For $H_{DW} > H_c$, $N_{1/2}$ depends weakly on $H_{DW}$. On the contrary, when $H_{DW} < H_c$, $N_{1/2}$ has a much stronger dependence on $H_{DW}$. This behavior reflects the magnetic properties of the CoPtCr layer. Note that the CoPtCr moment switches over a broad field range

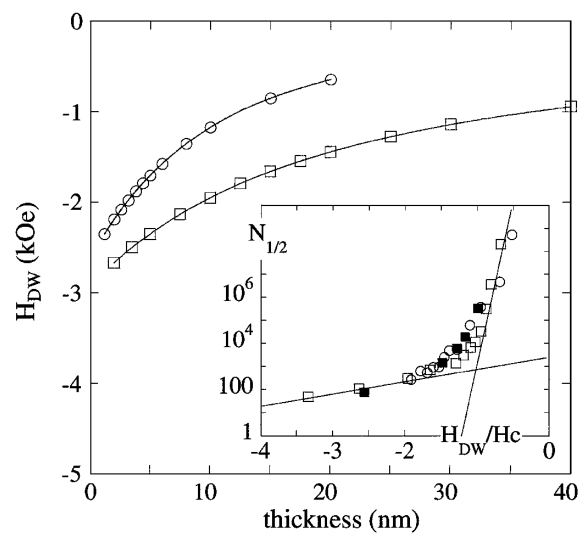


FIG. 4. Calculated effective domain wall stray fields averaged over the volume of a typical grain within the CoPtCr layer in CoPtCr/Al or $Al_2O_3$/Co trilayers corresponding to the samples of Fig. 2 plotted versus CoPtCr thickness (□) or the $Al_2O_3$ layer thickness (○). The inset is a plot of the stability parameter $N_{1/2}$ as a function of the reduced domain wall stray field $H_{DW}/\mathrm{Hc}$ for all three sets of samples of Fig. 2 (■ corresponds to samples with FeNi free layers). Note that the sign of $H_{DW}$ depends on the chirality of the DW.

(see, for example, the inset to Fig. 1) and $H_c$ reflects only the average switching field of the granular film. Thus,when $H_{DW} > H_c$, most of the grains may be switched directly by the stray field of the DWs sweeping in the soft layer. Even if $H_{DW}$ is increased further, the overall demagnetization rate is not expected to change very much. On the contrary, when $H_{DW} < H_c$, only a small fraction of the grains can be switched directly by the DW fields. The reversal of the main part of the sample may occur only when $H_{DW}$ is aided by magnetostatic interactions within the hard layer. Thus, the stability strongly increases when $H_{DW}$ decreases, as the fraction of grains which switches directly is reduced. This picture is supported by micromagnetic simulations [14] and magnetic microscopy studies [15], which suggest a demagnetization scheme in two stages. Reversed clusters of grains are nucleated during the first few cycles. Then these clusters slowly grow when the number of field cycles increases. A similar mechanism has also been reported in a single CoPtCr layer under the perturbation of a MFM tip [16].

In principle, the set of data obtained for the FeNi free layer in Fig. 2 should also scale onto the master curve. However, $H_{DW}$ depends strongly on the DW width. While both sets of samples with Co free layers have similar DW widths, the DW width of FeNi is different and is not known precisely. Thus we have chosen to use it as a parameter, so as to rescale this third set of data onto the master curve (Fig. 4, inset). A good scaling is found for $q \sim 55$ nm, which is a reasonable value for this material as discussed above.

Finally, we address another interesting experimental feature of these hard/soft trilayers, namely a slight increase of the coercive field of the free layer which is observed as the hard layer is progressively demagnetized. For both Co and FeNi free layers, the coercive field increases by about 10% from ~54 to 60 Oe. This may be connected to the reciprocal effect of the stray fields from the domain walls present in the hard layer once it is demagnetized. These fields are much smaller than those calculated above from the DWs in the free layer because of the lower $M_s$ and narrower DWs of CoPtCr. Moreover, they must be randomly oriented, since the magnetization of the CoPtCr grains point in all directions in the demagnetized state. We propose that this effect may be accounted for within the framework of a random field acting on the free layer, in analogy to that proposed by Zhang *et al.* to account for the increased coercivity of exchange biased FM layers [17]. The external field needed to move domain walls in the free layer must be increased to overcome statistical fluctuations of the local stray fields from the CoPtCr DWs.

In summary, a simple model is developed to provide for a quantitative mechanism of the demagnetization of a hard ferromagnetic layer induced by cycling the moment of a neighboring soft ferromagnetic layer. It is shown that domain walls sweeping through the soft layer during its reversal generate stray fields which may locally reach an intensity as high as a few kOe. These fields progressively demagnetize the hard layer. The dependence of the rate of demagnetization on the thickness of the hard and soft layers and the separation of these layers can be well described within this model using reasonable magnetic parameters for the ferromagnetic layers.

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[1] M. N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988); G. Binasch, P. Grunberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989); S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).
[2] S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).
[3] P. Bruno, Phys. Rev. B **52**, 411 (1995).
[4] S. Toscano, B. Briner, and M. Landolt, in *Magnetism and Structure of Systems in Reduced Dimensions*, edited by R. Farrow *et al.*, NATO ASI, Ser. B, Vol 309 (Plenum, New York, 1993), p. 257.
[5] Y. Lu, *et al.*, Appl. Phys. Lett. **70**, 2610 (1997); K. S. Moon, R. E. Fontana, and S. S. P. Parkin, Appl. Phys. Lett. **74**, 3690 (1999).
[6] L. Néel, C. R. Acad. Sci. **255**, 1676 (1962); S. Demokritov *et al.*, Phys. Rev. B **49**, 720 (1994).
[7] H. W. Fuller and D. L. Sullivan, J. Appl. Phys. **33**, 1063 (1962).
[8] S. Gider, B.-U. Runge, A. C. Marley, and S. S. P. Parkin, Science **281**, 797 (1998).
[9] J. J. Prejean and J. Souletie, J. Phys. (Paris) **41**, 1335 (1980).
[10] S. Lemerle *et al.*, Phys. Rev. Lett. **80**, 849 (1998).
[11] A. H. Morris, in *The Physical Principles of Magnetism* (John Wiley and Sons, New York, 1965), p. 9.
[12] A. Aharoni, in *Introduction to the Theory of Ferromagnetism* (Clarendon Press, Oxford, 1996), p. 157.
[13] Q. Peng *et al.*, IEEE Trans. Magn. **31**, 2821 (1995).
[14] M. Scheinfein (private communication).
[15] A study of the demagnetization process in the CoPtCr is in progress using photoemission electron microscopy, and will be published elsewhere.
[16] B. Walsh, S. Austvold, and R. Proksch, J. Appl. Phys. **84**, 5709 (1998).
[17] S. Zhang *et al.*, J. Magn. Magn. Mater. **198–199**, 468 (1999).