Magnetoresistance in a Constricted Domain Wall

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We show that a thin Gd layer inserted between two thicker layers of permalloy contains an in-plane domain wall whose width can be controlled by varying the thickness of the Gd layer. The magnetoresistance of this structure has been measured with the current perpendicular to the plane, thus eliminating spurious contributions which have complicated previous measurements. This is the first measurement to show unambiguously that the domain wall contributes an additional resistance whose magnitude is in good agreement with theory.

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The magnetoresistance (MR) due to domain walls (DW) has been a subject of considerable research in recent years. A DW is an interface between two, quite often, antiparallel domains. In principle, if the DW is as narrow as the interface region in a GMR material [1], we should be able to observe GMR caused by the presence of the DW. An experimental measurement of this effect is complicated for a number of reasons.

First of all, it is not easy to configure a system with a large number of thin DW in order to generate a measurable signal. The most popular material is Co, because of its high crystalline anisotropy and narrow DWs of the order of 15 nm. The ultrahigh anisotropy material $SrRuO_3$ has also been used [2].

Second, even in materials where the DW is naturally narrow, there are other sources of MR that can obscure the intrinsic contribution of the DW. Anisotropic MR (AMR), which depends on the angle of the magnetization to the current, is a common contribution in a transport measurement in a ferromagnetic material and can be as high as 1%–2%. To avoid AMR in a DW transport measurement we have to make sure that there are no closure domains and that the DW is perpendicular to the current. A number of lithographic shapes have been used by different authors to generate DW or rotation of the magnetization, for instance, crosses [3] or zigzags [4,5]. Xu *et al.* demonstrated [3] with a numerical calculation that the reported negative contribution of the DW to the resistivity could be caused by a misinterpreted AMR contribution.

Even for systems in which closure domains are avoided and the DW is perfectly perpendicular to the current, there are other sources of error arising from the Hall effect and Lorentz MR (movement of the electrons due to the Lorentz force within each domain). For more detailed information, the reader is referred to Kent *et al.* [6], who also describe another possible negative nonintrinsic contribution of the DW to the resistivity, arising from the "orbital motion" of the conduction electron around the DW (see Fig. 1 of that reference).

These parasitic contributions make it difficult to measure accurately the intrinsic contribution of DW to the resistivity. The confusion in the literature extends not only to the value of this contribution but also the sign. In fact, in recent years there have been similar numbers of reports claiming positive and negative contributions. Theoretical treatments also describe a positive contribution [7] based on the spin dependent scattering of the spin polarized current, a negative contribution [8] based on the loss of the weak localization of the electrons, and positive or negative contributions [9] depending on the relaxation times of spin-up and spin-down carriers.

In this Letter, we present measurements on a new configuration to determine the MR of a DW. The sample is a trilayer of permalloy-Gd-permalloy, and, under the conditions described below, the Gd holds an in-plane DW constricted to its thickness, so the width of the DW can be controlled. The current flows perpendicular to the plane, so we can avoid the contribution of closure domains, Lorentz MR, or orbital motion around the DW.

Rare earths have been used previously to generate a DW in the plane of the sample. Some studies use rare earth based compounds with different coercivities to achieve a springlike domain when the external field is removed [10,11]. Others use the fact that certain rare earths couple antiferromagnetically with transition metals [12]. In particular, Gd has been used to create an in-plane Zeeman DW (a DW whose dimensions depend on the external field) at Gd-Fe [13] and Gd-Co [14] interfaces.

Gd has its Curie temperature at 293 K. At low temperatures it is a strong ferromagnet, having a moment of $7.55\mu_B$ at 10 K. At Gd-transition metal interfaces, the Gd tends to align with the field because it has a higher moment. The transition metal at the interface aligns antiparallel with the field because of antiferromagnetic coupling with the Gd. Because the rest of the transition metal layer tries to align with the field, the result is an in-plane Zeeman DW whose energy is supplied by the external field. At higher temperatures, where the Gd is a weaker

ferromagnet than the transition metal, the DW is created in the Gd. This effect has been widely studied for both epitaxial films [14] and for sputtered samples [15] where some interdiffusion has been observed [16]. The antiferromagnetic coupling between the Gd and the transition metal is transmitted through a few atomic layers (for example, 1.2 nm for the Gd-Fe interface [17]) and competes with the Gd exchange interaction.

Our samples are sputtered permalloy $(Ni_{80}Fe_{20})_{100\,nm}$-$Gd_{t\,nm}$-permalloy$_{100\,nm}$, where the Gd has different thicknesses t from 2 to 20 nm. In this system at high temperatures, around or over the Curie temperature of Gd, the system behaves as permalloy (Py)-nonmagnet-Py, and the Py layers align antiparallel to each other to minimize the magnetostatic energy in zero external field. This can be clearly seen in Fig. 1. This figure shows the low field part of the hysteresis loop in one of these samples (2×2 mm^2). The first transition (A) before $H = 0$, corresponds to the switching of one of the Py layers. The flat part (B) is where the magnetostatic coupling keeps the Py layers in an antiparallel state, and the high permeability transition (C) corresponds to the switching of the other Py layer when the external field is strong enough to unbalance the magnetostatic coupling. This behavior occurs even for very thin Gd layers (2 nm). In-plane transport measurements confirm the antiparallel coupling of the Py layers for $H = 0$.

Bitter decoration on trilayer samples reveals no sign of DWs in the Py layers, confirming an antiparallel coupling between Py layers to minimize the magnetostatic energy. This can be seen in Fig. 2, where a sample of Py-(10×10) μm $\times$ 200 nm shows the normal closure domain structure, and by just inserting 4 nm of Gd, we can remove any sign of domain walls in the Py.

At intermediate temperatures, when the Gd is weakly ferromagnetic, the behavior of the Py-Gd-Py sample is expected to be very similar to the behavior shown in Fig. 1 at room temperature. In this configuration, when the Py layers are antiparallel to each other, the Gd will hold a DW in-plane as shown in Fig. 2(a). At lower temperatures, when the Gd has a higher magnetic moment than the Py, the magnetostatic flux configuration of the trilayer is different. The Py layers can then align parallel to each other and close their stray field through the antiparallel Gd layer, especially when it is thicker [Fig. 2(b)].

The behavior expected at intermediate temperatures is found for all samples. For instance, above $\sim$100 K, the sample with Gd-20 nm shows the "double loop" behavior of Fig. 1, while at lower temperatures, the hysteresis loop is smooth and does not show any particular jump. For thinner Gd layers, though, the double loop shape shown in Fig. 1 is retained to lower temperatures. For thin Gd (a few nanometers), the shape of the hysteresis loop remains like the one in Fig. 1 even at 77 K. An antiparallel configuration of the Py layers at 77 K, when the Gd is ferromagnetic, necessarily implies the existence of a domain boundary within the Gd, as shown in Fig. 2(a),

We may calculate the energy of the in-plane DW taking into account the nonlocality of the antiferromagnetic coupling. Following Koehler *et al.* [18], we let the antiferromagnetic interaction decay exponentially with z distance from the interface: $J_{\text{Gd-Py}} \exp[-z/\lambda]$, where $J_{\text{Gd-Py}}$ is the antiferromagnetic exchange interaction and λ the propagation distance of this interaction. If the 180° rotation of the in-plane DW occurs within the thickness t of the Gd, a standard calculation [19] of the energy per unit of area of the DW (neglecting the low anisotropy energy in Gd) at $H_{\text{ext}} = 0$ is

$$E = \frac{J_{\text{Gd}} S_{\text{Gd}}^2 \pi^2}{at} - J_{\text{Gd-Py}} S_{\text{Gd}} S_{\text{Py}} \frac{4\lambda t^2 (1 + e^{-t/\lambda})}{a^3(\lambda^2\pi^2 + t^2)}, \quad (1)$$

where a is the interatomic distance in Gd, S_X is the spin of each material, and J_{Gd} is the ferromagnetic exchange interaction between Gd atoms. Equation (1) shows how the antiferromagnetic coupling of the interface can decrease the energy of an in-plane DW in Gd through the

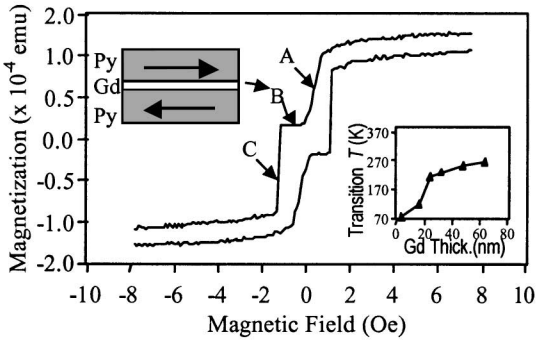

FIG. 1. Low field part of the hysteresis loop of a trilayer Py(100 nm)-Gd(25 nm)-Py(100 nm) at room temperature. The inset shows how the transition temperature from a "double loop" to a standard hysteresis loop decreases as the Gd thickness decreases. For a very thin Gd layer, the shape of the hysteresis loop, as it is shown in this figure, remains up to 77 K.

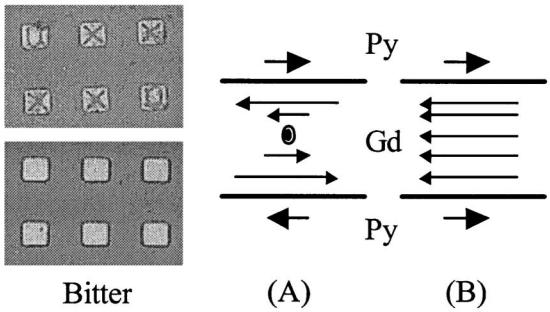

FIG. 2. Bitter pattern of (10×10) μm squares of Py-200 nm, showing the characteristic closure domain structure (top), and Py(100 nm)-Gd(4 nm)-Py(100 nm), showing no domain walls (bottom). The domain arrangement indicates how magnetostatic energy is minimized in different ways. (A),(B) Diagrams of possible configurations in the Gd layer.

second term in the expression. Because the antiferromagnetic coupling between the Gd and transition metals persists above the Curie temperature of Gd [20], we can assume $J_{\text{Gd-Py}} > J_{\text{Gd}}$. With that assumption, the second term in Eq. (1), for a thickness t of few nanometers and $\lambda \sim 1$ nm, could be comparable to the normal exchange energy term. The value of λ chosen is similar to that reported for Fe-Gd [18]. This value is reasonable because it makes the exponential antiferromagnetic coupling decay to zero in the distance of the mean free path of the electron in Gd (2.5 nm at 77 K). For thicker Gd, the second term in Eq. (1) goes to zero and no longer reduces the energy of the in-plane DW. Note that if J at the interface is very strong (for instance, $J_{\text{Gd-Co}} \sim 0.3 J_{\text{Co}}$ [21]), the Gd layer would prefer to be uniformly antiparallel to both transition metal layers [Fig. 2(b)].

We have measured the MR of this in-plane DW with the current perpendicular to plane (CPP). In order to increase the output voltage, we have connected in series a nominal 2000 $\text{Py}_{100\,\text{nm}}$-$\text{Gd}_{t\,\text{nm}}$-$\text{Py}_{100\,\text{nm}}$ trilayer mesas of dimensions $(10 \times 10)\ \mu\text{m} \times (200 + t)$ nm, with t the thickness of the Gd layer (see inset of Fig. 3). This connection in series increases the signal but also the total contact resistance. Some other authors have approached the problem of measuring the MR of a localized DW, by generating a large number of DWs and using a Wheatstone bridge configuration to minimize the resistance from the rest of the material [22,23]. In these experiments, the bridge was formed in one lithographic step. In our case, the connection in series of all the mesas requires four lithographic steps: Cu contacts, trilayer deposition, insolating layer (SiO_2) and Cu contacts again. This makes it very difficult to balance a Wheatstone bridge perfectly. Therefore, the final result depends mainly on how good the device is and how precisely the resistance can be measured, and not so much on the configuration.

Figure 3 indicates the MR curve for different thicknesses t of the Gd layer (the curves are vertically displaced for clarity). The vertical axis is the resistance change of the device with the external field. The total resistance value of the samples is approximately 0.5 kΩ, but this value comes almost entirely from the Cu (280 nm thick) used to connect the mesas in series. The value varies somewhat from sample to sample but the change in resistance versus field obtained (Fig. 3) is always the same, and we can assume this has its origin in the magnetic part of the device (the trilayer). The value estimated from the resistivity of the Cu and the dimensions of all the contacts matches always the experimental value within a 10% error. Figure 3 indicates that the sample shows some MR only for a Gd thickness below 10 nm, in agreement with the fact that the scattering of the polarized carriers increases as the DW gets narrower.

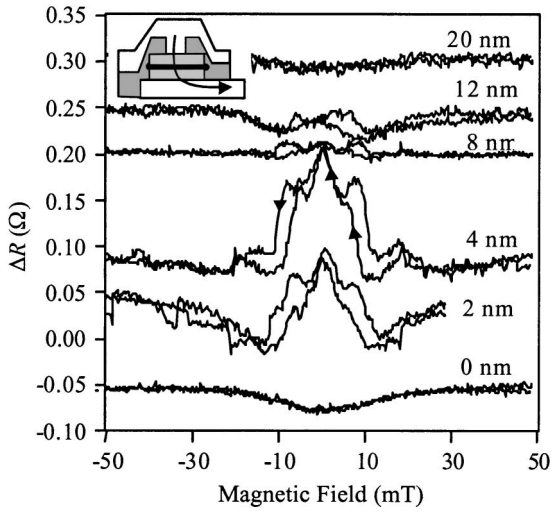

FIG. 3. Magnetoresistance curves at 77 K for different thicknesses of the Gd layer. The arrows on one of the curves indicate the plotting direction. The inset is a schematic diagram of one of the trilayer mesas connected in series used to measure these curves: the white areas indicate Cu contacts and the hatched filling is an isolating layer of SiO_2.

To elucidate the shape of these curves, we have performed CPP transport measurements for different temperatures on the sample with 4 nm of Gd. Figure 4 shows how the central peak of the MR curve does not change with temperature. The rest of the curve goes to zero when we increase the temperature. We can therefore assume that the temperature dependent MR comes exclusively from the DW in Gd. The central peak does not vanish with temperature, and it is likely to be due to a spin valve effect between the two antiparallel Py layers. This is justified by the fact that that peak is not present for thick Gd layers (Fig. 3) because there is no spin transmission from the top Py to the bottom (mean free path of the electron in Gd at 77 K is 2.5 nm).

In order to establish the degree to which the DW is constricted to the Gd, we have calculated the energy per unit of area of an in-plane 180° DW when a rotation of angle ϕ takes place within a distance d in the Py layers:

$$\gamma = \frac{2J_{\text{Gd}}S_{\text{Gd}}^2(\pi-\phi)^2}{ta} - \frac{2J_{\text{Gd-Py}}S_{\text{Gd}}S_{\text{Py}}}{a^2}\int_0^{t/a}(e^{-ax/\lambda} - e^{(ax-t)/\lambda})\cos[a(\pi-\phi)x/t]dx + \frac{J_{\text{Py}}S_{\text{Py}}^2\phi^2}{a_{\text{Py}}\delta} + \frac{\delta K_u}{4}(2\phi - \sin\phi). \quad (2)$$

The values of ϕ and δ are obtained by minimizing the energy ($\partial\gamma/\partial\phi = 0$ and $\partial\gamma/\partial\delta = 0$), using the following values: $a = 0.36$ nm, $J_{\text{Gd}} = 10^{-22}$ J, $J_{\text{Py}} = 2 \times 10^{-21}$ J, $S_{\text{Gd}} = 7/2$, $S_{\text{Py}} = 1/2$, $K_u = 400\ \text{J/m}^3$ (experimental value in

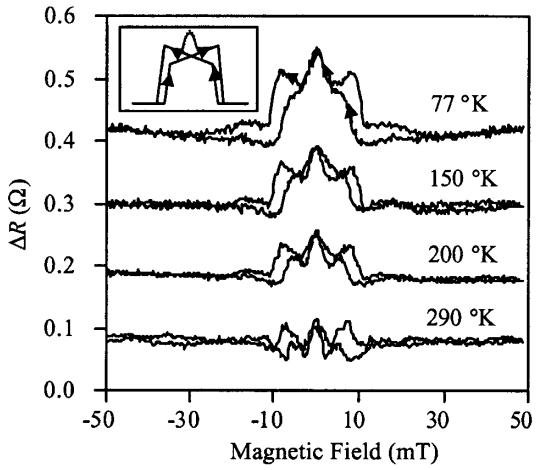

FIG. 4. The magnetoresistance curve for different temperatures for a sample with a 4 nm thick layer of Gd. Plots vertically displaced for clarity. The inset is a schematic diagram of the contribution to this curve of the DW in Gd (solid line). The central peak (dotted line in the inset) does not vanish with temperature and, from its magnitude, it is likely to be due to a spin valve effect between the two antiparallel Py layers. We assume that this peak has no hysteresis because for low fields the Py layer coherently rotates before the irreversible transition shown in the hysteresis loop of Fig. 1 (transition *C*).

our samples), and $\lambda = 1$ nm. For example, for a Gd thickness of $t = 5$ nm at 77 K, we obtain that for $0.3J_{\mathrm{Py}} > J_{\mathrm{Gd\text{-}Py}} > J_{\mathrm{Gd}}$, the rotation in the Gd layer comprises more than 160° of the total 180°. Higher values of $J_{\mathrm{Gd\text{-}Py}}$ give yet higher rotation within the Gd layer.

This analysis confirms that the in-plane DW within the Gd layer is stable at low temperatures. As a consequence, a perpendicular transport measurement will provide an accurate measure of the MR of a well defined DW in Gd.

To obtain the absolute MR value of this in-plane DW, we have to estimate the total resistance of the Gd layers. For instance, in the sample with a 4 nm Gd layer, the number of trilayer mesas connected in series is 1632 and the resistance of the Gd layer in every trilayer is $\rho_{\mathrm{Gd}} t/A$, where $t = 4$ nm and $A = 5 \times 5\ \mu\mathrm{m}^2$, the area of the window in the SiO_2 layer. The experimental value of ρ_{Gd} for our films is 170 $\mu\Omega \cdot$ cm (77 K), measured in 75-nm-thick film with a standard four point technique. So the total resistance of the Gd in this sample is 0.44 Ω. With this value the MR from Fig. 3 is $\Delta R/R = 0.1/0.44$ or ~23%. The same calculation for the Gd-2 nm sample with 1904 trilayer mesas connected in series gives an MR of $\Delta R/R = 0.08/0.26$ or ~31%.

This experimental value can be compared with the theory using the formula for CPP from Levy and Zhang [7] with the values $k_F = 8\ \mathrm{nm}^{-1}$, $m = 3$, $J_{ex}(\mathrm{Gd}) = 2.5 \times 10^{-19}$ J (0.15 eV), $\rho_0^{\uparrow}/\rho_0^{\downarrow}=3$ [24], we obtain a value of 13% for 4 nm and 52% for 2 nm DW. The second value will be decreased somewhat because for Gd-2 nm a greater proportion of the rotation of the DW is taking place in the Py.

The experimental and theoretical values are of the same order of magnitude. We can compare the value obtained with Ref. [2], where 3 nm width DWs were studied. The MR value extracted from the data supplied by the authors is ~11% for CPP. This value is also higher than the ~2% or smaller usually reported for Co or Fe [6], where the DWs are wider than 15 nm.

In conclusion, we have presented a new method to constrict a DW within a thin Gd layer sandwiched between two 100 nm Py layers. This allows transport measurements for different thicknesses of the DW, for the same material. Previously, the MR measurements in DWs for different thicknesses came from different materials, providing only a qualitative comparison. Also the geometry used, CPP with an in-plane DW, is a new approach to avoiding all the spurious sources of MR that can lead to misinterpretation of the intrinsic value of the DW magnetoresistance.

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