Spin Accumulation and Domain Wall Magnetoresistance in 35 nm Co Wires

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(Received 18 June 1999)

An enhancement of the resistance due to the presence of only one or two isolated domain walls is clearly evidenced by transport measurements in 35 nm epitaxial Co wires, 20 μm long. The deduced relative change in the resistivity is at least 1 order of magnitude larger than the one predicted from a model based on the mixing of spin channels occurring over the length scale of the domain wall width [P. M. Levy and S. Zhang, Phys. Rev. Lett. **79**, 5110 (1997)]. This inconsistency can be resolved by taking the effect of spin accumulation into account, which scales in the case of Co over the much larger distance of the spin diffusion length.

PACS numbers: 73.50.–h, 73.61.–r, 75.60.Ch, 75.70.Pa

Spin accumulation [1,2] is known to be at the origin of the giant magnetoresistance (GMR) observed in magnetic multilayers in the CPP geometry (current perpendicular to the plane) [2–4]. In recent efforts, this effect has also been taken into account to describe spin injection devices, in which the possibility of a magnetization reversal by means of a spin polarized current [5] is explored. Common to these devices is the magnetic/nonmagnetic/magnetic trilayer structure, where the nonmagnetic barrier thickness is thinner than the spin diffusion length. Recently, an analogy was drawn between CPP-GMR magnetic multilayers and homogeneous magnetic media, in which magnetic domain walls replace the nonmagnetic spacer layers [6,7]. It was concluded [6–8] that domain walls give rise to a similar enhancement of the resistance as GMR multilayers in the antiparallel configuration, due to the *mistracking* effect, where the transport electron spins lag behind in orientation with respect to the local magnetization orientation inside the domain wall. As a consequence of this mistracking [8], spin channel mixing occurs which is considered to be important only over the length scale of the domain wall width δ_w. However, the close analogy to the CPP-GMR configuration raises the question, whether due to the mistracking, a spin accumulation effect should be taken into account which relaxes over the much larger length scale of the spin diffusion length.

Here, experimental evidence is provided for the first time that spin accumulation should be considered in interpreting the enhancement of the resistance due to the presence of a well-defined and isolated domain wall. An unambiguous enhancement of the resistance is obtained from MR hysteresis loops of 35 nm Co wires, an example of which is given in Fig. 1(a). Scaling the resistance ratio $\Delta R_w/R_{\mathrm{sd}} = 0.1\%–0.3\%$ to the domain wall width $\delta_w(= 15$ nm for Co) yields a resistivity ratio of $\Delta\rho_w/\rho = 100\%–600\%$, much larger than observed in any other experiment [6,7,9–11] and larger than the value of 2%–11% predicted in [8]. In order to resolve this discrepancy, it is proposed here that the domain wall width is not the relevant length scale over which the spin channel mixing has to be considered. Instead, spin accumulation at the domain wall, which relaxes over the much larger distance of the spin diffusion length ($l_{\mathrm{sf}} = 60$ nm for Co at 77 K [4]) is considered as the underlying mechanism and will be used to explain the observed value of resistance enhancement.

Many experiments on the domain wall magnetoresistance (DWMR) were performed for systems containing a multiple domain structure, induced either by demagnetization fields or specific magnetization procedures [6,9–14]. The underlying idea was to take advantage of the high density of domain walls, assuming that the domain resistance and the DW resistance form a network of series resistors. However, in order to extract the contribution from

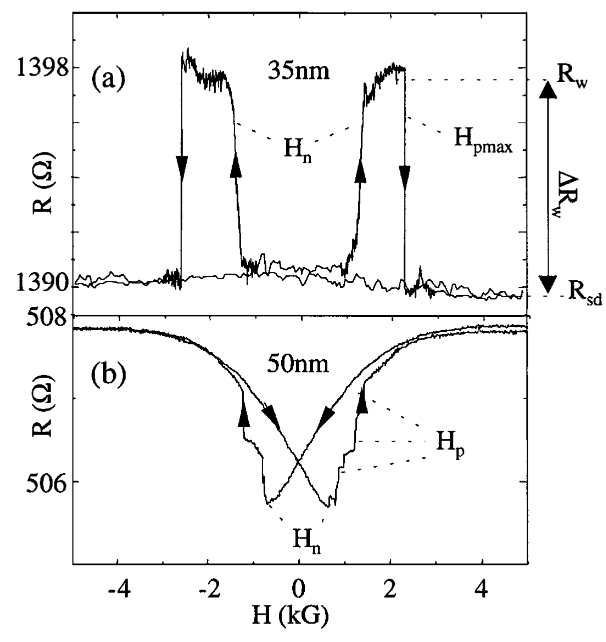

FIG. 1. MR hysteresis loops (at 77 K) for (a) a 35 nm and (b) a 50 nm Co wire for a field applied parallel to the wire axis. H_n and H_p indicate, respectively, the nucleation field and the propagation field of domain walls. R_{sd} denotes the signal level of the single domain wire, R_w the signal level of the wire including n domain walls, and $\Delta R_w = R_w - R_{\mathrm{sd}}$.

the domain wall, the presence of other MR effects, such as anisotropic magnetoresistance (AMR) [15] or Lorentz-MR [16], required a combination of the measured MR data in different magnetization configurations as well as at different temperatures [10,12,13]. Both an increase [6,7,9–11] as well as a decrease of the resistance [12–14] was reported. In light of the complicated analysis of previous results, it appears desirable to investigate the DWMR for an isolated domain wall in a well-defined geometry in which (independent of temperature) other MR contributions do not mask the DWMR. Such a geometry can be achieved by (i) keeping the domain magnetization **M** parallel or antiparallel to the current **J** during the magnetization reversal process and (ii) aligning the domain walls perpendicular to the current and thus to the magnetization. In thin films, such head-to-head wall configurations are usually avoided due to the magnetic charges located at the domain walls, preferring domain walls which are oriented parallel to **M**. However, upon reducing the lateral dimensions down to the order of the domain wall width, the domain wall can be forced into the desired configuration, as is shown in the following.

Co nanowires, investigated here, were prepared by electrodeposition inside the pores of track-etched polycarbonate membranes [4,17,18]. Here only some structural details shall be mentioned, which are relevant for the magnetocrystalline anisotropy. X-ray diffraction measurements as well as transmission electron microscopy reveal an epitaxial growth of Co in the hcp structure inside the pores of the membrane. For small diameter wires, on the order of 35 nm, it is found that the c axis is oriented preferentially parallel to the wire axis [18]. This is in contrast to the larger diameter wires where the c axis is oriented preferentially perpendicular to the wire axis [19]. It is therefore expected that in the 35 nm wires the magnetocrystalline easy axis is oriented very close to the wire axis, reinforcing the shape anisotropy. Hence, only two magnetization states, parallel and antiparallel to the wire axis, can be realized in wires of such small diameters. This is confirmed by magnetic force microscopy (MFM) imaging, as is shown in Fig. 2(a) for a 35 nm Co wire after application of a large field parallel to the wire axis ($H_{\parallel}$). The dark and bright contrasts at the wire extremities correspond to magnetic charge distributions at the end faces which arise when the magnetization is in a single domain state and aligned parallel (or close) to the wire axis.

In contrast to the saturation in $H_{\parallel}$, a multidomain state with head-to-head domain walls can be induced by saturation in a field perpendicular to the wire axis ($H_{\perp}$), as shown in Fig. 2(b). This multidomain structure arises since upon reduction of the field from perpendicular saturation to zero, the magnetization may rotate clockwise or counterclockwise towards the wire axis. The dark and bright contrasts visible along the wire axis arise from the magnetic volume charges located at the domain walls. As sketched in Fig. 2(c), a simple model for the domain wall structure is

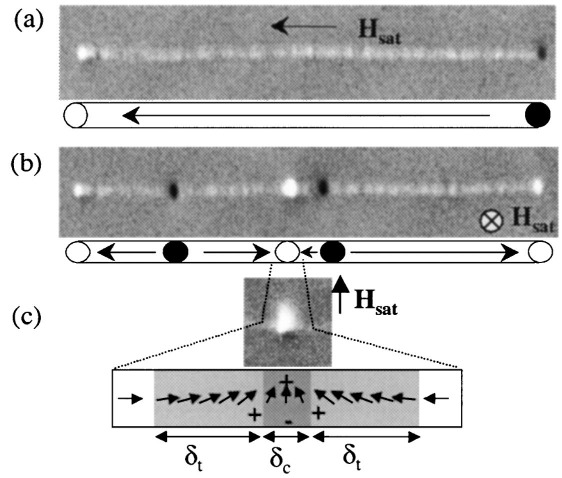

FIG. 2. Room temperature (RT) and zero field MFM images of a 35 nm Co wire after saturation in a field (a) parallel to the wire axis and (b) perpendicular to the wire axis and the substrate plane. (c) A zoom onto the domain wall region shows strong bright and weak dark contrasts across the wire diameter. This results from saturation in a field perpendicular to the wire but parallel to the substrate plane in contrast to (b). A possible domain wall configuration is sketched underneath, with δ_c denoting the wall core extension and δ_t the wall tail extension. Using the parameters typical for Co, a minimum length for δ_c can be estimated form $\delta_c = \sqrt{[A/(K + \pi M_s^2)]} = 10$ nm, ($A = 1.4 \times 10^{-6}$ erg/cm), $K = 5 \times 10^6$ erg/cm^3, and $M_s = 1.4 \times 10^3$ emu/cm^3).

assumed in which the wall center spins are oriented perpendicular to the wire axis. This model is supported by the MFM zoom around a domain wall shown in Fig. 2(c). Such a simple wall model can be further justified by considering the small wire diameter which should suppress more complex wall structures including vortices. This is analogous to Permalloy thin films in which vortex walls are replaced by Néel walls upon reduction of the film thickness [20].

The domain walls shown in Fig. 2(b) are stabilized at pinning sites. They can be moved along the wire by applying a field $H_{\parallel}$ larger than the local depinning field as is demonstrated in the image sequence of Fig. 3. It can be seen that weak and strong pinning sites are present in this wire. A similar pinning-propagation process of domain walls occurs during the single domain reversal in $H_{\parallel}$ with a maximum of two domain walls nucleating from the wire extremities.

We now turn to the MR hysteresis loop in Fig. 1(a), corresponding to the single domain reversal of a single 35 nm wire in $H_{\parallel}$. There are two striking features in this loop: (i) the background resistance level is almost flat over the field range measured, and (ii) two sharp jumps are visible, one upward at 1.3 kOe followed by a downward jump at 2.8 kOe. The flat background level indicates that the magnetization remains parallel to the current **J** during the whole reversal process, confirming that for the 35 nm Co wires the effective easy axis is aligned very close to the

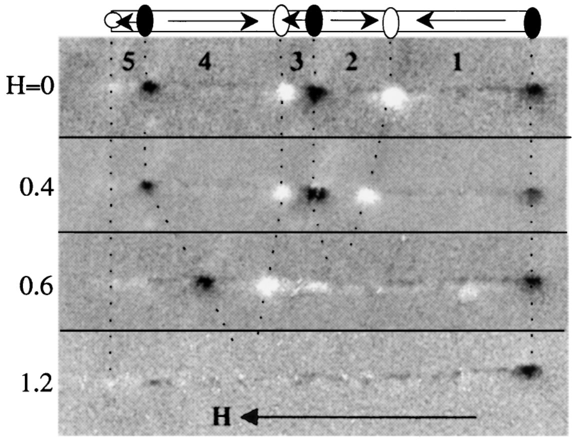

FIG. 3. Sequence of RT zero field MFM images of a 35 nm Co wire showing the domain wall displacement after applying a field of $H = 0$, 0.4, 0.6, and 1.2 kOe parallel to the wire axis. The configuration at $H = 0$ was obtained after saturation in $H_{\perp}$. Note the very weak contrast at the left wire extremity.

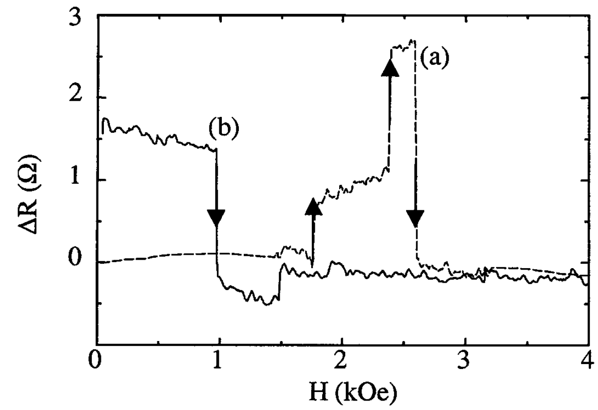

FIG. 4. (a) Quarter cycle of the single domain MR loop, revealing two upward jumps, corresponding to the nucleation of two domain walls. Note the difference to the single domain reversal for the other wire in Fig. 2(a) with only one upward jump. (b) Remagnetization in $H_{\parallel}$ after saturation in a perpendicular field.

wire axis. In contrast, a strong inclination of the effective easy axis with respect to the wire axis ($\parallel \mathbf{J}$) lowers the MR due to the AMR [21,22] as seen, for instance, in Fig. 1(b) for a 50 nm Co wire. The butterfly shape in Fig. 1(b) indicates that upon lowering and reversing the applied field $H_{\parallel}$ from saturation, the magnetization **M** rotates continuously away from the wire axis towards the effective easy axis until the nucleation of domain walls sets in at the nucleation field H_n. This causes the first upward jump, see Fig. 1(b), followed by successive upward jumps at the propagation fields H_p at which domain walls are depinned. The height of these jumps is a measure of the increase in volume of the reversed domain.

The absence of such rotation processes in the MR loop of the 35 nm Co wire in Fig. 1(a) means that **M** stays effectively parallel to **J** during the whole reversal process. Hence the background resistance level corresponds to the maximum AMR level. Additional measurements with fields applied perpendicular to the wire axis confirm this. Since the upward jump appears around the nucleation field value of $1 < H_n < 2$ kOe as found also from MFM experiments, the upward and downward jumps are respectively identified as the nucleation field H_n and the maximum depinning field $H_{p\,\max}$ at which all domain walls are expelled from the wire. From this it follows that the enhanced signal level in the field range $H_n < H < H_{p\,\max}$ can be attributed to the presence of domain walls. Consequently it is identified as a domain wall magnetoresistance.

It is noted that this resistance enhancement due to the presence of domain walls was found consistently for all wires with diameters of 35 nm and below and was confirmed by further experiments using different magnetization procedures. For example, saturation in $H_{\perp}$ leads to the inclusion of one or more domain walls, as illustrated in Fig. 2(b), and therefore should enhance the MR signal at zero field. This is clearly evidenced in Fig. 4 which compares the MR quarter cycles for (a) the single domain reversal in $H_{\parallel}$ (dashed line) and (b) the remagnetization in $H_{\parallel}$ after saturation in $H_{\perp}$ (full line). The high resistance state at $H = 0$ Oe which is followed by a sharp downward jump at $H = 1$ kOe in Fig. 4(b) indicates the presence of a domain wall at zero field which is expelled upon applying a strong enough field $H_{\parallel}$.

In conclusion, there is unambiguous evidence that the presence of a domain wall increases the resistance of Co wires with diameters of 35 nm and below. For all wires measured, the MR ratio for a single wall has a value of $\Delta R_w / nR_{\mathrm{sd}} = 0.1\%$–$0.3\%$ [for notation, see Fig. 1, n (number of walls) $= 1, 2$]. In terms of the resistivity ratio this would correspond to a huge enhancement of the resistivity ρ_w of Co inside the domain wall compared to its resistivity ρ_{sd} in the single domain state. Indeed, taking as the relevant length scale the domain wall width $\delta_w = 10$ to 15 nm and $l_{\mathrm{Co}} = 20\ \mu$m for the length of the Co wire, one obtains a resistivity ratio of $\Delta\rho_w/\rho_{\mathrm{sd}} = \Delta R_w / nR_{\mathrm{sd}}\ (l_{\mathrm{Co}}/\delta_w) = 100\%$–$600\%$. Such a huge resistivity ratio has never been reported before and cannot be explained through the expression derived in [8] for $\Delta\rho_w/\rho$, unless the domain wall width is reduced by a factor of 3 to 10. Feeding such a reduced δ_w value back into the experimental resistivity ratio, determined from the measured MR ratio [Fig. 1(a)], produces an even larger value. This contradiction indicates that the mechanism discussed in Refs. [6–8] is not sufficient to account for the resistance enhancement in the presence of a DW.

In general terms, the model of Refs. [6–8] applies the concept of spin dependent scattering and the mixing of spin channels (due to the mistracking of the electron precession) to the continuously varying magnetization distribution inside a domain wall of width δ_w. On the other hand, it is known from the Valet-Fert model [2] that in the CPP-GMR geometry an interface between two layers of opposite magnetization leads to a spin accumulation which relaxes by spin-flip scattering over the spin diffusion length and which enhances the magnetoresistance. This raises the question of whether a domain wall also gives rise to a spin accumulation effect. An obvious answer is that if the rotation (or a major part of the rotation) of the magnetization inside the domain wall occurs over a short distance, the mistracking effect will be large and spin accumulation effects ought to occur.

The system measured here with one or two isolated domain walls separating regions of opposite magnetization corresponds to the case, where the magnetic layer thickness $l_{\mathrm{Co}} = 20\ \mu\mathrm{m}$ is large compared to the spin diffusion length $l_{\mathrm{sf}}^{\mathrm{Co}} = 60$ nm [4] and the transition region (domain wall) $\delta_w = 10$–15 nm is smaller than $l_{\mathrm{sf}}^{\mathrm{Co}}$. Neglecting therefore, in a first approximation, the domain wall extension and considering an abrupt transition from one domain to another, the MR ratio can be estimated by the same equation as described in Refs. [2,4]. In the notation of Refs. [2,4], the relative resistance change is calculated in terms of a simple series resistor model, in which the resistance inside the domains is in series with the interface resistance caused by the spin accumulation. For an antiparallel configuration, the measured relative change in resistance for n walls is then given by [4]

$$\frac{\Delta R}{R_{\mathrm{sd}}} = \frac{2n\beta^2}{1 - \beta^2} \frac{l_{\mathrm{sf}}}{l_{\mathrm{Co}}}. \tag{1}$$

Here, β is the scattering asymmetry, whose value is 0.4–0.5 as determined in previous studies [4]. With $l_{\mathrm{Co}} = 20\ \mu\mathrm{m}$, the DWMR ratios are on the order of 0.12% to 0.2% for $n = 1$ and 0.2% to 0.4% for $n = 2$. These values are consistent with the DWMR ratios obtained in the present study, suggesting that spin accumulation effects should be considered to explain the enhancement of the resistance in the presence of domain walls.

It is noted that the MR ratio determined from Eq. (1) can be only an upper estimate, since the finite extension of the domain wall was neglected. Considering the extreme limit of large wall widths, the spins can adapt in an adiabatic way to the changing magnetization orientation [6,7]. Hence the mistracking and with this the spin accumulation effect will be reduced. The wall widths of the Co wires discussed here lie somewhere in the intermediate range of these two limiting cases. For Co, δ_w is relatively small due to the strong magnetocrystalline anisotropy with easy axis parallel to the wire axis. In contrast to this, in Ni wires the magnetocrystalline anisotropy is by 1 order of magnitude lower at room temperature (RT) [17]. However, as shown in [17], a uniaxial magnetoelastic anisotropy is induced upon lowering the temperature. While no DWMR effects were observed in Ni wires at RT, a similar MR loop as the one in Fig. 1(a) was observed at low temperatures, with a resistance enhancement which is by 1 order of magnitude smaller than observed for Co. This demonstrates the generality of the DWMR effect as well as its sensitivity to the domain wall width.

The authors wish to thank A. Fert for encouraging discussions, and R. Legras and E. Ferain for providing the polycarbonate membrane samples used in this work. L. P. is a Research Associate of the National Fund for Scientific Research (Belgium). This work was partly supported by the EC-TMR program "Dynaspin" No. FMRX-CT97-0124 and the EC-Brite-Euram program No. BRPR-CT95-0001, as well as by the Belgian Interuniversity Attraction Pole Program (PAI-IUAP P4/10).

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