Direct Observation of Domain Wall Scattering in Patterned $Ni_{80}Fe_{20}$ and Ni Nanowires by Current-Voltage Measurements

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We present measurements of domain wall resistivity, pinned by nanoconstrictions in single layer ferromagnetic wires of $Ni_{80}Fe_{20}$ and Ni. Unpinning domain walls from the constriction by current-induced switching allows for an unambiguous measurement of their resistivity changes, namely, 1.7% in $Ni_{80}Fe_{20}$ and 1.82% in Ni and both positive, which supports the theory of spin-dependent impurity scattering. By deriving an empirical relation for the various constriction widths, the large percentage changes of resistivity in ballistic nanocontacts are reproduced, showing a correlation between domain wall magnetoresistance and ballistic magnetoresistance.

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The study of domain wall contributions to magnetoresistance (DWMR) has seen a growing interest, fueled by progress in nanofabrication techniques. The definition of artificial pinning sites in nanomagnets, such as lateral constrictions, allows for a single domain wall to be trapped and characterized. Recent studies on NiFe rings with notches [1] have shown a negative contribution to magnetoresistance due to domain walls pinned at the constriction, which was accounted for by an anisotropic magnetoresistance (AMR) contribution. On the other hand, a positive contribution was observed for an in-plane domain wall in a Gd layer sandwiched between two NiFe layers [2]. Other positive contributions of domain walls to magnetoresistance have also been shown recently [3–7], which were discussed in terms of a spin-dependent scattering mechanism. There are currently two main theoretical treatments for the DWMR: for positive contributions a model based on spin-dependent impurity scattering was proposed by Levy and Zhang [8], while negative contributions are accounted for by the loss of weak localization of the electrons as shown by Tatara and Fukuyama [9]. On the other hand, large MR changes and nonlinear I-V characteristics have been shown recently in nanocontacts of ferrimagnetic crystals [10] and ballistic nanocontacts [11,12], where point contacts of only a few atoms give rise to the so-called ballistic magnetoresistance (BMR). This was explained by domain wall scattering due to the inability of the electron spin to accommodate itself adiabatically from one side of the domain wall to the other when the Fermi wavelength, λ_F, is comparable to the domain wall width [13]. Nonlinear I-V characteristics were also observed in the point contacts of ferrimagnetic crystals [10], which were discussed in terms of a “magnetic balloon” effect. In this Letter we present results of I-V measurements of ferromagnetic point contacts in a well defined geometry, and our results point to a convergence with the large percentage changes in resistivity observed in Refs. [10–12], in the limit of point contacts of only a few atoms. This is shown to be related to the spin-dependent impurity scattering mechanism at the domain wall, modeled by Levy and Zhang [8]. However, the main motivation of this study is the possibility of extracting information about the resistance contribution of domain walls directly from I-V measurements. The presence of a domain wall at constrictions in ferromagnetic wires and its subsequent removal by application of a spin-polarized current of sufficient current density has been shown previously [14]. The difference between the resistance state where a domain wall is pinned at the constriction and the resistance state where the domain wall is removed can be used to obtain a direct measurement of its resistivity. This has the advantage of canceling any additional contributions, such as AMR and Hall effect contributions, which can lead to misinterpreted domain wall scattering in DWMR studies.

A set of straight wires and necked wires were defined on a Si(100) substrate using electron beam lithography and lift-off technique, with a fixed length of 400 μm and width of 1 μm. For the necked wires a constriction was defined halfway along the wire, forming point contacts of nominal widths ranging from 50 to 350 nm, with an increment of 50 nm. Following thermal evaporation of $Ni_{80}Fe_{20}$, 30 nm thick with an Au capping layer, 2 nm thick, at a pressure of 10^{-5} mbar, ultrasonic assisted lift-off in acetone was used to obtain the patterned wires. A second level of lithography was used to define the electrical measurement pads followed by thermal evaporation of Al 150 nm thick and ultrasonic assisted lift-off as for the first level. The necked wire with 50 nm point contact width is shown in Fig. 1, together with the measurement pads geometry. A standard dc measurement method was used by bonding with Al wires to the pads. A set of I-V measurements was performed at zero applied magnetic field after reversal from saturation, with the applied current in a range of about 2 mA with a 10 μA step. All measurements were carried out at room temperature.

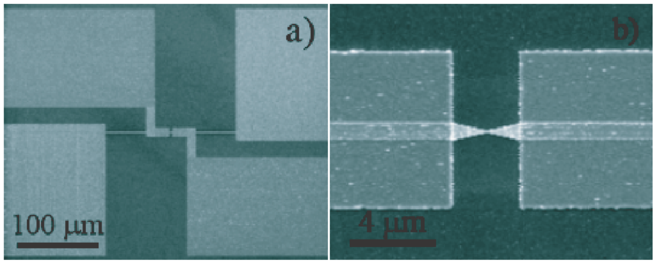

FIG. 1 (color online). SEM images of (a) measurement pads geometry and (b) necked NiFe wire with 50 nm constriction width.

Figures 2(a) and 2(b) show the resistance versus applied current for the necked wires with point contact widths 50–250 nm for NiFe and Ni, respectively. A sharp drop in resistance is observed for the necked wires with point contact width in the range 50–250 nm at a critical current termed the switching current, while for the wires with point contact width of 300 and 350 nm, no drop in resistance occurs (the latter is not shown). By comparing the switching currents with the cross-sectional areas at the constriction, it is found that the current density required to change the resistance is constant and of the order 10^7 A/cm^2 as shown in the insets of Figs. 2(a) and 2(b), namely 1.1×10^7 A/cm^2 for NiFe and 2.2×10^7 A/cm^2 for Ni, respectively. Also the percentage changes in resistance are seen to decrease monotonically with increasing point contact width, namely, from 0.13% to 0.024% for NiFe and from 0.124% to 0.028% for Ni, for constriction widths from 50 to 250 nm, respectively. The curves in Fig. 2 show a flat characteristic, above and below the switching current, with resistance values within the noise margins of the equipment, so that we may conclude that self-heating does not occur to any measurable extent, as a monotonic increase in resistance would be observed with larger applied current if self-heating did occur.

As predicted by Berger [15] and confirmed experimentally [16], domain walls can be displaced under the influence of a spin-polarized current. This effect is due to the exchange torque exerted by electrons in the conduction band on the constituent electrons of the domain wall. The net effect is a displacement of the domain wall in the same direction as that of the current carriers, known as current-induced *s*-*d* exchange interaction. The difference between the two resistance states is, therefore, attributed to the removal of the domain wall from the constriction at a critical current density of the order 10^7 A/cm^2 (Fig. 2). In the low resistance state, no domain wall is pinned at the constriction, while in the high resistance state the presence of a domain wall must be responsible for the additional resistance observed. Thus the difference between the two states can be used to obtain a direct measurement of the domain wall resistance, without the use of an applied magnetic field.

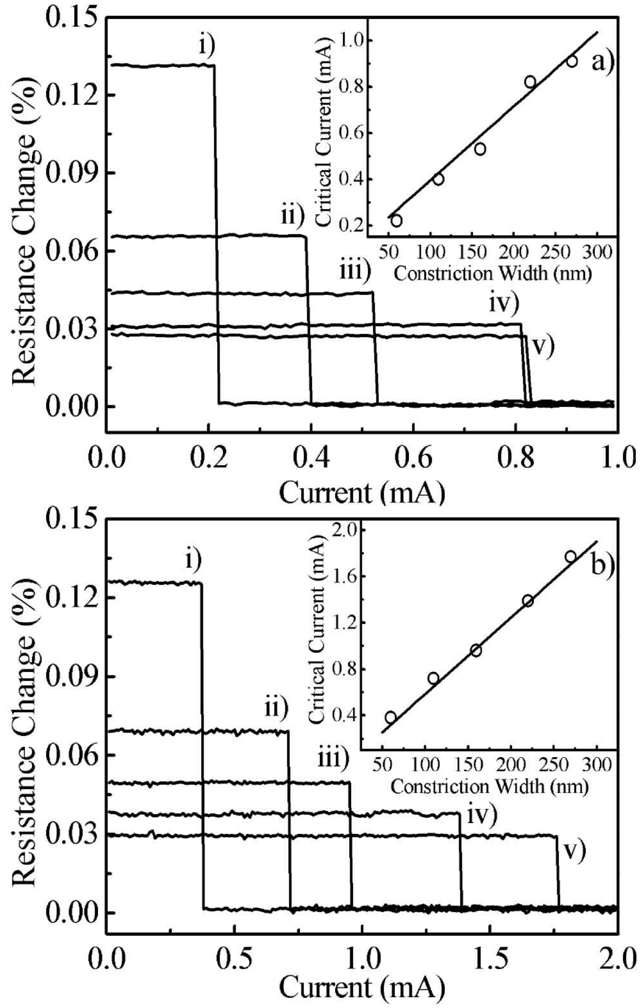

FIG. 2. *I*-*V* measurements for (a) necked NiFe wires and (b) necked Ni wires with constriction widths of (i) 50 nm, (ii) 100 nm, (iii) 150 nm, (iv) 200 nm, and (v) 250 nm. In the insets of (a) and (b) the average critical current density is plotted as a function of constriction width for NiFe and Ni, respectively.

The presence of a domain wall at the constrictions of our devices is supported by extensive micromagnetic simulations. These have shown the formation of a 180° domain wall at the narrowest part of the constriction at zero applied magnetic field—accessible reversibly from saturation—as shown in Fig. 3. We have also measured the magnetoresistance of the samples for both transverse and parallel configurations with a maximum applied field of 1.5 kOe. The ratios of the parallel to transverse anisotropic magnetoresistance were found to be close to zero, namely $8.7 \times 10^{-5} \pm 0.5 \times 10^{-5}$ for NiFe samples and $11.8 \times 10^{-5} \pm 0.5 \times 10^{-5}$ for Ni samples, which further confirm the formation of 180° domain walls rather than 90° domain walls. The rotation of magnetization occurs in plane, as for a Néel wall, since the thickness of the ferromagnetic layer prevents any Bloch walls from forming. This magnetic configuration was found to be stable

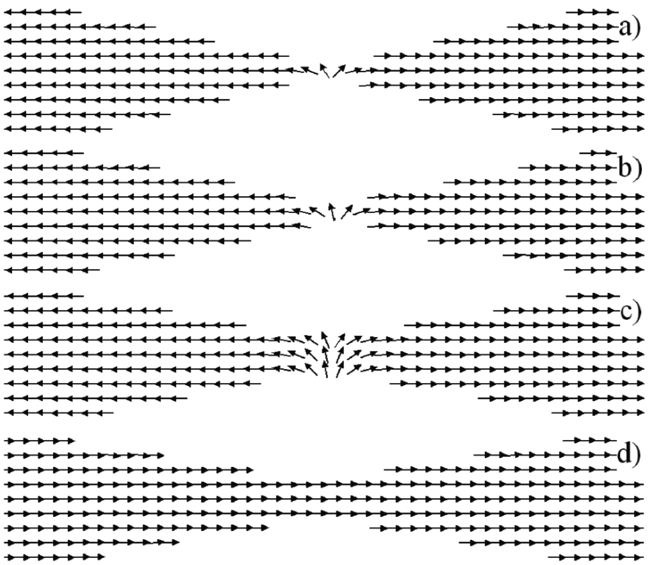

FIG. 3. Micromagnetic simulations for necked NiFe wires with constriction widths of (a) 50 nm, (b) 100 nm, (c) 250 nm, and (d) 300 nm.

for constriction widths up to 300 nm, for both NiFe and Ni, and any further increase simply resulted in a parallel alignment of the magnetization in both arms, with no domain walls pinned at the constriction. This is reflected in the results obtained from *I*-*V* measurements, where a change in resistance was observed for samples with nominal constriction width 50–250 nm, while the samples with constriction widths of 300 and 350 nm were characterized by a linear *I*-*V*.

The model proposed by Levy and Zhang [8] suggests that positive contributions of domain walls to resistance may be accounted for by a spin-dependent impurity scattering mechanism. The scattering of electrons in domain walls produces a mixing of the currents in the spin-up and spin-down conduction channels, and the additional resistance introduced by domain walls is then due to the different resistivities experienced by spin-up and spin-down electrons. For the current perpendicular to the domain wall, Eq. (1) may be used to calculate the resistivity ratio [8].

$$R_{\mathrm{CPW}} = \frac{\xi^2}{5}\,\frac{(\rho_0^{\uparrow} - \rho_0^{\downarrow})^2}{\rho_0^{\uparrow}\rho_0^{\downarrow}}\left(3 + \frac{10\sqrt{\rho_0^{\uparrow}\rho_0^{\downarrow}}}{\rho_0^{\uparrow} + \rho_0^{\downarrow}}\right). \qquad (1)$$

In the preceding equation, $\xi = h^2 k_F / 16\pi m d J$, where d is the thickness of the domain wall. Taking commonly accepted values of $k_F = 1$ Å^{-1}, $J = 0.5$ eV, $d = 30$ nm, and $\rho_0^{\uparrow}/\rho_0^{\downarrow} = 5$–$20$ for typical ferromagnetic materials of NiFe and Ni at room temperature [8], we find this ratio ranges from 0.7% to 3%. The resistance ratios $\Delta R/R_0$, i.e., resistance change (high state resistance minus low state resistance) divided by the low state resistance, were obtained directly from the *I*-*V* data. To compare our results with the theoretical predictions from spin scattering theory, we have converted the resistance ratios into resistivity ratios $\Delta\rho/\rho_0$ by solving for the particular current distribution in the geometry of our samples for both NiFe and Ni, assuming a domain wall thickness of 30 nm [17]. The results obtained are shown in Figs. 4(a) and 4(b). Empirical numerical relations may be obtained by curve fitting these points using Eq. (2), where S is the cross-sectional area at the constriction. For NiFe and Ni the constant K takes the values of 1.98×10^{-8} and 1.12×10^{-6}, respectively, and the exponent α has values of 0.42 and 0.3, respectively.

$$\frac{\Delta\rho}{\rho_0} = \frac{K}{S^{\alpha}}. \qquad (2)$$

For the largest constriction widths, the percentage changes in resistivity are within the range predicted by spin scattering theory. As the constriction width is decreased, however, the changes in resistivity with the presence of a domain wall are seen to increase rapidly. For constriction widths of only a few atoms across, the percentage changes would then be expected to be very large, as found by Versluijs *et al.* [10] and García *et al.* [11,12]. For a contact area of 1 nm^2, the percentage changes in resistivity due to domain wall scattering, as predicted by the empirical relations of Eq. (2), would then be ~70% for NiFe and ~30% for Ni. These predictions are in good agreement with the large values found for ballistic nanocontacts [11] at room temperature for a nominal contact area of 1 nm^2. Possible links between domain wall scattering and BMR have been discussed theoretically in previous work [12,13]. In particular, Tatara *et al.* [13] have shown that a domain wall trapped in a constriction region will strongly scatter electrons if

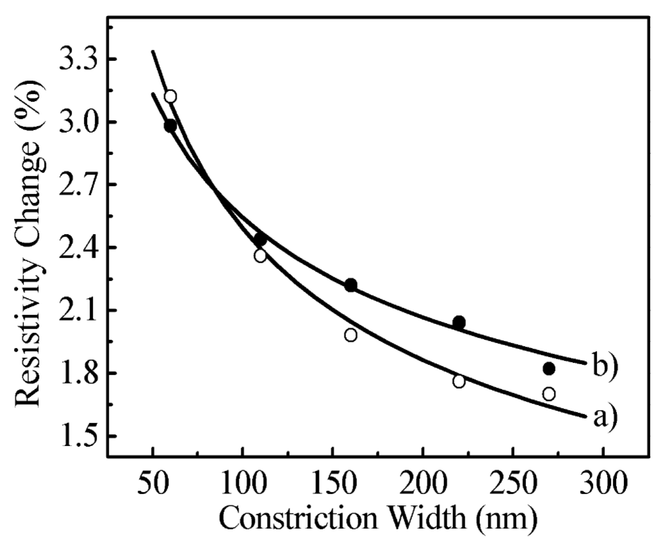

FIG. 4. Percentage change in resistivity versus constriction width for (a) NiFe and (b) Ni. The dots are the experimental results, and the lines are the simulations.

TABLE I. Summary of main DWMR studies compared with our results.

Temp.	DWMR	Samples
RT	$+1.7 \times 10^{-2}$	NiFe constricted wires
RT	AMR	NiFe rings [1]
77 K	$+0.23$	NiFe/Gd structure [2]
RT	$+3 \times 10^{-3}$	NiFe crosses [3]
RT	$+3.4 \times 10^{-3}$	NiFe zigzag wires [4]
RT	-1.4×10^{-3}	NiFe wires [18]
RT	$+1.82 \times 10^{-2}$	Ni constricted wires
RT	$+3 \times 10^{-5}$	Ni films [5]
77 K	$+1 - 3 \times 10^{-4}$	Co wires [6]
RT	$+5 \times 10^{-3}$	Co films [7]
5 K	-5×10^{-4}	Co zigzag wires [19]
65 K	-1×10^{-3}	Fe wires [20]

the Fermi wavelength, λ_F, is comparable to the domain wall width. This is due to the inability of the electron spin to accommodate itself adiabatically from one side of the domain wall to the other. Our experiments show that there is a correlation between BMR and spin-dependent impurity scattering. By examining Fig. 4, as the constriction width is increased, the percentage changes in resistivity are in good agreement with the theoretical predictions of spin-dependent impurity scattering, whereas for very small constriction widths they approach the values obtained from BMR experiments. The region in between these two extremes must then be explained as a combination of domain wall scattering and BMR effects. By considering the samples with constriction width of 250 nm, where the contributions due to BMR are negligible, we obtain values of DWMR of 1.7% for NiFe and 1.82% for Ni. Table I summarizes these results, where the results obtained from previous experimental studies are also included.

In summary, we have fabricated single layer NiFe and Ni nanowires with a variable constriction width in the range 50–350 nm, where a 180° domain wall is formed at the constriction for the contact widths smaller than 300 nm supported by micromagnetic simulations. The contributions due to domain wall scattering were extracted from the I-V measurements at zero external magnetic fields and found to increase with decreasing constriction width. By deriving an empirical relation from these results for constriction widths in the range 50–250 nm, we were able to reproduce the large percentage changes of ballistic magnetoresistance obtained in nanocontacts. For large constriction widths, approaching 250 nm, the percentage changes in resistivity were shown to be in good agreement with the predictions of spin-dependent impurity scattering of domain walls. This correlation suggests that there might be a unified model for ballistic magnetoresistance and domain wall magnetoresistance.

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