Detection of Domain-Wall Position and Magnetization Reversal in Nanostructures Using the Magnon Contribution to the Resistivity

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We show that magnetization reversal detection can be achieved at room temperature using the contribution of magnons to resistivity, in 50 nm wide nanowires with either perpendicular anisotropy (FePt) or in-plane magnetization (NiFe). Even though these nanowires are made from single layers, simple magnetoresistance measurements can be used to measure switching fields, or to detect the position of a domain wall along a nanowire. Surprisingly, in NiFe nanowires, and for applied fields nearly parallel to the wire, the magnon contribution is found to dominate the classical anisotropic magnetoresistance.

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Spintronics owes its development to a few magnetoresistances: giant magnetoresistance (GMR), tunneling magnetoresistance (TMR), anisotropy magnetoresistance (AMR) [1–3], and, at a lower level, to domain-wall resistance (DWR) and to the anomalous Hall effect (AHE) [4,5]. As they provide very good spatial and temporal resolutions, transport measurements are probably the most popular way to detect magnetization reversal in nanostructures. In this Letter, we prove that such a detection can be realized using magnon magnetoresistance (MMR), i.e., the contribution of magnons to resistivity. Studying FePt and NiFe nanowires, we show that MMR measurements can be used in systems with either perpendicular anisotropy or in-plane magnetization. These simple resistivity measurements can be achieved at room temperature in samples made from a single layer, and provide information such as the position of a domain wall (DW) along a nanowire, the values of switching fields, or the magnetization orientation in ferromagnetic electrodes. This effect also provides a change of paradigm in the study of in-plane magnetized nanowires: for certain field directions the magnon contribution dominates the magnetoresistance, clearly overcoming the anisotropic magnetoresistance (AMR).

Recently, it has been shown that at high fields the contribution of magnons to the resistivity decreases linearly with the magnetic field [6]. This general phenomenon can be simply described: when the applied field increases, the spin lattice becomes more rigid, leading to a decrease of the magnon population [7]. In Ref. [8], we studied FePt thin layers possessing a huge anisotropy field (∼ 10 T), and showed that in systems with perpendicular magnetization this contribution to the resistivity also depends on the orientation of the magnetization. In a partially reversed state, it was shown that it can be expressed as

$$\rho_{\mathrm{MMR}} = \alpha \frac{M}{M_S} B, \tag{1}$$

where M is the magnetization along the anisotropy axis, M_S is the saturation magnetization, B is the applied magnetic field (in the direction of the anisotropy axis) and $\alpha = (\frac{\partial \rho}{\partial B})_{\mathrm{sat.}}$ is the slope of $\rho_{\mathrm{MMR}}(B)$ taken in the saturated state of magnetization ($\alpha < 0$).

According to Eq. (1), the magnetization can be extracted from simple resistivity measurements. This property can be used to detect magnetization reversal and DW motion in FePt nanowires. Figures 1(a) and 1(b) show optical microscopy and scanning electron microscopy images of a 50 nm wide FePt nanowire, processed by electron beam

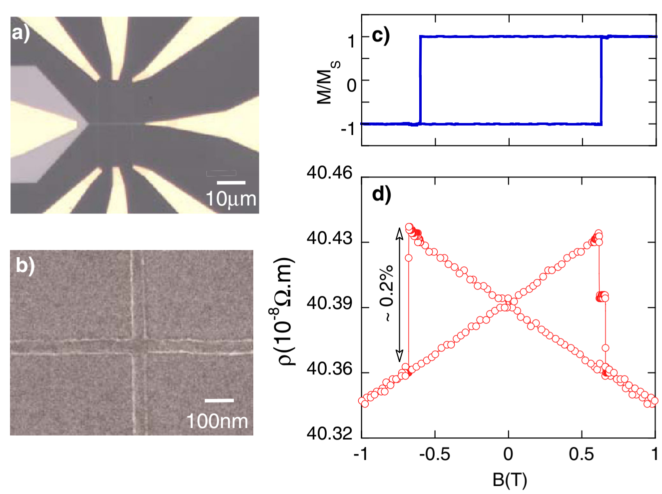

FIG. 1 (color online). (a) Optical microscopy image of a nanodevice, with a set of electrical leads designed to measure AHE within the Hall crosses, and resistances between two crosses. (b) Scanning electron microscopy image of the 50 nm wide FePt nanowire. (c) Room temperature hysteresis loop of the nanowire, measured in perpendicular field by AHE, and (d) corresponding magnetoresistance measurement, performed using standard lock-in technique at room temperature (four-probe measurements at 2×10^9 A/m^2 and 1023 Hz).

lithography and ion milling. The single and epitaxial FePt layer (10 nm thick) was grown by molecular beam epitaxy at 770 K, by codeposition of Fe and Pt [8]. A large magnetic area at one end of the nanowires acts as a nucleation pad, allowing to inject a single DW into the wire [9]. For applied fields perpendicular to the layer, the nanostructure exhibits a square hysteresis loop [cf. Figure 1(c)], with a coercive field of about 0.6 T.

Figure 1(d) shows the four-probe MMR measurement of the 6 μm long nanowire located between two Hall crosses. As previously seen in thin films [8], a drop of resistivity of 0.2%, due to the abrupt change of magnon density, appears in both positive and negative half loops, revealing the magnetization switching.

According to Eq. (1), ρ_{MMR} is proportional to (M/M_S), and therefore to the position of the domain wall along the wire. To confirm that hypothesis, a major MMR loop has been measured [cf. Fig. 2(a)], followed by a minor loop in which a domain wall is introduced within the wire. As seen in previous experiments (see Ref. [10]), the DW gets pinned on a structural defect, which allows to go back to zero field without inducing DW motion. According to Eq. (1), the slope of the minor loop during the return to zero field is equal to $\alpha\, M/M_S$. This results in a value of $M/M_S \sim -0.52$, i.e., the DW has reversed 24% of the length of the wire.

We then measured the DW position using magnetic force microscopy (MFM). The MFM image in Fig. 2(b) shows that a single domain wall is located at 1.4 μm between the two electrical contacts, which corresponds to the reversal of 23.3% of the 6 μm long wire, in agreement with the MMR measurement.

MMR also provides a way to investigate the dynamics of DW motion. In Fig. 2(c), a constant field is applied close to the reversal field, and the resistivity of the wire is measured as a function of time. The first sharp decrease of resistance corresponds to the introduction and to the motion of the DW within the wire. It then gets pinned on a defect for awhile, which corresponds to the observed MMR plateau. The DW is finally depinned by thermal activation, leading to the magnetic saturation of the wire. This behavior is exactly similar to what was measured in Ref. [9] using GMR, which emphasizes that MMR measurements provide, although with lower signals, the same information as TMR and GMR measurements (e.g., [9,11,12]). However, MMR measurements do not need a reference layer that may change the involved physics (DW dynamics, spin-transfer torque...) because of stray fields or spin accumulation effects. Also, MMR obviously offers a more accurate description of the reversal than DWR and AMR, which only detect the presence of a domain wall in the nanowire, and AHE, which only detects the presence of the DW in the Hall cross.

Surprisingly, MMR can also be used in systems with low anisotropy. Indeed, the replacement of the magnetocrystalline anisotropy by a shape anisotropy leads to very similar MMR properties. As an example, we have studied permalloy ($Ni_{84}Fe_{16}$) nanowires in the device geometry shown in Fig. 3(a). NiFe samples with 30 nm thickness were deposited by e-beam evaporation from NiFe alloy target, the nanowires being obtained using a lift-off process.

NiFe nanowires constitute model systems in which the magnetization reversal is governed by the shape anisotropy and they provide the basis of most experiments on field-induced DW dynamics and current-induced DW motion [13–16]. They are also used in numerous experiments and are the most commonly used spin injector in nonmagnetic nanowires [17–19]. Up to now, the magnetoresistance of NiFe nanowires has always been interpreted as the effect of AMR [e.g., [20–24]].

Figure 4(a) shows the magnetoresistance curves of a NiFe nanowire, for different orientations of the applied field (the rotation axis belongs to the plane of the sample, and is perpendicular to the wire). If the applied field is perpendicular to the wire, one observes the classical AMR curve [20–22]. However, at zero degree, the resistivity

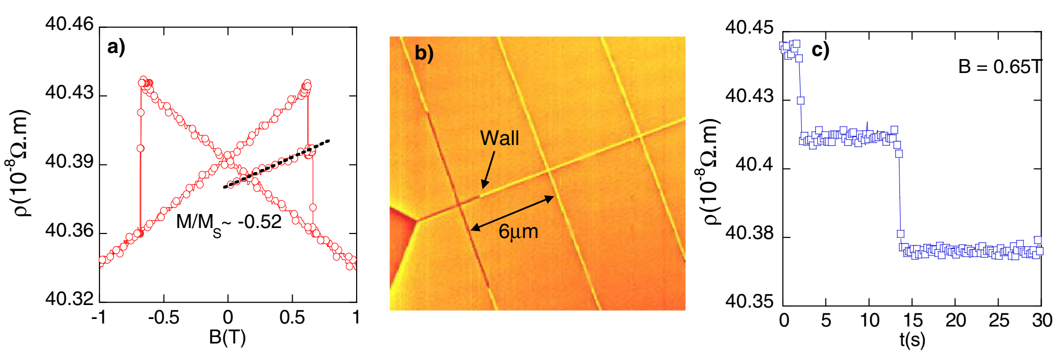

FIG. 2 (color online). Detection of the position of a DW along a FePt nanowire. (a) Major and minor MMR loops. The wire is partially reversed at +0.645 T. The slope of the minor loop corresponds to $M/M_S \sim -0.52$, i.e., to the reversal of around 24% of the length of the wire. (b) MFM image realized after measuring the minor loop, showing that the domain wall is located at around 23.3% of the length of the wire. The reversed domain appears in dark brown. (c) Resistivity of the nanowire as a function of time. The sample is firstly saturated in negative fields, and then submitted to a constant positive field, close to the reversal field.

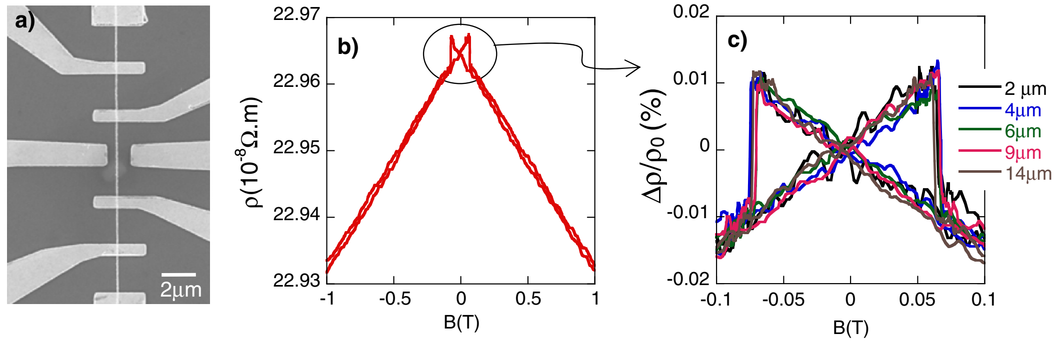

FIG. 3 (color online). (a) Scanning electron microscopy observation of a 50 nm wide NiFe nanowire, with Au contacts to perform four-probe resistance measurements. (b) Magnetoresistance curves of a NiFe nanowire, for an applied field parallel to the wire, and at low fields (c) for various lengths of nanowires. These measurements were realized using standard lock-in technique at room temperature (four-probe measurements at 3×10^{10} A/m^2 and $f = 6700$ Hz).

linearly decreases with the applied field, whereas according to AMR theory it should be constant. We attribute this non negligible decrease of the resistance to the electron-magnon diffusion. An alternative explanation based on AMR can be disregarded as it would require a misalignment of ~20° to give account of the observed slope.

More interestingly, the low field magnetoresistance curves at 0° [Figs. 3(b) and 3(c)] have an aspect very similar to the MMR loop observed in FePt, with a sharp decrease of resistivity during the magnetization reversal. We state that the magnetoresistance behavior at 0° is dominated by the MMR. The theoretical analysis of the MMR curve is the same as those provided for FePt [6], except that the magnetocristalline anisotropy field of FePt has simply to be replaced by the shape anisotropy of the 50 nm wide NiFe nanowire. Note that the observed loop corresponds to an increase of resistance, whereas AMR induces a decrease of resistance before the magnetization switching. We suppose that the clear observation of this effect is due to the small width of our wires, which leads to an high shape anisotropy, and to the use of straight wires.

Interestingly, the magnetoresistance curves of Fig. 4(b) show that the MMR effect can be performed to detect magnetization reversal for various field orientations. As the shape anisotropy is strong in comparison with the switching fields, there is no significant AMR contribution at angles smaller than 20°, and the MMR measurements allow to detect precisely the switching fields. These curves also underline, here again, the fact that the observed loop is not due to an AMR contribution, which might come from a misalignment of the applied field and of the wire. Moreover, in Fig. 3(c), the loop does not vary with the distance between contacts, even when using a two probe measurement (curve for the 14 μm long wire), which excludes any magnetoresistive contribution linked to the contacts.

Such a simple resistance measurement using a two probe configuration can be useful to detect the switching fields of ferromagnetic nanowires, in nanostructures possessing various geometries (e.g., injection electrodes as in lateral spin valves). Also, by applying fields smaller than the switching fields, it is possible to detect the magnetization orientation without reversing it: the sign of the $\rho(B)$ slope is negative if the magnetization is parallel to the field, and positive if it is antiparallel. Finally, our analysis is supported by the temperature dependence of the phenomenon shown in Figs. 4(c) and 4(d): whereas AMR increases when temperature is lowered, MMR is reduced when the magnon population decreases. Note that this implies that the MMR effect can be increased by heating, as seen in Fig. 5. When the temperature approaches the Curie temperature, the MMR slope is significantly increased, as the

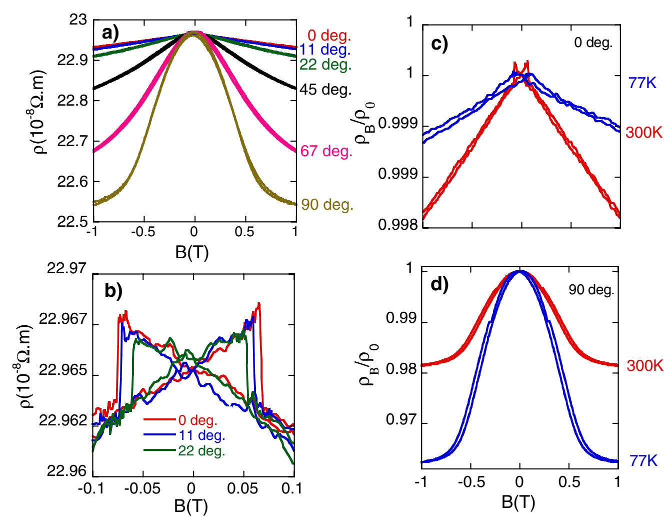

FIG. 4 (color online). Magnetoresistance curves of a NiFe nanowire for different angles between the wire axis and the applied field at (a) high field and (b) low fields and small angles. One observes the usual decrease of the coercive field with the angle (cf. ref. [21]). (c) Normalized magnetoresistance curves of a NiFe nanowire, for fields applied at (c) 0° and (d) 90°, at 77 and 300 K.

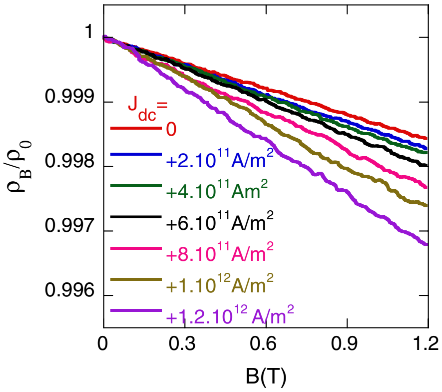

FIG. 5 (color online). Magnetoresistance curves of a NiFe nanowire, heated by different current densities (J_{dc}). The slope of each curve gives the amplitude of the MMR effect, which increases with the current density.

magnon contribution to resistivity increases relatively to other sources of resistivity (phonons,. . .).

To conclude, MMR should become a versatile tool for any scientist realizing transport experiments in magnetic nanostructures, and has to be taken into consideration when interpreting magnetoresistance curves of magnetic materials. Even though its magnitude is small for applications, it can be easily and precisely measured using standard lock-in techniques. Also, it can be increased: as seen in Fig. 5, that might be simply done by heating, but one can also imagine using high frequency currents or microwaves to increase the magnon population. Moreover, the magnitude of MMR is strongly material dependent [6], and materials engineering may provide samples with high MMR signals.

Finally, we demonstrated that the contribution of magnons to resistivity can be used to probe the magnetization. We suggest that it could also be used as a tool to probe the magnon population: when the magnon population increases, the resistivity should vary with the number of electron-magnon diffusion events.

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