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Direct experimental determination of the anisotropic magnetoresistive effects

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We present an experimental study devoted to determine the magnetoresistive signals as imposed by the system magnetic anisotropy and applied current direction in a model ferromagnetic system. By having direct experimental access to the magnetization vector during the reversal (measured through angular- and field-dependent vectorial-resolved magnetization loops), we can predict both longitudinal and transverse magnetoresistive signals, i.e., anisotropic magnetoresistance and planar Hall effect. This has been done by experimentally disclosing the resistance changes occurring during (and simultaneously to) the magnetization reversal processes. © 2014 AIP Publishing LLC.

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A wide class of recording, processing, and sensing ferromagnetic (FM)-based devices exploit the change of the electrical resistance depending on the orientation of the magnetization vector with respect to the charge current direction. However, despite the enormous market moving around the spintronic technologies, mainly for the production of magnetic sensors and memories, the microscopic understanding of magnetoresistive effects in low dimensional structures has not been fully addressed experimentally so far. The magnetoresistance (MR) signals are interpreted in light of spin-up/spin-down conduction, so that, in both single-layer and multilayer structures, high/low resistivity outputs are determined by electron current and system magnetization configuration. In the following, we demonstrate that anisotropic magnetoresistance effects are generic notion of this phenomenon.

The anisotropic magnetoresistance (AMR) is characterized by a voltage drop along the current (J) direction and is described for a single-domain system by $E_r = J \rho_{\parallel} + J(\rho_{\parallel} + \rho_{\perp})\cos^2 \theta$, where $\theta$ is the angle enclosed by the magnetization vector $\mathbf{M}$ and $\mathbf{J}$, and $\rho_{\parallel}$ and $\rho_{\perp}$ stand for the (in-plane) resistivities for current parallel and perpendicular to the external magnetic field, respectively. In addition, a transverse voltage drop arises whenever the current is neither perpendicular nor parallel to the magnetization. This, known as planar Hall effect (PHE), is described by $E_y = J(\rho_{\parallel} - \rho_{\perp})\sin \theta \cos \theta$ and is particularly exploited for sensors.

Actually, AMR and PHE being due to spin-orbit coupling, we might expect similar hysteretic magnetoresistive behaviors in function of the external applied magnetic field $\mu_0 \mathbf{H}$ and $\mathbf{J}$ for systems with similar intrinsic anisotropy. However, apparently contradictory results in both shapes and amplitudes (including positive and negative ratio) of the measured MR curves have been found in many systems, as transition metals, perovskite oxides, and diluted magnetic semiconductors for similar applied field and current direction.

In order to shed light on this issue, it is necessary to achieve full understanding on the system magnetic anisotropy that dictates the way how the magnetization reverses under an external magnetic field. The magnetic properties of a thin-film system are usually probed by investigating the angular dependence of the AMR (or PHE) via magnetotransport measurements under a field high enough to saturate its magnetization. By doing so, it may be possible to determine the magnetic anisotropy strength and direction, temperature-dependence, asymmetries, and magnetic torque, assuming $\mathbf{M}$ fixed. Therefore, it is not possible to disclose the relationships between $\mathbf{M}$ and MR at any field value and direction.

In this Letter, we have chosen a simple system, i.e., 10-nm thick Ni$_{0.8}$Fe$_{0.2}$ (Py) polycrystalline layer with well-defined uniaxial magnetic anisotropy, for the study of the angular-dependent relationships between the magnetization reversal mechanisms and the in-plane longitudinal and transverse MR changes for different direction of the applied current and external magnetic field. In our vectorial-resolved experiments, we get also direct access to the sample magnetization vector that immediately provides the angles $\alpha \equiv (\mathbf{M}, \mathbf{H})$ that defines the magnetic torque ($\propto \sin \alpha$) and $\mathbf{M}, \mathbf{J}$ that defines AMR and PHE (Figure 1(a)).

The 10-nm thick Ni$_{0.8}$Fe$_{0.2}$ (Py) sample was grown at room temperature (RT) by dc sputtering on oxidized Si substrate pre-covered with a 2-nm thick Ta buffer layer. The structure was then capped with a 2-nm thick Ta layer to prevent oxidation. During the deposition of the FM layer, an external magnetic field of about 250-mT (i.e., much higher than the anisotropy field of Py) was applied in order to define its magnetic anisotropy. Magnetization reversal processes and magneto-resistive properties were studied at RT by measuring simultaneously in-plane vectorial-resolved magnetization hysteresis loops and the corresponding resistance...
The sample was contacted using Au-wire bonding in a four-probe geometry. The measurements were performed using a lock-in amplifier with an ac current of 50 μA, with a frequency of 41 kHz through a load resistance of $R_l \approx 1 \, \Omega$, whereas the sample resistance is about 20 Ω. MR($H$) = $\frac{R(H)-R_m}{R_m}$, where $R_m$ is the resistance at saturation field (sample magnetization aligned to current direction), was hence extracted from the experimental $R(H)$ curves. The longitudinal and transverse resistance changes have been measured by employing in-line and in-cross electrical contacts, respectively. The magnetization loops were measured by high resolution vectorial-Kerr magnetometry by using p-polarized light focused between the inner electric probes and analyzing the two orthogonal components of the reflected light. This provides the (additional) simultaneous determination of the hysteresis loops of both in-plane parallel, $M_l$, and transverse, $M_T$, magnetization components as a function of the applied magnetic field.21–24

By looking at the vectorial-plot $M_l$ vs. $M_T$ representation in Figure 1(b) at selected angles $\alpha_H$ from e.a. to hard-axis (h.a.), we can visualize the direction of the magnetization vector (i.e., $\alpha$) and determine the mechanisms of the magnetization reversal. These plots reveal clearly that the sample magnetization rotates in order to get aligned to the anisotropy axis.

Figure 2 presents selected $M_l$-$H$, $M_T$-$H$, and MR-$H$ loops acquired simultaneously. By looking at panel (a), both in-plane magnetization components, $M_l$ and $M_T$, show either smooth fully reversible or sharper irreversible transitions. At e.a., i.e., $\alpha_H = 0^\circ$, the parallel component presents a perfect squared shape hysteresis loop. $M_T$ does not change from saturation ($M_S$) to remanence ($M_{||R}$), i.e., $M_{||R}/M_S \approx 1$, and there is only a sharp irreversible jump at the coercive field $H_C = 0.125$ mT, in which the magnetization reverses completely. $M_l(H) \approx 0$ in the whole field loop. Both are expected behaviors of a magnetization e.a. direction in which the reversal takes place via nucleation and further propagation of magnetic domains oriented parallel to the field direction.25,26 For $\alpha_H \neq 0^\circ$, clear reversible and irreversible transitions in both $M_l(H)$ and $M_T(H)$ loops are found.27

FIG. 1. (a) Scheme of the experimental M(R)/OKE set-up. (b) $M_l$ vs. $M_T$ vectorial-plots at selected angles $\alpha_H = 0^\circ$ is taken when the external field is aligned parallel to the direction of the uniaxial magnetic anisotropy ($K_u$), i.e., along the easy-axis (e.a.) of the system. Both in-plane magnetization components are normalized to the magnetization at saturation field $M_S$. It is clearly seen that the sample magnetization always follows the anisotropy axis: at e.a. the magnetization can only lie parallel to the external magnetic field, whereas close to h.a. $M_l$ vs. $M_T$ presents a quasi-circular loop describing the rotation of the magnetization vector during the reversal. Changes, as function of the sample in-plane angular rotation angle $\alpha_H$ keeping fixed the external magnetic field direction. $\alpha_H = 0^\circ$ is taken when the external field is aligned parallel to the direction of the uniaxial magnetic anisotropy ($K_u$), i.e., along the easy-axis (e.a.) of the system. The whole angular range was probed every 1.8°, with 0.5° angular resolution. The scheme of the experimental set-up is shown in inset of Figure 1(a). To measure MR, we have employed an ac technique varying the applied current direction from parallel to perpendicular to $K_u$, i.e., $\theta_J = 0^\circ$ and $\theta_J = 90^\circ$, respectively.

FIG. 2. Comparison of the vectorial-resolved $M$-$H$ and MR-$H$ loops at selected angles $\alpha_H$ from e.a. ($\alpha_H = 0^\circ$) to h.a. ($\alpha_H = 90^\circ$) magnetization direction. $M_l$ and $M_T$ are shown in panel (a). The vanishing perpendicular component at $\alpha_H = 90^\circ$ turns out after averaging many successive iterations in which for each one the magnetization can rotate along the positive and negative values of $M_l$. Panels (b) and (c) show MR-$H$ loops with current flowing parallel to e.a. ($\theta_J = 0^\circ$) and h.a. ($\theta_J = 90^\circ$), respectively. $M_l$ and $M_T$ are normalized to $M_S$ and MR to the maximum (2.4%)
When the field is applied along the h.a. \((z_H = 90^\circ)\), the \(M_1(H)\) loop shows an almost linear and reversible behavior of the magnetization, \(M_{1,R}/M_S \approx 0\) and \(\mu_0H_C \approx 0\) mT. These features are typical of an uniaxial magnetic anisotropy h.a.\(^{25}\) Resuming, around the e.a. direction, the reversible transitions correspond to a reversal by magnetization rotation, whereas the irreversible ones correspond to propagation of magnetic domains oriented parallel to the field direction. Around the h.a. direction, the hysteresis loops show similar (and large) \(M_J\), signals but with opposite sign, indicating that the magnetization vector rotates in-plane 180\(^\circ\) during the reversal.

The simultaneous transport measurements have been performed for both current parallel \((\theta_J = 0^\circ)\) and perpendicular \((\theta_J = 90^\circ)\) to \(K_U\) direction, as shown in Figures 2(b) and 2(c), respectively. From a first view, we notice that the MR-H curves acquired at \(z_H = 0^\circ\) are flat in whole magnetic loops, whereas present the largest variation at \(z_H = 90^\circ\). The maximum MR jump, i.e., \(\text{AMR} = \left| \rho_i - \rho_j \right|/\left[ (1/3)\rho_i + (2/3)\rho_j \right] \), is 2.4\%. If the current is injected parallel to the e.a. direction, i.e., \(\theta_J = 0^\circ\) (Figure 2(b)), the maximum MR values is obtained at \(z_H = 0^\circ\), i.e., when \(J \parallel M\). MR is constant because the sample magnetization is forced, by the intrinsic anisotropy of the system, to be parallel to the external magnetic field, that is, parallel or antiparallel to the applied current. Increasing \(z_H\), the MR shape changes and decreases smoothly for higher magnetic field. The MR jump becomes larger and larger approaching to h.a. \((z_H = 90^\circ)\), where \(J \perp M\). At h.a. in fact, \(M\) rotates in-plane during the reversal, whereas at the saturation field it points perpendicularly to the current direction. In clear contrast, different behavior is found when \(J\) is injected parallel to the h.a. direction, i.e., \(\theta_J = 90^\circ\) (Figure 2(c)). The maximum MR is obtained at \(z_H = 90^\circ\), which corresponds to \(J \parallel M\). The MR curve shows the maximum change at high magnetic field, where \(M \parallel J\). Approaching to e.a., MR progressively diminishes and, at \(z_H = 0^\circ\), becomes flat assuming its minimum value, i.e., \(M \perp J\).

It is worth noting that the angular-dependent study shows unambiguously that the MR values are always comprised within a maximum value, obtained when the current is parallel to the magnetization direction, and a minimum value, when the current and the magnetization vector are orthogonal. For a given \(z_H\), the MR maximum value and shape can be controlled therefore by the applied current direction.

The influence of the magnetic anisotropy of the system into both magnetization and magnetoresistive signals can be directly seen in Figure 3, in which we have separately the forward and backward branches of both \(M_{1,H}\) and MR-H hysteresis loops, and plotted the whole angular evolution in 2D color map.\(^{26}\) For instance, by looking at the top-graphs, the angular evolution of \(M_{1,H}\) reveal the angular-dependent behavior of the transition fields, coercive field \((\mu_0H_C)\) and switching field \((\mu_0H_S)\), i.e., yellow-bright color line, which present 180\(^\circ\) periodicity (two-fold symmetry) characteristic of a well-defined magnetic uniaxial anisotropy system.\(^{25}\)

Such a symmetry emerges also in the MR-H maps for both \(J \parallel K_U\) and \(J \perp K_U\) in Figures 3(b) and 3(c). At first glance, these 2D maps appear identical, apart from the inverted color-code. This corresponds to a MR that is, at e.a., maximum or minimum depending on the applied current direction, i.e., \(\theta_J = 0^\circ\) or \(\theta_J = 90^\circ\), respectively. The maximum changes of the MR are always obtained at the h.a. because the magnetization rotates in-plane during the reversal.

Remarkably, from the experimental vectorial-resolved magnetization loops, we can extract \(\theta\) between \(M\) and \(J\), that is, \(\theta = \theta_J - \alpha + z_H\), where \(\alpha = \arcsin(M_{1,H}/|M|)\). This is seen in the 2D maps, in Figure 4, in which the left-graphs show the predicted behaviors and the right-graphs the measured MR for (panel (a)) current parallel to \(K_U\) \((\theta_J = 0^\circ)\) and (panel (b)) for current perpendicular to \(K_U\) \((\theta_J = 90^\circ)\). By following the angular evolution at different field values (e.g., \(\mu_0H = 0\) mT, \(\mu_0H = 0.37\) mT, \(\mu_0H = 0.60\) mT, and \(\mu_0H = 1.72\) mT), we recover the theoretical \(\cos^2\theta\) behavior for the AMR\(^{24}\) only when the applied magnetic field is high enough to saturate completely the sample, that is, when the sample magnetization is forced to be aligned to the external field. As shown in Figure 4(d) for the forward branch of measured MR with \(\theta_J = 0^\circ\) (qualitatively it is the same for \(\theta_J = 90^\circ\)), for applied field comprised between zero and saturation field \((1.72\) mT), \(\cos^2\theta\) does not reproduce the experimental data. In panel (c), the transverse MR, measured perpendicular to the direction of the current (with current flowing at \(\theta_J = 45^\circ\), presents an angular evolution, as well as each single MR-H loop, similar to MR acquired when measuring the longitudinal field \(E_L\) with current \(\theta_J = 0^\circ\). The PHE angular behavior can be satisfactorily reproduced by \(\sin\cos\theta\), as shown in Figure 4(c).

In conclusion, we have presented a systematic angular- and field-dependent study on magnetization reversal processes and magnetoresistive responses, measured, simultaneously, in a ferromagnetic Py film with uniaxial magnetic anisotropy. We have demonstrated unambiguously that by having direct experimental access to the magnetization...
vector, we get the relevant information about the magnetization reversal mechanisms, allowing also the prediction (without any electrical contacts) of the magnetoresistive response. In Figure 4, we have highlighted the perfect agreement between the measured AMR (and PHE) with $\cos^2 \theta$ (and $\sin(\theta \cos \theta)$), demonstrating their exclusive dependence on the reversal processes (ultimately dictated by magnetic anisotropy of the system). Our experimental method can be applied in any kind of magnetic structure to directly correlate magnetization reversal and MR, opening a new route for magnetism manipulation.

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