Spin-orbit torques in ultrathin ferromagnetic metal layers

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ABSTRACT

The spin-orbit interaction constitutes a weak but essential perturbation to the Hamiltonian of magnetic systems. Linking spins with atomic structure, spin-orbit coupling assumes a prominent role in structures of reduced dimensionality, where it defines the internal anisotropy fields. In this paper, we discuss interface-enhanced spin-orbit effects that arise in metallic multilayers in the presence of an electric current. We demonstrate that a novel type of spin torque can be induced in ferromagnetic metal films lacking structure inversion symmetry through the Rashba effect. Owing to the combination of spin-orbit and exchange interactions, we show that electrons flowing in the plane of a Co layer with asymmetric Pt and AlO_x interfaces produce an effective transverse magnetic field of 1 T per 10^8 A/cm^2 of applied current. This torque does not require a current flowing through noncollinear magnetic structures, opening new perspectives for room temperature applications in spintronics.

Keywords: Spin-orbit interaction, spin torque, Rashba effect, magnetism

1. INTRODUCTION

Methods to manipulate the magnetization of ferromagnets alternative to external magnetic field open a wide spectrum of opportunities to integrate magnetic functionalities into electronic circuits. In recent years, much effort has been devoted to current-induced torques, which directly act inside the core magnetic element of a device without producing long-range stray fields. The aim is to reduce the dimensions and spacing of magnetic bits, integrating the read and write functions onto a single chip with acceptable energy consumption.

The possibility to use a spin polarized current to induce a local torque on the magnetization dates back to the seminal work of Berger[2] and Slonczewski[1] and since then it has been investigated extensively both theoretically and experimentally.[3–5] The physical principle behind this effect is called spin transfer torque (STT) and requires the flow of an electric current between noncollinear magnetic structures to transfer spin angular momentum from one to another. This is usually realized in heterostructures (pillars) comprising two ferromagnetic (FM) layers separated by a nonmagnetic metal spacer (spin valve) or insulator (magnetic tunnel junction), as well as in domain walls. Typical current density values required to induce the switching of one magnetic configuration with respect to the other range around 10^7A/cm^2. Despite its great fundamental and practical interest, the exploitation of STT to write information in, e.g., magnetic tunnel junctions still suffers from the need to compromise between large current density (requiring low junction resistance to avoid damage) and readability (requiring large magnetoresistance). Moreover, optimization of the spin polarization across the junction, stabilization of the "fixed" layer magnetization, and minimization of stray fields often result in complex stacking structures involving more than 10 different layers.

Very recently, an alternative way has emerged to control the magnetic state of a FM layer by means of an electric current, which we refer to as *spin-orbit torque*. Such a torque is fundamentally different from STT, as it relies on the presence of strong spin-orbit (SO) coupling intrinsic to the nuclear composition and atomic

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Spintronics III, edited by Henri-Jean M. Drouhin, Jean-Eric Wegrowe, Manijeh Razeghi, Proc. of SPIE
Vol. 7760, 77600Z · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.862356

structure of a material, and the transfer of orbital to spin angular momentum rather than that from one spin lattice to another. The correlation between charge current and spin polarization arising from the SO interaction has been extensively studied in nonmagnetic semiconductors since the 1970s[6–8] and recently reviewed in different publications.[9–11] It is only in the last two years, however, that current-induced SO effective magnetic fields have been predicted to occur in FM[12–14] and their existence demonstrated in a dilute magnetic semiconductors[15] and ultrathin metal films.[16] Such investigations bridge two of the main research areas in spintronics, the one based on magnetic multilayer devices[17] and the one "without magnetism", based on the manipulation of the electron spin in nonmagnetic conductors.[11] The observation of strong SO torques at room temperature combined with the simple layer structure and robust FM properties of metal films[16] open a promising new avenue to manipulate the magnetization of spintronic devices by means of electric currents.

2. COMBINED EFFECTS OF EXCHANGE AND SPIN-ORBIT COUPLING IN FERROMAGNETS

2.1 The Rashba Hamiltonian

The generation of spin-orbit torques is intimately related to the presence of structure inversion asymmetry (SIA). As is well known from semiconductor physics, SIA, through the Rashba interaction, provides a means to induce a net out-of-equilibrium component of the spin density, the direction of which depends on the cross product between the symmetry axis $\hat{\mathbf{z}}$ and the current density $\mathbf{j}$. It is easy to understand how SIA result in magnetic field-like interactions by considering the motion of electrons in an asymmetric crystal field potential (V). At nonrelativistic speed (v), the net electric field originating from such a potential $-\nabla V$ transforms into a magnetic field $(\mathbf{v} \times \nabla V)/c^2$ in the electron's rest frame. When transforming back into the laboratory's reference frame, the magnetic induction field experienced by the electron is corrected by a factor 2, giving $\mathbf{B}_{SO} = (\mathbf{v} \times \nabla V)/(2c^2) = (\hbar \mathbf{k} \times \nabla V)/(2m_e c^2)$.[18] The SO Hamiltonian is then given by $\sigma \cdot \mathbf{B}_{SO}$, where σ is the vector of Pauli spin matrices. This interaction, in the case of layered heterostructures,[19,20] is usually written in the form first given by Rashba,[21]

$$\mathcal{H}_R = \alpha_R(\mathbf{k} \times \hat{\mathbf{z}}) \cdot \sigma, \tag{1}$$

which correspond to the interaction of an effective $\mathbf{k}$-dependent magnetic field with the electron spin for a potential gradient along $\hat{\mathbf{z}}$. Here, α_R is a material-dependent constant that scales with the strength of the SO interaction and ∇V. For $\mathbf{j} = 0$, $\mathcal{H}_R$ cancels out as $\mathbf{k}$ and $-\mathbf{k}$ states are equally populated. In the presence of a charge current, however, the electron distribution in $\mathbf{k}$-space becomes asymmetric, producing a net effective field and inducing, on the conduction electrons, a nonequilibrium spin density perpendicular to $\mathbf{j}$.

2.2 Rashba Hamiltonian with $s-d$ exchange

The above discussion shows that it is possible to manipulate the polarization of the conduction electrons spin in the absence of external magnetic fields in a SIA system. Together with other forms of spin accumulation and spin currents that can be excited in semiconductors by electrical or optical means, this has generated considerable interest into a "magnet-free" approach to spintronics.[11] Moreover, several proposals have been made to exploit the intrinsic SO fields in semiconductors to control or modulate spin injection into FM electrodes through a semiconductor channel[22] or tunnel junction.[23] More recently, however, it has become clear that the very same SO effect is intrinsic also to ferromagnets (FM)[24] and can be used to induce a torque on the local magnetization in a single, uniformly magnetized FM structure[12–14] as well as domain wall motion in FM layers.[25]

The combined action of SO coupling and $s-d$ exchange interaction in a single FM layer with either SIA is described by the Hamiltonian

$$\mathcal{H} = \alpha_R(\mathbf{k} \times \hat{\mathbf{z}}) \cdot \sigma - J\hat{\mathbf{M}} \cdot \sigma, \tag{2}$$

where $\hat{\mathbf{M}} = \mathbf{M}/M_s$ is an adimensional unit vector, M_s the saturation magnetization of the FM (A/m units), and J (eV units) the exchange coupling parameter between the conduction electron spin and the local moments of the FM. The physical picture described by Eq. (2) is that, even though the spin of the conduction electrons in a FM is usually aligned parallel or antiparallel to the local magnetization $\mathbf{M}$, an out-of-equilibrium spin density noncollinear to $\mathbf{M}$ is created by the flow of a current. This component interacts with $\mathbf{M}$ through the exchange coupling between itinerant and localized electrons, i.e., between $p-d$ and $s-d$ states in a magnetic semiconductor

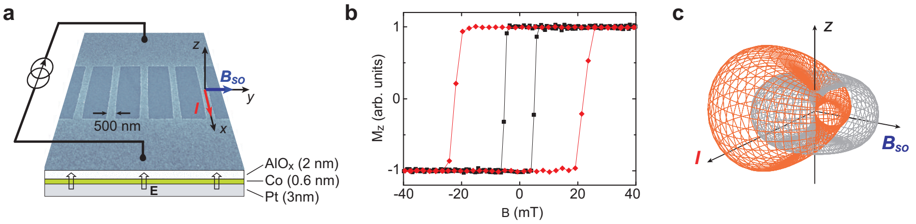

Figure 1. (a) Scanning electron micrograph detail of the patterned Pt/Co/AlO$_x$ wire array and schematic vertical cross section of the layer. Arrows indicates the direction of the current ($\mathbf{j}$), interfacial electric field ($\mathbf{E} = -\nabla V \parallel \hat{\mathbf{z}}$), and $\mathbf{B}_{sd}$. The sign of $\mathbf{E}$ is determined from the measured orientation of $\mathbf{j}$ and $\mathbf{B}_{sd}$ assuming positive polarization of the conduction electrons near the Fermi level. (b) Perpendicular magnetization of Pt/Co/AlO$_x$ (red diamonds) and Pt/Co/Pt (black squares) measured at room temperature by AHE. (c) Three-dimensional energy landscape of a uniaxial monodomain FM system with SIA in the absence (presence) of current, shown in gray (red).

and transition metal, respectively, in a way analogous to a magnetic field with fixed orientation, determined by the current and crystal structure.

Manchon and Zhang[12] have explicitly calculated the action of a current on the local moments, which turns out to be equivalent to that of an induction magnetic field (T units)

$$\mathbf{B}_{sd} = J\frac{\langle\delta\sigma\rangle}{M_s} = -\frac{m_e^*\alpha}{e\hbar M_s}Pj\,(\hat{\mathbf{z}}\times\hat{\mathbf{j}}), \tag{3}$$

or to that of a torque per unit volume

$$\mathbf{T}_{sd} = \hat{\mathbf{M}}\times J\,\langle\delta\sigma\rangle = \frac{m_e^*\alpha}{e\hbar}Pj\,(\hat{\mathbf{M}}\times\hat{\mathbf{y}}), \tag{4}$$

where the parameter $P = J/\varepsilon_F$ is approximately equal to the spin polarization of the current.

3. SPIN-ORBIT TORQUES IN ULTRATHIN METAL FILMS

Experimental studies of current-induced SO effects have traditionally focused on semiconductors[15, 26–28] since bulk metals present centrosymmetric crystal structures. However, Rashba-type SO splitting of the conduction bands can still take place at the interface between a metal and a dissimilar material, including vacuum. This was first recognized in angle-resolved photoemission measurements of the surface states of nonmagnetic 5d elements, in particular Au[29] and W.[30] Investigations of rare-earth surface states, notably of Gd[31] and Tb,[32] later revealed clear signatures of coexisting Rashba and exchange coupling in the case of FM metal films in the form of magnetization dependent asymmetry of the electron band dispersion. These studies coincide in showing that a heavy metal interface induces large Rashba splittings of the order of 100 meV and that increasing the asymmetry of the charge distribution at a metal surface leads to an increase of such an effect.[31]

The necessary conditions to induce a SO torque are therefore fulfilled in metal systems as well as semiconductors. Recently, we reported the first observation of a current-induced SO torque in a FM metal for a thin Co layer grown between asymmetric Pt and AlO$_x$ interfaces.[16] The structure of this system, shown in Fig. 1 (a), was chosen so as to optimize the SIA of the FM Co layer and produce a strong Rashba effect. Experiments were performed on a 0.6 nm thick Co film sandwiched between 3 nm Pt and 1.6 nm Al layers deposited by sputtering on a thermally oxidized Si wafer. The top Al layer was exposed to an oxygen rf plasma resulting in a fully oxidized AlO$_x$ interface at the Co boundary.[33, 34] SIA results from the presence of AlO$_x$ and Pt on either side of the Co layer, where Pt-Co hybridization enhances atomic SO coupling and both interfaces create a strong out-of-plane electron potential gradient. Measurements of the magnetic anisotropy energy and orbital

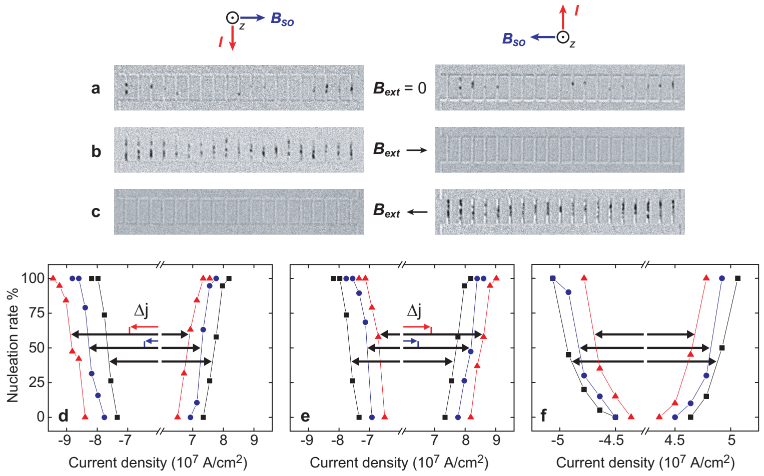

Figure 2. Difference between consecutive Kerr microscopy images of Pt/Co/AlO$_x$ wires recorded before and after current pulse injection for (a) $B_{ext} = 0$, (b) $B_{ext} = +47.5$ mT, (c) $B_{ext} = -47.5$ mT and positive (left) negative (right) current values at constant pulse amplitude $j = 7.8 \times 10^7$ A/cm^2. (d) Percentage of wires that present reversed magnetic domains after the injection of a current pulse as a function of j and B_{ext}. (a) Pt/Co/AlO$_x$, $\mathbf{B}_{ext} \parallel \hat{\mathbf{y}}$, (b) Pt/Co/AlO$_x$, $\mathbf{B}_{ext} \parallel -\hat{\mathbf{y}}$, (c) Pt/Co/Pt, $\mathbf{B}_{ext} \parallel -\hat{\mathbf{y}}$. Values of B_{ext} are 0 mT (black squares), ±47.5 mT (blue dots), ±95 mT (red triangles).

magnetization of Co/Pt,[35–38] the anomalous Hall effect (AHE) as well as the enhanced nonadiabatic spin torque component found in Pt/Co/AlO$_x$ domain wall constrictions[39] indicate that SO coupling in such a system is strong. Most importantly, the Co layer is FM at room temperature with 100% remanence, as shown in Fig. 1 (b). The Co magnetization has a saturation value close to the bulk, $M_s = 1090$ kA/m, and is very stable after oxidation. For control purposes, a symmetric structure Pt/Co/Pt was grown by replacing the AlO$_x$ layer with 3 nm Pt, with $M_s = 1110$ kA/m. Both samples present strong out-of-plane anisotropy and uniaxial anisotropy fields of 0.92 and 0.57 T, respectively, determined as the field required to achieve 90% magnetic polarization along the hard axis.

In order to observe the effects of current injection on $\mathbf{M}$, the two films were patterned into an array of wires, each 0.5 μm wide and 5 μm long, and contacted by two current pads. In this geometry, the application of a current is expected to produce an in-plane field $\mathbf{B}_{sd}$ perpendicular to the wires, as given by Eq. (3). By itself, this field will not induce deterministic switching of $\mathbf{M}$ between the up and down directions. However, if $\mathbf{B}_{sd}$ is sufficiently strong compared to the anisotropy field, the energy barrier for magnetization reversal will be distorted from the symmetric donut shape typical of uniaxial anisotropy to a strongly asymmetric profile, lowering the barrier in the $\hat{\mathbf{j}} \times \hat{\mathbf{z}}$ direction and raising it in the opposite one, as shown in Fig. 1 (c). Such a current-induced distortion can be compensated or enhanced by applying an in-plane external field B_{ext} collinear to it, providing a means to quantify the magnitude of B_{sd}. Starting from a monodomain out-of-plane configuration, the Co magnetization was monitored using wide-field polar Kerr microscopy as single current pulses of increasing amplitude and constant 100 ns duration were injected into the wires until the nucleation of reversed domains was observed. This occurred as the wires evolved from the saturated metastable monodomain state towards the macroscopically demagnetized ground state constituted by an equal mixture of up and down domains. Figure 2 (a) shows that about an equal amount of nucleation events occurs at a current density $j = 7.8 \times 10^7$ A/cm^2 for opposite current directions if $B_{ext} = 0$. However, as $B_{ext} \neq 0$, the domain nucleation rate becomes strongly asymmetric depending on the relative orientation of current and field [Figs. 2 (b) and (c)]. These results qualitatively prove the presence of a current-induced torque acting on the Co magnetization with the symmetry properties predicted by Eq. (3). It shall be noted that Joule heating caused by the current may also lower the domain nucleation barrier, but cannot explain the asymmetry of the nucleation rate observed at constant j. Artifacts due to a small unintentional misalignment of B_{ext} outside the xy plane are also ruled out, as these would be independent on the sign of j. Further, the Oersted field acting on Co produced by the current flowing in the Pt layer would have opposite effects compared to those observed in Fig. 2, and an estimated magnitude of less than 1 mT. Finally,

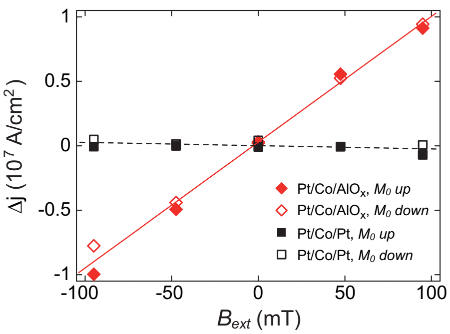

Figure 3. Variation of the current amplitude required to observe domain nucleation in 50% of the wires as a function of B_{ext}. Red diamonds correspond to Pt/Co/AlO$_x$, black squares to Pt/Co/Pt. Filled and open symbols refer to samples initially magnetized up ($\parallel \hat{\mathbf{z}}$) and down ($\parallel -\hat{\mathbf{z}}$), respectively. The lines are linear fits to the data.

similar measurements performed on Pt/Co/Pt do not yield any measurable asymmetry in the nucleation rate, providing a final proof of the SO origin of the torque in Pt/Co/AlO$_x$ related to SIA.

The quantitative dependence of B_{sd} on j was determined by making systematic use of B_{ext} as a known reference field, and plotting the percentage of wires for which at least one nucleation event was observed for a given combination of B_{ext} and j, as reported in Fig. 2 (d-f). Strong amplification or suppression of domain nucleation was observed depending on the orientation and amplitude of the current density and external field, leading to a rigid shift Δj of the nucleation rate curves measured for different values of B_{ext}. The inverse slope of the (B_{ext}, Δj) plot, reported in Fig. 3 for both Pt/Co/AlO$_x$ and Pt/Co/Pt, is a direct measure of the B_{sd}/j ratio, giving $(1.0 \pm 0.1) \times 10^{-8}$ T cm^2/A. This value shows that the SO torque acting on the Co magnetization is extremely large, matching the prediction of Eq. (4.3) for a Rashba constant $\alpha = 10^{-10}$ eV m, which is a realistic estimate considering that α ranges from 4×10^{-11} to 3×10^{-10} eV m at the interface of 5d metal systems and that oxidation may further enhance its value. Note that, as the current flows in both Co and Pt layers, the measured B_{sd}/j ratio in Pt/Co/AlO$_x$ depends also on the SO torque acting on the Pt induced magnetization.[35]

4. CONCLUSIONS

In summary, theoretical predictions and experimental observations show that strong SO torques acting on uniformly magnetized FM layers can be induced by the flow of an electric current. In FM metals, SO torques originate from SIA in combination with $s-d$ exchange, allowing for the transfer of orbital angular momentum from the crystal lattice to the local spin magnetization. Because of the intrinsic coupling between charge and spin, SO torques are equivalent to an effective magnetic field and can be induced in uniformly magnetized layers without the need of noncollinear polarization layers, contrary to STT. The current density required to produce sizeable SO-induced fields are in the range $10^6 - 10^8$ A/cm^2, comparable to those required by STT device operation.

ACKNOWLEDGMENTS

Work supported by the European Research Council (SG 203239 - NOMAD), the Spanish Ministerio de Ciencia y Innovación (MAT2010-15659) and Catalan Agència de Gestió d'Ajuts Universitaris i de Recerca (2009 SGR 695).

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