Spin Hall magnetoresistance in antiferromagnet/normal metal bilayers

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We investigate the emergence of spin Hall magnetoresistance in a magnetic bilayer composed of a normal metal adjacent to an antiferromagnet. Based on a recently derived drift-diffusion equation, we show that the resistance of the bilayer depends on the relative angle between the direction transverse

to the current flow and the Néel order parameter. While this effect presents striking similarities with the spin Hall magnetoresistance recently reported in ferromagnetic bilayers, its physical origin is attributed to the anisotropic spin relaxation of itinerant spins in the antiferromagnet.

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1 Introduction Transition metal multilayers have received a renewed interest lately with the search for current-driven spin–orbit torques [1, 2] and thermally-driven spin transport [3] in these systems. While bulk transition metal ferromagnets possess an anomalous conductivity tensor – hence displaying anisotropic magnetoresistance [4] and anomalous Hall transport [5] –, it has been recently realized that ultrathin films also display a peculiar form of the conductivity tensor. In particular, it has been shown that multilayers involving heavy metals possess a sizable anisotropic magnetoresistance with symmetries different from the one traditionally found in bulk ferromagnets [6]. While anisotropic magnetoresistance in bulk polycrystalline films [4] depends on the angle between the flowing current $\mathbf{j}_c$ and the magnetization direction, $\mathbf{m}$, i.e. $\sim(\mathbf{m} \cdot \mathbf{j}_c)^2$, in ultrathin films an additional (interfacial) anisotropic magnetoresistance emerges that depends on the angle between the magnetization and the direction *transverse* to the current flow, $\sim[\mathbf{m} \cdot (\mathbf{z} \times \mathbf{j}_c)]^2$, where $\mathbf{z}$ is the normal to the multilayer interfaces. Various origins have been proposed to explain this effect, such as anisotropic spin scattering arising from semiclassical size effect [6], interfacial Rashba spin–orbit coupling [7] and spin Hall effect taking place in the normal metal adjacent to the ferromagnet [8]. Now confirmed in a wide range of transition metal magnetic bilayers

[9], this effect is usually designated under the broad name of “spin Hall magnetoresistance” (SMR).

The research reported to date on the transport properties of ferromagnets has recently been extended to antiferromagnets, where spin–orbit torques [10, 11] and spin Seebeck effect [12] have been explored. The field of antiferromagnetic spintronics is now blooming, bearing promises for potential spin-based devices [13, 14]. In his Nobel lecture, Néel stated that any properties of ferromagnets that are *even* under magnetization reversal should also exist in antiferromagnets [15]. As a matter of fact, bulk anisotropic magnetoresistance [16], as well as tunneling anisotropic magnetoresistance [17] have been observed in several metallic antiferromagnets already and signatures of spin–orbit torques have been reported in antiferromagnetic bilayers [18, 19]. In this work, using a recently derived drift-diffusion model [20], we compute the spin Hall magnetoresistance in a metallic bilayer composed of an antiferromagnet adjacent to a normal metal. Such an effect has been recently reported in insulating antiferromagnets [21].

2 Model The system we consider is depicted in Fig. 1. A collinear, bipartite antiferromagnet (yellow) is deposited on top of a normal metal (green). The current is injected along x and the interface is normal to z . The antiferromag-

Figure 1 Schematics of the antiferromagnetic bilayer. The antiferromagnet (AF – yellow) is adjacent to a normal metal (NM – green). Due to spin–orbit coupling inside the normal metal, a flowing charge current along x (thick white arrow) creates a spin current flowing along z and polarized along y (thick pink arrow). The small black arrows represent the magnetic moments in the antiferromagnet.

net possesses a G-type (checkerboard) magnetic configuration, characterized by its Néel order parameter $\mathbf{n}$. The normal metal possesses spin–orbit coupling so that a spin Hall effect emerges: a flowing charge current $\mathbf{j}_c$ creates a spin current $\mathcal{J}_s^z = (\theta_{\text{sh}}/e) \mathbf{e}_i \times \mathbf{j}_c$, where $\mathcal{J}_s^i$ is the i -th spatial component of the spin current and θ_{sh} is the spin Hall angle. Notice that $\mathcal{J}_s$ is a 3×3 tensor, while $\mathbf{j}_c$ is a three dimensional vector. The spin diffusion equations in the normal metal read [22]

$$-e \partial_i \mathcal{J}_s^i / \mathcal{N} = \frac{1}{\tau_{\text{sf}}^{\text{N}}} \boldsymbol{\mu}, \quad (1)$$

$$e \mathcal{J}_s^i = -\sigma_{\text{N}} \partial_i \boldsymbol{\mu} + \theta_{\text{sh}}^{\text{N}} (\mathbf{e}_i \times \nabla) \boldsymbol{\mu}_c. \quad (2)$$

Here $\boldsymbol{\mu}_c(\boldsymbol{\mu})$ is the scalar (vector) of spin-dependent (spin-independent) electrochemical potential, $\mathcal{N}$ is the density of states and σ_{N} is the conductivity in the normal metal.

In a recent work, we derived the drift-diffusion equation for collinear, bipartite antiferromagnets based on quantum kinetic principles [20]. In this model, the metallic antiferromagnet is composed of two magnetic sublattices, say A and B , aligned antiferromagnetically with each other. The spin-dependent electrochemical potential on each sublattice can be written $\boldsymbol{\mu}_{A,B} = \boldsymbol{\mu} \pm \delta \boldsymbol{\mu}$, where $\boldsymbol{\mu}$ is the *uniform* component averaged over the unit cell, while $\delta \boldsymbol{\mu}$ is the *staggered* component. Since the spin Hall magnetoresistance is driven by the modulation of the (uniform) spin-dependent electrochemical potential $\boldsymbol{\mu}$ in the normal metal (see below), the staggered spin-dependent electrochemical potential $\delta \boldsymbol{\mu}$ in the antiferromagnet does not play any explicit role in the effect we are interested in. Hence, it is sufficient to compute the spatial profile of the uniform spin-dependent electrochemical potential $\boldsymbol{\mu}$ through the

structure. In the antiferromagnet, it fulfills the following drift-diffusion equation [20]

$$-e \partial_i \mathcal{J}_s^i / \mathcal{N} = \frac{1}{\tau_{\phi}^{\text{AF}}} \mathbf{n} \times (\boldsymbol{\mu} \times \mathbf{n}) + \frac{1}{\tau_{\text{sf}}^{\text{AF}}} \boldsymbol{\mu}, \quad (3)$$

where the first term in the right-hand side, $\sim 1/\tau_{\phi}^{\text{AF}}$, amounts for the spin dephasing that relaxes only the spin component that is *transverse* to the Néel order parameter, while the second term, $\sim 1/\tau_{\text{sf}}^{\text{AF}}$, is the conventional isotropic spin relaxation (driven by spin–orbit coupling, magnetic impurities etc.). The left-hand side involves the spatial gradient of the spin current density $\mathcal{J}_s^i$, defined as

$$e \mathcal{J}_s^i = -\sigma_{\parallel}^{\text{AF}} (\partial_i \boldsymbol{\mu} \cdot \mathbf{n}) \mathbf{n} - \sigma_{\perp}^{\text{AF}} \mathbf{n} \times (\partial_i \boldsymbol{\mu} \times \mathbf{n}), \quad (4)$$

where $\sigma_{\parallel(\perp)}^{\text{AF}}$ is the conductivity of carriers whose spin lies along (perpendicular to) the Néel order parameter $\mathbf{n}$.

Phenomenologically, one can understand Eqs. (3) and (4) in the following way: When itinerant spins enter an antiferromagnet, they precess and dephase around the local magnetic moments of each sublattice. Since these local moments are staggered, the spin precessions on the two antiferromagnetically aligned sublattices compensate each other so that no effective spin precession takes place at the level of the unit cell. In contrast, the spin dephasing adds up on opposite sublattices and does not cancel over the unit cell. As a result, Eq. (3) resembles the spin diffusion equation in ferromagnets, except that the spin precession term is absent. In other words, the drift-diffusion equations that govern the transport of the uniform spin-dependent electrochemical potential $\boldsymbol{\mu}$ in antiferromagnets, Eqs. (3) and (4), are quite similar to that in a normal metal except they are *anisotropic* with respect to the Néel order parameter $\mathbf{n}$. We now compute the spin-dependent electrochemical potential profile in the antiferromagnetic bilayer depicted in Fig. 1. For the boundary conditions, we neglect interfacial spin-flip so that $\mathcal{J}_s^z|_{z=0^-} = \mathcal{J}_s^z|_{z=0^+}$. Notice that interfacial spin-flip can be added by hand but renders the analytical expressions cumbersome. Since the spin transport in the antiferromagnet is anisotropic, we also consider an anisotropic interfacial resistivity such that

$$(\boldsymbol{\mu}_{\text{AF}} - \boldsymbol{\mu}_{\text{N}}) \cdot \mathbf{n} = r_{\parallel} \mathcal{J}_s^z \cdot \mathbf{n}, \quad (5)$$

$$\mathbf{n} \times [(\boldsymbol{\mu}_{\text{AF}} - \boldsymbol{\mu}_{\text{N}}) \times \mathbf{n}] = r_{\perp} \mathbf{n} \times (\mathcal{J}_s^z \times \mathbf{n}), \quad (6)$$

where $r_{\parallel(\perp)}$ is the interfacial resistivity for spins parallel (transverse) to the Néel order parameter. No spin current flows through the outer boundaries, $\mathcal{J}_s^z|_{z=-d_{\text{N}}} = \mathcal{J}_s^z|_{z=d_{\text{AF}}} = 0$, where d_{N} and d_{AF} denote the thickness of the normal metal and antiferromagnetic layers, respectively. We obtain the spin-dependent electrochemical potential in the structure

$$\frac{\boldsymbol{\mu}_{\text{AF}}}{\nabla_x \boldsymbol{\mu}_c} = - \left[\frac{\gamma_{\perp} \theta_{\text{sh}} \lambda_{\text{sf}}^{\text{N}}}{1 + \gamma_{\perp} \eta_{\perp} \tanh \frac{d_{\text{N}}}{\lambda_{\text{sf}}^{\text{N}}}} \frac{\cosh \frac{z - d_{\text{AF}}}{\lambda_{\perp}^{\text{AF}}}}{\cosh \frac{d_{\text{AF}}}{\lambda_{\perp}^{\text{AF}}}} \mathbf{n} \times (\mathbf{y} \times \mathbf{n}) + \frac{\gamma_{\parallel} \theta_{\text{sh}} \lambda_{\text{sf}}^{\text{N}}}{1 + \gamma_{\parallel} \eta_{\parallel} \tanh \frac{d_{\text{N}}}{\lambda_{\text{sf}}^{\text{N}}}} \frac{\cosh \frac{z - d_{\text{AF}}}{\lambda_{\parallel}^{\text{AF}}}}{\cosh \frac{d_{\text{AF}}}{\lambda_{\parallel}^{\text{AF}}}} n_y \mathbf{n} \right] \left(1 - \cosh^{-1} \frac{d_{\text{N}}}{\lambda_{\text{sf}}^{\text{N}}} \right), \quad (7)$$

$$\frac{\mu_N}{\nabla_x \mu_c} = - \left[\frac{\sinh \frac{z}{\lambda_{sf}^N} + \gamma_{\perp} \eta_{\perp} \left(\cosh \frac{z+d_N}{\lambda_{sf}^N} - \cosh \frac{z}{\lambda_{sf}^N} \right)}{1 + \gamma_{\perp} \eta_{\perp} \tanh \frac{d_N}{\lambda_{sf}^N}} \mathbf{n} \times (\mathbf{y} \times \mathbf{n}) + \frac{\sinh \frac{z}{\lambda_{sf}^N} + \gamma_{\parallel} \eta_{\parallel} \left(\cosh \frac{z+d_N}{\lambda_{sf}^N} - \cosh \frac{z}{\lambda_{sf}^N} \right)}{1 + \gamma_{\parallel} \eta_{\parallel} \tanh \frac{d_N}{\lambda_{sf}^N}} n_y \mathbf{n} \right] \frac{\theta_{sh} \lambda_{sf}^N}{\cosh \frac{d_N}{\lambda_{sf}^N}}. \quad (8)$$

where

$$\eta_{\alpha} = 1 + (r_{\alpha} \sigma_{\alpha}^{AF} / \lambda_{\alpha}^{AF}) \tanh \frac{d_{AF}}{\lambda_{\alpha}^{AF}}, \quad (9)$$

$$\gamma_{\alpha} = (\lambda_{\alpha}^{AF} \sigma_N / \lambda_{sf}^N \sigma_{\alpha}) \tanh^{-1} \frac{d_{AF}}{\lambda_{\alpha}^{AF}}, \quad (10)$$

with $\alpha = \parallel, \perp$. Notice that $\cosh^{-1} x = 1/\cosh x$ and $\tanh^{-1} x = 1/\tanh x$. We defined

$$\lambda_{\parallel}^{AF} = \sqrt{\mathcal{D}_{\parallel}^{AF} \tau_{sf}^{AF}}, \quad (11)$$

$$\lambda_{\perp}^{AF} = \sqrt{\mathcal{D}_{\perp}^{AF} / (1/\tau_{sf}^{AF} + 1/\tau_{\phi}^{AF})}, \quad (12)$$

where $\mathcal{D}_{\parallel(\perp)}^{AF} = \sigma_{\parallel(\perp)}^{AF} / e^2 N$. Assuming that $\mathcal{D}_{\parallel}^{AF} = \mathcal{D}_{\perp}^{AF}$, we obtain $\lambda_{\parallel}^{AF} / \lambda_{\perp}^{AF} = \sqrt{1 + \tau_{sf}^{AF} / \tau_{\phi}^{AF}}$: the stronger the spin dephasing, the larger the anisotropy of the spin relaxation. Finally, the charge current flowing through the normal metal reads [22]

$$\mathbf{j}_c = -\sigma_N \partial_x \mu_c - \theta_{sh} \sigma_N \partial_x \mu_y, \quad (13)$$

and therefore, the spin Hall magnetoresistance is given by the change in μ_y profile when the Néel order changes direction.

3 Numerical results Let us now compute the spin-dependent electrochemical potential and the associated spin Hall magnetoresistance. For simplicity and in the absence of detailed experimental data, we neglect the anisotropy in both conductivity and interfacial resistivity and only consider the impact of spin dephasing in the antiferromagnet. We choose $\mathcal{D}_{\parallel}^{AF} = \mathcal{D}_{\perp}^{AF} = 0.4 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$, $\sigma_{AF}^{\parallel} = \sigma_{AF}^{\perp} = \sigma_N = 10^6 \text{ } \Omega^{-1} \text{ m}^{-1}$, and $r_{\parallel} = r_{\perp} = 0.3 \text{ m}\Omega \text{ } \mu\text{m}^2$. Finally, for the spin relaxation and dephasing times, we choose $\tau_{sf}^N = 6 \times 10^{-14} \text{ s}$, $\tau_{sf}^{AF} = 10^{-14} \text{ s}$ and $\tau_{\phi}^{AF} = 10^{-15} \text{ s}$, such that $\lambda_{sf}^N = 5 \text{ nm}$ (unless stated otherwise), $\lambda_{\parallel}^{AF} = 2 \text{ nm}$ and $\lambda_{\perp}^{AF} = 0.6 \text{ nm}$. The magnitude of the spin relaxation and dephasing lengths are consistent with recent experimental reports [23, 24].

The spatial profile of the spin-dependent electrochemical potential μ_y through the structure is given in Fig. 2 for two configurations of the magnetic order, $n_y = 1$ (solid line) and $n_y = 0$ (dashed line). In the normal metal (N), μ_y is driven by spin Hall effect, while in the antiferromagnet (AF) μ_y simply relaxes with different decay rates depending on the direction of the Néel order parameter. Therefore,

the change in spin-dependent electrochemical potential is associated with the anisotropy of the spin relaxation length characteristic of collinear antiferromagnets.

Injecting Eq. (8) into Eq. (13), one obtains the expression of the spin Hall magnetoresistance,

$$\Delta \sigma_{xx} = \frac{(\gamma_{\parallel} \eta_{\parallel} - \gamma_{\perp} \eta_{\perp}) \left(1 - \cosh^{-1} \frac{d_N}{\lambda_{sf}^N} \right)^2 \lambda_{sf}^N \sigma_N \theta_{sh}^2}{\left(1 + \gamma_{\parallel} \eta_{\parallel} \tanh \frac{d_N}{\lambda_{sf}^N} \right) \left(1 + \gamma_{\perp} \eta_{\perp} \tanh \frac{d_N}{\lambda_{sf}^N} \right)}. \quad (14)$$

The longitudinal conductivity is simply $\sigma_{xx} \approx d_N \sigma_N + d_{AF} \sigma_{AF} + O(\theta_{sh}^2)$. More specifically, the spin Hall magnetoresistance is proportional to the anisotropy of the spin transport in the antiferromagnet,

$$\frac{\Delta \sigma_{xx}}{\sigma_{xx}} \sim \frac{\lambda_{\parallel}^{AF}}{\sigma_{\parallel}} \tanh^{-1} \frac{d_{AF}}{\lambda_{\parallel}^{AF}} - \frac{\lambda_{\perp}^{AF}}{\sigma_{\perp}} \tanh^{-1} \frac{d_{AF}}{\lambda_{\perp}^{AF}} + r_{\parallel} - r_{\perp}. \quad (15)$$

Equation (14) presents striking similarities with the one derived in ferromagnetic bilayers [9]. By comparing Eq. (14) given above with Eq. (1) in Ref. [9], one can define an effective spin mixing conductance for the interface between the normal metal and the antiferromagnet, such that

$$2\text{Re } G^{\uparrow\downarrow} = \frac{\sigma_{\perp}^{AF}}{\lambda_{\perp}^{AF}} \tanh \frac{d_{AF}}{\lambda_{\perp}^{AF}}. \quad (16)$$

Figure 2 Spatial profile of the spin-dependent electrochemical potential μ_y when the Néel order parameter lies along (solid line) and normal (dashed line) to the direction $z \times \mathbf{j}_c$. In these calculations, $d_N = 10 \text{ nm}$, and $d_{AF} = 5 \text{ nm}$.

Physically, the real part of the spin mixing conductance is associated with the amount of spin transfer occurring at the interface between a normal metal and a magnetic metal [25]. It is therefore reasonable to associate this quantity with the absorption of the transverse spin component, as explicitly given by Eq. (16). This relation is revealing as the spin Hall magnetoresistance in ferromagnetic and antiferromagnetic bilayers arise from the same source, i.e. the different interfacial spin resistance when the (ferro or antiferro) magnetic order lies along the direction $\mathbf{z} \times \mathbf{j}_c$ or normal to it. As a consequence, there is formally no difference in the physics of spin Hall magnetoresistance in ferromagnets and collinear antiferromagnets. Recent theories have computed the spin mixing conductance for special cases of antiferromagnets [26, 27]. With our set of parameters, we obtain $G^{\uparrow\downarrow} \approx 8 \times 10^{14} \Omega^{-1} \text{m}^{-2}$ (for $d_{\text{AF}} \gg \lambda_{\text{AF}}^{\text{N}}$), a value comparable to that of metallic ferromagnets [28], and to the one recently extracted at Pt/FeMn interface [29] ($G^{\uparrow\downarrow} \sim 5.5 \times 10^{14} \Omega^{-1} \text{m}^{-2}$) or even Pt/YIG interface [30] ($G^{\uparrow\downarrow} \sim 7.7 \times 10^{14} \Omega^{-1} \text{m}^{-2}$). Notice that the mixing conductance reported for Pt/SrMnO₃ has a smaller value [31] ($G^{\uparrow\downarrow} \sim 10^{13} \Omega^{-1} \text{m}^{-2}$).

Figure 3(a, b) represents the spin Hall magnetoresistance as a function of the thickness of (a) the normal metal and (b) the antiferromagnet. The dependence as a function of the normal metal thickness shows a peak, which reveals a competition between the progressive build-up of the spin Hall effect in the normal metal (for $d_{\text{N}} < \lambda_{\text{sf}}^{\text{N}}$) and the shunting of the current (for $d_{\text{N}} > \lambda_{\text{sf}}^{\text{N}}$). The dependence as a function of the antiferromagnet thickness shows a similar behavior with a sharp increase at small thicknesses, corresponding to the quenching of the transverse spin-dependent electrochemical potential in the antiferromagnet (for $d_{\text{AF}} < \lambda_{\text{AF}}^{\text{N}}$), and a slow decay corresponding to the shunting of the current through the antiferromagnet (for $d_{\text{AF}} > \lambda_{\text{AF}}^{\text{N}}$).

4 Discussion and conclusion The spin Hall magnetoresistance discussed in this work should be observable in any multilayers involving collinear antiferromagnets. The experimental observation of this effect requires manipulating the Néel order parameter, which can be achieved using

Figure 3 Spin Hall magnetoresistance ratio as a function of the thickness of (a) the normal metal (with $d_{\text{AF}} = 5 \text{ nm}$) and (b) the antiferromagnet (with $d_{\text{N}} = 10 \text{ nm}$). In these calculations, the spin relaxation length of the normal metal has been taken at $\lambda_{\text{sf}}^{\text{N}} = 2$ (black), 5 (red) and 10 nm (blue), respectively.

exchange bias with a proximate ferromagnet [17], field-cooling procedure [16, 32], or spin-orbit torque in the case of non-centrosymmetric antiferromagnets [10]. Noticeably, this effect has been observed in bilayers involving an insulating antiferromagnet such as Pt/SrMnO₃ [21] and should be observable with other antiferromagnetic insulators such as NiO, CoO, Cr₂O₃ etc. In these materials, the interfacial mixing conductance is associated with the absorption of the spin current mediated by (coherent or incoherent) spin waves inside the antiferromagnetic insulator [27, 33]. Recent experiments suggest that the absorption length can be quite large [34–36] (up to 10 nm in NiO [34]), and the associated mixing conductance can be much larger than their ferromagnetic counterpart due to its high temperature sensitivity [12, 37]. Lately, two reports investigated the behavior of spin Hall magnetoresistance upon the insertion of a NiO layer at the interface between YIG and Pt films [38, 39]. Since NiO carries spin information through spin waves, it is unclear whether NiO is at the origin of the magnetoresistive signal or whether it simply *mediates* the spin information to the YIG. Spin Hall magnetoresistance has also been reported in metallic FeMn/Pt [29]. In this work, FeMn presents a residual magnetization (it is not a pure antiferromagnet *per se*) and the spin Hall magnetoresistance signal scales with the residual magnetism. Recently, “electroresistance” has been reported in the same material, although its relation to spin Hall magnetoresistance remains unclear [31].

Finally, an interesting question that remains to be addressed is whether spin Hall magnetoresistance could be observed in *non-collinear* antiferromagnets. A simple-minded argument suggests that as long as a magnetic order parameter can be defined, spin Hall magnetoresistance should emerge, respecting the symmetries of the antiferromagnetic overlayer. Nevertheless, a thorough investigation of realistic systems is necessary.

In conclusion, we have showed that bilayers composed of a collinear antiferromagnet adjacent to a normal metal with spin-orbit coupling exhibit spin Hall magnetoresistance, similar to their ferromagnetic counterpart. In our model, the mechanism responsible for this effect is the anisotropic relaxation of itinerant spins inside the antiferromagnet with respect to the Néel order parameter. Several experimental methods have been recently used to investigate the emergence of anisotropic magnetoresistance in bulk collinear antiferromagnets, indicating viable routes for the detection of antiferromagnetic spin Hall magnetoresistance.

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