Antiferromagnetic Metal Spintronics

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Spintronics in ferromagnetic metals is built on a complementary set of phenomena in which magnetic configurations influence transport coefficients and transport currents alter magnetic configurations. In this Letter we propose that corresponding effects occur in circuits containing antiferromagnetic metals. The critical current for switching can be smaller in the antiferromagnetic case because of the absence of shape anisotropy and because spin torques act through the entire volume of an antiferromagnet. Our findings suggest that current-induced order parameter dynamics can be used to coarsen the microstructure of antiferromagnetic thin films.

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Introduction — Spintronics in ferromagnetic metals is based on one hand on the dependence of resistance on magnetic microstructure, and on the other hand on the ability to alter magnetic microstructures with transport currents. These effects are often largest and most robust in circuits containing ferromagnetic nanoparticles that have a spatial extent smaller than a domain wall width and therefore largely coherent magnetization dynamics. In this Letter we point out that similar effects occur in circuits containing antiferromagnetic metals. The systems that we have in mind are antiferromagnetic transition metals similar to Cr and its alloys or the rock salt structure intermetallics used as exchange bias materials which are well described by time-dependent mean-field-theory setting.

Our proposal that currents can alter the micromagnetic state of an antiferromagnet may seem surprising since spin-torque effects in ferromagnets are usually discussed in terms of conservation of total spin, a quantity that is not related to the staggered moment order parameter of an antiferromagnet. Our arguments are based on a microscopic picture of spin-torques in which they are viewed as a consequence of changes in the exchange-correlation effective magnetic fields experienced by all quasiparticles in the transport steady state. A spin torque that drives the staggered-moment orientation must also be staggered, and will be produced by the exchange potential due to an unstaggered transport electron spin-density in the plane perpendicular to n. The required alteration in torque is produced by the exchange potential due to an unstaggered transport current along and opposite to the staggered moment. The reflection amplitude for a spinors incident from opposite sides differ by changing the sign of n and the transmission amplitudes are identical. It then follows from composition rules for transmission and reflection amplitudes in a compound circuit containing paramagnetic source and drain electrodes and two antiferromagnetic elements with staggered moment orientations n1 and n2 separated by a paramagnetic spacer (see Fig.) that the transport electron spin-density in the n1 × n2 direction is periodic in the antiferromagnets. (We define the direction of n1 to be the direction of the local moment opposite the spacer.) The spin-torques that appear in this type of circuit therefore act through the entire volume of each antiferromagnet.

A proof of this property will be presented elsewhere. Here we illustrate the potential consequences of this property by using non-equilibrium Greens function techniques to evaluate antiferromagnetic giant magnetoresistance (AGMR) effects and layer-dependent spin-torques in model two-dimensional circuits containing paramagnetic and antiferromagnetic elements. We focus on the most favorable case in which the antiferromagnet has a single Q spin-density-wave state with Q in the current direction. In the following we first explain the model system that we study and the non-equilibrium Greens function calculation that we use to evaluate magnetoresistance and spin-torque effects. We conclude that under favorable circumstances, both effects can be as large as...
the ones that occur in ferromagnets. We then estimate typical current for switching an antiferromagnet. Finally, we discuss some of the challenges that stand in the way of realizing these effects experimentally.

**Antiferromagnetic giant magnetoresistance** — We start by analyzing the simplified two-dimensional lattice model of an antiferromagnetic heterostructure characterized by near-neighbor hopping, transverse translational invariance, and spin-dependent on-site energies, that is illustrated in Fig. 1.

\[
\mathcal{H}_k = -t \sum_{\langle i,j \rangle, \sigma} c_{k,i,\sigma}^\dagger c_{k,j,\sigma} + \text{h.c.} + \sum_{i,\sigma,\sigma'} \left[ (\epsilon_i + \epsilon_k) \delta_{\sigma,\sigma'} - \Delta_i \hat{\Omega}_i \cdot \hat{\tau}_{\sigma,\sigma'} \right] c_{k,i,\sigma}^\dagger c_{k,i,\sigma},
\]

Here, \( k \) denotes the transverse wave number, \( t \) the hopping amplitude and \( \epsilon_k \) the transverse kinetic energy. The second term in Eq. (1) describes the exchange coupling \( \Delta_i \) of electrons to antiferromagnetically ordered local moments \( \Omega_i = (-)^i n_i \) that alternate in each antiferromagnet. In the paramagnetic regions of these model systems \( \Delta_i = 0 \). The on-site energies \( \epsilon_i \) are allowed to change across a heterojunction.

We use the non-equilibrium Greens function formalism to describe the transport of quasiparticles across the magnetic heterostructure. The essential physical properties of the system are encoded in the real time Greens function \( \Gamma \), defined by the ensemble average, \( G^<_{\sigma,i,\sigma',j}(k; t, t') = i \langle c_{k,i,\sigma}^\dagger(t) c_{k,j,\sigma'}(t') \rangle \), from which the (spin) current and (spin) density can be evaluated.

To determine the model’s AGMR effect, we calculate the transmission coefficient as a function of the angle \( \theta \) between orientations \( \hat{\Omega}_i \) on opposite sides of the spacer layer. In Fig. 2 the transmission coefficient is shown for specific values of the number of layers \( N \) and \( M \), in the first and second antiferromagnet. The AGMR effect can be traced to the interference between spin-current carrying electron spinors reflected by the facing layers. (This is also the origin of spin transfer.) For the model we study the AGMR depends on the orientation of the layers opposite the spacer in the usual way, i.e. the resistance is highest for \( \theta = \pi \) and lowest for \( \theta = 0 \). Also, we find that the AGMR ratio, defined as the absolute difference between the maximum and minimum value of the transmission coefficient normalized to the minimum, saturates as a function of the length of the antiferromagnets.

**Current-driven switching of an antiferromagnet** — To address the possibility of current-induced switching of an antiferromagnet we evaluate spin transfer torques in the second antiferromagnet. The spin transfer torque originates from the contribution made by transport electrons to the exchange-correlation effective magnetic field and is given by \( \Gamma = \Delta_i \hat{\Omega}_i \times (s_i)/\hbar \), where \( \langle s_i \rangle \) is the nonequilibrium expectation value of the quasiparticle spin. We distinguish the spin-torque contribution in the plane spanned by \( \mathbf{n}_1 \) and \( \mathbf{n}_2 \) and the component out of this plane. In Fig. 3 we show the in-plane and out-of-plane transport-induced spin torques. As anticipated the in-plane spin transfer torque in this model is exactly staggered and is therefore extremely effective in driving order-parameter dynamics. We have checked numerically that staggered in-plane spin-transfer torques that do not decay also occur in continuum toy models of an antiferromagnet with piece-wise constant and sinusoidal exchange fields. These persistent spin torques are a generic property of antiferromagnetic circuits related to the absence of spin-splitting in the Bloch bands. The staggered in-plane spin-transfer is produced by an out-of-plane spin density that is exactly constant in our lattice model antiferromagnet and exactly periodic in a continuum model antiferromagnet.

If the exchange-interactions that stabilize the antiferromagnetic state are very strong, the magnetization dynamics of each antiferromagnetic element will be coherent and respond only to the staggered component of each spin-torque. In Fig. 4 we show the total staggered torque acting on the downstream antiferromagnet, as a function of the angle \( \theta \). Clearly, the out-of-plane component of the torque is small compared to the in-plane component. Fig. 5 shows the derivative of the spin transfer torque per unit current with respect to \( \theta \), which we denote \( M_q(\theta) \), at \( \theta = \pi \). As we will see, the critical current for reversal is inversely proportional to this quantity.

Having demonstrated the presence of spin transfer torques in a heterostructure containing two antiferromag-
We used the parameters $\Delta/t = \theta$ and $\epsilon_i = 0$. Therefore, we can focus our description on one ferromagnetic layer within the antiferromagnet, since the antiferromagnet ordering will be preserved as the antiferromagnet switches.

Within this approach, the dynamics of the staggered moment of the second antiferromagnet is analogous to the ferromagnetic case, and its equation of motion reads

$$\frac{dn_2}{dt} = n_2 \times \left[ -\frac{\gamma}{M_s} \frac{\partial E(n_2)}{\partial n_2} \right] + g(\theta)\omega_j n_2 \times (n_1 \times n_2)$$

Here, $\gamma \approx \mu_B/\hbar$ denotes the gyromagnetic ratio, and $M_s \approx \mu_B/a^3$ denotes the saturated staggered moment density, where $a \approx 0.3$ nm denotes the lattice constant of Cr. The term involving $\omega_j \equiv \gamma h_j/(2e\alpha M_s)$, with $j$ the current density and $e$ the electron charge, describes the in-plane spin transfer torque. We neglect the out-of-plane component because, as we have seen, it averages to a small value. Moreover, the out-of-plane component of the spin torque competes with the anisotropy, whereas the in-plane component competes with the damping term. For this reason it turns out that, even in ferromagnets, the in-plane component of the spin torque is most important in determining the critical current for current-driven switching. The last term in Eq. (3) describes the usual Gilbert damping, with a dimensionless damping constant for which we take the typical value $\alpha = 0.1$. The anisotropy constants are given by $K_1 = 10^3$ J m$^{-3}$ and $K_2 = 10$ J m$^{-3}$.

A linear stability analysis of Eq. (3) shows that for the optimal situation $n_1 = -\hat{x}$, the fixed point $n_2 = \hat{x}$ becomes unstable if

$$j \equiv j_c = \frac{e\alpha a}{g(\pi)\hbar} (K_1 + 8K_2) \approx 10^5 \text{A cm}^{-2},$$

where the value for $g(\pi)$ is found to be $g(\pi) \approx 0.05$.

This critical current is smaller than the typical value for switching an ferromagnet primarily because the spin transfer torques act cooperatively throughout the entire
antiferromagnet and also because of the absence of shape anisotropy. Using the model of Eq. (3) we also find that depending on the applied current, the staggered moment $\mathbf{n}_2$ can relax to stable fixed points at $\mathbf{n}_2 = \pm \hat{y}$ or completely reverse its direction.

**Discussion and conclusions** — The calculations we have performed are in the ballistic regime, and we expect the AGMR and spin transfer torque effect to occur only in sufficiently clean samples. Since both effects rely on interferences, however, we do not expect that disorder will make it impossible to realize the effect in typical nanoscale layered systems. Initial experimental explorations of this effect might be most easily interpreted in clean epitaxially grown materials. The complicated antiferromagnetic domain structure, known to play a complex role in exchange biasing materials [21], might cause AGMR and antiferromagnetic spin transfer to be smaller than expected on the basis of our calculation. We point out that it might be possible to use the effects discussed here to coarsen the domain structure of antiferromagnetic thin films. We therefore expect that the metallic materials used for exchange biasing are generally a good starting point in searching for materials displaying these antiferromagnetic spintronics phenomena. The materials combinations that will exhibit the effects we have in mind most strongly depend on a large variety of considerations and can be identified by a combination of experimental and theoretical work which follows in the footsteps of the successful ferromagnetic metals materials research. Finally we remark that related effects occur in hybrid circuits containing both antiferromagnetic and ferromagnetic elements.

In conclusion we propose that the experimental and theoretical study of the influence of current on microstructure in circuits containing antiferromagnetic elements will reveal interesting new physics only partly anticipated in this Letter, and that microstructure changes can be sensed by resistance changes. It is a pleasure to thank Ole Heinonen, Chris Palmstrom, and Maxim Tsoi for helpful remarks. This work was supported by the National Science Foundation under grants DMR-0115947 and DMR-0210383, by a grant from Seagate Corporation, and by the Welch Foundation.

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