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Planar Hall effect in epitaxial thin films of magnetite

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We measured the planar Hall effect (PHE) of magnetite (Fe_3O_4) films between 150 and 350 K. The PHE was measured both with a constant magnetic field rotating in the plane of the sample and in a remanent state after applying a field in specific directions. The PHE amplitude decreases with temperature; however, it changes little between 300 and 350 K. The remanent PHE signal is as high as 10 V/A, larger than previously observed in manganite films. We also measured the PHE in the remanent state and found that its magnitude and stability make it a viable candidate for magnetic random access memory applications. © 2007 American Institute of Physics.

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Magnetite (Fe_3O_4) has been a highly studied oxide in recent years because of its intriguing transport properties.¹ This compound is believed to be half metallic, namely, fully spin polarized at the Fermi level. Consequently, there have been hopes that magnetic tunnel junctions with magnetite films would exhibit exceptionally high magnetoresistance signals, which are useful for spintronic applications such as magnetic random access memory (MRAM). However, magnetic tunnel junctions fabricated with Fe_3O_4 electrodes show only small magnetoresistances, possibly due to spin flips at the interface with the insulating layer or because of the presence of a reduced oxide at this interface.² In this work, we explore a potential use for magnetite films for MRAM based on the planar Hall effect (PHE).³

The PHE in magnetic conductors occurs when the resistivity depends on the angle θ between the current density $\mathbf{J}$ and the magnetization $\mathbf{M}$, an effect known as anisotropic magnetoresistance (AMR).⁴ The AMR yields a transverse electric field when $\mathbf{J}$ is not parallel or perpendicular to $\mathbf{M}$. If we assume $\mathbf{J}$ is in the x direction and $\mathbf{M}$ is in the x - y plane, the generated electric field has both a longitudinal component,

$$E_{xx} = \rho_{\perp} j_x + (\rho_{\parallel} - \rho_{\perp}) j_x \cos^2 \theta, \quad (1)$$

and a transverse component,

$$E_y = (\rho_{\parallel} - \rho_{\perp}) j_x \sin \theta \cos \theta, \quad (2)$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistivities for magnetization parallel and perpendicular to the current, respectively. The latter component is called the planar Hall effect. Unlike the ordinary and extraordinary Hall effects, the PHE shows an even response upon inversion of $\mathbf{J}$ and $\mathbf{M}$. Therefore, the PHE is most noticeable when $\mathbf{M}$ changes its axis of orientation, in particular, between $\theta=45^\circ$ and $\theta=-45^\circ$.

The PHE was reported for 3d ferromagnetic metals such as Fe, Co, and Ni.⁸ It was used as a tool for studying the

in-plane magnetization of samples^{5,6} and for applications as low magnetic field sensors.⁷ Large PHE signals that are four orders of magnitude larger than in ferromagnetic metals were observed recently, first at low temperatures in the magnetic semiconductor (Ga, Mn)As,⁹ then at higher temperatures and even at room temperature in thin films of manganites ($\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$) (Ref. 10) and magnetite.¹¹ The large PHE effect seen in these materials has been denoted the giant planar Hall effect (GPHE).

In this work we show the GPHE in magnetite films at temperatures ranging from 150 to 350 K, and we demonstrate the potential use of magnetite films for nonvolatile magnetic memory applications based on this effect.

The sample we studied is a 9 nm thick magnetite film deposited by molecular beam epitaxy on a single-crystal MgO (100) substrate. Fe was evaporated from a high temperature effusion cell with an alumina crucible containing 99.995% pure Fe slugs. At the substrate temperature of 523 K, Fe was deposited with a rate of $\sim 0.6 \text{ \AA/s}$ and in oxygen excited by an electron cyclotron resonance (ECR) plasma source using an O_2 partial pressure of 2×10^{-6} Torr. The quality of the sample was determined using surface characterization techniques [reflection high energy electron diffraction (RHEED), low energy electron diffraction (LEED), and x-ray photoelectron spectroscopy (XPS)] and resistivity measurements, which exhibit a change in resistivity at the Verwey transition ($T_v=122 \text{ K}$) of close to two orders of magnitude. The film was patterned into a Hall bar shape (see inset of Fig. 1), and the active area (between C and D) on the current path is $10 \times 10 \text{ \mu m}^2$.

Figure 1 shows the transverse resistivity ρ_{xy} of the magnetite film with a constant magnetic field applied and rotated in the plane of the film. ρ_{xy} is presented as a function of θ , the angle between the magnetization and the current path. The magnetic field is larger than the coercive field of the sample magnetization; hence $\mathbf{M}$ is parallel to the field. The measurements were repeated at several temperatures.

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FIG. 1. (Color online) PHE measurements of a magnetite film. (a) Transverse resistivity ρ_{xy} vs θ , the angle between the current and the magnetization, at different temperatures with an applied field of 4 T. The curve is a fit to Eq. (2). (b) $\Delta\rho_{\text{PHE}}$, the amplitude of the PHE signal, at different temperatures and magnetic fields. Inset: A sketch of the pattern used for measurements.

Because of slight misalignment of the transverse leads, a longitudinal component is subtracted from the transverse signal measured between C and D. We can see that the PHE data fit Eq. (2) for the entire temperature range. We note that the amplitude of the PHE signal decreases as the temperature increases. However, in the temperature interval important for applications, 300–340 K, the signal decreases by only $\sim 10\%$.

For MRAM applications it is important to explore the PHE signal in the remanent state. We magnetize the film in directions that yield maximum PHE signals, ($\theta = \pm 45^\circ$) and measure the signal after the field is removed. Figure 2 shows the PHE signals with and without the external magnetic field. The results are shown for several temperatures. Removing the magnetic field lowers the PHE signal. However, the signal is still quite large, 9 V/A at 300 K, and it remains stable over 30 min of our measurement.

The results presented here show the potential use of magnetite thin films as the basis for a magnetic memory bit,

FIG. 2. (Color online) PHE signal measured for 200 min at several temperatures with a changing magnetic field. A field of 1 T is first pulsed at $\theta = -45^\circ$ and aligns the sample magnetization in this direction. A negative PHE signal is observed. The magnetic field is then removed, leaving the magnetization in its remanent state. After 30 min, the field is pulsed again, this time at $\theta = 45^\circ$, and a positive PHE signal is observed. The process is repeated several times. The lower graph shows the amplitude of the magnetic field along $\theta = 45^\circ$ (solid line) and $\theta = -45^\circ$ (dashed line).

where the two magnetization orientations at $\theta = \pm 45^\circ$ correspond to the two memory states. The different PHE signals are clearly distinguishable at temperatures as high as 350 K and remain stable over time.

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