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Paramagnetic anisotropic magnetoresistance in thin films of $SrRuO_3$

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$SrRuO_3$ is an itinerant ferromagnet and in its thin film form when grown on miscut $SrTiO_3$ has T_c of ~ 150 K and strong uniaxial anisotropy. We measured both the Hall effect and the magnetoresistance (MR) of the films as a function of the angle between the field applied and the normal to the films above T_c. We extracted the extraordinary Hall effect that is proportional to the perpendicular component of the magnetization and thus the MR for each angle of field applied could be correlated with the magnitude and orientation of the magnetization induced. We fit the MR data with a second order magnetization expansion, and it indicated large anisotropic MR in the paramagnetic state. The extremum values of resistivity were not obtained for currents parallel or perpendicular to the magnetization, probably due to crystal symmetry. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1676052]

I. INTRODUCTION

The phenomenon of anisotropic magnetoresistance (AMR) in magnetic conductors expresses the dependence of the resistivity ρ on the angle δ between the current **J** and the magnetization **M**. In polycrystals the AMR effect is commonly found to follow $\rho = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\delta$ where $\rho_\perp$ is the resistivity when $\mathbf{J}\perp\mathbf{M}$, and $\rho_\parallel$ is the resistivity when $\mathbf{J}\parallel\mathbf{M}$.[1] This simple relation is not expected to hold in crystalline samples where both the current orientation relative to the lattice as well as the magnetization orientation relative to the lattice play an important role.

Here we present AMR measurements of thin films of the $4d$ itinerant ferromagnet $SrRuO_3$ above T_c ($T_c \sim 150$ K). Those films are epitaxial and characterized by large uniaxial magnetocrystalline anisotropy (MCA).[2] In our measurements, we study the AMR under uncommon conditions: (a) while in most AMR measurements the orientation of **M** is changed without changing its magnitude, here, because of the large MCA both the orientation and magnitude of **M** change; (b) while in most AMR measurements the applied field **H** is parallel to **M**, here, because of the large MCA, $\mathbf{M}\nparallel\mathbf{H}$ except for cases where **H** is along the easy or hard axes. Therefore, to explore the AMR in $SrRuO_3$ it is not sufficient to measure MR as a function of the angle, but we need to independently determine both the magnitude and orientation of **M**.

Our films are grown on miscut (2°) $SrTiO_3$ substrates using reactive electron beam epitaxy. The films have an orthorhombic structure ($a = 5.53$ Å, $b = 5.57$ Å, $c = 7.85$ Å) and they grow uniformly (without twinning) with the c axis in the film plane and the a and b axes 45° out of plane (see Fig. 1).[3] The MCA is uniaxial with the easy axis along the b axis and thus uniform growth of the measured films can be confirmed by MR measurements in the ferromagnetic phase.[4] The films were patterned by photolithography to allow Hall effect (HE) and MR measurements. The sample whose results are presented here is 300 Å thick with $T_c \sim 147$ K and resistivity ratio of ~ 13.

II. MEASUREMENTS AND DISCUSSION

Our measurements have two parts: (a) extraordinary Hall effect (EHE)[5] measurements from which we extract both the magnitude and the orientation of **M** and (b) MR measurements for currents in the [001] and $[1\bar{1}0]$ directions. Combining the two measurements we show that the MR can be fit well by second order magnetization expansion.

Both HE and MR measurements were performed as a function of the angle ϕ between the applied field **H** and the easy axis, where **H** rotates in the (001) plane. Each film has two kinds of pattern: a pattern with current along the $[1\bar{1}0]$ direction (denoted P_{ab}) and a pattern with current along the [001] direction (denoted P_c). While in P_{ab} the angle be-

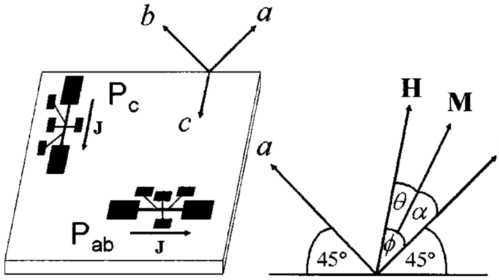

FIG. 1. Sketch of the patterned film. In pattern P_c current **J** is in the [001] direction. In pattern P_{ab} current **J** is in the $[1\bar{1}0]$ direction. Crystallographic directions b (easy axis) and a (hard axis) are 45° out of the plane of the film. In our measurements field **H** rotates in the (001) plane, ϕ is the angle between **H** and b, α is the angle between the induced **M** and b, and θ is the angle between **M** and **H**.

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tween **J** and **H** varies with ϕ, in P_c field **H** is always perpendicular to **J**. The measurement configuration is illustrated in Fig. 1.

The Hall field in magnetic conductors has two contributions,

$$\mathbf{E}_H = -R_0 \mathbf{J} \times \mathbf{B} - R_s \mathbf{J} \times \mu_0 \mathbf{M},$$

where **B** is the magnetic field, and R_0 and R_s are the ordinary and the extraordinary Hall coefficients, respectively. By measuring the HE in our films at a temperature where R_s vanishes ($\sim$130 K),[6] we determined R_0, which enabled us to extract $\mu_0 R_s M_\perp$ (where $M_\perp$ is the component of **M** which is perpendicular to the film plane) at all temperatures.[7] This is not sufficient, however, since we need to determine both components of **M**. For that we note that based on symmetry considerations we may assume that if field **H**, that is applied in the (001) plane at angle ϕ relative to the easy axis, creates magnetization **M** that points at angle α relative to the easy axis, then applying the same field at angle $-\phi$ will create the same magnetization, but at angle $-\alpha$.[8] In our case the easy axis is 45° out of plane, thus symmetry considerations yield $M_\parallel(\phi) = M_\perp(-\phi)$ where $M_\parallel$ and $M_\perp$ are the in-plane and perpendicular components of **M**, respectively. Consequently, by measuring the Hall resistivity (ρ_{EHE}) at ϕ and $-\phi$ we obtain $\rho_{\mathrm{EHE}}(\phi) = \mu_0 R_s M_\perp(\phi)$ and $\rho_{\mathrm{EHE}}(-\phi) = \mu_0 R_s M_\parallel(\phi)$, which allows us to determine **M** (multiplied by $\mu_0 R_s$, which is assumed constant for all data taken at a given temperature). Figures 2(a) and 2(b) show the change in magnitude and direction of **M** as a function of ϕ at $T = 170$ K determined with that method (the results from P_{ab} and P_c are indistinguishable). As expected, **M** obtains its maximum value at $\phi = 0$ and lags behind **H** except for **H** along a and b. It may be the first time that the EHE which is sensitive only to the perpendicular component of the magnetization is used to extract the full magnetization vector based on symmetry. This is possible only because of the tilted easy axis. When the easy axis is perpendicular or parallel to the film this scheme is not applicable.

Figures 2(c) and 2(d) present the MR measured at $T = 170$ K for $H = 3$ and 4 T in P_{ab} and P_c. To fit the MR data we expand MR in **M**, noting that due to the MR symmetry under field inversion the lowest order expansion is of second order. Since in our experiment **M** remains in the (001) plane it is sufficient to use two components of **M**. We use the freedom of choosing the principal axes to take them in the crystallographic directions of a and b. Therefore, the general expansion of the MR to lowest order is

$$\mathrm{MR} = [\rho(H) - \rho(0)]/\rho(0) = A(M_b^2 + \beta M_a^2 + \gamma M_b M_a), \tag{1}$$

where M_b and M_a are the components of **M** along the easy axis (b) and hard axis (a), respectively. The lines in Figs. 2(c) and 2(d) are fits of the MR data based on the measured **M** and Eq. (1).

We obtained the following fitting parameters at $T = 170$ K: $\beta = 1.4 \pm 0.2$, $\gamma = -0.6 \pm 0.1$ for the P_{ab} pattern, and $\beta = 1.7 \pm 0.2$, $\gamma = -0.1 \pm 0.1$ for the P_c pattern. The limit of error indicates the evaluated changes in fitting parameter in case there is a difference between the instrumental ϕ and the actual ϕ of up to 2°.

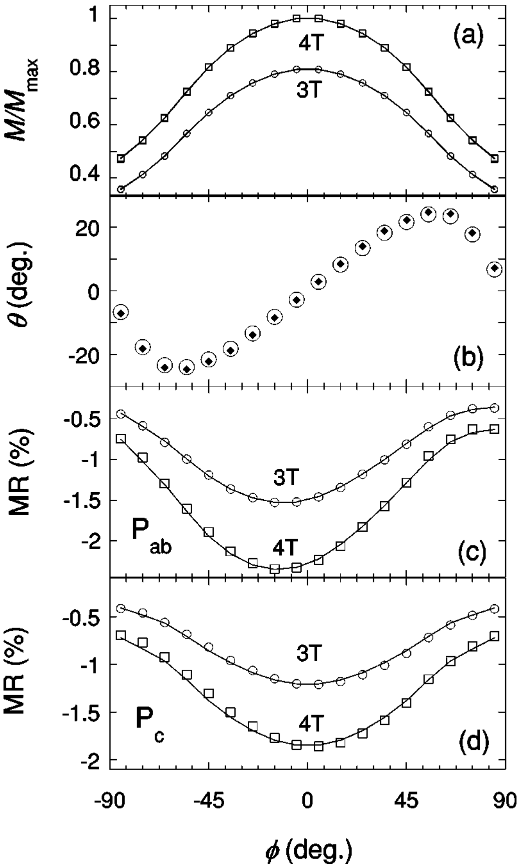

FIG. 2. Magnetization and MR data at 170 K as a function of angle ϕ between **H** and easy axis b, and fits of the MR data based on measured **M** and Eq. (1). (a) Magnitude of **M** relative to be that of $M_{\max}$, which is the magnitude of **M** obtained with $H = 4$ T applied along the easy axis. (b) Angle between **M** and **H** for $H = 4$ (open circles) and 3 T (closed diamonds). (c) MR in P_{ab}. (d) MR in P_c. For (c) and (d) the symbols represent the experimental results and the lines represent the fit.

The fits of the MR data based on Eq. (1) allow us to determine the "clean" AMR effect, namely, how would the resistivity change if we could rotate **M** in the (001) plane without changing its magnitude. Figure 3 shows the expected

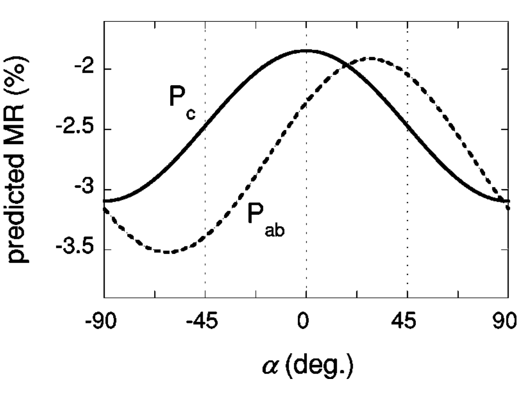

FIG. 3. Expected MR at 170 K and $H = 4$ T as a function of angle α between **M** and b, assuming M is constant, for P_c (solid curve) and P_{ab} (dashed curve).

behavior at $T=170$ K for P_{ab} and P_c for a value of magnetization obtained with $H=4$ T along the easy axis.

For P_c we note that although $\mathbf{J}\perp\mathbf{M}$ there is significant AMR ($\beta\neq 1$), and that $\gamma=0$ is within our experimental accuracy, as would be expected from symmetry considerations. These results exhibit strong dependence of the MR not only on the angle between **M** and **J** (which remains constant) but also on the direction of **M** relative to the crystal. For P_{ab} we note that the extremum values are not obtained for $\mathbf{J}\|\mathbf{M}$ or $\mathbf{J}\perp\mathbf{M}$ but at intermediate angles. In fact, the extremum values for P_{ab} are in between those obtained in P_c (along the *a* and *b* axes) and those observed in polycrystals (parallel and perpendicular to **J**). This shows that in our case the AMR related to the orientation of **M** with respect to the lattice is of the same order of magnitude as the AMR due to the relative orientations of **M** and **J**. We also note that for $\alpha=45°$, which corresponds to **M** perpendicular to the plane, the MR is different in P_{ab} and P_c despite the fact that in both cases $\mathbf{J}\perp\mathbf{M}$. This illustrates the dependence of MR on the direction of **J** relative to the crystal.

In conclusion, we have presented an AMR investigation of $SrRuO_3$ with simultaneous measurements of **M** and MR in the same pattern, thus enabling accurate determination of its AMR behavior despite the change in magnitude of **M** and in its relatively angle with **H**. The results indicate significant AMR even in the paramagnetic state, where **M** is relatively small, and a large effect of the orientation of **M** and **J** relative to the crystal axes.

Note added in proof: As mentioned in the text, the R_0 value was extracted at a temperature below T_c where R_s vanishes. However, we have recently discovered that even at that temperature the EHE contributes to the Hall effect measurements and therefore a different R_0 value should be used in the analysis (details will be published elsewhere). While this affects the extracted fit parameters, the qualitative properties of AMR reported here remain unchanged.

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[4] As the sample is rotated with magnetic field applied, jumps in magnetoresistance which correspond to magnetization reversal occur at angles consistent with uniform direction of the easy axis throughout the sample.

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[7] Our results are not very sensitive to possible small variations of R_0 as a function of the temperature. For example, if R_0 varies 10% between 130 and 170 K, the error in estimates for β and γ remains essentially the same.

[8] The demagnetizing field is not important since even for the zero-temperature limit of saturated magnetization (which is much bigger than the magnetization at 170 K with $H=4$ T), it would be smaller by an order of magnitude than the fields applied here.