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Kerr measurements on single-domain $SrRuO_3$ thin films

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We report on the magneto-optical measurements of an epitaxial $SrRuO_3$ film grown on $SrTiO_3$ (0 0 1), which previously was determined to be single domain orientated by x-ray diffraction and Raman spectroscopy techniques. Our experiments reveal a large Kerr rotation, which reaches a maximum value of about 0.5° at low temperature. By measuring magnetic hysteresis loops at different temperatures, we determined the temperature dependence of the Kerr rotation in the polar configuration. Values of the anisotropic magnetoresistance ~20% have been measured. These values are remarkably higher than those of other metallic oxides such as manganites. This striking difference can be attributed to the strong spin-orbit interaction of the Ru 4*d* ion in the $SrRuO_3$ compound. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861552]

A variety of experiments performed on $SrRuO_3$ (SRO) thin films has revealed the presence of a strong spin-orbit (SO) coupling.[1] This is explained by the presence of the magnetic Ru 4*d* ion, which has a SO coupling of about 900 cm^{-1} (≈110 meV), in contrast to the lower values of 3*d* ions, such as Fe (400 cm^{-1}).[1] This property is at the origin of the observed large anisotropic magnetoresistance (AMR),[2–4] the strong magnetocrystalline anisotropy,[5] or the anomalous Hall effect[6] in SRO. Large magneto-optical effects are also expected and, indeed, previous reports using a wavelength of $\lambda = 840$ nm have revealed a large Kerr rotation of about 0.85 deg.[1] However, the magneto-optical properties have been scarcely explored in the visible range. Recently, in a spectroscopy study of the magneto-optical activity of single-crystal SRO, a Faraday rotation of about 1.5×10^5 deg/cm was reported for light with energy of 2.75–3.1 eV ($\lambda \approx 400-450$ nm).[7]

Here we report on Kerr effect measurements using a wavelength of $\lambda \approx 630$ nm (HeNe laser source). A large Kerr rotation, which reaches a maximum value of about 0.5 deg at low temperature, has been measured for a SRO film with thickness $t = 190$ nm. The results also reveal the presence of a strong uniaxial magnetic anisotropy in single-crystal SRO films on (0 0 1) $SrTiO_3$ (STO) substrates, with the easy axis tilted somewhat away from the normal to the surface plane. As a result, there is a well-defined in-plane magnetic anisotropy determined by the in-plane projection of the magnetic easy axis. We report also large values of AMR (~20%), as expected from the strong SO coupling of SRO.

A SRO thin film with thickness $t = 190$ nm was grown on a nominally exact STO substrate by pulsed laser deposition. Two magneto-optical setups based on the Kerr effect, one in Toulouse and the other in Bellaterra, have been used. These systems were equipped with a cryostat allowing to reach temperatures down to 10 K. Transport measurements were carried out in a physical property measurement system (PPMS) system (Quantum Design) by means of the four-probe method.

Both ψ-φ coupled area scans around the nondegenerated x-ray diffraction peak (221) (orthorhombic indexation) and μ-Raman spectroscopy experiments revealed that the film was single crystalline, i.e., with a single crystallographic domain of the orthorhombic unit cell.[8] Consequently, there is a well-defined magnetic anisotropy that we have explored by means of Kerr measurements. Magneto-optical measurements were performed in Toulouse in a polar configuration and, thus, only the component of the magnetization perpendicular to the film plane was probed. A magnetic field was rotated around an axis included in the film plane [see Fig. 1(b)]. Note that by this configuration, the magnetic field could be applied both along the normal and along a parallel direction to the surface plane during a complete rotation. The experimental data, measured at a temperature of 60 K and a field $H = 1$ kOe, are plotted in Fig. 1(a). We observe a sharp transition between two states with Kerr rotation of the same magnitude and opposite sign. This means that the magnetization vector switches between two orientations along the direction of the easy axis. The data from Fig. 1(a) indicate that at the specified temperature, the easy axis of magnetization lies on a direction at ~20 deg with respect to the out-of-plane direction. This estimation agrees well with the findings of Klein *et al.*[5] These authors found from the magnetic

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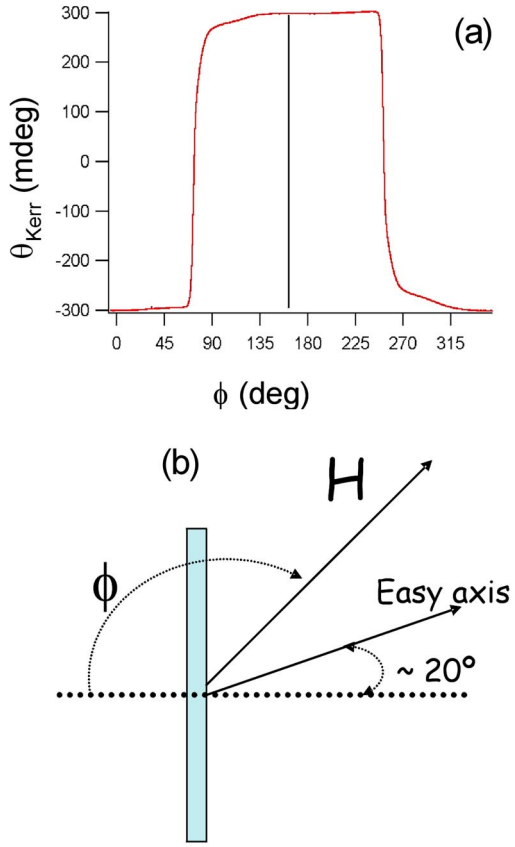

FIG. 1. (a) Kerr rotation measured as the applied field was rotated around and in-plane axis. This procedure allows us to find the direction of the easy axis. (b) Schematic illustration showing the relative orientation of the easy magnetic axis in SRO thin films.

measurements at low temperature of both the longitudinal and transverse components of the magnetization that the easy axis was at an angle $\theta \sim 30°$ with respect to the normal.

In a uniaxial anisotropy, the in-plane projection of the absolute easy axis determines a well-defined in-plane magnetic anisotropy. To explore this issue, magneto-optical measurements were done in the Kerr setup at the laboratory of Bellaterra. A longitudinal configuration was used, with the field applied along two orthogonal directions following the [1 0 0] and the [0 1 0] directions of the cubic STO substrate. The light coming onto the sample surface was directed at around 70 deg with respect to the normal to the surface. Therefore, the changes of the polarization state of the light came mainly from the in-plane projection of magnetization.[9] These measurements were done at a temperature $T=10$ K. The detected intensities, normalized to the value at saturation, are shown in Fig. 2(a). It shows the hysteresis loops measured with the field applied along the two orthogonal directions. The loops have different coercive fields and more important, the initial slopes dM/dH differ significantly, as shown in Fig. 2(b). Thus, these data indicate the presence of a remarkable uniaxial in-plane anisotropy in the SRO film. This should be expected, since, as pointed out above, the film had a single crystallographic domain structure.

By measuring the magnetic hysteresis loops at different temperatures, we determined the temperature dependence of the Kerr rotation. These measurements were carried out in a

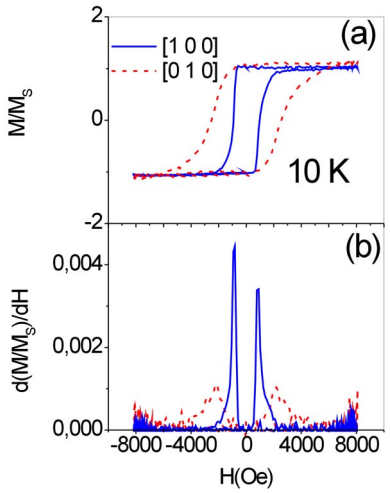

FIG. 2. (a) *M-H* loops determined by Kerr rotation, with normalized magnetization values at saturation (M/M_S). (b) The derivative $d(M/M_S)/dH$ is plotted against the field H.

polar configuration. Therefore, only the component of magnetization perpendicular to the film plane was probed. The field was applied along the normal to the film and, thus, near the easy axis. Figure 3 shows the experimental results. We note that at low temperature a large Kerr rotation of about 0.5 deg is observed. These large values have to be compared with the other values reported for other ferromagnetic oxides. In particular, for $La_{2/3}Sr_{1/3}MnO_3$ thin films, a Kerr rotation of an order of ~ 0.01 deg at 1 eV ($\lambda \approx 1240$ nm) and ~ 0.002 deg at 2 eV ($\lambda \approx 620$ nm) as reported (see Fig. 2 of Ref. 10). These values are one to two orders of magnitude smaller than the magneto-optical signal measured in the SRO films. The SO coupling in $La_{0.7}Sr_{0.3}MnO_3$ crystals has been determined to be of the order of 1 meV (see Table I in Ref. 10), i.e., two orders of magnitude lower than in SRO (≈ 110 meV). Thus, the ratio between the values of the Kerr rotation for both compounds is consistently related to the ratio of the corresponding SO constants.

Anisotropic magnetoresistance can be described by

$$\mathrm{AMR} = f(\Delta_{\mathrm{SO}})\left(\frac{M}{M_S}\right)^2 \sin^2\theta, \tag{1}$$

where Δ_{SO} is the spin-orbit energy, M_S is the magnetization at saturation, and θ is the angle between the current and the magnetization M [see the inset in Fig. 4(b)]. Since the orbital

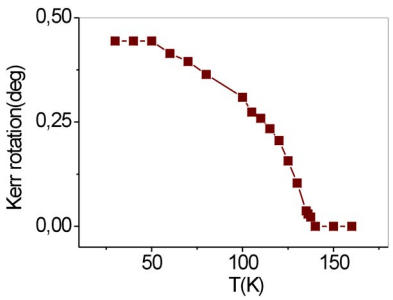

FIG. 3. Temperature dependence of the Kerr rotation. The magnitude of the Kerr rotation was determined from the maximum value of the hysteresis loop at each temperature $10\ \mathrm{K} < T < 180\ \mathrm{K}$.

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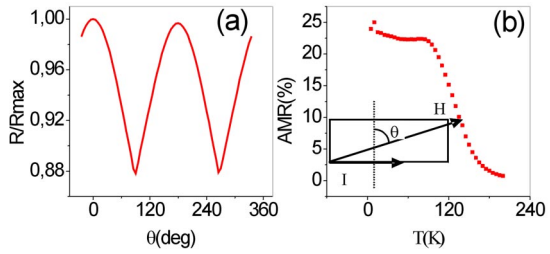

FIG. 4. (a) Angular dependence of the resistance $R(\theta)$ with $H=9$ T and $T=10$ K. (b) Temperature dependence of the AMR. Inset: geometry of the experiment intended to measure the $R(\theta)$ curves.

magnetoresistance is negligible in SRO,[11,12] we can reliably measure the AMR by setting a field high enough to saturate the sample in any direction. To evaluate the AMR, the electrical resistance was measured by the four-probe method in a PPMS, with a magnetic field of $H=9$ T. The field was applied in the film plane, and was rotated around a normal axis, while the current injection was preserved. With this configuration, any contribution from the demagnetizing fields was avoided. For each rotation angle θ, the electrical resistance was recorded. These magnetotransport measurements allowed us to determine the angular dependence $R(\theta)$ under the magnetic field. Figure 4(a) shows the resulting $R(\theta)$ curve recorded at 10 K; according to the geometry of the measurement, illustrated by the inset in Fig. 4(b), the minima in the $R(\theta)$ curve correspond to the magnetization being parallel to the current, whereas the maxima are found when M is normal to it. It follows, then, that $\rho_\perp > \rho_\parallel$. This situation is the reverse to what is commonly observed in normal ferromagnetic metals, i.e., $\rho_\perp < \rho_\parallel$. However, it is worth recalling that in manganites a $\rho_\perp > \rho_\parallel$ has also been reported (see, e.g., Ref. 13). We note also that at high field, a $\sin^2\theta$ dependence is expected for the resistance when no other magnetoresistive effects other than AMR are present. Instead, as it is observed in Fig. 4(a), the minima are sharper than the maxima and, consequently, the $\sin^2\theta$ angular dependence is not found. When the field is applied along the direction of these minima, the applied field H cannot overcome the magnetic anisotropy and the magnetization does not follow the direction of H. Thus, the hard in-plane axis of the magnetization coincides with the direction at which the minima appear.[11] Note that this means that even at 9 T the magnetic anisotropy is not overcome.

The temperature dependence of the AMR was evaluated from the $R(\theta)$ curves at different temperatures taking the difference between the maxima and minima at $H=9$ T, and using the expression,

$$\mathrm{AMR} = \frac{R_\parallel - R_\perp}{1/3R_\parallel + 2/3R_\perp}. \tag{2}$$

Figure 4(b) shows the temperature dependence of the AMR. We observe that the value of the AMR ($\sim 20\%$) is strikingly higher, by one or two orders of magnitude, than the usual values measured in other ferromagnets. As an example, values of AMR of an order of 0.2% at low temperature were reported for $La_{0.7}Ca_{0.3}MnO_3$ films.[14] As pointed out above, this is not an unexpected result, since the SO coupling constants are two orders of magnitude larger in SRO than in manganites. On the other hand, from these experimental results, no enhancement of the AMR near the Curie temperature is found in the SRO film,[11] contrary to what is observed in manganite films.[15] This result is consistent with an unchanged spin-orbit coupling Δ_{SO} when crossing the Curie temperature in SRO. Instead, Jahn–Teller distortions appear in manganites when the transition temperature is approached, leading to an unquenching of the orbital moment. Since the SO coupling hamiltonian is expressed as $H_{so}=\Delta_{so}LS$, where L and S are, respectively, the orbital and magnetic moments, that might explain why the AMR in manganites is strongly enhanced in the neighborhood of the Curie temperature.[11]

In summary, we have measured the temperature dependence of the Kerr rotation of a SRO film at a wavelength in the visible range ($\lambda=630$ nm). A Kerr rotation about two orders of magnitude larger than in manganite compounds has been measured. This is attributed to the large spin-orbit coupling of the Ru ion, which also leads to a strong uniaxial magnetic anisotropy and an unusual high anisotropic magnetoresistance.

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