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Magnetoresistance of $SrRuO_3$ ultra-thin films

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Abstract

We have studied the presence and relevance of magnetic disorder in epitaxial $SrRuO_3$ ultra-thin (3.5,7 nm) films grown by pulsed laser deposition on $SrTiO_3$ (0 0 1) substrates with miscut angle $\theta_V = 1.5^\circ$ and 4°. The magnetotransport measurements reveal that the disorder induced during film deposition is strongly dependent on the substrate miscut angle. Moreover, it is shown that disorder is essentially developed near the interface, since by increasing the thickness, its effects on the magnetotransport properties are largely reduced. These findings are relevant for the understanding of functional properties of oxide multilayered structures with $SrRuO_3$ electrodes.

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The functionality of devices based on multilayered oxide structures is strongly dependent on the structural properties at the interfaces. Due to its good electrical and chemical properties [1], $SrRuO_3$ (SRO) has been commonly integrated as electrode in prototypes of these functional structures. Fabrication of micro- or nano-structured devices with SRO electrodes requires an understanding of the impact of growth-induced disorder on magnetotransport properties of SRO films. These effects are more prominent near the interfaces and, thus, a thorough knowledge of the physical properties of ultra-thin SRO films is required.

We have recently shown that at early stages the growth of SRO films on nominally exact $SrTiO_3$(0 0 1) substrates proceeds by the formation of finger-like units following the substrate steps [2]. Measurements of the electrical conductivity for different in-plane current injection directions reveal an in-plane anisotropy of transport properties, resulting from the initial anisotropic growth mode [3]. On the other hand, the presence of resistivity minima at low temperature has been ascribed to weak localization effects [4,5]. The origin of these quantum corrections is the shortening of the mean free path l when at a large enough amount of disorder $l \approx \lambda_F$, where λ_F is the Fermi wavelength [6]. These effects are enhanced when the disorder is large and, as a consequence, the resistivity minima are shifted to higher temperatures.

We have explored the impact of disorder induced at the first stages of growth on the magnetotransport properties of SRO ultra-thin (3.5,7 nm) films. The samples were grown by pulsed laser deposition on STO substrates with controlled miscut angle θ_v with values 1.5° and 4°. The substrates were held at 750 °C

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during deposition and the oxygen pressure was set to 0.1 mbar. Additional details of the deposition conditions, as well as on epitaxial nature and magnetotransport properties can be found elsewhere [2–4].

The electrical resistance was measured by the four probe method in a PPMS system of Quantum Design. Fig. 1 shows the temperature dependence of the normalized resistance of SRO films grown on substrates with miscut angle $\theta_V = 1.5^\circ$ ($t = 3.5\,\mathrm{nm}$, 7 nm) and $\theta_V = 4^\circ$ ($t = 3.5\,\mathrm{nm}$). Both the residual resistance ratio $\mathrm{RRR} = R(300\,\mathrm{K})/R(5\,\mathrm{K})$ and the temperature $T_{\min}$ at which the minimum resistance appear are related to the degree of disorder. We observe that the lowest RRR and higher $T_{\min}$ correspond to the ($\theta_V = 1.5^\circ$, $t = 3.5\,\mathrm{nm}$) film. Growing a film of same thickness on a $\theta_V = 4^\circ$ substrate gives a higher RRR and a lower $T_{\min}$, indicating a smaller disorder in this sample. A stronger effect is observed for the film grown on a $\theta_V = 1.5^\circ$ substrate, but with a larger thickness ($t = 7\,\mathrm{nm}$). This film showed the largest RRR and the lowest $T_{\min}$, i.e., it is the film with the highest quality of the present series. In addition, this also indicates that disordered regions develop near the interface and become less relevant as the thickness is increased. Finally, these data reveal that the amount of disorder developed during film deposition depends strongly on the substrate miscut angle and on the thickness.

We have complemented these data with measurements of the resistance R made by the four probe method in a PPMS System of Quantum Design. The sample holder was rotated in order to sweep the applied magnetic field all around in the plane of the film while the current injection direction was preserved. Thus, we could obtain the $R(\theta)$ curves, where θ is the angle between the magnetization M and the electrical current I (see inset in Fig. 2(a)).

In Fig. 2 we show the $R(\theta)$ curve measured at 5 K under a magnetic field of $H = 9\,\mathrm{T}$ for the film with thickness $t = 3.5\,\mathrm{nm}$ grown on the 4° substrate. We observe first, that $R(\theta = 90^\circ) < R(\theta = 0^\circ)$, i.e., the resistance is smaller when the electrical current runs parallel to the applied magnetic field. On the other hand, the expected $\sin^2\theta-$dependence for the resistance, when no magnetoresistive effects other than AMR are present, is not found. Indeed, as observed in Fig. 2, the minima are sharper than the maxima. The observed $R(\theta)$ curves can be explained by assuming that when the magnetic field is applied along certain directions, the magnetization is hardly aligned towards the applied field. These in-plane directions are signaled by the sharp minima of the $R(\theta)$ curves in Fig. 2(a). Upon rotating 90° the current injection direction, the minima appear sharper than the maxima (data not shown), revealing that the in-plane magnetic anisotropy has also been by rotated by 90°. However, with these experiments it is not possible to accurately determine the in-plane magnetic anisotropy. According to the results displayed in Fig. 2, the magnetization is more easily aligned towards the applied field when $\theta = 0^\circ$, although it does not mean that the in-plane magnetic easy axis is exactly along this direction. A strong uniaxial anisotropy has been reported, with the easy axis at an angle ~30° with respect to the normal [7]. Thus, the in-plane magnetic anisotropy is determined by the in-plane projection of this magnetic axis.

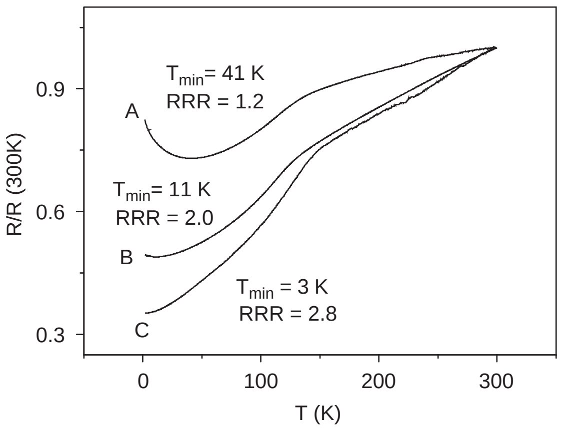

Fig. 1. Plot of the temperature dependence of the resistance of films grown on 1.5° and 4° $SrTiO_3$ substrates. These films are: A (1.5°, $t = 3.5\,\mathrm{nm}$), B (4°, $t = 3.5\,\mathrm{nm}$) and C (1.5°, $t = 7\,\mathrm{nm}$). The resistance values are normalized to the high-T value.

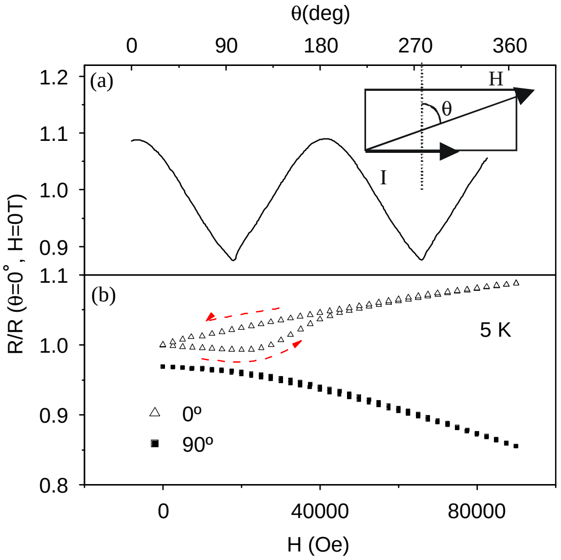

Fig. 2. (a) Plot of the angular dependence of resistance of the ($\theta_V = 1.5^\circ$, $t = 3.5\,\mathrm{nm}$) film. θ is the angle between the magnetization M and the injected current I. (b) Field dependence of the same sample for field applied along $\theta = 0^\circ$ and 90°, after cooling in zero field.