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Epitaxial-strain control of quantum conductance corrections and weak antilocalization in $SrIrO_3$ thin film*

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We study the low-temperature quantum conductance corrections in epitaxial $SrIrO_3$ thin films grown on substrates that impose biaxial strain of different sign and magnitude. The most instructive pair is the films on $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PMN-PT) and $SrTiO_3$, which carry strain of opposite sign and nearly equal magnitude – tensile $\varepsilon = +1.5\%$ and compressive $\varepsilon = -1.4\%$ – while $NdGaO_3$ and $(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ (LSAT) provide progressively stronger compression. In all films the resistivity rises logarithmically on cooling, the signature of two-dimensional quantum corrections, and the magnetoconductance is well described by the two-dimensional Maekawa-Fukuyama model with a classical quadratic orbital background. The sign of the strain governs the character of the corrections: the tensile PMN-PT film sustains weak antilocalization, seen as a zero-field conductance peak, whereas the compressive films cross over to weak localization, where the magnetoconductance is parabolic and shows no peak – the Maekawa–Fukuyama model describes both regimes equally well. The extracted phase-coherence length follows the temperature dependence expected for two-dimensional electron-electron (Coulomb) scattering, confirming the two-dimensional nature of the corrections despite the finite film thickness. The tensile and weakly compressed films display an intrinsic, hysteresis-free anomalous Hall effect of Berry-curvature origin, which is suppressed under the strongest compression. The sign and magnitude of the substrate-imposed strain thus govern the quantum conductance corrections in $SrIrO_3$ thin films.

Results and discussion

Strontium iridate $SrIrO_3$ is a nonsymmorphic Dirac semimetal with strong spin-orbit coupling (SOC, $\simeq 0.5\,$eV), in which the linear bands near the Dirac points are protected by the glide symmetry of the Pbnm space group.[1,2] Epitaxial strain imposed by the substrate breaks this symmetry and modifies the IrO_6 octahedra, which changes both the band structure and the effective SOC seen in transport.[2,3] At low temperatures this strong SOC gives rise to quantum conductance corrections – weak antilocalization (WAL) – whose analysis yields the characteristic dephasing and spin-orbit lengths.[3,4] How the sign of the substrate-imposed strain controls these corrections has remained unexplored; in particular, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) substrates had not been used for $SrIrO_3$ growth before. Here we compare $SrIrO_3$/PMN-PT (tensile, $\varepsilon = +1.5\%$) and $SrIrO_3/SrTiO_3$ (compressive, $\varepsilon = -1.4\%$), 35 nm thick, over 2–50 K. Films deposited on $NdGaO_3$ and $(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ (LSAT) were also studied with compression $\varepsilon = -2.5\%$ and $\varepsilon = -2.3\%$.

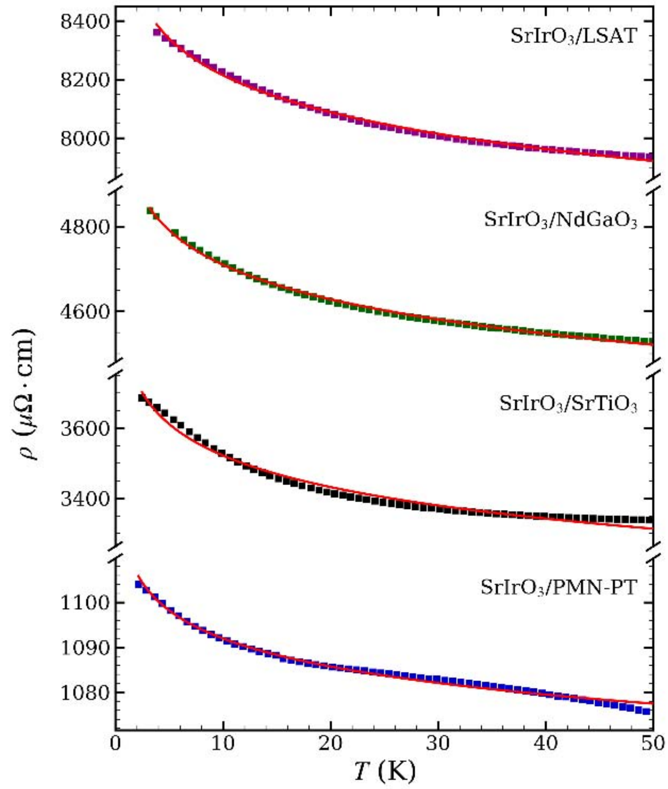

Figure 1. Resistivity ρ vs. temperature for $SrIrO_3$/LSAT, SrIrO3/$NdGaO_3$, $SrIrO_3/SrTiO_3$ and $SrIrO_3$/PMN-PT (top to bottom) over $2-50$ K. Red lines: logarithmic fits according to Eq. (1).

The films were deposited by radio frequency magnetron sputtering; X-ray diffraction confirmed epitaxial growth with out-of-plane parameters $c = 3.94\,$Å(PMN-PT) and $c = 4.03$Å($SrTiO_3$) relative to the bulk pseudocubic $a_0 = 3.96\,$Å, giving $\varepsilon = +1.5\%$ and -1.4%, respectively.[5] Magnetotransport was measured on Hall bar bridges in fields up to 10 T in the low temperature range 2-10 K.

For all four films residual resistivity $\rho(T)$ increases on

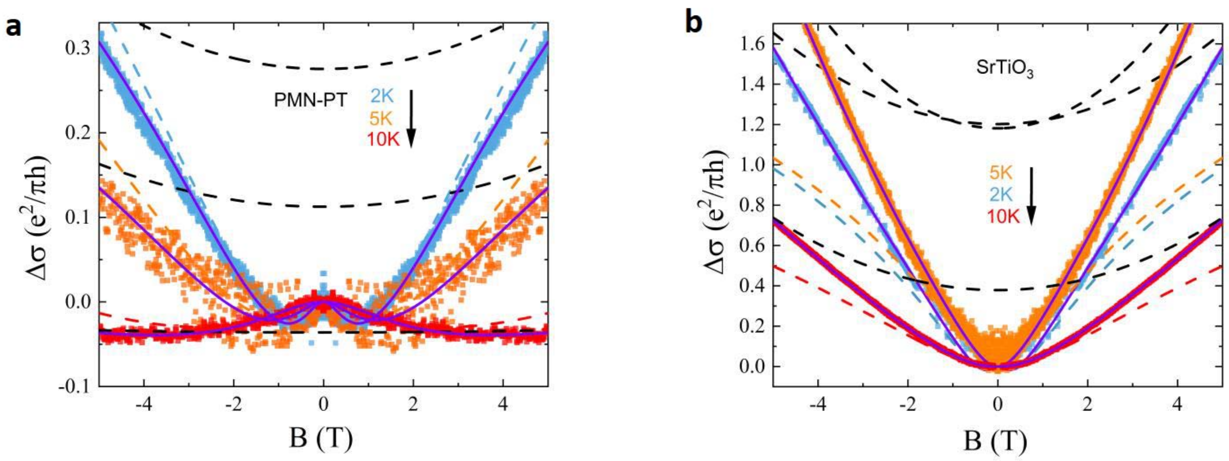

Figure 2. Magnetoconductance $\Delta\sigma(B)$ at 2–10 K fitted by the Maekawa–Fukuyama model with a classical B^2 background. **a** – $SrIrO_3$/PMN-PT; **b** – $SrIrO_3/SrTiO_3$. Black dashed lines: $C \cdot B^2$ term; colored dashed lines: Maekawa–Fukuyama term; solid purple lines: total fit.

cooling and follows the logarithmic law

$$\rho(T) = \rho_0 - A \cdot \ln\left(\frac{T}{T_0}\right), \tag{1}$$

the fingerprint of two-dimensional quantum corrections (see figure 1); A and ρ_0 are fitting parameters, $T_0 = 1\,\mathrm{K}$. The residual resistivity increases strongly with the degree of compression, being lowest for the tensile $SrIrO_3$/PMN-PT film and highest for the most strongly compressed $SrIrO_3$/LSAT film. The amplitude is much larger for $SrIrO_3/SrTiO_3$ ($A = 122\,\mu\Omega\cdot\mathrm{cm}$) than for $SrIrO_3$/PMN-PT ($A = 8.7\,\mu\Omega\cdot\mathrm{cm}$): under compressive strain the weak-localization and electron–electron contributions add, whereas under tensile strain the WAL correction partially compensates the electron-electron term.[6]

The magnetoconductance $\Delta\sigma(B) = \sigma(B) - \sigma(0)$ was fitted (figure 2) by the two-dimensional Maekawa-Fukuyama model plus a classical quadratic term[7]

$$\Delta\sigma(B) = \frac{e^2}{2\pi^2\hbar}\left[-\Psi\left(\frac{1}{2} + \frac{B_e}{B}\right) + \right.$$
$$+\frac{3}{2}\Psi\left(\frac{1}{2} + \frac{B_\varphi + B_{\mathrm{SO}}}{B}\right) - \frac{1}{2}\Psi\left(\frac{1}{2} + \frac{B_\varphi}{B}\right)$$
$$\left. - \ln\left(\frac{B_\varphi + B_{\mathrm{SO}}}{B_e}\right) - \frac{1}{2}\ln\left(\frac{B_\varphi + B_{\mathrm{SO}}}{B_\varphi}\right)\right] +$$
$$+ C \cdot B^2 \tag{2}$$

with $B_\varphi = \hbar/(4eL_\varphi^2)$, $B_{\mathrm{SO}} = \hbar/(4eL_{\mathrm{SO}}^2)$, and $B_e = \hbar/(4eL_e^2)$ the dephasing, spin-orbit and elastic characteristic fields, and Ψ the digamma function.[7]

The extracted lengths are collected in table 1. In $SrIrO_3$/PMN-PT the condition $B_{\mathrm{SO}} > B_\varphi/2$ holds at all temperatures and the WAL peak is well resolved ($L_{\mathrm{SO}} \simeq L_\varphi \simeq 13 - 26\,\mathrm{nm}$). In $SrIrO_3/SrTiO_3$ the classical $C \cdot B^2$ term is an order of magnitude larger and masks the peak; for $T \geq 5\,\mathrm{K}$ the film crosses over to weak localization ($B_{\mathrm{SO}}/B_\varphi < 0.5$). The elastic length $L_e \simeq 1\,\mathrm{nm} \ll L_\varphi$ in both films, and $L_\varphi \propto T^{-p/2}$ with $p \simeq 1$ confirms two-dimensional Coulomb dephasing despite the 35 nm thickness.[8]

This difference is mirrored in the magnetoresistance: $SrIrO_3/SrTiO_3$ shows a V-shaped negative magnetoresistance down to -3.3% at 10 T (quantum correction plus orbital B^2 background), whereas $SrIrO_3$/PMN-PT shows a much smaller signal ($\simeq -0.1\%$) with a distinct zero-field WAL peak. In addition, both paramagnetic films display a hysteresis-free, S-shaped anomalous Hall effect of intrinsic Berry-curvature origin, associated with the $J_{\mathrm{eff}} = 1/2$ states and strong SOC.[9,10] The films grown on NdGaO3 and LSAT show no anomalous Hall effect at any temperature. This suggests that beyond a compressive strain of about -2.3% the epitaxial distortion widens the gap at the Dirac (nodal-line) crossings and shifts the Berry-curvature hot spots away from the Fermi level, so that the intrinsic, field-induced anomalous Hall response of the $J_{\mathrm{eff}} = 1/2$ states can no longer develop.

Conclusion

The sign and the mismatch value of the substrate-imposed epitaxial strain control the low-temperature quantum conductance corrections of $SrIrO_3$ thin films. Tensile strain (PMN-PT) sustains weak antilocalization up to 10 K, whereas compressive strain ($SrTiO_3$) drives a crossover to weak localization with a large orbital B^2 magnetoresistance. The Maekawa–Fukuyama analysis gives L_φ, $L_{\mathrm{SO}} = 13 - 42$ nm, $L_e \simeq 1\,\mathrm{nm}$ and $\rho \simeq 1$, confirming two-dimensional Coulomb dephasing. The more strongly compressed $NdGaO_3$ and LSAT films follow the same trend, extending the strain–correction correlation into a continuous series.

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Film	T, K	L_φ, nm	L_{SO}, nm	L_e, nm
$SrIrO_3$/PMN-PT ($\varepsilon = +1.5\%$)	2.4	26.2	22.0	0.9
	5.0	20.7	18.0	0.9
	10.0	12.9	14.8	6.1
$SrIrO_3/SrTiO_3$ ($\varepsilon = -1.4\%$)	2.0	41.6	35.9	1.0
	5.0	25.3	57.8	1.3
	10.0	19.3	28.8	1.3
$SrIrO_3$/LSAT ($\varepsilon \approx -2.3\%$)	2.0	9.1	19.1	6.3
	10.0	9.6	13.3	1.7
$SrIrO_3/NdGaO_3$ ($\varepsilon \approx -2.5\%$)	2.0	16.2	36.7	12.4
	10.0	10.0	15.1	1.8

Table 1. Characteristic lengths obtained from the Maekawa–Fukuyama fit for films deposited on four different substrates.

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