Rashba induced magnetoconductance oscillations in the LaAlO$_3$-SrTiO$_3$ heterostructure

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We report measurements of the normal state in-plane magnetoconductance in gated LaAlO$_3$-SrTiO$_3$ samples. As the orientation of the magnetic field changes within the plane of the interface, the signal displays periodic oscillations with respect to the angle between the field and the direction of the current. We show that in the underdoped to optimally doped range, a Fermi surface reconstruction takes place due to the Rashba spin-orbit term and that the oscillations are due to a magnetic field induced opening and closing of a gap at the $\Gamma$ point for those Ti out-of-plane orbitals having their band minimum close to the Fermi energy of the system.

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B spin-orbit (model of the confined electron gas, \( m \)) taking into account temperature. The superconducting phase (2D SC, blue region) and the transition indicates the corresponding applied voltages for the reference sample. We note that the trends, we include data points slightly beyond the diffusive regime. (c) Variation of the transport effective mass \( \sigma \) at \( B = 0 \) for the sample of this work and a reference sample (data from Ref. 13) in the diffusive regime. The top voltage scale is consistent with the picture of an interface charge transport mechanism dominated \((0.2 m_S)\). Using these prescriptions, we present the variations of conductance \( \sigma_{2D} \), with \( \sigma_{2D} \) highlighting the crossing at \( \sigma_{2D} \sim 0.6 \text{ mS} \). Data points extend slightly beyond the diffusive regime. (c) Variation of the transport effective mass \( m^* \) with \( \sigma_{2D} \). Here \( m_{\text{max}} \sim 2.2m_e \), WL, WAL, and AM shaded regions denote the weak localization, weak antilocalization, and anomalous metal regimes, respectively.

\[
m^* = \frac{\hbar^2}{4\pi \lambda E} \sqrt{\frac{B_{\text{so}}}{\Phi_0}}
\]

(\( \Phi_0 = \frac{\pi e^2}{2m_e} \)) and hence \( \tau \) (or \( B_{\text{el}} \) the elastic magnetic field) in the WL regime (see the Supplemental Material\(^{11} \)).

When Eq. (1) holds, i.e., in the range of \( V \) such that spin-orbit terms contribute to diffusive processes, we consider that \( \lambda \) has little \( \lambda \) dependence. By contrast, changing the gate voltage modifies the sheet carrier density \( n_S \) and causes a variation of \( E \). The change in \( E \) can be determined from an electrostatic model of the confined electron gas,\(^{16} \) taking into account the electric field dependence of the STO dielectric constant (see Ref. 17).

Using these prescriptions, we present the variations of \( B_{\text{el}}, B_{\text{so}} \) and \( m^* \) with \( \sigma_{2D} \) (or \( V \)) in Figs. 1(b) and 1(c). To highlight the trends, we include data points slightly beyond the diffusive regime (see below). We note that \( m^* \) is \( \sim 3.5 \) lighter in the underdoped regime than in the optimally doped regime, which is consistent with the picture of an interface charge transport evolving from being \( d_{xy} \) dominated \((m^* \sim 0.64m_e, \text{ \( m_e \) is the bare electron mass}) \) to being \( d_{xz},d_{yz} \) dominated \((m^* \sim 2.2m_e)\), upon increasing \( V \) beyond \( \sigma_{2D} \sim 0.5 \text{ mS} \).\(^{13,14,19-23} \) The concomitant increase in \( \tau \) (Fig. S2 of the Supplemental Material\(^{11} \)) fits with this picture, since it signals that additional conduction channels start contributing. As reported in Refs. 13 and 14, \( \tau_{\text{so}} \) decreases steeply across \( V_c \), to the extent that \( \tau_{\text{so}} \sim \tau \) for \( \sigma_{2D} \sim 0.6 \text{ mS} \) [Fig. 1(b)]. When this occurs, spin-orbit processes cease to be diffusive. The spin-orbit time is no longer given by the D’yakonov-Perel’ expression and the Rashba term becomes a genuine additional energy scale in the problem, on equal footing with the kinetic part. The band structure needs to be recalculated in the presence of the (Fermi surface reconstructing) Rashba Hamiltonian. The evolution towards this AM regime is suggestive of a scenario of spin-orbit protected transport (against disorder) in the 2D conducting sheet.

\( \text{Ab initio} \) density functional theory (DFT) band structure calculations have been carried out for the LAO/STO system.\(^{23-26} \) These studies reveal that the conduction band consists of a manifold of \( t_{2g} \) states originating from a decomposition of the \( t_{2g} \) triplet into subbands, in response to the interfacial confining electric field.\(^{17,18,27} \) The energy minima of these subbands are located at the \( \Gamma \) point; the lower the value of the energy at the minimum, the closer the wave function is to the interface in the \( z \) direction. According to Ref. 26, for values of \( n_S \sim 10^{14} \text{ cm}^{-2} \), the states which lie closest to the interface, i.e., which do not extend beyond the first 3 unit cells from the STO boundary, on the STO side, have \( d_{xy} \) symmetry and account for a large part of the carrier concentration. \( d_{xz},d_{yz} \) subbands spread out deeper into the (STO) bulk, and, as they are being filled, they contribute to \( n_S \) on the order of \( 10^{13} \text{ cm}^{-2} \). These out-of-plane orbitals lie close to the Fermi surface and we argue below that they control charge transport in the AM regime.

To showcase the significant role played by the \( d_{xz},d_{yz} \) states, we measure the angular MC of the two-dimensional electron gas (2DEG) when a magnetic field is applied in plane and rotated from parallel to perpendicular to the current. In this geometry the magnetotransport is not affected by orbital contributions. Figure 2 shows the variation of the conductance with the angle \( \phi \) for four values of the magnetic field when \( \sigma_{2D} \) is \( 1 \text{ mS} \) [Fig. 2(a)] and \( 2 \text{ mS} \) [Fig. 2(b)]. Maxima of the conductance are seen for both dopings when the external magnetic field is applied perpendicularly to the current. However, the maximum of the oscillation \( \sigma_{2D}(B,\phi = \pi/2) \) evolves in a nonmonotonic way for the first doping, which is not the case for the higher conductance state. Note that oscillations of the MC in the parallel field geometry have been reported by Ben Shalom \textit{et al.}\(^{28} \) For the range of sheet conductances and the field intensity that they considered (typically higher than ours) they found a positive MC for \( \phi = 0 \), and suggested that a magnetic order forms at the interface.

For the doping range considered here, we may understand the behavior of the parallel MC as the field is rotated within the \( xy \) plane if we note that carriers in the \( d_{xz} \) or \( d_{yz} \) subbands have one light and one heavy mass \((m_l \sim 20m_e)\).\(^{18,19} \) Thus, qualitatively, the \( d_{xz} \) and \( d_{yz} \) orbitals are 1D-like and, since current flows along \( x \), we focus on the former type, which gives a higher contribution to transport. In the presence of the Rashba term, the spin-split bands exhibit an energy gap at the \( \Gamma \) point
when \( B \) is along \( x \) (\( \phi = 0 \)) and a Zeeman-like offset when \( B \) is along \( y \) (\( \phi = \frac{\pi}{2} \)) (Fig. S3 of the Supplemental Material\(^{11} \)). The impact of this effect on transport depends on the position of \( E_F \), the energy of the electronic states at the \( \Gamma \) point when \( B = 0 \), since the density of states (DOS) at the Fermi energy \( g(E_F) \) enters the expression of \( \sigma_{2D} \). The conductivity will thus show a dip for \( \phi = 0 \), provided \( E_F \sim E_{\Gamma} \). If \( E_F \) is not close to \( E_{\Gamma} \), \( g(E_F) \) is almost unchanged as compared to its \( B = 0 \) value. As mentioned above, in the underdoped to optimally doped range, \( E_{\Gamma} \) of most of the subbands with a \( d_{xy} \) character is well below \( E_F \), yet the \( E_{\Gamma} \) of \( d_{xz}, d_{yz} \) symmetry bands are close to \( E_F \). So the Rashba induced modulation of \( g(E_F) \) is controlled by the change in the \( d_{xz} \) carrier DOS. Insofar as one may reasonably assume that \( \tau \) does not depend on \( B \) in the 2D case, one expects a periodic variation of the MC with \( \phi \), displaying crests for \( B \) along \( y \) and troughs for \( B \) along \( x \).

In the framework of this 1D picture and with the additional simplifying assumption that the variation of \( \sigma_{2D} \) with \( \phi \) is entirely due to the \( d_{xz} \) subband closest to \( E_F \), we find \[ [\sigma_{2D}(B, \phi = \pi/2) - \sigma_{2D}(B, \phi = 0)]/\sigma_{2D}(B, \phi = 0) = 1/(8(\Delta_s/E_F)^2) \] when the Zeeman energy is larger than the condensation energy of the Rashba state (\( \Delta_s \)) (see also Ref. 29). Beyond the qualitative 1D model, we have modeled the evolution of the band structure for the \( d_{xy} \) orbitals in the applied \( B \). We use a tight binding model featuring kinetic and Rashba terms and we take into account the finite value of \( m_h \) and the anisotropy of \( \lambda \) in the \( xy \) plane for the \( d_{xz}, d_{yz} \) orbitals. The mobility, \( \lambda \), and the gyromagnetic factor \( g \) all depend on \( V \), but we consider that they do not change appreciably with \( \phi \) nor with the magnitude of \( B \) in our experiments. For a given \( V \), the variation of \( \delta n \)—i.e., the change in the \( d_{xz}, d_{yz} \) carrier concentrations—with \( \phi \) and \( B \).

FIG. 2. (Color online) (a) and (b) Experimental and theoretical plots of the conductance \( \sigma_{2D}(B, \phi) \) vs \( \phi \), the angle between the in-plane magnetic field \( B \) and the current for various values of \( B \). (a) corresponds to \( \sigma_{2D}^0 = 1 \text{ mS} \) and (b) to \( \sigma_{2D}^0 = 2 \text{ mS} \). (c) and (d) are experimental and theoretical dependences of the conductance on the in-plane magnetic field for \( \phi = \pi/2 \).

FIG. 3. (Color online) Experimental and model determined plots of \( \Delta \sigma_{2D} \) vs \( B \) for \( \sigma_{2D}^0 = 1 \text{ mS} \) and \( \Delta \sigma_{2D} = 2 \text{ mS} \).
depends on the values of the spin orbit and of the Zeeman energies. The conductance \(\sigma_{2D}(B,\phi)\) is then proportional to \(\Delta n\). Experimental data and plots obtained from the model are shown in Figs. 2(c) and 2(d). We note that while \(\Delta n\) increases monotonically with \(B\), \(\sigma_{2D}(B,\phi)\) increases monotonically with \(B\) at fixed \(\phi\) for \(\sigma_{2D}^{0}=2\) mS, such is not the case for \(\sigma_{2D}^{0}=1\) mS, a feature which is correctly captured by our model. Figure 3 displays the evolution of \(\Delta \sigma_{2D} = \sigma_{2D}(B,\phi=\pi/2) - \sigma_{2D}(B,\phi=0)\) vs \(B\) according to our model and the experimental results. We find good agreement using \(\Delta \sigma_{0} = 7(2.5)\) meV for \(\sigma_{2D}^{0}=2(1)\) mS, respectively. These values fall within the range of previous experimental estimates.\(^{13,14}\)

Figure 4 shows the evolution of the experimental oscillation amplitude \(\Delta \sigma_{2D}\) as a function of \(\sigma_{2D}^{0}\) for different magnetic fields. As can be seen, \(\Delta \sigma_{2D}\) tends to zero for a sheet conductance in the 0.1–0.3 mS range. These sheet conductance values—which lie in the diffusive regime—are close to the QCP, suggesting a potentially important role played by the \(d_{xz},d_{yz}\) orbitals in establishing superconductivity.

In summary, our findings underscore the evolution that takes place in the LaAlO\(_3\)-SrTiO\(_3\) heterostructure, as one tunes the gate voltage in the range where superconductivity is observed at low temperature. For low \(V\), conduction is diffusive and is dominated by the \(d_{xy}\) orbitals, as the impact of disorder is expected to be more severe for the 1D-like \(d_{xz},d_{yz}\) states. For larger values of \(V\), the nature of transport changes and the out-of-plane \(d_{xz},d_{yz}\) orbitals start contributing to the zero field conductivity, as evidenced by the evolution of \(m^*,B_{g3},B_{so}\) and by the oscillations of the in-plane magnetocconductance. For these orbitals, the effect of the strong spin-orbit interaction has to be taken into account at the band structure level for the calculation of their contribution to the transport.

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