Shubnikov–De Haas Oscillations in $SrTiO_3/LaAlO_3$ Interface

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Quantum magnetic oscillations in $SrTiO_3/LaAlO_3$ interface are observed in the magnetoresistance. We study their frequency as a function of gate voltage and the evolution of their amplitude with temperature. The data are consistent with the Shubnikov–de Haas theory. The Hall resistivity ρ_{xy} is nonlinear at low magnetic fields. ρ_{xy} is fitted assuming multiple carrier contributions. We infer the density of the mobile charge carriers from the oscillations frequency and from Hall measurements. The comparison between these densities suggests multiple valley and spin degeneracy. The small amplitude of the oscillation is discussed in the framework of the multiple band scenario.

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The two-dimensional electron gas (2DEG) formed at the interface between two insulating perovskites is a subject of intense scientific interest [1]. The most widely studied interface has been the one created between $SrTiO_3$ and $LaAlO_3$ [2]. At low temperatures this 2DEG has a superconducting ground state, whose critical temperature can be modified by an electric field effect [3]. The nature of the charge carriers and their origin are still a matter of debate [4–11]. The thickness of the conducting layer has been estimated to be of a few nanometers by both transport measurements [12,13] and by using a conducting atomic force microscope [14]. From the atomic force microscope data analysis Copie *et al.* conclude that two types of charge carriers screen the local electric fields. The magnetoresistance is strongly anisotropic [12] and effected by a gate-dependent spin-orbit interaction [15,16]. ρ_{xy} is nonlinear in magnetic field [15,17], and therefore it does not relate in a simple way to the number of charge carriers. The effective mass has been estimated using elipsometry [18] to be $2.2m_e$ with m_e the electron mass. The number of charge carriers, their effective mass, and the effect of gate voltage on their mobility are a subject of vigorous research.

Quantum oscillations in magnetic fields have been extensively used to study the electronic properties of metals semiconductors and correlated systems. In the standard theory of Shubnikov–de Haas (SdH), the amplitude of the oscillating part of the resistance is [19]

$$\Delta R = 4R_c R_T R_D \sin\left[2\pi\left(\frac{F}{B}-\frac{1}{2}\right) \pm \frac{\pi}{4}\right] \quad (1)$$

where R_c is the nonoscillating part of the resistance. The oscillation amplitude decays with temperature as given by

$$R_T = \frac{2\pi^2 m^* k_B T}{\hbar eB} \Big/ \sinh\left(\frac{2\pi^2 m^* k_B T}{\hbar eB}\right) \quad (2)$$

with m^* the quasiparticle effective mass. The Dingle factor is

$$R_D = \exp\left(-\frac{\pi}{\omega_c \tau_D}\right) \quad (3)$$

with $\omega_c = \frac{eB}{m^*}$ and τ_D the Dingle scattering time, which is related to the Dingle temperature by $k_B T_D = \hbar/2\pi\tau_D$. This factor determines the decay of the amplitude of the oscillations as the field decreases. Increasing the magnetic field, lowering the temperatures, and decreasing the scattering rate should all lead to increasing oscillation amplitude.

In this Letter, we report longitudinal and Hall resistance measurements at low temperatures and intense magnetic fields of up to 31.5 T. The high magnetic field enables us to detect quantum oscillations in the longitudinal resistivity, as well as nonlinearities in the Hall resistance. The data are consistent with the SdH theory, enabling us to extract the high mobility carrier concentration, their effective mass, and the scattering rate. In addition, we fit the Hall data over the entire field range assuming high and low mobility carriers. The obtained mobile carrier concentration is much higher than the one inferred from the SdH frequency. This suggests multiple valley and spin degeneracy. We find that the carrier concentration and the scattering rate of the high mobility band obtained from the transport agree with the SdH analysis within a factor of 3. However, the amplitude of the oscillations is unexpectedly small.

We use a sample with 15 unit cells of $LaAlO_3$, deposited by pulsed laser on a TiO_2-terminated $SrTiO_3(100)$ substrate. Deposition conditions are similar to Ref. [15]. A $60 \times 120\ \mu m^2$ Hall bar was patterned using the procedure of Schneider *et al.*, [20] allowing a standard four-probe resistivity and Hall measurements. A gold layer was evaporated and used as a bottom gate when biased relative to the 2DEG. Aluminum or gold contacts were sputtered after drilling holes through the $LaAlO_3$ over layer using an ion miller. The gate voltage was first set to +200 V. It was then used to control the state of the sample, i.e., the carrier concentration and the corresponding zero field resistivity R_0. We present the analysis as a function of R_0 and not the gate voltage since the latter may change from one cycle to the other.

Figure 1(a) presents the sheet resistance at base temperature (400 mK) for 3 values of R_0 (controlled by the gate). As previously reported [12] a strong, positive magnetoresistance is observed. Figure 1(b) demonstrates the data of $R_0 = 75\ \Omega$ [(red) squares] after subtraction of a straight line for $H > 10$ T. Conspicuous magnetic oscillations are observed.

Figure 2(a) depicts ΔR versus $1/\mu_0 H$ for the various R_0 after subtracting their polynomial background. We made sure that this background is smooth and contains no oscillations in the field range under study. The background for $R_0 = 75\ \Omega$ is shown in Fig. 1(b) [solid (green) line].

Figure 2(b) presents the same measurement for $R_0 = 75\ \Omega$ at three different temperatures. From the temperature dependence of the amplitude, using Eq. (2) we can extract m^*. At a constant field the oscillation amplitude depends solely on m^* if we assume that τ is constant at this temperature range. This is consistent with the temperature-independent resistance observed below 2 K (not shown). From the analysis we find $m^* = 2.1 \pm 0.4 m_e$. The main errors stem from the uncertainty in temperature that may vary during the field scan. The complicated shape of the background introduces another source of uncertainty to the amplitude. Yet, since this background is smooth and temperature independent, its contribution to the uncertainty is minor. Moreover, upon using a band-pass filter instead of the polynomial subtraction we obtained the same effective mass.

The dashed lines in Fig. 2(a) are the theoretical curves using Eq. (1), leaving R_c as a free parameter. This assumption will be discussed later. We find a good match for all values of R_0 and all temperatures when $R_0 = 75\ \Omega$. For this gate voltage we find $T_D = 2 \pm 0.4$ K. If we assume constant m^* we can evaluate T_D for $R_0 = 92$ and $50\ \Omega$ to be 2.1 and 1.5 K, respectively. It is possible, however, that the effective mass varies with carrier concentration.

The various R_0 exhibit different frequencies in $1/H$: 76, 60, 57.5 T for $R_0 = 50$, 75, and 92 Ω, respectively. The SdH frequency and the area of the Fermi surface are related by Onsager relation [19] $F = \frac{\hbar}{2\pi e} A(\epsilon_F)$, where $A(\epsilon_F)$ is the area in momentum space of a closed orbit at the Fermi level. The magnetoresistance was measured while applying the field parallel to the current, no oscillations were observed (not shown). This is consistent with a two-dimensional (2D) Fermi surface. According to Luttinger's theorem, $A(\epsilon_F)$ is directly related to n_{2D} by: $n_{2D} = N_v N_s eF/h$, where N_v and N_s are the valley and spin degeneracies, respectively. Ignoring any degeneracy, the obtained frequencies correspond to carrier densities of the order of 10^{12} cm^{-2}. This is much lower than the numbers obtained from the Hall coefficient or from those predicted theoretically [5]. We attempt to reconcile this puzzle by a more careful analysis of the Hall resistivity, which is sensitive to the existence of two types of charge carriers (or more), in particular to low mobility carriers which do not contribute to the SdH effect.

Figure 3 shows the Hall resistivity measured for various gate voltages and sample resistances. A nonlinear regime is observed at low magnetic fields. ρ_{xy} is fitted using a two-band model. In this model the field dependence of ρ_{xy} is given by

$$\rho_{xy} = \frac{\sigma_1^2 R_1 + \sigma_2^2 R_2 + \sigma_1^2 \sigma_2^2 R_1 R_2 (R_1 + R_2) B^2}{(\sigma_1 + \sigma_2)^2 + \sigma_1^2 \sigma_2^2 (R_1 + R_2)^2 B^2} B \quad (4)$$

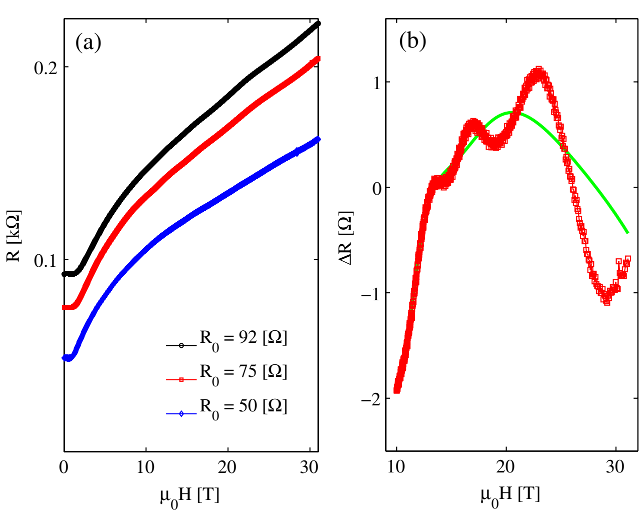

FIG. 1 (color online). (a) Sheet resistance as a function of magnetic field at 0.4 K. The zero field resistances is tuned by gate voltage. (b) Squares: The curve for $R_0 = 75\ \Omega$ after a subtracting of a linear fit. The solid line is a polynomial background used in the data analysis.

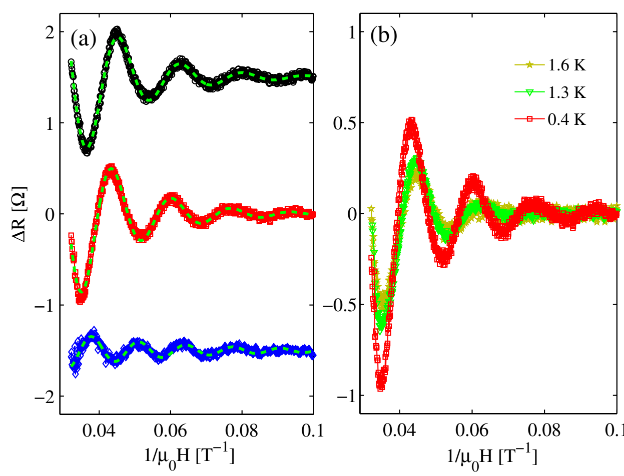

FIG. 2 (color online). (a) The data in Fig. 1 after subtraction of a polynomial background for the various R_0 The data are shifted for clarity by 1.5 Ω. From top to bottom: $R_0 = 92$, 75, 50 Ω. The dashed lines are model fittings using Eq. (1). (b) The data for $R_0 = 75\ \Omega$ for various temperatures after subtraction of a polynomial background. The value of R_0 is constant for this temperature range.

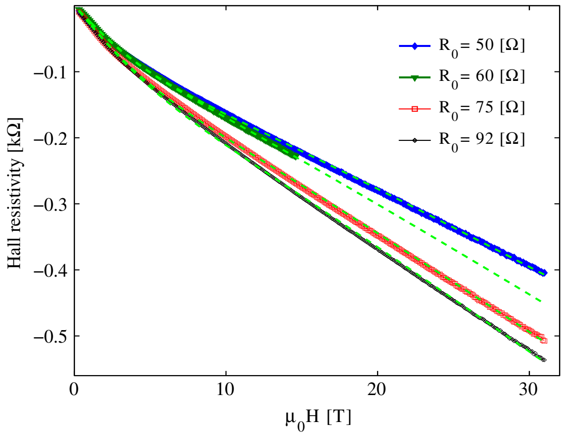

FIG. 3 (color online). Hall resistivity as a function of magnetic field for the various R_0. The dashed lines are model fittings using Eq. (4).

with R_i and σ_i the Hall coefficient and conductivity of the ith type of carrier. The zero field resistance is $\frac{\rho_1\rho_2}{\rho_1+\rho_2}$. In Fig. 3 we show the fits to ρ_{xy} for the entire field range using Eq. (4) and the measured zero field resistance. From the fit we can extract the concentrations and mobilities of both types of carriers [21]. Sometimes, the same model can also be used for fitting the magnetoresistance. However, the shape of the magnetoresistance is rather complicated and includes effects that cannot be described by a simple orbital model [12]. We therefore used only the zero field resistivity as a constraint for the fitting.

The results of such fitting of the Hall resistivity are summarized in Fig. 4. The upper panel presents the obtained carrier concentrations for the various R_0. The concentration n_1 of the low mobility charge carriers is about

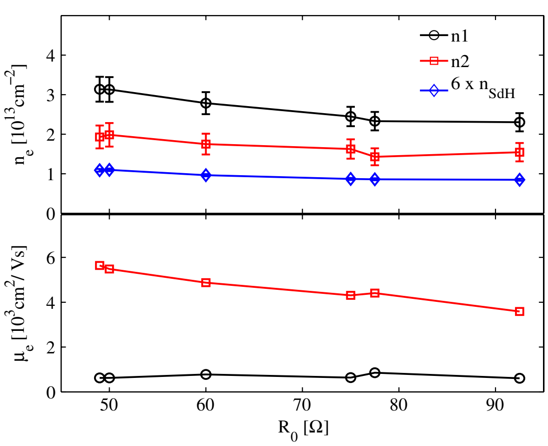

FIG. 4 (color online). Upper panel: The carrier densities for the various R_0 inferred from the analysis of the Hall resistivity n_1 and n_2 correspond to the low and high mobility charge carrier density. The blue diamonds are the carrier densities obtained from the SdH frequency assuming six-fold degeneracy. Lower panel: The mobilities of the two types of carriers inferred from the Hall analysis.

50% larger than n_2, the concentration of the high mobility ones. The respective mobilities μ_1 and μ_2 are shown in the lower panel, where it can be seen that μ_2 is 6–9 times larger. This observation explains the absence of oscillations corresponding to majority carrier concentration n_1. It seems that both bands respond to the gate variation.

In addition, we present the carrier concentration n_{SdH} obtained from the SdH analysis multiplied by six. The six-fold degeneracy is reasonable if one assumes a valley degeneracy of three and spin $1/2$. It is needed to better match n_2 and n_{SdH}. We have previously proposed that valley degeneracy of 3 is required to reconcile the root mean square amplitude and the width of the universal quantum fluctuations [22]. The three-fold valley degeneracy is consistent with SdH measurements on $SrTiO_3$ [23]. The valley degeneracy picture is probably oversimplified. Furthermore, there is still a factor of 2 discrepancy between n_{SdH} and n_2 which cannot be reconciled.

The obtained mobilities exhibit different behavior with R_0 or gate voltage. While the mobility of the "slow" charge carriers, μ_1 remains almost constant, μ_2 increases with the total number of carriers. This is consistent with the observation of Bell *et al.* [24].

We note that the phase of the SdH oscillations is determined by Eq. (1). This phase is calculated assuming parabolic bands [19]. Our data matches Eq. (1) including this phase for $R_0 = 75$, 92 Ω. No other frequencies can be detected. It seems, however, that for $R_0 = 50$ Ω there is a phase shift of $\pi/2$ [minus sign is used in Eq. (1)].

All scattering processes contribute to τ_D while only backscattering enters the transport scattering time τ_t. For $R_0 = 75$ Ω, $\tau_D = 6 \times 10^{-13}$ sec. From a simple calculation of the scattering time using the Hall mobility and the effective mass (found from the SdH analysis) we obtain $\tau_t = 2 \times 10^{-12}$ sec. The factor of 3 difference is reasonable, taking into account the over simplified two-band analysis.

The smearing of the Landau levels $k_B T_D \simeq 0.2$ meV is much smaller than their spacing $\hbar\omega_c = 1.65$ meV (for 30 T). In addition the Landau level degeneracy is of the order $\phi/\phi_0 = 7 \times 10^{11}$, with ϕ_0 being the flux quantum. This is not very far from the carrier concentration found from the naive SdH frequency analysis. Therefore, the amplitude of the SdH oscillations is expected to be very large. Yet, we observe a rather small effect $\Delta R/R \ll 1$. Moreover, for 400 mK and 30 T we get $R_T \simeq 1$ and $R_D \simeq 0.1$; therefore, the oscillations are expected to be 10% of R_c. The amplitude of the oscillations $\simeq 1$ Ω yields $R_c \simeq 10$ Ω, which is at least by an order of magnitude smaller than the measured nonoscillating part of the resistance, i.e., $R_c \ll R_0$.

The small amplitude of the SdH oscillations may be due to a three-dimensional Fermi surface. Since there are no SdH oscillations in the parallel field orientation, one should require no Landau quantization for this configuration. Satisfying the above conditions requires $R_L \gg d \gg \lambda_F$, with $R_L = \sqrt{\frac{h}{eB}}$ and $\lambda_F = \frac{2\pi}{k_F}$. Using $n = 10^{13}$ cm^{-2} carriers we find $\lambda_F \simeq 10$ nm while $R_L \simeq 12$ nm for $B = 30$ T. This means that the layer thickness d, λ_F, and R_L are all at the same order of magnitude and the inequality above is not easily obeyed. Another possibility is that the spin degeneracy is lifted, yet strong spin scattering results in smearing of the Zeeman dip. The resemblance of the data to the theoretical SdH curve cast doubt on this scenario.

In summary, we measured longitudinal and transverse resistances in $SrTiO_3/LaAlO_3$ interfaces with various gate voltages and at various temperatures. The longitudinal resistance exhibits quantum oscillations with a single frequency. An analysis of the data according to the SdH theory yields the carrier density, effective mass, and scattering rate. The transverse resistance is fitted using a two types of charge carriers model. In order to reconcile these two measurements we had to invoke multiple valley and spin degeneracy. This yields an agreement within a factor of 2 in concentration and a factor of 3 in scattering rates. The small amplitude of the oscillations at high fields is still unclear.

Our results suggest that separating out the low mobility band may result in a highly conducting oxide interface with gate tuning capabilities.

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Note added.—Recently we became aware of another work reporting SdH oscillations in this system with a lower carrier concentration [25]. Their effective mass is somewhat smaller. This may be indicative of an effective mass variation with carrier concentration.

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