

Angular Dependence of the Magnetoresistance of the SrTiO₃/LaAlO₃ Interface

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We study the magnetoresistance (MR) of the quasi-2-D electron liquid at the interface that forms between SrTiO₃ and LaAlO₃ as a function of the magnitude and orientation of the magnetic field. We find that at $T \geq 60\text{K}$, the MR is described by $a + b \cos^2 \theta + c \sin^2 \theta \cos^2 \varphi$, where θ is the angle between the field and the film normal and φ is the angle between the in-plane component of the field and the current. For $\theta = 0^\circ$ (field perpendicular to the plane), we show that the MR obeys Kohler's rule while for $\theta = 90^\circ$ (field in the plane) the MR is significantly smaller, and it is almost temperature independent, suggesting it is dominated by interface scattering.

Index Terms—Interface phenomena, Kohler's rule, magnetoresistance, 2-D electron liquid.

SINCE its recent discovery, the 2-D electron liquid (2DEL) that forms at the interface between the two insulating oxides SrTiO₃ (TiO₂ terminated (001)) and LaAlO₃ (LAO/STO) has attracted considerable interest [1]–[9], [16], [17] for its fascinating properties and its potential key role in future oxide-based electronics and spintronics [10], [18], [19].

One of the important tools used for elucidating the nature of the 2DEL is magnetoresistance (MR) measurements. In a recent report, we have shown that with decreasing temperature and increasing fields the MR becomes antisymmetric. We have suggested that the origin of this phenomenon could be nonuniform extraordinary Hall effect, which indicates nonuniform field-induced magnetization [11]. Here, we concentrate on a temperature range between 60 and 100 K where on the one hand the antisymmetric contribution to the MR is negligible, and on the other hand there is still a sizable MR effect. We find strong angular dependence of the MR. For fields perpendicular to the film, Kohler's rule is obeyed and strong temperature dependence is observed. On the other hand, for in-plane fields, the MR is much smaller and almost temperature independent.

The patterned samples used in this study were prepared in Augsburg. Full preparation details are reported elsewhere [12]. We note that the samples were grown in an oxygen atmosphere of 2×10^{-5} mbar and that eight unit cells of LAO were deposited on TiO₂ terminated (001) STO surfaces by pulsed laser deposition. The current paths are 100 microns wide and the voltage leads allow for simultaneous longitudinal and transverse voltage measurements. Fig. 1 shows the temperature dependence of the sheet resistance (R_s) and the Hall mobility (μ). The data are similar to those reported previously for samples with conductivity dominated by intrinsic interface doping [1], [4], [7], [8], [13], [16], [17].

Fig. 2(a) shows the MR defined as $(R(H) - R(H = 0)) / (R(H = 0))$ as a function of H with a magnetic field

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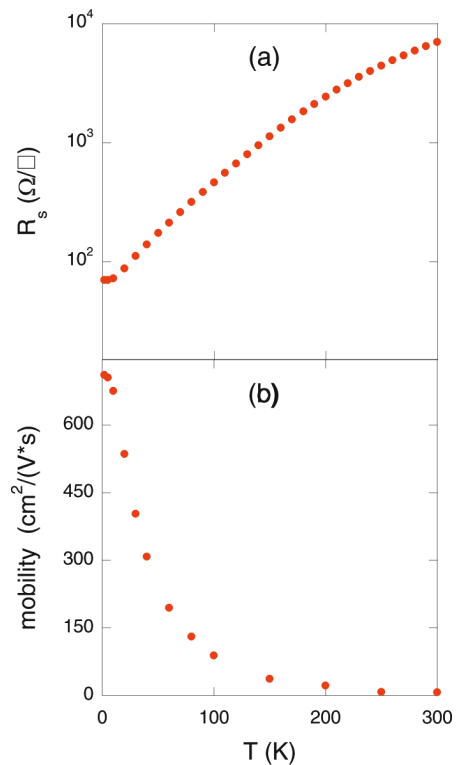


Fig. 1. (a) Sheet resistance as a function of temperature. (b) Mobility as a function of temperature.

applied perpendicular to the interface, at different temperatures. We see that as a function of $((H)/(R_s(H = 0)))^2$, the data collapse on a single linear curve for $T \geq 60\text{K}$ [see Fig. 2(b)]. This implies that only in the higher temperature range the MR data obey Kohler's rule [14]; namely, $\Delta\rho/\rho$ scales with H/ρ . This indicates that the MR is a function of $\omega_c\tau$ where $\omega_c = eH/m^*$ is the cyclotron frequency and τ is the scattering time for orbits in the plane perpendicular to H . Moreover, we find that $(\Delta R)/(R) = C(\mu H)^2$ with $C \sim 1$ where μ is the mobility measured for this sample [see Fig. 1(b)]. These observations indicate that in this temperature range, the transport properties

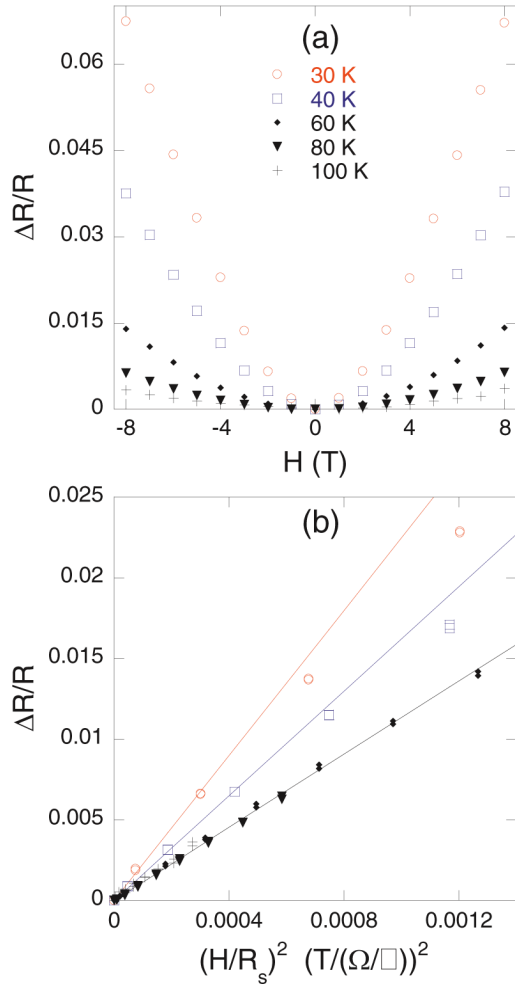


Fig. 2. (a) Magnetoresistance as a function of H (applied perpendicular to the interface), at different temperatures. (b) Scaling of the magnetoresistance in the temperature range between 60 K and 100 K. R_s is the sheet resistance measured at zero magnetic field.

of the electron liquid are compatible with the behavior of a free electron gas with a single dominant scattering rate.

For angular dependent MR measurements, we set the magnetic field at $H = 8$ T and rotate it in three different planes: a plane perpendicular to the current path (the “first plane”), a plane perpendicular to the sample plane which contains the current path (the “second plane”), and the film plane (the “in plane”), as shown in Fig. 3(a). Fig. 3(b) shows the angular dependence of R_s ($H = 8$ T) at $T = 60$ K in the three planes. To switch between the planes the sample had to be warmed and removed from the cryostat. Due to known relaxation effects of the 2DEL [15], the values of $R_s(H = 0)$ in the three measurements varied by few percents. Therefore, for clarity we shifted the y-scale of two of the graphs with small constants. The figure shows a good fit with the equation

$$R_s = A + B \cos^2 \theta + C \sin^2 \theta \cos^2 \varphi \quad (1)$$

indicating that

$$\frac{\Delta R}{R} = a + b \cos^2 \theta + c \sin^2 \theta \cos^2 \varphi \quad (2)$$

where θ is the angle between the field and the normal to the interface and φ is the angle between the field component which

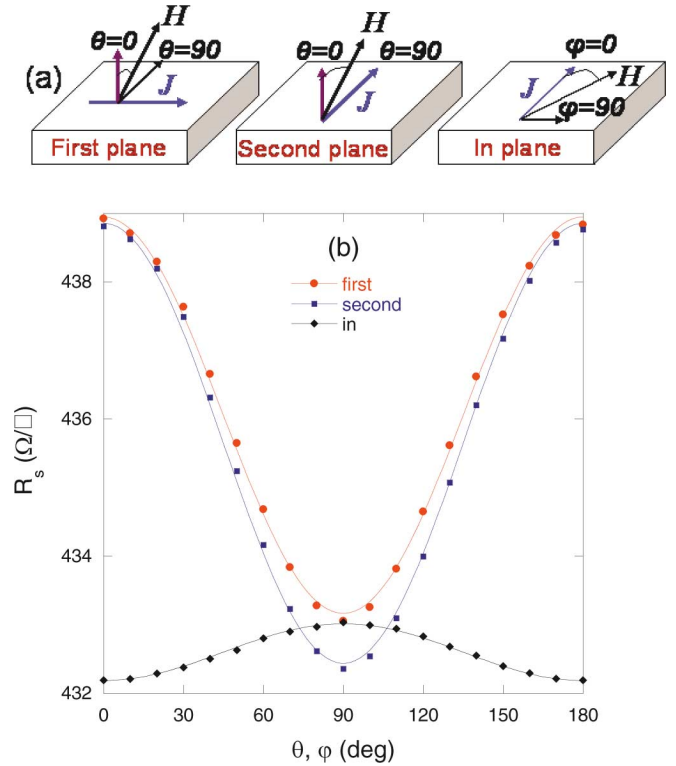


Fig. 3. (a) Sketch of the three planes of rotation (see text). (b) Sheet resistance as a function of θ measured with a field of 8 T at 60 K. The lines are fits according to (1).

is parallel to the interface and the current path [see Fig. 3(a)]. It is found that the MR consists of two different contributions: a contribution proportional to the square of the field component perpendicular to the interface ($b \cos^2 \theta$) and a contribution proportional to the square of the field component parallel to the current path ($c \sin^2 \theta \cos^2 \varphi$).

The coefficients a, b, c are field-dependent and can be expanded in even powers of H . Fig. 2 indicates that $b(H) \sim b_0 H^2$ (since the MR is proportional to H^2 when $\theta = 0^\circ$) for $T \geq 60$ K. The same behavior is observed for $c(H)$. The field dependence of $a(H)$ is less obvious due to its very small magnitude.

The lines in Fig. 3(b) are fits to (1). In the “first plane” $\varphi = 90^\circ$ so R_s is given by $A + B \cos^2 \theta$, and in the “in plane” $\theta = 90^\circ$ so R_s is given by $A + C \cos^2 \varphi$. In the “second plane” $\varphi = 0^\circ$ so R_s is given by $A + B \cos^2 \theta + C \sin^2 \theta$; i.e., the “second plane” is a combination of the two contributions. As expected, we obtain that the amplitude of the variations in R_s when the field rotates in the “second plane” is the sum of the other two amplitudes obtained in rotations in the “first plane” and the “in plane”.

The 2-D nature of the electron liquid is clearly observed by comparing the MR for fields applied perpendicular to the sample with MR for fields applied parallel to the sample. Fig. 4 shows MR measurements of two patterns with perpendicular and parallel fields. For one pattern the parallel field is parallel to the current (open circles) and for the other pattern the parallel field is perpendicular to the current (open squares). We note that at 60 K the square root of the ratio of the perpendicular and parallel MR is ~ 4 . This ratio may be related to the ratio between the scattering length for orbitals in a plane parallel to the 2DEL

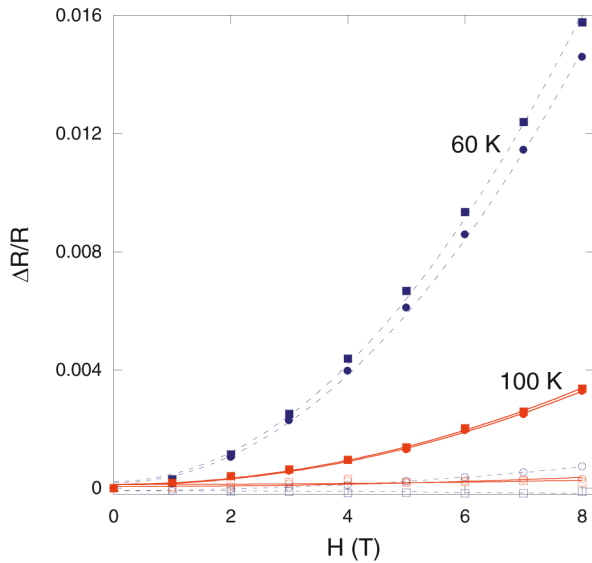


Fig. 4. Magnetoresistance as a function of the magnetic field applied perpendicular (full symbols) and parallel (open symbols) to the interface, at two different temperatures: 60 K (dash line, blue) and 100 K (solid line, red). Square symbols are used for the “first plane” while circle symbols are used for the “second plane” (see text).

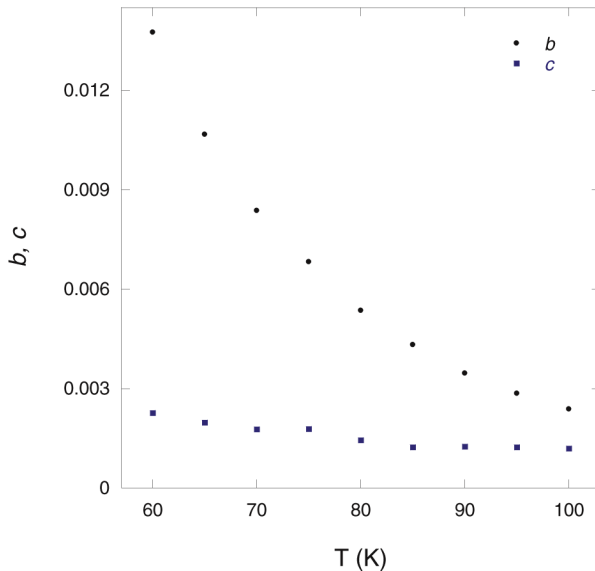


Fig. 5. Temperature dependence of the coefficients b and c in a field of 8 T.

and the effective scattering length for orbitals in planes that are perpendicular to the 2DEL (assuming an orbital effect also for the in-plane MR). If the dominant scattering process in the latter case is at the interface, then this length is likely to be related also to the confinement of the 2DEL.

Fig. 4 shows the data for two temperatures: 60 and 100 K. We see strong temperature dependence of the MR when the applied field is perpendicular to the sample as expected by the strong temperature dependence of R_s and the applicability of Kohler’s rule in this temperature range. The significant difference in temperature dependence between perpendicular and parallel field MR is also demonstrated by Fig. 5 which compares the temper-

ature dependence of the coefficients b and c . We see that the coefficient b is significantly larger and it exhibits a much stronger temperature dependence.

In summary, we have demonstrated several features of the MR at $T \geq 60$ K: (a) the MR for fields perpendicular to the sample obeys Kohler’s rule, indicating a single dominant scattering time for orbitals in the plane parallel to the sample; (b) the MR for fields parallel to the sample is much smaller, indicating its 2-D nature; (c) a simple equation describes the angular dependence of the MR, indicating its dependence on a component of the field perpendicular to the sample and on a component of the field which is parallel to the current.

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