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Multi-band Conduction Behaviour at the Interface of $LaAlO_3/SrTiO_3$ Heterostructures

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We have measured the Hall resistance and magneto-resistance (MR) of $LaAlO_3/SrTiO_3$ heterojunctions at magnetic fields up to 30 T in a temperature range $T = 4$ K to 70 K. For temperature below 7 K and above 50 K the devices display linear Hall resistance, indicating that one type of charge carriers dominate the transport. For temperatures between 10 K and 40 K, the Hall resistance is strongly non-linear, and is accompanied by a large positive MR, which is governed by the component of magnetic field normal to the interface. This behaviour in the intermediate temperature regime can be related to thermally activated high-mobility carriers.

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I. INTRODUCTION

The physics of strongly correlated electrons at interfaces between thin films of transition metal oxide is an emerging field of research. In 2004, Ohtomo and Hwang [1] reported a high-mobility conducting interface between the band insulating perovskite oxides $SrTiO_3$ (STO) and $LaAlO_3$ (LAO). The LAO/STO interface has subsequently been found to exhibit superconductivity below 200 mK [2], magnetism [3–5], electric field-controlled metal-insulator and superconductor-insulator transitions [6, 7], quantum oscillations [1, 8, 9], and, very recently, coexistence of superconductivity and ferromagnetism in two dimensions [10–12]. Three basic mechanisms have been proposed to describe the origin of conductivity at the LAO/STO interface: (i) electronic interface reconstruction [13–15]; (ii) formation of oxygen vacancies [16, 17]; and (iii) lattice deformation due to cation disorder, as in conventional semiconductors [18]. The relative contribution of each mechanism to the conducting interface depends on many factors, including the growth conditions of the heterostructure [3]. Magneto-transport measurements of the LAO/STO interface have revealed a variety of behaviour (positive MR, negative MR, magnetic hysteresis and a low-temperature upturn in the sheet resistance) for samples with different thicknesses of the LAO layer [3–5,19,20], however, a detailed study of the MR in a wide range of temperatures at high magnetic fields is still missing.

Here we report systematic magneto-transport studies on a $LaAlO_3/SrTiO_3$ heterostructure in the temperature range from 4 K to 70 K, at magnetic fields up to 30 T. Both MR and Hall resistance exhibit behaviour which cannot be explained in terms of a conventional 2D (*e.g.* GaAs quantum well), single sub-band system. For temperatures above 40 K, a small positive MR and a linear Hall effect are observed; for temperatures between 40 K and 10 K, a large positive MR and a non-linear Hall effect are observed; and for temperatures below 7 K, a negative MR, with a minimum around zero magnetic field, and a linear Hall resistance are observed. We show that the experimental data can be qualitatively explained by considering multi-band conduction, which depends strongly on temperature and magnetic field.

II. EXPERIMENTAL DETAILS

The measurements discussed here were performed on samples with 26 unit cells of LAO (10 nm thick), grown

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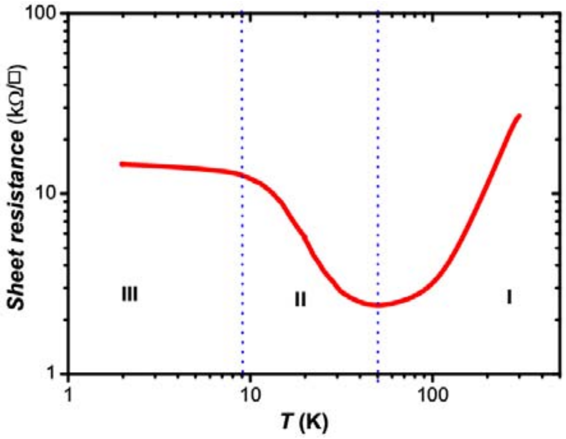

Fig. 1. (Color online) Temperature dependence of the sample sheet resistance.

on a TiO_2 terminated, single crystal STO [001] substrate. The LAO film was deposited by pulsed laser deposition, at 850°C, in a partial oxygen pressure of 2×10^{-3} mbar, using a single-crystal $LaAlO_3$ target. The full details of the deposition procedure are discussed elsewhere [3]. The sample size was 5 × 5 × 0.5 mm^3, and the sheet resistance and MR were measured in van-der-Pauw geometry, using a standard low-frequency lock-in technique with an excitation current of 1 μA. Magneto-transport measurements as a function of magnetic field orientation were conducted in a temperature controlled ^{4}He flow cryostat, in magnetic fields up to 30 T. Note that the applied magnetic field was always perpendicular to the current direction in the sample.

III. RESULTS AND DISCUSSION

In Fig. 1, we show the sheet resistance of the sample as a function of temperature between 250 K and 2 K. This temperature dependence of the resistance was observed previously [3]. It is distinctly different from a simple metal (or metallic semiconductor), where R increases monotonically with T. Three distinct regimes of behaviour were observed: Region (I), above 50 K, the sample resistance decreases as the temperature is reduced to 50 K, typical metallic behaviour; Region (II), 50 K to 10 K, further cooling leads to a large upturn in the sample resistance; Region (III), below 10 K, a slow increase of the resistance is observed, without saturation, down to 2 K. The sheet resistance depends logarithmically on temperature in this region which can be attributed to a Kondo type behaviour, due to scattering of mobile carriers from localized magnetic moments [3]. Other possible, non-magnetic, scatterers such as frozen out/localized carriers could also contribute to or be responsible for the low temperature upturn in the sheet resistance [19]. The three distinct behavioural regimes we have identified in the sheet resistance, are also evident in the MR and Hall resistance, as we now discuss.

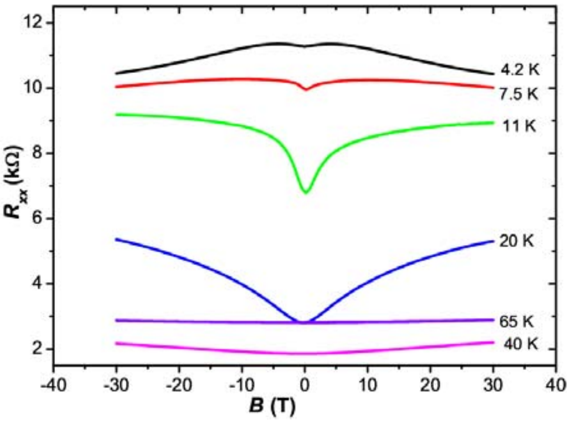

Fig. 2. (Color online) Magnetoresistance at different temperatures between 4.2 K and 65 K, with magnetic field oriented perpendicular to the LAO/STO interface.

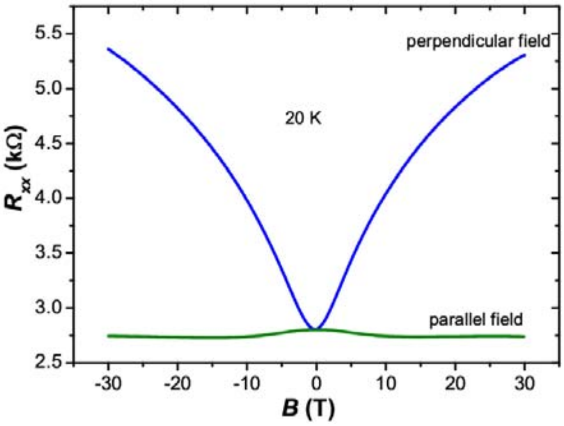

Fig. 3. (Color online) Magnetoresistance for perpendicular and parallel field orientations, at 20 K.

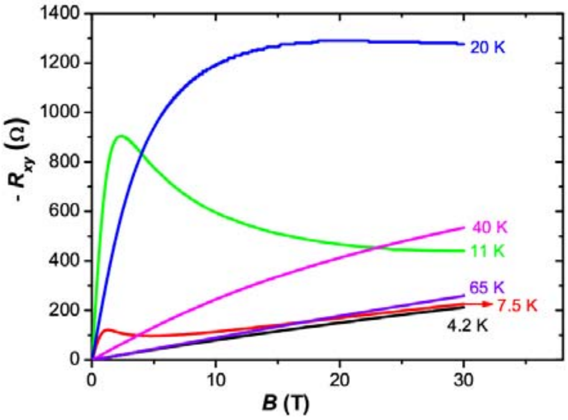

Fig. 4. (Color online) Hall resistance at different temperatures between 4.2 K and 65 K, with magnetic field oriented perpendicular to the LAO/STO interface.

In Fig. 2, we show the MR as a function of temperature in the range from 4.2 K to 65 K. The MR at 7.5 K and 4.2 K (region III) is negative, with a dip at around zero magnetic field, and is independent of the magnetic field orientation. For higher temperatures, the MR is positive, but with very different behaviour in regions I and II. Between 10 K and 40 K (region II), the MR is strongly positive, but with magnetic field dependence that is neither quadratic (as is typical for a semiconductor with a single mobile carrier type), nor linear (as expected from a compensated metal). The MR at 65 K (region I) is significantly smaller, reaching only few ohms at 30 T, and is quadratic in the applied magnetic field. The positive MR in regions I and II depends only on the component of magnetic field perpendicular to the LAO/STO interface. Figure 3 shows the MR at 20 K (region II) for applied field perpendicular and parallel to the interface. In parallel magnetic field, positive MR turns into very small negative MR at low fields and becomes completely field-independent at high fields.

In Fig. 4, we show the symmetrised Hall resistance data $((R_{xy}(+B) - R_{xy}(-B))/2)$ measured at various temperatures between 4.2 K and 65 K: B is the applied field, R_{xy} is Hall resistance and R_{xx} is MR. The Hall resistance is approximately linear in magnetic field for 4.2 K (region III) and 65 K (region I), which suggests that a single type of charge carrier is dominating the transport at these temperatures. Based on this assumption, we can extract the carrier concentration ($n_s = B/R_{xy}e$) and the mobility ($\mu = 1/R_{xx}en_s$) from the slope of the Hall resistance. The linear fit to the Hall resistance at 4.2 K yields $n_{s(4.2K)} = 8.7 \times 10^{13}$ cm^{-2} and $\mu_{(4.2K)} = 10$ cm^2/Vs. The linear fit to the Hall resistance at 65 K, gives $n_{s(65K)} = 7 \times 10^{13}$ cm^{-2} and $\mu_{(65K)} = 120$ cm^2/Vs. The order-of-magnitude difference in electron mobility at these two temperatures suggests that highly mobile, thermally activated electrons dominate transport at high temperatures, whereas carrier freeze-out and increased scattering from 'frozen' carriers and defects leads to low-mobility electronic transport at low temperatures.

In the region between 10 K and 40 K, the Hall resistance is non-linear, and cannot be described by a single-carrier model. Similar non-linear Hall resistance has been observed previously in $LaTiO_3/SrTiO_3$ [21] and STO/LAO/STO structures with a thin LAO layer [22]. They are explained in terms of two-channel conduction from electronic bands with different mobilities and carrier densities. We attempted to model our non-linear Hall results in this way, using the simple two-band expression for ρ_{xy} given as [23]:

$$\rho_{xy} = \frac{B}{e} * \frac{(\frac{n_1\mu_1^2}{1+(\mu_1 B)^2} + \frac{n_2\mu_2^2}{1+(\mu_2 B)^2})}{(\frac{n_1\mu_1}{1+(\mu_1 B)^2} + \frac{n_2\mu_2}{1+(\mu_2 B)^2})^2 + B^2(\frac{n_1\mu_1^2}{1+(\mu_1 B)^2} + \frac{n_2\mu_2^2}{1+(\mu_2 B)^2})^2} \tag{1}$$

When all contributing bands satisfy $\mu_i B \ll 1$ (low field limit) or $\mu_i B \gg 1$ (high field limit) the Hall resistance is linear with B. Only when $\mu_i B \approx 1$ for at least one of the bands involved, nonlinearities in the Hall resistance appear. In this respect, the non-linear Hall resistance observed between 10 and 40 K at a field of a few tesla points to the presence of high mobility carriers with $\mu \approx 0.1...1$ m^2/Vs. Though it is possible to fit qualitatively the observed behaviour with a simple two-channel model (one high mobility electron band and a low mobility hole band or, alternatively, two electron bands with different mobilities), such a fit does not capture all the physics of transport in this complex system. We note that for a complete description, factors such as magnetic field dependence of the carrier densities and mobilities, or the contribution to transport of additional conduction bands/subbands, may also need to be considered.

IV. CONCLUSIONS

We performed magneto-transport measurements on $LaAlO_3/SrTiO_3$ interfaces with 26 layers of LAO grown under high oxygen partial pressure (2×10^{-3} mbar), at temperatures between 65 K and 4.2 K, in magnetic fields up to 30 T. The sheet resistance of our samples is strongly temperature dependent, and shows three different regimes of behaviour: (I) metallic behaviour at high temperature; (II) steeply increasing resistance as the temperature is reduced from 50 K to 10 K; (III) logarithmically increasing resistance, as the temperature is reduced below 10 K. The MR and Hall resistance also show distinct behaviour in these three temperature regimes. In region I, the Hall resistance is linear, and the MR is small, positive and quadratic in the applied magnetic field. In region II, the Hall resistance is strongly non-linear and the MR is large and positive. In region III, the Hall resistance is again linear, and the MR is negative. Our analysis of the Hall resistance, using single-carrier and two-band conduction models, suggest that at high temperatures (region I) the transport is dominated by thermally activated electrons. As the temperature is reduced, the carrier mobility increases until several types of carrier contribute to transport. With further reduction in temperature, the mechanisms of carrier freeze out and increased scattering from defects and frozen carriers reduce the mobilities of all carrier types, until, at the lowest temperatures, transport is dominated by low-mobility electrons. This scenario, however, is still tentative, and further investigations of magneto-transport, particularly of the Hall effect, are clearly necessary to gain a full and quantitative understanding of the transport behaviour of this LAO/STO system. This work is currently in progress.

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