Physica C 470 (2010) S746–S748

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Anomalous magneto-transport at the superconducting interface between $LaAlO_3$ and $SrTiO_3$

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ARTICLE INFO

Article history:
Accepted 12 November 2009
Available online 11 December 2009

Keywords:
$LaAlO_3$–$SrTiO_3$ interfaces
Two dimensional electron gas
Magnetism
Magnetoresistance anisotropy
Superconductivity

ABSTRACT

The magnetoresistance as a function of temperature and field for atomically flat interfaces between 8 unit cells of $LaAlO_3$ and $SrTiO_3$ is reported. Anomalous anisotropic behavior of the magnetoresistance is observed below 30 K for superconducting samples with carrier concentration of 3.5×10^{13} cm^{-2}. We associate this behavior to a magnetic order formed at the interface.

It has been shown that if $LaAlO_3$ is epitaxially grown on TiO_2-terminated $SrTiO_3$ a two dimensional electron gas is formed at the interface between these insulators [1]. This interface was latter shown to be superconducting [2] and magnetic [3]. Recently Caviglia et al. have shown that the superconducting transition temperature can be controlled by solely varying the number of charge carriers at the interface using a gate voltage [4]. These unexpected results and the potential for development of high performance oxide based electronics motivated an effort to understand the properties of this interface and to improve it.

Magnetic effects have been theoretically predicted for $SrTiO_3\backslash LaAlO_3$ interfaces [5,6]. Recent observations of magnetic hysteresis below 0.3 K along with magneto-resistance oscillations with periodicity proportional to $\sqrt{B}$ have been explained in terms of commensurability of states formed at the terrace edges of the $SrTiO_3$ substrate [7].

While superconductivity in this interface has been shown to be two dimensional in nature [2] the way such interface can exhibit magnetic properties is still a puzzle.

In this paper we show that for carrier concentrations of $\sim 3 \times 10^{13}$ cm^{-2} the two dimensional electron gas is superconducting at 100–300 mK, yet, novel magneto-transport effects are observed below 35 K. Our data support possible evidence for a magnetic order formed below this temperature. A magnetic impurities scenario is ruled out.

Eight unit cells of $LaAlO_3$ were deposited from a single crystal target onto a TiO_2-terminated $SrTiO_3$ by pulsed laser deposition. We use pulse rate of 1Hz and energy density of 1.5 J $\times$ cm^{-2} at oxygen pressure of 1×10^{-4} Torr and temperature of 800 °C and a final annealing stage at a pressure of 200 mTorr O_2 and temperature of 400 °C for 1 h. The deposition was monitored by reflection high energy electron diffraction (RHEED). The maxima of the RHEED intensity oscillations indicate a complete layer formation and used as a measurement for the sample thickness. High resolution transmission electron microscope imaging revealed a high quality interface and confirmed the thickness measurement by the RHEED. The samples were patterned using reactive ion etch into Hall bars with bridge dimensions of 50×750 μm squared. Two bridges on the same substrate were aligned 90° to each other (perpendicular or parallel to the terrace edges). The resistance was measured in a dilution refrigerator using Lakeshore 370 AC resistance bridge and at liquid He temperatures using a standard four wire DC resistivity method.

In Fig. 1 we present the number of charge carriers as a function of temperature for bridge 2 and the normalized resistance for another bridge on the same film at low temperatures.

The magnetoresistance (MR) is strongly anisotropic both in plane and out of plane [8]. When the magnetic field is applied perpendicular to the interface a large positive MR is observed while for field applied parallel to the current a strong negative MR is seen. In Fig. 2 The sheet resistance as a function of temper-

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doi:10.1016/j.physc.2009.11.111

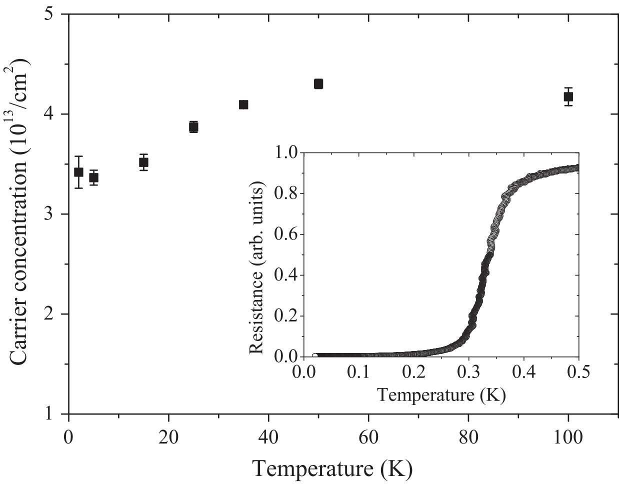

Fig. 1. Number of charge carriers as inferred from the Hall resistivity as a function of temperature. Note the small variation of the Hall number with temperature. Insert: resistance as a function of temperature below 0.5 K.

ature is shown at zero field (circles) and at 14 T applied parallel to the interface and to the current (triangles) for bridges 1 and 2. First, we note that these bridges are rather similar despite the fact that one of them is patterned along the terraces while the other is perpendicular to them. The small difference could be due to the time elapsed between the measurements of the two bridges (about 10 days). The similarity between the bridges rules out the terraces as the origin for the strong magnetoresistance effects. The strong parallel MR must therefore be related to a magnetic scattering. Above 30 K the zero field curve and the 14 T one merge together. This suggests that the magnetic effects responsible for the parallel negative MR onset below 30 K. We have previously reported in-plane anisotropy of the parallel MR and related it to spin-orbit coupling resulting in the anisotropic magnetoresistance, which is well known for magnetic materials [8].

In Fig. 3 the MR for the two bridges at 14 T is plotted as a function of the angle φ between the magnetic field and the normal to the film. 90° corresponds to in plane magnetic field applied parallel to the interface and to the current. The angular dependence of the MR shown in Fig. 3 is extremely sharp around 90°. The relative MR defined as $\frac{R(H,\varphi)-R(H=0)}{R(H=0)}$ changes sign at 87° (or 93°).

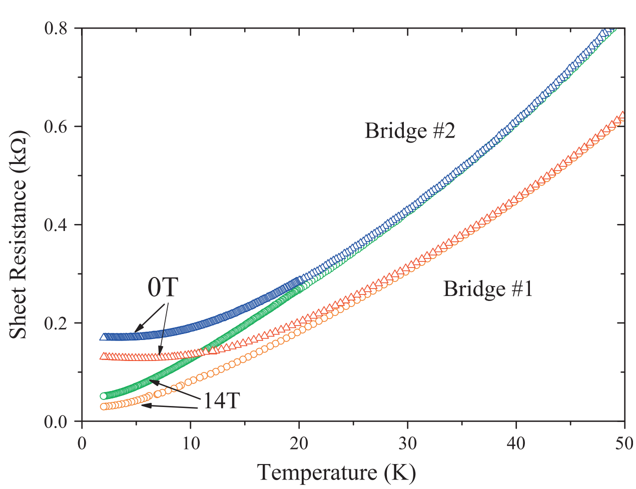

Fig. 2. The sheet resistance for bridge 1 and bridge 2 at zero field and at a magnetic field of 14 T applied parallel to the current. The two curves merge above ~30 K.

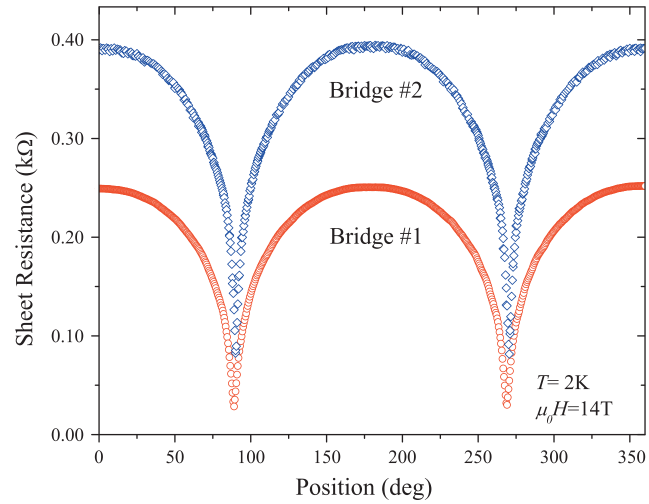

Fig. 3. The magnetoresistance as a function of the angle between the perpendicular to the interface and the magnetic field.

The fact that the MR changes sign for a variation of 3° implies that a small perpendicular field component is sufficient to mute the mechanism responsible for the parallel negative MR. This is due to the fact that when $\varphi = 93°$ the parallel field component is almost unchanged (13.98 T) while the perpendicular component is only 0.73 T. Such a component is too small to induce any orbital MR [8].

The strong anisotropy of the magnetoresistance is a key observation in our study. The only element in our system with such strong directionality is the interface itself. This gives possible evidence for the existence of magnetic order confined to a few layers near the interface. This magnetic order vanishes above 30 K according to the data in Fig. 2 (for the carrier density and $LaAlO_3$ thickness under study). We also note that the MR effects become more pronounced at lower temperatures where superconductivity appears (not shown, to be published).

In summary, below 30 K a magnetic phase emerges. This phase is extremely sensitive to an out of plane magnetic field. This sensitivity is unclear to us, yet, it rules out magnetic impurities as the origin for this effect. Impurity effects are isotropic, in strong contrast with our data. Our data therefore suggest that the magnetic order appearing below 30 K is confined to the vicinity of the interface. For carrier density and thickness under study superconductivity is seen together with the magnetic effects. Since superconductivity disappears at rather low fields and the effects reported here are observed at stronger magnetic fields it is not clear if the magnetic effects exist at zero field. Further experiments are needed to clarify this question.

Acknowledgements

This research was partially supported by the Bikura program of the Israeli Science Foundation Agreement No. 1543/08 by the Israel Science Foundation Agreement No. 1421/08 and by the Wolfson Family Charitable Trust. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0654118, by the State of Florida, and by the DOE.

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