Transport properties of novel quasi-2D electron system formed in $LaAlO_3/EuTiO_3/SrTiO_3$ heterostructure

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I. COMPARISON BETWEEN LOCALIZATION AND KONDO SCATTERING

In this section we show additional transport characterizations and magneto-transport data on LAO/ETO/STO heterostructures, and a comparison between data fitting using Weak Localization (WL) and Kondo-scattering models to demonstrate that Kondo-scattering is the most plausible mechanism explaining the low-temperature upturn in the resistivity.

Weak-localization (anti-localization) is the dominant scattering mechanism in LAO/STO interfaces which show superconducting behavior at low temperatures. In general carrier localization give rise to an upturn of the resistivity at low temperature in otherwise metallic system. However, localization is characterized by the absence of saturation at the lowest temperatures, which is manifested in a positive curvature of R vs. T at all temperatures below the minimum. Kondo-scattering, on the other hand, is characterized by a change of the curvature of the sheet resistance (d^2R/dT^2) from positive (no saturation) to negative (saturation effect) at low temperature. This is usually considered an indication that the dominant scattering is Kondo-like (see for example supplementary reference [1]).

In Fig. S1 we show the low temperature sheet resistance measured with high accuracy on a LAO(10)/ETO(2uc)/STO interface (sample set A) down to 0.8 K. Below 9 K the d^2R/dT^2 curvature becomes negative. This is a very good indication that resistance upturn is not due to weak or strong localization effects.

Additionally, we have tried to fit the low temperature data using WL theory. In Fig. S2, we plot the same resistance curves shown in Fig. 4(a) of the main text, together with fitting curves corresponding either to Kondo (gold continuous lines) or WL (black continuous lines) mechanisms. The fitting formulas of the Kondo model are described in the main text of the paper. On the other hand, for the weak localization mechanism we used the formalism of ref. [2] (see eq. 2.29b therein). For

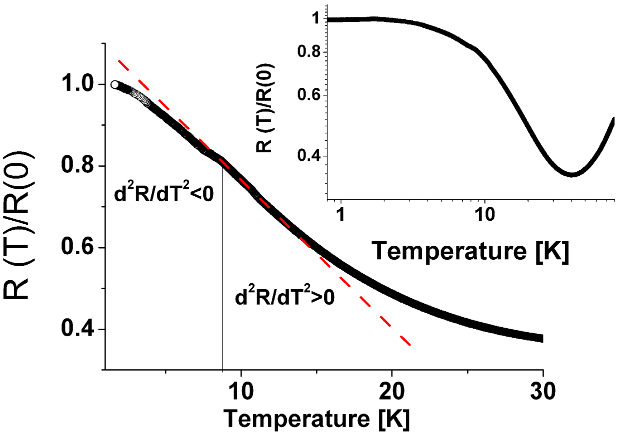

FIG. S1: Temperature dependence of the sheet resistance (normalized to the (1.5 K value) down to 0.8 K measured with high accuracy in order to verify the change of the R vs. T curvature from positive to negative. In the inset the same data are shown on wider temperature range in a log-log scale.

the LAO/ETO/STO samples exhibiting resistance upturn, we used as free parameters the inelastic scattering time, found to be of the order of $\tau_0 \sim 2\text{x}10^{-14}$s, and the exponent p of the power law temperature dependence of the inelastic scattering time ($\tau_i \propto T^{-p}$) for which we got values from 11 to 15. The values of the exponent p obtained from the WL fit are very anomalous (p between 1 to 3 depending on the scattering mechanism and on the dimensionality) and actually unreasonable. Moreover, regardless the values of the fitting parameter, the Kondo model reproduces satisfactorily the *R(T)* shape, while weak localization fails. This is related to the fact that any localization mechanism is characterized by an upward (positive) curvature of the sheet resistance at all temperatures below the minimum, which is on the other hand well reproduced by Kondo-model using reasonable fitting parameter. Hence these analyses allow us to rule out weak localization as responsible for the low temper-

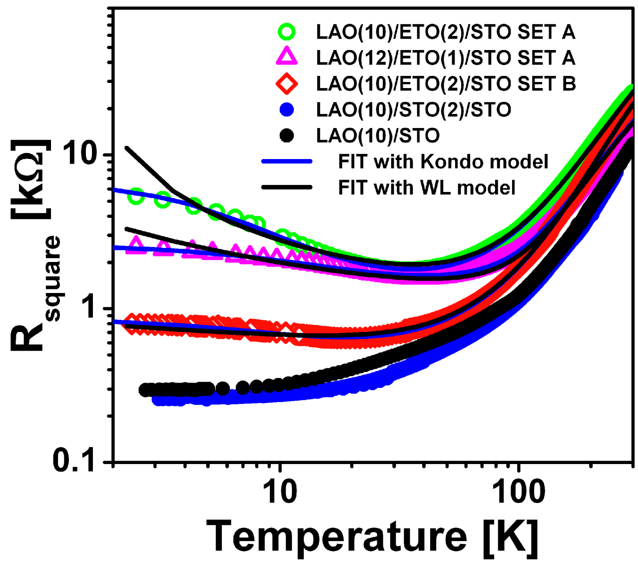

FIG. S2: Measured sheet resistance curves presented in Fig.4 of the main text, plotted together with fitting curves obtained by assuming Kondo (black continuous lines) or weak localization (blue continuous lines) mechanisms at low temperatures.

ature resistivity upturn in our interfaces.

II. XAS AND XMCD SPECTRA ON EU AND FERROMAGNETISM

Due to the single-two layer thicknesses of the ETO films, the use of conventional, lab-based techniques to study the magnetism of these samples is extremely difficult. Thus, we have used synchrotron based x-ray absorption scattering, in a set up which is capable of applying a magnetic field in the range between -7 and +7 Tesla.

X-ray magnetic circular dichroism technique allows determining the projection of the magnetic moment associated to a specific ion in the structure along the photon beam direction. The circular polarization of the light carries a moment, which is transferred to the absorbing atom. Selection rules imply different XAS spectra for the two opposite (left c+ and right c-) circular polarizations if the absorbing ion is characterized by a magnetic moment component along the beam direction.

All the XMCD data presented in the paper are obtained averaging multiple spectra with each configuration, called parallel (P) and antiparallel (A), as defined by the combination of magnetic field direction and photon circular polarization handedness (c+ or c-), described by the helicity vector. Both vectors lie along the photon propagation axis. The spectra are acquired following a sequence of c+c-c-c+ and c-c+c+c- helicity for each of the magnetic field. Hysteresis loops, with field sweeping in forward and backward directions, were acquired by measuring the difference between Plus (I^+) and Minus (I^-) XAS intensity measured at one energy (at the

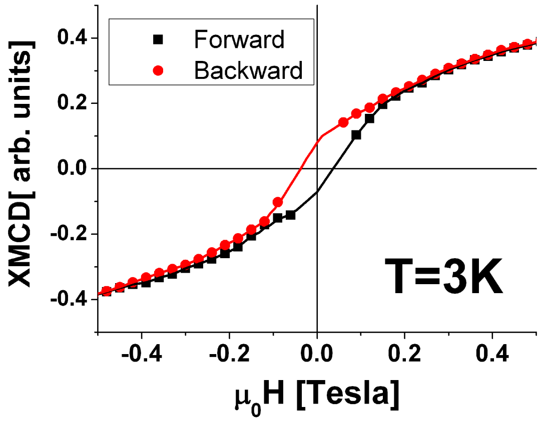

FIG. S3: Difference between Plus (I^+) and Minus (I^-) XAS intensity at M_5 edge as function of the magnetic field. Black and red symbols are for forward and backward magnetic field sweeps.

maximum of the XMCD) and normalized to the intensity below the M_5 edge.

The direct proof of ferromagnetism of 1-2 unit cells ETO films embedded in LAO/ETO/STO heterostructures is given in the inset of Fig. 2(a) of the main text, where we have shown an XMCD spectra for a LAO/ETO/STO interface acquired at 0.02 Tesla. The choice of 0.02 Tesla (and not zero nominal field) is due to the fact that in superconducting magnets built for high magnetic fields (such the X-Treme one), are never reliable below 0.02 T due to trapped currents in the coils generating a non zero field for nominally zero field condition. This is the reason why we have to measure at finite and reliable fields i.e. B>0.02T.

Same considerations apply to the hysteresis loop shown in Fig. 2 and in Fig. S3, where the XMCD signal is obtained by making the difference between c+ and c+ normalized TEY data acquired at the energy for which the XMCD is maximum. From this data, one can clearly see that the XMCD intensity acquired in reliable low-field regions extrapolates to a value different from zero, and in particular to a negative value when the field is swept from negative to positive and to a positive one if the field is swept from positive to negative (the extrapolation is done by cubic spline method using the -0.5 T to 0.5 T data). We can notice that the coercive field is small, of the order of 0.1 T while a full saturation is obtained above 1 T. These data are similar to data published on as-deposited ETO thick films as shown in Fig.4c of ref. 3. This is an additional proof of the ferromagnetic character of the ETO ultra thin films.

III. MAGNETO-RESISTANCE DATA

Magneto-resistance data have been acquired as function of the temperature on LAO/ETO/STO samples up

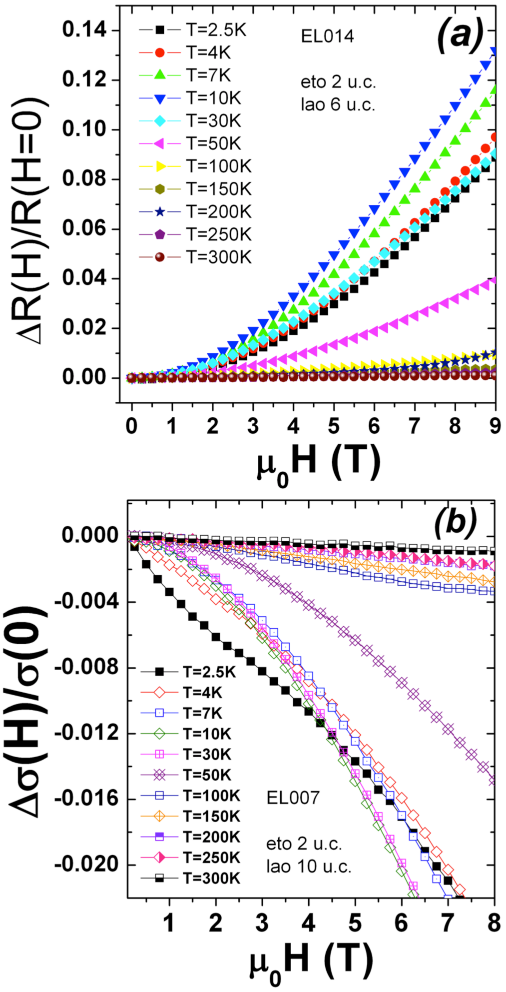

FIG. S4: (a) Normalized magneto-resistance data for LAO(10uc)/ETO(2uc)/STO (set A) and (b) magneto-conductance data for LAO(6uc)/ETO(2uc)/STO (set B) samples as function of the temperature

to a field of 9 Tesla perpendicular to the interface.

The magneto-resistance show classical cyclotronic magnetic field dependence ($\Delta R \sim H^2$), with some deviation at low field (<2T) and low temperatures (<10K), which are related to weak-anti-localization due to spin-orbit scattering [Fig. S4]. These results are very similar to the one shown in ref. [1] for liquid gated STO in perpendicular magnetic field. However, at large fields (>3-4T), where the antilocalization contribution to the scattering mechanism is not anymore important, the magneto-resistance decreases as function of the temperature below the ferromagnetic transition of the ETO layer. However, while this could indicate a possible coupling between the Q2DES and Ferromagnetism in ETO, other explanations are equally possible. In particular, Kondo scattering could compete with the classical cyclotronic term (at large fields) and with weak anti-localization (at low fields), giving a negative magnetoresistance term which decreases the magnetoresistance value.

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