Magnetic field induced transition in superconducting $LaTiO_3/SrTiO_3$ interfaces

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Magnetic field induced transition in superconducting $LaTiO_3/SrTiO_3$ interfaces

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Abstract.
Superconductivity at the $LaTiO_3/SrTiO_3$ interface is studied by low temperature and high magnetic field measurements as a function of a back-gate voltage. We show that it is intimately related to the appearance of a low density (a few 10^{12} cm^{-2}) of high mobility carriers, in addition to low mobility ones always present in the system. These carriers form superconducting puddles coupled by a metallic two-dimensional electron gas, as revealed by the analysis of the phase transition driven by a perpendicular magnetic field. Two critical fields are evidenced, and a quantitative comparison with a recent theoretical model is made.

1. Introduction

Superconductivity at the interface between insulating oxides[1] has raised considerable interest, all the more so the superfluid density can be tuned by a gate voltage[2, 3, 4]. This discovery opens the way to fundamental investigations on superconductivity in a two-dimensional electron gas (2DEG), as for instance the exploration of the specific role of quantum confinement, disorder, Coulomb repulsion and screening in a true two-dimensional superconductor. Specific features of quantum wells, such as Rashba spin orbit coupling[5], further enhance the interest for these systems by enabling tunable pairing symmetry [6], or exotic spin dependent behaviours[7, 8]. However, the electrostatic control of the 2DEG properties both in the normal and the superconducting state is not fully understood yet. In this article, we show that two types of carriers are present in the 2DEG, and that superconductivity is intimately related to the occurrence of high-mobility ones which set at the edge of the quantum well. By applying a perpendicular magnetic field, we show that the superconducting behaviour is characteristic of a disordered array of superconducting puddles coupled by a tunable normal metal. This intrinsic behaviour has to be taken into account when studying basic properties of the superconducting 2DEG[4].

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2. Two types of carriers

Samples were grown by pulsed laser deposition of a 15 unit cells thick layer of $LaTiO_3$ on TiO_2-terminated (001)$SrTiO_3$ substrates (see Biscaras *et al.*[9] for details). A metallic back-gate was deposited at the rear of the 500 μm thick substrate and connected to a voltage source (V_G). Standard four-probe resistance measurements were made with a current sufficiently low to avoid any heating of the electron at the lowest temperatures. After the cool-down, the gate voltage V_G is ramped up to +200 V. This polarisation procedure insures that all voltage sweeps made subsequently are reversible and reproducible [10].

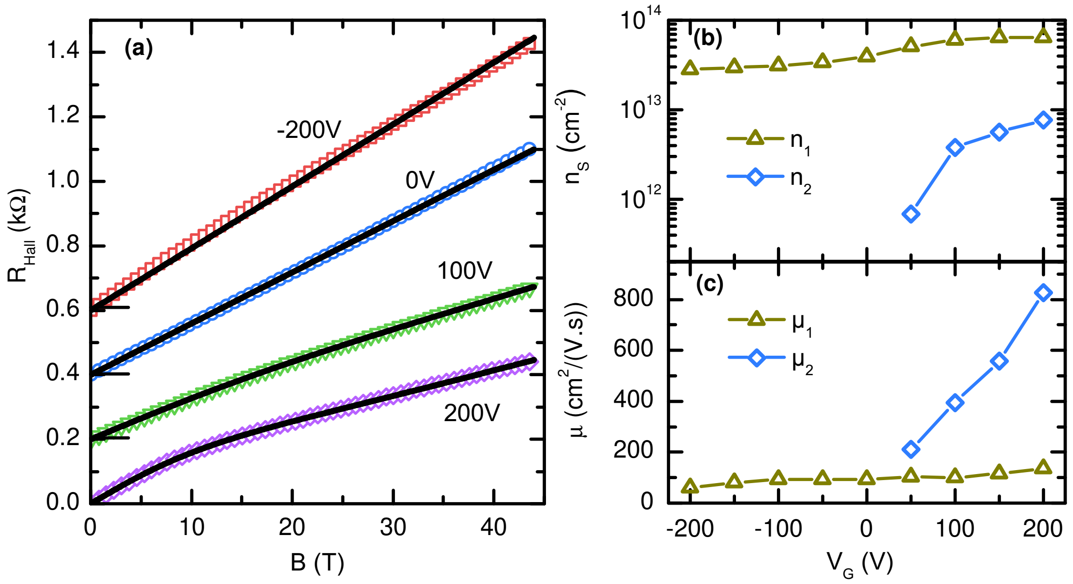

Figure 1. (a) Hall resistivity R_H as a function of the magnetic field B measured at 4.2 K for different V_G. R_H is linear in B for negative V_G, and non linear for positive V_G. (b) Carrier density n_S as a function of V_G, for the two types of carriers : n_1 majority carriers, n_2 minority carriers. (c) Mobility μ as a function of V_G, for the two types of carriers : μ_1 low mobility carriers (LMC), μ_2 high mobility carriers (HMC).

We performed Hall effect measurements up to 45 T in pulsed magnetic field. Results at a temperature of 4.2 K are presented in Fig. 1 (a). For negative V_G, the Hall effect is linear in magnetic field as expected, whereas it displays two distinct slopes (low field and high field) for positive V_G. The latter situation is characteristic of a multi-carriers electronic transport. We fitted the experimental curves using a two-carriers model whose parameters are the densities n_1 (majority carriers) and n_2 (minority carriers) and the corresponding mobilities μ_1 and μ_2[3]. Their variations with V_G are displayed in Fig. 1 (b) and (c). Majority carriers (n_1) are always present with a low and almost constant mobility (μ_1). For positive V_G, minority carriers appear (n_2), with a high and rapidly increasing mobility (μ_2). In the following, theses two types of carriers will be referred to as Low Mobility Carriers (LMC) and High Mobility Carriers (HMC).

To understand the origin of these two types of carriers we modelled the quantum well at the interface using a semi-conductor type model [3]. We assumed that the 2DEG is confined within the $SrTiO_3$ by an infinite potential barrier corresponding to the $LaTiO_3$ Mott gap. Carriers are therefore free to move within the interface plane, but are confined in the perpendicular direction, leading to a discrete 2D character of the energy spectrum. We solved the Schrödinger and the

Poisson equations self-consistently, introducing the appropriate boundary conditions imposed by the gate voltage V_G and taking into account the non-linear dielectric constant of $SrTiO_3$. The shape of the quantum well given by the bending of the $SrTiO_3$ conduction band and the envelops of the wave-functions for different sub-bands are computed (figure 2 inset). Details of the calculations are given in reference [3]. For negative V_G, a few sub-bands are occupied, corresponding to wave-functions confined close to the interface. These carriers are submitted to surface scattering and their mobility is low. For positive voltage, more sub-bands are filled, and the wave functions of the upper energy levels extent deeper in $SrTiO_3$ substrate (inset Fig. 2), where the scattering is weaker and the mobility higher. According to our simulations, these carriers appear only for positive gate voltage, when the conduction band is sufficiently bent. As seen in Fig. 2, their extension increases with V_G, so does the HMC density ($n_{HMC} = n_2$). Therefore, it is clear that LMC correspond to carriers deep in the well and HMC to those which set at the edge of the quantum well.

When adding on the same graph T_C as a function of V_G (Fig. 2), we observe that superconductivity is intimately related to the presence of HMC in the well ($n_{HMC} \neq 0$). Unfortunately, as no superfluid density measurement is available on the $LaTiO_3/SrTiO_3$ interface, it is not possible to directly linked the HMC to the superconducting carriers at low temperature. However, we notice that our observation is consistent with a recent measurement of the superfluid density in the similar superconducting $LaAlO_3/SrTiO_3$ interface. [11]. Indeed, they found that only a small fraction of the total carrier density is superconducting (typically a few 10^{12} cm^{-2}). This value is of the same order as the HMC density we measure in the normal state of the $LaTiO_3/SrTiO_3$ interface. They also showed that the superfluid density increases roughly linearly with V_G for positive gate voltage as we observed for HMC (Fig. 2). As a conclusion, we think that only the HMC condense in the superconducting state while the LMC remain in a metallic state. It is worth noticing that Bert *et al.* found that the superfluid density is spatially inhomogeneous, especially in the low doping region. It seems that superconductivity is observed in some regions of the sample, connected by non-superconducting ones. We will come back to this point in the second part of this article.

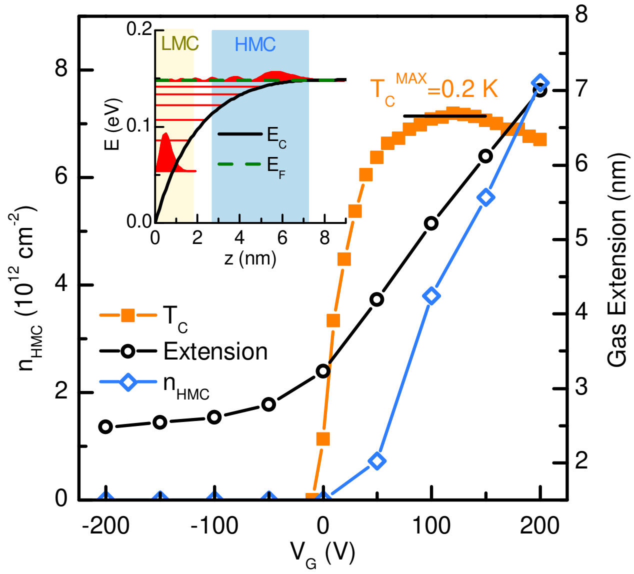

Figure 2. HMC sheet density n_{HMC} (left scale), calculated gas extension (right scale) and T_C as a function of V_G. Inset : Shape of the quantum well at the interface for positive V_G. The sub-bands energy levels and the corresponding wave-function envelops are shown in red. The dashed green line is the Fermi level E_F. Majority carriers (yellow area) lie very close to the interface, whereas minority carriers (blue area) set deeper in the bulk.

3. Magnetic field induced transition

As can be seen in Fig. 3 (a) for $V_G = -15$ V, a perpendicular magnetic field drives the system towards a non superconducting state. A zoom on the low temperature part of the graph reveals that for a critical field $B_\times = 0.1$ T, a plateau corresponding to at the sheet resistance $R_\times = 2176\ \Omega/\square$ separates the superconducting behaviour from a weakly localizing one (Fig. 3 (b)). When $V_G = +80$ V, the transition occurs in two steps, as can be seen in Fig. 3 (c) and (d). A first plateau in R_S is observed between 0.1 and 0.2 K for a characteristic field $B_\times = 0.185$ T ($R_\times = 372.4\ \Omega/\square$), and a second one at lower temperature for a critical field $B_C = 0.235$ T, ($R_C = 376.6\ \Omega/\square$).

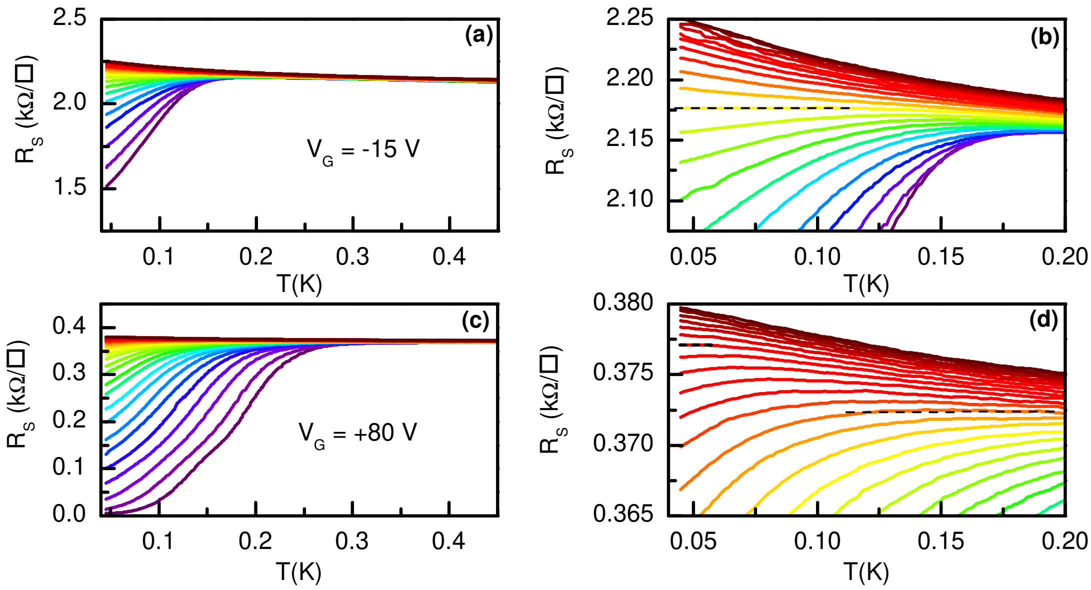

Figure 3. (a) Sheet resistance R_S as a function of temperature T for magnetic field ranging from 0 to 0.3 T ($V_G = -15$ V). (b) Zoom on the same data : a plateau in R_S is seen below 0.12 K (dashed line). (c) Sheet resistance R_S as a function of temperature T for magnetic field ranging from 0 to 0.3 T ($V_G = +80$ V). (d) Zoom on the same data : two plateaus (dashed lines) in R_S are evidenced (see text).

In Fig. 4 (a), we report the characteristic fields as a function of V_G, and distinguish two regions. In region I, a single critical field is observed, whereas in region II, $B_\times$ and B_C are distinct. In this region, we can see that $B_\times$ is roughly constant at a value B_d. In the whole phase diagram, T_C clearly follows B_C, which is therefore the field for which superconductivity disappears. To account for these observations, we propose the following scenario based on the XY model where superconductivity is destroyed by phase fluctuations in a two-dimensional superconductor. We suppose that the system consists in superconducting islands coupled by non-superconducting metallic regions (see Fig. 4(b) for a sketch). Taking into account the two types of carriers mentioned above, we assume that the HMC form the superfluid with an intrinsic inhomogeneity due to its very low average density and the associated density fluctuations, and that the LMC form the metal which provides a long range coupling. The system is therefore described as a disordered array of superconducting puddles (HMC) of size L_d coupled by a metallic 2DEG (LMC) (see sketch in Fig. 4(b)).

Such a situation has been theoretically studied by Spivak, Oreto and Kivelson (SOK)[12]. Superconducting phase coherence of the array is governed by the transport properties of the metallic part through the proximity effect, and depends on the 2DEG conductance G_{2DEG}. If the coupling is strong enough (high G_{2DEG}), puddles can develop full local superconductivity and two transitions can be observed corresponding respectively to the one of the puddles themselves and to the one of the disordered array of puddles. In the opposite case (low G_{2DEG}), decoupled puddles are always in a fluctuating regime, and only the full array transition can be seen at low temperature. These two situations are observed in our $LaTiO_3/SrTiO_3$ interfaces, corresponding to regions II and I respectively. The gate voltage V_G is the tuning parameter to switch from one to the other as it controls the sheet conductance of the 2DEG $G_S = 1/R_S$ [3, 4], and therefore the coupling between puddles. Here, G_S is taken to be the inverse of the sheet resistance measured in the normal state. In region I, G_S takes small values and the coupling is too weak to insure full local superconductivity on the puddles. There is therefore only one critical field that corresponds to the transition of the whole array. In region II, G_S takes larger value and we can observe separately the transition of the puddles ($B_\times$) at high temperature and the one of the array (B_C) at lower temperature. In that case, the first transition occurs when the magnetic flux threading a puddle of typical size L_d reaches the flux quantum Φ_0. Experimentally this takes place for a constant dephasing field $B_d \sim \Phi_0/L_d^2$ (Fig. 4 (a)). The typical value of L_d is of the order of 100 nm. The SOK model [12] predicts that B_C is related to the coupling parameter G_{2DEG} (in our case G_S) in a specific way. At low conductance, $B_C \propto G_{2DEG}$, whereas as high conductance, $B_C \propto [G_{2DEG}]^{1/4}$. To test the model in more details, we plotted the critical field B_C as a function of the conductance G_S on a log-scale in Fig. 4 (c). The data are in good agreement with the theory. Not only the two regimes can be clearly identified, but also the values of the slopes correspond to the calculated one. This is a strong indication that the SOK model is a good representation of the physics involved in these experiments.

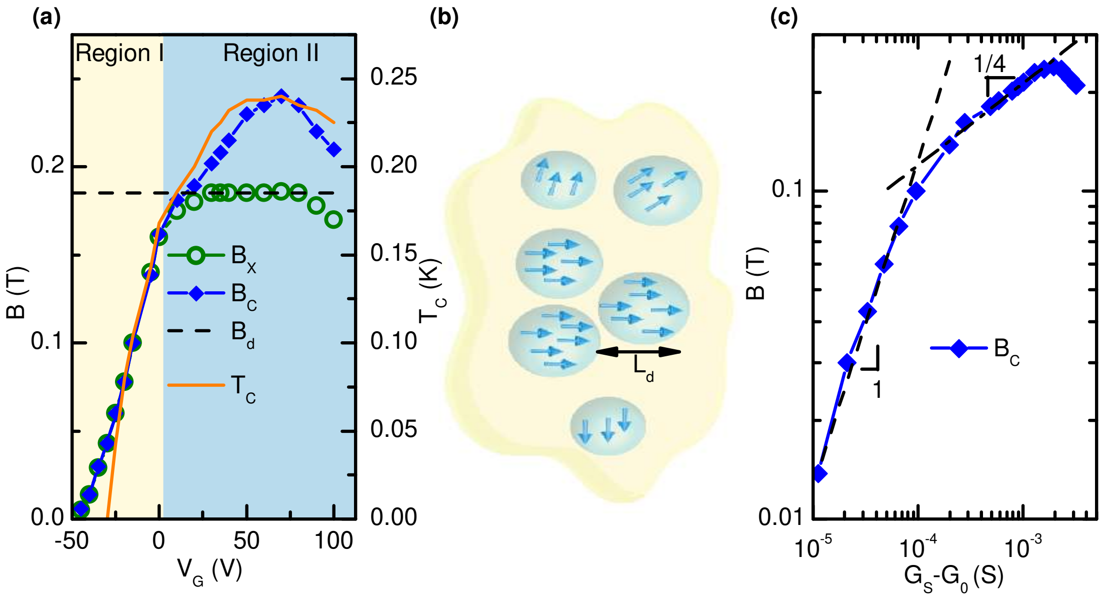

Figure 4. (a) $B_\times$, B_C (left scale) and T_C (right scale) as a function of V_G. The dashed line corresponds to B_d (see text). Regions I and II refer to the low, and respectively high, coupling regimes (see text). (b) Sketch of a piece of material. In this drawing, superconducting puddles (in blue) are coupled through a 2DEG (in yellow). The arrows symbolize the local phase of the superconductor. (c) B_C as a function of G_S on a log scale. $G_0 = 356\ \mu$S is the conductance at V_G =-45V where BC goes to zero. Dashed lines have slopes 1 and 1/4 respectively as expected from the SOK model.

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4. Conclusion

As a conclusion, superconductivity in $LaTiO_3/SrTiO_3$ interfaces is related to the appearance of Highly Mobile Carriers which set at the edge of the quantum well upon positive back-gate biasing. Their density is very low, in the 10^{12} cm^{-2} range, as compared to the majority Low Mobility Carriers one ($10^{13} - 10^{14}$ cm^{-2}). The transition to the non-superconducting state in a perpendicular magnetic field reveals that this low density superconductivity is inhomogeneous, and that the superfluid is organized in puddles (HMC) coupled by a metallic 2DEG (LMC). The back-gate voltage controls the coupling parameter (namely the 2DEG conductance), and drives the system from a single transition situation to a double one, where the puddles themselves and the disordered array of puddles display separate transitions.

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