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Magnetism and superconductivity at LAO/STO-interfaces: the role of Ti 3d interface electrons

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Ferromagnetism and superconductivity are in most cases adverse. However, recent experiments reveal that they coexist at interfaces of LaAlO3 and SrTiO3. We analyze the magnetic state within density functional theory and provide evidence that magnetism is not an intrinsic property of the two-dimensional electron liquid at the interface. We demonstrate that the robust ferromagnetic state is induced by the oxygen vacancies in SrTiO3- or in the LaAlO3-layer. This allows for the notion that areas with increased density of oxygen vacancies produce ferromagnetic puddles and account for the previous observation of a superparamagnetic behavior in the superconducting state.

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The formation of a metallic state at the interface of the bulk insulators LaAlO3 and SrTiO3 has become a prototype for the reconstruction of electronic states in systems with artificially reduced dimensionality. This two-dimensional (2D) electronic system is affected by sizable electronic correlations which allow characterizing the extended interface electronic states as an electron liquid2,3. The correlations not only induce a superconducting state4 but also support magnetism5. A novel yet unexplained phenomenon is the coexistence of magnetism and superconductivity6,7 in the 2D electron liquid.

Recent measurements by Dikin et al.8 demonstrate a hysteretic behavior in the field-dependences of magnetoresistance and critical temperature which suggests the existence of ferromagnetism in the superconducting samples of LaAlO3 (LAO) grown on SrTiO3 (STO). Moreover, Dikin et al. take the viewpoint that two distinct electronic systems are associated with the antagonistic superconducting and ferromagnetic properties: the electrons that are generated by the polar catastrophe mechanism are suggested to be related with magnetism while superconductivity is associated with the charge carriers induced by the presence of oxygen vacancies. The concept of two different types of charge carriers which could contribute to the interface electrical transport has been discussed also in8–11.

Very recently, Li et al.7 probed magnetism through torque magnetometry which allows detecting directly the magnetic moment of the interface in an external magnetic field H. They found a strong superparamagnetic torque signal in the superconducting state. With the assumption that the signal originates from the STO layer next to the interface, they obtained the magnetic moment M of 0.3 – 0.4 μB per unit cell and a collective magnetic moment of the superparamagnetic grains of the order of 1000 μB. The observation of a superparamagnetic M(H) indicates that ferromagnetic grains form even in the superconducting state. Magnetic oxygen sites at the AlO2- surface (cf. Ref.12) and the build-up of triplet coupling of Ti 3d states through the oxygen bonds (or possibly vacancies) in the TiO2 interface plane (cf. Ref.13) have been proposed7 as scenarios for the formation of a magnetic state.

The interpretation of the experimental results opens a compelling question: can the Ti 3d orbitals that were identified in the previous band structure calculations (see, e.g., Refs.14–22) be responsible both for the metallic and magnetic states coexisting at the same interface? In this paper, we present the results of density functional studies which support the existence of a robust ferromagnetic state at the LAO/STO interface induced by oxygen vacancies. We demonstrate that both the magnetism and conductivity occur involving the Ti 3d electrons but the magnetism is due to rather confined electrons around O vacancies while the conductivity is a result of the 2D electron gas caused by electronic reconstruction. We argue that this behavior is a prerequisite of co-existence of magnetism and superconductivity which are observed at low temperatures.

To explore whether a ferromagnetic state is induced at these interfaces, we consider oxygen vacancies as a mechanism responsible for magnetism. We generate a number of supercells which consist of two symmetric LAO/STO parts, where each part contains a stack of 4 unit-cell (uc) thick LAO layers deposited on a STO-slab of a thickness varying between 1.5 uc and 6 uc. The interfacial configuration is considered as TiO2/LaO. The LAO-STO-LAO parts are separated by a 13 Å thick vacuum sheet. Oxygen vacancies are assumed to lie in the first interfacial TiO2-layers or in one of the AlO2-layers of the LAO-film. A cell with an oxygen vacancy in MO2 (M=Ti, Al) is sketched in Fig. 1(b). The vacancy is introduced by excluding the oxygen atom O(a/2, b/2) in the center of the M2O4-plaquette. The location of the vacancy at the interface is motivated by the experimental evidence of O-vacancies present in STO in samples grown at oxygen
FIG. 1: Schematic view of the SrTiO$_3$/LaAlO$_3$ heterostructure. The supercell contains a 4 unit cell thick LaAlO$_3$ layer deposited on a 2.5 unit cell thick SrTiO$_3$ slab. The full supercell consists of two symmetric parts of the depicted structure and a vacuum layer of 13 Å. The structures on the right side show (a) a projection of the supercell of STO/LAO on the ($x, y$)-plane of TiO$_2$, and (b) a M$_2$O$_4$ (M=Ti, Al)-plaquette generated for the study of the system with O-vacancies. The position of an O-vacancy is identified by a red dashed circle.

pressures below $10^{-5}$ mbar$^{23,24}$.

Density functional calculations are performed using the Generalized Gradient Approximation (GGA) in the Perdew-Burke-Ernzerhof pseudopotential implementation$^{25}$ in the Quantum Espresso (QE) package$^{26}$. We use a kinetic energy cutoff of 640 eV and the Brillouin zone of the 106- to 166-atom supercells sampled with $5 \times 5 \times 1$ to $9 \times 9 \times 1 k$-point grids. An increase of the $k$-point mesh from $(5 \times 5 \times 1)$ to $(7 \times 7 \times 1)$ leads to a negligibly small change of the total energy by 0.005Ry and to an increase of the Ti magnetic moments by small values of about 0.05 $\mu_B$ in the presence of O-vacancies. The difference between the Ti magnetic moments for the two different $(2n \times 2n \times 1)$ and $(nx2nx1)$ $k$-meshes for $n=4$ is about 0.02 $\mu_B$, which is a negligibly small value. In our calculations we account for a local Coulomb repulsion of Ti 3$d$ electrons by employing a GGA+$U$ approach with $U_{\text{Ti}} = 2$ eV$^2$. First, we consider pure stoichiometric TiO$_2$/LaO-interfaces as reference for the oxygen doped interfaces. The supercells which contain $(2 \times 2)$ planar unit cells have been structurally relaxed along the $z$-axis by a combination of the optimization procedures of the full potential WIEN2k-package and the pseudopotential QE package$^{26,27}$. The in-plane lattice constants have been fixed to their bulk-STO cubic values ($a_{\text{STO}} = b_{\text{STO}} = 3.905$ Å). Similar to the previous calculations$^{14–19}$, we find that a metallic state is produced at the LAO/STO interface due to the electronic reconstruction.

Fig. 2 presents the projected Ti 3$d$ densities of states (DOS) for both spin directions in the system with supercells containing 4 LAO uc and 4 STO uc along the $z$-direction (the full supercell contains twice the number of LAO unit cells). The difference in the spin-projected DOS implies a non-zero spin polarization. For the pure system without oxygen vacancies, the occupancies of the spin-up and spin-down 3$d$ states are almost identical. The maximal magnetic moments of the interface Ti are about 0.005 $\mu_B$ and the polarization from the more distant TiO$_2$ planes is negligible. The calculated magnetic moment per $(1 \times 1)$ unit cell of LAO/STO interface is 0.03 $\mu_B$ which originates mostly from the surface oxygen sites. This polarization is too small to support a robust ferromagnetic state suggesting that magnetism is not due to the pure interface electron gas.

The situation with O-vacancies is different. An oxygen vacancy adds two extra electrons at the interface to preserve charge neutrality. The two electrons are most likely localized in the vicinity of the O-vacancy as found for CaO by Elfimov et al.$^{12}$ As shown below, this enhances the charge density and increases the exchange splitting of the spin bands; consequently O-vacancies stabilize the ferromagnetic order.
First, we assume that the oxygen vacancy lies within the TiO$_2$ plane at the interface. In the oxygen-deficient system, we find sizable Ti magnetic moments at the interfacial TiO$_2$-plane (see Fig. 3). The magnetic moment of the Ti atoms next to the O-vacancy is about $0.33 \mu_B$ and that of the more distant Ti(0,0) atoms at the interfacial plane is about $0.34 \mu_B$. Magnetic moments on Ti atoms away from the interface are negligible (Fig. 3). We also find a sizable magnetic moment on the AlO$_2$ surface plane of about $-0.18 \mu_B$ aligned antiparallel to the magnetic moment of the interface Ti atoms. Needless to say, the concentration of O-vacancies in these model structures is far higher than the average density in the experimentally investigated heterostructures. Nevertheless, it is evident that a triplet coupling is induced between the nearest-neighbor Ti sites and that ferromagnetism is enhanced in O-vacancy rich regions of the interfacial plane.

The elimination of the central oxygen in the $(2 \times 1)$-configuration results in the formation of stripes of O-vacancies along the $y$-direction characterized by two vacancies near Ti(0,0) and no vacancies near Ti(0,0) atom. To test the stability of such an “inhomogeneous” distribution of O-vacancies, we have also performed GGA+$U$ calculations of a supercell with an ordered “homogeneous” arrangement of the vacancies corresponding to exactly one vacancy per each Ti atom. This can be obtained by elimination of one oxygen in the square ($\sqrt{2} \times \sqrt{2}$)-supercell shown in Fig. 1(a). The comparison of the calculated total energy with the energy for that of the $(2 \times 1)$-supercell (Fig. 1(b)), both containing a 4 u.c. thick-STO layer, gives an energy gain of about 0.25 eV per interface u.c. which indicates a tendency towards an inhomogeneous spatial distribution of oxygen vacancies in LAO/STO.

It is expected that areas with an increased density of oxygen vacancies allow for the formation of ferromagnetic puddles, as was recently observed by Bert et al.\textsuperscript{28}. Their respective collective magnetic moments are a likely candidate for the source of the superparamagnetic behavior observed by Li et al.\textsuperscript{7}. As compared to the ferromagnetically ordered structure, the total energy of the $(2 \times 1)$-configuration with antiferromagnetically ordered interface increases by 0.36 eV/u.c. which implies a high stability of the ferromagnetic state.

The ferromagnetic ordering can be examined in the framework of the Stoner model for ferromagnetism. This model treats the stabilization of the ferromagnetic state as a result of the difference between the reduction of the Coulomb interaction for the 3d electrons with parallel spins of neighbouring Ti ions and the increase of the kinetic energy caused by the widening of the 3d-bands for the electrons of the same spin\textsuperscript{21}. The condition for the appearance of ferromagnetism is based on the Stoner criterion $I \rho(\varepsilon_F) > 1$. The interaction $I = \Delta/m$ parameterizes the exchange splitting $\Delta$, and $m$ is the magnetic moment of Ti in the ferromagnetic state (per $\mu_B$): $\rho(\varepsilon_F)$ is the paramagnetic density of states at the Fermi level. The parameters appearing in the Stoner criterion are derived from the results of the GGA+$U$-calculations and presented in Table I. The Stoner condition is satisfied irrespective of the thickness of the STO-layer, which implies that the ferromagnetic state is favourable in these systems although the magnetic moment and exchange splitting slightly decrease with increasing STO thickness, consistent with Ref. 21. The excess 3$d$ charge in the vacancy-doped supercells leads to a substantial increase of $\rho(\varepsilon_F)$ up to $\sim 1.5 - 1.8$ eV$^{-1}$ as compared to the pure systems with $\rho(\varepsilon_F) \approx 0.5 - 0.7$ eV$^{-1}$. The enhanced $\rho(\varepsilon_F)$ contributes to the strong increase of the Ti magnetic moments in the oxygen-deficient systems.

O-vacancies strongly influence the electronic structure of the Ti 3$d$ states: the excess charge originating from the eliminated O atom in the interfacial TiO$_2$ plane leads to a redistribution in the occupancy of the five 3$d$ orbitals. The contribution of the 3$d$ $e_g$ orbitals to the magnetic moment formation is rather insignificant. In contrast, a substantial amount of the excess electron charge is transferred to the $t_{2g}$ spin-up orbitals (Fig. 2). In a $(2\times1)$-unit cell, the location of the O-vacancy along the $y$-direction between the two Ti-atoms (see Fig. 1(b)) leads to symmetry breaking, splitting the two $t_{2g}$ ($3d_{yz}$ and $3d_{xz}$) orbitals. Due to the random distribution of O-vacancies along the $x$- and $y$-directions in LAO/STO samples, the appearance of ferromagnetism is based on the Stoner criterion $I \rho(\varepsilon_F) > 1$. The interaction $I = \Delta/m$ parameterizes the exchange splitting $\Delta$, and $m$ is the magnetic moment of Ti in the ferromagnetic state (per $\mu_B$): $\rho(\varepsilon_F)$ is the paramagnetic density of states at the Fermi level.

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\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
n & $m_{Ti} (\mu_B)$ & $\Delta (eV)$ & $I \rho(\varepsilon_F)$ \\
\hline
1.5 & 0.31 & 1.15 & 3.89 \\
2.5 & 0.33 & 0.82 & 1.26 \\
3.5 & 0.34 & 0.98 & 1.64 \\
\hline
\end{tabular}
\caption{Calculated magnetic moments of interface Ti ions nearest to the O-vacancy, the exchange splitting ($\Delta$) and the parameter $I \rho(\varepsilon_F)$ of the Stoner criterion for (LaAlO$_3$)$_n$/(SrTiO$_3$)$_n$ heterostructures with different n.}
\end{table}
between the top AlO
12-layer (per u.c.) in (2STO)/(4LAO)-supercells with a change
relations show that the placement of an O-vacancy in the
interface and another one hybridized at the AlO
xy-spin
The lowest total energy is achieved
25%-concentration of surface vacancies produces two electrons
per (2×1)-unit cell, with one electron transferred to the
interface and another one hybridized at the AlO
surface close to a central O vacancy, similarly to\textsuperscript{12}. Our calculations show that the placement of an O-vacancy in the
AlO2-planes of the LAO-layer still induces a significant magnetic moment on the interface Ti atoms (Fig. 4(a)).
This magnetic moment originates from the spin polarization of the occupied Ti-3d states due to the electron charge transferred from the O-vacancy site. Interestingly, when the O-vacancy lies close to the surface of LAO we find a sizable magnetic moment in the AlO2-layer with the O-vacancy (Fig. 4(a)), similarly to that obtained when the O-vacancy is placed in the interface TiO2 layer. This magnetic moment is due to the exchange splitting of the not fully occupied local oxygen-vacancy-centered state of a mixed Al s–p-character which produces quasi-one-dimensional electronic bands and ferromagnetic moments in the AlO2-layer antiparallel to that of the interface Ti atom\textsuperscript{29}.
Recent studies of the LAO/STO interfaces distinguish two different types of charge carriers in terms of the interfacial localized Ti 3d electrons and the mobile 3d_{xy} electrons of several distant Ti layers\textsuperscript{10}, or they relate magnetism to the interfacial electrons produced by the electronic reconstruction and associate superconductivity to the charge carriers induced by O-vacancies\textsuperscript{6}. Our findings open a new perspective: both the magnetism and the superconductivity are due to the interfacial Ti 3d electrons. The magnetism, however, is a result of the spin splitting of the populated electronic states induced by O-vacancies, while the metallic behavior of the interface results from the 2D electron liquid caused by the electronic reconstruction. The metallic state has been related to a superconducting state below 300 mK and the predicted scenario suggests that the corresponding charge carriers move in regions of small or vanishing O-vacancy concentrations.

Note added during revision: After the submission of the manuscript we were informed that Bert et al.\textsuperscript{28} in fact observed submicrometer puddles of ferromagnetism in the presence of the superconducting state at the LaAlO3/SrTiO3 interface. An alternative scenario has recently been proposed by K. Michaeli et al.\textsuperscript{31} who suggest a homogeneously polarized interface layer which is magnetically coupled to a second superconducting layer.

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\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{(a) Magnetic moments of the interface Ti and AlO2-layer (per u.c.) in (2STO)/(4LAO)-supercells with a change of the position of the O-vacancy along the (001)-direction between the top AlO2-layer (left) and interface TiO2 (right). (b) Variation of the total energy $E_{\text{tot}} - E_{\text{tot}}(1)$ with the change of the position of the O-vacancy along the (001)-direction. Here $E_{\text{tot}}(1)$ is the total energy for the system with an O-vacancy located in the top AlO2 surface.}
\end{figure}


The details of the spin and charge distribution will be published separately.