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SUPERCONDUCTIVITY AND ITS APPLICATIONS

Interface superconductivity

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ABSTRACT

Low dimensional superconducting systems have been the subject of numerous studies for many years. In this article, we focus our attention on interfacial superconductivity, a field that has been boosted by the discovery of superconductivity at the interface between the two band insulators $LaAlO_3$ and $SrTiO_3$. We explore the properties of this amazing system that allows the electric field control and on/off switching of superconductivity. We discuss the similarities and differences between bulk doped $SrTiO_3$ and the interface system and the possible role of the interfacially induced Rashba type spin–orbit. We also, more briefly, discuss interface superconductivity in cuprates, in electrical double layer transistor field effect experiments, and the recent observation of a high T_c in a monolayer of FeSe deposited on $SrTiO_3$.

Contents

1. Introduction

Low dimensional systems have had an enduring fascination for the condensed matter community. This is understandable from the perspective of fundamental research since disorder, fluctuations and correlation effects all play a particularly important role in reduced dimensions and thus offer opportunities to tackle tough theoretical and experimental challenges. It may seem more surprising insofar as applied research is concerned. While engineering bulk material components, such as memristors, is being actively pursued, the ubiquity of nanowires and two-dimensional (2D) electron gases in our current technology is evidence for the merit of transport in confined geometries. Several considerations help explain this apparent paradox. One is that the increasing versatility of functionalities in portable electronic devices requires one to pack and connect more and more transistors on centimeter square size chips. Two, charge control through electric fields – i.e. gating – is more effective in lower dimensions as screening effects become more relevant. Furthermore, fluctuations effects, correlations effects and nesting of potentially significant portions of the Fermi surface in lower dimensions are factors that promote the appearance of novel quantum electronic states, paving the way for promising future technologies; in this respect, copper oxide

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superconductors could qualify as a Rosetta stone, owing to their quasi-2D, layered, structure, to the large value of the on-site electron–electron Coulomb repulsion, and to the strong antiferromagnetic correlations that are observed in a broad region of their phase diagram. The latter are advocated in some models to be the source of the pairing energy for superconductivity and the reason for the observed high value of the transition temperature T_c.

Historically, nesting of the Fermi surface was envisioned as an effective way to boost T_c [1]. It causes Van Hove singularities, implying high densities of states when the Fermi energy is tuned to a singularity. There were hopes that this scenario would help one attain high temperature superconductivity (HTSC), despite the fact that, in accordance to the Peierls–Mermin–Wagner theorem, thermal fluctuations preclude the establishment of long range order in one-dimensional (1D) and in 2D systems. For 1D organic materials nesting effects are particularly pronounced but fluctuations, unfortunately, promote competing instabilities of the Fermi sea and the attained values of T_c remain fairly small [2]. Thermal fluctuations in layered materials such as cuprates or in superconducting films have a "milder" impact on T_c.

More recently, the discovery of interfacial superconductivity in heterostructures whose building blocks consist of transition metal oxide compounds has attracted a lot of attention. A frontrunner in that category is the interface between the two band-insulators $LaAlO_3$ (LAO) and $SrTiO_3$. It was found to be conducting (in 2004 [3]), superconducting (in 2007 [4]), and host to a sizable spin–orbit interaction (in 2010 [5,6]). Quite remarkably, all these properties, conductivity, superconductivity and spin–orbit strength can be controlled by an electric field. In copper-oxide based heterostructures, where none of the constituents exhibit superconductivity, HTSC was demonstrated to develop in a single atomic CuO_2 plane [7]. Evidence for high T_c superconductivity has also been reported for FeSe atomically thin films prepared on $SrTiO_3$ [8]. Using the electrical double layer transistor (EDLT) technique, which allows one to achieve very large changes in carrier density, it is possible to induce superconductivity at the surface of insulating crystals [9] and to dramatically tune the value of the superconducting T_c at the surface of known superconductors [10].

The possibility of boosting T_c at metallic surfaces embedded in otherwise semiconducting or even insulating materials has been advocated by several authors. The driving force for the increase is a spatial dichotomy between Cooper pairs which reside in the conducting sheet, and the source of pairing which originates from the "non-metallic" bulk part. Accordingly, the adverse impact of the Coulomb repulsion on superconductivity is somewhat lessened [11]. Near the interface, on the pairing side, the density of states can be much enhanced [12,13]. Besides, large attractive interactions between electrons of the surface sheet can be mediated by excitations coming from the unscreened (or poorly screened) bulk region; for instance, these can be excitonic [14] or driven by polarization effects [15–17]. This is shown in Fig. 1. A similar scenario has been proposed in the context of LAO/STO compounds in order to model the evolution of T_c with doping [18].

In this paper, we will focus our attention on the prototypical LAO/STO interface, discussing the physics of this system, the relation between interfacial and bulk superconductivity observed in doped STO, the nature of superconductivity and the role possibly played by spin–orbit interaction. We will also, briefly, discuss other systems of interest that have been studied recently.

2. Some history and progress in oxide thin film technology

In the 80s, there have been many important studies of metallic low-dimensional superconducting systems (ultrathin films, and superlattices). Those include experiments on Kosterlitz–Thouless physics, the role of disorder, superconductor–insulator transitions, dimensional crossovers, and related effects. There is unfortunately too little space here to describe these remarkable contributions. Some of the achievements and references can be found in the article "Superconductivity of Very Thin Films: The Superconductor–Insulator Transition" by Lin, Nelson and Goldman in this special issue and in the book "Synthetic Modulated Structure" [19].

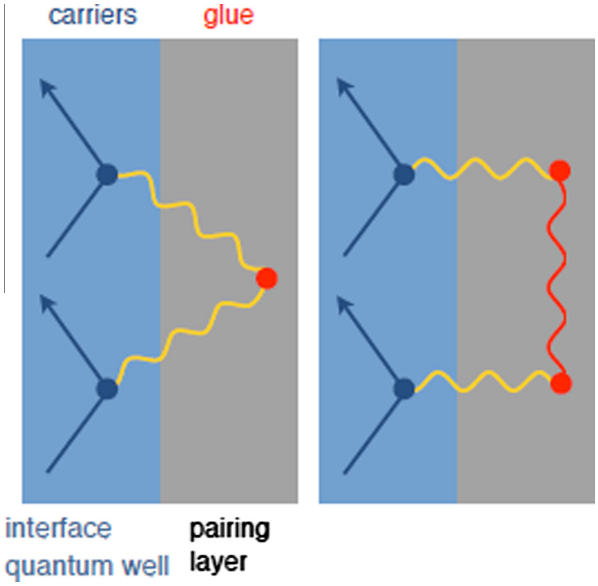

Fig. 1. (Left) Two electrons (blue) interact (yellow) with a site (red) in the pairing layer, creating a virtual excitation. This excitation, for example polarization of an oxygen ion, causes the pairing. (Right) Each electron excites a different site in the pairing layer, but both sites are coupled (red), and by this close the pairing channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Following the discovery of high T_c superconductors, a large effort has been devoted to growing epitaxial films of complex oxides. 28 years later, these developments allow oxide heterostructures with atomically sharp interfaces to be grown using several techniques including molecular beam epitaxy, pulsed laser deposition and sputtering. A more recent advance in the area of oxide heterostructures concerns oxide interfaces. Thanks to the chemical and structural compatibility of many oxides, these structures have allowed materials with very different electronic properties to be combined. The further use of strain, confinement or more generally interfacial effects has given rise to a variety of exciting work; we refer here to the reviews of Mannhart and Schlom [20], Zubko et al. [21] and Hwang et al. [22]. This new research area has been developing rapidly after the seminal work of Akira Othomo and Harold Hwang who studied $LaTiO_3/SrTiO_3$ – an interface between a Mott and a band insulator [23] – and $LaAlO_3/SrTiO_3$, an interface between two band insulators [3]. The discovery of conductivity and high electron mobility at the interface between LAO and STO generated a large amount of work aiming at an understanding of the origin of the conduction and at the exploration of the properties of these mobile electrons hosted in a complex oxide. As we will see, this system indeed displays amazing properties.

3. The LAO/STO system

In their bulk state, both LAO and STO are insulators with a sizable band gap of 5.6 eV and 3.2 eV – respectively. It was found that the growth on an epitaxial film of LAO on a (0 0 1)-oriented TiO_2-terminated single crystal of STO leads to a conducting interface if the LAO thickness is larger than three unit cells [24]. Early on,