Towards an ab-axis giant proximity effect using ionic liquid gating

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Summary

Superconductivity is a phenomenon characterized by electrons condensing into a Bosonic state, described as a single, quantum mechanical function. The Bardeen-Cooper-Schliefer (BCS) theory for superconductivity, formulated in 1957, is able to characterize only a select class of superconductors, generally having a critical temperature (T_c) below 30 K. The theory does not (seem to) be valid for high-T_c superconducting copper oxides (cuprates). These cuprate superconductors behave differently in a number of important aspects.

Cuprate superconductors typically have an insulating ground state, and doping of this insulator changes its electronic properties. Only when the cuprate is supplied with the correct amount of doping does one get superconductivity below its T_c. Hence, the cuprate is characterized with distinct insulating and superconducting phases in a so-called phase diagram of doping vs. temperature. However, between those two phases, one finds an ill-understood pseudogap phase, that is believed to be crucial for the understanding of cuprate superconductivity.

Cuprates are highly anisotropic in their electronic properties such as ξ, the superconducting coherence length. This is due to the layered nature of their unit cell structure, consisting of the crucially important superconducting CuO_2 planes, parallel to the a and b axes of the unit cell (i.e., in-plane directions). Indeed, for a compound like $La_{2\text{-}x}Sr_xCuO_4$, $\xi_{a,b} \simeq 100\xi_c$.

The coherence length plays a crucial role in the superconducting proximity effect. This effect arises when a normal metal is sandwiched between two superconductors and is characterized by an exponential decrease of the superconducting wave function across the normal metal. The superconductors on top and bottom may be either of the conventional type or of the high-T_c type.

What happens now when we replace the normal metal with a

cuprate in its pseudogap phase with its *c*-axis parallel to the interface normal? Surprisingly, the coherence length is amplified by a factor 100 or more; this stunning result is known as the Giant Proximity Effect (GPE). The exact origins of the GPE are still unknown, and could be related to the pseudogap physics of the cuprate.

Given the fact that $\xi_{a,b} \simeq 100\xi_c$, one may expect to observe a proximity effect for distances of up to 10^2 nm along the *ab*-axis for typical cuprates. With these in mind, the GPE, and in particular the GPE along the *ab*-axis, forms the central theme of this thesis.

We have employed two methods to induce a GPE along the *ab*-axis, the first of which is ionic liquid (IL) gating, motivated in part because this approach allows creating a junction in a film that is structurally homogeneous. This method makes use of a molten (molecular) salt to achieve high charge carrier densities. The application of a bias voltage across the ionic liquid forms an electric double layer at the surface of the material which can be gated. This method results in charge carrier densities of the order of $10^{14}/\text{cm}^2$, which is sufficient to traverse the phase diagram of a typical cuprate. The method has its own intricacies and Chapter 2 provides a glimpse into these.

Chapter 3 describes the methods used for the growth of cuprates, namely pulsed laser deposition combined with reflection high energy electron diffraction. In this chapter, the ways of using RHEED data to interpret in-situ growth is explained, along with different parameters for the growth of a number of materials, in particular cuprates such as $Nd_{2\text{-}x}Ce_xCuO_4$, $La_{2\text{-}x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7\text{-}x}$. Furthermore, the methods for attaining *ab*-axis Josephson junctions are described, among other important aspects pertaining to device manufacturing and ionic liquid handling.

The ionic liquid gating method has first been extensively used on a non-cuprate, namely $SrTiO_3$, as discussed in Chapter 4. Here, we have found a way of differentiating between electrochemical and electrostatic processes induced by ionic liquid gating. We have found that performing the measurements at low temperatures (close to the melting point of the ionic liquid, 183 K) and at low pressures (10^{-6} mbar) completely removes the electrochemical mechanism, in which case $SrTiO_3$ charges homogeneously. The resulting 2D electronic system at the surface of $SrTiO_3$ is characterized by percolation driven transport.

Similar studies have been performed for the cuprates $Nd_{2\text{-}x}Ce_xCuO_4$

(Chapter 5) and $La_{2-x}Sr_xCuO_4$ (Chapter 6). With the Nd compound we were unable to induce a substantial change in the charge carrier density. Rather, we found that the thin films of $Nd_{2-x}Ce_xCuO_4$ were very susceptible to electrochemical reactions. These also play a role in the study of the La compound. Albeit in the form of oxygenation, this effectively hole dopes the compound and induces superconductivity in thin $La_{2-x}Sr_xCuO_4$ films.

Chapter 8 describes the application of the methods presented in Chapter 3 for making an in-plane Josephson junction. Here, ionic liquid gating is applied for an initially superconducting film with low T_c. An artificial junction area of AlO_x is made so that the gating effect on top of this area is blocked by means of a barrier. Although the increased carrier density on the gated areas leads to a higher T_c in the barrier area over distance much larger than $\xi_{a,b}$ (about two orders of magnitude), the results are not yet conclusive as the effect might be caused by possible barrier imperfections, namely porosity.

The second method makes use of etched bilayers (Chapter 7). In short, this method involves the deposition of a film of low T_c ($La_{2-x}Sr_xCuO_4$) followed by one of high T_c ($YBa_2Cu_3O_{7-x}$). Next, the top layer is etched away in a specific area using argon ion dry etching. In doing so, a quasi *ab*-axis junction is formed where the flow of electrons between both high-T_c layers passes through the low-T_c area. Backed up by magnetic field measurements, the results seem to support a long range proximity effect along distances much larger than $\xi_{a,b}$. However, inhomogeneities in the method pertaining to the nature of etching process requires further improvements of this approach.

The thesis is finalized with an outlook and conclusion on the origins of the GPE based on key measurements made with both methods in Chapter 9. Despite the limitations of the junctions investigated we conclude that two of the proposed mechanisms of GPE are not favored by the experimental observations.