Size effects in microstructured superconductors and quantum materials

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SUMMARY

This thesis examines how size reduction and geometry influence Josephson junctions with normal and ferromagnetic weak links, as well as the properties of highly correlated electron matter through transport experiments. Central to achieving this goal is a top-down sample fabrication technique: by combining mechanical exfoliation of bulk single crystals with focused ion beam (FIB) processing, we can produce microstructured correlated oxide materials. Besides, FIB milling allows us to structure Josephson junctions with arbitrarily-shaped electrodes from macroscopic thin films, having feature sizes well below 1 μm. The thesis is divided into three parts, which I will detail below.

PART ONE: JOSEPHSON PHYSICS IN THIN FILM PLANAR JUNCTIONS

The first part introduces basic concepts of superconductivity and the most fundamental building block of superconducting electronics: the Josephson junction. Chapter two explains that superconductivity is a state of matter characterized by a change of charge carrier statistics from Fermionic to Bosonic nature. This allows them to occupy a single quantum mechanical state, which results in zero electrical resistance and the expulsion of magnetic fields from the center of the bulk, among other properties. The currents that expel the magnetic fields are called shielding currents and are driven by the quantum mechanical phase. Therefore, superconductivity is a manifestation of quantum mechanics at the macroscale. This becomes clear in Josephson junctions, which are two superconducting electrodes separated by a non-superconducting link. The maximum supercurrent such an object can sustain, called critical current (I_c), oscillates as a function of magnetic field (B), resulting from the interference between the shielding currents running in the electrodes.

The shielding currents in the electrodes are determined by the local vector potential for a macroscopic junction. However, when a Josephson junction is situated between two superconducting films that are thinner than the penetration depth of the magnetic field (i.e., London penetration depth), this radically changes. Instead, non-local electrodynamics start to play a role, and the $I_c(B)$-pattern is determined by the geometry of the electrodes. The third chapter extends the model proposed by John Clem in 2010, which calculated $I_c(B)$ for a rectangular superconducting strip of length L and width W, separated in the middle by a Josephson junction, to include ellipsoid and rhomboid geometries. We find the periodicity of the $I_c(B)$-pattern to have universal limits

for $L \gg W$ and $L \ll W$, independent of the geometry of the electrodes. Furthermore, we experimentally verify the L/W dependence of this periodicity by fabricating elliptically shaped planar S−N−S junctions with various aspect ratios. This part concludes by establishing a relation between the $I_c(B)$-pattern and the spatial distribution of critical current in a planar junction between thin films that can be used to analyze possible current channels.

PART TWO: MESOSCOPIC SF-HYBRID JOSEPHSON JUNCTIONS

Ferromagnetism and superconductivity are typically antagonistic properties. In the last twenty years, however, it has been shown that magnetic inhomogeneity at the interface between a superconductor and a ferromagnet can induce long-range triplet (LRT) correlations, penetrating the ferromagnet over long distances. Alternatively, ferromagnetic vortices and Skyrmions were proposed to generate LRT correlations based on their ferromagnetic spin textures, although these lacked experimental realization. In the second part of this thesis, we replace the metallic layer of the S−N−S junctions described in the first part with a ferromagnet, resulting in S−F−S Josephson junctions that feature a deterministic ferromagnetic spin texture due to the shape of the electrodes. We use these junctions to study the interplay of supercurrents and spin texture, which had remained experimentally elusive before.

Specifically, in the fourth chapter, we show that the presence of a ferromagnetic vortex leads to the LRT proximity effect in disk-shaped S−F−S devices. By employing the relation between the $I_c(B)$-pattern and the spatial distribution of critical current developed in the first Part, we find the LRT currents to flow in highly localized channels located at the rim of the device. We explain the emergence of these 'rim currents' through the equivalence between the spin texture and an effective spin-orbit coupling, which results in an accumulation of spin at the sample−vacuum boundary that gets transformed into LRT correlations. By modifying the spin texture, we show that we can alter the relative phase between the channels, manifesting itself as the appearance of 0 and π channels.

In Chapter five, we transition to elliptical S−F−S devices to create a stable and nonvolatile superconducting memory element that combines the ultra-fast manipulation of spins with dissipationless readout. It functions based on the bistability of magnetic textures of the ferromagnet: the sample can either be uniformly magnetized along its long axis or contains two magnetic vortices at zero applied field. The two states yield considerably different critical currents, which facilitates electrical readout of the bit. We call the low critical current the "1" state and the high I_c state resembles the "0". By quantifying the fields emerging from the ferromagnet using micromagnetic simulations, we show that the change in critical current is caused by the local stray field penetrating the Josephson junction.

PART THREE: STRONGLY CORRELATED RUTHENIUM OXIDE MICROSTRUCTURES

In Part three of this thesis, we use size-reduction in specific geometries to study two strongly correlated ruthenium oxide materials, namely, the isostructural counterparts Ca_2RuO_4 and Sr_2RuO_4. The first is a Mott insulator at room temperature exhibiting an insulator-to-metal transition (IMT) at surprisingly low current densities, making it a candidate material for developing Mott-based electronics. In Chapter six, we study the current densities required for driving Ca_2RuO_4 crystals out of the insulating phase, using size as the principal tuning parameter. We find a four orders of magnitude increase in the current density that induces the current-maintained metastable phase (preceding the fully metallic state) when the crystal size is reduced to the micrometer scale. This effectively shatters the promise of applications using this material. Furthermore, we tackle the hotly debated issue of possible heating effects driving the transition by including a microscopic thermometer on our micrometer-sized samples. We conclude from our thermometry experiments and simulations that heating effects cannot explain the found size dependence. Instead, our findings suggest that an inhomogeneous current distribution over the cross-sectional area is responsible for the size dependence.

One of the large open questions of condensed matter physics is the nature of the electron pairing in the superconductor Sr_2RuO_4. At the moment, the proposals range widely. An attractive approach to differentiate between these proposals is the chirality of the order parameter. A chiral superconductor is characterized by a finite angular momentum of the Cooper pairs, which causes the superconducting order parameter to spontaneously break up into spatially separated domains, each corresponding to a single chirality. In a previous work, we found an experimental signature of the chiral domain walls separating two chiral domains: the order parameter is locally suppressed at the domain wall, which acts as a Josephson junction. In Chapter seven, we further examine the properties of these chiral domain wall junctions. We find that the chiral domain walls are stable in mesoscopic samples of quite different geometries. Furthermore, the $I_c R_N$ product associated with domain wall junctions exhibits a universal temperature dependence. By obtaining the Shapiro response of our samples, we provide definite proof of the Josephson coupling of the domain-wall-associated junctions. Besides, we gain insight into their current-phase relation and find that we can alter the domain structure by applying small in-plane magnetic fields (in the ab-plane of the crystal; $H < H_{c1}$), which is indicated by the appearance of half-integer Shapiro steps in the IV-characteristic. In-plane fields also reveal a bistable critical current, which can be switched by reversing the bias current polarity: by applying either a positive or negative current bias, we switch between a low and high I_c state. We interpret the bistability of I_c as unpinned, and therefore mobile, domain walls in our samples. Finally, we conclude that a chiral d-wave order parameter is best suited for describing superconductivity of Sr_2RuO_4.