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Spin transport and superconductivity in half-metallic nanowires and junctions

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Introduction

Spin is inherent to the nature of an electron and has either an up ($e^{\uparrow}$) or a down ($e^{\downarrow}$) state in the description of the quantum world, manifesting itself by a magnetic moment. The other quantity describing an electron is its charge. Charge transport in the form of an electric current can be driven by a voltage and is responsible for traditional electronics. Beyond charge transport, spin transport brings an additional degree of freedom to electronic transport and yields spin current. Spin transport concerns the spin-conserving motion of conduction electrons over a spin diffusion length (λ_{sf}). Within a length scale of λ_{sf}, spin maintains the initial state, *i.e.* either up or down. Because of spin scattering and spin-orbit interaction (SOI), a spin is typically flipped when it travels a distance exceeding λ_{sf}. Spin transport gives rise to a variety of physical scenarios and draws attention in both fundamental research fields and in practical applications [1–3].

From the study of spin transport has emerged the research area of spintronics, in which spin and charge can both operated with, and intriguing physical phenomena are found. The generation, manipulation, and detection of spin currents are the main interests in the field of spintronics. Literally, the spin current is carried by spin-polarized electrons, meaning that the number of spin up electrons $n(e^{\uparrow})$ and that of spin down electrons $n(e^{\downarrow})$ are unequal. The imbalance of $e^{\uparrow}$ and $e^{\downarrow}$ exists intrinsically in a ferromagnet (F). Due to the exchange field that shifts the two spin-subbands in a ferromagnet, a non-equilibrium spin population occurs, *i.e.* $n(e^{\uparrow}) \neq n(e^{\downarrow})$, resulting in a net macroscopic magnetic moment. At the Fermi level E_f, spin scattering rates for $e^{\uparrow}$ and $e^{\downarrow}$ will in general be different, and correspondingly, the conductivity $\sigma(e^{\uparrow})$ differs from $\sigma(e^{\downarrow})$. As a consequence, the electric current flowing in F is spin-polarized. By simply connecting a normal metal (N) to the F metal, a spin potential difference is established between N and F. Pure spin current can be injected into the N and exists over a length λ_{sf} in the N [4].[1]

Spin current can also be generated in a nonmagnetic material through the Spin Hall effect (SHE) [5]. Although SOI suppresses the spin transport in a N, it plays a major role in the SHE. Assume an electric current flowing along the long axis in a bar-shaped thin film of a nonmagnetic material with strong intrinsic SOI (such as Pt), a pure spin current polarized along the out-of-plane axis is generated naturally by the SHE, flowing transverse to the current direction. Reciprocally, a pure spin current can produce an electric current via the so-called inverse SHE (ISHE). The ISHE is of importance in the research field of spin pumping [6, 7]. When the magnetization of a ferromagnet is changed in time by ferromagnetic resonance, the yielded spin dynamics turn back to equilibrium by spin relaxation, emitting a spin current. Placing a nonmagnetic material owning strong SOI (spin sink) next to the ferromagnet, the spin current is then collected by the neighboring spin sink and measured in the form of electric voltage, thanks to the ISHE.

So far, the discussion was about spin current generated in conductors. In ferromagnetic insulators, spin transport is in the form of spin-wave propagation, that is, magnonics, which is generally induced by ferromagnetic resonance [8]. The principle is simple. Flipping a spin affects the adjacent spin due to exchange interaction. Spins therefore coherently precess and damp, giving rise to the collective spin waves. In contrast to λ_{sf}, the length of spin-wave propagation is up to several millimeters because of the ultralow dissipation [8, 9].

Spin transport is not only of interest in N metals (F/N hybrids), it is also of interest in F/S hybrids (S a superconductor) [10, 11]. Combining S and F enable the mutual manipulation of superconducting and magnetic order parameters. This could lead to appealing applications in the form of superconducting spintronics. In conventional S metals, the supercurrent is spinless as Cooper pairs consist of opposite spins (singlets). Since the band structure of F is spin-split, Cooper pairs are broken, and supercurrents in F are quenched. However, through a process of spin mixing and spin rotation, zero-spin singlets can be converted to equal-spin triplets. Triplets are able to exist in F freely and can carry a spin-polarized supercurrent. In spintronics, spin-polarized currents are used, among others to manipulate magnetic moments (*e.g.* in a thin film or domain wall) by an effect called spin-transfer torque (STT). Re-orienting magnetic moments by STT usually requires very high current densities. Spin-polarized supercurrents could enable STT without, or with very little, Joule heating.

Alongside learning to generate spin currents in a wide range of material systems, the

[1] λ_{sf} varies from the order of nm to μm and is strongly correlated with SOI, depending on the selected material.

detection methods of spin transport have been developed. Here, the focus lies on electrical detection. As we know, in N metals, the electrical resistance mainly comes from electron scattering and is temperature-dependent. However, the resistance of F metals comes from two sources, *i.e.* spin scattering and electron scattering. A simple example is the well-known anisotropic magnetoresistance of F metals. If the magnetization of F is saturated at a high field, the measured resistance is nearly constant. Sweeping the field to zero, and with some angle relative to the direction of the current, the measured resistance changes by a small amount. This is due to the contribution of spin scattering in addition to the normal electron scattering. The spin-scattering yielded variation of resistance is not only present in F but also observed in materials with strong SOI. Electrical detection has been proven to be sufficiently sensitive to the variation of both the magnitude and direction of spin transport.

A special case concerns the electrical detection of the transport of spin-polarized supercurrent in S/F/S hybrids. Typically, a zero-resistance state arises in the current versus voltage measurement. Under the action of a field, the critical current is modulated periodically, showing an interference pattern as a result of macroscopic quantum coherence. The other signature of macroscopic quantum coherence is quantized Shapiro steps, which can also be characterized electrically upon the excitation of radio-frequency stimulus.

Spin transport exhibits plenty of intriguing physical phenomena and yields novel spintronics applications for sensors and logic devices. A well-known example from the recent past is giant magnetoresistance (GMR). By stacking two F layers with a nonmagnetic spacer, the spin transport is determined by the respective magnetization orientations of the F1 and F2 layers. In the case of aligned magnetizations of F1 and F2, spins pass through the stacking trilayer approximately without scattering. If F1 and F2 are anti-aligned, spin transport, and its accompanying charge transport, encounters resistance. Consequently, manipulating F1 and F2 gives low and high values in electrical detection. The discovery of GMR has revolutionized the modern electronics world. Also, spin transport brings up STT. The local magnetic structures can be altered by STT from the spin-polarized current. The relevant prototype has been developed, *i.e.* racetrack memory, in which magnetic domain walls act as memory bits and are manipulated by spin transport. Moreover, using spin-polarized supercurrent leads to no Joule heating and meanwhile retains high-efficient STT. The emerging superconducting spintronics is hence drawing considerable attention. In comparison to charge-operation-based electronics, (superconducting) spintronics promises lower-power consumption as no charge transport is needed and faster operating speed up to THz.

Outline of this thesis

In this thesis, we study spin transport in normal and superconducting half-metallic junctions based on $La_{0.7}Sr_{0.3}MnO_3$ (LSMO). LSMO is a well-known half metal, meaning the current flowing in LSMO is fully spin-polarized and thus can dramatically enhance the efficiency of STT in relevant spintronics applications. Modulating both the magnetic and electrical properties of LSMO can be done by strain engineering, *i.e.* choosing an appropriate single-crystal substrate. Here, $(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ (LSAT) is used and offers very weak compressive strain due to the very small lattice mismatch (-0.2%) with LSMO. Epitaxial LSMO thin films have a quite small damping constant ($\sim 10^{-4}$), which further benefits STT control of local magnetic structures [12]. In normal LSMO-based junctions, a low-density current on the order of 10^8 A/m^2 has been verified to be able to manipulate the local magnetic structures [13]. This is almost four magnitudes smaller than that of the threshold current in conventional ferromagnets. More intriguingly, through special spin mixing and spin rotation, creating spin-polarized supercurrent in LSMO is viable [14]. This could enable efficient STT without Joule heating, which may pave the way to superconducting spintronics.

Chapter 2: Fundamental concepts
This Chapter introduces the theoretical background of this thesis, including the fundamentals of ferromagnetism and superconductivity, and in particular the interplay of magnetic order and superconductivity. Our focus lies on spin transport in normal metal nanowires and superconducting half-metallic junctions.

Chapter 3: Domain wall pinning and depinning in notched $La_{0.7}Sr_{0.3}MnO_3$ nanostructures
This Chapter demonstrates the pinning and depinning of magnetic domain walls (DW) in notched LSMO nanostructures with various dimensions, across a wide range of temperatures (10 K to 300 K).

Chapter 4: Non-local spin transport based on a half-metallic ferromagnet
This Chapter studies the electrical injection and detection of spin transport in Ag/LSMO hybrids in a non-local configuration. Our theoretical calculations predict LSMO is quite efficient in inducing a high spin polarization in Ag by injecting spin-polarized currents. This is thoroughly examined by performing non-local spin detection and Hanle precession measurements, using magnetic field sweeps and temperature variations. We find a spin-active interface that leads to a discrepancy between the theoretical calculations and experimental observations.

Chapter 5: Triplet supercurrents in lateral Josephson junctions with a half-metallic ferromagnet

This Chapter focuses on creating triplet supercurrents in differently shaped lateral NbTi/LSMO junctions. We see unambiguously the existence of triplets in all junctions regardless of the geometry by inspecting the superconducting quantum interference patterns. Furthermore, removing the spin texture with a magnetic field yields no decay in triplet supercurrents, hinting that the triplet generation is related to an intrinsic magnetic inhomogeneity. Besides, $I_c(T)$ is measured and analyzed in the framework of short half-metallic Josephson junctions.

Chapter 6: Inducing triplet supercurrent in long half-metallic ferromagnets

The final Chapter investigates the long-range proximity in NbTi/LSMO junctions with varying dimensions. The existence of Josephson coupling is firmly established in all junctions by observing Gaussian-like patterns of superconducting quantum interference. Also, $I_c(T)$ curves are recorded. Quantitative analysis of $I_c(T)$ may require a rigorous theoretical description of half-metallic Josephson junctions.