Spin-transport in superconductors

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Spin-transport in superconductors is a subject of fundamental and technical importance with the potential for applications in superconducting-based cryogenic memory and logic. Research in this area is rapidly intensifying with recent discoveries establishing the field of superconducting spintronics. In this perspective we provide an overview of the experimental state-of-the-art with a particular focus on local and nonlocal spin-transport in superconductors, and propose device schemes to demonstrate the viability of superconducting spin-based devices.

Spintronics has developed as an extension of semiconductor transistor based electronics by utilising both the spin and charge degrees of freedom of electrons. Spintronic devices rely on the creation and transfer of spin-angular momentum through spin current transport in magnetic and nonmagnetic materials10. Ferromagnets are key materials for spin generation, detection and manipulation in semiconductors along with normal (nonmagnetic) metals for transmitting spin information between ferromagnetic elements in a circuit. However, equivalent experiments in which the normal metal is replaced with a superconductor such as Al or Nb are far less understood. In a standard s-wave superconductor, the electrons pair (“Cooper pairs”) with opposite spins in a so-called spin-singlet state. Singlet pairs and thus singlet supercurrents do not carry a net spin and hence spin transmission in the superconducting state depends on the superconducting gap and is also highly sensitive to the magnetisation structure of the proximitized ferromagnete19.

The conflict between superconductivity and ferromagnetism results in intriguing spin-related phenomena at s-wave superconductor/ferromagnet (SC/FM) interface20. Supercurrents are dissipationless and Cooper pairs are coherent and hence, combining superconductivity and spin-related phenomena offers the potential for new devices. These device may offer an energy efficient means of generating spin-currents21 and also exciting avenues for spin-dependent quantum phenomena22 as well as the discovery of quantum materials23 and energy efficient computing24.25 In this perspective, we survey recent advances and outstanding issues in the area of spin-dependent transport in superconductors, and outline device concepts that could exploit spin supercurrents in active devices.

Quasiparticle (i.e. unpaired electrons) spin currents have been investigated through spin current injection experiments into superconductors, both in local26, 27  and non-local28,29  device geometries. At a FM/SC interface, an electron injected from FM can either enter the SC as a quasiparticle with an energy above the superconducting gap or form a Cooper pair via Andreev reflection30. As shown in Fig. 1(a), since singlet pairs cannot carry a net spin angular momentum, spin-polarised electrons are injected as quasi-particles in a SC with a voltage bias31,16,15,29 and/or thermal excitation21,25.

An injected current from a FM induces a non-equilibrium accumulation of charge and spin at a SC/FM interface, which results in a charge and spin imbalance within the SC near the SC/FM interface32. Since the transport equations for spin and charge imbalances are different in a SC, the decay length of spin imbalance can be longer than that of charge imbalance33. Therefore, the diffusion of spin-imbalance (i.e. spin diffusive currents) without a charge imbalance is possibly away from the junction point as illustrated in Fig. 1(b). This can be termed as a “pure spin-imbalance” as an analogue of pure spin currents which are a spin current without a net charge current in NM. The pure spin-imbalance was detected as a spin signal using a nonlocal FM probe — e.g. F. Hübber et. al30 and C. H. L. Quay et. al30 reported evidence for spin-polarised quasiparticle diffusive currents in a lateral spin-valve using superconducting AI as the spin-current channel and injected the spin-polarised current from a FM into the Zeeman-spin-split superconducting density of states in AI.

The spin diffusive current in a SC is described by diffusion
equations with key parameters including the spin-polarisation and spin-diffusion time/length. To manipulate a spin diffusive current in a SC and utilise the spin for applications, these parameters should be carefully investigated and understood. They have been estimated through techniques including the Hanle and spin Hall effects, and the local/nonlocal spin signals in spin-valve structures. Despite intensive investigation of the spin diffusion current within SCs, the relationship between spin-relaxation times and diffusion lengths remains unclear and much debated.

A second potential type of spin current is the condensate spin current (so-called spin supercurrent), which is carried by spin-triplet Cooper pairs. Spin-triplet Cooper pairs are spin-polarised and therefore triplet supercurrents are able to carry a net spin. Spin-triplet pairs have been detected in SC/FM hybrids as long-range correlations in a FM through critical temperature measurements of SC/FM multilayers supercurrents in SC/FM/SC Josephson junctions and density of state measurements. At a homogeneously magnetized SC/FM interface, spin-zero triplet pairs form through a spin-mixing process. Spin-zero triplet pairs decay on the same length scale as singlet pairs which is typically a few nanometres in a FM. In the presence of magnetic inhomogeneity and/or appropriate spin-orbit coupling at a SC/FM interface, the spin-zero triplet pairs convert to spin-polarized triplet pairs as illustrated in Fig. 2(a). Spin-polarized triplet pairs propagate through a FM over the triplet coherence length, which is tens of nanometres.

Evidence for pure spin supercurrents in a SC were first shown by K.-R. Jeon et al. through spin-pumping experiments using Pt/Nb/Pt/FM interfaces. Here the effective Gilbert damping (which is proportional to the spin-current density) of the precessing Py (Ni$_{80}$Fe$_{20}$) magnetization increased below the superconducting transition temperature, indicating that the spin sink efficiency of Pt increased as a superconducting gap in Nb opened as schematically illustrated in Fig. 2(b). The explanation is that the strong spin-orbit coupling in Pt induces an evanescent spin-orbit interaction in Nb which, in conjunction with an induced magnetic exchange in Pt from Py through Nb, creates triplet channel through superconducting Nb. Since this equal-spin density of states channel in Nb offers a pathway for transferring spin angular momentum, the spin current at the Py/Nb interface is additionally transferred and absorbed in Pt, resulting in an enhanced spin current density above the normal state. Although further work is required in order to establish the spin transfer mechanism(s), this work provided compelling evidence for spin supercurrents.

As a result of the interplay between spin supercurrents and the absolute phase of the superconducting state, spin supercurrents should be considered as more than just a low dissipation equivalent of normal state spin currents. Nevertheless, the generation of nondissipative spin currents without dissipative charge currents is of great importance for low energy computing applications. Even under the unlikely assumption of 100% spin polarisation, the current densities achievable in the superconducting state have not yet reached the necessary magnitudes required for conventional spin-transfer torque switching. Therefore, the ability to exploit spin supercurrents is dependent on other interactions and phenomena, which are only just being explored. Moreover, fundamental parameters such as the spinpolarisation, the conversion rate from singlet-to-triplet pairs, decay lengths and times are experimentally unclear and require intensive study both theoretically and experimentally.

The discovery of pure spin supercurrents in a conventional SC offers the potential for the separation of spin and charge components in the superconducting state, which is the analogue of non-local spin transport in normal state lateral devices. In the case of a diffusive current, the current is driven by a gradient of electrochemical potentials. Since the spin supercurrent is carried by coherence Cooper pairs we can expect that a gradient of absolute phase of the superconducting condensate to act as an electrochemical potential. This alters the structures required to generate this spin and charge separation of a triplet state. A structure to test this is a SC/spin-mixer/FM/SC/spin-mixer/SC structure as shown in Fig. 3. Here, the spin-mixing layers perform the necessary singlet-to-triplet pair conversion process, and the central FM spin filters the spin-polarized triplet pairs. Although the charge component of the injected spin supercurrent flows in accordance with the conventional coherence conditions, the equilibrium current-phase relations for spin and charge components will be different. In other words, it may be possible to have a non-zero spin supercurrent while the phase difference between the two superconductors is zero. Hence a spin accu-
The spin supercurrent induced by the left-hand loop can control a supercurrent in the right-hand loop through (a) shared superconducting channel or (b) strong spin-orbit material (spin sink).

An alternative coupling arrangement is shown in Fig. 4(b). Here, a supercurrent flowing in the left loop pumps spin into the spin sink which is the high spin-orbit material forming part of the right-hand loop. The effective exchange field induced by spin accumulation in this material acts with the spin-orbit coupling to create a triplet channel in the right-hand loops which only has one conventional spin mixer. As a result, the spin supercurrent in the right-hand loop can be controlled by that in the left-hand-loop. We would like to stress that, in the structure shown in Fig. 4(b), the injecting spins into the spin-orbit materials are not necessary to be generated from superconductivity. The conventional spin injection or spin-polarised quasiparticles are also available to induce an effective exchange field. There must be some dissipation due to the spin flow in the spin-orbit materials, but this could be small.

There are a few key underlying assumptions in these proposals. In the spin supercurrent, the charge and spin components must be manipulated separately – i.e. the spin polarization of the spin supercurrent is determined without regard to the flow of the charge component in the superconductor. In Fig. 4(b), assuming that the triplet proximity channel can carry only Cooper pairs, the conversion in spin current between condensates and quasi-particles at the contact between SC and a high spin-orbit materials is inevitable to be absorbed or extracted. Moreover, the injected spin accumulation in the spin-orbit materials has to act as an effective exchange field. Experimental results show some possibilities, but there has so far been no detailed theoretical exploration of them.

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