Dynamic pair breaking in cuprate superconductors via injection of spin-polarized quasiparticles in perovskite F-I-S heterostructures

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Abstract

We report experimental evidence of dynamic Cooper pair breaking induced by spin-polarized quasiparticles in cuprate superconductors by studying the critical current density and quasiparticle density of states of ferromagnet-insulator-superconductor (F-I-S) heterostructures. The spin diffusion length and relaxation time are also estimated.

Non-equilibrium superconductivity has been extensively studied since the 1970's [1]. Most of the investigation has focused on the effects of simple quasiparticle (QP) injection and extraction in conventional s-wave superconductors. In contrast, there is insufficient theoretical understanding of spin-polarized QP transport in superconductors, largely due to the complications of combined non-equilibrium [1] and magnetic pair-breaking effects [2] induced by spin-polarized currents. Recently, the concept of spin injection has been investigated in high-temperature superconductors (HTS) by passing an electrical current through a perovskite ferromagnetic manganite to introduce spin-polarized quasiparticles (QP's) [3,4]. However, the reported suppression of critical currents in the perovskite ferromagnet-insulator-superconductor (F-I-S) appear to be primarily induced by Joule heating. To amend this problem, we adopted a pulsed current technique and in-situ thermometry [5], so that the effect of Joule heating is limited to < 10 mK. In this work, we report macroscopic and microscopic experimental evidence of dynamic pair breaking induced by spin-polarized QP currents in perovskite F-I-S heterostructures. These results are compared with control samples of N-I-S heterostructures (N: non-magnetic metal).

The F-I-S and N-I-S samples are fabricated using the pulsed-laser deposition technique [5]. The chemical formulae and thicknesses of the constituent layers are:

- F: La0.7Ca0.3MnO3 (LCMO) and La0.7Sr0.3MnO3 (LSMO), 100 nm.
- I: SrTiO3 (STO), 2.0 nm; and yttria-stabilized-zirconia (YSZ), 1.3 nm.
- N: LaNiO3 (LNO), 100 nm.
- S: YBa2Cu3O7 (YBCO), 100 nm.

The effect of spin-polarized current I_m on the critical current density (J_c) of YBCO is shown in Figure 1(a), and the absence of effect in the N-I-S sample is illustrated in Figure 1(b). We note that the suppression of J_c in F-I-S becomes statistically...
near $T_c$, due to the diverging QP relaxation time $[1]$. In analogy to the simple QP relaxation through inelastic electron-phonon scattering $[1]$, we may assume a relaxation process of spin-polarized QPs through the spin exchange interaction. The relaxation time is given by $\tau_s(T) \approx 3.7\tau_{ex} k_B T_c/(\Delta(T))$, where $\tau_{ex} \approx (h/E_{ex})$ is the interaction time associated with the exchange energy $E_{ex} \approx 30$ K in YBCO $[5]$. Hence, for an average $d$-wave superconducting energy gap $\Delta(T) \approx \Delta_d[1 - (T/T_c)]^{1/2}$ with $\Delta_d \approx 20$ meV, we obtain $\tau_s \approx 3 \times 10^{-13}[1 - (T/T_c)]^{-1/2}$. The spin diffusion length $\ell_s$ may be estimated by $\ell_s \approx \sqrt{\tau_s v_F T}$, where $\ell_s$ is the electron mean free path, and $v_F$ is the Fermi velocity $[1]$. For $v_F \approx 10^5$ m/s and $\ell_0 \approx 20$ nm, we find that $\ell_s \approx 25$ nm for $T \to 0$ and $\ell_s \approx 80$ nm ($\approx$ sample thickness) at $[1 - (T/T_c)] \approx 0.01$. This estimate is consistent with the observed strong dependence of $J_c$ on $I_m$ in F-I-S only near $T_c$.

The main panel of Figure 2(a) illustrates the differential conductance $(dI/dV)$ versus bias voltage $(V)$ data of YBCO, taken with a low-temperature STM, for $c$-axis tunneling at 4.2 K and under various $I_m$. The inset shows the dependence of QP density of states (DOS) on $I_m$ at the Fermi level $(V = 0)$. The spectra appear invariant for $I_m$ up to 35 mA $[6]$, above which spectral smearing appears, showing excess QP-DOS near the zero bias, which is consistent with Cooper pair breaking. The threshold current $I_m^* \approx 35$ mA corresponds to an injection energy $(eI_m^* R_J) \approx 21$ meV, comparable to $\Delta_d$ for a measured junction resistance $R_J \approx 0.6\Omega$. At higher $I_m$, the QP-DOS may be fitted to an effective QP temperature $(T^* \approx 60$ K), even under negligible Joule heating $[6]$. In contrast, spec.

References


