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Spin diffusion in a superconductor through mesoscopic ferromagnet/superconductor interfaces

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Abstract

We measured the suppression of the superconductivity in a mesoscopic Al wire in proximity contact with an overlaid ferromagnetic Co wire. We estimated the resultant spin diffusion length of spin-polarized quasiparticles in the superconductor, which appeared to be related to the pair condensation of quasiparticles through opposite spin channels.

Keywords: Spin injection; Spin relaxation in superconductors; Spin-polarized transport

Studies on spin-related transport phenomena have become a focus of recent research effort, which require retaining the spin information of conduction electrons in the systems under study. The spin relaxation in superconductors (S), in particular, has attracted much research interest because of the interaction of spin-polarized conduction electrons with the superconducting order. A number of studies on the spin diffusion in S [1–6], however, have revealed contradicting results.

In this study we investigated the suppression of the superconductivity in a mesoscopic superconducting Al wire in proximity contact with ferromagnetic Co wire when the spin-polarized current was injected through the F/S interface. We extracted the spin-diffusion length d_s from the finite resistance of the Al wire below the bulk value of T_c, which resulted from the pair breaking by the injection of the spin-polarized current. The temperature dependence of d_s suggested that the spin relaxation in a superconductor was related to the pair condensation of nonequilibrium quasiparticles through opposite spin channels.

A specimen was fabricated on a Si substrate covered with native oxide layers. The ferromagnetic wire and extended contact electrodes were made by electron-gun evaporation of a 66-nm-thick Co film on a patterned layer of e-beam resist and by lifting off subsequently to the width of about 270 nm. A 74-nm-thick Al layer was then ion-beam deposited as a superconducting strip on the second patterned resist and lifted off to the width of about 400 nm. To enhance the transparency of the Co/Al interface, the surface of the ferromagnetic layer was cleaned using low-energy Ar-ion milling right before the Al deposition. The diffusivity of the Al wire determined from the residual resistivity was $D = 7.44\ \mathrm{cm^2/s}$, which was small because of the structural disorder in the ion-beam-deposited wire.

Data were taken by the conventional four-probe lock-in technique at 38 Hz. A spin-polarized current (I_{sp}) was applied between Leads A and C and the voltage drop V_{BD} between Leads B and D was measured (see Fig. 1). V_{BD} consisted of the voltage drop across the portion of Al wire in its normal state between the junction and the branching position of Leads C and D as well as the voltage drop across the junction itself. Since the interfacial resistance of the F/S junction was only about 0.2 Ω, however, V_{BD} was dominated by the resistance of the Al wire.

The differential resistance of Al wire between Leads B and D, dV/dI, exhibited two peaks for both polarities (see the inset of Fig. 2). The higher-current peak at I_{c0} corresponded to the bulk critical current of the Al wire located beyond the spin-diffusion length from the junction, while the lower-current peak at $I_{c,supp}$

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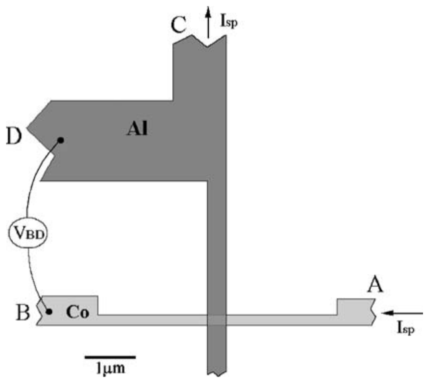

Fig. 1. Schematic configuration of the specimen which shows a spin-polarized current injection.

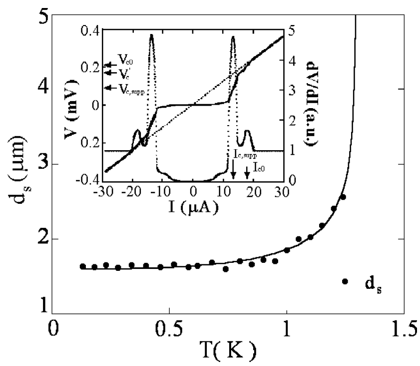

Fig. 2. The temperature dependence of the spin-diffusion length of the Al wire below T_c. Inset: I–V characteristics and the differential resistance dV/dI versus the spin-polarized bias current at $T = 0.13$ K.

corresponded to the suppressed critical current of the Al wire due to the proximity contact to the ferromagnetic wire within the spin-diffusion length. In the inset of Fig. 2 we denoted the voltage V_c', which was extracted from the voltage value of the extended normal-state background current–voltage (I–V) characteristics at the lower critical current $I_{c,supp}$. In the figure we also denoted the voltages V_{c0} and $V_{c,supp}$ which were the observed voltages at the critical currents I_{c0} and $I_{c,supp}$, respectively. We extracted the effective spin-diffusion length d_s from a simple relation $V_{c,supp}/V_c' \simeq d_s/L$, where L ($\simeq 3$ μm) was the average spacing between Leads B and D. This relation was obtained by the fact that, over the region of the spin-diffusion length, the superconductivity would be suppressed by the pair breaking, giving rise to the finite voltage $V_{c,supp}$ at the suppressed critical current $I_{c,supp}$. In Fig. 2 we plot the temperature dependence of the thus-determined d_s. It is insensitive to the temperature far below T_c with the zero-temperature-limit value of $d_s = 1.6$ μm, but increases with T and diverges near T_c. This result is in agreement with Ref. [1] but in clear contradiction with the result in Ref. [4], where d_s decreases approaching T_c. It also contradicts with Ref. [5], where it is claimed that the spin-diffusion length should be the same both in the normal and in the superconducting states.

Employing the picture of the relaxation of charge-imbalanced nonequilibrium quasiparticles in superconductors [7], the spin-diffusion time was suggested to follow the relation [8] $\tau_s \sim \tau_{ex} k_B T_c/\Delta(T)$. Here, τ_{ex} is determined by the spin exchange as $\tau_{ex} \sim \hbar/h_{ex}$ (h_{ex} is the exchange energy inside the superconductor) and $\Delta(T)$ is the superconducting energy gap. Then the temperature dependence of the spin-diffusion length, expressed as $d_s = \sqrt{D\tau_s}$, is determined by the temperature dependence of Δ as $\Delta(T)^{-1/2}$. The best fit to this temperature dependence is shown in Fig. 2 as a solid curve. In the fit we used the empirical formula $\Delta(T) = \Delta(0)\tanh(1.74\sqrt{T_c/T - 1})$ for the temperature dependence of the gap, which was valid for all the temperature range below T_c ($= 1.3$ K). Combining $d_s(0) = 1.6$ μm with $D = 7.44\ \mathrm{cm^2/s}$, the spin relaxation time in the Al wire is estimated to be $\tau_s \sim 3 \times 10^{-9}$ s, corresponding to the exchange energy of $h_{ex}/k_B \sim 1.4$ mK. The nice fit of the temperature dependence of d_s indicates that the spin diffusion in superconductors is governed by the energy relaxation between the opposite spin channels as well as the pair condensation over the superconducting gap.

Acknowledgements

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