Phase coherent transport in Kondo/superconducting hybrid structures

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We present measurements of the transport properties of hybrid structures consisting of a Kondo AuFe film and a superconducting Al film. The temperature dependence of the resistance indicates the existence of the superconducting proximity effect in the Kondo AuFe wires over the range of \( \sim 0.5 \mu m \). Electronic phase coherence in the Kondo AuFe wires has been confirmed by observing the Aharonov-Bohm effect in the magnetoresistance of the loop structure. The amplitude of the magnetoresistance oscillations shows a reentrant behavior with a maximum at \( \sim 870 \text{ mK} \), which results from an interplay between the Kondo effect and the superconducting proximity effect.

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Phase coherence has been a prime subject of interest in mesoscopic systems. The phenomena of electron phase coherence have been widely investigated in low-dimensional structures such as quantum dots [1], carbon nanotubes [2], and metal films [3]. It is well known that phase coherence is affected by the coupling of electrons to an environment. In a system containing magnetic impurities, the coupling between the electron spin and the magnetic impurity spin provides a very efficient source of decoherence. Magnetic impurities of fluctuating spins randomize the phase of electrons during the scattering process. A small amount of magnetic impurities can greatly shorten the phase coherence time, \( \tau_\phi \). In a recent experiment [4] of a mesoscopic dilute-magnetic-impurity system, however, \( \tau_\phi \) was seen to be as long as a few nsec at low temperatures. In addition, phase coherence was reported to be preserved in a semiconductor quantum dot in the Kondo regime [5]. Thus, one may expect an observation of the phase coherent transport in a diffusive metallic Kondo wire.

The Kondo effect originates from spin-flip scattering mediated by the exchange coupling between a conduction-electron spin and a localized impurity spin, which leads to a logarithmic increase of the low-temperature resistance. For a dilute-magnetic-impurity system in contact with a superconductor, the Kondo effect can compete with the superconducting proximity effect. The microscopic mechanism of the superconducting proximity effect is the Andreev reflection: an incident electron reflects as a hole at the normal metal/superconductor interface, simultaneously producing a Cooper pair which propagates into the superconductor. Possible coexistence of both effects was studied for systems where the Kondo temperature \( T_K \) was comparable to the superconducting gap energy \( \Delta \).

In this paper we report the observation of phase coherent transport through a mesoscopic Kondo system, to which superconducting wires are connected with high transparency. The Kondo system is a AuFe wire with a Fe concentration of 26 ppm, and Al film is used for a superconductor. The number of Fe ions in the 1-\( \mu m \)-long AuFe wire of this experiment is estimated to be approximately 1800. The Kondo effect is confirmed by logarithmic temperature dependence of the resistivity at low temperatures. In addition, the superconducting proximity effect has been observed in the AuFe wire when the temperature, \( T \), is lowered below the superconducting transition temperature, \( T_c \), of the Al films. The resistance starts to drop as the samples are cooled through \( T_c \) and continuously decreases until \( T \) reaches \( \sim 0.3 \text{ K} \). Phase coherent transport has been confirmed by the magnetoresistance oscillations of the hybrid loop consisting of a AuFe wire and an Al wire. More interestingly, it has been found...
that the amplitude of the magnetoresistance oscillations shows a strong temperature dependence. The oscillation amplitude initially increases as $T$ is decreased, showing a maximum around $\sim 870 \text{ mK}$, and then decreases rapidly as $T$ is further lowered. The non-monotonic temperature dependence of the magnetoresistance oscillations is attributed to an interplay between the Kondo effect and the superconductivity.

The samples in this experiment were patterned by using the multilevel electron-beam lithography and lift-off process. In the first lithography step, a 500-A-thick film was deposited by thermal evaporation of 99.999%-pure Au. After lift-off, the pure Au film was implanted with Fe ions to a concentration of $\sim 26$ ppm, which was estimated subsequently from the slope of the temperature-dependent resistivity of a control AuFe wire. In the second lithography step, a 1200-A-thick Al film was deposited to make hybrid structures in the middle of the sample wires, the length of which was $\sim 4.7 \mu m$. The area of the interface between the AuFe film and the Al film was approximately $0.12 \times 0.14 \mu m^2$. The interface resistance was estimated to be $\sim 0.1 \Omega$. Figure 1 shows the scanning electron micrographs of two hybrid structured samples. Sample A is shown in Fig. 1(a), and sample B is shown in Fig. 1(b). In sample A, a horse-shoe-type Al wire was located at the center of the AuFe wire, making a rectangular hybrid loop composed of a superconductor and a Kondo wire. However, in sample B, one arm of the rectangular hybrid loop was not lithographically completed, so the Al contacts made two separate interfaces with the AuFe wire.

The samples were measured in a dilution refrigerator using standard lock-in techniques with a four-terminal ac resistance bridge. The four-terminal measurement configurations for the two samples are described in Fig. 1(a) and (b), respectively. The resistivity of the control AuFe wire at 4.2 K was $1.37 \mu \Omega \text{cm}$, and the thermal length of the AuFe wire, $L_T = \sqrt{\hbar D/k_B T}$, was $\sim 0.47/\sqrt{T(\mu m)}$ at a temperature $T$. Here, $D$ is the diffusion constant.

Figure 2 shows the zero-magnetic-field temperature dependent resistivity of sample A, B, and the control AuFe wire. The control AuFe wire was co-fabricated with samples on the same substrate by using the simultaneous lithographical processes and Fe implantation. The control AuFe wire has the dimensions of 374-\mu m length and 0.14-\mu m width. At temperatures above $\sim 7.0$ K, where phonon contribution dominates the resistivity, the resistivity of the AuFe wire decreases as $T$ is lowered. For $T$ below $\sim 7.0$ K, the resistivity $\rho(T)$ of the control AuFe wire shows the Kondo effect. For the resistivity of dilute magnetic alloys, the lowest-order calculation in the second Born approximation yields a term linear in $\log T$. When the Kondo temperature $T_K$ is compared to the experimental temperatures, the purely logarithmic dependence is slightly modified. Considering the nature of the spin correlations over the temperature range above and below $T_K$, Hamann derived a specific functional form for the Kondo contribution to $\rho(T)$:

$$\Delta \rho(T) \sim \frac{1}{2} \rho_0 \left(1 \pm \frac{S(S + 1)\pi^2}{\ln(T/T_K)^2}\right).$$

where the positive sign is for $T < T_K$, the negative sign is for $T > T_K$, and $\rho_0 = 4\pi e^2/ze^2k_F$ with $c$ being the concentration, $z$ the number of conduction electrons per atom, and $k_F$ the Fermi wave vector. And, $S$ is the effective spin of the magnetic impurity in a host metal. The Hamann expression in Eq. (1) readily explains the parabolic dependence of $\rho(T)$ for $T \ll T_K$. By fitting to Eq. (1), one can determine $T_K$ of a dilute magnetic alloy. The solid line in Fig. 2 represents a fit to the Hamann function with $S = 0.12$ and $T_K = 0.99$ K. The magnitude of $T_K$ is comparable to the known values from the previous studies on the dilute-magnetic-impurity system of AuFe.

The resistivity for samples A and B also increases as $T$ is lowered below $\sim 7.0$ K, yielding a similar feature of resistivity minimum as in the control AuFe wire. The temperature dependence of $\rho(T)$ ensures the presence of the Kondo effect in samples A and B. In addition, however, a sharp drop of $\rho(T)$ occurs for both samples as $T$ is lowered below $T_c$ of the Al film, which is approximately 1.6 K in this experiment. For sample A, an anomalous peak is observed at temperatures above $T_c$. Similar resistance anomalies have been reported near the superconducting transition of mesoscopic Al samples.

Explanations in terms of nonequilibrium charge imbalance around phase-slip centers and pinching of the conducting path near the nodes of the voltage leads.
FIG. 3: The normalized resistance $R/R_N$ for samples $A$ (solid line) and $B$ (dashed line) as a function of temperature. $R_N = 11.5 \, \Omega$ and $R_N = 8.7 \, \Omega$ for sample $A$ and $B$, respectively. The anomalous peak in the resistance of sample $A$ still exists above $T_c$, but it is not clearly seen in the scale of this figure.

were proposed. In sample $B$ the current path does not include the Al wire explicitly, so the resistance anomaly is not observed.

Since Giroud et al. reported an anomalous temperature dependence in the resistivity of mesoscopic Co/Al hybrid structures [17], existence of superconducting proximity effect in magnetic systems has been a subject of continuing experimental and theoretical interest [18, 19].

For a dilute-magnetic-impurity system, the superconducting pair correlations are likely to penetrate into a normal metal even longer than for a weak ferromagnetic metal. The proximity effect, which is sensitive to $T$, would cause a continuous change of resistance at temperatures below $T_c$. Such a temperature dependence of the resistance has been found for both samples $A$ and $B$, as shown in Fig. 3. The normalized resistance in zero magnetic field begins to decrease rapidly as $T$ is lowered below $T_c$ of the Al film. Since a part of the AuFe wire in sample $A$ is shorted by the superconducting Al arm, a resistance drop of sample $A$ is larger than that of sample $B$. Following a slow initial decrease, the resistance of sample $B$ decreases rapidly below $T \sim 1.1 \, K$, which may be associated with Josephson coupling between two separate Al contacts in sample $B$.

Since an injected electron below the superconducting gap energy is Andreev-reflected with phase memory of the superconducting condensate, the resistance of a normal metal wire between two normal metal/superconductor (N/S) interfaces can be modulated by the macroscopic phase of the superconducting condensate. An easy way to manipulate the phase is achieved by applying a magnetic field through the loop geometry. However, a prerequisite for the resistance modulation is phase coherence in the normal metal between the two N/S interfaces. Therefore, the magnetoresistance oscillations in the AuFe/Al hybrid loops provide direct evidence of phase coherent transport in the Kondo AuFe wire. The strong Aharonov-Bohm effect shown in Fig. 4(a) in the magnetoresistance of the hybrid loop (sample $A$) presents such evidence. The oscillation period of $\Delta B \approx 25.4 \, G$ corresponds to the superconducting flux quantum, $\Phi_0 (= h/2e)$, divided by the loop area, which is equal to the area enclosed by the center of the hybrid loop ($\approx 0.80 \pm 0.01 \mu m^2$).

Figure 4(b) shows the amplitude of the magnetoresistance oscillations for sample $A$. The amplitude was deter-
minded by the difference between $R (B=12.7 \text{ G})$ and $R(0)$. The amplitude shows a reentrant behavior with a maximum at $T_m \sim 870 \text{ mK}$. The temperature dependence above $T_m$ is related to the superconducting proximity effect, which becomes stronger as $T$ is lowered. However, the temperature dependence of $\Delta R_{osc}$ qualitatively different from the data previously reported for the loops consisting of nonmagnetic metal films and superconducting films. In the previous reports the oscillation amplitudes were seen to decay as either a power law or an exponential form in temperature. The peculiar temperature dependence above $T_m$ in Fig. 4(b) is likely due to the superconducting proximity effect in the presence of spin-flip scattering of the conduction electrons on the magnetic impurities.

At lower temperatures the $s-d$ exchange coupling between a conduction electron spin and a localized impurity spin makes the spin-flip scattering even more enhanced, leading to the so-called Kondo effect. As the spin-flip scattering increases, electron phase coherence becomes weaker. Consequently the amplitude of the magnetoresistance oscillations decreases as the temperature is further lowered. Assuming that the scattering rate in a dilute magnetic system is decomposed into a term for spin-flip scattering and another for all other processes, one obtains a rough description for the temperature dependence of the amplitude below $T_m$ in Fig. 4(b). The scattering rate is given by $\tau_b^{-1} + b \log(T/T_K)$, where $\tau_0$ represents the effective scattering time originating from all other processes except for the spin-flip scattering, and $b$ is a negative constant. Considering spin-flip scattering dominates the low-temperature decoherence, $\tau_0$ is assumed to be independent of temperature in our rough estimate. As the scattering rate increases, phase coherence of the conduction electron becomes weaker. The amplitude of the magnetoresistance oscillations, $\Delta R_{osc}$, is expected to be inversely proportional to the scattering rate: $\Delta R_{osc} \propto (a + b \log(T/T_K))^{-1}$. The solid line in Fig. 4(b) represents a fit to the above relation with $a = 0.57$ and $b = -3.21$, keeping $T_K = 0.99 \text{ K}$ for the AuFe wires in this experiment. The fit describes $\Delta R_{osc}(T)$ reasonably well in the temperature range below $T_m$.

Mesoscopic length scales which play an important role in this experiment are the thermal length, $L_T$, and the phase coherence length, $L_\phi$. $L_T$ of the AuFe wires is estimated to be $\sim 0.47/\sqrt{T_K} \mu\text{m}$. Characterized by $L_T$, the range of the superconducting proximity effect already extends over the entire AuFe arm ($\sim 0.5 \mu\text{m long}$) of the hybrid loop when the temperature reaches $T_c$ of the Al film. However, the superconducting proximity effect is also bound by the phase coherence length, $L_\phi$, which is affected by the spin-flip scattering on the magnetic impurities. The Aharonov-Bohm effect in the magnetoresistance is disturbed as $L_\phi$ becomes shorter than the length of the normal arm of a hybrid loop. Although a specific estimate of $L_\phi$ is not available in the present work, the existence of magnetoresistance oscillations indicates that $L_\phi$ in the Kondo AuFe wire below $T_c$ is longer than the separation between the two N/S interfaces in sample A. This is consistent with the previous estimate by Schopfer et al. of the phase coherence time in quasi-one-dimensional AuFe wires. In future studies on AuFe films with various Fe concentrations in close proximity to a superconductor, we expect to elucidate the characteristic interplay between $L_T$ and $L_\phi$ in the superconducting proximity effect.

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