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Novel phase modulation of magnetoresistance oscillations in Kondo/superconducting hybrid loops

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Low temperature transport measurements have been performed for Kondo AuFe/superconducting hybrid loops. For both 26-ppm-AuFe/Al loop and 70-ppm-AuFe/Al loop, magnetoresistance shows Aharonov-Bohm type oscillation with a period corresponding to the superconducting flux quantum. The phase of the oscillations can be modulated by applying dc bias current through the samples. However, phase shift by the dc current is so effective that only 26-μA-current can induce 2π change.

1 Introduction Hybrid structures composed of a magnetic metal and a superconductor have attracted great attention for their importance in technical applications as well as their rich fundamental physics [1–3]. Thanks to recent progress in micro- and nano-fabrication techniques, the interface between a magnetic metal film and a superconducting film can be specifically controlled to achieve high transparency. In an interface with very high transparency (high conductance), the superconducting pair correlations can penetrate into a normal metal and give rise to the proximity effect. However, for a magnetic metallic film in contact with superconductor, the existence of the superconducting proximity effect is still in debate [4, 5].

To elucidate this problem we have fabricated a mesoscopic hybrid loop consisting of a dilute magnetic AuFe wire and a superconducting Al wire, and have studied magnetoresistance under *dc* bias current through the sample. In measurements of the resistance of the AuFe wire, we have observed logarithmic temperature dependence, which is a sign of the Kondo effect. Remarkably we have observed the Aharonov–Bohm type magnetoresistance oscillations which arise from phase coherent transport in the AuFe Kondo wire/Al hybrid loop. More interestingly, we have found that the phase of the magnetoresistance oscillation is sensitive to the dc current which is applied between two-terminals of the hybrid loop. As the dc current is increased, the change of the phase of the magnetoresistance oscillations initially increases. However, the change of the phase is larger by a factor of ~300 than the expected amount estimated from a simple picture of the current-induced magnetic flux through the hybrid loop. When the *dc* current is increased above a certain critical value, the change of the phase starts to decrease with dc current.

2 Sample fabrication and measurement The samples were patterned by using the multilevel electron-beam lithography and lift-off process. A 500-Å-thick film was deposited by thermal evaporation of 99.999%-pure Au slugs in the first lithography step. After lift-off, 120-nm-wide and 4.7-μm-long pure Au wires were obtained. In the subsequent process, the pure Au wires were implanted with Fe ions to concentrations of 26 ppm and 70 ppm [6]. In the second lithography step, a 1200-Å-thick Al film was

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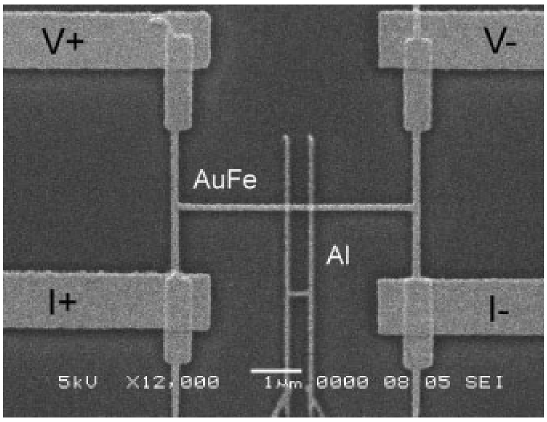

Fig. 1 Scanning electron micrograph of the AuFe/Al hybrid loop. An Al wire of "H" shape is in contact with a AuFe wire, making a hybrid loop at center. The length of the AuFe wire is 4.7 μm, and the dimension of the loop is $0.5 \times 1.6\ \mu m^2$.

deposited to make hybrid loop in the middle of the AuFe wires. The Al film was deposited after an in-situ Ar milling to make an electrically-high transparent interface. The resistance multiplied by the interface area (RA) is $6.7 \times 10^{-3}\ \Omega\ \mu m^2$ at temperature of 1 K. Figure 1 shows the scanning electron micrograph of a representative 26-ppm-AuFe/Al hybrid loop measured in this experiment. We have also fabricated a 70-ppm-AuFe/Al hybrid loop of the same structure by using the same lithography steps, and measured for comparison.

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 are described in Fig. 1. The probing ac signal was 1 μA at 79.7 Hz, and an additional dc bias current was applied between *I*+ and *I*– leads. The voltage was measured between *V*+ and *V*– as a function of magnetic field which was applied in the perpendicular direction to the sample plane. The resistivity of the 26-ppm-AuFe/Al loop at 4.2 K was 1.4 μΩ cm, and Thouless length of the 26-ppm-AuFe wire, $L_T = (hD/2\pi k_B T)^{1/2}$, was ~0.47 μm at $T = 1.0$ K. Here, D is the diffusion constant of the 26-ppm-AuFe wire. The Al wire shows a transition to the superconducting state below $T = 1.6$ K.

3 Experimental results and discussion Figure 2 shows magnetoresistance of the 26-ppm-AuFe/Al loop under various positive dc bias currents at $T = 98$ mK. The period of the oscillation is 25.4 G, which corresponds to the superconducting flux quantum, Φ_0 (= h/2e = 20.7×10^{-16} Wb), divided by the loop area. The amplitude of magnetoresistance oscillations at zero dc bias is ~0.018 Ω. This small amplitude

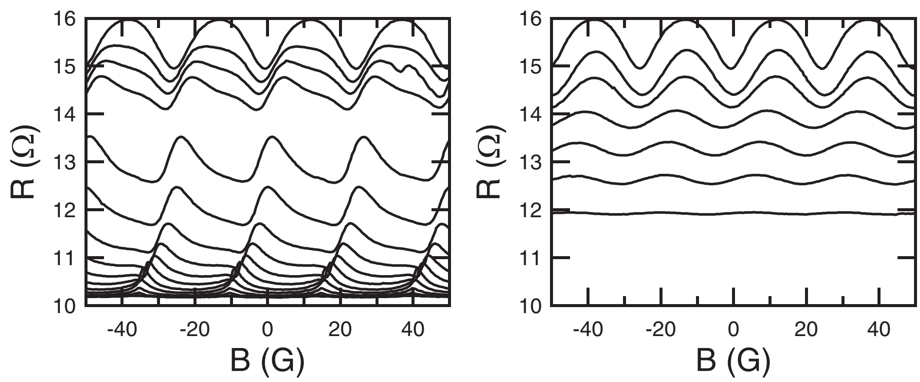

Fig. 2 Magnetoresistance of the 26-ppm-AuFe/Al loop at various positive bias currents, I_{dc} = 0, 2, 4, 6, 8, 10, 12.5, 15, 17.5, 20, 22.5, 24, 25, 25.25, 25.5, 26 μA from bottom to top. The right figure shows magnetoresistance of the AuFe/Al loop at I_{dc} = 26, 27.5, 28, 29, 30, 31, 33 μA from top to bottom. The measurements were performed at $T = 98$ mK.

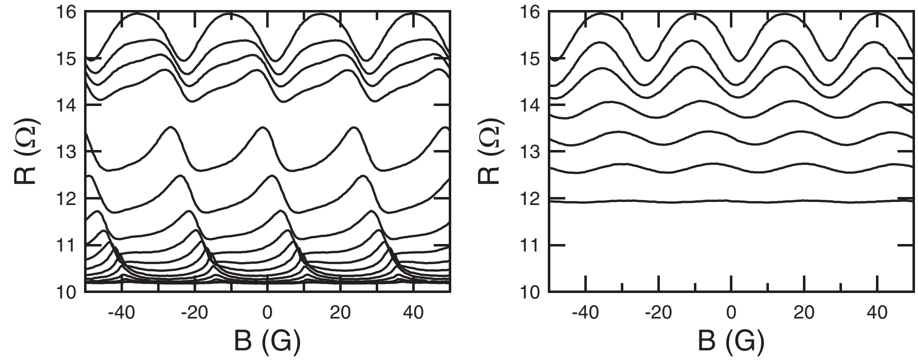

Fig. 3 Left figure shows magnetoresistance of the 26-ppm-AuFe/Al loop at various negative bias currents, I_{dc} = 0, –2, –4, –6, –8, –10, –12.5, –15, –17.5, –20, –22.5, –24, –25, –25.25, –25.5, –26 μA from bottom to top. The right figure shows magnetoresistance of the AuFe/Al loop at I_{dc} = –26, –27.5, –28, –29, –30, –31, –33 μA from top to bottom. The measurements were performed at T = 98 mK.

grows as dc bias current (I_{dc}) between I+ and I– is increased to 26 μA, and then decreases as the dc bias current is further increased. Above I_{dc} = 31 μA the Al wire was driven to a normal state, and hence the magnetoresistance oscillations disappeared completely. The phase of magnetoresistance oscillations shifts to the positive direction in the magnetic field axis.

Figure 3 shows magnetoresistance of the 26-ppm-AuFe/Al loop under various negative dc bias currents at T = 98 mK. Very similar results as in Fig. 2 were obtained. However, the phase shift occurred in the negative direction and the shape of the oscillations was symmetrically flipped with respect to the zero-magnetic-field-axis. We have also observed a similar behaviour in the magnetoresistance oscillations of a 70-ppm-AuFe/Al loop.

Figure 4(a) shows phase shift, $\Delta\phi/2\pi$, of magnetoresistance oscillations as a function of dc bias current. $\Delta\phi/2\pi$ is obtained by dividing the difference between peak positions of the oscillations by the period of the oscillations, 25.4 G. The phase shift is symmetric on the direction of I_{dc} with respect to $\Delta\phi = 0$. To our surprise, the phase shift shows non-monotonic dependence on I_{dc}. For the 26-ppm-AuFe/Al loop, the maximum $\Delta\phi$ reaches almost 2π around 26 μA, and then $\Delta\phi$ decreases as I_{dc} is further increased. For the 70-ppm-AuFe/Al loop, maximum $\Delta\phi$ reaches almost 1.6π around 25 μA. Figure 4(b) shows magnitude of relative magnetoresistance oscillations as a function of dc bias current. For both samples, the magnitudes increase up to the bias current at which the maximum phase shift occurs.

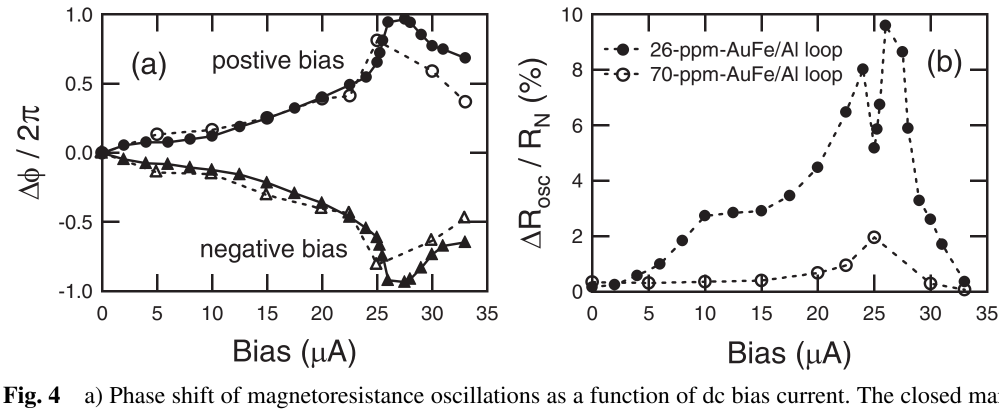

Fig. 4 a) Phase shift of magnetoresistance oscillations as a function of dc bias current. The closed marks represent phase shift for the 26-ppm-AuFe/Al loop, and the open marks represent phase shift for the 70-ppm-AuFe/Al loop. (b) Magnitude of relative magnetoresistance oscillations as a function of dc bias current. The normal state resistance, R_N, is 10.2 Ω for the 26-ppm-AuFe/Al loop, and 4.6 Ω for the 70-ppm-AuFe/Al loop. The measurements were performed at T = 98 mK for the the 26-ppm-AuFe/Al loop, and at T = 811 mK for the the 70-ppm-AuFe/Al loop.

Since the magnetic field induced by the dc current is added to the applied magnetic field, the phase shift of magnetoresistance oscillations should depend on I_{dc}. Amount of an expected $\Delta\phi/2\pi$ can be estimated by calculating the magnetic flux induced by I_{dc}. The induced magnetic flux is given by LI_{dc}, where L is the self inductance of the loop. L is easily calculated for a rectangular shape of loop, and $L \approx 1.54 \times 10^{-12}$ H for our loops [7]. The magnetic flux (Φ_{ind}) induced by 26 μA is ~40.04×10^{-18} Wb. Consequently the expected $\Delta\phi/2\pi$, which is given by Φ_{inc}/Φ_0, is 0.0064π. The estimation is about 300 factors smaller than the measurement. The explanation for this discrepancy is beyond the scope of this paper, but superconducting fluctuation in the dilute magnetic systems may be associated with the enhanced phase shift in the magnetoresistance oscillations.

4 Conclusion In conclusion, we report our study on the phase-coherent transport in Kondo/superconducting hybrid loops. We have observed magnetoresistance oscillations and novel phase modulation by dc bias current. As the dc current is increased from 0, the phase shift in the magnetoresistance oscillations occurs. However, the phase shift is enhanced by a factor of 300 than the expected amount estimated within the simple framework of a current-induced magnetic flux through the hybrid loop. The phase shift does not monotonically depend on the dc bias current. When the applied dc current is above a certain critical value, the amount of the phase shift starts to decrease with dc current. The magnitude of the magnetoresistance oscillation also shows a non-monotonic dependence on dc bias current. The magnitude initially increases as dc bias current is increased, and starts to decrease when dc bias current is above the same critical current value. Although the observations are not fully understood yet, superconducting fluctuation effect may give rise to these novel phenomena in the dilute magnetic impurity systems.

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References

[1] M. Giroud, H. Courtois, K. Hasselbach, D. Mailly, and B. Pannetier, Phys. Rev. B **58**, R11872 (1998).
[2] T. Kontos, M. Aprili, J. Lesueur, and X. Grison, Phys. Rev. Lett. **86**, 304 (2001).
[3] V. V. Ryzanov, V. A. Oboznov, A. Yu. Rusanov, A. V. Veretennikov, A. A. Golubov, and J. Aarts, Phys. Rev. Lett. **86**, 2427 (2001).
[4] W. Belzig, A. Brataas, Y. V. Nazarov, and G. E. W. Bauer, Phys. Rev. B **62**, 9726 (2000).
[5] J. Aumentado and V. Chandrasekhar, Phys. Rev. B **64**, 54505 (2001).
[6] The samples were implanted at a dose of 1.3×10^{13} ions/cm^2 and energy of 80 keV for 26-ppm-Fe concentration, and at a dose of 5.0×10^{13} ions/cm^2 and energy of 100 keV for 70-ppm-Fe concentration. The Fe concentration is estimated by a slope of Kondo resistance (~0.11 nΩ cm/ppm decade K) for the AuFe data taken from J. Loram, P. J. Ford, and T. E. Whall, shown in: A. J. Heeger, Solid State Physics, edited by H. Ehrenreich, F. Seitz, and D. Turnbull (Academic Press, New York, 1969), Vol. **23**, p. 283.
[7] The low-frequency single turn rectangular loop made of rectangular wire can be calculated by using a program in http://www.qsl.net/in3otd/ind2calc.html.