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Superconducting proximity effect on a magnetic domain wall

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Abstract

It was theoretically expected that the singlet Cooper pair is converted into the triplet one by the inhomogeneous exchange interaction. To demonstrate this transition, we investigate the electrical transport properties of a Ni-Fe nanowire with a vortex-type magnetic domain wall under the supercurrent injection from the Nb electrode. The electrical resistance of the Ni-Fe wire with the domain wall is found to show a greater reduction than that expected from the anisotropic magneto-resistance. This additional reduction increases with decreasing the temperature. These results imply that the triplet state was formed by the Cooper-pair propagation in the domain wall.

1. Introduction

A spin-triplet superconductivity is an exciting subject because the triplet Cooper pair carries the spin current together with the charge current under the dissipationless condition, which open a new avenue for developing ultra-low-consumption spintronic devices. However, the triplet Cooper pair can be stabilized only in special superconducting materials such as Sr_2RuO_4 and UPt_3[1]. Therefore, it was believed to be difficult to use the triplet state in the practical application. Recent theoretical studies indicate that the triplet Cooper pair can be formed also in ferromagnet/superconductor hybrid structures by using the inhomogeneous exchange interaction (Fig. 1). To realize such a situation experimentally, uses of the vortex-like magnetic domain wall and misaligned magnetized layers were proposed[2, 3]. To observe such a transition, we investigated the transport properties of the supercurrent through the magnetic domain wall by using a laterally-configured Nb/Ni-Fe multi-terminal hybrid structure.

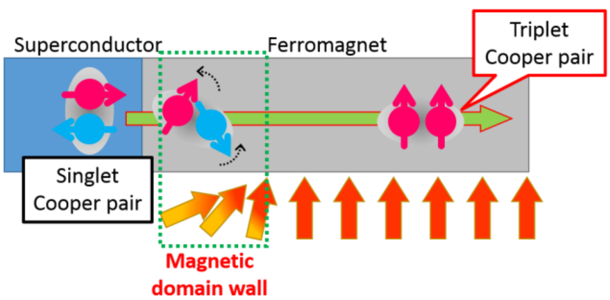

Fig. 1 Conversion of Cooper pair from singlet state to triplet state through magnetic domain wall.

2. Method

Figure 2(a) shows a SEM image of the fabricated superconducting device consisting of a Nb injector and a Ni-Fe wire. First, we have fabricated a Ni-Fe nanowire with notches on a SiO_2/Si substrate by a standard lift-off technique with e-beam lithography. Here, the 20-nm-thick Ni-Fe film is deposited by e-gun evaporation under the base pressure of 10^{-5} Pa. We then fabricated the Nb wire across the Ni-Fe wire. Here, the 60-nm-thick Nb film is deposited by a magnetron sputtering. The superconducting transition temperature T_C of the fabricated Nb wire is as high as 7.2 K, assuring the good quality of the Nb.

To investigate the transport properties of the supercurrent through the magnetic domain wall, the geometry and the dimension of the Ni-Fe wire was determined from the micromagnetic simulation using OOMMF[4]. The right hand side of the Ni-Fe wire is connected to a large pad in order to control the nucleation position of the domain wall. The injected domain wall is trapped at the notches with forming a vortex structure, as shown in Fig. 2(b). The superconducting Nb wire is deposited on the Ni-Fe wire after the cleaning of the Ni-Fe surface using the low-voltage Ar-ion milling. By fabricating the Nb/Ni-Fe junction on the notches, we can investigate the supercurrent transport through the vortex-type domain wall.

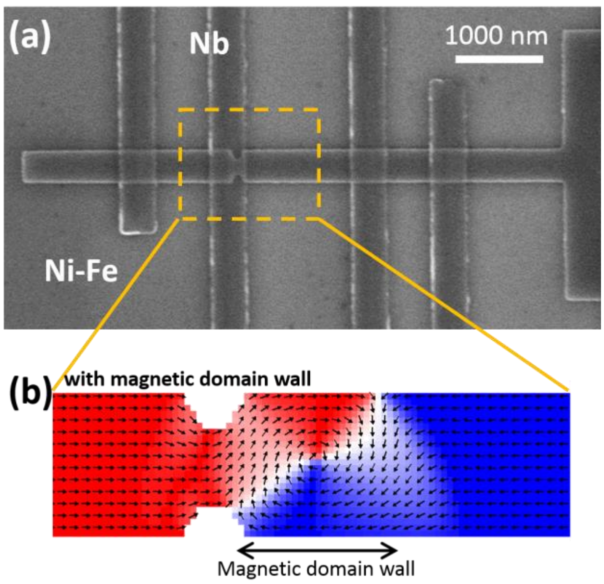

Fig. 2 (a) SEM image of the fabricated sample and (b) result of the micromagnetic simulation of a Ni-Fe wire.

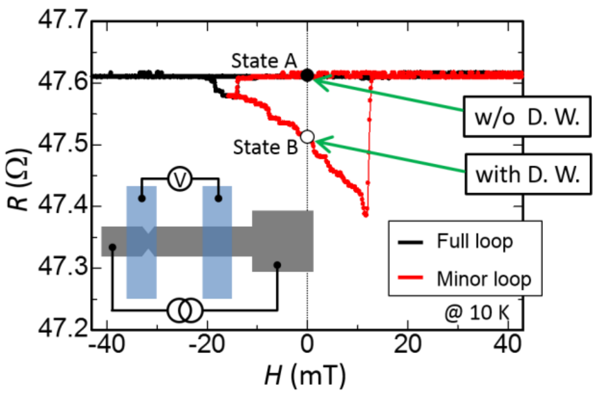

Fig. 3 Magnetic field dependence of resistance of Ni-Fe. The difference of the resistance between state A and state B is due to the anisotropic magneto-resistance. The inset shows the probe configuration for the measurement.

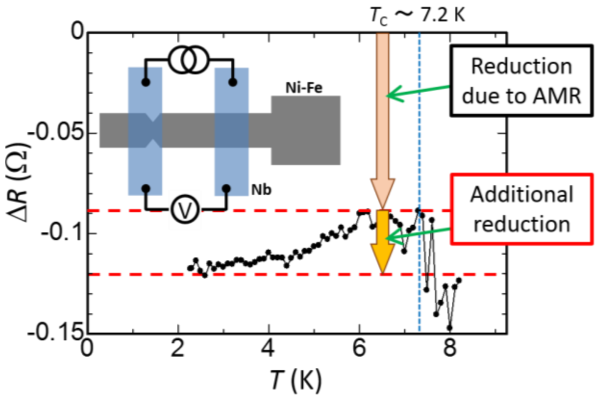

Fig. 4 Temperature dependence of the difference of the Ni-Fe resistance between with and without the magnetic domain wall. The inset shows the probe configuration for the measurement.

3. Results and Discussions

We firstly measure the magneto-resistance of the Ni-Fe wire under the longitudinal magnetic field with the probe configuration shown in the inset of Fig. 3. Since the current flows mainly in the Ni-Fe wire in this configuration, we can detect the domain wall trapped at the notches from the resistance change due to the anisotropic magneto-resistance (AMR). As can be seen in Fig. 3, we see a clear negative resistance jump at H = -13.8 mT. Here, we performed the minor sweep, in which the sweep direction was reversed just after the nucleation of the domain wall, in addition to the conventional full field sweep. From the minor loop, we confirmed that the trapped domain wall can be stabilized in the absence of the magnetic field.

We then perform the supercurrent injection by changing the probe configuration as shown in the inset of Fig. 4. Here, we focus on the resistance difference ΔR at zero magnetic field as a function of the temperature. Here, ΔR is defined by the resistance at the remanent state for the full sweep and that for the minor sweep, indicating the resistance change due to the domain wall. The main contribution of ΔR is caused by the AMR effect of the domain wall. ΔR is found to increase with decreasing the temperature. According to the result of our reference sample consisting of a Cu/Ni-Fe junction, the resistance change due to the AMR does not show any temperature dependence in this temperature range. Therefore, we should consider the additional contribution for the negative resistance. If we assume that this additional negative resistance is caused by the conversion of the singlet Cooper pair into the triplet one through the magnetic domain wall, we can estimate 0.3-percent Cooper pair is converted with the coherence length even in the Ni-Fe wire which have a higher exchange energy than that of a very weak ferromagnet such as Ho[5] and PdNi, CuNi[6].

5. Conclusion

We have fabricated the multi-terminal lateral structure consisting of Ni-Fe and Nb crossed junction. The singlet Cooper pair is injected into the domain wall trapped in the ferromagnet wire and we measure the electrical resistance of the domain wall under the supercurrent injection. From the temperature dependence of the resistance, we observe unconventional negative resistance which cannot be understood by a simple AMR behavior due to the domain wall. In order to understand the observed additional negative resistance, we consider the possibility for the formation of the triplet Cooper pair through the inhomogeneous exchange interaction due to the domain wall.

References

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