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Transport Properties of Ferromagnetic Semiconductors with Superconducting Electrodes

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Abstract. We report on the transport properties of ferromagnetic p-$In_{0.96}Mn_{0.04}As$ with Nb superconducting electrodes. We observed conductance reduction within the superconducting gap. This behavior can be qualitatively understood by considering the suppression of Andreev reflection caused by spin polarization in p-$In_{0.96}Mn_{0.04}As$

Keywords: superconductor, ferromagnetic semiconductor, Andreev reflection
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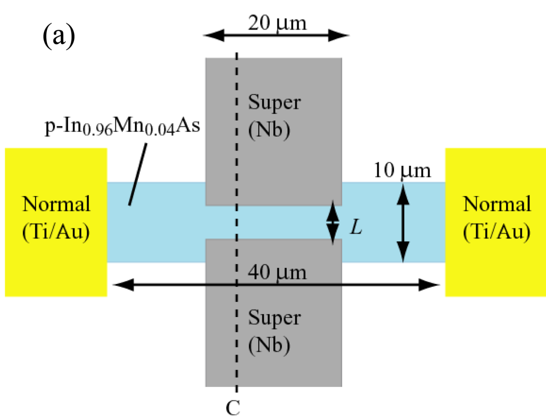
INTRODUCTION

Superconductor/ferromagnet (S/F) junctions have attracted considerable interest both theoretically and experimentally [1]. This is because new quantum phenomena can be expected from the interplay between the superconductivity and the spin polarization of the ferromagnet. Ferromagnetic metals such as Ni-Fe and Co have already been used as ferromagnetic materials. However, such ferromagnetic metals have a large number of carriers contributing to the transport and it is difficult to control this number with the electric field effect. In contrast, since p-$In_{0.96}Mn_{0.04}As$ is a kind of ferromagnetic semiconductor [2], it is reasonable to suppose that the number of carriers in p-$In_{0.96}Mn_{0.04}As$ can be changed by using the electric field effect. In this paper, we report on the transport properties of ferromagnetic p-$In_{0.96}Mn_{0.04}As$ with Nb superconducting electrodes.

EXPERIMENT AND DISCUSSION

We fabricated Nb/p-$In_{0.96}Mn_{0.04}As$/Nb junctions with Hall voltage probes as shown in Fig. 1. The p-$In_{0.96}Mn_{0.04}As$ heterostructure was grown by using molecular beam epitaxy (MBE) on a semi-insulating (100) GaAs substrate. The critical temperature T_C of the Nb electrodes was about 8.2 K. The coupling length L between the two Nb electrodes was designed to be 0.8 ~ 10 μm. The superconducting Nb electrodes as well as the normal Ti/Au ones were deposited on p-$In_{0.96}Mn_{0.04}As$ just after cleaning the InMnAs surface. Figure 2 shows the magnetic field dependence of the Hall resistance for p-$In_{0.96}Mn_{0.04}As$ as a function of



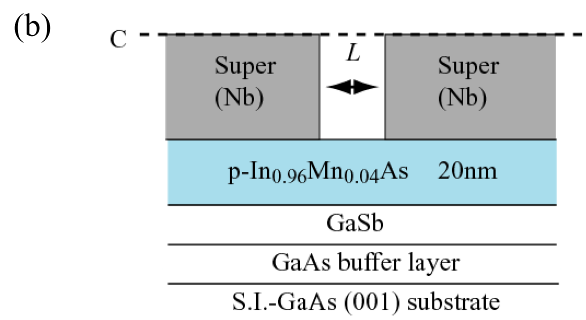


FIGURE 1. Schematic diagram of a superconductor-ferromagnet junction: (a) top view, (b) cross-sectional view.

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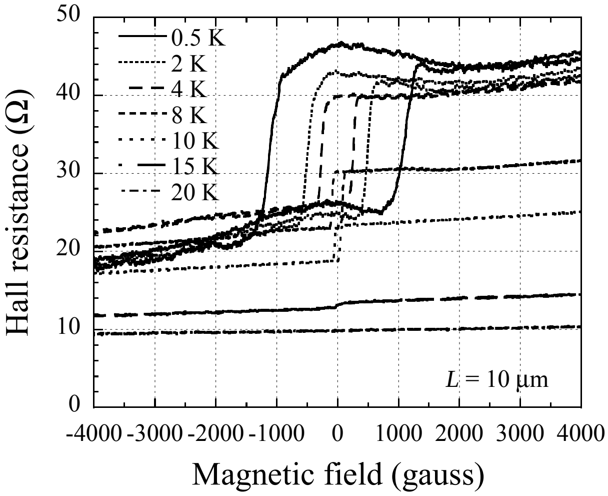

FIGURE 2. Hall resistance curve of p-$In_{0.96}Mn_{0.04}As$ as a function of temperature.

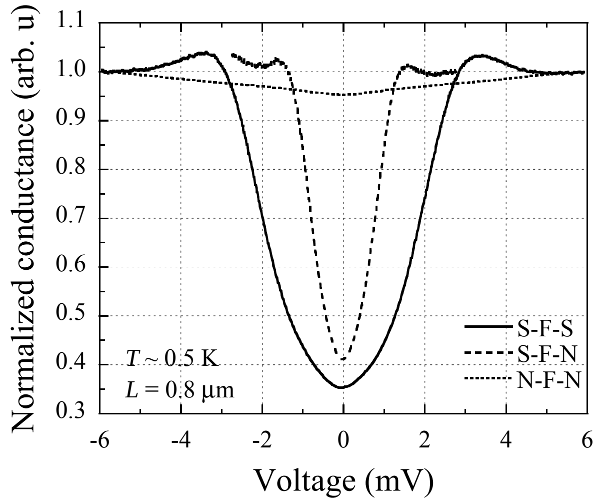

FIGURE 3. Normalized differential conductance as a function of bias voltage for three different measurement setups at 0.5 K.

temperature. We observed the anomalous Hall effect below about 15 K. At 0.5 K, the reverse magnetic field was about 1000 gauss. This result indicates that p-$In_{0.96}Mn_{0.04}As$ becomes ferromagnetic below the T_C of the Nb electrodes (~ 8.2 K). Figure 3 shows normalized differential conductance as a function of bias voltage for three different measurement setups at 0.5 K. The differential conductance of each junction is normalized by the value at the maximum bias voltage. We have obtained nearly linear voltage dependence in the N-F-N junction. This result indicates that we have obtained the ohmic contact without any process after deposition of N and S metals. Thus, we can claim that there is almost no barrier at the interface between metals and p-$In_{0.96}Mn_{0.04}As$. In contrast, we obtained a large conductance reduction within $|V| \leq 1.5$ mV in the S-F-N junction and within $|V| \leq 3$ mV in the S-F-S junction. When we take the Nb superconducting energy gap Δ_S of ~ 1.5 meV into consideration, we can assume that this conductance reduction appears within the superconducting gap.

Next, we will discuss the origin of the conductance reduction. R. J. Soulen Jr. et al. have measured the differential conductance via a superconducting Nb point contact on ferromagnetic CrO_2 [3]. In this case, the differential conductance decreased below the superconducting energy gap of Nb. This behavior is similar to our results and its origin is as follows. In the Andreev reflection process, the incident electron requires the opposite spin electron to be removed from the normal region for conversion to a Cooper pair. Therefore, when there is no opposite spin electron, the conversion to a Cooper pair does not occur. Namely, with S-F junctions, the Andreev reflection is limited by the minority spin population. Therefore, our experimental results can be understood qualitatively by considering the suppression of the Andreev reflection that is caused by the spin polarization in p-$In_{0.96}Mn_{0.04}As$.

CONCLUSIONS

We have investigated the transport properties in Nb/ p-$In_{0.96}Mn_{0.04}As$/Nb junctions. We observed the anomalous Hall effect below ~15 K. The reverse magnetic field was ~ 1000 gauss at 0.5 K. We observed conductance reduction within the superconducting gap. These experimental results arise from the interplay between superconductivity and spin polarization.

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