Evaluation of spin polarization in $p$-In$_{0.96}$Mn$_{0.04}$As using Andreev reflection spectroscopy

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Abstract. We report on the transport behavior and spin polarization $P$ of carriers for superconductor/ferromagnetic semiconductor (S-F) junctions. We fabricated Nb/ferromagnetic semiconductor $p$-In$_{0.96}$Mn$_{0.04}$As junctions with Hall voltage probes. Below $\sim$15 K, $p$-In$_{0.96}$Mn$_{0.04}$As becomes ferromagnetic and then the anomalous Hall effect is observed. Below the $T_C$ of the Nb electrodes (~8.2 K), we observed a conductance reduction within the Nb superconducting energy gap voltage owing to the suppression of Andreev reflection by spin polarization in $p$-In$_{0.96}$Mn$_{0.04}$As. We evaluated the degree of spin polarization in $p$-In$_{0.96}$Mn$_{0.04}$As experimentally by comparing the measured differential conductance with that obtained with Strijkers’ model extended for spin-polarized Andreev reflection including the inverse proximity effect. Consequently, the $P$ value extracted experimentally for $p$-In$_{0.96}$Mn$_{0.04}$As at 0.5 K was 0.795 assuming $Z = 0$.

1. 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. For instance, this competition allows us to determine experimentally the spin polarization $P$ of carriers in a ferromagnet using Andreev reflection spectroscopy [2-4]. The underlying principle is that the Andreev reflection process is sensitive to the spin of carriers and then the spin polarization leads to the suppression of the Andreev reflection probability. Strijkers et al. [5] have proposed an extension of the Blonder-Tinkham-Klapwijk (BTK) theory [6] for conventional Andreev reflection including spin polarization. Previous studies have estimated the $P$ value in a ferromagnet quantitatively from a fit of the conductance spectrum obtained by using Strijkers’ model. In contrast, it transpires that in an S-F junction, the pair potential $\Delta$ in the superconductor is weakened as a result of the penetration of the
Figure 1. Schematic diagram of a Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As junction: (a) top view, (b) cross-sectional view.

exchange field into the ferromagnet, where it is called the inverse proximity effect [7]. To estimate the $P$ value in the ferromagnet more accurately using Andreev reflection spectroscopy, we must also consider the inverse proximity effect in the S-F junction.

In this paper, we report our estimation of the $P$ values in ferromagnetic semiconductor p-In\textsubscript{0.96}Mn\textsubscript{0.04}As using Andreev reflection spectroscopy in Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As S-F junctions. We evaluated the $P$ values experimentally by comparing the measured differential conductance with that obtained with the extended Strijkers' model, which includes the inverse proximity effect.

2. Experiment and discussion

We fabricated Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As/Nb junctions with Hall voltage probes as shown in figure 1. The p-In\textsubscript{0.96}Mn\textsubscript{0.04}As heterostructure was grown by using molecular beam epitaxy (MBE) on a semi-insulating (001) 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. Both the superconducting Nb electrodes and the normal Ti/Au electrode were simply deposited on p-In\textsubscript{0.96}Mn\textsubscript{0.04}As. We used no additional post-deposition procedure to achieve ohmic contact. We observed the anomalous Hall effect below about 15 K (not shown). At 0.5 K, the reverse magnetic field was about 1000 gauss. This result indicates that p-In\textsubscript{0.96}Mn\textsubscript{0.04}As becomes ferromagnetic below ~ 15 K. Therefore, the Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As junction can be considered an S-F junction below the $T_C$ of the Nb electrodes (8.2 K). Figure 2 shows the normalized $dI/dV - V$ characteristics of a Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As junction as a function of temperature. The $dI/dV - V$ characteristics exhibited almost no voltage dependence above the $T_C$ of Nb. This result indicates that we have obtained ohmic contact without the need for any post-deposition process. In contrast, we obtained a conductance reduction of ~ 1.5 mV below the $T_C$ of Nb. The conductance reduction gradually increased as the temperature decreased. When we take the typical Nb superconducting energy gap of ~ 1.5 meV into consideration, we can assume that this conductance reduction appears within the superconducting gap. Moreover, there are almost no conductance peaks near ~ ±1.5 mV. These features suggest that the Nb/p-In\textsubscript{0.96}Mn\textsubscript{0.04}As junction has a high transparent metallic contact with a $Z$ value close to zero, and that the $P$ value in p-In\textsubscript{0.96}Mn\textsubscript{0.04}As must be sufficiently high. Our results are similar to those reported in previous studies [2, 3], and the reason 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, no conversion occurs. 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 caused by the spin polarization in $p$-$\text{In}_{0.96}\text{Mn}_{0.04}\text{As}$.

Next, we discuss the estimation of the spin polarization in $p$-$\text{In}_{0.96}\text{Mn}_{0.04}\text{As}$. We have quantitatively evaluated the degree of spin polarization in $p$-$\text{In}_{0.96}\text{Mn}_{0.04}\text{As}$ from a fit of the differential conductance obtained by using an extension of Strijkers’ model including the inverse proximity effect. To include the inverse proximity effect, we have combined Strijkers’ model with van Son’s model, which extends the BTK theory to study the effect of a gradual variation in the pair potential near an interface [8]. Here, we assume that the $\Delta$ distribution at the S-F interface is Gaussian, $\Delta$ in the ferromagnet is zero, and $\Delta$ in the superconductor is linearly increased from the S-F interface, and reaches that of bulk Nb at the BCS coherence length $\xi_s$ from the S-F interface into the superconductor as shown in figure 3. Here, $\Delta_s$ is the pair potential of bulk Nb, and $\Delta_{s0}$ is the pair potential at the S-F interface. The Andreev reflection probabilities $A(E)$ and the normal reflection probabilities $B(E)$ are calculated by integrating the Bogoliubov-de Gennes equation based on van Son’s method. $A(E)$ and $B(E)$ are represented by $A(E) = |a_e|^2$ and $B(E) = |b_e|^2$, respectively. Here the coefficients $a_e$ and $b_e$ are the amplitudes of the Andreev-reflected wave and the ordinary reflected wave, respectively, for an incident electron wave with amplitude 1. These coefficients are given by:

$$a_e = \frac{u(0)v(0)}{(1 + Z^2)u(0)^2 - Z^2v(0)^2}$$

$$b_e = \frac{iZ(1-iZ)(v(0)^2 - u(0)^2)}{(1 + Z^2)u(0)^2 - Z^2v(0)^2}$$

where $Z$ is the barrier strength at the S-F interface, and $u(0)$ and $v(0)$ are the complex values at $x = 0$, which corresponds to the S-F interface. These $u(0)$ and $v(0)$ values are governed by the following Bogoliubov-de Gennes equation where higher-order terms are neglected.

**Figure 2.** (a) Normalized $dl/dV - V$ characteristics of a Nb/$p$-$\text{In}_{0.96}\text{Mn}_{0.04}\text{As}$ junction as a function of temperature and (b) measurement setup.
Here, $E$ is the energy from the Fermi energy and $\Delta(x)$ is the spatially varying pair potential. The total current $I$ through the S-F junction as a function of the bias voltage is given by:

$$ I = \int_{-\infty}^{\infty} \left[ f(E - V, T) - f(E, T) \right] \left[ 1 + A(E) - B(E) \right] dE $$

(3)

where $f(E)$ is the Fermi-Dirac distribution function. According to Strijkers’ model, the $I$ separates into two parts:

$$ I = (1 - P)I_u + PI_p $$

(4)

where $(1 - P) I_u$ is the fully unpolarized part of the current where Andreev reflection is allowed, and $PI_p$ is the fully polarized part of the current where $A(E)$ is zero. $I_u$ and $I_p$, respectively, are calculated by solving Eq. (2) with the above calculated $A(E)$ and $B(E)$ based on van Son’s method. The $dI/dV - V$ curve can then be calculated by differentiating Eq. (4) as a function of the applied bias voltage $V$. Both $Z$ and $P$, which are fitting parameters, must be determined so that the best fit is obtained between the calculated and measured differential conductance. In figure 4, we compare the calculated $dI/dV - V$ characteristics with experimental data obtained at 0.5 K. $dI/dV$ is normalized by the value near $V = 2$ mV. As mentioned above, it is reasonable to suppose that $Z = 0$, which corresponds to the absence of a barrier. By using both a $Z$ of 0 and a $P$ value of 0.795, the measured $dV/dI - V$ characteristics at 0.5 K can be very well fitted by using Strijkers’ model extended with the inverse proximity effect. Here, we use a $\Delta_S$ of 1.4 meV, a $\zeta_S$ of 40 nm, a mean $\mu$ of 1.4 meV and a variance $\sigma^2$ of 0.5929. In contrast, Strijkers’ original unextended model cannot provide a good fit to the experimental data. These results indicate that the inverse proximity effect plays an important role as regards the transport in a Nb/p-In$_{0.96}$Mn$_{0.04}$As junction. Here, it should be noted that a discrepancy remains between the experimental

Figure 3. (a) Schematic model of the system where the pair potential in the S region varies near the S-F interface and the pair potential vanishes in the F region. (b) Calculated probability distribution for the pair potential at the S-F interface $\Delta_S$ assuming a Gaussian distribution with a mean $\mu$ of 1.4 meV and a variance $\sigma^2$ of 0.5929.
and calculated data near \(\pm 1.5\) mV even when we use the extended Strijkers’ model. The reason for this discrepancy remains unclear. We must find a way to refine the extended Strijkers’ model.

3. Conclusions

We investigated the transport behavior and \(P\) values for Nb/\(p\)-In\(_{0.96}\)Mn\(_{0.04}\)As junctions. We observed that the subgap conductance was suppressed and that there were almost no conductance peaks near \(eV = \pm \Delta\). These experimental results indicate high transparent metallic contact between Nb and \(p\)-In\(_{0.96}\)Mn\(_{0.04}\)As with a high \(P\). The conductance reduction can be understood by considering the suppression of the Andreev reflection caused by the spin polarization in \(p\)-In\(_{0.96}\)Mn\(_{0.04}\)As. We have evaluated the \(P\) values in \(p\)-In\(_{0.96}\)Mn\(_{0.04}\)As experimentally by comparing the measured differential conductance with that obtained with Strijkers’ model extended for spin-polarized Andreev reflection including the inverse proximity effect. Consequently, the \(P\) value extracted experimentally for \(p\)-In\(_{0.96}\)Mn\(_{0.04}\)As at 0.5 K was 0.795 assuming \(Z = 0\).

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