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Spin-polarized Carrier Injection Effect in Ferromagnetic Semiconductor/Diffusive Semiconductor/Superconductor Junctions

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Abstract. We study the transport properties of a p-InMnAs/n-InAs/Nb junction where a p-InMnAs can be regarded as a spin injector. Differential conductance of the n-InAs channel is measured as a function of injection current from p-InMnAs or from Nb at 20 mK. A conductance minimum appears at zero-bias voltage with no current injection. As the injection current from p-InMnAs increases, the minimum gradually disappears. This conductance behaviour is very different from that of the injection case from Nb. We also calculate the conductance in the n-InAs channel by taking account of the exchange field in the InAs channel that is induced by InMnAs ferromagnet. The difference between the conductance behaviours on injection current direction can be explained by the inverse proximity effect that the exchange field is also induced in the superconducting electrode.

1. Introduction
The combination of ferromagnet (F) and superconductor (S) has provided interesting phenomena like π-junction [1] or crossed Andreev reflection [2, 3], etc. The former one discussed interplay between Cooper-pair and exchange field in F and the latter clearly showed how spin polarization affects Andreev reflection. S/F structures have still much room to be investigated especially when ferromagnetic semiconductor is used as F. The ferromagnetic semiconductor allows us not only gate-controllability but also high spin injection efficiency into the semiconductor due to small conductance mismatch between them, compared with ferromagnetic metals. We report on transport properties in a superconductor/semiconductor (S/Sm) junction with a ferromagnetic semiconductor electrode as a spin injector.
2. Experiments

We fabricated p-In$_{0.94}$Mn$_{0.06}$As/n-InAs/Nb junctions as shown in Fig. 1. The p-InMnAs/n-InAs heterostructure was grown by using molecular beam epitaxy (MBE) on a semi-insulating (001) GaAs substrate. First, the resist patterns for the p-InMnAs electrodes were defined, and then the useless part of the p-InMnAs was removed by chemical etching to fabricate the spin-injector electrode. Next, the resist pattern for the Nb electrode was defined. Then, the InAs oxidation layer was removed by Ar sputtering in a Nb evaporation chamber. After that Nb was deposited by electron beam deposition and the deposited Nb pattern was lifted off. Finally, two Ti/Au electrodes were deposited on n-InAs layer.

Magnetization $M$ of p-In$_{0.94}$Mn$_{0.06}$As was measured using the SQUID magnetic meter. Rapid increase of $M$ below $\sim 60$ K indicates that the Curie temperature of InMnAs is around 60 K and InMnAs electrode becomes ferromagnetic below 60 K. Therefore, when the temperature is below the $T_C$ of the Nb electrodes (\(\sim 8.8\) K), the p-InMnAs/n-InAs/Nb junction contains both a ferromagnet/semiconductor (p-InMnAs/n-InAs) interface and a superconductor/diffusive-semiconductor (Nb/n-InAs) one. When spin-polarized holes from p-InMnAs are diffusively injected into the nonmagnetic n-InAs channel, electrons in the n-InAs channel should be spin-polarized. On the other hand, the

![Figure 1: Schematic diagram of p-InMnAs/n-InAs/Nb junctions: (a) top view, (b) cross-sectional view. The distance $L$ is about 0.8 $\mu$m.](image1)

![Figure 2: The bias voltage $V$ dependence of the differential conductance of the n-InAs channel between two Ti/Au electrodes as a function of injection current (a) from Nb and (b) from p-InMnAs at 20 mK.](image2)
proximity effect from the Nb electrode affects the local conductivity at a point in the n-InAs channel from the interface. Novel phenomena of electric transport in the p-In_{0.94}Mn_{0.06}As/n-InAs/Nb junction can be expected from the interplay between spin polarization and proximity effect.

Figure 2 shows the bias voltage $V$ dependence of the differential conductance of the n-InAs channel between two Ti/Au electrodes as a function of injection current from p-In_{0.94}Mn_{0.06}As or from Nb at about 20 mK. We obtained a conductance minimum without current injection. This minimum can be explained by the exchange field in n-InAs and proximity effect. It is noted that the conductance minimum disappeared over the temperature of $T_c$ of the Nb electrode (about 8.8 K). With increasing injection current from p-InMnAs, the conductance minimum gradually disappeared (Fig. 2(b)). On the other hand, in the case of current injection from Nb, the conductance minimum split into two dips and the two dips shifted toward higher bias regime with increasing injection current, as seen in Fig. 2(a). The difference between these dependences on injection current can be explained by the inverse proximity effect in the Nb electrode discussed in the next section.

3. Theory

Proximity effect in the ferromagnet/superconductor (F/S) junction has been studied both theoretically and experimentally to understand the zero energy peak of the local density of state in the F or $\pi$-state of the Josephson junctions [1]. On the other hand, it is not fully studied that the pair potential in the S is weaken due to the penetration of the exchange field in the F. This effect is called the inverse proximity effect. For theoretical calculation, we used a model of one dimensional diffusive ferromagnet/superconductor – superconductor/diffusive ferromagnet (DF/S-S/DF) junction as shown in Fig. 3, where we assume that the diffusive semiconductor n-InAs becomes DF due to the exchange field in the ferromagnet InMnAs. Here, $V \propto I_i$ is the chemical potential shift induced by the injection current $I_i$. $R_s, R_e, R_j$ denote the resistance of DF, that at the electrode/DF interface and that at the DF/S interface, respectively. We employ the quasiclassical Green’s functions in DF (S) that are expressed as functions in DF (S) that are expressed as $G_{\text{r(i)} S}(x, \varepsilon) = \cos \theta_{\text{r(i)} S}(x, \varepsilon)$ and $F_{\text{r(i)} S} = \sin \theta_{\text{r(i)} S}(x, \varepsilon)$, where functions $\theta_{\text{r(i)} S}$ for majority (minority) spins in DF(S) obey the Usadel equations [4] with the diffusion constant $D_{\text{r(i)} S}$ in DF (S) and the exchange field $h(x)$. Here, $\varepsilon$ is energy of the quasi-particle. The exchange field is assumed to be expressed as

$$h(x) = \begin{cases} h_x, & -L < x < 0 \\ h_x \exp(-x/\xi_x^c), & x > 0 \end{cases}$$

where $\xi_x^c = \sqrt{D_x^c / 2\pi T_c}$ is the thermal coherence length in DF (S). This expression indicates that the injected spin-polarized current is considered to penetrate into S and induce the exchange field in S. Solving Usadel equation and the gap equation self-consistently [5], we calculate both $\Delta(x)$ and $\theta_{\text{r(i)} S}(x, \varepsilon)$, where $\Delta(x)$ denotes the pair potential in S. For $x \to \infty$, $\Delta(x)$ coincides with the bulk value of the pair potential $\Delta_0$. Electric current $I_i$ is expressed as a distribution function at the right (left) electrode. Total conductance of the junction is given by $\sigma^+ = \sigma^+_s + \sigma^-_s$, where $\sigma^\pm_s$ is the differential conductance of right (left) DF/S junction. In the following, we fix parameters as $T/T_c = 0.1$, $V \propto I_i$.
$R_s/R_s = R_s/R_s = 1$, $(D_F/L^2)/\Delta_0 = 0.01$, $h_F/\Delta_0 = 10$, and we focus on $V$ dependences of normalized conductance $\sigma_T = \sigma_S/\sigma_N$, where $\sigma_N$ is conductance in the normal state.

Figure 4 (a) shows $V$ dependences of $\sigma_T$ for various values of $V_i$ and $h_S = 0$. Peaks at $V = \pm\Delta_0/e$ move to $V = \pm(\Delta_0/e + V_i)$ and the zero-bias minimum split into two dips due to the injection current $I_i$. As a result, the zero-bias conductance peak appears for $V_i \geq \Delta_0/e$. This result is qualitatively consistent with the experiment that current is injected from Nb (Fig. 2(a)). On the other hand, Fig. 4 (b) shows $V$ dependences of $\sigma_T$ for various $V_i$ values and $h_S = eV_i$, which corresponds to the case where spin-polarized current induces the exchange field in S. It is noted that the equation $h_S = eV_i$ indicates that the exchange field in S is proportional to the injection current. As a result of synergistic effect of injected current and the exchange field in S, the zero bias conductance peak is suppressed. The result is qualitatively consistent with the experiment where the current is injected from p-InMnAs (Fig. 2(b)).

![Figure 4: Calculated $V$ dependences of $\sigma_T$ for various values of $V_i$ in the case of (a) $h_i = 0$ and (b) $h_i = eV_i$.](image)

4. Conclusions

We have measured the transport properties of a (Ti/Au)/n-InAs/(Ti/Au) junction whose n-InAs part has connections with p-InMnAs and Nb, where a p-InMnAs can be regarded as a spin injector. The differential conductance of n-InAs channel as a function of bias voltage showed a conductance minimum. The conductance minimum showed different behaviours against current injection from Nb and that from p-InMnAs. We also calculated the conductance as a function of bias voltage for n-InAs channel by Usadel equation and the gap equation self-consistently. We found that spin-polarized current from InMnAs induced the exchange field in the Nb electrode and this so-called inverse proximity effect could explain the difference of the conductance behaviours measured in experiments.

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