Andreev Reflection in Narrow Ferromagnet/Superconductor Point Contacts

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The Andreev reflection of narrow ferromagnet/superconductor point contacts is theoretically studied. We show that the conductance quantization depends on whether the contact region is superconducting or ferromagnetic as well as on the strength of the exchange field in the ferromagnet. The Andreev reflection of the ferromagnetic contact is more suppressed than that of the superconducting contact. We also show that the conductance-voltage curve has a bump at zero bias-voltage if there is no interfacial-scattering. On the contrary, the conductance-voltage curve shows a dip if the system has an interfacial-scattering.

The spin-dependent transport through a magnetic nano-structures is of current interest both in fundamental physics and application to spin-electronics [4]. The magnetic quantum point contact is one of these magnetic nano-structures, which exhibit rich and elegant physics [1,2] and have potential applications such as magnetic recording devices [3,5]. Recently much attention has been focused on magnetic point contacts with superconducting electrode since it is shown that the spin polarization of the conduction electrons can be measured by using the Andreev reflection [3].

De Jong and Beenakker have shown that the Andreev reflection in a ferromagnet(F)/superconductor(S) point contact is strongly suppressed as the Fermi surface polarization is increased [4]. The Fermi surface polarization, P, is defined as $P = (N_{↑} - N_{↓})/(N_{↑} + N_{↓})$, where $N_{↑(↓)}$ is the number of transmitting channels in the spin-up/spin-down band. If $N_{↓} < N_{↑}$ then only $2N_{↓} = N_{↑} + N_{↑}/N_{↑}$ channels are available for the Andreev reflection and the corresponding conductance is $G = 4N_{↓}e^{2}/\hbar$. Therefore, the Andreev reflection is strongly suppressed if $P$ is large. The suppression of the Andreev reflection in F/S point contacts has been observed experimentally by several groups [6,12]. Their results are qualitatively well explained by de Jong and Beenakker’s theory.

Now we believe that the narrow F/S point contact where the conductance is quantized is within the current nano-technology. It is then needed to study the spin-dependent transport through narrow F/S point contacts taking account of the geometry of contact and the mixing of channels. In this paper, we theoretically study the spin-dependent transport through narrow F/S point contacts, where the Andreev reflection plays an important role. We show that the conductance quantization depends on whether the contact region is superconducting or ferromagnetic as well as on the strength of the exchange field. The Andreev reflection of the ferromagnetic contact is more suppressed than that for the superconducting contact. For the ferromagnetic contact, the width of the contact where the new transmitting channel opens increases with increasing the exchange field. We also show that the conductance-voltage curve shows a bump at zero bias voltage if the system has no interfacial-scattering between the ferromagnet and superconductor. On the contrary, the conductance-voltage curve shows a dip for the contact with an interfacial-scattering.

We consider the system consisting of three cylinders as shown in Figs. 1(a) and 1(b). The left and right electrodes with a diameter $W_{E}$ are connected by the contact with a diameter $W_{C}(<W_{E})$ and a length $D$. We employ the simple Stoner model with exchange field $h$ for the ferromagnet.

FIG. 1. (a) The geometry of the point contact. The point contact is represented by the coaxial cylinders. (b) The cross-section along the z-direction. The length and width of the contact region are $D$ and $W_{C}$, respectively. The width of the electrodes is $W_{E}$.

The system we consider is described by the following Bogoliubov-de Gennes (BdG) equation:

\[
\begin{pmatrix}
H_{0}(r) - h(z)\sigma & \Delta (T) \\
\Delta^{*}(T) & -H_{0}(r) - h(z)\sigma
\end{pmatrix}
\Psi_{\sigma}(r) = E\Psi_{\sigma}(r),
\]

where $H_{0}(r) \equiv -(\hbar^{2}/2m)\nabla^{2} + V(r) - \mu_{F}$ is the single-particle Hamiltonian with the constriction potential $V(r)$, $E$ is the quasiparticle energy measured from the Fermi energy $\mu_{F}$, $h(z)$ is the exchange field, $\Delta(T)$ is the superconducting energy gap and $\sigma = (+)(-) for the spin-up/spin-down band$.

We assume that effective mass of an electron $m$ is the same both for ferromagnet and superconductor. The exchange field is $h(z) = 0$ for the superconductor and $h(z) = h$ for the ferromagnet. The constriction potential is $V(r) = \infty$ outside the constriction represented by the shadow in Fig. 1(b). Inside the constriction, $V(r) = (\hbar^{2}k_{F}Z/m)b(z - z_{0})$, where $Z$ represents the interfacial-scattering potential at position $z_{0}$.

We assume that the superconducting energy gap $\Delta(T)$ is con-
constant and neglect the proximity effects [11].

The stationary scattering state is obtained by connecting wave functions at the boundary of contact [13,14]. Since the system has cylindrical symmetry, wave functions $\Psi_\sigma$ can be written as

$$\Psi_\sigma(r) = \sum_{n,l} N_{n\sigma}^l \psi_{nl}(z) J_n\left(\frac{2\gamma_{nl}}{W_{EC}}r\right)e^{i\phi}$$

(2)

where $\gamma_{nl}$ is the $l$th zero of the Bessel function $J_n(r)$, $N_{n\sigma}^l$ is the normalization constant [13]. The set of quantum numbers $(n,l,\sigma)$ defines the channel. Substituting Eq. (2) into Eq. (1), we obtain the following BdG equation for $\psi_{nl}(z)$:

$$\left(H_0(z) - \hbar(z)\sigma - \Delta(T)\right)\psi_{nl}(z) = E\psi_{nl}(z),$$

(3)

where $H_0 = (\hbar^2/2m)(d^2/dz^2 - (2\gamma_{nl}/W(z))^2) + (\hbar^2k_F Z/m)\delta(z - z_0)$.

Let us consider the F/S/S system consisting of ferromagnetic and superconducting electrodes connected by the superconducting contact. Assuming that the electron in channel $(n,l,\sigma)$ is incident from the left electrode, the wavefunction $\psi_{nl}(z)$ is written as

$$\psi_{nl}(z) = \begin{cases} e^{iq_{nl}^+)z} \left(\begin{array}{c} 0 \\ 1 \end{array}\right) J_n\left(\frac{2\gamma_{nl}}{W_E}r\right)e^{i\phi} + \sum_{s=1}^{M_E} \left\{ a_{n\sigma s} e^{iq_{nl}s^+ z} \left(\begin{array}{c} 0 \\ 1 \end{array}\right) \right. \\ \left. + b_{n\sigma s} e^{-iq_{nl}s^- z} \left(\begin{array}{c} 1 \\ 0 \end{array}\right) \right\} \times J_n\left(\frac{2\gamma_{nl}s}{W_E}\right)e^{i\phi} \end{cases}$$

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number of open channels. The number of open channels are determined by the condition that \( \text{Re}(2m/h^2)(\mu_F - \sqrt{E^2 - \Delta(T)^2}) - (2\gamma_{nl}/W_C(E))^2 > 0 \). The diameter of electrodes and the length of contact are taken to be \( W_F = 60.8/k_F \) and \( D = 5.0/k_F \), respectively. The superconducting energy gap is assumed to be \( \Delta(0)/\mu_F = 1.5 \times 10^{-3} \), which is of the same order of that for Al \[17\]. The position of the interfacial-scattering is located at \( z_0 = -D/2 + D/2 \) for the F/S/S (F/F/S) system.

In Fig. 2(a) the zero-bias conductance of the F/S/S system is plotted against the width of contact \( W_C \). In the adiabatic picture, the number of transmitting channels are determined by the condition that \( \text{Re}(2m/h^2)(\mu_F - \sqrt{E^2 - \Delta(T)^2}) - (2\gamma_{nl}/W_E)^2 > 0 \) and does not depend on the strength of the exchange field in the ferromagnet electrode. However, as the exchange field increases, the conductance is suppressed due to the mismatch of the Fermi wavelength as shown in Fig. 2(a).

The conductance of the F/F/S system also decreases as the exchange field increases as shown in Fig. 2(b). Note that the width \( W_C \) at which the new transmitting channel opens increases with increasing the exchange field, \( h \). The shift of the conductance steps can be explained as follows. In the ferromagnetic contact, electrons in the spin-up and spin-down bands feel the different exchange fields \( -h \) and \( h \), respectively. Therefore, the number of transmitting spin-down channels \( N_{\downarrow} \) is smaller than that of transmitting spin-up channels \( N_{\uparrow} \). As pointed out by de Jong and Beenakker, the number of channels contributing to the Andreev reflection is restricted by \( N_{\uparrow} \). In the adiabatic picture \[18\], \( N_{\downarrow} \) is determined by the condition that \( (2m/h^2)(\mu_F - E - h) - (2\gamma_{nl}/W_C)^2 > 0 \). Therefore, the conductance steps shift leftward with increasing the exchange field.

In the narrow F/F/S system, the suppression of the Andreev reflection discussed by de Jong and Beenakker appears as the shift of the width of the contact \( W_C \) at which the new transmitting channel opens as shown in Fig. 2(b). Even when the contact is superconducting (F/S/S), the conductance is suppressed due to the mismatch of the Fermi wavelength as shown in Fig. 2(a). However, the magnitude of suppression is smaller than that for the F/F/S system.

Figures 3(a) and 3(c) show the conductance(G)-voltage(V) curves for the F/S/S system and Figs. 3(b) and 3(d) show those for the F/F/S system. The conductance is normalized by that for the F/normal-metal(N) contact. One can see that the conductance for the F/F/S system is smaller than that for F/S/S system since the number of transmitting channels are limited by the Andreev reflection.

In order to investigate the effect of the interfacial-scattering, we plot the G-V curve for the interfacial-scattering of \( Z = 0.3 \) in Figs. 3(c) and 3(d). Without the interfacial scattering, \( Z = 0 \), the G-V curve has a bump at zero bias voltage as shown in Figs 3(a) and 3(b). However, the G-V curve for \( Z = 0.3 \) shows dip as shown in Figs. 3(c) and 3(d). These dip and bump in the G-V curve are similar to the energy dependence of conductance for F/S tunnel junctions discussed by Zutić and Valls \[19\].

Comparing our theory with the experimental results of Soulen et al. \[8,9\], we conclude that in their experiments there is no interfacial-scattering in the contacts with Ni, NiFe and Co film, whereas the interfacial-scattering exists in the contacts with NiMnSb, La_{0.7}Sr_{0.3}Mn_3 and CrO_2 film.

Soulen et al. \[8\] have also studied the conductance of
two different systems with the same material: a sharpened Ta point placed in contact with a single crystal Fe thin film, and a sharpened Fe point placed in contact with a polycrystalline Ta foil. They found the difference in the G-V curve near zero bias voltage and concluded that this difference is due to varying amounts of interfacial-scattering, Z. However, we propose that such difference in the G-V curve can occur if the material of the contact is different: one system has the superconducting contact and the other system has the ferromagnetic contact. We also insist that the spin-polarization obtained by analyzing the experimental data \[10, 12\] depends strongly on whether the contact region is ferromagnetic or superconducting.

In Figs.4(a)-4(d), we show the G-V curve of the F/F/S system at \(T/T_c = 0.2\) and 0.4. The horizontal axis is normalized by the superconducting energy gap \(\Delta(T)\). The temperature dependencies of the G-V curves for the F/S/S system are not shown since they are similar to those for the F/F/S system shown in Figs.4(a)-4(d).

One can clearly see that the difference of the curvature in the G-V curve can occur if the material of the contact is different: one system has the superconducting contact and the other system has the ferromagnetic contact. We also propose that such difference in the G-V curve can occur if the material of the contact is different: one system has the superconducting contact and the other system has the ferromagnetic contact. We also insist that the spin-polarization obtained by analyzing the experimental data \[10, 12\] depends strongly on whether the contact region is ferromagnetic or superconducting.

In conclusion, we theoretically study the Andreev reflection of narrow F/S point contacts. We show that the conductance depends on whether the contact is superconducting or ferromagnetic as well as on the strength of the exchange field in the ferromagnet. The conductance of the ferromagnetic contact is more suppressed than that of the superconducting contact. For the ferromagnetic contact, the width of the contact where the new transmitting channel opens increases with increasing the exchange field. We also show that the conductance-voltage curve has a bump at zero bias-voltage if there is no interfacial-scattering between the ferromagnet and superconductor. On the contrary, if the contact has an interfacial-scattering, the conductance-voltage curve has a dip at the zero bias-voltage.

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