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# Conductance oscillations due to geometrical resonance in *FNS* double junctions

Hiroyuki Ohtori[1,2] and Hiroshi Imamura[2]
[1]*Institute of Applied Physics, University of Tsukuba, Tsukuba 305-8573, Japan*
[2]*NRI, AIST, Central 2, 1-1-1 Umezono, Tsukuba 305-8568, Japan*
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We theoretically analyzed the Andreev reflection in ferromagnetic metal/nonmagnetic metal/superconductor double junctions with special attention to the electron interference effect in the nonmagnetic metal layer. We showed that the conductance oscillates as a function of the bias voltage due to the geometrical resonance. We found that the exchange field, and therefore the spin polarization of the ferromagnetic metal can be determined from the period of the conductance oscillation, which is proportional to the square root of the exchange field.

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Recently much attention has been focused on the Andreev reflection (AR) in ferromagnetic metal (FM)/superconductor (SC) contacts[1–10] since the spin polarization of conduction electrons is measured through the suppression of the conductance below the superconducting gap. This method is called point-contact Andreev reflection (PCAR) spectroscopy.

On the other hand, the quasiparticle (QP) interference in nonmagnetic metal (NM)/SC junctions has been extensively studied in the past.[11–18] As shown in Refs. 12–14, the interference of QPs in the SC layer brings about the oscillation of the density of states against the QP energy, which is called a Tomasch oscillation. The interference in the NM layer also brings about the oscillation of the density of states in the NM layer,[11,15] which is known as the de Gennes–Saint-James bound state or the McMillan-Rowell oscillation. Nesher and Koren measured the dynamic resistance of $YBa_2Cu_3O_{6.6}/YBa_2Cu_{2.55}Fe_{0.45}O_y/YBa_2Cu_3O_{6.6}$ junctions and determined the renormalized Fermi velocity of QPs in the $YBa_2Cu_{2.55}Fe_{0.45}O_y$ layer from the period of the McMillan-Rowell oscillation.[16]

In this Brief Report, we theoretically analyze the Andreev reflection in a FM/NM/SC double junction system with special attention to the electron interference effect in the NM layer. Following the work of Blonder, Tinkham, and Klapwijk (BTK),[19] we solve the Bogoliubov-de Gennes (BdG)[20] equations and calculate the conductance. We show that the conductance due to the Andreev reflection oscillates as a function of the bias voltage because of the geometrical resonance predicted by de Gennes and Saint-James. We obtain the analytical expression of the probability of the Andreev reflection under the Andreev approximation and find that the period of the conductance oscillation is proportional to the square root of the exchange field. Therefore, we can determine the exchange field and, therefore, the spin polarization of the FM layer from the period of the conductance oscillation.

The system we consider is comprised of the FM/NM/SC double junctions shown in Fig. 1(a). The current flows along the $x$ axis, and the interfaces between FM/NM and NM/SC are located at $x=0$ and $x=d$, respectively. The system is described by the following BdG equation:[20]

$$\begin{pmatrix} H_0 - h(x)\sigma & \Delta(x) \\ \Delta^*(x) & -H_0 - h(x)\sigma \end{pmatrix}\begin{pmatrix} f_\sigma(\boldsymbol{r}) \\ g_\sigma(\boldsymbol{r}) \end{pmatrix} = E\begin{pmatrix} f_\sigma(\boldsymbol{r}) \\ g_\sigma(\boldsymbol{r}) \end{pmatrix}, \quad (1)$$

where $H_0 \equiv -(\hbar^2/2m)\nabla^2 + V(x) - \mu_F$ is the single-particle Hamiltonian, $E$ is the QP energy measured from the Fermi energy $\mu_F$, $V(x)$ is the interfacial barrier,[21] and $\sigma=+(-)$ represents the up-(down-)spin band. The exchange field function $h(x)$ is given by $h(x)=h_0[1-\Theta(x)]$, where $h_0$ represents the exchange field in the FM layer and $\Theta(x)$ is the Heaviside step function. We employed the two-band Stoner model for the FM layer for simplicity. The superconducting gap function is expressed as $\Delta(x)=\Delta_0\Theta(x-d)$, where $\Delta_0$ represents the superconducting gap in the SC layer. We assume that the system has translational symmetry in the transverse ($y$ and $z$) direction, and therefore the wave vector parallel to the interface $\boldsymbol{k}_\parallel \equiv (k_y, k_z)$ is a conserved quantity.

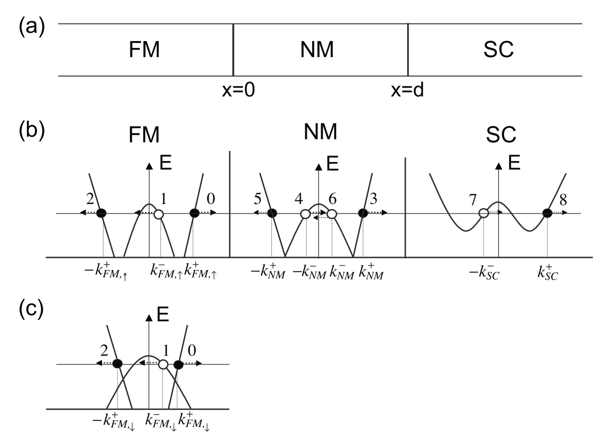


FIG. 1. (a) Schematic diagram of a FM/NM/SC double junction. An NM with a thickness of $d$ is sandwiched by FM and SC layers. (b) Schematic diagrams of energy vs momentum of the FM/NM/SC double junction for a spin-up incident electron are shown. The open circles denote holes, the filled circles denote electrons, and the arrows point in the direction of the group velocity. The incident electron with up-spin is denoted by 0, along with the resulting scattering processes: Andreev reflection (1), normal reflection (2) at the FM/NM interface, transmission to the NM (3, 4) and reflection at the NM/SC interface (5, 6), and transmission as a electronlike quasiparticle to the SC (7) and that as a holelike quasiparticle (8). (c) Schematic diagrams of energy vs momentum in the FM layer for a spin-down incident electron are shown.

 

The general solutions of BdG Eq. (1) in the FM (NM) layer are given by

$$\Psi_{\pm k^{+}_{\mathrm{FM(NM)},\sigma}}(\boldsymbol{r}) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{\pm i k^{+}_{\mathrm{FM(NM)},\sigma} x} \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel), \tag{2}$$

$$\Psi_{\pm k^{-}_{\mathrm{FM(NM)},\sigma}}(\boldsymbol{r}) = \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{\pm i k^{-}_{\mathrm{FM(NM)},\sigma} x} \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel), \tag{3}$$

where $\mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel)$ represents the eigenfunction in the transverse direction in the $\boldsymbol{k}_\parallel$ channel and $k^{+(-)}_{\mathrm{FM(NM)},\sigma}$ is the $x$ component of the wave number of an electron (hole) with $\sigma$ spin defined as $k^{\pm}_{\mathrm{FM},\sigma} = \frac{\sqrt{2m}}{\hbar}\sqrt{\mu_F \pm E + \sigma h_0 - E_\parallel}$ and $k^{\pm}_{\mathrm{NM}} = \frac{\sqrt{2m}}{\hbar}\sqrt{\mu_F \pm E - E_\parallel}$, where $E_\parallel = \frac{\hbar^2}{2m}k_\parallel^2$. In the SC layer, we have

$$\Psi_{\pm k^{+}_{\mathrm{SC}}}(\boldsymbol{r}) = \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{\pm i k^{+}_{\mathrm{SC}} x} \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel), \tag{4}$$

$$\Psi_{\pm k^{-}_{\mathrm{SC}}}(\boldsymbol{r}) = \begin{pmatrix} v_0 \\ u_0 \end{pmatrix} e^{\pm i k^{-}_{\mathrm{SC}} x} \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel), \tag{5}$$

where $u_0$ and $v_0$ are the coherence factors expressed as $u_0^2 = 1 - v_0^2 = \frac{1}{2}[1 + \frac{\sqrt{E^2 - \Delta^2}}{E}]$, and $k^{+(-)}_{\mathrm{SC}}$ is the $x$ component of the wave number of an electron(hole)like QP defined as $k^{\pm}_{\mathrm{SC}} = \frac{\sqrt{2m}}{\hbar}\sqrt{\mu_F \pm \sqrt{E^2 - \Delta^2} - E_\parallel}$.

The wave function of the FM/NM/SC double junction is given by the linear combination of the above general solutions. Let us consider the scattering of an electron in the $\boldsymbol{k}_\parallel$ channel with up-spin injected into the NM from the FM; the eight processes shown in Fig. 1(b) are active. Therefore, the wave function in the FM layer ($x < 0$) takes the form

$$\Psi^{\mathrm{FM}}_{\sigma,\boldsymbol{k}_\parallel}(\boldsymbol{r}) = \left[ \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{i k^{+}_{\mathrm{FM},\sigma} x} + a_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{i k^{-}_{\mathrm{FM},\sigma} x} + b_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-i k^{+}_{\mathrm{FM},\sigma} x} \right] \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel). \tag{6}$$

In the NM layer ($0 \leq x < d$), we have

$$\Psi^{\mathrm{NM}}_{\sigma,\boldsymbol{k}_\parallel}(\boldsymbol{r}) = \left[ \alpha_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{i k^{+}_{\mathrm{NM}} x} + \beta_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{-i k^{-}_{\mathrm{NM}} x} + \xi_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-i k^{+}_{\mathrm{NM}} x} + \chi_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{i k^{-}_{\mathrm{NM}} x} \right] \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel), \tag{7}$$

and in the SC layer ($x \geq d$),

$$\Psi^{\mathrm{SC}}_{\sigma,\boldsymbol{k}_\parallel}(\boldsymbol{r}) = \left[ c_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{i k^{+}_{\mathrm{SC}} x} + d_{\sigma,\boldsymbol{k}_\parallel} \begin{pmatrix} v_0 \\ u_0 \end{pmatrix} e^{-i k^{-}_{\mathrm{SC}} x} \right] \mathrm{S}_{\boldsymbol{k}_\parallel}(\boldsymbol{r}_\parallel). \tag{8}$$

The coefficients $a_{\sigma,\boldsymbol{k}_\parallel}$, $b_{\sigma,\boldsymbol{k}_\parallel}$, $c_{\sigma,\boldsymbol{k}_\parallel}$, $d_{\sigma,\boldsymbol{k}_\parallel}$, $\alpha_{\sigma,\boldsymbol{k}_\parallel}$, $\beta_{\sigma,\boldsymbol{k}_\parallel}$, $\xi_{\sigma,\boldsymbol{k}_\parallel}$, and $\chi_{\sigma,\boldsymbol{k}_\parallel}$ are determined by matching the wave function at the boundary of the contact $x=0$ and $d$. Following the BTK theory[19] the probabilities of the AR and the normal reflection are given by $A_{\sigma,\boldsymbol{k}_\parallel}(E) = (k^{-}_{\mathrm{FM},\sigma}/k^{+}_{\mathrm{FM},\sigma}) a^{*}_{\sigma,\boldsymbol{k}_\parallel} a_{\sigma,\boldsymbol{k}_\parallel}$ and $B_{\sigma,\boldsymbol{k}_\parallel}(E) = b^{*}_{\sigma,\boldsymbol{k}_\parallel} b_{\sigma,\boldsymbol{k}_\parallel}$, respectively. Since we assume that the temperature is zero, the conductance at bias voltage $V$ is given by $G = \frac{e}{h}\sum_{\sigma,\boldsymbol{k}_\parallel}[1 + A_{\sigma,\boldsymbol{k}_\parallel}(eV) - B_{\sigma,\boldsymbol{k}_\parallel}(eV)]$, where we assume that the voltage drop occurs at the NM/SC interface for simplicity. Below the superconducting gap, i.e., $eV < \Delta_0$, the probabilities $A_{\sigma,\boldsymbol{k}_\parallel}(E)$ and $B_{\sigma,\boldsymbol{k}_\parallel}(E)$ satisfy the relation that $1 + B_{\sigma,\boldsymbol{k}_\parallel}(E) = A_{\sigma,\boldsymbol{k}_\parallel}(E)$ and then we have

$$G = 2\frac{e}{h}\sum_{\sigma,\boldsymbol{k}_\parallel} A_{\sigma,\boldsymbol{k}_\parallel}(eV). \tag{9}$$

Let us first consider the most idealistic case where the interfacial scattering potential, $V(x)$, is assumed to be zero. This simplification enables us to obtain the analytical expression of $A_{\sigma,\boldsymbol{k}_\parallel}(E)$ under the Andreev approximation,

$$A_{\sigma,\boldsymbol{k}_\parallel}(E) \simeq \frac{4(1-\zeta)\sqrt{1-\eta^2}}{2\{(1-\zeta)^2 + (1-\zeta)\sqrt{(1-\zeta)^2 - \eta^2}\} - \eta^2\{\epsilon^2 + (1-2\epsilon^2)\cos^2[(k^{+}_{\mathrm{NM}} - k^{-}_{\mathrm{NM}})d] - \epsilon\sqrt{1-\epsilon^2}\sin[2(k^{+}_{\mathrm{NM}} - k^{-}_{\mathrm{NM}})d]\}}, \tag{10}$$

where we introduced the normalized parameters $\eta = h_0/\mu_F$, $\zeta = E_\parallel/\mu_F$, and $\epsilon = E/\Delta_0$. We note that Eq. (10) contains trigonometric functions in the denominator. For the FM/SC junction, i.e., $d=0$, the trigonometric functions become constant and Eq. (10) reproduces the de Jong and Beenakker results of the zero-bias conductance.[1] For the FM/NM/SC junctions with $d \neq 0$, the trigonometric functions in Eq. (10) give rise to the oscillation of the conductance against the bias voltage. The origin of the conductance oscillation is the interference of electrons in the NM layer.[11,15] In the FM/NM/SC double junctions, the injected electron propagates across the NM layer to the interface as an electron (3 in Fig. 1) and is scattered into a hole (6 in Fig. 1) by the superconducting gap. The superconducting gap can pair an excited electron with an electron inside the Fermi sea, leaving a hole excitation. The hole propagates back across the NM layer; however, it cannot interfere with the original electron. In order for interference to occur the hole must be reflected at the FM/NM interface, propagate to the NM/SC interface, be scattered into the electron state (5 in Fig. 1) by the superconducting gap, and propagate as an electron in the NM layer. It can interfere with the original electron (3 in Fig. 1). This interference produces an oscillation of the conductance against the bias voltage, and the period of the oscillation is determined by the thickness of the NM layer.

In order to analyze the interference effect on the conductance oscillation, we consider the AR probability $A_{\sigma,\boldsymbol{k}_\parallel}(E)$ of the one-dimensional system; i.e., only the transverse channel

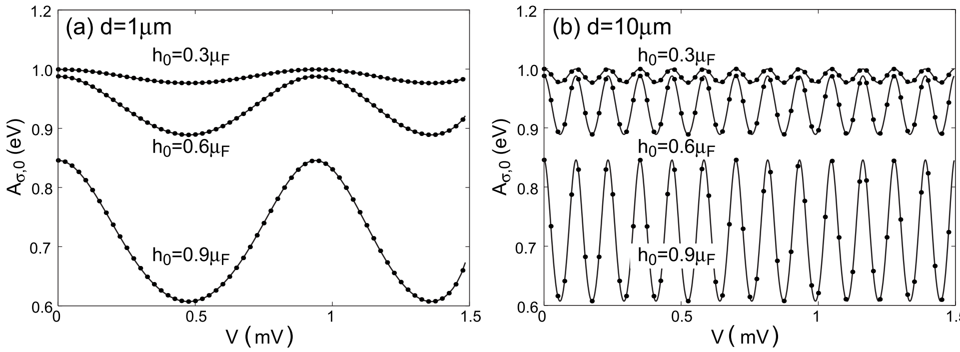


FIG. 2. (a) Probability of the AR $A_{\sigma,0}(eV)$ for the FM/NM/SC double junction with $d=1$ $\mu$m is plotted against the bias voltage $V$. The exact numerical results and the value of Eq. (10) are plotted by lines and circles, respectively. The value of the exchange field is taken to be $h_0=0.3,0.6,0.9\mu_F$ from top to bottom. (b) Same plot for $d=10$ $\mu$m.

with $\boldsymbol{k}_\parallel=0$ is considered. In Figs. 2(a) and 2(b) we plot the probability $A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ of the FM/NM/SC double junctions with $d=1$ $\mu$m and 10 $\mu$m, respectively, as a function of the bias voltage. Since Eq. (10) is an even function of normalized value of the exchange field $\eta$, $A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ is independent of the spin direction $\sigma$; i.e., $A_{\uparrow,\boldsymbol{k}_\parallel}(eV)=A_{\downarrow,\boldsymbol{k}_\parallel}(eV)$. The Fermi energy and the superconducting gap are assumed to be $\mu_F=3.8$ eV ($k_F=1.0$ Å$^{-1}$) and $\Delta_0=1.5$ meV, respectively. The exact numerical results and the approximate values of Eq. (10) are plotted by lines and circles, respectively. The value of the exchange field is taken to be $h_0=0.3,0.6,0.9\mu_F$ from top to bottom.

As shown in Figs. 2(a) and 2(b), Eq. (10) and therefore the Andreev approximation are valid for all values of the exchange field. According to Eq. (10), the period of the oscillation is determined by the condition that $k^+-k^-=n\pi$, where $n$ is an integer. Since $k^\pm\simeq k_F(1\pm E/2\mu_F)$, the period is obtained as

$$\Delta V_{1\mathrm{D}}\simeq\frac{\hbar^2\pi k_F}{2med},\tag{11}$$

which is inversely proportional to the thickness of the NM layer, $d$. For the one-dimensional system, the period $\Delta V_{1\mathrm{D}}$ is independent of the exchange field of the FM layer as shown in Figs. 2(a) and 2(b) and in Eq. (11). However, as we shall show later, the period of the conductance oscillation due to the geometrical resonance depends on the exchange field of the FM layer because the number of $\boldsymbol{k}_\parallel$ channels available for the AR is restricted by the exchange field.

The period of the oscillation of $A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ with finite $\boldsymbol{k}_\parallel$ is given by $\Delta V_{\boldsymbol{k}_\parallel}\simeq\frac{\hbar\pi}{\sqrt{2m}d}\sqrt{\mu_F-E_\parallel}$. From Eq. (9) the conductance is obtained by summing up $A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ for all available $\boldsymbol{k}_\parallel$. Since the spin of the Andreev reflected hole is opposite to that of the incident electron, the maximum value of $k_\parallel$ and therefore $E_\parallel$ is limited by the exchange field $h_0$ as max $E_\parallel=\mu_\mathrm{F}-h_0$. We assume that oscillations of $A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ with different periods cancel out each other and the period of the sum $\Sigma_{\sigma,\boldsymbol{k}_\parallel}A_{\sigma,\boldsymbol{k}_\parallel}(eV)$ is determined by the shortest period. Thus, the period of the conductance oscillation of the three-dimensional (3D) system is obtained as

$$\Delta V_{3\mathrm{D}}\simeq\min\Delta V_{\boldsymbol{k}_\parallel}=\frac{\hbar\pi}{\sqrt{2m}ed}\sqrt{h_0}.\tag{12}$$

In Figs. 3(a)–3(c) we plot the conductance of the FM/NM/SC junction, $G_{FNS}$, normalized by that of the FM/NM/NM junction, $G_{FNN}$, against the bias voltage. As shown in Fig. 3(a), the oscillation due to the geometrical resonance does not appear in the conductance-voltage curve if the thickness of the NM layer, $d$, is less than or of the order of nm. The conductance-voltage curve is indistinguishable from that of the FM/SC junction. Hence, we can use the conventional PCAR analysis for a FM film, the surface of which is coated by a thin (less than a few nm) NM layer.

Figures 3(b) and 3(c) show the conductance-voltage curves for the FM/NM/SC double junctions with $d=1$ $\mu$m and $d=10$ $\mu$m, respectively. One can see that the period does depend on the exchange field, $h_0$, in the FM layer as well as the thickness of the NM layer. The period is a decreasing function of the exchange field. We can easily confirm that the period is proportional to the square-root dependence of the exchange field by looking at Fig. 3(d). The exact numerical results (filled circles) agree well with Eq. (12) (dotted line). The results suggest that we can determine the exchange field and therefore the spin polarization of the FM layer from the period of the conductance oscillation.

Next we consider the effect of the interfacial scattering potential at the NM/SC interface. We assume that the interfacial potential is represented by the delta function as $V(x)$

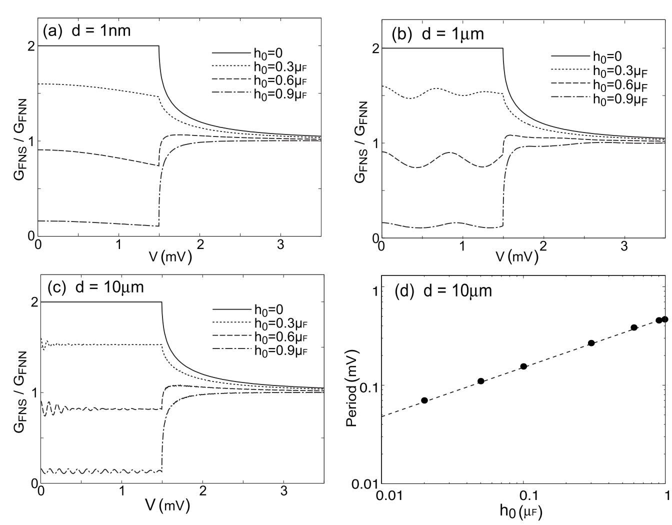


FIG. 3. (a) The conductance of the FM/NM/SC double junction $G_{FNS}$ with $d=1$ nm is plotted against the bias voltage. The conductance is normalized by that of the FM/NM/NM junction $G_{FNS}$. (b) Same plot for $d=1$ $\mu$m. (c) Same plot for $d=10$ $\mu$m. (d) The period of the conductance oscillation of the FM/NM/SC double junction with $d=10$ $\mu$m is plotted against the exchange field $h_0$.

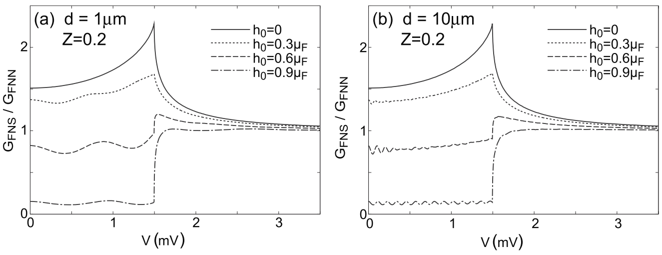


FIG. 4. (a) The normalized conductance $G_{FNS}/G_{FNN}$ for $d = 1$ $\mu$m and $Z=0.2$ is plotted against the bias voltage. (b) Same plot for $d=10$ $\mu$m and $Z=0.2$.

$=(\hbar^2 k_F Z/m)\delta(x-d)$, where $Z$ is the dimension less parameter which characterize the strength of the interfacial scattering potential. For simplicity, we neglect resistances of the FM/NM interface and the FM layer which do not change the oscillation period of the conductance but reduce the amplitude of it. In Figs. 4(a) and 4(b), we show the normalized conductance-voltage curves for junctions with $d=1$ $\mu$m and $d=10$ $\mu$m. The parameter $Z$ is assumed to be 0.2.[6] Because the conductance oscillation is due to the geometrical resonance in the NM layer, the period of the oscillation is not affected by the interfacial scattering potential and is given by Eq. (12).

In the present analysis we employed the simplest BdG approach and consider the clean FM/NM/SC junctions with perfect interfaces. In the real experiments the conductance oscillation we predicted might be smeared out due to the interface roughness and imperfections. However, recent advances in fabrication technology enables us to fabricate epitaxial FM/NM/SC trilayers of high quality.[22] We expect that the conductance oscillation we predicted can be observed in such epitaxial trilayers. For further understanding of the transport properties of FM/NM/SC trilayers, we have to take into account the effects of finite mean free path, band structures, and self-consistent determination of the electron's distribution function and electric potential, which is beyond the scope of this Brief Report.

In summary, we studied the conductance oscillation due to the geometrical resonance in a FM/NM/SC double junction theoretically. We showed that the conductance due to the Andreev reflection oscillates as a function of the bias voltage due to the geometrical resonance. We found that the exchange field and therefore the spin polarization of the FM layer can be determined from the period of the conductance oscillation because the period of the conductance oscillation is proportional to the square root of the exchange field.

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