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Asymmetric interfacial scattering effect on tunneling conductance of ferromagnet/superconductor/ferromagnet junctions

K. Pasanai [1]

Theoretical Condensed Matter Physics Research Unit, Department of Physics, Faculty of Science, Maha-Sarakham University, Khamriang Sub-District, Kantarawichai District, Maha-Sarakham 44150, Thailand

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ABSTRACT

The tunneling conductance spectra of a magnetic tunnel junction between ferromagnet/superconductor/ferromagnet material interfaces were theoretically studied using the scattering approach in a two dimensional system. As the main area of interest, the interfacial scattering at the two interfaces was modeled by Dirac delta potentials and set to be unequal in their values to verify which potential was more sensitive to the conductance spectra of the junctions. It was found that the conductance spectra in the region where the energy was less than the energy gap of the superconductor were sensitive to the potential strength at the first interface that is the incident side of an electron. When the electron was injected from different sides of the junctions, the conductance spectra of these two incident processes were different in magnitude in the case of asymmetric scattering potential. Particularly, the greater the different values of the two potential strengths, the larger the difference in the conductance spectra. This result can be used to identify the quality of a magnetic tunnel junction that is composed of a superconductor material. Moreover, the effect of the exchange energy and the superconducting thickness on the transport properties was analyzed.

1. Introduction

Magnetic tunnel junctions (MTJs) are one of the recent areas of extensive research because knowledge of this kind of junction can be directly applied to practical uses, for example, in read sensors in hard disk drive technology and data storage for computer devices or magnetoresistive random access memory (MRAM) [1–6]. The application devices involved are referred to as "spintronics" [5]. This interesting topic originated from the discovery of the giant magnetoresistance (GMR) in Fe/Cr/Fe junctions [7,8], where Cr is a non-magnetic material. Moreover, the study was extended to the magnetic junction with a superconductor, when the middle layer is replaced by a superconductor [9–11]. The novel physics of MTJ with superconductor material is linked to the Andreev reflection scenario, where a Cooper pair in the region of energy lower than the Fermi level is generated in SC [9,12,13]. This kind of reflection will especially affect the main result in this work, in particular.

As the resistance value of GMR is crucial in the above application devices, a method of increasing the GMR in the MTJs is one of the main interesting research areas in the present time. Particularly, the corresponding methods concerned with two important areas of physics are (i) the development of the magnetic properties of the materials in the junctions and (ii) the understanding of the physics of the interfaces between materials in the junctions. That is, the first method considers, calculates, and determines the way, for example, to produce an exciting magnetic material with a high spin polarization value like a ferromagnetic semimetal [14] or to interact with the material like spin–orbit interaction affects the magnetoresistance (MR) [15]. The second method is interesting because one can obtain a higher value for the MR by embedding the magnetic impurities [16–20] or inserting a thin insulating layer at the interfaces [4,21]. These will produce the scattering potential at the interfaces as pronounced spin-flip and non-spin-flip scattering potentials, respectively. In previous work, we found that the spin-flip and non-spin-flip potentials can play a crucial role in enhancing the conductance spectra in a metal/ferromagnet junction to reach a maximum value when these two potentials are equal in their magnitudes [22]. However, there is no way to determine the strength of these potentials in the magnetic junction, especially, in a ferromagnet/supperconductor/ferromagnet (FM/SC/FM) double junction system.

In the present paper, we study theoretically the tunneling conductance of an FM/SC/FM double junction system using BTK formalism to suggest the strength of the interfacial potential in terms of the quality of the magnetic double junction. Due to the main focus of the research on the effect of asymmetric interfacial

E-mail address: krisakronmsu@gmail.com
[1] Fax: +66 43754379.

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scattering on the conductance spectra of FM/SC/FM junctions, the middle layer is only considered as an s-wave superconductor. In Section 2, the formalism is expressed and how to calculate the conductance spectra in the double junction system is described, and how to model the potential strength at the two interfaces. After that, the main area of interest, such as the effect of the exchange energy, the superconducting layer, and the interfacial scattering on the transport properties is analyzed in Section 3.3. Finally, there is the conclusion.

2. Model and formulation

In this work, the method used was based on the theoretical approach of the tunneling spectra in the BTK model [23]. In this model, the transport particles were considered to be in the ballistic regime during the scattering process, injection, reflection, and transmission, and were calculated at the same energy level. However, we neglect the proximity effect between the materials that refers to the overlap of the wave function of the electron-like or hole-like quasiparticle from a ferromagnet and a superconductor near the interfaces. This effect can cause some parts of the ferromagnet near the interfaces to develop superconductivity, and, at the same time, the ferromagnetic state can induce the exchange energy in the SC layer [24]. Furthermore, there is a magnetic field due to the magnetization in the FM but this field is neglected because it is a factor of a thousand smaller than the exchange energy in the FM. The effect of this magnetic field on the properties of the SC state is also neglected because the field in this case is parallel to the interfaces, so this factor is too small. However, the two FMs in the junctions are set to be identical to reduce the complexity of the problem of the velocity mismatch in the junctions.

2.1. Hamiltonian and wave functions

The junctions in this work consist of a ferromagnet/superconductor (FM/SC) interface in the left side and a superconductor/ferromagnet (SC/FM) interface in the right side that are respectively located at $x=0$ and $x=L$. The current of the junctions flows from the left to the right when the voltage is applied across the junctions. The Bogoliubov–de Gennes (BdG) equation of the system is given by Eq. (1) [25]. As there are two spin sub-bands of each conduction particle, electron and hole with spin-up and spin-down, four the matrix components of BdG are as follows:

$$\begin{bmatrix} H_0(x,y) - h_{ex}\hat{m}\cdot\hat{\sigma} & \Delta_k(x,y) \\ \Delta_k^*(x,y) & -H_0(x,y) - h_{ex}\hat{m}\cdot\hat{\sigma} \end{bmatrix}\begin{bmatrix} f_\sigma(x,y) \\ g_{\bar{\sigma}}(x,y) \end{bmatrix} = E\begin{bmatrix} f_\sigma(x,y) \\ g_{\bar{\sigma}}(x,y) \end{bmatrix}, \tag{1}$$

where $H_0(x,y) = -(\hbar^2/2m)\nabla^2 + V(x) - \mu_F$ represents the 2×2 single particle matrix Hamiltonian, $V(x) = U_1\delta(x) + U_2\delta(x-L)$ refers to the delta potential at the left (U_1) and the right (U_2) interfaces as shown in Fig. 1 (left panel). m is the particle effective mass, μ_F is the chemical potential, and h_{ex} represents the exchange energy in the ferromagnetic material, where the splitting between spin-up and spin-down bands is equal to $2h_{ex}$. This energy scale vanished in the normal and superconducting states. However, the sign of the exchange energy h_{ex} does not change when the quasiparticle is a hole-like quasiparticle, but it does for a spin-down particle, instead. In this work, a unit vector of the magnetization direction, $\hat{m}$, points along the $+z$ direction, so the spin-up (majority spin band) and spin-down (minority spin band) directions point along the $+z$ and $-z$ directions, respectively. In the superconducting state, we only consider the case of an s-wave superconductor. Thus, $\Delta_k(x,y)$ equals Δ, where Δ is a maximum gap of this material.

The following will explain how to calculate the physical quantities of the double junction, such as the reflection and transmission probabilities, and the conductance spectra. Fig. 1 (right panel) shows the reflection and transmission transports in the junctions, where the electron and hole have to be injected from the different sides of the junctions to conserve the current, but, in reality, these two processes occur in the same time. It was found that there are 16 transport coefficients in these junctions. All of them will be obtained by using quantum physics theory as described below.

Due to there being two spin bands for each conducting particle in the ferromagnet, the electron incident will equally likely be both electrons with spin-up and spin-down. When the electrons with spin-up and spin-down are injected from the left side, the wave functions in the left ferromagnet in these two cases are, respectively:

$$\Psi^{\uparrow}_{L(e)} = \left\{ \begin{bmatrix}1\\0\\0\\0\end{bmatrix} e^{ik^+_{x,\uparrow}x} + r_\uparrow \begin{bmatrix}1\\0\\0\\0\end{bmatrix} e^{-ik^+_{x,\uparrow}x} + r_\downarrow \begin{bmatrix}0\\1\\0\\0\end{bmatrix} e^{-ik^+_{x,\downarrow}x} + a_\uparrow \begin{bmatrix}0\\0\\1\\0\end{bmatrix} e^{ik^-_{x,\uparrow}x} + a_\downarrow \begin{bmatrix}0\\0\\0\\1\end{bmatrix} e^{ik^-_{x,\downarrow}x} \right\} e^{ik_y y}, \tag{2}$$

and

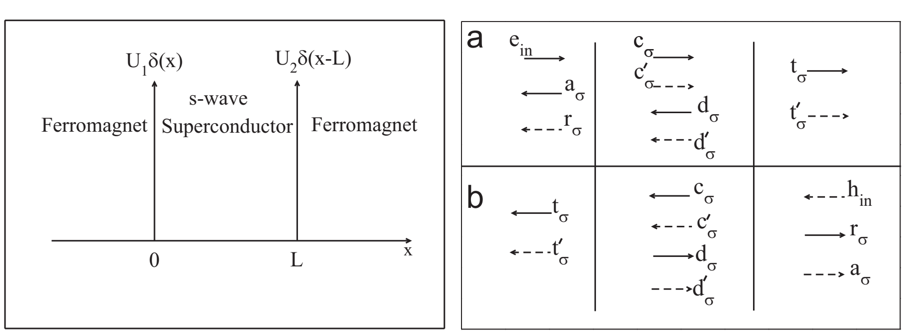

Fig. 1. (Left panel) Geometry of the FM/SC/FM junctions. (Right panel) Reflection and transmission coefficients in the junctions. Solid lines with arrows refer to the electron transport, while dashed lines refer to the hole transport. (a) The electron incident (e_{in}) from the left ferromagnet and (b) the hole incident (h_{in}) from the right ferromagnet. All coefficients are defined in the text.