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Spin dependent transport in diluted magnetic semiconductor/superconductor tunnel junctions

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ABSTRACT

A modification of Blonder–Tinkham–Klapwijk (BTK) model is proposed to describe transport properties of diluted magnetic semiconductor (DMS)/superconductor(SC)/DMS double tunneling junctions. Coherent spin-polarized transport is studied by taking into account the Andreev reflection on spatial variation of SC barrier parameters in the heterostructure. It is shown that the conductance spectrum exhibits an oscillatory behavior with quasi-particle energy, and the oscillation amplitude is reduced with increasing temperature. We also examine the dependence of tunneling magnetoresistance (TMR) on the barrier strength (κ) and spin polarization (P) of two DMS layers. Our results show that TMR decreases with increasing temperature and barrier strength, which may be useful in designing the nano spin-valve devices based on DMS and SC materials.

1. Introduction

Recently, the study of spin-dependent transport properties through magnetic tunnel junctions (MTJs) has attracted a great deal of interest in the field of developing spintronics [1,2], for research and application [3,4]. The science of spintronics (short for spin electronics) is a new technology that utilises a quantum property in computers and magnetic sensor technologies, and is based on the spin degree of freedom of carriers as well as their charge [5–7]. After the discovery of the first measurements of tunneling magnetoresistance (TMR) in a typical MTJ consist of two ferromagnetics separated by a nonmagnetic tunnel barrier [8,9] and giant magnetoresistance (GMR) in Fe/Cr magnetic multilayers [10], many efforts have been made to investigate these effects in other material tunneling junctions. For such structures, the magnetoresistance arise due to different conductivity of parallel and antiparallel alignment of the magnetizations in both electrodes. The origin of these effects can be explained by imbalance in the transmission probability for electrons with spin-up and down through the magnetic junctions [11]. Also, the magnitude of magnetoresistance depends on the spin polarizations of the two magnetic electrodes and the role of interface between the adjacent layers [8].

Apart from the magnetoresistance observed in metallic MTJs, the spin-polarized transport effect is also observed in magnetic semiconductor multilayers. Many experiments have been carried out to study of spin dependent transport in MTJs with ferromagnetic semiconductors (FMSs) and diluted magnetic semiconductors (DMSs). These are appealing because such a system may have both semiconducting and ferromagnetic properties, so they have a better compatibility with conventional microelectronics [12,13]. Using FMSs, such as EuS, the TMR has also been investigated in single [11,14] and double [15–17] magnetic barrier junctions. In these structures, the FMSs, which act as spin filters, are used as tunnel barriers. One of the key elements in spintronics is diluted magnetic semiconductors (DMSs), where a small (<10%) concentration of magnetically active atoms such as Mn is distributed at the cation sites of common III–V and II–VI compound semiconductors. In DMSs, the exchange interaction between the itinerant carriers in the semiconducting band and the localized spins on magnetic impurity ions leads to Zeeman splitting [18,19]. For a type of III–V compound, the discovery of a higher T_C about 110 K in GaAs based ferromagnetic semiconductor, $Ga_{1-c}Mn_cAs$, with optimal Mn concentration $c \sim 0.05$ [18] has generated much attention.

Recently, the effect of barrier strength and spin polarized transport in FM/iron-pnictide-superconductor (SC)/FM structures for *s*-wave pairing for the SC [20,21]. LiMing et al. have been investigated the tunneling spectrum of an electron and a hole on a superlattice of metal/Sc junctions using the BTK method [22]. On the other hand, semiconductor SC hybrid structures have received a lot of attention due to the interesting physics arising from

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coupling between these two materials. Most of studies on these hybrid structures, have been focused on the electrical properties [23,24] and much less attention was given for the magnetic properties [25,26]. On the other hand, the spin-dependent transport phenomena in the MTJs based on $\mathrm{Ga}_{1-c}\mathrm{Mn}_c\mathrm{As}$/(GaAs or AlAs) heterostructures have been studied by several groups [27–30]. In our recent works [31], we have studied the spin-polarized transport in GaMnAs/GaAs/GaMnAs tunnel junctions by considering the effect of spontaneous magnetization of GaMnAs layers. In another work [19], we have developed the analytical studies on coherent spin-polarized transport in this heterostructures by considering the effects of angular dependence of the magnetization of electrodes of the DMS layers. GaMnAs is a good candidate for DMS properties due to the relatively high T_C, the spontaneous magnetization and the feasibility of preparing GaAs-based DMSs. Therefore, it is great importance to have a DMS spin injector which could work at higher temperature. Recently, a direct measurement of spin polarization have been carried in GaMnAs using Andreev reflection spectroscopy by Barden et al. [32]. Furthermore, the study of magnetotransport has been extended in tunnel junctions contains SC layers with a small thickness of the SC interlayer.

In this work, we study several spin-dependent properties of GaMnAs/SC/GaMnAs heterostructures by considering the effect of spontaneous magnetization of GaMnAs layers within the mean-field approximation along the lines of our recent work [19,31]. Our calculations are based on the transfer matrix model and the Blonder–Tinkham–Klapwijk (BTK) approach within the phase coherent transport regime, in which the SC layer is smaller than the phase coherence length. We assume that the carrier wave vector parallel to the interfaces and the carrier spin are conserved in the tunneling process through the whole system. This effect may be considered because in an experiment by Tomasch [33], the geometric resonance nature of the differential conductance oscillations in superconductor/nonmagnetic metal tunnel junctions has been attributed to the quasi-particle interference in the SC layer. Here, we emphasis the variation of barrier height and polarization parameter and the incident carrier energy on the spin-dependent conductance through the structure. Then, the TMR and spin polarization of tunneling carriers are calculated at several different temperatures.

The organization of this paper is as follows. In Section 2, a theoretical model to investigate the superconducting layer effect on the spin dependent transport properties in the GaMnAs/SC/GaMnAs tunnel structure is given. The numerical results of the coherent transport through the system are presented in Section 3. The paper is ended by a conclusion in Section 4.

2. Theoretical model and formalism

In this section, we investigate the spin-dependent transport properties in a new type of MTJ based on DMS and SC materials by including the current-carrying Andreev bound states and multiple Andreev reflection. The structure consists of two semi-infinite DMS electrodes separated by a SC layer of thickness t_{SC} by two thin insulating barriers. For simplicity, we assume that the left and right electrodes are made of the same $\mathrm{Ga}_{1-c}\mathrm{Mn}_c\mathrm{As}$ and all the interfaces are flat shown in Fig. 1. From the panel (a) of figure it is seen that for a spin-σ hole incident on the left DMS/SC interface from the left DMS, there are two sets of reflected quasiparticle waves in the left DMS: normal reflection as an hole of spin-σ with probability $A_\sigma(E)$ and Andreev reflection as a electron of the opposite spin-$\bar\sigma$ with probability $B_{\bar\sigma}(E)$. In the right DMS, there are two sets of transmitted waves: hole like quasiparticle with probability $F_\sigma(E)$ and electron-like quasiparticle with probability $G_{\bar\sigma}(E)$. The conservation of probability requires that $A_\sigma(E)+B_\sigma(E)+F_\sigma(E)+G_\sigma(E)=1$. From this conservation condition, one finds that current calculated at the left DMS/SC interface by use of $1-A_\sigma(E)+B_{\bar\sigma}(E)$ is unequal to that calculated at the right interface by use of $F_\sigma(E)-G_{\bar\sigma}(E)$. That is, the current conservation condition [34] can not be satisfied, which they not only differ in magnitude from each other, but also have a phase difference in the metallic limit. The latter arises from the creation and annihilation of Cooper pairs in SC. In order to solve this difficulty, it is proposed that in the presence of a voltage drop between the two DMS electrodes, not only there are spin-polarized holes incident on the left DMS/SC interface from the left DMS, but also there are spin-polarized electrons incident on the right SC/DMS interface from the right DMS [35,36], as shown in Fig. 1(b). Therefore, along the lines of above consideration, one finds that current calculated at the right SC/DMS interface by use of $1-\tilde A_\sigma(E)+\tilde B_{\bar\sigma}(E)$ is unequal to that calculated at the left interface by use of $\tilde F_\sigma(E)-\tilde G_{\bar\sigma}(E)$.

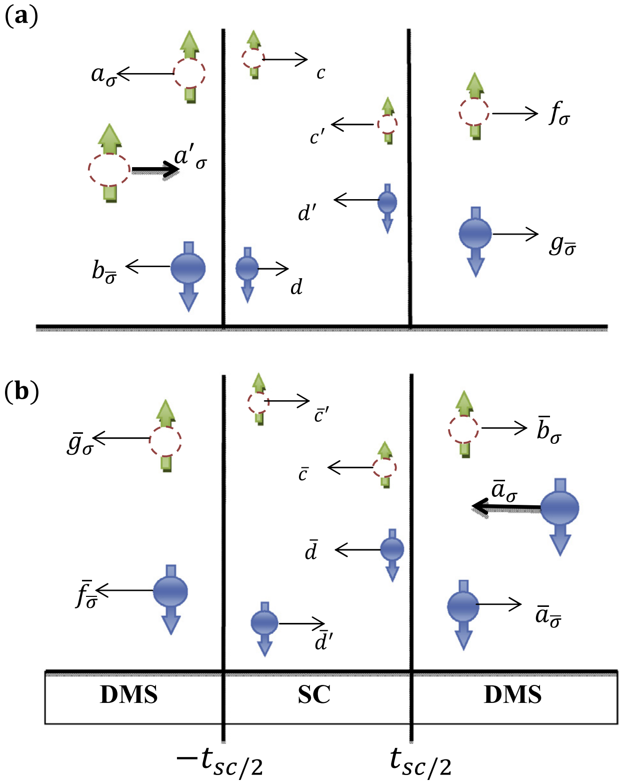

Fig. 1. Schematic representation of reflections and transmissions of quasiparticles in an DMS/SC/DMS structure.

Using a small difference (by an applied voltage) between the chemical potentials of two DMS electrodes and determining all the transmission and reflection probabilities for a range of energies, we can calculate the transmitted steady-state current densities flowing through the left and right DMS/SC interfaces. In the parallel (P) configuration, the current coming into the SC interlayer via the left DMS/SC interface is given by [35,37]

$$I_{\mathrm{L}} = e(\mu_{\mathrm{L}}-\mu)\sum_{\sigma=\uparrow,\downarrow} P_\sigma[1-A_\sigma+B_{\bar\sigma}] + e(\mu-\mu_{\mathrm{R}})\sum_{\sigma=\uparrow,\downarrow} P_\sigma[\tilde F_\sigma-\tilde G_{\bar\sigma}], \quad (1)$$

where μ_{L} and μ are the chemical potential of left electrode and SC layer, respectively. In the parallel configuration, the current coming out of the SC interlayer via the right DMS/SC interface is given by

$$I_{\mathrm{R}} = e(\mu_{\mathrm{L}}-\mu)\sum_{\sigma=\uparrow,\downarrow} P_\sigma[F_\sigma-G_{\bar\sigma}] + e(\mu-\mu_{\mathrm{R}})\sum_{\sigma=\uparrow,\downarrow} P_\sigma[1-\tilde A_\sigma+\tilde B_{\bar\sigma}], \quad (2)$$

where $P_\uparrow = 1-P_\downarrow$. The current conservation requires two the current densities be equal together, from which μ can be determined.