Solid State Communications 236 (2016) 17–22

Contents lists available at ScienceDirect

Solid State Communications

journal homepage: www.elsevier.com/locate/ssc

Spin-polarized current in Zeeman-split d-wave superconductor/quantum wire junctions

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ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form
11 March 2016
Accepted 16 March 2016
by Y.E. Lozovik
Available online 21 March 2016

Keywords:
A. Superconductors
D. Tunneling phenomena

ABSTRACT

We study a thin-film quantum wire/unconventional superconductor junction in the presence of an intrinsic exchange field for a d-wave symmetry of the superconducting order parameter. A strongly spin-polarized current is generated due to an interplay between Zeeman splitting of bands and the nodal structure of the superconducting order parameter. We show that strongly spin-polarized current is achievable for both metallic and tunnel junctions. This is because of the presence of a quantum wire (one-dimensional metal) in our junction. While in two-dimensional junctions with both conventional [F. Giazotto, F. Taddei, Phys. Rev. B 77 (2008) 132501] and unconventional [J. Linder, T. Yokoyama, Y. Tanaka, A. Sudbo, Phys. Rev. B 78 (2008) 014516] pairing states, highly spin polarized current takes place just for a tunnel junction.

Also, the obtained spin-polarized current is tunable in sign and magnitude in terms of exchange field and applied bias voltage.

1. introduction

The investigation of the active control and manipulation of spin degrees of freedom in solid state systems has generated a research field known as spin electronics or spintronics [1–5]. In spintronics, the combination of electronics and magnetism which are two main branches of physics takes place and it leads to the generation of spin polarized currents. The role of magnetism on spin-polarized transport as well as Josephson current has been addressed in different works [6–9]. One of the main questions in this field is related to manipulating the spin polarization of an electrical current. In relation to this matter, one of the good suggestions has been the use of semiconducting materials. In these materials there is a coupling between the electron orbital motion and the spin degree of freedom [10–14]. This coupling stems from the spin–orbit coupling which exists in such materials. Thus, they have a good potential for controlling the spin injection in spintronic devices.

Using the superconductors in spintronic applications caused to create a subfield known as superspintronics. The idea is based on the combination of useful superconducting properties with spin manipulation [15–17]. The Cooper pair in most superconductors has a spin singlet symmetry and as the result it does not carry a net spin. Introducing the strong magnetic sources into such superconductors can help us obtain a strong spin polarized current which can be done by either "proximized" superconductors or Zeeman-split superconductors. In relation to "proximized" superconductors, an exchange field is induced into the superconductor via the proximity effect [18,19]; therefore, by applying a static magnetic field in a superconductor, a Zeeman-split superconductor can be produced.

Giazotto and Taddei [18] studied a normal metal/insulator/s-wave superconductor junction, subjected to an in-plane magnetic field and showed that the junction could produce a strongly spin-polarized current if two conditions were satisfied: low temperatures and strong barrier strength (tunneling limit). In Ref. [19], the effect of the orbital symmetry of the superconducting pair potential on the spin-polarized current is studied theoretically. It showed that spin-polarization is strongly changed by different kinds of superconducting pair states and hence, spin-polarization can be used as a tool for finding the information about the symmetry of pair potential of superconductors. In two-dimensional normal metal/d-wave superconductor junctions, the formation of Andreev bound states has a crucial role on tunneling spectra in a way that it leads to the formation of zero-bias peaks. However, in quantum wire/d-wave superconductor junctions, zero-bias peaks disappear in tunneling spectra which is due to the quantum-mechanical diffraction of the electron waves by narrow opening [20–22]. Accordingly, the presence of a quantum wire can affect the spin-polarized current, the case which we examine in this paper.

In the current study, we investigate a quantum wire/d-wave superconductor junction in the presence of a Zeeman-splitting exchange field. For a quantum wire aligned along the (100)-axis of the superconductor, we have found a high spin-polarized current in the tunneling limit (strong barrier strength) and for the weak

http://dx.doi.org/10.1016/j.ssc.2016.03.012
0038-1098/

barrier strength (transparent interfaces), the results show that the current gets negative values which means the current is dominated by minority-spin carriers. For (110)-axis of the superconductor, the situation is completely different, because there is a strong spin-polarized current when the interface barrier between the normal metal and the superconductor is absent. In fact, there is a strong spin polarization for perfectly transparent interfaces which is an interesting result that does not appear in two-dimensional junctions. As it is mentioned in Refs. [18,19], a strong spin-polarized current is produced just in the tunneling limit (strong barrier strength) for two dimensional junctions.

2. Theory

The system under study consists of a quantum wire of width (w) and a thin superconducting film and they form a quantum wire–insulator–superconductor (QwIS) junction. We assume a static magnetic field (H) which is applied to a thin-film superconductor, with d-wave symmetry (see Fig. 1(a)). The condition $T_s \ll \lambda$ should be satisfied, where λ is the magnetic penetration depth and T_s is the thickness of the superconducting film. Consequently, a Zeeman energy, $h = \frac{g\mu_B}{2}H$, is induced, in which g is the gyromagnetic factor and μ_B is the Bohr magnetron. One can imagine an equivalent setup as QwIS/F where F indicates a ferromagnetic layer which is in a good contact with the superconductor (see Fig. 1(b)) where the ferromagnetic layer can produce an exchange field by proximity effect.

The experimental set-up which is introduced in Fig. 1 is similar to those represented in Refs. [2,23,24] but with the following differences: in Fig. 1 we have used one normal single mode

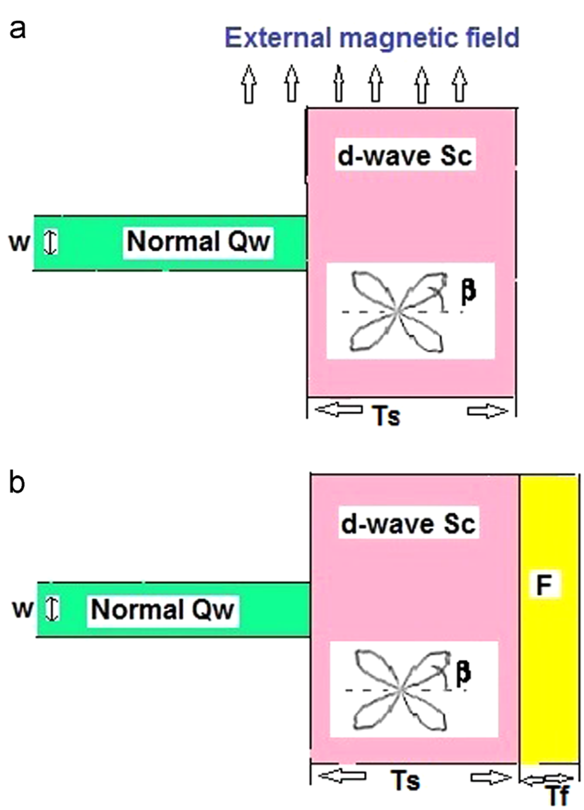

Fig. 1. (Color online) Schematic representation of the system under study: (a) a normal quantum wire–d-wave superconductor junction in an external magnetic field which is a "Zeeman-split" superconductor layout; (b) a normal quantum wire/d-wave superconductor/ferromagnetic metal, where an exchange field is induced by a ferromagnetic layer which is in contact with superconductor and induced the ferromagnetism via the proximity effect.

quantum wire with wave vector $k_x = \sqrt{\frac{2mE}{\hbar^2} + k_F^2 - \left(\frac{\pi}{w}\right)^2}$ which is in contact with a ferromagnetic d-wave superconductor while in Refs. [23,24] the system is based on two ferromagnetic quantum wires in contact with a superconductor. For applicable purposes, in our model one can use $CeCoIn_5$ which is a ferromagnetic superconductor [26]. In Fig. 1, we have used a single mode quantum wire which is in contact with a d-wave superconductor under an external magnetic field. In what follows we show that how these set-up configurations can produce a spin polarized current which can be used in spintronic devices.

We consider the quasiparticle tunneling into the superconducting side from a quantum wire with width (w). The quantum wire and the superconductor are in the same plane and we assume that the thickness of both of them is infinitesimally small. In order to calculate the current flowing across the junction, we apply the formalism of Blonder et al. [25], hence, we should obtain the quasiparticle wave functions and excitation energies. For this purpose, we need to solve the following equations:

$$(H_0 - \sigma h)u^\sigma_{\vec{k}}(\vec{r}) + \Delta(\vec{k}, \vec{r})v^\sigma_{\vec{k}}(\vec{r}) = Eu^\sigma_{\vec{k}}(\vec{r})$$
$$(-H_0^* - \sigma h)v^\sigma_{\vec{k}}(\vec{r}) + \Delta^*(\vec{k}, \vec{r})u^\sigma_{\vec{k}}(\vec{r}) = Ev^\sigma_{\vec{k}}(\vec{r}) \quad (1)$$

Where $H_0 = \frac{p^2}{2m} + V(\vec{r}) - E_F$ is the one-particle Hamiltonian with E_F the Fermi energy. We assume the effective mass and Fermi energy to be identical in both sides of the junction and use the step function model for the order parameter, while we assume it to be zero in the quantum wire side. In the superconductor region, the anisotropic order parameter is a function of the wave vector $\Delta\left(\vec{k}, \vec{r}\right)$ where $\vec{k}$ is fixed at the Fermi surface.

We use a step function form for order parameter and exchange field as $\Delta\left(\vec{k}, \vec{r}\right) = \Delta(\vec{k})\theta(x)$, $h(\vec{r}) = h\theta(x)$ in a way that they are completely zero in quantum wire region whereas they get non-zero values in superconductor region.

The dependence of order parameter on temperature and exchange field is determined from the following self-consistent equations:

$$1 = \frac{\lambda}{2\pi}\int_0^{2\pi} d\phi \int_0^{\varepsilon_c} d\varepsilon \frac{\cos^2(2\phi)}{\sqrt{\varepsilon^2 + \Delta^2(T,h)\cos^2(2\phi)}}(g_+ + g_-) \quad (2)$$

Where λ is the electron–phonon coupling parameter and ε_c is the cut-off Debye energy, and $g_\pm$ is defined as:

$$g_\pm = \tanh\left[\frac{\sqrt{\varepsilon^2 + \Delta^2(T,h)\cos^2(2\phi)} \mp h}{2k_B T}\right] \quad (3)$$

From the above equations, we can find the dependence of order parameter on the temperature and exchange field.

At a finite temperature, the order parameter decreases with the increase of temperature in such a way that it has a sudden drop from a finite value to zero at a critical temperature and shows a first order phase transition which stems from the presence of an exchange field. It should be noted that at zero exchange field the superconducting transition is a second- order phase transition.

At zero temperature, Eqs. (2) and (3) indicate that order parameter does not depend on the exchange field and when the exchange field equals $\Delta_0(\Delta_0 = \Delta(T=0, h=0))$, the order parameter drops to zero. It means that at zero temperature $\Delta(h) = \Delta_0$ for $0 \le h \le \Delta_0$ and $\Delta(h) = 0$ for $h > \Delta_0$.

Nevertheless, it is shown in Refs. [26,27] that the allowable values for the exchange field are just for $0 \le h \le 0.56\Delta_0$. In fact for $h > 0.56\Delta_0$ the normal state has lower energy than the superconducting state and the stable state becomes the normal state. In the exchange fields less than $0.56\Delta_0$, the calculation of thermodynamic potential of