Josephson effect in superconducting junctions with different types of magnetic barrier between the superconductors

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Abstract

Microscopic theory of Josephson effect in S-MB-S junctions (S denotes bulk superconductor, MB - magnetic barrier) with different types of MB is presented. The junctions with MB created by uniformly polarized ferromagnetic metal (F)- or ferromagnetic insulator-layer and also with MB created by FNF or FIF structures (N being the normal metal, I is the insulating layer) for arbitrary mutual orientation of the exchange field (parallel to the FS interfaces) in the F layers are investigated. The conditions of the transition from conventional ("0-type") to π-type of junctions are studied. The cases of ballistic and diffusive electron transport are investigated. For ballistic junctions the effect pair-breaking in the S electrodes on the Andreev discrete states and on the supercurrent are studied.

Key words: Josephson effect; magnetic barrier; Andreev discrete states

1. Introduction

In the last years, there is a growing interest to the investigation of spin-dependent transport in hybrid superconductor-ferromagnet (S-F) structures. Especial interest is drawn to the study of Josephson junctions (JJ) with magnetically active S or hybrid S/F electrodes and also to JJ with magnetic barriers (MB) between the S electrodes (see [1] and references therein). There are different reasons of such interest related, in particular, with the possibility of the realization of π-type of junctions and the possible enhancement of the supercurrent due to the presence of the exchange field in the electrodes or in MB.

The purpose of this work is the study the Josephson effect in S-MB-S junctions, where MB is a short (in comparison with the superconducting coherence lengths) channel describing by different types of the transfer matrix $\hat{\mathbf{M}}$. For the case of ballistic transport the Green's functions may be found for arbitrary transfer matrix $\hat{\mathbf{M}}$, using equations for the components of the quasiclassical Green's functions in the directional space $\check{G}_{\alpha\beta}$ $(\alpha,\beta = \pm 1)$ [2](a), [3]. The result has a compact form being written with the use of the supermatrix $\check{\mathbf{G}} = \left\| \alpha \check{G}_{\alpha\beta} \right\|$. Using the boundary conditions connecting Green's functions $\check{\mathbf{G}}(\pm)$ at different sides of the barrier [3] after calculations similar to those carried out in the author's work [2](a) we found the compact expression [2](b) $\check{\mathbf{G}}(-) = (\check{\mathbf{G}}_+)^{-1}(\check{\mathbf{I}} + \check{\mathbf{G}}_-)$, where $\check{\mathbf{G}}_\pm = (\check{\mathbf{G}}_1 \pm \check{\mathbf{G}}_2)/2, \check{\mathbf{G}}_1 = \check{G}_1\hat{\Gamma}_3, \check{\mathbf{G}}_2 = \hat{\mathbf{M}}\check{G}_2\hat{\Gamma}_3\hat{\mathbf{M}}^{-1}$, $\check{G}_{1,2}$ are the equilibrium Green's functions of the electrodes, $\hat{\Gamma}_3$ $(\hat{\Gamma}_j)$ is the Pauli matrix in the directional space (the direct matrix product is implied in the expressions). We applied these result for calculations of the current for different types of MB. One of the important case corresponds MB with uniformly polarized exchange field. Then $\hat{\mathbf{M}}$ may be represented in the following form $\hat{\mathbf{M}} = \frac{1}{2}(\hat{\sigma}_0 + \hat{\sigma}_3)\exp(i\theta\hat{\Gamma}_3)\hat{M}_\uparrow \exp(i\vartheta\hat{\Gamma}_3) + \frac{1}{2}(\hat{\sigma}_0 - \hat{\sigma}_3)\hat{M}_\downarrow$, where $\hat{\sigma}_3$ $(\hat{\sigma}_0)$ is the Pauli (unit) matrix in the spin space, and $\hat{M}_\nu = [\hat{\Gamma}_0 + \sqrt{R_\nu}\hat{\Gamma}_1]/\sqrt{D_\nu}$, $D_\nu = 1 - R_\nu$ $(\nu = \uparrow, \downarrow)$ is the transparency of the barrier corresponding ν-orientation of the electron spin, $\theta = \theta_\uparrow - \theta_\downarrow$ and $\vartheta = \vartheta_\uparrow - \vartheta_\downarrow$ are the phase shifts. Using the found expression for $\check{\mathbf{G}}$ we calculated the dc su-

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percurrent dependence on the order parameter phase difference φ and obtained the expression

$$eR_N I(\varphi) = C\hbar\Delta \sin\varphi F(\varphi), \quad (1)$$

where $F(\varphi) = \Delta T \sum_{n=0}^{\infty}(\Delta^2 u_n^2 \cos\psi_+ + \varepsilon_+\varepsilon_-)/(\Delta^2 u_n^2 + \varepsilon_+^2)(\Delta^2 u_n^2 + \varepsilon_-^2)$. Here Eq.(1) is written for the model of the transfer matrix independent on the momentum direction (as it takes place for a single-mode constriction). Then $C = 4\pi\sqrt{D_\uparrow D_\downarrow}/(D_\uparrow + D_\downarrow)$, the normal state resistance of the junction, $R_N = 2R_0/(D_\uparrow + D_\downarrow)$, R_0 is the resistance in the absence of the barrier, $\varepsilon_\mu = \Delta\cos(\Phi_\mu)$, $\Phi_\mu = \Phi + \mu\psi_+/2$ $(\mu = \pm)$, $2\Phi = \arccos[\sqrt{D_\uparrow D_\downarrow}\cos\varphi + \sqrt{R_\uparrow R_\downarrow}\cos\psi_-]$, $\psi_\pm = 2(\theta \pm \vartheta)$, $\omega_n = \pi T(2n+1)$, $u_n \equiv u(\omega_n)$ the function $u(\omega) \equiv u$ determines the Matsubara Green's functions of the S electrodes, $g = u/\sqrt{u^2+1} = uf$. For barriers with spatial left-right (LR) reflection symmetry, due to the relation between the phase shifts θ_ν and ϑ_ν [4], we have $\psi_+ = 2(\Theta - s\pi)$, $\psi_- = 2s\pi$, $s = 0, \pm 1$, i.e. $\cos\psi_- = 1$ and the current depends only on a single phase shift Θ. For the case of the S electrodes with the "ideal" BCS quasiparticle spectrum the supercurrent is carried via Andreev discrete states (DS) corresponding the energies $\pm|\varepsilon_\mu|$ and is given by the expression (1), where $F(\varphi) = [4\sin(2\Phi)]^{-1}\sum_{\mu=\pm}\sin(\Phi_\mu)\tanh(\varepsilon_\mu/2T)$. Note that for spin-independent transparency and LR-symmetric barrier our expression for $I(\varphi)$ corresponding BCS quasiparticle spectrum reduces to the one found in [1] (b). The free energy of the junction $\Omega(\varphi) = -\frac{\hbar}{2e}\int_0^{\varphi} d\varphi_1 I(\varphi_1)$ shows that the transition from 0 to π-state can occur at temperature $T_{0\pi}$, determined by the parameters of the barrier $D_{\uparrow,\downarrow}$ and $\psi_\pm$. Similar to conclusions of Refs.[1] (b), (c) we found that the critical current for small $D_\uparrow$, $D_\downarrow$ may exhibit non-monotonous $I_c(T)$ dependence with the cusp but in the absence of LR symmetry ($|\cos\psi_-| \neq 1$) the function $I_c(T)$ becomes monotonous. We found also that the value of $I_c(T)$ may be enhanced by the exchange field [1] (a),(b) and exceed the value $I_c(0)$ for conventional barrier (with the same resistance): it is possible at low $T \ll \Delta$ in some intervals of ψ_+ near $\psi_+ = \pi$. The important problem is the study of the effect on the current of quasiparticle spectrum deviation from the BCS form. This problem was investigated by taking into account the effect of pair-breaking (PB) in the S electrodes. For one of the universal dependences of the spectrum on the PB parameter γ, when $\omega/\Delta = u\left[1 - \gamma/(1+u^2)^{1/2}\right]$, one gets that (for given $\psi_\pm$) the number of Andreev DS may be equal to 4 or 2 and the intervals of φ, where the DS exist are determined by the condition $|\sin(\Phi_\mu)| > \gamma^{1/3}$; the position of the DS corresponds the energies $\pm\Delta|\cos(\Phi_\mu)|\,[1 - \gamma/|\sin\Phi_\mu|]$. It should be emphasized that even weak PB ($\gamma \ll 1$) may affect strongly the position and the number of the DS and modify the qualitative form of $I(\varphi)$ and $I_c(T)$ dependences.

We applied our method for calculation of the dc supercurrent in the ballistic junctions with MB created by the FNF structure which may be considered as a channel with two magnetic barriers. We found the supercurrent for arbitrary angle χ between the exchange fields (parallel to the F/S interfaces) in the F layers. For parallel and antiparallel alignment of these fields and small length of the N layer ($d \ll \hbar v_F/\Delta$) the current reduces to the relatively simple expression (1), in which D_μ and $\psi_\pm$ are now correspond to the parameters of the double-barrier structure that depend on the exchange fields alignment. The mentioned above features of the supercurrent turn out to be particularly interesting for such junctions because of high sensitivity of the current to the influence of the magnetic field that manifests itself even in the normal state due to the effect of the giant magnetoresistance.

We studied also the dc supercurrent in the junctions with MB created by the diffusive channel FcF (the mean free path l is small in comparison with its length d_F), where c is a short constriction with nonmagnetic barrier of arbitrary transparency D. Calculation of the current for the case of short length of the F regions, $d_F \ll \xi_F$, $\sqrt{\hbar D_F/h}$, where D_F is the diffusion constant and h is the exchange energy. Carrying out calculations on the basis of the theory developed in Refs.[2] (a),(c) we found supercurrent-phase relationship for arbitrary angle χ between the exchange fields (parallel to the F/S interfaces) in the F regions. For particular case $\chi = 0$ our results reduce to those found recently in Ref.[1] (e). Note that the dependence of the supercurrent on $\cos\chi$ turns out to be rather nontrivial (if D is not small) and significantly deviates from that for junctions with small transparency [1] (a).

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