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The theory of long-range Josephson current through a single-crystal ferromagnet nanowire

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ABSTRACT

Theoretical model of the singlet long-range Josephson transport is proposed. Taking into account the mismatch of the electron effective masses of majority and minority spin subbands the Eilenberger-like equations are obtained with renormalized effective exchange interaction. The critical Josephson current is calculated through ferromagnet nanowire. It is shown that the effective exchange field can be completely compensated and thereby the long-range spatial supercurrent arises. Within the proposed theoretical model, the long-range proximity effect observed in the Co single-crystalline nanowire (Wang et al., 2010) can be qualitatively understood.

1. Introduction

Due to the proximity effect [1] in artificial superconductor (S) – ferromagnet (F) structures the induced singlet superconducting correlations can penetrate into the F region, strongly exponentially decay and oscillate at length $\xi_h = \sqrt{D/h}$ for dirty limit, where D is diffusion constant and h is exchange field in ferromagnet. For conventional ferromagnets such as Co, Fe, Ni, *etc.* this decay length is very small, $\xi_h \sim 1 \div 10\,\text{nm}$. The corresponding penetration depth for the non ferromagnet (N) metal, $\xi_N = \sqrt{D/2\pi T}$ (T is temperature), is much greater than in F metal, and ξ_N can reach $0.1 \div 1\,\mu\text{m}$. The strong suppression of induced superconductivity in F metals is caused by relatively large value of the exchange field $h \gg T$. This field tends to parallel electron spins, destroying superconducting spin-singlet Cooper pairs with antiparallel spins. It is well-known as pair breaking effect of the exchange field, this effect is clearly seen experimentally and it corresponds to the simple picture of the destruction of the singlet superconductivity by the exchange field [2–4]. An oscillatory part of superconductivity induced in F metal links with the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) pairing [5,6], when the electrons with different values of momentum can be combined into pair in F metal and the inhomogeneous gapless FFLO-like superconducting state can appear [2–4].

However the superconducting correlations can penetrate sufficiently deep into a F region when they become insensitive to exchange field, and $\xi_h \sim \xi_N$. It is called a long-range proximity effect, it can be occurred when the exchange field is essentially inhomogeneous. In this case the superconducting *triplet* correlations appear with total spin projection $S_z = \pm 1$ [3,4,7]. The triplet long-range proximity effect can be realized in the FS multilayers with noncolinear magnetizations in different F layers [8–12], in the presence of a spin-active interface [13] or domain walls [14–16].

Not long ago Wang et al. [17] firstly observed the long-range *singlet* proximity effect for clean SFS structure. They investigated the transport properties of the single-crystal ferromagnetic cobalt nanowire sandwiched between superconducting wolfram electrodes. The most striking features of the cited work were (a) the zero resistance was detected at the excitation current about of 1 μA at wire length of $L = 600\,\text{nm}$ (the magnitude of the critical current I_c at zero magnetic field for 40 nm-diameter Co nanowire is equal about $I_c \approx 12\,\mu\text{A}$); ($b$) the Co wires did not contain any magnetic inhomogeneities, they were monocrystal and monodomain.

The first theoretical attempt to explain this long-range proximity-induced superconductivity in nanowire [18] was undertaken by Konschelle et al. The authors [18] basing on the Eilenberger equations [19] have obtained that the standard singlet SF proximity effect becomes long ranged in ballistic regime for one-dimensional (1D) F wire. Their single-channel critical current was proportional $I_{c0} \sim \cos(L/a_f)$, which exhibits undamped strong oscillations on the spin stiffness length $a_f = v_F/2h \sim 1 \div 10\,\text{nm}$.

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