Magnetic-field-induced supercurrent enhancement in hybrid superconductor/magnet metal structures

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Abstract

The dc transport properties of the (S/M)I(M/S) tunnel structure - proximity coupled superconductor (S) and magnetic (M) layers separated by an insulator (I) - in a parallel magnetic field have been investigated. We choose for the M metal the one in which the effective magnetic interaction, whether it arises from direct exchange interaction or due to configuration mixing, aligns spins of the conducting electrons antiparallel to the localized spins of magnetic ions. For tunnel structures under consideration, we predict that there are the conditions when the destructive action of the internal and applied magnetic fields on Cooper pairs is weakened and the increase of the applied magnetic field causes the field-induced enhancement of the tunnel critical current. The experimental realization of the novel interesting effect of the interplay between superconducting and magnetic orders is also discussed.

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With recent experimental observations of the $\pi$-phase state with the critical current inversion in superconductor (S) - ferromagnet (F) hybrid structures [1-3] and theoretical prediction of the supercurrent enhancement in SF tunnel structures with very thin F layers [4-6], systems exhibiting a nontrivial interplay between magnetism and superconductivity attract a lot of attention. A common drawback of the FS systems is that, in ferromagnetic metals, the exchange field acting on the spin of conducting electrons is in general so large as to suppress superconductivity. Several options of how to enhance the superconductivity of nanoengineered SF structures have recently been discussed in the literature. In particular, magnetic-field-induced superconductivity is predicted and observed [7] in superconductor/lattice-of-magnetic-nanodots system due to the compensation of the applied field between the dots by the stray field of the dipole array.

In the general case, when an external magnetic field is applied, superconductivity is suppressed due to both orbital and spin pair breaking effects. However, there are magnetic metals, such as (EuSn)Mo$_6$S$_8$ [8,9] or (MoMn)Ga$_4$ [10] where the applied magnetic field can induce superconductivity. Several mechanisms that may enable superconductivity to develop in such materials have been investigated in more or less detail (see [11,12] and references therein). In the pseudoternary compounds, field induced superconductivity is assumed to be due to the so-called Jaccarino-Peter compensation effect [13]. It takes place in ferro- or paramagnetic metals where, due to Hund coupling energy, the exchange interaction, $J_s S$, orients the spins $s$ of the conducting electrons antiparallel to the spins $S$ of rare earth magnetic ions. In such magnetic metals, the effective field acting on the spin of conducting electron is $H + J < S >$ with $J < 0$. I.e., the exchange field $J < S >$ can be reduced by the external magnetic field $H$ and the destructive action of both fields on the conducting electrons can be weakened or even canceled. If, in addition, these metals posses an attractive electron-electron interaction, it is possible to induce bulk superconductivity by magnetic field.

In this report, we investigate a way to enhance the superconducting properties of proximity coupled superconductor-magnetic (M) metal hybrid structures by choosing the M metal with some specific properties. Namely, we suppose that in the M film, due to Hund rules, the localized magnetic moments of the ions, oriented by magnetic field, exert the effective interaction, $H_E$, on spins of the conduction electrons. The latter, whether it arises from the usual exchange interaction or due to configuration mixing, is the antiferromagnetic type. In particular, such material can be a thin layer of the pseudoternary compounds like (EuSn)Mo$_6$S$_8$ or dilute superconducting systes as Mo$_{77}$Ir$_{23-x}$Fe$_x$ [12], or some ferromagnetic intermetallic compounds. (While experimentally the compensation effect was observed [11,12] for paramagnets, the Jaccarino-Peter mechanism is applicable both to ferromagnetic and paramagnetic metals, and both type of the orders will be assumed here.) There are no specific requirements to the superconductor, so that it can be any superconducting film proximity coupled with the M metal. We will consider the layered S/M system under the effect of
a parallel magnetic field. It should be noted that the applied magnetic field is too weak to induce the superconducting properties through the Jaccarino-Peter scenario, if the M metal is the pseudoternary compound, i.e., we suppose that superconductivity of the M metal is due to proximity effect. To be definite, we calculate the dc critical current of the tunnel structure where both electrodes are proximity coupled S/M bilayers in weak external magnetic field. It will be demonstrated that in the region where the destructive action of the fields is decreased, an increase of the magnetic field causes the enhancement of the Josephson critical current.

The system we are interested in is the (S/M)I(M/S) tunnel structure of the superconducting S/M bilayers separated by an insulating barrier (I) (see fig.1). Let us assume that both films are very thin: i.e., \( d_S < (\xi_S, \lambda_S) \), \( d_M < (\xi_M, \lambda_M) \). Here \( \xi_{S(M)} \) is the superconducting coherence length of the S(M) layer; \( \lambda_{S(M)} \) is the London penetration depth of the S (M) layer. To tackle the physics, we will suppose that the S and M metals are in good electric contact and the transparency of the insulating layer is small enough to neglect the effect of a tunnel current on the superconducting state of the electrodes. Longitudinal dimension of the junction, \( W \), is supposed to be much less than the Josephson penetration depth, \( W \ll \lambda_J \), so that a flux quantum can not be trapped by the junction.

As far as the thicknesses of the films are small, it is reasonable to assume that magnetic field is homogeneous in the S/M bilayer. The conditions ensure also that the orbital effects can be neglected. Also, in the limit \( d_S < \xi_S \), \( d_M < \xi_M \), the influence of the M layer on superconductivity in the S/M bilayer is not local and is equivalent to inclusion of a homogeneous exchange field with a reduced value. Other physical quantities characterizing the S metal in the S/M bilayer should be modified, as well. Such an approach was recently discussed in [4,14] for SFIFS structures, and, as was demonstrated, under these assumptions, a thin S/F bilayer is equivalent to a superconducting ferromagnetic film with a homogeneous superconducting order parameter and an effective exchange field. Similarly, we can characterize the S/M bilayer by the effective values of the superconducting order parameter \( \Delta_{ef} \), the coupling constant \( \gamma_{ef} \) and the exchange field \( H_{Eef} \) described by the relations:

\[
\frac{\Delta_{ef}}{\Delta_0} = \frac{\gamma_{ef}}{\gamma} = \frac{\nu_S d_S (\nu_S d_S + \nu_M d_M)^{-1}}{1}, \quad (1)
\]

\[
\frac{H_{Eef}}{H_E} = \frac{\nu_M d_M (\nu_S d_S + \nu_M d_M)^{-1}}{1}, \quad (2)
\]

where \( \nu_S \) and \( \nu_M \) are the densities of quasiparticles states in the superconductor and magnetic metal, respectively; \( \Delta_0 = \Delta(0,0) \) is the BCS value of the superconducting order parameter of the S metal at \( T = 0 \) in the absence of the applied magnetic field, \( \gamma \) is the coupling constant in the S metal. If the M metal is the pseudoternary compound and can posses a nonzero electron-electron interaction, we will neglect this interaction, so that the relations (1) remain valid in the case as well.

The low transparency of the junction barrier allows to use the relation of the standard tunnel theory [15]. According to this theory, the distribution of
the Josephson current density $j_T(x)$ flowing in z-direction through the barrier takes the form $j_T(x) = j_C \sin \varphi(x)$, where $\varphi(x)$ is the phase difference of the order parameter across the barrier. In the case of a finite electrode thickness, the phase difference of the order parameter is described by the well known equations [16]. The Josephson current density maximum, $j_C$, is determined by the electrode properties and here we focus on calculation of the $j_C$.

Assuming that the exchange field $H_{ef}$ and the external magnetic $H$ field act only on the spin of electrons, and in the conventional singlet superconducting pairing, we can write the Gor’kov equations for the S/M bilayer in the magnetic field in the form:

\begin{align}
[i\varepsilon_n - \xi - (H_{ef} - H)]G_{\sigma\uparrow} + \Delta_{\sigma\uparrow}F_{\sigma\uparrow} &= -1, \\
[i\varepsilon_n + \xi - (H_{ef} - H)]F_{\sigma\uparrow} + \Delta_{\sigma\uparrow}G_{\sigma\uparrow} &= 0,
\end{align}

where $\xi = \varepsilon(p) - \varepsilon_F$, $\varepsilon_F$ is the Fermi energy, $\varepsilon(p)$ is the quasiparticle spectrum, $\varepsilon_n = \pi T(2n + 1)$, $n = 0, \pm 1, \pm 2, \pm 3, \ldots$ are Matsubara frequencies; $T$ is the temperature of the junction (we have taken the system of units with $\hbar = \mu_B = k_B = 1$); $G_{\sigma\uparrow}$ and $F_{\sigma\uparrow}$ are the normal and anomalous Green functions, and $\uparrow, \downarrow$ (or $\sigma = \pm 1$ in eqs. (6), (7), below) is spin variable. The additional set of equations for $G_{\sigma\downarrow}$ and $F_{\sigma\downarrow}$ can be readily written down from symmetry arguments. The equations are also supplemented with the well known self-consistency equations for the pair potential $\Delta_{\sigma}(T, |(H_{ef} - H)|)$. In our case one can easily obtain:

\begin{equation}
\ln \left( \frac{\Delta_0}{\Delta} \right) = \frac{\omega_D}{\omega_D + \Delta} \frac{1}{\exp((\sqrt{\Delta^2 + (H_{ef} - H)})/T) + 1},
\end{equation}

Here and below $\Delta \equiv \Delta_{\sigma}(T, |(H_{ef} - H)|)$; $\omega_D$ is the Debye frequency. If $H_{ef} = H$ the formula (5) is reduced to eq. (16.27) of Ref.17.

Following the Green’s function formalism, the (S/M)I(M/S) tunnel junction critical current can be written as follows:

\begin{equation}
I_C = (2\pi T/eR_N) \sum_{n, \sigma = \pm 1} f_{\sigma}(H_{ef} - H) f_{\sigma}^{\dagger}(H_{ef} - H),
\end{equation}

where $R_N$ is the contact resistance in the normal state and $f_{\sigma}$ are averaged over energy $\xi$ the anomalous Green functions $F_{\sigma\uparrow,\downarrow}$. One can easily find that:

\begin{equation}
f_{\sigma} = \Delta^{\dagger}(\varepsilon_n - i\sigma(H_{ef} - H))^2 + \Delta^2)^{-1/2}.
\end{equation}

Using eqs. (6) and (7), after summation over spin index we find for the reduced (i.e. $I_C eR_N(4\pi T^2:\Delta^2)^{-1}$) quantity

\begin{equation}
\frac{T}{T_C} \sum_{n > 0} \frac{\varepsilon_n^2 + \Delta^2 - (H_{ef} - H)^2}{\varepsilon_n^2 + \Delta^2 - (H_{ef} - H)^2 + 4\varepsilon_n^2(H_{ef} - H)^2}
\end{equation}
The Josephson critical current of the junction, as function of the fields and temperature, can be calculated using formula (8) and self-consistency equation (5) [18]. In the general case, the dependence of the superconducting order parameter on effective field can be complex enough due to the possibility of transition to the nonhomogeneous (Larkin-Ovchinnikov-Fulde-Ferrell) phase [19,20]. To keep the discussion simple, we will not touch upon this scenario here, restricting the consideration below to the region with the homogeneous superconducting state. Even in this case at arbitrary temperatures the values of the $\Delta_{ef}(T, |(H_{Eef} - H)|)$ can be determined only numerically. The phase diagram of a homogeneous superconducting state in the $H-T$ plane has been obtained previously [14]. At finite temperatures, it is found that $\Delta(T, H)$ has a sudden drop from a finite value to zero at a threshold of $H$, exhibiting a first-order phase transition from the superconducting state to normal state. Using the results of Li et al., from Eq. (5) we take only one branch of solutions, corresponding to a stable homogeneous superconducting state.

We are now able to analyze the critical current dependence on the fields value and temperature. Figure 2 shows the results of numerical calculations of the expression (8) for the Josephson critical current versus external magnetic field for the case of low $T = 0.05\Delta_0$ and medium $T = 0.2\Delta_0$ temperatures, and different values of the exchange field. As is seen in fig.2, for some interval of the applied magnetic field the enhancement of the dc Josephson current takes place in comparison with the case of $H = 0$. Note that, in the range of our formulas validity, the larger the effective field $H_{Eef}$ is, the larger growth of the critical current can be observed (compare the $j_C$ curves for $H_{Eef} = 0.25\Delta_0$ and $H_{Eef} = 0.6\Delta_0$ at $H = 0$ in fig. 2). This behavior is also predicted by the expression (8). A sudden break off in $j_C(H)$ dependences in the presence of $H$ results due to a first-order phase transition from a superconducting state with finite $\Delta$ to a normal state.

The magnetic-field enhancement of the critical current can be qualitatively understood using the simple fact that the Cooper pairs consist of two electrons with opposite spin directions. Pair–breaking effect due to spin-polarized electrons is weakened, if the applied field increased remaining $H \leq H_{Eef}$, since the spin polarizations from the exchange field of the magnetic ions and the applied field are of opposite signs and reduce each other. On the other hand, the paramagnetic effect is again increased, if the applied field increased for $H > H_{Eef}$. These dependencies determine the ($S/M$)I($M/S$) critical current behavior on the field in the region $0 \leq |H_{Eef} - H| < 0.755\Delta$.

We emphasize that the scenario of the applied field enhancement of the critical current differs from those studied before in [4,5,6,14] for SFIFS tunnel structures. Note that the exchange field may increase $j_C$ of the SFIFS junction for antiparallel mutual orientation of the layers magnetization and only at low temperatures $T \ll T_C$ [4,14]. In our case the mechanism described above is valid for full temperature region of the homogeneous superconducting state. To illustrate qualitative behavior at finite temperatures, let us consider the case with $(\Delta, |H_{Eef} - H|) \ll \pi T_C$. Direct calculation of eq. (8) gives then for the
critical current

\[ j_C(H, \Delta) \sim \frac{\Delta^2}{T \sqrt{\Delta^2 + (H_{Eef} - H)^2}} \text{th}(\frac{\sqrt{\Delta^2 + (H_{Eef} - H)^2}}{2T}), \]  

(9)

If \( \Delta \to 0 \) one obtains

\[ j_C(H) \sim \frac{\Delta^2}{T^2} \text{ch}^{-1}(\frac{H_{Eef} - H}{2T}), \]  

(10)

We also investigated [21] the case when only one electrode of a junction is magnetic and the mechanism [4-6,14] definitely does not work - the SMIS tunnel structures. The effect of magnetic-field-induced supercurrent enhancement is predicted for such structures as well.

In conclusion, using specific properties of a magnetic material, we have discussed a new way to enhance the superconductivity of superconductor - magnetic metal hybrid structures by magnetic field. The idea is quite straightforward: the magnetic metals are those where the effective magnetic interaction, whether it arises from an exchange interaction or due to configuration mixing, aligns the spins of the conducting electrons and the magnetic ions in opposite direction. There are no specific requirements to the superconductor proximity coupled with the magnetic metal. As predicted, magnetic-field-induced enhancement of superconductivity of such hybrid systems should be observed. To implement the idea, we consider the dc Josephson effect for the (S/M/I)(M/S) tunnel structure in parallel magnetic field. Using approximate microscopic treatment of the S/M bilayer we have demonstrated the effect of magnetic-field-induced supercurrent enhancement in the tunnel structures. This striking behavior contrasts with the suppression of the critical current by magnetic field. The existing large variety of magnetic materials, the ternary compounds in particular, should allow experimental realization of this interesting new effect of the interplay between superconducting and magnetic orders.
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18As far as $H_E = J < S >$, a self-consistency equation should be used for $H_{E_{ef}}$, as well. However, we will suppose that $H_{E_{ef}}$, being much smaller than in isolated M film, is still larger than $\Delta_{ef}(T, |H_{E_{ef}} - H|)$ for full temperature region of the homogeneous superconducting state. So, proceeding in the way to tackle the new physics, we will ignore the temperature dependence of the $H_{E_{ef}}$.
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Figure captions

7
FIG. 1. (S/M)I(M/S) system in a parallel magnetic field. Here S is a superconductor; M is a magnetic metal; I is an insulating barrier; W is longitudinal dimension of the junction.

FIG. 2. Critical current of the SMIMS tunnel junction vs external magnetic field for $T = 0.05\Delta_0$, $T = 0.2\Delta_0$ and different values of the effective exchange field in the S/M bilayer: $H_{E\text{eff}}/\Delta_0 = 0.0, 0.25, 0.4$ and 0.6.
Fig. 1

V. Krivoruchko
Fig. 2

V. Krivoruchko