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Proximity effect in heterosructures based on superconductor/half-metal system

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The study of two antagonistic phenomena in solids, superconductivity and magnetism, is a very actively studied problem in condensed matter physics. One important aspect of the research area is the interaction of these two phenomena in nanoscale heterostructures and multilayer structures in which the superconducting (S) and ferromagnetic (F) materials are in close contact with each other. These structures exhibit a so called S/F proximity effect, whose main properties have been studied for quite some time (for a review see, e.g., [1, 2]). Nevertheless, despite new activities in this area promise opening new frontiers in superconducting spin electronics (see, e.g., [3]), the proximity effect at the S/F interfaces is still far from being quantitatively understood. Furthermore, although in S/F heterostructures many combinations of materials are potentially possible to realize, the proximity effect at the interface between an S layer and the F layer made of a half-metallic ferromagnet (HMF), i.e., a ferromagnet with 100 % polarization of the conduction band, has not been experimentally studied so far to the best of our knowledge. This is quite striking since HMFs represent the class of materials which have recently attracted a considerable interest due to their possible applications in spin electronics.

The possibility to develop a superconducting spin valve (SSV) based on the S/F proximity effect has been theoretically substantiated in 1997 by Sanjiun Oh et al. [4]. They proposed the F1/F2/S layer scheme where an S film is deposited on top of two F-layers with decoupled magnetizations and concluded that temperature of superconducting transition (T_c) at the antiparallel (AP) mutual orientation of magnetization should be smaller than for the parallel (P) case. This is because the mean exchange field from two F layers acting on the Cooper pairs in the S layer is smaller for the AP configuration of the magnetizations of these layers compared to the P case. It took more than ten ears before a full switching between the normal and superconducting states of this device has been realized [5] meaning that the magnitude of the spin-valve effect $\Delta T_c = T_c^{AP} - T_c^{P}$ exceeds the width of the superconducting transition temperatures δT_c (here T_c^{AP} and T_c^{P} are the superconducting transition for AP and P mutual orientation of magnetizations of the F-layers, respectively).

At present, most of fundamental issues concerning the physics of the superconducting spin-valve effect seem to be clarified. Our recent studies as well as studies of other groups show that the use of elemental ferromagnets as construction materials for the superconducting spin-valve exhausts their functionality with regard to record parameters of the superconducting spin- valve. To overcome this limitation new unconventional ferromagnetic materials are required. We have concentrated our attention on the spin-valve construction containing the Heusler alloy (HA) $Co_2Cr_{1-x}Fe_xAl_y$ which in principle may have 100 % spin polarization of the conduction band for the optimal preparation conditions.

The major goals of the present work are: (a) understanding the processes taking place at the interface between a superconductor and a half-metallic ferromagnet; (b) a comprehensive study of the spin-valve effect and triplet pairing induced by the S/F proximity effect for F1/F2/S heterostructures containing the HA $Co_2Cr_{1-x}Fe_xAl_y$ as one of two ferromagnetic layers.

We used HA $Co_2Cr_{1-x}Fe_xAl_y$ as half-metallic ferromagnet in our research. The choice of HA is determined by the possibility to change easily the degree of the spin polarization (DSP) of the conduction band by changing, e.g., the substrate temperature during the growth of the HA film (see, e.g., [6]). It is suggested that for the optimal preparation conditions one can reach 100 % DSP in such a film (see, e.g., [7]). In fact, the maximal DSP in our samples amounted to 70 %. In particular, our experimental finding suggests that the superconducting Cooper pairs are predominantly reflected from the S/HMF interface thus favoring the theoretical con-

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cept by Takahashi et al. [8]. We demonstrated that with increasing the exchange splitting of the conduction band of a ferromagnet and, respectively, of the degree of the spin polarization, the probability of transmission of the superconducting Cooper pairs through the S/F interface decreases. We concluded that the spin imbalance plays a key role in the processes taking place at the interface between a superconductor and a ferromagnet with spin-polarized conduction electrons.

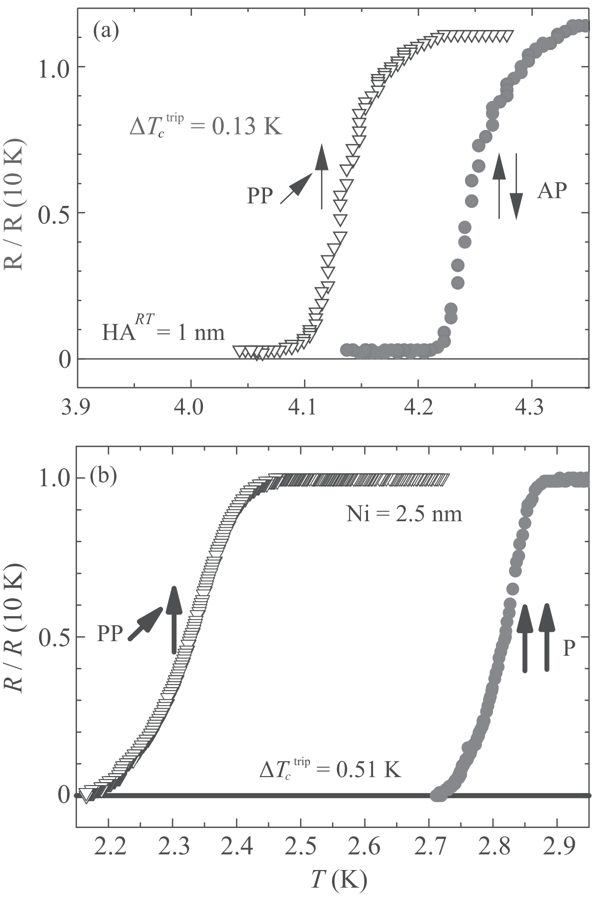

Fig. 1. Superconducting transition curves for different mutual orientations of the magnetizations of F layers in external magnetic field H_0 for two samples: (a) – sample CoO_x(3.5nm)/Py(5nm)/Cu(4nm)/HA^{RT}(1nm)/-Cu(2.5nm)/Pb(80nm) at $H_0 = 1.0$ kOe (for AP and PP) and (b) – sample HA^{hot}(20nm)/Cu(4nm)/Ni(2.5nm)/Cu(1.5nm)/-Pb(105nm) at $H_0 = 3.5$ kOe (for P and PP)

In general, in order to get the maximal magnitude of the spin-valve effect ΔT_c and of the amplitude of the long-range triplet component (LRTC), two conditions should be fulfilled. The first and the main condition is that the thickness of the F2 layer d_{Fe2} proximate to the S layer should be smaller than the penetration depth of the Cooper pairs into the F2 layer $\xi_h = \sqrt{\hbar D_f/h}$ (where D_f is the diffusion constant of conduction electrons in the F layer and h is the exchange splitting of conduction band of ferromagnet). This is necessary in order to have more Cooper pairs between the F1 and F2 layers, where the compensation of the exchange fields from F1 and F2 layers at the antiparallel mutual orientation of their magnetizations takes place. The condition $d_{F2} < \xi_h$ is not easy to fulfill. For elemental ferromagnets such as Fe, Co, Ni the value of h amounts approximately to 1 eV. This gives $\xi_h \leq 1$ nm. Fabrication of the continuous films with a thickness $d_{F2} < 1$ nm is a complicated task. Therefore, one has to choose a ferromagnet with a much smaller value of h, i.e., this should be a weak ferromagnet with $h \ll 1$ eV. The second condition to be satisfied is that the DSP of the F1 layer should be as large as possible. The paper by Singh et al. [9] proposes a half-metallic ferromagnet as a highly efficient F1 layer. Both requirements for high performance of the F1/F2/S spin valve can be satisfied using a HA. We used HA in two roles: as a weak ferromagnet on the place of the F2 layer and as a half-metal on the place of the F1 layer. In the first case, we obtained the full switching between the normal and superconducting states that was realized with the dominant aid of the long-range triplet component of the superconducting pair condensate which occurs at the perpendicular mutual orientation of magnetizations (see Fig. 1a). In the second case, we observed separation between the superconducting transitions for perpendicular and parallel configurations of magnetizations reaching 0.5 K (see Fig. 1b).

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