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The superconducting spin-valve and triplet superconductivity

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Immediately after the first observation of indication of the long-range triplet component (LRTC) when studying the angular dependence of the superconducting transition temperature T_c in CoO_x/Fe1/Cu/Fe2/Pb spin-valve structure [1] we have found the sample degradation on a time scale of a week. This prevented a long-term detailed study of the properties of the samples. We suppose that this degradation is caused by the absence of wettability of Fe and Pb at the Fe2/Pb interface. To overcome this problem we introduced the copper interlayer into the Fe2/Pb interface. This gave us a possibility to improve considerably the stability of the superconducting properties of the samples [2] and to perform a comprehensive study of the physical properties of the spin valve excluding the restrictions which appeared in the analysis of data in our previous paper [3]. All microscopic parameters which were used in this analysis were obtained from the normal-state transport properties and from Pb-layer critical thickness $d_{\rm Pb}^{\rm crit}$ which is defined as the thickness below which there is no superconductivity in the S/F bilayer. It was found that the copper interlayer leads to improvement of the quality of the interface in terms of ease penetration of the Cooper pairs from the superconductor in the ferromagnet. Thus, the design of the samples for the study of the spin-valve effect and LRTC induced by the proximity effect was chosen as MgO(001)/CoO_x/Fe1/Cu/Fe2/Cu/Pb. In this construction MgO(001) is a high quality single crystalline substrate, cobalt oxide antiferromagnetic layer plays a role of the bias layer which pins the magnetization of the F1 layer; Fe stands for the ferromagnetic F1- and F2-layers; Cu as a normal metallic N-layer which decouples the magnetizations of F1- and F2-layers; finally Pb is an S-layer. All samples were were magnetically characterized using a 7T VSM SQUID magnetometer. Magnetic hysteresis loops were measured at $T = 10$ K with the magnetic field in the film plane. First, the sample was cooled down from 300 to 10 K in the presence of the in-plane magnetic field +4 kOe. At 10 K the magnetic field was varied from +4 kOe down to −6 kOe and back again. During this variation the in-plane magnetic moment of the sample was measured. It turns out that for most of the CoO_x/Fe1/Cu/Fe2/Cu/Pb structures the magnetic field of about ±500 Oe is enough to get fully saturated magnetization of the free Fe2 layer while the magnetization of the Fe1 layer remains fixed up to the operating field of the order of −1.5 kOe. This means that the switching field $H_0 = 500$ Oe is sufficient to sustain a homogenous magnetization for the Fe2 layer following the switching field direction without formation of the domain structure. The $\Delta T_c(d_{\rm Fe2})$-dependence exhibits a well-defined sign-changing oscillating behavior. First, at $d_{\rm Fe2} = 0.5$ nm the ΔT_c has a maximum of +40 mK. The positive value implies the direct effect, $T_c^{\rm AP} > T_c^{\rm P}$. An increase of $d_{\rm Fe2}$ value causes a reduction of ΔT_c down to 0 mK around $d_{\rm Fe2} = 0.8 \div 1$ nm. Notably, when $d_{\rm Fe2}$ increases further above 1 nm, the ΔT_c falls down to a negative minimum of −15 mK at $d_{\rm Fe2} \sim 1.3$ nm and then rises up back to 0 at $d_{\rm Fe2} \sim 1.5$ nm.

The triplet spin-valve effect in F1/F2/S systems manifests itself in a non-monotonic variation of the T_c value upon a continuous change of the angle α between magnetizations of the F1 and F2 layers from 0 to 180°, with a minimum of T_c corresponding to a noncollinear orientation. This feature is a fingerprint of the LRTC arising in the system. This component is generated from the short-range triplet component at the F1/F2 interface. In its turn, the short-range triplet component with zero projection of spins is generated from the conventional singlet Cooper pairs penetrating from the S layer into the magnetic part of the structure. The result of this proximity effect is a decrease of T_c due to "leakage" of Cooper pairs from the S layer. The "leakage channel" caused by the generation of LRTC at the F1/F2 interface should be sensitive to the number of Cooper pairs reaching the interface. Hence, the magnitude of the triplet spin-valve effect is sensitive to the F2 layer thickness. The deepness of the T_c minimum rises up to 67 mK when the $d_{\rm Fe2}$ decrease down to 0.8 nm. This value for Fe/Cu/Pb systems is by 30 % higher than for Fe/Pb based samples. Such difference can be obviously attributed to a higher transparency of the Fe/Cu/Pb interface as compared to that of the Fe2/Pb. An increase of $d_{\rm Fe2}$ leads to a decrease of the effect. The physics

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of this decrease is obviously related to the suppression of the singlet components' amplitude at the Fe1/Fe2 interface which serves as a source for the triplet components. Our analysis shows the maximal effect should occur at d_{Pb} less than 0.5 nm. With the available experimental set-up we have failed to prepare the samples with an iron layer thickness of 0.4 nm or smaller. This is associated with the fact that the iron layer of such a thickness becomes discontinuous due to the initial island growth, and its influence on the superconductivity becomes ambiguous. The universal coordinate in the dependence $\Delta T_c(d_{\mathrm{Fe1}}, d_{\mathrm{Fe2}})$ is the ratio d_{Fe}/ξ_h. This suggests that, in order to reach the range of F-layer thicknesses achievable in our case, it is necessary to increase the penetration depth $\xi_h = (\hbar D_{\mathrm{F}}/h)^{1/2}$, where D_{F} and h are the diffusion coefficient of conduction electrons and exchange field in the F layer. Consequently, for the observation of the theoretically predicted maximum of the superconducting spin-valve effect ΔT_c, it it is necessary to choose a ferromagnet characterized by a weaker exchange field h as compared to iron. The first and simplest step in this direction was to use permalloy ($\mathrm{Py} = \mathrm{Ni}_{0.81}\mathrm{Fe}_{0.19}$), even though, a priori, it is not obvious that the exchange field h in permalloy is weaker than that in iron. Nevertheless, our investigations of the dependence of the critical temperature T_c on the permalloy-layer thickness demonstrated that the exchange field in the permalloy is approximately two times smaller than that in iron. This means that ξ_h for permalloy is of the order of 1.1 nm. For this system we studied the triplet pairing induced by the proximity effect. In order to determine experimentally the influence of the morphology of the superconducting layer, we measured the dependences of T_c on the thickness of the lead layer d_{Pb} for the Py/Pb and Py/Cu/Pb structures with the rough and smooth superconducting layers at a fixed thickness $d_{\mathrm{Py}} = 5$ nm, which significantly exceeds the penetration depth ξ_h of Cooper pairs into the ferromagnetic permalloy. The $T_c(d_{\mathrm{Pb}})$ dependences also demonstrate that the morphology of the superconducting layer of the samples does not affect the T_c-suppression.

For the structures with a rough superconducting layer upon switching between the antiparallel and parallel orientations of the magnetizations of the ferromagnetic layers, ΔT_c was found to be less than 10 mK. At the same time, for the spin-valve structure with a smooth superconducting layer, the magnitude of the spin-valve effect ΔT_c reached 100 mK or even more.

We have studied the CoOx/Py1/Cu/Py2/Cu/Pb superconducting spin-valve samples with variable thicknesses of the Py2 layer d_{Py2} and smooth superconducting layer. Magnetic measurements suggest that, after cooling the sample in a magnetic field, the parallel and antiparallel orientations can be reliably achieved by applying magnetic fields of +0.1 and −0.1 kOe, respectively.

Further, we analyzed the dependence of T_c on the angle α between the magnetizations of the Py1 and Py2 ferromagnetic layers in the magnetic field $H_0 = +100$ Oe applied in the plane of the sample. The most interesting results on the dependence $T_c(\alpha)$ were obtained for the structures CoOx/Py(3)/Cu(4)/Py(0.6)/Cu(2)/Pb(70) and CoOx/Py(3)/Cu(4)/Py(3)/Cu(2)/Pb(70). The angular dependences of T_c of these samples have a nonmonotonic behavior. The dependence $T_c(\alpha)$ passes through a minimum in the range between the parallel ($\alpha = 0°$) and antiparallel ($\alpha = 180°$) orientations in the vicinity of the orthogonal configuration of the magnetizations. For the sample with $d_{\mathrm{Py}} = 0.6$ nm the magnitude of the superconducting spin-valve effect ΔT_c exceeds the width of the superconducting transition. Consequently, in this structure, there is a possibility of a complete on/off switching of the superconducting current. The complete on/off switching of the superconducting current due to a combination of the conventional and triplet spin-valve effects indeed was found. The temperature dependence of the electrical resistivity $\Delta R = R(\alpha = 90°) - R(\alpha = 180°)$ indicates that the complete switching $\Delta R/R(10\,\mathrm{K}) = 1$ between the antiparallel and perpendicular configuration is observed.

The results obtained in this study show that the studied spin-valve heterostructures represent the promising candidates for the development of the devices for the superconducting spintronics in which the triplet Cooper pairs carry not only the charge but also polarized spin.

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