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* In Kazan University the Electron Paramagnetic Resonance (EPR) was discovered by Zavoisky E.K. in 1944.

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Superconducting spin-valves in spintronics

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A brief review of investigations carried out in recent years by teams of the Laboratory of Physics of Magnetic Nanostructures and Spintronics and the Laboratory of the Synthesis and Analysis of Thin-Film Systems is presented.

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Our manuscript is dedicated to the 85th anniversary
of our dear Teacher, Professor B.I. Kochelaev

1. Introduction

The term “spintronics” (SPIN Transport ElectrONICS), introduced in 2000 [1,2], denotes the field of electronics intended for manufacturing of devices whose electrical characteristics are controlled by changing their spin states. The appearance of spintronics is usually associated with observation of the effect of giant magnetoresistance (GMR, 1988) in three-layer and multilayer metallic F/N structures (F, N are ferromagnetic and normal metals, respectively) [3,4]. Indeed, this discovery, firstly, initiated a tremendous increase of research in this area, and secondly, it found an application in the decade after, based on reading heads for hard disks raising the information storage capacity to a new revolutionary high level. However, it was emphasized in [5,6], the basic research that can be attributed to spintronics had been started long before these events. The starting point was the Mott’s paper [7] (1936), in which a “two-current conductivity model” was proposed to explain the temperature dependence of the resistivity of nickel. Two relaxation times were introduced for electrons with spin projections parallel and antiparallel to the magnetization vector. The model was confirmed in experiments (started in 1966), which served as a basis for formulation of an applied problem: the control of solid-state conductivity by acting on the spin degrees of freedom of the system. This, in turn, stimulated research in the main areas of spintronics, namely, the dynamics of magnetization (magnetodynamics), spin transport, and spin relaxation processes in magnetic solid-state heterostructures [5,6,8–11]. Rapid progress in solving of these problems occurred after the development of high-precision technologies for fabrication of layered nanostructures under high and ultra-high vacuum conditions in the early 1980s [11]. In addition to key experiments performed over the next $15-20$ years (a detailed analysis can be found in review [5]), a theoretical spintronics description formalism was developed, which includes the Boltzmann kinetic equation formalism and the Kubo linear response theory, see [1–11] and references therein. Interestingly, the idea of controlling superconductivity with the help of magnetism was invented by de Gennes [12] in 1966, long before the experiments on giant magnetoresistance in F/N nanostructures. In the structure proposed by him, a thin superconducting (S) film with a thickness of $d_{\mathrm{S}} < \xi_{\mathrm{S}}$ (ξ_{S} is the length of superconducting coherence) was sandwiched between two ferromagnetic insulators (FI). As a result of the exchange interaction of the electrons of the superconductor with the first magnetized atomic layers of the ferromagnets, these electrons acquire exchange fields, causing the splitting of their spin states. Due to the small thickness of the S-layer, the average exchange field (the exchange splitting energy) $\overline{h}$ is considered homogeneous (the so-called Cooper limit) and its dependence on the angle θ between the magnetic moments $\mathbf{M}_1$ and $\mathbf{M}_2$ of the ferromagnets is assumed as follows: $\overline{h} = 2\,|\Gamma|\,(a/d_\mathrm{S})\,S\cos(\theta/2)$, where Γ is exchange integral, a is interatomic distance, and S is the ferromagnet's atom spin (in original notations Ref. [12]). At the qualitative level, when the maximum of $\overline{h}$ is higher than the Clogston-Chandrasekhar $\Delta/\sqrt{2}$ limit (see Ref. [13]), the S-layer has normal conductivity in the region of angles close to $\theta = 0$ (the magnetic moments $\mathbf{M}_1$ and $\mathbf{M}_2$ are parallel – the magnetic state "P", and the exchange fields induced by the both ferromagnets are summed up). By rotating the magnetic moment of a magnetically softer (regardless of the cause) ferromagnet relative to the other to increase the angle θ, the superconductivity can be restored provided that $\overline{h}$ shifts below the Clogston-Chandrasekhar limit (partial or complete cancellation of the exchange fields in antiparallel states of $\mathbf{M}_1$ and $\mathbf{M}_2$ – "AP"). On a more stringent basis, de Gennes has shown that the free energy of the FI/S/FI structure is a monotonically decreasing function of the angle θ between $\mathbf{M}_1$ and $\mathbf{M}_2$. For a given temperature range, the structure can be either in the normal state, when the vectors $\mathbf{M}_1$ and $\mathbf{M}_2$ are in the P-state, or in the superconducting case in the opposite AP case. On this basis, de Gennes [12] proposed a spintronic memory device (in modern terms), which has (literally) zero resistance for $\theta = \pi$ and finite resistance for $\theta = 0$. Inspired by the prediction of de Gennes, Deutscher and Meunier [14] and Hauser [15] conducted experiments; in the first of them, a layer of indium 250 nm thick was in between of the layers of permalloy and pure nickel with a thickness of 150 nm each. Ferromagnets were isolated from direct contact with indium by oxidizing the surface of the F materials of the layers during the deposition process. The condition $d_\mathrm{S} < \xi_\mathrm{BCS}(\mathrm{In}) = 330\,\mathrm{nm}$ [16] was met, but the rest can hardly be estimated, however, the difference between the transition temperatures of the parallel (P) alignment (T_c^P) and the antiparallel (AP) alignment (T_c^AP) of the magnetizations, $\Delta T_\mathrm{c} = T_\mathrm{c}^\mathrm{AP} - T_\mathrm{c}^\mathrm{P}$, was found positive and reaching 200 mK (see Fig. 1 in [14]). In the Hauser experiment, an indium film 150-400 nm thick was placed between 200 nm thick magnetite $\mathrm{Fe_3O_4}$ films grown in a magnetic field to premagnetize each of the magnetic layers in a given direction. Measurements of the transition temperature have shown that $T_\mathrm{c}^\mathrm{AP} > T_\mathrm{c}^\mathrm{P}$, and the difference ΔT_c was found to be about 2 K [15], which is still practically inaccessible. If one looks at the formulation of the problem by de Gennes (see also Ref. [17]) from the modern point of view, an alternative approach to the physics of the FI/S/FI spin valves can be proposed, considering the FI/S interface as a spin-active boundary [18–20]. The concept of the spin-active boundary implies that electrons acquire spin-dependent phase shifts upon reflection from the interface with a ferromagnetic insulator (for a graphic representation, see Ref. [21], Fig. 7). Since Cooper pair in the S-layer consists of two electrons with opposite spins, the pair acquires a total phase and can be decomposed into singlet and triplet components (see Ref. [21], Fig. 8), which affects the superconducting temperature T_c. Indeed, calculations in the framework of the semiclassical theory [22] show that ΔT_c in this approach is positive and can reach ten percent of BCS T_S. Modern experiments [23] with the FI/S/FI system (FI = EuS, 1.5 and 4.0 nm and S = Al, 3.5 nm thick) have shown that ΔT_c can be large enough to switch the system between the states with superconducting and normal conductivities. However, the scenario of the singlet-triplet mixing at the interfaces of SF heterostructures was not discussed as switching physics (see, however, a discussion of the differences between the physics of spin valves FI/S/FI and F/S/F in [24]). Most recent research was focused on the proximity effect between a superconductor and a metallic ferromagnet. In the situations discussed above, the FI layers were rather thick, and the reverse effect of the S-film superconductivity on the mutual orientation of the FI magnetization vectors was negligible. However, if one reduces the thickness of one of the FI films in the FI/S/FI system and/or reduce its magnetic anisotropy in any other way, the situation may change to the opposite. Namely, the S-film in the FI/S/FI spin valve can impose antiferromagnetic ordering of the magnetizations of FI layers, as if there is a kind of exchange interaction between FI layers [25, 26]. Zhu and his colleagues used a series of three-layer GdN/Nb/GdN configurations with different thicknesses of the intermediate superconducting layer Nb and investigated the hysteresis of resistance and magnetization as a function of the applied magnetic field. These measurements allowed them to demonstrate a new type of exchange coupling due to superconductivity in the intermediate layer. To prove the key role of superconductivity in their experiments, they conducted a series of tests, including replacing Nb with a non-superconducting Ta layer and adding thin AlN dielectric layers between GdN and Nb. In both cases, the effects disappeared, confirming that this is indeed due to superconductivity in the interlayer and does not result from the stray fields. Thus, the observed antiferromagnetic ordering of magnetic moments in the GdN/Nb/GdN heterostructure can be a manifestation of the long-range indirect exchange of RKKY-type magnetic moments in superconductors [27]. This exchange is always antiferromagnetic between magnetic moments of the identical type; the manifestations of this unconventional interaction in magnetic resonance measurements were analyzed in Refs. [28–30].

Generally, superconductivity and ferromagnetism are considered as antagonistic long-range orders that cannot coexist in a homogeneous medium [31]. Indeed, ferromagnetism is expected to suppress singlet superconductivity, because the presence of exchange splitting of the conduction band breaks the symmetry of the Cooper pair in time. Fulde-Ferrell and Larkin-Ovchinnikov (FFLO) [32, 33] showed that, nevertheless, superconductivity can persist in the presence of a magnetic background, but is limited to an extremely narrow range of parameters [34]. The idea was that a Cooper pair with zero total spin acquires a non-zero pairing momentum. This idea has become much more applicable for systems in which superconductivity and ferromagnetism are separated on a nanometer scale due to artificial stratification. Latest systems will be the focus of this review. Artificially layered metal systems are ultra-thin film heterostructures in which superconductivity and ferromagnetism are located in different adjacent or closely spaced layers, but interact strongly through interfaces. This connection of superconductors with non-superconducting metals through interfaces, the so-called proximity effect, was introduced into consideration by de Gennes and Guyon [35] and Werthamer [36], and was precisely formulated by de Gennes as a boundary problem [37]. Experimental results at an early stage, summarized in a review by Jin and Ketterson [38], mainly showed the expected suppression of superconductivity due to proximity to the neighboring ferromagnet; however, some signs of nonmonotonic dependence of this suppression on the thickness of the ferromagnetic layer in multilayers have already been noticed. Continuing progress in thin-film deposition methods has led to a surge in activity in the field of superconductor-ferromagnetic SF heterostructures, both experimental and theoretical. It quickly became clear that due to the proximity of superconductor to ferromagnet, the FFLO-like pairing with a finite momentum is induced by the penetration of singlet Cooper pairs through the S/F interface into the ferromagnetic metal. This is due to the exchange splitting of the conduction band of the ferromagnetic metal, which makes the Fermi momenta of the spin conduction subbands unequal, as illustrated in Fig. 1 of Ref. [39] for the simplest model of a parabolic conduction band. The resulting pairing wave function oscillates in space along the normal to the S/F interface. When the oscillation scale and attenuation length of the pair function are comparable with the thickness of the ferromagnetic layer, we can expect different interference effects, namely, temperature oscillations of the superconducting transition

T_c, depending on the thickness of the ferromagnetic layer d_F in the S/F bilayers; T_c oscillations in multilayer S/F structures as a result of switching between "zero" and "π" phase differences between adjacent S-layers in the stack; reentrant superconductivity as a function of F-layer thickness; π-Josephson junctions – transmission with an intrinsic phase difference π through a weak ferromagnetic coupling; and some others. Most of these unusual properties of SF heterostructures are described and explained in detail in several reviews [13, 21, 40–48]. Special attention was paid to non-zero spin pairing, which can be implemented in SF heterostructures on top of the ferromagnetic background. Indeed, Bergeret, Volkov, and Efetov have shown that the pairing of triplet s-waves can be induced by a conventional superconductor near the ferromagnetic subsystem containing non-collinear magnetizations (see review [45] and references therein). This pairing is non-oscillating and unusually distant [45, 46], which makes it a promising mediator of the spin-polarized Josephson current.

2. Superconducting spin valve in S/F1/N/F2 structures

The main (primary) problem of superconducting spintronics, namely, controlling the superconducting state by changing the magnetic state, has the simplest practical solution for spin valves based on SF structures, which are multilayer structures with noncollinear magnetization of F layers. Since triplet pairing in SF heterostructures [21,47–49] received more and more evidence of existence, Fominov *et al.* [50] revised the FFS-valve theory of Oh, Youm, and Beasley to explicitly take into account the effect of triple pairings (zero projection, s_{10}, and ± 1 projections – $s_{1,\pm 1}$) on the superconducting T_c at an arbitrary angle α between the magnetic moments of the FM layers and under the constraints $d_{F2} \to \infty$ and $T = 1$ (T is transparency of the S-F interfaces). The analysis performed within the framework of the quasiclassical Usadel formalism (dirty limit) has shown that three switching modes can be implemented in the SFF structure, when triplet pairings are taken into account on equal basis with the singlet pairing (see Fig. 3 in Ref. [50]). The first mode corresponds to $T_c^{AP} > T_c^{P}$ and is called the standard switching mode (curve 2 in Fig. 3 from Ref. [50]); in the second mode, the transition temperature for the AP orientation is lower than for the P orientation, $T_c^{AP} < T_c^{P}$, it is the inverse switching mode (curve 4 in Fig. 3 from Ref. [50]); finally, the triplet switching mode (curve 3 in Fig. 3 from Ref. [50]) is characterized by a pronounced concave angular dependence $T_c(\alpha)$ with an absolute minimum at $T_c^{NC} < \{T_c^{P}, T_c^{AP}\}$ (NC means non-collinear magnetizations). At the same time, the unusual behavior of $T_c(\alpha)$ in the triplet switching mode can serve as indirect evidence of the generation of triplet pairing in SFF heterostructures. Moreover, in the triplet switching mode, the dependence $T_c(\alpha)$ can take the form of the reentrant superconductivity when the S-layer thickness is properly adjusted [50]. The suppression of the critical temperature when the vector $\mathbf{M}_1$ deviates from the direction of $\mathbf{M}_2$ is due to the induction of the triplet component in the superconducting condensate. Relations between the singlet and triplet components of the pairing functions in the S/F1/F2 structure were obtained in [51] for a more general case, namely, for arbitrary transparencies of interfaces. Unusually, the triplet component, unlike that in the F1/S/F2 structure, may be largest not in the vicinity of $\alpha = \pi/2$, but, for example, with a slight violation of the $\mathbf{M}_1$ and $\mathbf{M}_2$ collinearity [51]. In addition, it turned out that the natural assumption of full transparency of the F1-F2 interface as a condition for the maximum of the triplet component turns out to be too strong. This fact favors the S/F1/F2 structures, since in all experimental systems there is an N-spacer between the F1 and F2 layers, therefore, perfect transparency of the F1-F2 interface is impossible (in [51] the N-intermediate layer is taken into account by the free parameter γ_B). In this regard, we note that if the S-material is used as a buffer layer (this is convenient from technological point of view), then it can play an active role in the formation of the distribution of superconducting condensate.

3. Development of technology for the preparation and studies of the physical properties of thin films of superconducting, ferromagnetic, normal metals and their heterostructures

For the preparation of ultrathin films of superconducting (Nb), normal (Pd, Cu) and ferromagnetic (Fe, Ni) metals and alloys (co-evaporated solid solutions) metals, an ultrahigh vacuum installation of the companies SPECS-BESTEC (Berlin, Germany) was used. The pressure of residual gases in the chamber of molecular beam epitaxy (MBE) does not exceed 3×10^{-10} mbar, in the chamber of magnetron sputtering (MR) – 5×10^{-9} mbar. The setup includes an analytical chamber in which X-ray photoemission spectroscopy (XPS) and secondary ion mass spectrometry (SIMS) methods are realized to characterize the resulting films and heterostructures. The transport of substrates and samples between the three main chambers is carried out without breaking the vacuum through the ultra-high vacuum transmission line. Using this setup, as well as the conversion electron Mössbauer spectrometer (CEMS by WissEl, Germany) at temperatures from room temperature down to 100 K, the universal system for measuring physical properties (Quantum Design PPMS-9, USA) in the temperature range 1.8-1000 K and the atomic force microscope (NT-MDT, Russia) – all equipment of Kazan Federal University (KFU), the following work was performed and the results given below were obtained.

1. The technology of preparation has been developed and samples of Nb films on sapphire substrate were obtained in a magnetron chamber. The pressure of residual gases in the chamber was 5×10^{-9} mbar, the pressure of argon plasma-forming gas was $(5-6)\times10^{-3}$ mbar, the deposition rate of the niobium film was 0.05 nm/s, 0.02 nm/s, 0.01 nm/s to the layer thicknesses from 1 to 40 nm. Using the appropriate insertion of the PPMS-9 physical properties measurement system, the superconducting transition temperature was measured by a resistive method for films obtained at different deposition rates. The dependence of the superconducting transition temperature on the thickness of the films obtained with different deposition rates was constructed.

2. The technology of preparation was developed and samples of metallic films and alloys of the iron group (Fe (0.1 nm/s), Co (0.02 nm/s), Py-permalloy (0.015 nm/s)) were obtained in the magnetron chamber; the hysteresis properties of the magnetic properties of films were measured as a function of their thickness.

3. The technology of preparation has been developed and samples of epitaxial films of $\mathrm{Pd}_{1-x}\mathrm{Fe}_x$ palladium-iron alloy with iron content $x = 0.01$-0.1 (deposition rate 0.11-0.13 nm/min) with a residual gas pressure of 5×10^{-10} mbar were obtained in a molecular-beam deposition chamber. For films with a thickness of 20 nm, the temperature dependence of the magnetic moment was measured, and the transition temperatures from the paramagnetic to ferromagnetic state were determined, and the dependence of the magnetic moment of saturation on the iron concentration in the alloy was determined. Magnetic resonance measurements [52] determined the magnitudes of the magnetic anisotropy constants of the epitaxial alloy film and established cubic symmetry with tetragonal distortion due to the mismatch of the lattice constants in the film plane. The dependence of the magnetocrystalline anisotropy constants on the iron concentration in the alloy was measured.

4. The preparation technology has been developed and samples of thin films of Nb bilayers with Co and Ni were obtained in the magnetron chamber. The residual gas pressure in the chamber was 5×10^{-9} mbar, the pressure of argon plasma-forming gas was $(5-6)\times10^{-3}$ mbar, the deposition rate of the niobium film (substrate – sapphire) was 0.1 nm/s to layer thicknesses from 10 to 60 nm, Co deposition rate – 0.02 nm/s, Ni – 0.03 nm/s. Bilayers of V (0.01 nm/s) with Co (0.002 nm/s) and with Ni (0.002 nm/s) were also prepared. For films with a variable niobium thickness and a large ferromagnet layer thickness (20 nm), the superconducting tran-

sition temperature T_{c} was measured by a resistive method (using the appropriate insert of the physical properties measuring system PPMS-9). T_{c} shows monotonous growth with increasing of niobium layer thickness, starting from nominally zero T_{c} (lowest measurement temperature is 1.8 K) at a critical thickness of about 14.5 nm, while the transition width monotonously decreased from about 80 mK to 14 mK. Similar measurements for vanadium give a critical thickness of 21 nm (Co) and 18 nm (Ni) with similar trends in T_{c} with layer V thickness, the transition width also decreases (from 60 to 10 mK). The dependences of T_{c} on the thickness of the layers of nickel and cobalt exhibit non-monotonic behavior; however, there is a large scatter in the value of T_{c} of samples made by sequential preparation.

5. Samples of two-layer films of thick (physically infinite thickness of 40-50 nm) CuNi and Ni ferromagnet with a variable thickness of a superconducting niobium layer were prepared. Measurements of the dependence of superconducting transition temperature on the niobium layer thickness make it possible to determine a number of fitting parameters necessary for calculating the superconducting transition temperature of the superconductor-ferromagnetic spin valves and its dependence on the angle between the magnetizations of the ferromagnetic layers.

6. The technology of exchange bias (pinning) of the magnetic moment of diluted ferromagnetic alloy (CuNi) at its direct contact with an antiferromagnet (CoO) is developed and corresponding samples are obtained. The high-purity oxygen supply line for the magnetron sputtering chamber (nominally 99.9999 % at the outlet of the Perkin-Elmer chromatographic filter) was installed and launched. The experiments were performed on reactive sputtering of cobalt in argon mixed with oxygen (approximately $6:1$) and measurements of the elemental composition on an XPS built-in spectrometer, which showed closeness of the composition to the CoO stoichiometry. Since such works on the selection of synthesis modes and measurements of stoichiometry are costly in terms of resources and time, and also require high-resolution transmission electron microscopy, the possibilities of German colleagues were used, which allows minimizing your own costs of resources and time. In the joint work with German colleagues, exchange pinning of the magnetic moment of the CuNi alloy with an exchange bias value of several hundreds oersted was achieved at first in Ref. [53].

7. Samples of spin-valve structures of Nb/Ni/Ta/Co and Ni/Nb/Co types (auxiliary layers are not indicated) on sapphire substrates were obtained, their hysteresis loops at 10 K were measured, and resistive curves of superconducting transitions of the samples were measured. To measure the dependence of the superconducting transition temperature on the magnetic field, special holders have been acquired that allow the sample to be rotated while maintaining the magnetic field vector in the sample plane. The changes in T_{c} are obtained with the frequency of occurrence along the magnetic hysteresis loop of the heterostructure. These changes are within the width of the superconducting transition and the allowable variation of the sample temperature control at the holder.

4. Proximity effects in superconducting spin valves F2/F1/S, F2/N/F1/S and F2/S/F1/S

The critical temperature T_{c} of a three-layer F2/F1/S structure (F is a ferromagnetic metal, S is a singlet superconductor) is investigated in Refs. [54, 55], in which a long-range triplet component generated with noncollinear magnetizations of F layers has been taken into account. To calculate the temperature T_{c} as a function of the trilayer parameters, in particular, the relative orientation of the magnetizations and transparency of the F2/F1 boundary, an asymptotically exact numerical method was used. Previously, by selecting combinations of the ferromagnetic and superconducting layer thicknesses, we were able to reproduce different qualitative behaviors of the superconducting transition temperature as a function of the angle between the magnetizations of the ferromagnetic layers: the "direct" switching mode when the superconducting transition temperature with antiparallel ordering of magnetizations is higher than that for parallel ordering of magnetizations; the "triplet" switching mode, in which there is an absolute minimum of the superconducting transition temperature at intermediate angles; and the mode of reentrant superconductivity as a function of the angle between the magnetizations of the ferromagnetic layers. We have shown that it is possible to select the spin-valve effect modes ("direct" switching, "triplet" switching, and reentrant superconductivity) by varying both the transparency of the F2/F1 boundary and the exchange splitting energy. Additionally, it is shown that the position of the minimum T_c with respect to the angle between the magnetizations of the ferromagnetic layers can be changed by a joint variation of transparency of the F2/F1 boundary and the layer thicknesses.

To determine the conditions on the parameters of heterostructures (layer thickness, boundary transparency) of a superconductor-ferromagnet, under which they acquire functional properties – either an anomalously large change in electrical resistance, and, in the limit, switching between superconducting and normal states (*i.e.* infinite magnetoresistance) in magnetic field, calculations are performed in a fully self-consistent multimode calculation scheme [56, 57]. The dependences of the critical temperature T_c of the spin-valve structure S/F1/F2 (Fi are layers of a ferromagnetic metal, S is a layer of a superconductor) on the angle between magnetizations of the ferromagnetic layers were evaluated, and distribution of the amplitude (or modules) of the singlet and triplet components of the superconducting pairing were visualized for the direct, inverted and triplet switching modes. Such calculations are important for planning of experiments by preliminarily estimations of the layers thicknesses enabling the heterostructure to obtain functional properties. Also, this kind of calculations is necessary to accompany experimental studies in optimizing the parameters of the synthesized samples providing maximal spin-valve effect.

Calculations have been made and the dependences of T_c on the angle between magnetizations of the ferromagnetic layers were obtained for a realistic spin-valve structure F2/N/F1/S (N is a normal metal layer used to decouple magnetizations of the ferromagnetic layers) [58, 59]. Additionally, dependences of the superconducting transition temperature of S1/F1/S2/F2 spin-valve structure (Fi is a ferromagnetic metal layer, Si is a superconductor layer) on the angle between the magnetizations were obtained, and the amplitude (or modules) distribution for the singlet and triplet pairings were visualized for direct, inverted and triplet switching modes of the spin-valve structure in a fully self-consistent multimode calculation scheme [60]. The presence of the second superconducting layer increases the temperature of the superconducting transition of the heterostructure, thereby facilitating its measurement, and slightly increases the difference between the minimum and maximum temperatures T_c of the heterostructure when its magnetic configurations change. We analyzed correlations of the pairing functions distributions among the layers with realization of various switching modes of the spin valve: direct, triplet, and inverse. To perform the calculations, we used numerical algorithms for solving the resulting equations on a multi-core platform using the INTEL Visual Fortran 12 programming language and the IMSL library of mathematical subroutines for it (license provided by KFU).

5. Dependence of the triplet spin valve effect on the thickness of the ferromagnetic layers in superconductor-ferromagnet-ferromagnet heterostructures [61]

In S/F1/N/F2/AF layered heterostructures, the generation of the long-range, odd in frequency triplet component of superconductivity with noncollinear magnetizations of the F1 and F2 layers depletes the phase space of the singlet paired state, which leads to the possibility of a global minimum for the superconducting transition temperature T_c near a mutually perpendicular orientation, *i.e.* to the effect of the triplet spin valve. The triplet spin valve is realized with S = Nb as a singlet superconductor, F1 = $Cu_{41}Ni_{59}$ and F2 = Co are ferromagnetic metals, AF = CoO_x is an antiferromagnetic oxide, and N = nc-Nb is a normal conducting (nc) non-magnetic metal that "decouples" F1 and F2 layers. The noncollinear orientation of the magnetizations is realized by applying an external magnetic field parallel to the layers of the heterostructure and using the intrinsic perpendicular easy axis for magnetization of the $Cu_{41}Ni_{59}$ thin film in combination with the exchange bias between CoO_x and Co. Magnetic configurations are confirmed by the SQUID magnetization measurements. The effect of a triplet spin valve was investigated for various thicknesses of the F1 layer, d_{F1}, its decrease with increasing the d_{F1} thickness was found. The long-range triplet component is generated from the singlet component mainly at the N-F2 interface, where the amplitude of the singlet component is exponentially suppressed with increasing d_{F1}. It is established that this attenuation length is comparable to the double electron mean free path in F1 and, thus, with the attenuation length of the singlet component in the F1 layer.

6. The effect of a triplet spin valve in the superconductor-ferromagnet $Co/CoO_x/CuNi/Nb/CuNi$ heterostructure and its switching by a magnetic field [24]

In collaboration with colleagues from Chisinau (Moldova) and Augsburg (Germany), samples of superconducting spin-valve heterostructures were prepared and their superconducting properties were measured in a magnetic field to establish the dependence of T_c on the magnetic configurations realized in the system. The attention was payed to the possibility of switching the heterostructure between the superconducting and normal conducting states with a relatively small magnetic field. As a result of a detailed study and modeling of the physical properties (magnetic and superconducting) of the $Co/CoO_x/CuNi/Nb/CuNi$ heterostructure (CuNi = $Cu_{41}Ni_{59}$) with a thickness of 4.6, 16.0, 2.2, 11.4, and 2.5 nm, respectively, the full switching between superconducting and normal states with a measuring current of $500\,\mu$A and cycling of the magnetic field in the range of ± 4 kOe was achieved. This result demonstrates the functional properties of superconductor-ferromagnetic heterostructures as switches or magnetoresistive memory cells. The latter is possible, since the state in which the heterostructure sets in depends on prehistory of its magnetization. If the heterostructure was cooled to a superconducting state in a magnetic field, say, with the positive direction in the film plane, it remains superconducting after the field is switched off. If after this the heterostructure is magnetized to saturation in a field of the opposite direction, and then the magnetic field is switched off, the heterostructure changes to the normal conducting state. A holding field does not required to maintain either the superconducting (low-resistance) or the normal (high-resistance) state after it is reached.

7. Summary

The part of the results described above were obtained utilizing the ultra-high vacuum deposition system allowing precision control of the layers thickness at the level of angstroms. The options for co-deposition and co-sputtering from several sources are unique. The thin PdFe alloy films are poorly studied system, while the recent results of the ISSP RAS group on implementation of the Josephson memory on superconductor-ferromagnetic heterostructures indicate the promises of PdFe alloy as a magnetic weak link in functional superconducting heterostructures. Previously, the preparation of such kind of samples was possible only in several laboratories in the USA, Germany and Japan.

The physical properties of the obtained samples were investigated utilizing using the most advanced analytical equipment of well-known scientific instrument brands like Quantum Design, Bruker, Wissel, IceOx, NT-MDT. The location of self-sufficient complex of instruments for deposition and characterization of ultra-thin and thin-film at KFU, supported by the experimental and theoretical experience of the Institute of Physics staff and partners, creates prerequisites for obtaining new original results and synergistic strengthening of the scientific potential.

The studies were aimed at materials and heterostructures for superconducting spintronics. Therefore, in parallel, the research has been done on development of models and calculations of the superconducting properties of spin gates with the model parameters closest to the experimental ones. The parameters of heterostructures with PdFe alloy will be used to calculate the spin-valve properties of superconductor-ferromagnetic heterostructures. The results of the studies were summarized in the chapters of collective monographs of the Springer publishing house [62–64].

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