Physics – Uspekhi **42** (7) 653 – 667 (1999)

REVIEWS OF TOPICAL PROBLEMS

PACS numbers: **73.40.–c**, **74.50.+r**, **74.80.-g**, 75.50.Dd

Quantum tunneling in multilayers and heterostructures with ferromagnetic semiconductors

A S Borukhovich

Contents

Abstract. **Experimental data promising exciting possibilities for quantum tunneling in multilayers and heterostructures with ferromagnetic semiconductors are comprehensively surveyed for the first time. The practical utilization of two- or single-particle tunneling in such structures gives impetus to the tunneling spectroscopy of ferromagnetically ordered materials and, based on spin filtering, magnetic-field-shaped volt-ampere characteristics, and some other salient features of such structures, paves the way to a new generation of unconventional solid-state micromagnetoelectronic cryogenic devices, including those operated in millimeter or submillimeter wavelength ranges.**

1. Introduction

In recent years a practical interest in the possibility of realizing the tunneling of quasi-particle pairs through a ferromagnetically ordered barrier and in the physics of M(S)/F and S/F/S multilayers has been rekindled, where M, S and F denote normal metal, superconductor and ferromagnet, respectively [1 – 8]. The phenomena occurring when a single-particle current or a Cooper-pair current (Josephson current or supercurrent) traverses such multilayer structures are so unusual that the study of these phenomena has been unaffected by the conjuncture 'surges' of solid-state science associated with the discovery of high-temperature superconductivity (HTSC) or the finding of giant negative magnetoresistance in the old 'new' materials — lanthanum manganites. And it is quite justified, since many properties of such heterostructures and multilayers are capable of providing their competition with classical systems of cryoelectronics.

Historically, the question of whether it is possible to observe the tunneling of Cooper pairs through a ferromagnetic barrier arose in connection with the discovery of the Josephson effect in 1961. In its 'classical' variant — one-particle tunneling — this question was solved by Esaki, Stiles, and von Molnar [9] who observed a tunnel current flowing between two normal metals separated by an interlayer made from the magnetic dielectrics EuS and EuTe.

The earlier notions of the impossibility of coexisting superconductivity and ferromagnetism in metallic systems had at that time sufficient experimental support. In the first place, none of the ferromagnets known at that time was superconductive [10] and, according to Ref. [11], the supercurrent of a multistructure Sn/Fe/Sn decay even when the thickness of the Fe layer was as small as 0.05 nm. On other evidence [12, 13], the presence of local magnetic moments (in particular, the magnetic moments of manganese or gadolinium atoms) in the barrier interlayer also led to fast exponential decay of the supercurrent in the tunnel junction with increasing width of the metal barrier. Some results of these works, however, inspired optimism: as the concentration of the local moments of impurity in the barrier interlayer was raised to some threshold or an external magnetic field was applied to the junction, the ordering of the local moments promoted both reset of the supercurrent and observation of the gap-dependent peculiarities of superconducting banks (two edge layers in a tunnel structure) inherent in Josephson tunneling on the current-voltage characteristic (CVC) of the junction. This fact really pointed both to the possibility of Josephson tunneling through a barrier containing ferromagnetically ordered magnetic moments and to the influence of the width of such a barrier on the amplitude of a Cooper-pair

A.S. Borukhovich Institute of Solid State Chemistry, Ural Branch of the Russian Academy of Sciences,
ul. Pervomaĭskaya 91, 620019 Ekaterinburg, Russian Federation
Tel. (7-3432) 74 59 52. Fax (7-3432) 74 44 95
E-mail: bamburov@ihim.uran.ru

Received 3 September 1998, revised 2 December 1998
Uspekhi Fizicheskikh Nauk **169** (7) 737 – 751 (1999)
Translated by V M Matveev; edited by A Radzig

flow (alternatively, on the value of the transition temperature T_c of a superconductor being in contact with an F metal). This fact was first highlighted in paper [14] and in recent years again became the subject of experimental and theoretical studies in connection with improvements in the fabrication technology of metal multilayers of the S/F type, such as Nb/Gd, Nb/Gd/Nb, and Nb/Fe [3, 15].

The present review is the first attempt to summarize the results of experimental investigations of multilayers (thin-film planar structures) or heterostructures (interface layers between bulk crystals in contact) containing ferromagnetic semiconductors (FSs) on the basis of the data available in the physics literature. It is common practice to assign to ferromagnetic semiconductors those compounds of 3d or 4f metals which exhibit ferromagnetic ordering of spins located on metal atoms in combination with semiconductor-type conductivity. 'Classical' representatives of such compounds are europium monoxide, EuO, and europium monosulphide, EuS, with Curie temperatures T_C of about 70 K and 16 K, respectively, as well as chalcogenide spinels $CdCr_2S_4$ ($T_C = 80$ K), $CdCr_2Se_4$ ($T_C = 130$ K), $HgCr_2Se_4$ ($T_C = 120$ K) and perovskite-type phases on the base of $LaMnO_3$, with T_C being as high as 350 K. Scientific and practical interest in such phases is determined by the extraordinary strong interdependence of the parameters of their electronic and magnetic subsystems that allows one to exert purposeful control over their electrical, magnetic, optical, magneto-optical and frequency characteristics, acting on a bulk FS or FS-containing structure by an external electric or magnetic field. This latter circumstance, i.e. the presence of an additional 'degree of freedom' and the possibility of exerting magnetic control over the properties of FSs, which is not always possible for ordinary (nonmagnetic) semiconductors and devices built on their base, has attracted the attention of scientists and engineers to the indicated FS phases in the light of opening prospects for the extension of the functionalities of existing cryomicroelectronic devices.

Perhaps, one of the most remarkable properties of FSs (which first of all determines the newness of their use in cryoelectronics) is the dependence of the shift of the optical-absorption edge (or the forbidden gap in the electron spectrum E_g) on the order parameter of the magnetic structure and the external magnetic field. The maximal (for FSs) value of the shift to the red region of the spectrum as the sample temperature decreases from T_C to 20 K is attained in EuO where this value is equal to 0.25 eV (0.16 eV in EuS and phases on the base of $LaMnO_3$ at $T < T_C$). The external magnetic field H adds some additional 10% to this shift ΔE_g. Thus, owing to this external parameter, it is possible to control both the intrinsic and impurity conductivity of FSs by influencing the carrier concentration and mobility in the conduction band.

Record value (for ferromagnets) of the magnetic moment of a europium ion in the state of saturation ($\sim 7\mu_B$) and the saturation magnetization of EuO crystals ($4\pi\sigma_s = 2.43$ T) lead to the fact that current carriers in EuO are to the maximum extent (close to 100%) polarized in spin. This fact renders the application of FSs in structures (including tunnel structures) capable of providing high spin polarization of an emission current prospective. Investigations carried out in the field of tunneling spectroscopy of FSs are directed in particular towards the study of their such fundamental characteristics as spin-fluctuation dynamics and the spin-correlation function, a knowledge of which is important in the theory of magnetic phenomena.

Being band conductors and typical Heisenberg ferromagnets with the s–d or d–f exchange interaction, FSs still remain something of a 'touchstone' for all fundamental developments in the theory of ferromagnetism. Experimentally and practically, developments in the field of fabrication of FS-containing multilayers and heterostructures can extend the range of investigations of solid-state structures to the submillimeter range of the spectrum which is essentially beyond the reach of the existing structures built on the base of nonmagnetic semiconductors, and this lays the foundation for creating a new generation of microelectronic devices.

It should be noted that, technologically, the pursuance of such research, which has already yielded rather unusual and at the same time capacious results, can be presently performed by only two research groups in the world. One of them works in National Magnetic Laboratory, Massachusetts Institute of Technology, Cambridge, USA. The other group, whose representative is the author of the present review, works in Ekaterinburg, Russia. The latter includes a small number of scientists working at the Institute of Physics of Metals and the Institute of Solid-State Chemistry of the Ural Branch of the Russian Academy of Sciences. For the most part, this review presents the results of research of this latter group obtained earlier and in recent years.

2. Experimental results. S/FS multilayers

Experiments [9] have shown that the presence of a ferromagnetic semiconductor in a tunnel junction opens up the possibility for controlling the value of the threshold voltage across the junction using an external magnetic field which affects the value of FS conduction-band spin splitting near the Fermi level. As a consequence, necessary conditions providing control of the energy height of a tunnel barrier in such a structure are realized. The 'bleaching effect' of the barrier and a decrease in its effective height are due to the presence of an exchange interaction in this barrier. Moreover, the giant magnitude of the red shift of the bottom of the conduction band observed in FSs, when the magnetic ordering of spins (for example, the spins of 4f electrons in europium ions) takes place, further enhances this process [16].

For these reasons as well as in view of the fact that even in degenerate FSs the concentration of current carriers is several orders of magnitude less than in ferromagnetic metals (and, therefore, the influence of the 'proximity' effect and the Andreev reflection from the S/F boundary is minimal), tunneling through an FS barrier appears to be energetically preferable to that through an F metal. In this case the use of the FS barrier as an element of a tunnel structure or M(S)/FS, NS/FS and similar multilayers (NS denotes nonmagnetic semiconductor) allows one to realize the idea of creating a Zener magnetic-controlled cryodiode or stabilitron whose inverse breakdown voltage can be controlled by an external magnetic field.

Another no less important advantage of the use of an FS barrier in a tunnel multilayer structure as compared to an F metal is determined by technology, namely, by the absence of strict limitations on the thickness of the barrier interlayer, though the last affects the amplitude of the tunnel current (including supercurrent). At the same time it should be noted that by virtue of existing physical and chemical restrictions on the fabrication conditions for thin-film layers of the well-known FSs, the realization of a chemically homogeneous interface layer between FSs and other materials is not always feasible. In particular, this is true for a barrier made from europium monoxide or europium monosulphide which, as has appeared, can enter into chemical interaction with a surface when deposited on some superconductors. Much less rigid requirements are placed upon the use of the last-mentioned FSs for one of the banks of FS/M(S) multilayers created and investigated in Refs [17, 18]. The authors of papers [17, 18] realized quasi-particle tunneling both into a superconducting metal (Al) and into a ferromagnet (Fe).

The author of the present review and his colleagues apparently for the first time were able to create a Josephson tunnel junction on the base of an $S_1/FS/S_2$ multilayer structure and to detect a supercurrent j_c of up to 130 μA at $V_b = 0$ (V_b is the bias voltage) as well as characteristic gap-dependent features of the junction at $H \geqslant 0$. All this was briefly reported in our publication [19] which was preceded by a number of author's certificates applied in 1982–1986.

The results of an investigation of the current-voltage characteristic of $S_1/FS/S_2$ multilayer structures given below concern predominantly the 'cross'-type structures with a tunnel contact area of about 1 mm^2. The structures were formed on high-resistance silicon substrates [20] (Fig. 1). The width of superconducting banks was above 0.2 μm and exceeded the width d of an FS barrier which was varied from 0.01 to $\approx$0.05 μm. The measurements of the CVCs were performed by the harmonic-detection method using the classical four-probe technique. The bias voltage across the junctions was varied from −30 mV to +30 mV; the experimental error of the measurements was no more than ±0.05 mV. The normal resistance of the junctions at room temperature was found to be several tens of ohms.

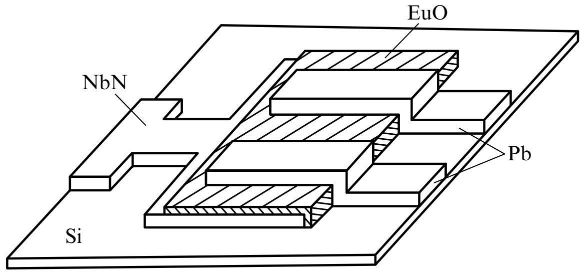

Figure 1. Actual view of a NbN/FS/Pb multilayer with the Josephson tunnel junction, fabricated by planar technology (FS — EuO or EuS).

2.1 NbN/EuO/Pb structure; $H = 0$

Figure 2 shows a representative CVC of the multilayer tunnel structure NbN/EuO/Pb at $T = 4.2$ K and $H = 0$, and, for comparison, that of the 'classical' Josephson tunnel junction NbN/I/Pb with an insulating (I) barrier made from aluminium oxide Al_2O_3.

The characteristic gap-dependent features of the junctions seen in this figure imply the occurrence in them of a Josephson tunnel contact. However, whereas in the case of the I barrier the value of the supercurrent was estimated as $j_c = 2 \times 10^{-2}$ A cm^{-2}, for the structure with the EuO barrier it was nearly two orders of magnitude smaller. The inflection points on the CVC (by which the energy differences and sums of the junction-bank superconducting gaps are estimated), located between the extrema *1* and *2* and the points *2* and *3*,

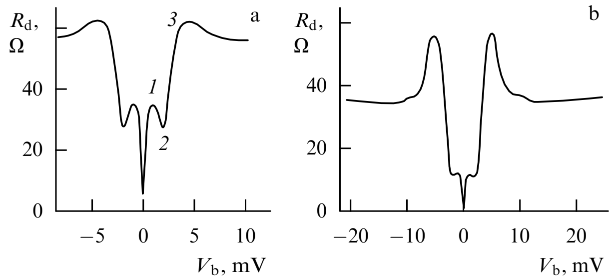

Figure 2. Differential CVC of tunnel junctions NbN/I/Pb (a) and NbN/EuO/Pb (b) ($T = 4.2$ K, $H = 0$).

respectively, in both cases were found to be symmetric about the major minimum of CVC at $V_b = 0$ that made it possible to determine the widths of these superconducting gaps in the case of the I barrier: $\Delta_{NbN} = 2.50 \pm 0.05$ meV and $\Delta_{Pb} = 1.20 \pm 0.05$ meV. Accordingly, the displacements of the inflection points were $V_2 = 1.3$ mV and $V_3 = 3.7$ mV.

When compared with the NbN/I/Pb structure, it was found that in the case of the EuO barrier the inflection points V_2 and V_3 were displaced much the same from their positions in the CVC of the junction, so $\Delta V_2 \approx \Delta V_3 = 0.15 \pm 0.05$ mV. If it is granted that the effective magnetic field of the spontaneously ordered EuO barrier in the NbN/EuO/Pb junction is not too high, so that this difference cannot be interpreted as a lowering of the T_c values of superconducting banks due to an existing dependence $\Delta(T)$ (in fact, their T_c values in the NbN/EuO and EuO/Pb contacts determined by the resistance measurements for $d_{EuO} = 0.01$ μm were found to be 16.4 K and 7.2 K, respectively), then it is natural to assign the obtained difference $|\Delta V_i|$ in the positions of any one of the indicated points in the CVC of this junction to the contribution of an exchange field in the EuO barrier. If so, this result turns out to be remarkable by itself, since it allows one to obtain the energy parameters of an FS barrier in tunneling experiments. It is known that for 'classical' superconducting tunnel junctions with an Ib barrier such a possibility is problematic [21].

In support of the aforesaid one can adduce the results of investigating the second derivative of the CVC of the superconducting tunnel junction NbN/EuO/Pb. As is known [22], the experimental determination of the function $\partial^2 V/\partial J^2$ in an explicit form versus the bias voltage across a junction in the near-above-gap region allows one to reconstruct the low-frequency spectrum of the branches of the electron–phonon interaction (EPI) function in superconductors, i.e. the part of their phonon spectrum nearest to the Fermi level.

The data in Fig. 3 are presented for the range of bias voltages from 8 to $\approx$ 40 mV only so as to eliminate from consideration the bias-voltage range shown in Fig. 2b, which includes the characteristic gap-dependent features of the spectrum of a tunnel junction and their associated geometrical (dimensional) resonances of the EPI function. In the absence of an external magnetic field, an identification of the positions of resonance maxima and minima of the EPI function in relation to the bias voltage applied to the structures with I and EuO barriers was performed. For the latter barrier, the positions of these extrema correspond to bias voltages indicated in Table 1. A comparison with the 'classical' junction testifies [23] that in the spectrum there exist yet unidentified resonances (at $V_b = 12.5$, 16 and 25.5 mV)

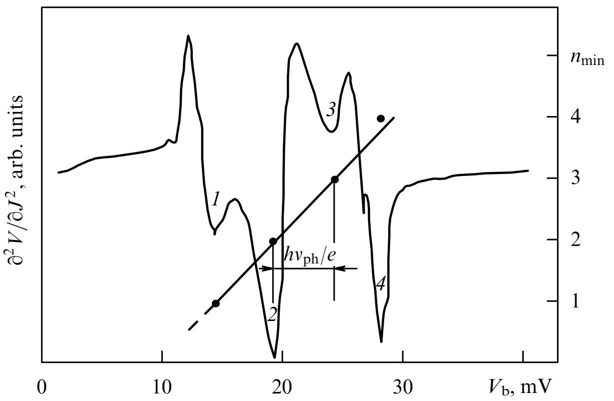

Figure 3. Spectral dependence of the $\partial^2 V/\partial J^2(V)$ function of a tunnel junction NbN/EuO/Pb ($T = 4.2$ K, $\mathbf{H} = 0$). The bias-voltage dependence of $n_{min}(V)$ is also shown (n_{min} is the ordinal number of a minimum in the spectrum).

Table 1

V_b^{max}, mV	11.0	12.5		16.0		21.5		25.5	27.0	
V_b^{min}, mV			14.5		19.5		24.5			28.5
Points in Fig. 3			*1*		*2*		*3*			*4*

which apparently correspond to the contributions of the EuO-barrier EPI function to the process of quasi-particle tunneling. With the aim of detailing the dominant (over the given area of bias voltages) mechanism of quasi-particle scattering in tunneling through a EuO barrier, a procedure for determining the periodicity of portions of the $\partial^2 V/\partial J^2(V)$ curve was carried out [24] by a method put forward in Ref. [25]. For 'classical' structures $S_1/I/S_2$ in the case that only the electron – phonon mechanism of quasi-particle scattering is dominant in tunneling, such periodicity is observed for points with ordinates equal to half the difference between the ordinates of the maxima in the spectrum and their next minima. Contrastingly, for junctions with a EuO barrier periodicity is established (with an interval $\Delta V \approx 5$ mV) in the positions of the minima of the function $\partial^2 V/\partial J^2(V)$ in tunneling spectra in the bias-voltage region from 14 to 25 mV. This is indicated by the observed linear dependence $n_{min}(V_b)$ (see Fig. 3) that can signify the initiation of a definite type of standing wave when one of the dominant (for a given FS barrier) mechanisms of scattering of tunneling quasi-particles is realized.

Taking into consideration the value of the Debye temperature for EuO ($\Theta_D = 350$ K), one might expect that the inherent resonances of the EuO EPI function in the tunneling spectrum will manifest themselves in the region of rather high bias voltages $V_b = h\nu_{ph}/e \approx 80$ mV corresponding to the energy of phonon resonance $h\nu_{ph} \approx 80$ meV. Considerably lower-energy resonances of the function $\partial^2 V/\partial J^2$ observed in experiments (see Fig. 3) as well as their periodicity are most likely determined by that part of the EuO-barrier EPI function which corresponds to the magnon excitation energy. This is in particular indicated by the frequency $\nu_m = e\Delta V/h \approx 10^{12}$ s^{-1} calculated from the experimental value of the periodicity ΔV. According to data on Raman scattering [26], this frequency corresponds to the energy of magnons in EuO and its value is $h\nu_m \approx 44$ cm^{-1} that is in agreement with the above-mentioned value of ΔV.

The magnetic nature of the marked peculiarity of the function $\partial^2 V/\partial J^2(V)$ for the NbN/EuO/Pb tunnel junction is evidenced by the data presented in Fig. 4, where the behavior of a portion of the tunneling spectrum from Fig. 3 is shown. This spectrum was appropriated in an external magnetic field aligned with the plane of the multistructure ($\mathbf{H} \perp \mathbf{n}$, $\mathbf{n}$ is the normal to the plane of the structure). Such experimental geometry corresponds to magnetization along the light magnetic axis of the EuO barrier, and this axis simultaneously turns out to be a hard direction for the entry of magnetic flux vortices into the superconducting banks and the Josephson contact. In the external magnetic field, termination of the resonant features of the EPI spectrum takes place as the magnetization of the EuO barrier is increased. In other words, a rise in the EuO-barrier spin ordering is accompanied by weakening of quasi-particle scattering in the tunneling process.

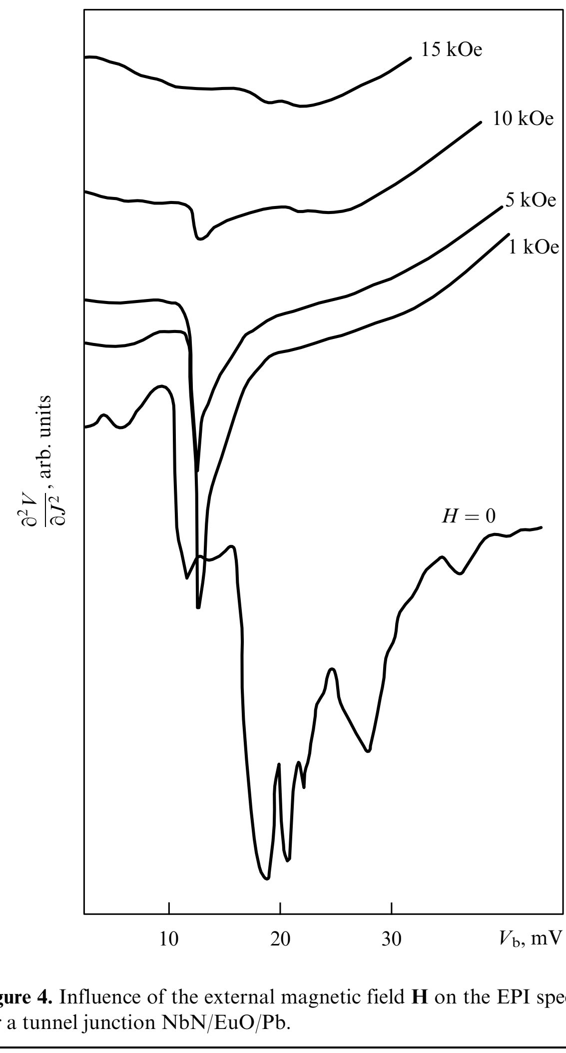

Figure 4. Influence of the external magnetic field **H** on the EPI spectrum for a tunnel junction NbN/EuO/Pb.

Thus, the experimentally established peculiarities of Josephson tunneling through an FS barrier, which role plays europium monoxide, as well as its EPI spectrum uniquely testify to the involvement of magnons in the phenomena of quasi-particle tunneling. This fact opens up additional possibilities for the study of the electronic and magnetic structures of such multilayer materials using the tunneling spectroscopy method.

2.2 NbN/EuO/Pb structure; $H > 0$

Let us trace now the influence of an external magnetic field on the CVC of the tunnel junction in the gap range of bias voltages. As before, we will perform a comparison of data for a 'classical' junction with an I barrier and a junction with a EuO barrier. These data are presented in Figs 5 and 6. Except in a few cases, the main transformations of the CVCs of these structures are observed at small bias voltages in the region of an absolute minimum of their differential resistance R_d at $V_b \approx 0$. If for the first junction, the external magnetic field scarcely affects the form of the CVC in the range from 0 to $H^* \approx 0.9$ kOe, that is, when its intensity does not exceed the value of the upper critical field of lead $H_{c2} = 870$ Oe, and then, at $H > H^*$, sharply changes the steepness and the sign of the curvature of R_d in the region of its minimum, then for the second junction — an NbN/EuO/Pb structure — these transformations of the steepness of R_d in the same region of bias voltages are more smooth. However, the change of the sign of curvature for the main nonlinearity of the CVC occurs in this case, too, at the moment when the external magnetic field disrupts the superconductivity of lead. True, in this case the strength of the external magnetic field turns out to be somewhat smaller than in the first case. Therefore, it would be more proper to speak about an 'effective' magnetic field **B** acting on this junction, which is combined of an external magnetic field **H** and the magnetization of a EuO interlayer in the junction. A further increase of the magnetic field is accompanied by an increase of R_d in the region $V_b \approx 0$ with the opposite sign of the curvature of R_d. This increase of R_d apparently tends to saturate.

In both the structures, the external magnetic field scarcely affects the position of the inflection point V_3 in the CVCs, but instead of two other inflection points V_1 and V_2, there appears one point — the superconducting gap in lead vanishes.

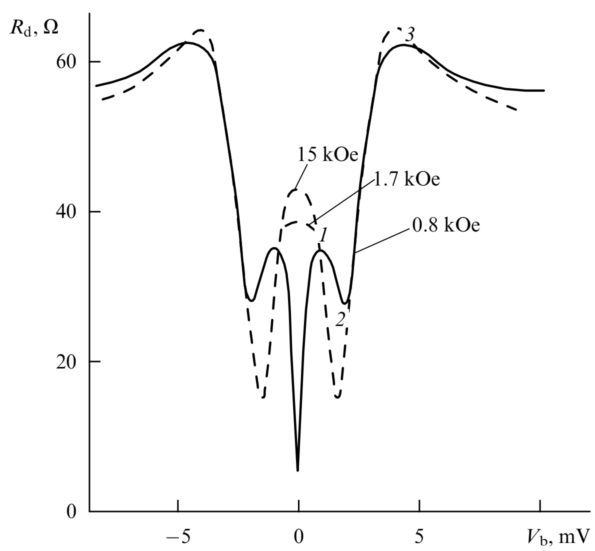

Figure 5. Transformations of the CVC of a tunnel junction NbN/I/Pb in the external field **H**.

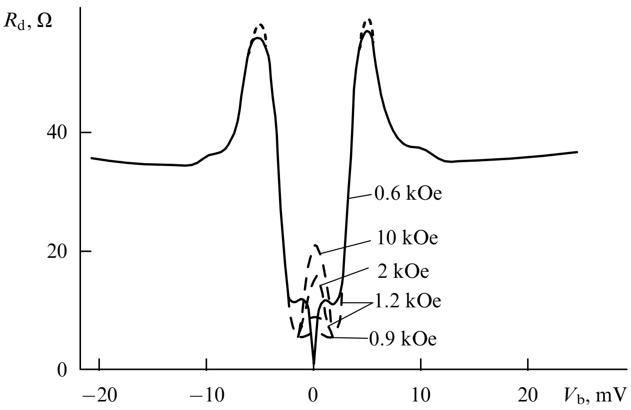

Figure 6. Transformations of the CVC of a tunnel junction NbN/EuO/Pb in the external field **H**.

2.3 NbN/EuS/Pb structure

The use of another ferromagnetic semiconductor — europium monosulphide — in multilayer structures F/M(S) or S_1/EuS/S_2 is determined both by the less rigid technological requirements imposed on the process of its deposition on metal and by the fact that the deposited layer can be obtained in a crystalline or amorphous state depending on the deposition conditions. This fact reflects in particular on the form of the CVC of the tunnel junction S_1/EuS/S_2. Finally, under the conditions of congruent evaporation of an EuS phase, it is easier to control the width of barrier layers and to eliminate 'short-circuiting' in tunnel structures.

The following data concern structures also grown onto Si substrates with about 0.05 μm thick EuS barrier layers. Technologically, the crystalline or amorphous structure of a barrier deposited on NbN was achieved by the temperature regime of the substrate. According to the data from Ref. [27], the CVCs of these structures, superficially similar to the CVCs of junctions with a EuO barrier, are characterized by the symmetry of the R_d curve with respect to $V_b = 0$ at $H = 0$, but differ among themselves in the following details (Fig. 7). Firstly, the value of the supercurrent for structures with a crystalline barrier was found to be $j_c \approx 130$ μA at $V_b = 0$, whereas for structures with an amorphous barrier it is much smaller and negative. Secondly, it turned out (see Table 2) that in the CVC of junctions with a crystalline barrier along with salient gap-dependent features like the difference $\Delta_{NbN} - \Delta_{Pb}$ (point *2*) and the sum $\Delta_{NbN} + \Delta_{Pb}$ (point *6*) there exist inflections at the points *3* and *5* reflecting the widths of superconducting-bank gaps by themselves and the points *1* and *4* defining their half-difference and half-sum, respectively.

It should be noted that the manifestation of nonadditive gap-dependent contributions in the CVCs of tunnel junctions until now was found only in multilayer structures with a large transparency of tunnel barriers (such as Cu/I/Sn/I/Pb [28]), in superlattices [29] as well as in studies of a three-level tunnel device — a quinteron [30]. In all cases the mechanism of these nonadditivities is associated with the 'bleaching effect' of a barrier, provided the processes of one-particle tunneling of quasi-particles are dominant. According to paper [28], such a feature of the CVC showed itself only in the case that the injection of phonons is conducted from the base junction Pb/I/Pb, and the device investigated in Ref. [30] in addition had the property of amplifying a tunnel current.

In the case of structures with a crystalline EuS barrier, in the region of bias voltages $V_b > 10$ mV a slightly marked

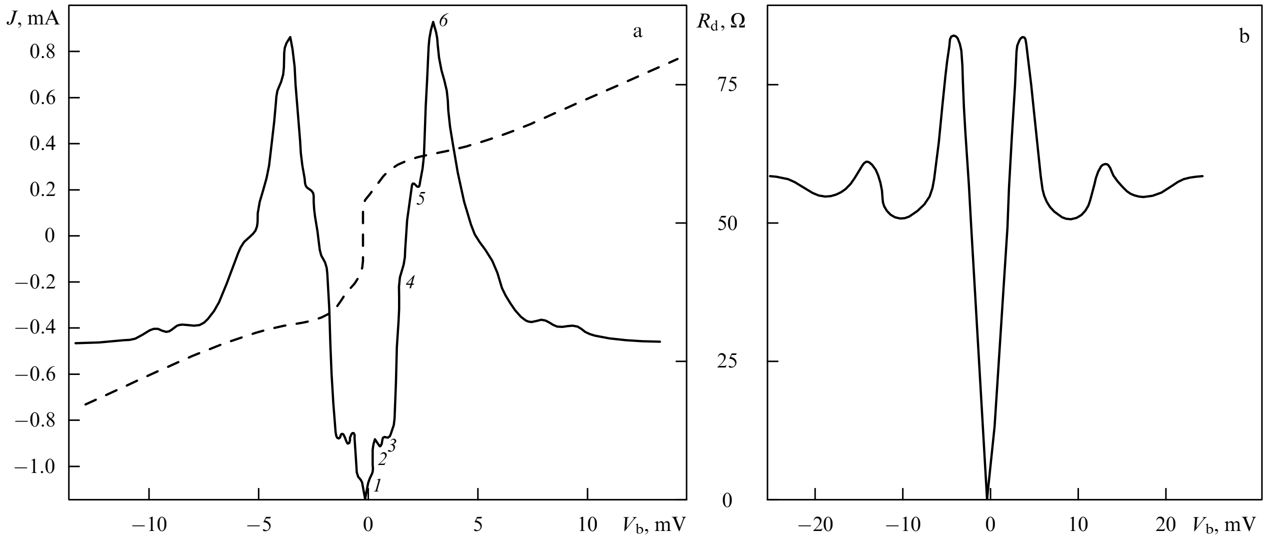

Figure 7. View of the CVC of NbN/EuS/Pb junctions with crystalline (a) and amorphous (b) interlayers ($T = 4.2$ K, $\mathbf{H} = 0$). Solid line — $R_d(V)$ dependence, dashed line — $J(V)$ dependence.

Таблица 2. Numerical values of the bias voltage for anomalous CVC points of the tunnel junction NbN/EuS/Pb and their correspondence to gap-dependent peculiarities of superconducting banks (from the data of Fig. 7)

CVC points	*1*	*2*	*3*	*4*	*5*	*6*
V_b, mV	0.35	0.75	1.25	1.80	2.10	3.3 – 3.4
Gap-dependent peculiarity	$(\Delta_{NbN} - \Delta_{Pb})/2$	$\Delta_{NbN} - \Delta_{Pb}$	Δ_{Pb}	$(\Delta_{NbN} + \Delta_{Pb})/2$	Δ_{NbN}	$\Delta_{NbN} + \Delta_{Pb}$

nonperiodicity of $R_d(V)$ was observed, which rather rapidly smoothed out with a further increasing of V_b. With an amorphous EuS interlayer in this region of bias voltages, on the contrary, a pronounced oscillating behavior of this dependence with a period of about 8.8 mV was established. The amplitude of these oscillations noticeably varied in value for different junctions, and the oscillations smoothed out in 1 – 2 periods.

It should also be noted that in accordance with theoretical predictions [31, 32] the negative sign of the supercurrent $j_c < 0$ (at $H = 0$) determined for this structure at zero bias voltage could be indicative of the realization in the NbN/EuS/Pb structure of a so-called π-contact in the ground state ($V_b = 0$), when the phase difference $\varphi_1 - \varphi_2$ for tunneling quasi-particles in S banks is equal to π instead of zero. Such a case corresponds to the absence of ferromagnetic ordering between the local magnetic moments of the europium ions in the barrier. More recently, such a contact was realized by the authors of publication [3] in metal multistructures Nb/Gd/Nb.

Besides, as an external magnetic field is applied in the geometry $\mathbf{H} \perp \mathbf{n}$, the form of the tunneling anomaly for the junctions in question changes drastically both in the CVC intragap and above-gap regions of bias voltages (Figs 8 and 9). At $H > 0$, some broadening of the peak in $R_d(V_b)$ near its main minimum is observed for both junctions. For the structure with an amorphous EuS barrier, first the inversion of the sign of j_c is observed and only then the change of the sign of the CVC curvature and the smoothing of peculiarities associated with Δ_{Pb}/e in magnetic fields $H \geqslant 0.09$ T take place.

In all the multilayers under discussion — superconducting tunnel junctions with an FS barrier — no hysteresis features were found in the CVC structure when changing sign of bias voltage, even when a magnetic field is applied to them.

For $H > 0$, in the above-gap region of the CVC the smoothing of the oscillation of $R_d(V, H)$ is always observed, and the inflection points *5* and *6* slightly shift to the centre. The intensity of the anomaly at point *6* slightly increases in this case.

Summing the foregoing experimental data relevant to the FS tunnel barrier in $S_1/FS/S_2$ multilayers, it can be said with assurance that for such systems in the CVCs of tunnel structures the features inherent in nonadditive contributions of the processes of one-particle tunneling through an FS barrier appear. The mechanism of occurrence of these contributions is most likely to be photon injection (generation), reflecting in this case the presence in the junction of an S/FS boundary and its associated phenomena of spin orientation of tunneling quasi-particles. Analogous phenomena occurring on the FS/NS boundary in the processes of magnetoplasma absorption were intimated in paper [33]. Since the degree of such spin orientation is determined by the amount of the magnetic energy of an FS barrier equal to $AS/2$ (A is the exchange parameter, and S is the magnetic-ion spin), the calculated frequency of such photon generation caused by flip-flop of one of the electron spins of a Cooper pair in its passage through this boundary must correspond to the value $\omega_0 \approx 10^{14} - 10^{15}$ s^{-1}. This frequency range covers the near-infrared range of the spectrum and is of interest for practical applications at the interface between microwave technology and optics.

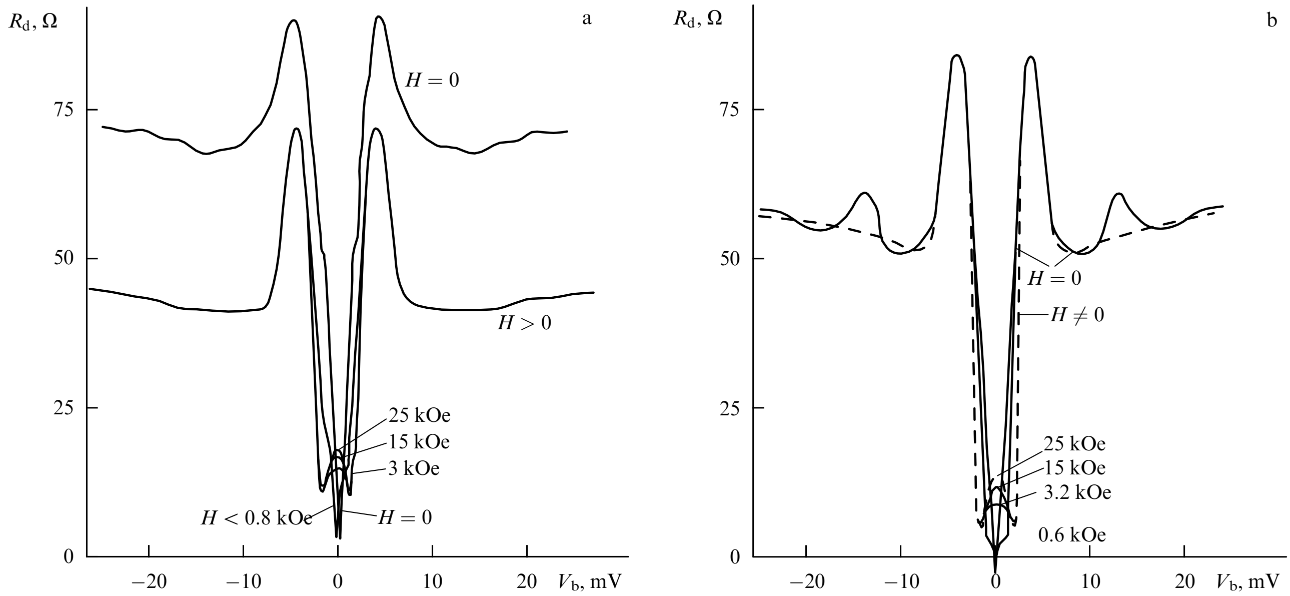

Figure 8. Variations of the CVC of NbN/EuS/Pb junctions in an external field **H**: (a) crystalline barrier, (b) amorphous barrier.

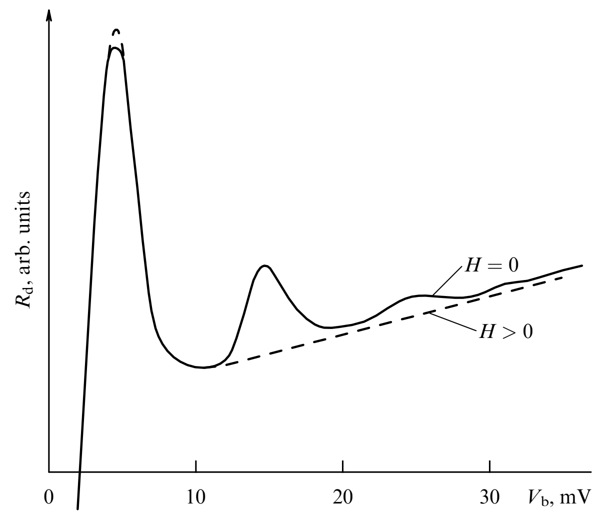

Figure 9. Fragment of the $R_d(V, H)$ dependence in the above-gap region of bias voltages for a tunnel junction with an amorphous EuS barrier.

3. Magnetization of S/FS multilayers

When conducting the above investigations of CVCs of superconducting tunnel junctions NbN/FS/Pb in magnetic fields created by a superconducting solenoid, in a number of cases phenomena of electrical breakdown of the structure were observed if it was placed in a 'hot' solenoid (with remanent induction ~ 100 Oe). The electrical resistance of the structure sharply dropped to zero, and the measurements of CVCs became technically infeasible. It was obvious that the breakdown is of a magnetic nature, since it did not occur if the structure was placed in a 'cold' solenoid (that is, which was cooled and previously not turned on). This fact caused our research group to turn to magnetic measurements proper of planar S/FS multilayers. The intrinsic magnetic characteristics of EuO and NbN films were reported in papers [34, 35]. According to these works, EuO films fall into the category of soft ferromagnetic materials with a coercive force $H_c \approx 60$ Oe. NbN films are type-II hard superconductors with $H_{c2} \approx 10-20$ T. The measurements of the magnetization $\sigma(H)$ of these multilayers were performed both along their easy magnetization axis (in the plane of the structures), $\mathbf{H} \perp \mathbf{n}$, and along the hard direction of magnetization, $\mathbf{H} \parallel \mathbf{n}$. The value of T_c for the NbN film proper in this experiment was ≈ 16 K.

A salient feature of the field-dependent magnetization $\sigma(H)$ in the case $\mathbf{H} \perp \mathbf{n}$ (Fig. 10) is the existence of an open hysteresis loop and the absence of partial magnetic-reversal loops in magnetic fields up to $H \approx 7$ T at $T = 4.2$ K. The effective value of H_c for this structure is equal to 100 Oe, which is close to the value of the lower critical field H_{c1} in the NbN film and nearly 1.6 times larger than H_c for the EuO film. The magnetization and demagnetization curves bounding the contour of the hysteresis loop are substantially separated and come close together in sufficiently high fields.

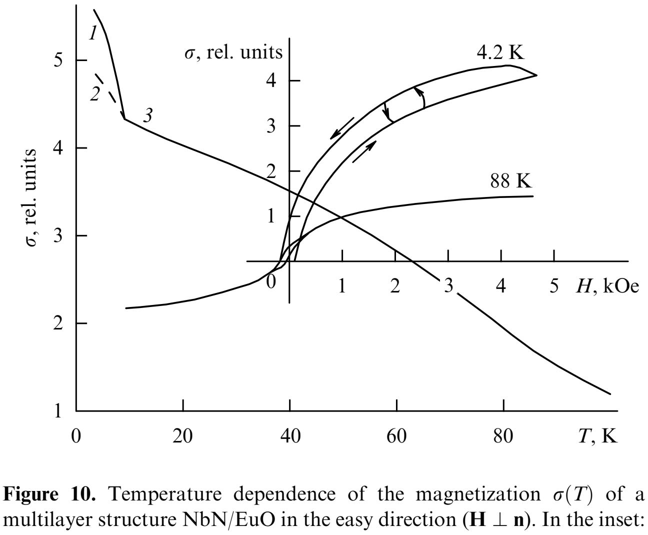

Figure 10. Temperature dependence of the magnetization $\sigma(T)$ of a multilayer structure NbN/EuO in the easy direction ($\mathbf{H} \perp \mathbf{n}$). In the inset: the shape of the hysteresis loop and the $\sigma(H)$ dependence.

When attempts were made to obtain partial remagnetization loops of the structure through the change of sign of the magnetic-field increment ΔH, a transition between these boundary curves was observed. For $\Delta H < 0$, there occurred a transition of σ from the lower curve to the upper one, and in the case $\Delta H > 0$, a reverse transition took place. The change of $|\sigma|$ is practically of a threshold character and reproduced when moving along any partial closed contour of the loop. With increasing temperature above the transition point T_c for the NbN film, the magnetization curve of the S/FS contact takes a form which is typical of ferromagnets, degenerating in $H_c(T)$. As is seen from Fig. 10, at $T = 88$ K a hysteresis loop still remains visible which is inherent in a EuO film and indicates that the Curie temperature of this film has not yet been reached (in this case it is just higher than 90 K).

The behavior of the contact $\sigma(T)$ dependence at temperatures below the T_c temperature of a NbN film is determined by its prehistory (magnetization conditions). When cooling in a rather high magnetic field up to $H = 5-7$ T (MF cooling) with a subsequent fixation of the $\sigma(T)$ dependence in a field of 2 T, the run of the low-temperature portion of the magnetization curve corresponds to the segment *3 – 1* in Fig. 10. But if the contact is cooled in a zero magnetic field (ZMF cooling) and then smoothly magnetized up to $H = 2$ T, then the same low-temperature portion of the magnetization curve corresponds now to the segment *2 – 3*. The point *3* in this portion of the $\sigma(T)$ dependence conforms to a temperature of $\sim 10-12$ K that is close to the value of the T_c for an NbN film placed in a magnetic field of $\sim 3-4$ T [35]. Since the actual intensity of the external magnetic field in this experiment was as low as 2 T, its elevated 'effective' value in the multilayer structure is set up owing to the presence of an FS (EuO) film. If the thickness of the FS layer is fixed, the difference $\Delta\sigma$ corresponding at $T = 4.2$ K to the difference of the ordinates of the points *1* and *2* in the low-temperature segment of the $\sigma(T)$ dependence is determined by the thickness of the superconducting film. In the case that the thicknesses d_{EuO} and d_{NbN} of both the layers in a contact are comparable, this difference $\Delta\sigma = 0$, and the superconducting properties of such a structure are suppressed. This relation is indicative of the decisive role of the magnetic-flux penetration-depth parameter of an NbN film. At $d_S > d_{FS}$, the FS film merely promotes the 'freezing' of a magnetic flux which has entered the surface layer of a thick superconductor with partial retention of superconductivity.

Thus, these results are evidence of the presence in the S/FS contact under discussion of an 'effective' magnetic field from the side of FS which reduces the actual value of T_c relating to the superconductor layer. In this case ΔT_c makes $\approx 2-3$ K, and the efficiency of additional magnetic induction in the structure is estimated at $1-2$ T.

Even more striking threshold changes $\Delta\sigma$ are observed for such an S/FS structure when it is magnetized in the hard direction. The data presented in Fig. 11 are indicative of the existence of a near-rectangular magnetization loop for this structure with the threshold-switching value $\Delta\sigma \approx 2|\sigma|$ in the initial portion of the magnetization curve in the case of sign-alternating variations of the increments of an external magnetic field. Such variation within the hysteresis loop results in the indicated change $\Delta\sigma(H)$ at any point of the loop that makes it possible to move along the partial contours of the magnetization curve, such as the contour $A-A'-B-B'$ marked in Fig. 11. As before, the sensitivity of the threshold disruption of the structure magnetization to the

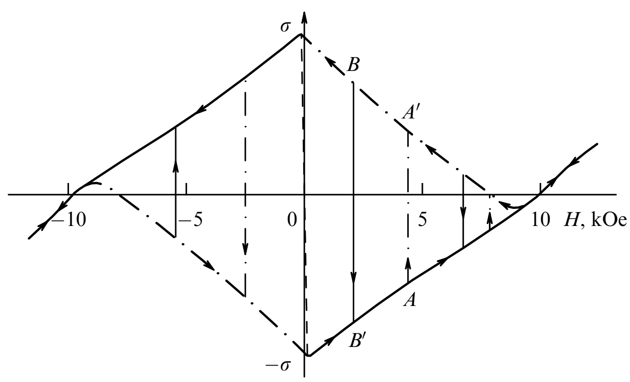

Figure 11. Magnetic-reversal loop of an NbN/EuO structure in the hard direction (**H**||**n**).

value of the external field variation is determined by the ratio between the thicknesses of the S and FS layers in a multilayer structure.

This phenomenon has been observed in S/FS multilayers in the cases when the base superconducting layer was made from a type-II 'hard' superconductor. Whether this phenomenon is reproduced for metallic superconductors and metallic ferromagnetic coatings will be seen from further investigations.

The mechanism of magnetization switching in a planar S/FS multilayer is determined essentially by quantum effects, namely, by the quantization of magnetic-flux vortices and their pinning on inhomogeneities of the NbN film under the action of an intrinsic field of the FS film in a varying external magnetic field. The role of an FS layer in such a structure consists in creating additional centres of pinning — magnetic-domain boundaries — in the surface layer of a superconductor, fixing magnetic vortices on them and strengthening the magnetic-flux creep. This is proved by the fact that the magnetized state of a multilayer contact remains unchanged as long as is wished, if the external magnetizing field is stabilized at temperatures T below T_c (for an NbN film).

Variations $\Delta H/\Delta t$ (t is the time) restore the original state of the magnetization σ in the contact. Since the angle α of magnetization (the tilt angle of magnetization-switching segments of hysteresis loops) for 'dirty' superconductors of type II is determined by the initial portion of the magnetization curve $\sigma(H)$ at $H < H_{c1}$ and depends on the shape of the sample, and in a multilayer structure moreover on the demagnetizing factor N of the FS layer for which $\tan\alpha \sim 1-1/N$ [10]; therefore in thin layers, when $N \to 1$, the disruptions of σ are of a threshold character, since $\tan\alpha \to 0$.

The foregoing results in many respects explain the phenomenon of electrical breakdown of tunnel structures NbN/FS/Pb in low external magnetic fields. They can become the basis for designing a large variety of cryoelectronic devices capable of switching and detecting magnetic fluxes as well as for creating original technology making it possible to obtain quantum microcontacts in multilayer superconducting tunnel structures.

4. HTSC/FS multilayers

The appearance of materials possessing the property of high-temperature superconductivity determined one of their possible applications — in tunnel multistructures which can in function become high-temperature analogues (for liquid-nitrogen temperatures $T > 78$ K) of the well-known cryoelectronic devices [36, 37], including those described above. For purely technological reasons and by virtue of existing physical and chemical restrictions, attempts to create a multilayer structure HTSC/FS/HTSC have not yet met with success. Therefore, at present, the operation of a two-layer HTSC/FS contact capable of serving as a magnetic-flux switch at liq. nitrogen (and lower) temperatures is of interest. The 'classical' FSs — EuO and EuS — are replaced in this case by their 'high-temperature' analogue, namely, by an FS based on a solid solution $Eu_{1-x}Sm_xO$ with the Curie temperature $T_C = 130$ K and possessing semiconductor-type conductivity [38] as well. Physically and chemically, the HTSC phase $EuBa_2Cu_3O_{7-\delta}$ (Eu-123) with $T_c = 94$ K is best suited for creating such a two-layer structure with a physically homogeneous boundary.

It is known that HTSC materials in their properties are Josephson media with numerous and sufficiently ramified I barriers along the grain boundaries. Therefore they are typical 'hard' type II superconductors with strong pinning [39], and their magnetic-reversal curves in many respects are similar to those of the NbN/EuO contact, presented in Fig. 11. For HTSC phases of composition R-123, where R is yttrium or a rare-earth metal, the $\sigma(H)$ dependences are of the same type [40] and they exhibit rather sharp, but not threshold, changes $\Delta\sigma$ within hysteresis loops. The angle of magnetization disruption ($\approx 20-30°$) for these loops is also determined by the initial linear portion of the magnetization curve (at $H < H_{c1}$). Such loops $\sigma(H)$ are presented in Fig. 12 for HTSC phase Eu-123 at $T = 4.2$ K and $T = 77$ K. As a whole, the mechanism of formation of the magnetization curves for such phases is consistent with the theory of the critical state of granular superconducting ceramics [41, 42].

The two-layer structure Eu-123/$Eu_{1-x}Sm_xO$ was fabricated through evaporation of a 0.05 μm thick layer of $Eu_{1-x}Sm_xO$ onto a superconducting ceramic substrate about 0.5 mm in thickness. It follows from Fig. 13 that the magnetic-reversal curve for this structure is similar to the $\sigma(H)$ dependence for the Eu-123 substrate in itself, with the only difference being that the angle of its initial magnetization and jumps $\Delta\sigma$ become close to threshold ones. And in this case there is a tendency for a decrease in the angle of magnetization disruption with decreasing the thickness of the superconducting substrate. One would expect that on meeting the necessary conditions (when fabricating thin-film contact layers), the threshold switching of magnetization will be realized in the HTSC/FS structure in case of sign-alternating variations of an external magnetic field.

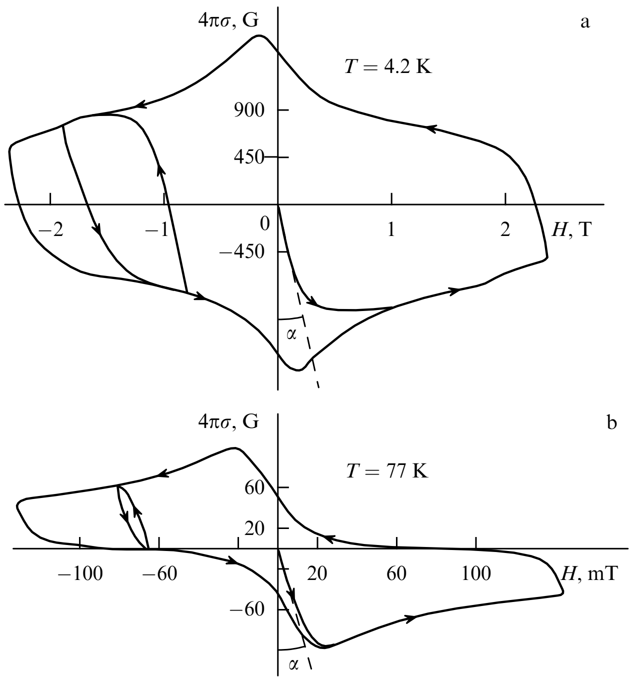

Figure 12. Magnetization loops of a phase Eu-123 at $T = 4.2$ K (a) and $T = 77$ K (b).

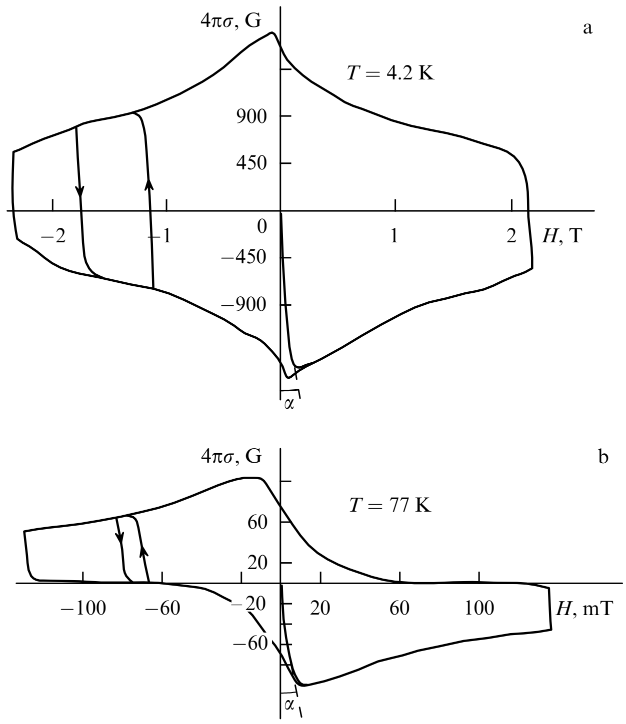

Figure 13. Magnetization loops of a Eu-123/EuSmO structure at $T = 4.2$ K (a) and $T = 77$ K (b).

5. Spin filtering through FSs

5.1 M/FS structures as solid-state sources of polarized electrons

The above-mentioned feature of a ferromagnetically ordered barrier, namely, the capability for passing with a higher probability the one-particle tunnel current of spin-polarized carriers whose spin orientation coincides with the magnetization vector of the F barrier, finds an interesting practical application.

The exchange splitting of the conduction band of ferromagnetic metal into spin-'up' (↑) and spin-'down' (↓) subbands results in the arising of an additional energy barrier for the tunneling quasi-particles of a specific spin orientation. In the case that their spin direction coincides with the spin direction of the lower-energy subband of an F barrier, the energy of tunneling is less, and the transparency of such a barrier is more, than for particles of opposite spin orientation. Thus, the F barrier in a tunnel multilayer structure M(S)/F acts as a distinctive spin filter. In view of the azimuth asymmetry of scattering of spin-polarized electrons, the current of such electrons finds direct application, for example, in experimental atomic physics and high-energy physics in studies of low-energy processes of electron scattering on a target, effects of conservation of parity and some other effects [43]. In this case the informative value of such processes sharply increases.

At the same time, it is known [44] that the degree of spin polarization of current carriers in F materials at $T < T_c$, determined by the mechanism of their s–d (d–f) exchange interaction with localized magnetic moments, strongly depends on the electron–electron interaction as well (in other words, on the concentration of current carriers n^*) and ranges from values $\sim 1-10\%$ in ferromagnetic metals, where $n^* \approx 10^{23}$ cm^{-3}, up to nearly 100% in FSs, for which $n^* \ll 10^{18}$ cm^{-3}. From this it follows that ferromagnetic metals by themselves cannot serve as a sufficiently effective source of spin-polarized electrons or a spin filter.

Prior to the use of FSs as spin filters, metals or semiconductors with a small value of the photoelectric work function, such as metal cesium or gallium arsenide, were used as solid-state sources of spin-polarized electrons. A rather cumbersome device for operation in an accelerating chamber included a large variety of optical systems and magnets. The final degree of spin polarization of an electron photocurrent was in this case as much as 0.65 [45] and 0.40 [46]. The authors of paper [47] were able to increase the degree of electron polarization and to attain considerable miniaturization of a source using europium sulfide deposited in the form of a monolayer onto a metal base — a tungsten needle. When operated in vacuum $\sim 10^{-11}$ Torr and at $T = 9.5$ K, such a solid-state source in a longitudinal electric field up to ≈ 1 kV provided a degree of polarization P of emitted electrons up to the values ~ 0.85.

When operating in an accelerating chamber, the EuS coating, if magnetized to saturation, acts as a filter for electrons emitted by tungsten, namely, passing predominantly electrons with one of two possible spin polarizations. At the Fermi level there are no more than 50% of such electrons. For electrons with spins opposite in direction to the magnetization of the FS coating, the potential barrier height for tunneling is greater by a value equal to the red shift of the bottom of the EuS conduction band in a magnetically ordered state, viz. $\Delta = 0.16$ eV (at $T = 4.2$ K).

The spin-filtering parameters of the W/EuS solid-state emitter of electrons realized in experiment [47] are likely not to be limiting. Firstly, the real possibility exists to increase them owing to higher values of the conduction-band exchange-splitting energy and the red shift of the bottom of the conduction band in europium monoxide, where $\Delta = 0.25$ eV. Secondly, with the use of a ferromagnetic metal such as Ni for the metal base of the emitter, in its electronic spectrum, if this metal was magnetized, its own energy difference (so-called exchange gap) arises between the electron states at the Fermi level with opposite spin orientations. Therefore, the probability of subbarrier emission (or, differently, the height of the potential barrier in tunneling defined as an energy difference between electron quasi-levels in metal and an FS) for one spin orientation of electrons will be reduced by the value of this difference and for the other ones will be increased (Fig. 14). The theoretically admissible degree of spin polarization of electrons for a solid-state emitter of the FM/FS type (FM denotes ferromagnetic metal) is expressed by the value of $P = 0.93-0.96$ and limited only by the natural broadening of the Fermi-distribution function on the 'tail' of the electron density of states in FSs ($\sim 4\%$) [48, 49].

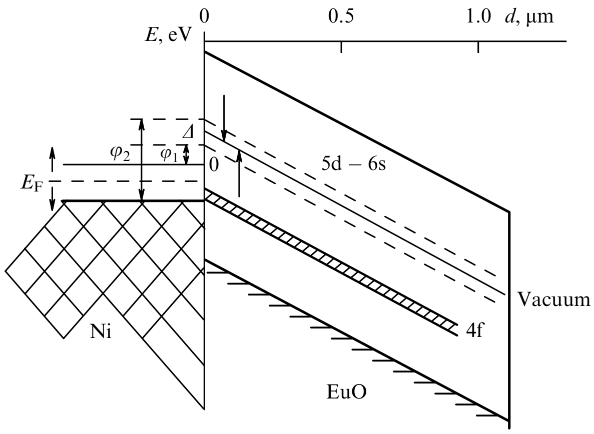

Figure 14. Band structure of an Ni/EuO emitter. Here $\varphi_{1,2}$ are the barrier heights for electrons with spins ↑ and ↓, respectively, and Δ is the exchange splitting of a EuO conduction band.

Compared to the W/EuS emitter, the FM/EuO source of polarized electrons is capable of operating in a high vacuum down to liquid-nitrogen temperatures. True, in these conditions the value of P has to be affected by the inherent 'noise' of the phonon subsystem, and this situation calls for special study. The technology of such a source developed in Ref. [49] allows one to create miniature emitters with reproducible technical parameters outside the work chamber that can provide their interchangeability and the possibility of operation in high-energy cyclic accelerators.

5.2 M/FS structures as magnetically controlled diodes

Another, not so exotic, application of M/FS multicontacts is connected with a direct embodiment of Esaki's notions concerning the creation of magnetic microelectronic structures on the base of MOS junctions controlled by an external magnetic field. The function of a 'classical' semiconductor in these structures is performed by a ferromagnetic semiconductor. The recent discovery of outstanding physical properties of FSs based on lanthanum manganite [50] makes the operation of such MOSF structures at room temperatures quite possible, since the values of the Curie temperatures for many of them are as high as 350 K.

An implementation of the rectifying effect in a multilayer M/FS contact, thanks to the formation of a Schottky barrier in the paramagnetic ($T > T_C$) region of a triple FS based on a $CdCr_2Se_4$ phase, was reported in paper [51]. However, only the authors of paper [52] have demonstrated additional features of an M/FS heterocontact (with an n-type $HgCr_2Se_4$ crystal as an FS) for $T < T_C$ (= 120 K) determined by the exchange splitting of the conduction band of this FS into two subbands, which results from ferromagnetic ordering of the spins of Cr^{3+} ions through the s–d exchange mechanism:

$$\Delta_{sd} = \pm\frac{1}{2}A_{sd}S\frac{\sigma(T)}{\sigma(0)}\,.$$

Here, S is the ion spin, A_{sd} is the s–d exchange integral, $\sigma(T)$ and $\sigma(0)$ is the saturation magnetization of the FS at T and

0 K, respectively. With a positive bias voltage on metal, electrons tunnel from the metal into the upper subband of the FS and populate this subband. As this takes place, beginning with some bias voltage $U > U_{cr}$, a decrease in the electric conductivity of the structure is observed as a result of decreasing the mobility of current carriers in the FS because of electron – magnon scattering.

The experimental data [52] presented in Fig. 15 illustrate this process for an $HgIn/HgCr_2Se_4$ contact at different temperatures. So, if with lowering temperature from 300 to 200 K the diode (i.e. rectifying) properties of the contact are impaired, then at $T < 120$ K and $U > U_{cr}$ they are again improved. In this case the temperature dependence of $U_{cr}(T)$ for different σ follows the behavior of the magnetic gap $\Delta_{sd}(T)$ in the FS (Fig. 16), and the blocking voltage in the structure arises at a negative potential on the metal.

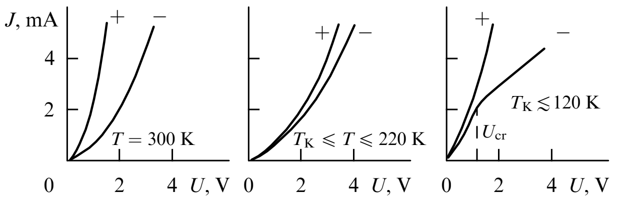

Figure 15. Rectifying properties of an $HgIn/HgCr_2Se_4$ contact at different temperatures (the signs + and − correspond to the polarity of the potential on metal) [52].

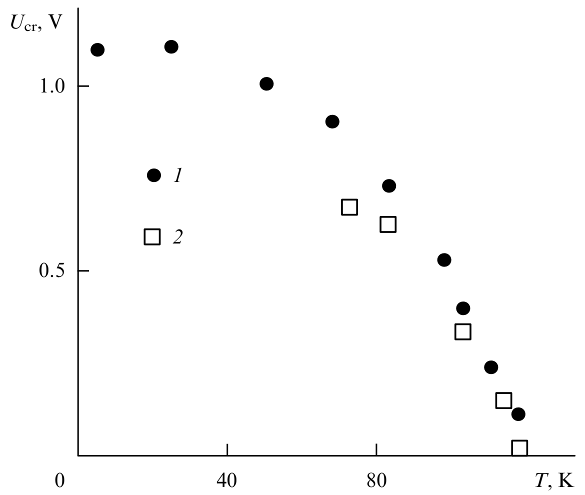

Figure 16. Temperature dependence of the critical voltage $U_{cr}(T)$ for $M/HgCr_2Se_4$ contacts: M — W (*1*) and HgIn (*2*)

In contrast with this heterostructure, in the case of a p-type $M/HgCr_2Se_4$ contact the blocking voltage arises at the positive polarity of metal [53], corresponding to 'classical' M/NS contacts [54]. However, at $T < T_C$ the rectifying properties of this contact vanish altogether, and it becomes ohmic, as well as an n-type $HgCr_2Se_4$ FS by itself.

5.3 FS/NS structures as the base of submillimeter magnetic microelectronics

In connection with the practical realization of FS/NS heterocontacts new possibilities arise for their application, since in modern heterostructures and multilayers with nonmagnetic semiconductors used in microelectronic devices the spin direction of current carriers is of no importance and in no way affects the mechanisms of physical phenomena underlying their operation. As mentioned above, these possibilities are associated with the spin injection of polarized electrons from an FS into an NS, which can radically alter the properties of the latter. In particular, the possibility was pointed out in Ref. [55] of polarized luminescence occurring during unpolarized illumination of a system of spin-polarized electrons. Owing to the influence of such a 'magnetization' effect on the spin state of current carriers in NS, the microwave characteristics of NS in an external magnetic field must undergo a change as well. For example, at the frequency of EPR $h\nu = \mu_B g H$ (h is the Plank constant, μ_B is the Bohr magneton, and g is the magnetic splitting factor for conduction electrons in NS), radiation may arise depending on the degree of the population inversion of Zeeman levels during the injection of current carriers from FS into NS, being tuned by external magnetic field.

The effects outlined were realized for the first time by the authors of papers [56, 57] in the following FS/NS microcontact heterostructures: n-$HgCr_2Se_4$/n-InSb (I); n-EuO/n-InSb (II) and p-$HgCr_2Se_4$/n-InSb (III). The study of microwave processes when passing a current of a definite polarity through the structure I provided a possibility to observe radiation absorption in the millimeter region of the spectrum at the EPR frequency of free current carriers in n-InSb (Fig. 17) [56]. The amplitude of this absorption is proportional to the current.

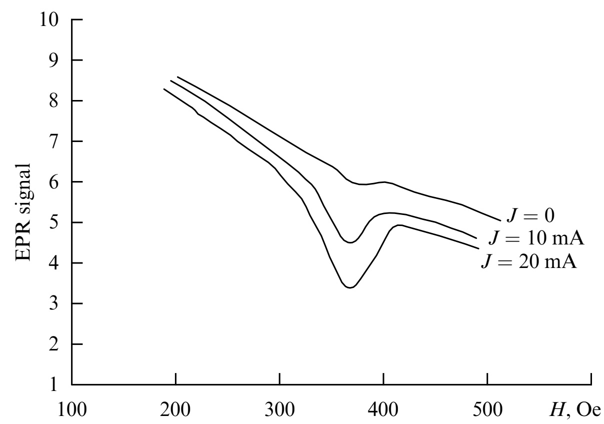

Figure 17. EPR signal of conduction electrons in n-InSb for different currents in the heterostructure I at 26 GHz [56].

For the heterostructures II and III at the same current polarity radiation was detected whose frequency, being the EPR frequency appropriate to the intensity of an applied external magnetic field H, can be varied by this magnetic field from the near-centimeter (8 mm) to submillimeter (0.2 mm) region (Fig. 18) [57]. Assuming that this radiation arises in an NS when an electron from an FS moves to the upper Zeeman level of the NS and then drops back to an unoccupied lower level with the emission of a photon at the frequency of EPR, one obtains an upper theoretical limit to the output power of an emitting heterostructure: $N = \mu_B gHJ/e \equiv h\nu J/e$, where J is the current passing through the heterostructure, and e is the electron charge. Estimates made in paper [58] give the following values of the output power: $N = 156\ \mu W\ A^{-1}$ for the region ~ 8 mm, and $N = 12\ mW\ A^{-1}$ for 0.1 mm. The experimental values of the output power obtained for these

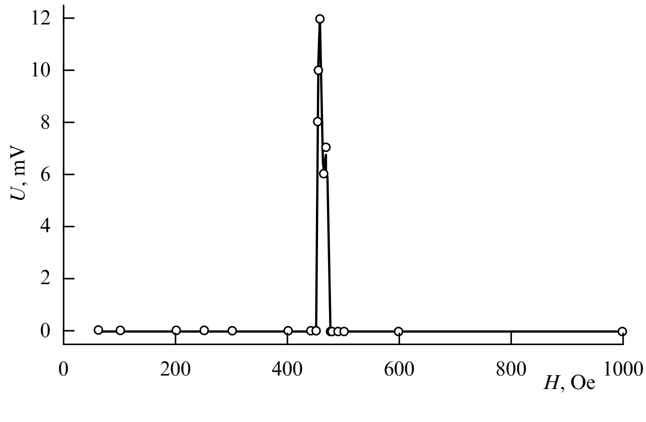

Figure 18. Emission line (linewidth ≈ 20 Oe) of the heterostructure III at a current of 2 A and $T = 77$ K. The frequency of a re-entrant cavity is 33.4 GHz [57].

frequency regions in the structure III have turned out to be nearly two orders of magnitude smaller. Nevertheless, there are purely technical possibilities for its increase up to the theoretical limit, since the heterostructure can conduct currents of up to 10 A in a pulse.

From the above-stated relation for the output power of an FS/NS heterostructure it is seen that N is directly proportional to the frequency and the intensity of an external field **H** that makes it possible to use such a structure as a generator of millimeter and submillimeter radiation and to control the parameters of the generator with the help of an external magnetic field. Such control cannot be realized in existing semiconductor generators, since their output power varies with the frequency as ν^{-4}. Thus, it is shown experimentally that heterostructures and FS/NS microcontacts can form a base for creating a new generation of narrow-band solid-state micromagnetoelectronic devices operating in the millimeter and submillimeter regions of the electromagnetic spectrum and tuned and modulated in frequency by a magnetic field as well as current-controlled generators, amplifiers, receivers, filters and other devices.

6. To the theory of the problem

One would think that the theory of superconductivity based on the notions of the phonon mechanism of pairing electrons with oppositely directed spins (singlet pairing), so that the total spin of a pair is $\mathbf{S}_p = 0$ (the BCS theory), provided an explanation for the incompatibility of the two most prominent phenomena in solid-state physics — superconductivity and ferromagnetism. The presence of an exchange field induced by localized magnetic moments leads to the breaking of a superconducting quasi-particle — the Cooper pair — and to the suppression of superconductivity (the 'closing' of the superconducting gap, $\Delta \to 0$). Thus, in the same material the coexistence of ferromagnetism and superconductivity is impossible. But what is occurring when a superconductor and a ferromagnet are in contact? What is the mechanism for the practical implementation of the phenomenon of weak superconductivity — the Josephson effect — in S/F multilayers?

The development of the theory answering these questions has been ahead of relevant experimental possibilities based in many respects on the advancement in the last-decade of high technologies and the technology of fabricating planar multilayer structures. Most publications available in the physics literature and concerned with the above questions relate to the theory of S/F metal contacts. A critical review of these publications is of independent interest and is not a subject of consideration in the present review. Restricting ourselves to a specifically narrow theme announced in the title of the present review, we will analyze very few works having at least some kind of relationship to S/FS contacts. Any special consideration of the physics both of these contact structures and all other ones up to the present has practically not been carried out. For the most part, the experimental results presented in the review have yet to be analyzed theoretically.

The authors of papers [60, 61] were apparently the first to consider the theoretical possibility for realization of superconductivity in thin S/F layers; they put forward the superposition mechanism of superconductivity, namely, the singlet BCS pairing of electrons with a constant-sign pair amplitude in the S layer and the same pairing, but with an oscillating wave function, in the F layer (the Larkin – Ovchinnikov – Fulde – Ferrell, or LOFF mechanism). According to this mechanism, an important condition for retention of superconductivity in such a structure is the presence of a rather thick S layer, $d_S \gg d_F$, in combination with a small transparency of the S/F boundary. In such a case one of the conditions of the 'classical' proximity effect in S/M layers is fulfilled, that is, the flow of Cooper pairs from the superconductor into a metal is proportional to the product of the coefficient of transparency by the value of the pair-amplitude jump at the S/M boundary. Because of the proximity effect, pair correlations will also be induced in boundary F layers, although the exchange splitting of the conduction band $2AS \gg k_B T_c$ (k_B is the Boltzmann constant) will change the conditions of pairing in the F layer. In this layer the pair quasi-particles are formed from isoenergetic spin-singlet electrons with different in magnitude quasi-momenta ($\mathbf{p}$, $\uparrow$) and ($-\mathbf{p} + \mathbf{k}$, $\downarrow$), where $|\mathbf{k}| = 2A/V_F$ is the coherent momentum of a pair (V_F is the Fermi velocity in the ferromagnet). Such a LOFF state of a superconducting quasi-particle in the F layer is characterized by a pair amplitude oscillating with a period $a_F \sim |\mathbf{k}|^{-1}$. The presence of nonmagnetic impurities in the F layer results in scattering of tunneling quasi-particles on these impurities and decaying of the LOFF phase, so that the pair oscillations in such a 'dirty' F layer have to damp out over distances of the order of the mean free path $L_F = V_F t_F$ from the S/F boundary ($L_F > a_F$). Hence it follows that the possibility of experimental observation of such effects associated with the amplitude of a Cooper-pair flow through the indicated boundary is determined by its transparency and regulated by the fabrication technology for such structures.

The development of modern concepts of the LOFF pairing mechanism in S/F layers was continued in papers [8, 62] in connection with obtaining experimental data indicative of the oscillation character of variation of the critical temperature T_c in multilayers S/F [4] and S/F/S [3]. These results are illustrated in Fig. 19. In this case the theory operates with a finite transparency of the S/F boundary and offers an explanation for the variations of T_c with the thickness d_F of ferromagnetic metal in this contact.

The theory of the Josephson effect by itself in tunnel structures $S_1/F/S_2$ evolves somewhat differently. As a rule, the tunnel-Hamiltonian method is used with consideration for magnetic impurities localized in a barrier [63, 64]. The presence of these impurities results in the barrier bleaching

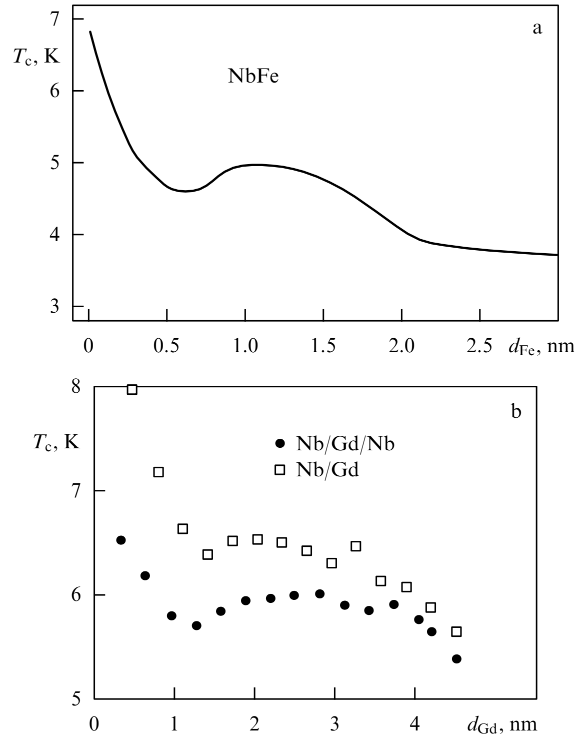

Figure 19. Dependence of T_c on the thickness of ferromagnetic metal d_F in multilayers Nb/Fe ($d_{Nb} = 40$ nm) [4] (a), Nb/Gd ($d_{Nb} = 50$ nm) and Nb/Gd/Nb ($d_{Nb} = 25$ nm) [3] (b).

effect, but only for particles whose spins are parallel to the spin of the magnetic impurity. In other words, the Cooper pair has to break at the S/M boundary with the spin flip-flop of one electron. On increasing the thickness of a 'dirty' M interlayer in such junction, the Josephson current exponentially decreases. The theoretical statements of these works are valid on condition that the concentration of magnetic impurities in the M barrier is low.

Other possibilities of the theory were exhibited in studies of a ferromagnetic metal interlayer between two superconductors [65]. The 'classical' Josephson junction $S_1/I/S_2$ shows an oscillating and decreasing character of the supercurrent dependence on the external magnetic field:

$$j_c \approx \left| \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0} \right| ,$$

where Φ is the magnetic flux which penetrates into the junction, and Φ_0 is its quantum. This is a consequence of the electron phase interference in Cooper pairs. Contrastingly, in the $S_1/F/S_2$ tunnel junction such interference is also determined by the exchange field of the ferromagnetic interlayer. Thus, ferromagnetic ordering in a barrier not only admits a certain probability of Josephson tunneling through this barrier, but is also favorable to the determination of the energy parameters of the F barrier, that is, to the advancement of tunneling spectroscopy of F materials. The inclusion of the electron–electron interaction in the process of tunneling through ferromagnetic metal not only makes a contribution to the supercurrent ($j_c \sim (n^*)^{2/3}$), but also determines its sign. In this case the density j_c can increase, and the supercurrent damps out in an external magnetic field over distances twice as large as in the case of the usual Josephson current [66].

The absence of free current carriers in an insulating F barrier, i.e. actually in an FS barrier, can promote not only one-particle tunneling with spin flip-flop but also pair tunneling through the mechanism of triplet pairing, when the spins of pair's electrons are parallel to each other, $S_p = 1$ [67]. However, the probability of formation of such a pair and the kinetics of its tunneling through an FS barrier remain practically not understood.

Without considering the possibility of triplet pairing, in the case of an FS barrier the Josephson effect in $S_1/FS/S_2$ multilayers may not be observed because of the breaking of Cooper pairs. In the simplest case of one-particle tunneling at $T = 0$ K and the stepwise function of the Fermi distribution for conduction electrons near the Fermi level E_F of a metal, the expression for the tunnel current is written in the form [19]:

$$J \sim \int_{-eV+\Delta+\hbar\omega_0}^{-\Delta} dE\, n_{1S}(E)\, n_{2S}(E + eV - \hbar\omega_0) \int_0^E dE_x D(E_x) ,$$

where n_{iS} are the reduced densities of states for electrons in the S_i banks defined in a model with a constant width of the superconducting gap $\Delta = \text{const}$ by the expression

$$n_S = \begin{cases} \dfrac{|E|}{(E^2 - \Delta^2)^{1/2}} , & |E| > \Delta , \\ 0 , & |E| < \Delta . \end{cases}$$

Here, $D(E_x)$ is the coefficient of transparency of the S/FS boundary in the plane perpendicular to the tunneling direction. For different superconducting banks with Δ_1 and Δ_2 gaps the law of conservation of energy for a tunneling electron requires that the energies of its initial and final states be equal, i.e.

$$eV = E_1 + E_2 > \Delta_1 + \Delta_2 + \hbar\omega_0 .$$

When integrating, in the expression for the current J and in the last equation, the energy $\hbar\omega_0$ of the flip-flop of one of the spins in a Cooper pair in its tunneling through the FS boundary is taken into account. As before, this energy is determined by the magnetic energy of the barrier.

In the case of tunneling of electrons with the initial energy of their ground state, the current J takes the following form:

$$J \approx \begin{cases} D\left[(eV - \hbar\omega_0)E(\theta) - \dfrac{2\widetilde{\Delta}^2 K(\theta)}{eV - \hbar\omega_0}\right], & eV - \hbar\omega_0 > \Delta_1 + \Delta_2 , \\ 0 , & 0 < eV - \hbar\omega_0 < \Delta_1 + \Delta_2 . \end{cases}$$

Here $\theta = [(eV - \hbar\omega_0)^2 - 4\widetilde{\Delta}^2]^{1/2}$, $\widetilde{\Delta} = \langle \Delta_1, \Delta_2 \rangle$ is the average of these two values, $E(\theta)$ and $K(\theta)$ are the complete elliptical integrals of the I and II kind, respectively.

It follows from these relations that at $T = 0$ K and in the absence of spin-flip-flop magnetic scattering in an FS barrier, the threshold bias voltage in the CVC of a tunnel junction will include along with Δ/e the contribution $\hbar\omega_0/e = AS/(2e)$ which, as mentioned above, takes into account an exchange field. A possible excess of energy ΔE of an electron due to its passage through an FS barrier can stimulate high-frequency oscillations in this barrier, $\Delta E \sim AS/2 = \hbar\omega_0$. In the case of EuO we have $AS = 0.5$ eV, $\omega_0 \approx 10^{15}$ s^{-1} that corresponds to the frequency of possible photon generation on the S/FS boundary. The calculated frequency falls within the near-infrared region of the spectrum (see Section 2.1).

Within the framework of the given assumptions, the above relations made it possible to estimate the effective value of the exchange interaction in a EuO barrier using the results of tunneling experiments presented in Section 2.1. This value turned out to be $A = (8 \pm 1.5) \times 10^{-2}$ meV that correlates well with the well-known magnetic data for the first exchange parameter of EuO: $I_1 = 6.5 \times 10^{-2}$ meV [16].

7. Conclusions

The discovery of a giant negative magnetoresistance in ferromagnetic semiconductors based on lanthanum manganite in 1994 marked the 'third advent' of interest to magnetic semiconductors. The intent study of these materials was initiated by the discovery of the ferromagnetism of EuO in 1961. The next impetuous stage of their investigation is associated with a near-doubling of the Curie temperature, up to $T_C \sim 130$ K, in solid solutions $Eu_{1-x}Sm_xO$ and $Eu_{1-x}Gd_xO$ (1977). The results of these two stages were summed up in the monographs [16, 68, 69]. With a new stage of such investigations, real prospects open for the practical use of these materials in modern microelectronics. The well-known 'old' ferromagnetic semiconductors for the most part were 'only-for-cryogenics' materials and, despite their outstanding physical properties [16], remained unclaimed because they were not competitive with 'classical' nonmagnetic semiconductors which were used in base devices operating at room temperatures. Therefore, the new stage of widespread investigations of FSs possessing the same interesting characteristics as, for example, those of EuO, which manifest themselves even at $T > 290$ K, instills confidence of success in relevant engineering as well. This shows promise of compensating the moral and material expenses of scientists engaged in the physics of low-temperature FSs.

Notice that the results presented in this review have been obtained mainly at a time when all the natural-science world was interested in high-temperature superconductivity and its associated phenomena only. Recent publications listed at the beginning of the list of the cited literature in many respects only repeat the results presented in the review. As experience shows, the new features which are inherent in multilayers or heterostructures containing FSs and directly relevant to the term 'micromagnetoelectronics' used here will most likely be found in analogous structures containing FSs on the base of $LaMnO_3$. The physical prerequisites for this have been created. The matter, as it usually happens, depends on the development of the appropriate physical and chemical basics of technology.

In conclusion I consider it my pleasant duty to express heartfelt acknowledgment to K K Likharev who in many respects furthered the formation of the discussed tunneling investigations of FSs as well as to S V Vonsovskiĭ and A A Abrikosov for attention and support in the work.

As the creation of FS containing multilayers requires high technological proficiency, it will be just to name a technologist 'from God', as the saying is, V I Fomin, whose engineering skills have predetermined the success of the experimental research discussed in the present review.

The author is also grateful to A A Samokhvalov, V V Osipov, and N A Viglin for giving him a chance to look through the manuscript of their work [58] and to use its results.

References

1. Koorewaar P et al. *Phys. Rev. B* **49** 441 (1994)
2. Strunk C et al. *Phys. Rev. B* **49** 4053 (1994)
3. Jiang J S et al. *Phys. Rev. Lett.* **74** 314 (1995); *Phys. Rev. B* **54** 6119 (1996)
4. Muhge T et al. *Phys. Rev. Lett.* **77** 857 (1996)
5. Radović Z et al. *Phys. Rev. B* **44** 759 (1991)
6. Buzdin A I, Bujicic B, Kupriyanov M Yu *Zh. Eksp. Teor. Fiz.* **101** 231 (1992) [*Sov. Phys. JETP* **74** 124 (1992)]
7. Khusainov M G *Zh. Eksp. Teor. Fiz.* **109** 524 (1996); 110 966 (1996) [*Sov. Phys. JETP* **82** 279; Proshin Yu N, Khusainov M G *Zh. Eksp. Teor. Fiz.* **113** 1708 (1998) [*JETP* **86** 172 (1998)]
8. Tagirov L R, in *Tezisy Dokladov XVI Mezhdunarodnoĭ Shkoly-Seminara 'Novye Magnitnye Materialy'* (Proc. XVI Int. School-Seminar 'Novel Magnetic Materials in Microelectronics') Ch. 2 (Moscow: Izd. URSS, 1998) p. 616
9. Esaki L, Stiles P J, Von Molnar S *Phys. Rev. Lett.* **19** 852 (1967)
10. Vonsovskiĭ S V *Magnetizm* (Magnetism) (Moscow: Nauka, 1979)
11. Zavaritskiĭ N V, Grigor'ev V N *Pis'ma Zh. Eksp. Teor. Fiz.* **14** 112 (1971) [*JETP Lett.* **14** 73 (1971)]
12. Niemeyer J, von Minnigerode G *Z. Phys. B* **36** 57 (1979)
13. Stageberg F et al. *Phys. Rev. B* **32** 3292 (1985)
14. Hauser J J, Theuerer H C, Werthamer N R *Phys. Rev.* **142** 118 (1966)
15. Wong H K et al. *J. Low-Temp. Phys.* **63** 307 (1986)
16. Bamburov V G, Borukhovich A S, Samokhvalov A A *Vvedenie v Fiziko-Khimiyu Ferromagnitnykh Poluprovodnikov* (Basic Physical-Chemical Properties of Ferromagnetic Semiconductors) (Moscow: Metallurgiya, 1988)
17. Tedrow P M, Tkaczyk J E, Kumar A *Phys. Rev. Lett.* **56** 1746 (1986)
18. Hao X, Moodera J S, Meservey R *Phys. Rev. Lett.* **67** 1342 (1991)
19. Efimova L V, Borukhovich A S "Magnitnye primesi v sverkhprovodyashchem tunnel'nom perekhode" ("Magnetic impurities in superconducting tunneling junction") Dep. VINITI, No. 7968-V (1985)
20. Borukhovich A S et al. *Dokl. Akad. Nauk SSSR* **296** 332 (1987)
21. Svistunov V M, Belogolovskiĭ M A, D'yachenko A I *Metallofizika* **5** (4) 9 (1983)
22. Svistunov V M, Belogolovskiĭ M A *Tunnel'naya Spektroskopiya Kvazichastichnykh Vozbuzhdeniĭ v Metallakh* (Tunneling Spectroscopy of Quasi-Particle Excitations in Metals) (Kiev: Naukova Dumka, 1986)
23. Motulevich G P et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **36** 313 (1982) [*JETP Lett.* **36** 391 (1982)]
24. Borukhovich A S *Dokl. Akad. Nauk SSSR* **313** 594 (1990)
25. Tomash V J, in *Tunneling Phenomena in Solids* Ch. 23 (Eds E Burstein, S Lundqvist) (New York: Plenum, 1969) [Translated into Russian (Moscow: Mir, 1973) p. 300]
26. Günterodt G, Tzeier R, in *Light Scattering in Solids IV* Ch. 4 (Eds M Cardona, G Güntherodt) (Heidelberg: Springer-Verlag, 1983) [Translated into Russian (Moscow: Mir, 1986)]
27. Borukhovich A S, Sukhov V A *Pis'ma Zh. Eksp. Teor. Fiz.* **53** 413 (1991) [*JETP Lett.* **53** 440 (1991)]
28. Nevirkovets I P *Pis'ma Zh. Eksp. Teor. Fiz.* **51** 50 (1990) [*JETP Lett.* **51** 50 (1990)]
29. Yang Q S, Falco C M, Schuller I K *Phys. Rev. B* **27** 3867 (1983)
30. Faris S M *Zarubezhnaya Radioelektronika* (2) 95 (1984)
31. Kulik I O *Zh. Eksp. Teor. Fiz.* **51** 1952 (1966) [*Sov. Phys. JETP* **24** 1307 (1966)]
32. Bulaevskiĭ L N, Kuziĭ V V, Sobyanin A A *Pis'ma Zh. Eksp. Teor. Fiz.* **25** 314 (1977) [*JETP Lett.* **25** 346 (1977)]; Bulaevskiĭ L N, Kuziĭ V V, Sobyanin A A *Solid State Commun.* **25** 1053 (1978)
33. Osipov V V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **52** 996 (1990) [*JETP Lett.* **52** 1608 (1990)]
34. Borukhovich A S, Bamburov V G *J. Magn. Magn. Mater.* **53** 80 (1985)
35. Antonova E A, Sukhov V A *Fiz. Met. Metalloved.* **56** 712 (1983)
36. Alfeev V N *Poluprovodniki, Sverkhprovodniki i Paraélektriki v Krioélektronike* (Semiconductors, Superconductors and Paraelectrics in Cryoelectronics) (Moscow: Sov. Radio, 1979)
37. Likharev K K *Vvedenie v Dinamiku Dzhozefsonovskikh Perekhodov* (Dynamics of Josephson Junctions and Circuits) (Moscow: Nauka, 1985) [Translated into English (London: Gordon and Breach, 1986)]

38. Borukhovich A S *Sverkhprovodimost' FKhT* **3** 1748 (1990) [*SPCT* **3** (8, pt. 1) 1416 (1990)]
39. Meĭlikhov E Z *Sverkhprovodimost' FKhT* **2** (4) 91 (1989) [*SPCT* **2** (4) 113 (1989)]
40. Borukhovich A S et al. *Sverkhprovodimost' FKhT* **5** 2021 (1992) [*SPCT* **5** (11) 1920 (1992)]
41. Dersch H, Blatter G *Phys. Rev. B* **38** 11391 (1988)
42. Kokorina E E, Medvedev M V *Sverkhprovodimost' FKhT* **7** 1127 (1994)
43. Agranovich V L et al. *Istochniki Polyarizovannykh Elektronov* (Sources of Polarized Electrons) (Moscow: TsNIIatominform, 1984)
44. Kessler J *Polarized Electrons* (Heidelberg: Springer-Verlag, 1976) [Translated into Russian (Moscow: Mir, 1988)]
45. Baum G, Lubell M S, Raith W *Phys. Rev. Lett.* **25** 267 (1970)
46. Pierce D T, Meier F *Phys. Rev. B* **13** 5484 (1976)
47. Kisker E et al. *Phys. Rev. B* **18** 2256 (1978)
48. Auslender M I, Irkhin V Yu *Solid State Commun.* **50** 1003 (1984)
49. Borukhovich A S et al. "Tverdotel'nyĭ istochnik polyarizovannykh elektronov" ("Solid-state source of polarized electrons") USSR Author's Certificate No. 1267983 (1986)
50. Nagaev E L *Usp. Fiz. Nauk* **166** 833 (1996) [*Phys. Usp.* **39** 781 (1996)]
51. Buzhor V P, in *Tez. Dokl. IV Vsesoyuz. Konf.* '*Troĭnye Poluprovodniki i Ikh Primenenie*' (Proc. IV All-Union Conference 'Triple Semiconductors and Their Applications') (Kishinev: Shtiintsa, 1983) p. 7
52. Osipov V V et al. *Fiz. Tverd. Tela* **31** 37 (1989)
53. Osipov V V, Morozova N A, Kochev I V *Fiz. Tverd. Tela* **33** 2293 (1991)
54. Bonch-Bruevich V L, Kalashnikov S G *Fizika Poluprovodnikov* (Semiconductor Physics) (Moscow: Nauka, 1977)
55. Aronov A G, Pikus G E *Fiz. Tverd. Tela* **10** 825 (1968)
56. Viglin N A, Osipov V V, Samokhvalov A A *Phys. Low-Dim. Struct.* (9/10) 89 (1996)
57. Viglin N A et al. *Phys. Low-Dim. Struct.* (1/2) 89 (1997)
58. Osipov V V, Viglin N A, Samokhvalov A A *Phys. Lett. A* **247** 353 (1998)
59. Shmidt V V *Vvedenie v Fiziku Sverkhprovodnikov* (Elementary Superconductor Physics) (Moscow: Nauka, 1982)
60. Larkin A I, Ovchinnikov Yu N *Zh. Eksp. Teor. Fiz.* **47** 1136 (1964) [*Sov. Phys. JETP* **20** 745 (1965)]
61. Fulde P, Ferrell R A *Phys. Rev.* **135** A550 (1964)
62. Proshin Yu N, Khusainov M G *Zh. Eksp. Teor. Fiz.* **113** 1708 (1998) [*Phys. JETP* **86** 548 (1998)]
63. Bulaevskiĭ L N, Kuziĭ V V *Fiz. Nizk. Temp.* **3** 725 (1977)
64. Kuplevakhskiĭ S V, Fal'ko I I *Fiz. Nizk. Temp.* **10** 691 (1984)
65. Buzdin A I, Bulaevskiĭ L N, Panyukov S V *Pis'ma Zh. Eksp. Teor. Fiz.* **35** 147 (1982) [*JETP Lett.* **35** 211 (1982)]
66. Altshuler B L, Khmelnitskiĭ D E, Spivak B Z *Solid State Commun.* **48** 841 (1983)
67. Spivak B Z, Khmel'nitskiĭ D E *Pis'ma Zh. Eksp. Teor. Fiz.* **35** 334 (1982) [*JETP Lett.* **35** 412 (1982)]
68. Methfessel S, Mattis D K *Magnetic Semiconductors* (Heidelberg: Springer-Verlag, 1968) [Translated into Russian (Moscow: Mir, 1972)]
69. Nagaev E L *Fizika Magnitnykh Poluprovodnikov* (Physics of Magnetic Semiconductors) (Moscow: Nauka, 1979) [Translated into English (Moscow: Mir, 1983)]