where I_{c0} is the critical current in the absence of the field, $\Phi = HLd$ is the magnetic flux through the junction with thickness d and length L, Φ_0 is the magnetic flux quantum, and $H_0 = \Phi_0/Ld$ is the period of dependence on the external field. The absence of distortion and the agreement between the period of the field dependence and the size of the sandwich interlayer point to the high homogeneity of the thickness and the properties of the Josephson layer along the junction.

4. The effect of residual magnetic induction in a ferromagnetic layer on the Josephson properties of SFS sandwiches

Theoretical studies [10–15] concerned with SFS structures and the influence of an exchange field on the behavior of superconducting electrons in ferromagnets, actually disregard the impact of the domain structure and the macroscopic magnetic induction in the F layer. To study these effects on the Josephson properties of SFS junctions, the samples were magnetized (applying the magnetizing field along the F layer for several minutes) at temperatures falling between the transition temperature of the niobium electrodes in the Nb–Cu/Ni–Nb sandwich and the Curie point of the Cu/Ni alloy. The magnetization procedure precluded trapping of Abrikosov vortices in the superconducting electrodes of the junction. Figure 2 shows the $I_c(H)$ curves (at $T = 4.2$ K) for the parent and magnetized sandwiches. We see that magnetization shifts the Fraunhofer curves by an amount equal to the residual magnetic induction in the F layer. In addition, the irregularities of the domain structure, arising in the ferromagnetic material magnetized below magnetic saturation, also affect the Josephson properties of sandwiches and result in certain distortions of the dependences: a change in the amplitude of the central peak, and the faster decline of subsequent peaks as the magnetic field intensity increases. By increasing the magnetizing field it was possible to shift the central peak steadily, while its amplitude varied in a quasi-periodic fashion.

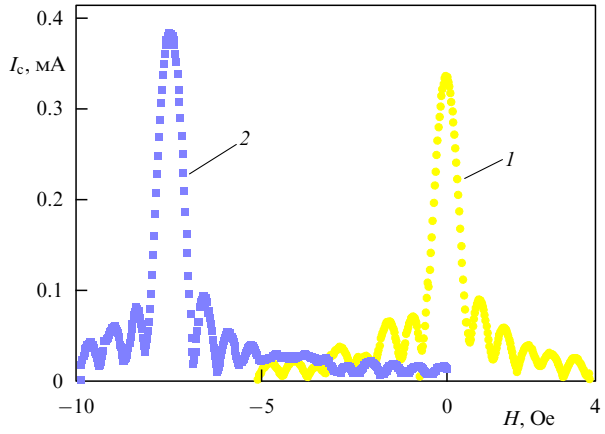

Figure 2. Shift of the $I_c(H)$ curve after magnetization of a sample: *1* — curve $I_c(H)$ before magnetization; *2* — the same after magnetization.

5. Conclusions

Several types of Josephson superconducting structures capable of exhibiting a shift of the macroscopic phase difference in the absence of a magnetic field and superconducting current through such a structure (π-contacts) have been proposed and are being studied currently. Superconductor–ferromagnet–superconductor junctions based on conventional superconductors and dilute ferromagnets seem to be most promising for application to quantum logic circuits, because such thin-film structures can be fabricated through the use of customary microelectronic technologies.

In this report we have presented the results of the first observation of Josephson superconducting currents flowing through ferromagnetic layers. It is shown that in nonmagnetized specimens the averaging of the domain magnetic structure in the F layer ensures a highly homogeneous passage of superconducting current across the ferromagnet. Magnetization of the ferromagnetic layer gives rise to irregularities in the amplitude of supercurrent and creates a phase difference along the SFS junction owing to the nonuniformity of the domain structure and the existence of noncompensated (residual) macroscopic magnetic induction. Experiments are currently underway with two-contact superconducting interferometers containing SFS and SNS junctions (the latter with a nonmagnetic interlayer) and aimed at separating the phase shift associated with the exchange field, and producing π-contacts.

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New type of domain boundaries in multilayer magnetic structures

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The discovery of giant magnetoresistance [1] drew keen attention to multilayer structures made up of alternating ferromagnetic (Fe, Co) and nonmagnetic (Cr, Cu) metallic layers. Since the indirect exchange RKKY [1] interaction

[1] Ruderman–Kittel–Kasuya–Yosida interaction.

between ferromagnetic layers oscillates with the thickness of the nonmagnetic interlayer [2, 3], at some values of this thickness, when the sign of the exchange interaction is positive, the collinear ferromagnetic ordering of magnetizations of adjacent magnetic layers has to be observed, while at other values, when the sign of the exchange interaction is negative, the collinear antiferromagnetic ordering of magnetizations of adjacent magnetic layers will occur.

In the latter case, application of an external magnetic field will cause a change of magnetizations orientation from antiferromagnetic to ferromagnetic, which results in a drop of electric resistance by tens of percent (hence 'giant').

This simple picture corresponds to perfectly smooth and sharp interfaces between the layers when the magnetizations of ferromagnetic layers are homogeneous. The real interface is always rough because of the atomic steps that present on it and change the thickness by one monatomic layer. Therefore, the phase diagram of real multilayer structures is much more diverse: the emergence of noncollinear orientations of magnetizations of ferromagnetic layers and occurrence of polydomain states are possible. Observe that the domains arise not because of the relativistic effects (demagnetizing fields), but rather because of the roughness of interfaces between layers.

To prove this statement, consider a highly simple system consisting of two ferromagnetic layers separated by a nonmagnetic interlayer. The change in the thickness of interlayer d by one atomic monolayer under certain conditions may change the sign of the exchange interaction $J_\perp$ between the magnetic layers. In this case, the areas with opposite signs of the exchange integral $J_\perp$ are brought about on the layer surfaces owing to their irregularities. If the characteristic distance between the atomic steps R exceeds a certain threshold, then the breakdown of layers into domains becomes energetically advantageous. Inside a domain, the magnetizations of ferromagnetic layers are parallel or antiparallel depending on the sign of $J_\perp$. The domain boundaries coincide with the atomic steps separating the areas with opposite signs of $J_\perp$. Domains are separated by walls that pass throughout the layers. To assess the parameters of the domain wall, consider the energy of the spin system, assuming that the thickness l_i of the ith magnetic layer ($i = 1, 2$) and that of the nonmagnetic interlayer d are much smaller than the width of the domain wall δ. Then the magnetization is distributed uniformly throughout the depth of a layer.

The energy of inhomogeneity of the spin structure inside the layer can be expressed as

$$W_i = \int \frac{\alpha_i}{2} \left(\nabla \vartheta_i(\boldsymbol{\rho})\right)^2 \mathrm{d}^2\boldsymbol{\rho}\,, \tag{1}$$

where the integral is taken over the plane of the layer, ϑ_i is the angle between the spin lying in this plane and the selected axis, and

$$\alpha_i \approx \frac{J_0^i S_i^2 l_i}{b}\,, \tag{2}$$

where b is the lattice constant, J_0^i is the exchange integral between adjacent spins in the layer, and S_i is the mean value of spin of atoms in the ith layer.

The energy of interaction between the layers is given by

$$W_{\mathrm{int}} = \pm \int \beta(\boldsymbol{\rho}) \cos(\vartheta_1 - \vartheta_2)\, \mathrm{d}^2\boldsymbol{\rho}\,, \tag{3}$$

where

$$\beta(\boldsymbol{\rho}) \sim \frac{J_\perp(\boldsymbol{\rho}) S_1 S_2}{b^2}\,. \tag{4}$$

Varying the total energy with respect to ϑ_i, we find the magnitude of δ [4]:

$$\delta \approx \pi \left(\frac{\alpha^*}{J_\perp^{\min} S_1 S_2}\right)^{1/2}, \tag{5}$$

where $\alpha^* = \alpha_1\alpha_2/(\alpha_1 + \alpha_2)$, and $J_\perp^{\min}$ is the smaller in magnitude of the two values of $J_\perp$ on either side of the step.

The width of these 'unconventional' domain walls depends on the relation between intralayer and interlayer exchange interactions and can be much smaller than that in ordinary domain structures. Using typical values $J_0/J_\perp \approx 300 - 500$, $l_i/b_i \approx 3 - 5$, we get $\delta \approx 300 - 500$ A. Partition into domains is energetically advantageous when the distance R between the atomic steps is greater than the thickness δ of the domain wall [4]. Microdomains with characteristic size of the order of 0.1 μm, whose boundaries coincided with the atomic steps, were observed in the three-layer Co/Cu structure [5].

Otherwise, when $\delta \gg R$, the domains cannot form. In principle, then only small deviations of the angles ϑ_i from their mean values are possible. These deviations, however, reduce the energy of the system only when the mean magnetizations of layers are noncollinear. This correction to the energy is phenomenologically attributed to the biquadratic exchange interaction with a negative value of the exchange integral [6]. The experimentally established noncollinearity of magnetizations of ferromagnetic layers was just attributed to the biquadratic exchange [7 – 9].

By an order of magnitude, the biquadratic exchange integral is equal to [10]

$$J_{\mathrm{bq}} \approx -\frac{J_\perp^2 R^2 b}{J_0 S^2 l_{\min}}\,. \tag{6}$$

In the range of $\delta \gg R$, the amount of biquadratic exchange is not sufficient for causing noncollinear orientation of magnetizations. Because of this, the presence of noncollinear magnetization in a multilayer structure with nonmagnetic interlayer points to the origination of a microdomain state, which ought to be involved in the interpretation of the experimental findings.

The situation is different when the interlayer between the ferromagnetic layers is made up of a stratified antiferromagnet consisting of alternating ferromagnetic atomic planes with antiparallel spin orientation in adjacent planes. Neutron diffraction patterns indicate that this is the state of the chromium interlayer in Fe/Cr multilayers at temperatures below 500 K [11].

The occurrence of antiferromagnetism changes the nature of the interaction between ferromagnetic layers. Now it is determined by the antiferromagnetic order parameter, i.e. the difference in magnetizations of sublattices. When the number of planes in the interlayer is even, the antiparallel orientation of the adjacent ferromagnetic layers is energetically advantageous; and the parallel orientation emerges when the number of planes in the intermediate layer is odd (Fig. 1a).

The presence of atomic steps on the layer interfaces at either sign of the exchange integral $J_{\mathrm{f,af}}$ between the spins of adjacent atoms belonging to different layers leads to frustrations in the case of a homogeneous distribution of ferromag-

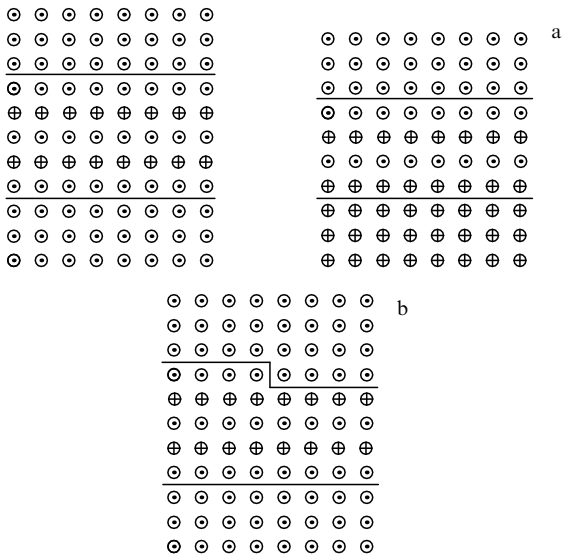

Figure 1. Orientation of spins in a three-layer system consisting of two ferromagnetic layers and an antiferromagnetic interlayer, in the case of smooth interfaces and an odd or even number of atomic planes in the interlayer (a), and frustration in the three-layer system caused by an atomic step at the interface (b).

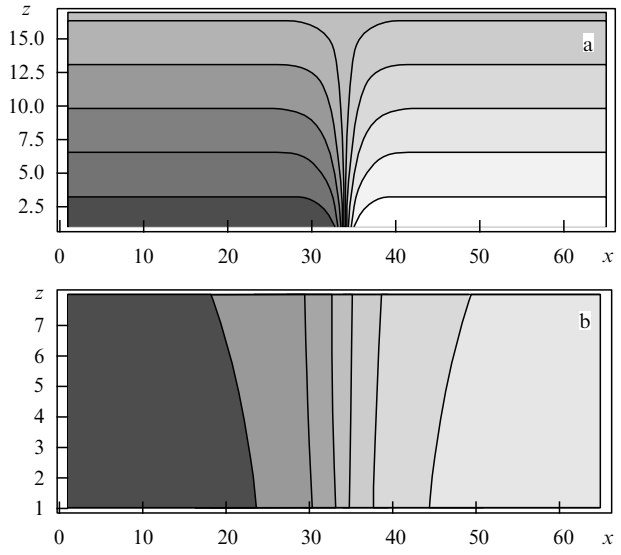

Figure 2. Distribution of the antiferromagnetic order parameter in the domain wall bringing about near the edge of the step, when $\eta \gg 1$ (a), and $\eta \ll 1$ (b). The magnetizations of ferromagnetic layers are mutually perpendicular. The lines of constant ϑ_{af} are drawn with a $\pi/10$ interval; the lengths are reduced to interatomic distances.

netic and antiferromagnetic order parameters (Fig. 1b). If the distance R between the steps exceeds the critical value but is not too large, the distortions that arise in the antiferromagnetic interlayer embrace its entire volume.

The energy of distortions of the antiferromagnetic order parameter inside the interlayer can be expressed similarly to Eqn (1), integrating over the volume of the layer, since this time the order parameter may vary in general across the layer. The interface energy of interaction between the layers is given by Eqn (3), where $J_\perp(\boldsymbol{\rho}) = \pm J_{f,af}$, the signs being opposite on the two sides of the step.

If the exchange interaction in the ferromagnetic layers is much stronger than in the interlayer, then given that R is not too large their magnetizations may be considered homogeneous. Then the distortions of the order parameter in the interlayer depend on the dimensionless parameter

$$\eta = \frac{J_{f,af} S_f d}{J_{af} S_{af} b}\,, \tag{7}$$

where the subscripts 'f' and 'af' refer to ferromagnetic and antiferromagnetic materials, respectively.

Numerical solution of equations obtained by varying the total energy with respect to ϑ_i gives the distribution of the order parameter shown in Fig. 2a [12]. It is easy to see that, when $\eta \gg 1$, the domain wall is initiated at a step, expands away from the interface, unfolds and occupies the entire volume of the interlayer. In the vast majority of the latter volume, the quantity ϑ_{af} varies in a practically linear fashion from one layer boundary to the other. The values of ϑ_{af} on the boundaries of the layer correspond to the minimum of the boundary energy. The critical value of R is equal to the width δ_0 of the domain wall near the step:

$$\delta_0 \approx \frac{b(J_{f,af} S_f + J_{af} S_{af})}{J_{f,af} S_f}\,. \tag{8}$$

The quantity δ_0 can be of the order of the interatomic distance, so the effects of broadening of domain walls in the case of $\eta \gg 1$ are predominant. If $\eta \ll 1$, the quantity ϑ_{af} remains practically the same across the layer, and the effects of broadening of domain walls are negligible (Fig. 2b). The critical value of R is $\delta \approx d/\sqrt{\eta}$.

In both cases the energy of distortions depends on the relative orientation of magnetizations of the ferromagnetic layers and is minimum when they are at right angle to each other [13]. It is in the case of an antiferromagnetic interlayer that noncollinear orientation of practically homogeneous ferromagnetic layers is possible, for the description of which Slonczewski proposed his phenomenological model of 'magnetic proximity' [14]. Microscopic calculations allowed the parameters of this model to be found and showed that the energy of interaction between ferromagnetic layers decreases with the thickness of the interlayer as d^{-1} in the range $\eta \gg 1$, and does not depend on d in the range $\eta \ll 1$ [13].

As the characteristic distance between the steps increases, the state when the domain walls pass through all three layers becomes energetically advantageous — that is, the ferromagnetic layers split up into domains whose boundaries coincide with the edges of the atomic steps, like in the case of a nonmagnetic interlayer. Then there are no distortions of the order parameter in the bulk of the domains. The specific energy of such a state is proportional to R^{-1}, whereas the energy of phase with the homogeneous ferromagnetic layers is practically independent of R. The phase diagram 'thickness–roughness' of a three-layer system was plotted in Ref. [13].

How does the partition of layers into domains affect the magnitude of magnetoresistance? The commonly accepted view is that the reflection coefficient for a broad (on the atomic scale) domain wall is quite small [15]. However, as shown in Ref. [16], the existence of domain boundaries leads to mixing of the spin states of electrons, and may give a considerable contribution to the magnetoresistance. Being proportional to δ^{-2}, this effect is especially important in the

case of an antiferromagnetic interlayer, when the widths of domain walls are tens of ångströms.

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Quantum interference of a moving charge density wave on columnar defects containing magnetic flux [1]

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1. Introduction

As is known, below the temperature of Peierls transition a condensed state is formed in quasi-one-dimensional conductors — the charge density wave (CDW), characterized by a gap in the excitation spectrum and the space modulation of the density $\rho(x)$ of charge condensed in the CDW [3]:

$$\rho(x) = \rho_0\left[1 + \alpha\cos(Qx + \varphi)\right],$$

where α and φ are the amplitude and phase of CDW, with a period of $1/Q$ equal to the inverse Fermi wave vector $2\pi/Q = 2\pi/2k_F$. In the external electric field exceeding a certain threshold, the CDW can move and give a collective contribution to conductivity, which depends on the total density of the charge condensed under the gap [3]. The movement of the CDW is accompanied by the generation of narrow-band oscillations, whose frequency is proportional to the velocity of propagation of the CDW [4]. Several theories [5–8] have been put forward for describing the motion of CDWs, which can be divided into two classes. One treats the motion of a CDW as the motion of a classical object, either rigid [5] or in the form of a deformable medium [6], in a periodic potential. The other considers a CDW as a quantum object, and its motion as coherent tunneling [8]. Until recently, however, there had been no convincing demonstrations of the quantum nature of CDWs. Most of the observed properties of CDWs, including the narrow-band generation, were well enough described by the appropriate classical models [5–7]. Quantum tunneling of CDWs was only surmised at very low temperatures [9, 10].

[1] Based on Refs [1, 2].

At the same time, there were theoretical predictions of the possible observation of quantum interference effects of CDWs in a ring of quasi-one-dimensional conductor of small diameter (comparable with the coherence length of the CDW), containing magnetic flux [11]. As the CDW moves along the ring consisting of one conducting chain, oscillations of magnetoresistance with the period corresponding to a change of flux in the ring equal to one 'superconducting' magnetic flux quantum $\Phi_0 = hc/2e$ were predicted. This theory stimulated the experimental quest for quantum interference effects in materials with CDWs [1, 2], the results of which are discussed below.

2. Results and discussion

The idea of the experiment was to select a thin (less than 1 micrometer) crystal with the CDW ($NbSe_3$), containing columnar defects (CD) created by the bombardment of the material with heavy ions with an energy of the order of 1 GeV. As is known [12], a CD is a homogeneous amorphous cylinder in the material crystal matrix, about 10 nanometers in diameter and 10 micrometers long. It is formed along the track of the travelling particle because of melting and subsequent fast quenching of matter. Since each CD is created by one identical particle, they all have the same size. It was assumed that since the defect is smaller than the amplitude coherence length of the CDW across the chains, the CDW passing the defect will 'flow around' it, retaining the coherence of motion. In a magnetic field directed along the axis of the defect, the CD will behave as a solenoid giving an Aharonov – Bohm contribution [13] to the phase of the wave function of the CDW having passed the defect. In the limit of coherent motion of the CDW throughout the entire crystal, the contributions from individual defects may be synchronized, much increasing the probability of detection of the effect.

Selected perfect single crystals of $NbSe_3$ were irradiated at two large accelerators: VIKSI (Berlin), and GANIL (Caen, France). Part of the specimen was usually shielded from irradiation for comparison studies. There were several series of irradiation with ions of Xe, Pb, and U with energies from 0.3 to 6 GeV. The density of defects varied from 2×10^9 to 2×10^{10} def. per square centimeter. The direction of motion of heavy ions in the beam corresponded to the a^* axis of the irradiated crystal. The divergence of the beam was less than 0.5°. The diameter of defects was measured by TEM and HREM techniques, and was about 16 nm (see inset to Fig. 1).

The studies on differential current-voltage characteristics of the exposed specimens and the spectra of Shapiro steps [14] at the frequency of about 10 MHz revealed that the introduction of columnar defects to concentrations of up to 10^{10} def. per square centimeter had little effect on the transport characteristics of CDWs, and the coherence of motion of CDWs is preserved over the entire length of the specimen (about 0.5 mm) [2]. Such samples were selected for measurements of magnetoresistance, which were performed with the Bitter magnet in fields up to 23 T at the laboratory of high magnetic fields (Grenoble). The specimen was usually equipped with six probes, which permitted simultaneous measurement of magnetoresistance on both the part containing the columnar defects and the defect-free part. With fixed temperature and current through the specimen, the magnetic field slowly swept up to its maximum and back. The results of measurements were stored and averaged over both scans.