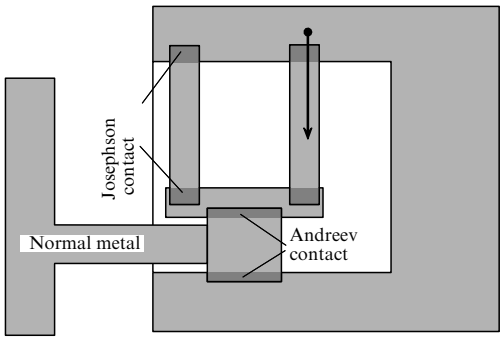


**Figure 1.** Four-contact SQUID with an Andreev probe for measuring the coherence time.

This is possible, however, if we take advantage of the unusual properties of contacts with high-temperature superconductors (HTSC) [10]. It has been firmly established [11] that superconducting pairing in the main families of HTSCs (YBaCuO, BiSrCuO) possesses an unusual symmetry: the wave function of a Cooper pair $\Psi(\mathbf{p}) = \langle c_{\mathbf{p}} c_{-\mathbf{p}} \rangle$, where $c$ is the operator of creation of an electron, strongly depends on the orientation of the unit vector on Fermi surface $\mathbf{n} = \mathbf{p}/p$ with respect to the axes of a crystal lattice: $\Psi(\mathbf{n}) \propto (n_x^2 - n_y^2)$. In other words, the sign of the pair wave function is different for various directions of $\mathbf{n}$. The left-hand part of Fig. 2 shows the scheme of the phase-sensitive experiment conducted by D Wollman et al. [11]: the different signs of wave functions of pairs escaping the HTSC crystal in directions (010) and (100) give rise to a spontaneous magnetic flux penetrating the $\pi$-circuit. As described in Ref. [10], the $d$-wave symmetry of superconducting state in HTSC can be used for creating a Josephson SDS′ contact, whose energy depends on the phase difference as $E_{\mathrm{SDS}}(\phi) = -E_2 \cos 2\phi$. In other words, such a contact has two equivalent minima of Josephson energy over the standard period of phase variation $\phi \in (0, 2\pi)$. Connecting to the SDS′ contact the ordinary Josephson contact (as shown in the right-hand part of Fig. 2) with a low critical current, we can introduce an asymmetry between the states (that so far had been degenerate with respect to energy) with the phase difference $\phi = 0, \pi$. The fundamental advantage of such a qubit is that there is no current in the SQUID contour in either of the basis states $\phi = 0$, $\phi = \pi$ (which only differ in the phase), and so the problem of spurious interactions is removed.

The simplest version of a phase qubit — a four-contact SQUID in a magnetic field — has yet another disadvantage: one has to maintain a magnetic flux equal to $\Phi_0/2$ at its 'working point' with an aid of the external current, which by itself is a source of noise. In place of the magnetic flux, however, one can use a Josephson $\pi$-contact inserted in the SQUID contour. One possible realization of such a contact was described above (see the left-hand part of Fig. 2). Another and more technologically accepted way was proposed in Ref. [12], where a Josephson SFS contact with a critical current was realized for the first time.

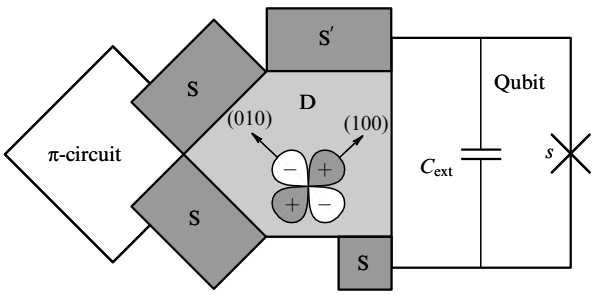


**Figure 2.** SQUIDs of conventional and high-temperature superconductors.

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PACS numbers: 03.67.Lx, 73.23.Hk, **73.40.–c**, 85.25.Cp

# Josephson superconductor – ferromagnet – superconductor $\pi$-contact as an element of a quantum bit (experiment)

V V Ryazanov

## 1. Introduction

The authors of Refs [1, 2] proposed several realizations of a quantum bit on the base of superconducting structures including the Josephson '0'- and $\pi$-junctions — that is, ordinary superconducting contacts with a weak link, and the contacts exhibiting a spontaneous $\pi$-shift of macroscopic phase difference of superconducting wave functions (order parameter) on the electrodes of the Josephson junction. A brief account of theoretical and experimental studies on structures exhibiting spontaneous phase shift is given in Section 2 of this presentation. The main part of this report deals with the results of investigations participated in by the author and concerned with SFS (superconductor – ferromagnet – superconductor) junctions that appear to be most promising for the construction of perspective quantum-logic elements.

## 2. Josephson structures exhibiting spontaneous $\pi$-shift of a phase difference

Recent works on $\pi$-contacts have been mostly concerned with the study of the nontrivial order parameter in high-temperature superconductors (HTSC). In the case of assumed $d$-wave symmetry ($d_{x^2-y^2}$), the sign of the order parameter depends on the direction in the basal plane of the HTSC crystal and must change upon passing from one crystal face to the normally arranged another (which

corresponds to the change of the phase of order parameter by $\pi$). The idea of such a $\pi$-contact on the bicrystalline boundary of a 'nontrivial' superconductor was first put forward in Ref. [3] and was subsequently checked in a number of phase-sensitive interference experiments with bicrystalline contacts [4], two-contact superconducting rings [5, 6], and angular $(0-\pi)$-contacts [7] containing HTSC and conventional superconductor with isotropic (*s*-wave) symmetry of the order parameter. The body of experimental data that has been accumulated is convincing evidence of the existence of the nontrivial order parameter in HTSC and the spontaneous shift of phase difference in bicrystalline and SD contacts involving HTSCs. Practical applications of such contacts are obstructed by the technological difficulties of obtaining reproducible monocrystalline and bicrystalline thin-film HTSC structures.

Superconducting junctions with HTSC do not represent the only way of obtaining a $\pi$-shift in Josephson structures. A recent publication by Baselmans et al. [8] deals with the experimental examination of an effect predicted earlier in Ref. [9] and related to the transition into the $\pi$-state of a mesoscopic SNS (superconductor – normal metal – superconductor) contact controlled by the current through an N layer. The voltage applied along the layer of normal metal in the plane of junction alters the energy distribution of states that carry the superconducting current across the junction — that is, the mesoscopic section of normal metal that separates the superconductors. Over a certain range of control voltages, the behavior of the junction is determined by the states responsible for the negative sign of supercurrent, which correspond to the difference between the superconducting phases at the junction equal to $\pi$ in the ground state. A possible drawback of using such phase switches in quantum logic circuits is the need for external control that brings noise into the coherent circuit.

A third possible type of $\pi$-contacts was predicted as early as 1977 [10] but has not yet been convincingly detected in experiments. The specific behavior of SFS junctions is associated with space oscillations ($\sim \cos Qx$) of the induced superconducting order parameter in the ferromagnetic layer near the FS interface, which are indebted to the nonzero total momentum of the pair $Q = E_{\rm exc}/v_{\rm F}$ originated owing to the exchange field in the ferromagnet [11 – 14]. Here $E_{\rm exc}$ is the exchange energy, $v_{\rm F}$ is the Fermi velocity in ferromagnet. By adjusting the thickness of an F layer in the Josephson SFS junction and the magnitude of exchange energy of the ferromagnetic alloy, it is possible, in principle, to achieve the $\pi$-state of the SFS contact subject to the condition that the amplitude of the order parameter does not damp out over the thickness of the F layer [15].[1] Transport experiments with SF structures have so far been restricted to measuring only the resistive properties along the layers, which is primarily explained by the low values of the transverse resistance of layered structures. Research work at the Institute of Solid-State Physics, RAS (Chernogolovka) sponsored by the Scientific Society of The Netherlands (NWO) [16] was concerned with measuring the transverse superconducting transport characteristics (with respect to layers) of SFS structures, which provide direct indications of the behavior of the induced order parameter in thin ferromagnetic layers near the superconductor.

[1] *Note added in proof*: A short time ago we have observed [see Veretennikov A V et al., in *Proc. LT-22* (Helsinki, Finland, 1999); to be published in *Physica B* (2000)] $I_{\rm c}(T)$ oscillations associated with a crossover of the SFS junction from '0'- to '$\pi$'-state due to temperature dependence of the spatial oscillation period of induced superconducting order parameter in a weak ferromagnet [11].

## 3. Superconducting currents through ferromagnetic layers

Decay of the induced superconducting order parameter enhances with a rise in the exchange energy $E_{\rm exc}$ in the ferromagnet. The coherence length of pairs in a ferromagnet can be estimated by substituting the exchange energy $E_{\rm exc}$ in place of $kT$ into the conventional expression for the coherence length in impure normal metal [14, 17]:

$$\xi_{\rm F} \sim \left(\frac{\hbar D}{2\pi E_{\rm exc}}\right)^{1/2} \sim \left(\frac{\hbar D}{2\pi k T_{\rm C}}\right)^{1/2},$$

where $D$ is the diffusion coefficient of electrons in ferromagnet, and $T_{\rm C}$ is the Curie point. This relation holds when $kT_{\rm C} \gg kT$ and $\hbar/E_{\rm exc} \ll \tau_{\rm so}$ (the time of spin-orbital scattering in ferromagnet). Estimates made for classical ferromagnetic (Ni, Fe, Co) films with $T_{\rm C} \sim 10^3$ K give $\xi_{\rm F} < 1$ nm. The use of dilute ferromagnetic alloys allows tenfold decrease in the Curie temperature and the exchange energy, thus making it possible to prepare thin-film SFS sandwiches with homogeneous ferromagnetic interlayers 10 – 20 nm in thickness comparable with $\xi_{\rm F}$, and to observe the superconducting currents flowing through the ferromagnetic interlayer. In Ref. [16], Josephson superconducting supercurrents were detected in sandwiches with ferromagnetic Cu/Ni layers.

We used cross-shaped thin-film SFS Nb – Cu/Ni – Nb sandwiches with ferromagnetic layers 10 – 20 nanometers thick. Upon transition from paramagnetic to ferromagnetic alloy (the boundary concentration being about 44 at.% Ni), the critical currents in sandwiches dropped sharply. Figure 1 shows the current-voltage characteristic and the critical current $I_{\rm c}$ versus the applied magnetic field $H$ for the junction with a Cu/Ni interlayer 10 nanometers thick, containing 47 at.% Ni. Measurements were made with a superconducting picovoltmeter based on RF SQUID with a sensitivity better than $10^{-11}$ V. The curve $I_{\rm c}(H)$, to a good precision, is described by the known 'Fraunhofer relation'

$$I_{\rm c} = I_{\rm c0}\left|\frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}\right|,$$

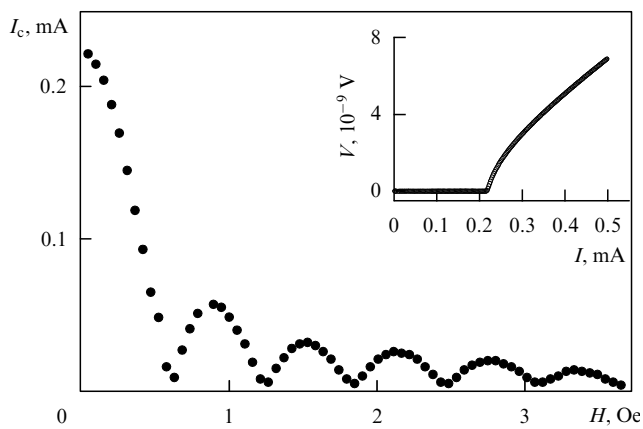


**Figure 1.** Critical current in the SFS sandwich with a 10 nm thickness ferromagnetic interlayer vs. external magnetic field ($T = 4.2$ K). Inset shows current-voltage characteristic in zero field.

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 $L$, $\Phi_0$ 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.

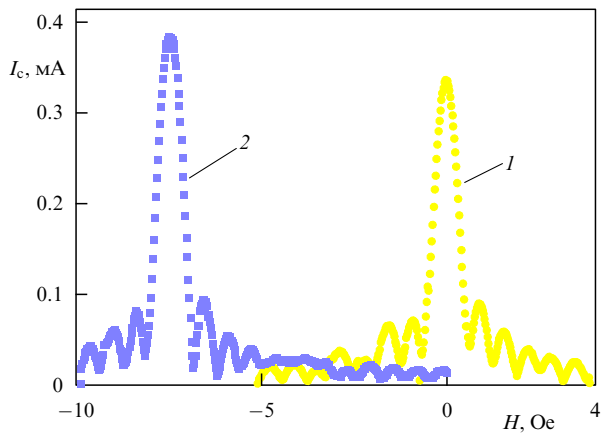


**Figure 2.** Shift of the $I_c(H)$ curve after magnetization of a sample: *1* — curve $I_c(H)$ before magnetization; *2* — the same after magnetization.

## 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

A I Morozov, A S Sigov

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.