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Spin-dependent conductivity of iron-based superconductors in a magnetic field

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ABSTRACT

We study *dc* conductivity of iron-based superconductors α-FeSe and LaOFFeAs by measuring the conductance of point-contact heterojunctions in NS and NN modes of transport (N and S denote normal and superconducting states, respectively). In the NS regime, measurements were performed in case of *defect-free* NS boundary due to shifting it inside the superconductor by the transport current. Under these conditions, we observed the contact conductance to increase at the NS → NN transition driven either by temperature or by magnetic field, and to decrease at the reverse transition. We attribute this effect to the manifestation of spin-dependent nature of the Andreev reflection (spin accumulation) in consequence of the magnetism at the normal side of the NS boundary. Investigating normal conductance in a magnetic field we revealed the nonpersistent hysteresis and square-law dependence of positive magnetoresistance on the magnetic field which fact confirmed this conclusion and pointed to the leading role of itinerant magnetism in the normal ground state of the superconductors studied.

Based on the experimental findings and analysis we conclude that there exists a long-range magnetic order in the normal ground state of investigated iron-based superconductors with nematic ferromagnetic exchange interaction between band conduction electrons and local magnetic moments of the ions.

One of the most urgent problems of condensed matter physics remains search and study of crystal systems with low symmetry of a "layer" type characterized by the anisotropy in electronic and magnetic properties, leading to superconductivity. Currently, superconductivity has been observed in a large variety of such compounds including a wide range of rare earths, pnictogens, chalcogens, and transition elements Mn, Fe, Co, Ni, Cu, and Ru. In particular, the observation of superconductivity in iron-based systems suggests that the anisotropy in properties is apparently an essential condition wherein in the same material, magnetic interactions can coexist with interactions promoting the superconducting pairing. While the ideas of crystal structures of such superconductors and the nature of coupling in them are sufficiently developed and experimentally proved, their magnetic and electronic structures, and specially the nature of the interactions between those structures in the ground state, are still the subject of intense debate [1–5]. In this regard, it becomes significant to study transport phenomena in the systems with such superconductors since the nature of transport may directly depend on the itinerant magnetism of conduction electrons that can interact with the sublattice of localized magnetic moments of the magnetic atoms.

Here, we present the results of our study on electron transport in the point-contact samples of iron-based superconductors in NS and NN mode of *dc* transport, in the absence and presence of a magnetic field. NS regime was investigated with defect-free NS boundary arranged inside the superconductor. Iron-based superconductors are presented by single crystal binary phase of α-FeSe and by oxyarsenide pnictide LaOFFeAs in a granular form. They share a structural unit of the symmetry type of PbO ($P4/nmm$) which predetermines the affinity of the exchange interactions in quasi-two-dimensional electron bands [6–8].

1. Experiment

1.1. Formulation

As we have shown previously [9], use of heterojunctions "normal metal (N) – superconductor (S)" allows us to solve two

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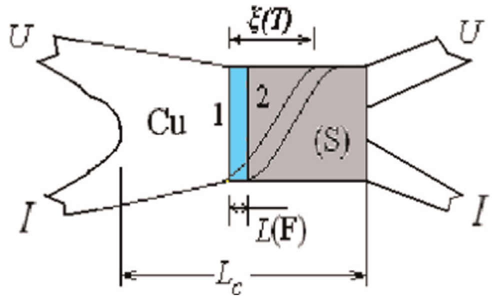

Fig. 1. Schematic representation of a typical microheterocontact with its distinctive spatial parameters under the proximity effect. L_c = 1.5–3 mm is a total length of the contact corresponding to the distance between the measuring potential probes in the NN state; 1 and 2 denote the NS boundary position without (1) and with (2) the transport current I; L(F) is a part of the superconductor (S) passed into the normal state as a result of NS boundary shifting.

problems at once: (i) to study, through the "Andreev conductance", the characteristics of conversion of dissipative current into supercurrent at the NS boundary and (ii) to explore conductivity of the superconductors in the normal ground state. The latter is possible due to the proximity effect in which region the superconducting order parameter disperses from 1 to 0 within the scale of the Ginzburg–Landau coherence length $\xi_T \sim \xi_0(1 - T/T_c)^{-1/2}$. Owing to this dispersion, an arbitrarily low intrinsic magnetic field of the transport current is capable of shifting the NS boundary from the interface into the superconductor, thereby setting in it a *defect-free* NS boundary which separates normal and superconducting phases (see Fig. 1).

Thus, in the binary NS contacts, the nature of converting a dissipative current into supercurrent at the NS boundary, located inside the superconductor, is directly dependent on the characteristics of the superconductor in its normal ground state, such as, for example, magnetism. We used this fact in [9] investigating the Andreev reflection in non-ballistic NFS contacts with iron-based superconductors. In particular, we noted that the Ginzburg–Landau parameter $\kappa = \lambda_T/\xi_T$ (λ_T is the penetration depth) for these superconductors was ≥1, and hence, the discussed superconductors must have the properties of type II superconductors with the London penetration depth $\lambda_L \simeq 0.2$ μm [10]. The results from Ref. [9] also indicated that the energy W of the intrinsic magnetic field of the measuring current 1 mA flowing through the contact Cu/FeSe, with the cross Section $\mathcal{A} \geq 10^{-4}$cm^2, was of order of or slightly greater than the energy gap Δ (in the BCS approximation) for FeSe ($W \geq 0.5$ meV; $\Delta_{FeSe} \sim 0.5$ meV). At the same time, in the contact Cu/LaOFFeAs under similar condition, $W \leq \Delta$ ($\Delta_{LaOFFeAs} \approx 6\Delta_{FeSe}$). It follows that at the transport current 1 mA, the normal layer thickness of the superconductor, L(F), at the normal side of the NS boundary is of the order of λ_T. Therefore, at helium temperatures, L(F) approximately amounts to (10^{-5}–10^{-6}) cm (at I= 100 mA, it is ln 100 times greater).

We may conclude that reasonable values of the transport current can shift a real NS boundary in the contact from the physical interface by a distance of the order of, at least, a spatial dispersion of the order parameter. It allows one to get, in NS mode of transport, a mesoscopic layer of normal-phase superconductor which thickness is large enough to detect magnetic properties of the ground state of the superconductor. It is easy to understand that the displacement of the boundary by virtue of a magnetic field cannot exceed the coherence length ξ_T since the complete destruction of the superconducting state, when the order parameter is of the order of 1, is possible only at rather large values of the field comparable with the critical ones. Thus, a regular NS mode of transport with defect-free NS boundary inside the superconductor can be maintained to very high magnetic fields, at least those in which, for example, any reconstruction of the electron spectrum does not occur.

1.2. Samples

Superconductors that have been used as the basis of point contacts had different structure according to the technology for their manufacture. Pnictide La($O_{0.85}F_{\sim 0.1}$)FeAs was prepared by solid-phase synthesis, such as that described in [11], and had a polycrystalline structure of granular type. Iron monochalcogenide FeSe was made in the single crystal form [12].

It is known that the current–voltage characteristics of macroscopic samples of granular superconductors often exhibit hysteresis in magnetic fields, the nature of which is usually associated with a variety of possible scenarios of the current flow including percolation, tunnelling (intergranular or intragranular interphase), and intragranular mechanisms of conductivity special for a given superconductor [13–15]. To except the first two factors contributing the greatest uncertainty in the results, it is desirable to approximate the sample size to that of the granules themselves. The latter typically amounts to $d \sim 10^{-4}$ cm in materials prepared for a variety of technologies. The size of the point contacts just satisfies this condition. As we have shown previously [16], in this case the length of the measurement area is usually of the order of a few microns, typical non-ballistic mesoscopic scale.

Here, we present our results on the conductance of point-contact samples with ohmic characteristics similar to those investigated by us in Ref. [9]. Contacts were implemented by pressing a hard bronze or copper etched tip to a superconductor. For the experiment, samples were selected with the contact resistance between 0.5 and a few Ohms. *dc* current–voltage characteristics were measured by a four-pin method (for distinctions of measuring contact samples by this method, see [16]). In case of sufficiently low-resistive samples, we used a picovoltmeter based on the superconducting commutator [17]. Measurements were carried out in the mode of a fixed current (1–100 mA) derived from high-stabilized constant current sources (with a stabilization factor not less than 10^{-3}%).

2. Results and discussion

Below we present the resistivity data from NS heterojunctions in moderate magnetic fields which include the Andreev resistance of a defect-free NS boundary and the resistance of the area L(F) as a part of a superconductor in the normal state (see Section 1.1).

Figs. 2 and 3 show the resistance R_H of heterojunctions Cu/FeSe and Cu/LaOFFeAs in magnetic fields normalized to the *total* resistance of the contact in zero magnetic field $R(H = 0)$ as $[R_H/R(H = 0)] - 1 = \Delta R_H/R(H = 0)$, at temperatures T below and above (for Cu/LaOFFeAs) superconducting transition temperatures T_c (FeSe: $T_c \approx 5$ K; LaOFFeAs: $T_c \approx 26$ K). We found the following features of the resistance: (1) At $T < T_c$, magnetoresistance in systems with different superconductors shows the different sign: in Cu/FeSe – positive, in Cu/LaOFFeAs – negative. (2) Magnetoresistance in the same system, Cu/LaOFFeAs, has different sign at different currents: at a greater current 100 mA, the addition to the resistance ΔR_H is positive, even at $T < T_c$ (see Fig. 3, asterisks), while at a lower current 1 mA it is negative for T both lower and higher than T_c. The same addition for contacts Cu/FeSe is mostly positive in the whole range of currents and comparable range of fields except some range of fields, wherein it is negative. (3) In both systems, the magnetoresistance shows hysteresis. For greater clarity, in Fig. 4, we reproduce the first two features of the magnetoresistance for heterojunction Cu/LaOFFeAs without hysteresis, for only one direction of the field.

Below we show that all the variety of features of NS point-contact conductance in NS transport mode is most likely