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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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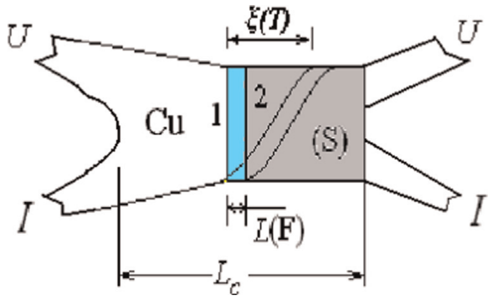

Fig. 1. Schematic representation of a typical microheterocontact with its distinctive spatial parameters under the proximity effect. L_c = 1.5–3 mm is a total length of the contact corresponding to the distance between the measuring potential probes in the NN state; 1 and 2 denote the NS boundary position 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 $\lambda_L \simeq 0.2\ \mu$m [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; $\Delta_{\rm FeSe} \sim 0.5$ meV). At the same time, in the contact Cu/LaOFFeAs under similar condition, $W \leq \Delta$ ($\Delta_{\rm LaOFFeAs} \approx 6\Delta_{\rm FeSe}$). 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

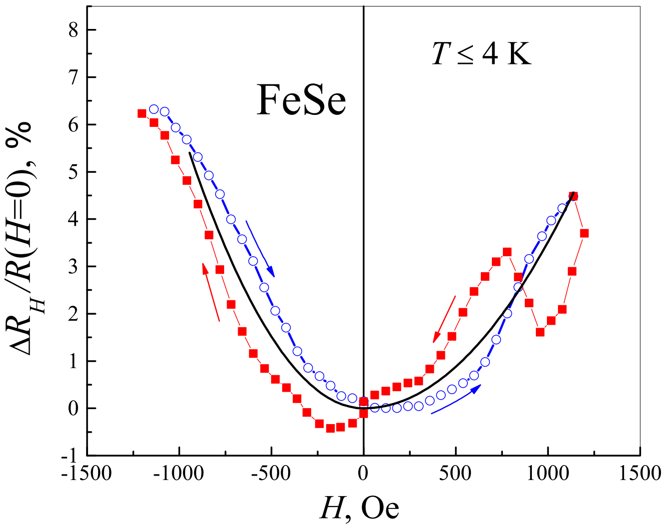

Fig. 2. Magnetoresistance with hysteresis of heterojunction Cu/FeSe normalized to the total contact resistance measured at $T \le 4$ K and $I=1$ mA [$(T+eV^*) \sim \Delta$]. Solid line represents a spin-dependent magnetoresistance calculated in accordance with Eq. (11).

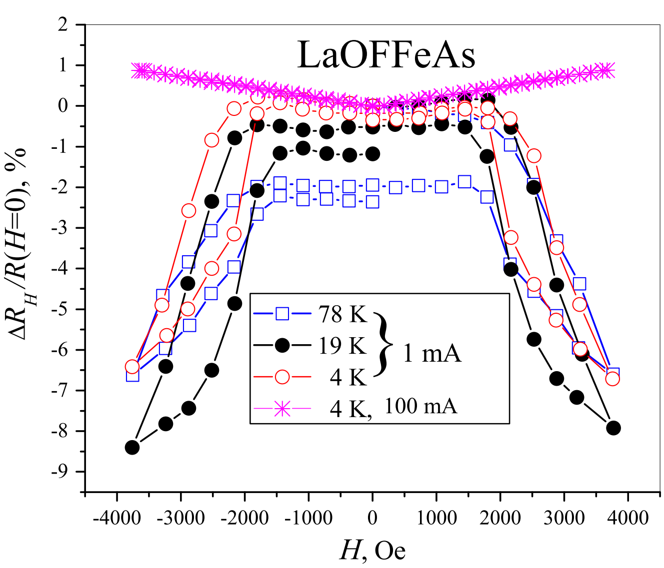

Fig. 3. Magnetoresistance with hysteresis of heterojunction Cu/LaOFFeAs normalized to the total contact resistance: open and filled circles denote data measured at $T=4$ K and 19 K, respectively, and $I=1$ mA [$(T+eV^*) < \Delta$]; asterisks, at $T=4$ K and $I=100$ mA [$(T+eV^*) \sim \Delta$]; squares, at $T=78$ K and $I=1$ mA [$(T+eV^*) > \Delta$].

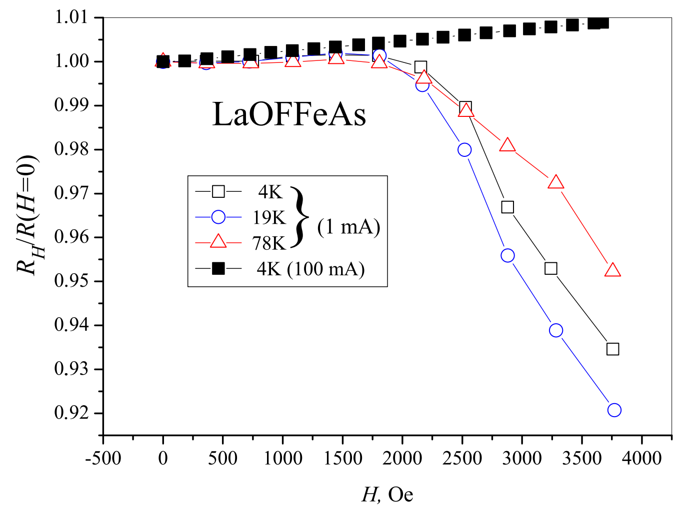

Fig. 4. Negative magnetoresistance of the heterocontact Cu/LaOFFeAs normalized to its total resistance (at H=0): open squares and circles denote data measured at $T=4$ K and $T=19$ K, respectively, and $I=1$ mA [$(T+eV^*) < \Delta$]; filled squares, at $T=4$ K and $I=100$ mA [$(T+eV^*) \sim \Delta$]; triangles, at $T=78$ K and $I=1$ mA [$(T+eV^*) > \Delta$].

associated with both the relation between the energy of carriers and the energy gap at NS boundary and the magnetic state of the contact N side.

2.1. NS mode. Negative magnetoresistance

The most impressive effect in NS transport mode was the increase in conductivity in a magnetic field in contacts with Cu/LaOFFeAs. To understand the nature of the observed features, let us consider the configuration of the investigated contacts. Their effective (working) length, not exceeding a few microns, in NS mode includes four areas: the inevitable part of a normal-metal probe (Cu, brass), the oxide barrier at the interface, and two adjacent N and S regions of the same superconductor. Since the resistance of the materials of the former two areas can only increase weakly in low magnetic fields (see, for example, Ref. [9]) it is clear that the negative magnetoresistance is due solely to the latter two ones.

It is known that an increase in conductivity in a magnetic field (excluding the values of the fields corresponding to large Zeeman energies, capable of inducing, for example, metamagnetism) indicates either the presence of spin-dependent effects in the transport of itinerant conduction electrons [18] or the degradation of the weak-localization interference resistive addition [19]. Assessing the weak-localization interference correction to the conductivity, we find that in the studied range of fields, the negative contribution to the magnetoresistance of the contacts under elastic electron scattering (at helium temperatures), due to the destruction of the interference of self-intersecting electron trajectories by a magnetic field, may be of the following order:

$$\frac{\Delta\rho_H}{\rho(H=0)} = -\,\Delta\sigma_H\cdot\rho_H \approx -\,5\times(10^{-5}\text{–}10^{-3}), \tag{1}$$

where $\Delta\sigma_H = \sigma_H - \sigma(H=0) \sim \left(e^2/\hbar\right)(eH/\hbar c)^{1/2}$; $H = 2\times10^3$ Oe, and possible values of $\rho(H=0)$ for the materials forming the contact are within the interval (1–100) $\mu\Omega$ cm (from measurements on bulk samples). Comparing this estimate with the data in Figs. 2 and 3, we find that the value of weak-localization correction is clearly insufficient to explain the magnitude of the experimentally observed negative magnetoresistance, which is, more likely, understated by normalizing to the *total* contact resistance. Therefore, the most probable reason for the observed negative magnetoresistance is spin-dependent nature of transport of conduction electrons in terms of their itinerant magnetism. It spatially associates the change in resistance, ΔR_H, with that part of the contact which occupies two neighboring regions of a superconductor, in the normal [L (F)] and in the superconducting state.

With this in mind, we obtain a correct idea of the magnitude and behavior of the magnetoresistance $\Delta\rho_H/\rho(H=0)$ by dividing the change in resistance ΔR_H not by the total resistance of the contact, as is done in Figs. 2, 3 and 4, but only by the resistance of normal regions occupied by a superconductor. In NS mode, it is the resistance $R_{L(\mathrm{F})}(H=0)$ of the area L(F) of the contact while at $T > T_c$ (in particular, at 78 K) it is the resistance $R_{S(\mathrm{N})}$ of the entire area of the superconductor in the normal state up to the borders of the probes. When this is done, the value and behavior of the magnetoresistance appear on a different scale, such as given on the right axis in Fig. 5. While recalculating we used the following values of

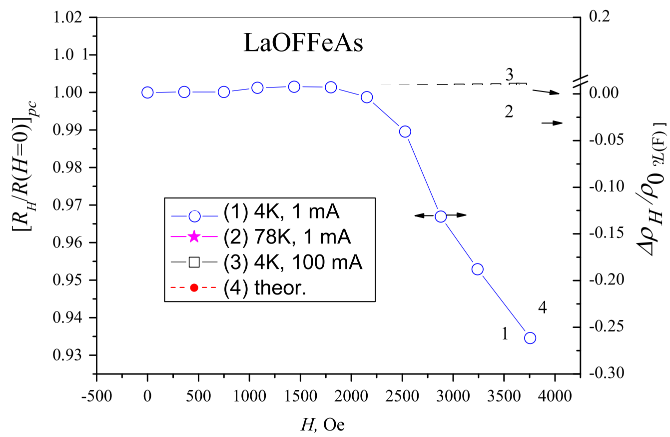

Fig. 5. Negative magnetoresistance of heterocontact Cu/LaOFFeAs normalized to the resistance of the normal regions of the superconductor (right axis). For comparison, left axis reproduces the scale from Fig. 4. Curve 1 was taken at $(T + eV^*) \ll \Delta$; curve 2, at $(T + eV^*) > \Delta$; curve 3, at $(T + eV^*) \sim \Delta$. Curve 4 represents a *fit* to curve 1 in accordance with Eq. (2).

the parameters: $\rho(H = 0)_{L(\mathrm{F})} \sim 10^{-4}\,\Omega\,\mathrm{cm}$; $\lambda_T \simeq 0.2\,\mu\mathrm{m}$; $D \simeq 20\,\mu\mathrm{m}$ (contact diameter); $L(\mathrm{F})_{4\,\mathrm{K},1\,\mathrm{mA}} \simeq \lambda_T$; $L(\mathrm{F})_{4\,\mathrm{K},100\,\mathrm{mA}} \simeq \lambda_T(1 + \ln 100)$; $L_{\mathrm{S(N)},78\,\mathrm{K}} \approx 3\,\mathrm{mm}$.

From a comparison of measured effects, scaled in this way, with the above estimated weak-localization correction (1) it follows that the latter is really too small to generate negative magnetoresistance $\Delta\rho_H/\rho(H = 0)$ in NS mode at $I=1$ mA, such as described by curve 1 in Fig. 5. At the same time, at 78 K (curve 2), when NS boundary is absent, the negative value of $\Delta\rho_H/\rho(H = 0)$ in the field of order of 10^3 Oe is comparable to the resistive weak-localization contribution, suppressed by the magnetic field and not related, as shown by the measurements, with the value of the transport current (at least, up to 100 mA).

Thus, the most likely cause of the negative magnetoresistance observed in a heterojunction in NS mode, at $T < T_c$ and $I=1$ mA, while magnetic field H is enhanced (curve 1, Fig. 5), is a decrease in a certain positive spin-dependent resistive contribution which appears at $H=0$ at the NS boundary due to prohibiting certain processes of the Andreev reflection under spin polarization of the current. As known, this polarization may occur in conditions of itinerant magnetism of conduction electrons due to the difference in the spin densities in the electron subbands. It leads to the spin accumulation during the conversion of the dissipative current into supercurrent at the NS boundary, through the mechanism of the Andreev reflection with the corresponding resistive contribution [20]. We have earlier received [9,16] the evidence for existence of such a contribution from the study of temperature properties of the Andreev reflection in FS contacts.

The relative magnitude of this resistive contribution in a magnetic field will obviously depend on the product of two probabilities. The first is the probability $r_{\lambda s}$ of maintaining the dispersion of the spin subbands within the length L of the L (F) regions (it depends on the spin relaxation length λ_s); the second is the probability of implementation of the Andreev reflection $r_{\xi(H)} = \hbar v_{\mathrm{F}}/\epsilon\xi_H$ in a magnetic field, which destroys the electron–hole coherence when e and h trajectories are splitted by a distance greater than the de Broglie wavelength [21]. Strictly speaking, some other positive additive to the resistance can occur, namely, the contribution from coherent electron–hole scattering by impurities [22], which we do not discuss here, considering the mean free path of electrons to be greater than L(F). Then, the spin-dependent contribution due to the spin accumulation in the conditions of the Andreev reflection can be written as

$$\frac{\Delta\rho_H}{\rho(H = 0)} = \{r_{\lambda s}\}\{r_{\xi(H)}\}, \tag{2}$$

where, in accordance with [20],

$$\{r_{\lambda s}\} = \frac{\lambda_s}{L}\cdot\frac{P^2}{1 - P^2},\; P = (\sigma_\uparrow - \sigma_\downarrow)/\sigma;\; \sigma = \sigma_\uparrow + \sigma_\downarrow \tag{3}$$

(here, σ, $\sigma_\uparrow$ and $\sigma_\downarrow$ are the total and spin-dependent conductivities; P is the polarization) and

$$\{r_{\xi(H)}\} = \int_{\epsilon\mathrm{min}}^{\epsilon\mathrm{max}} \left(-\frac{\partial f_0}{\partial\epsilon}\right) r_{\xi(H)}\, d\epsilon \sim \xi(H)/L \tag{4}$$

($\epsilon_{\mathrm{min}} = \hbar v_{\mathrm{F}}/L$).

As a result, we can expect that the magnetoresistance of NS contact must behave as the magnetoresistance of a normal region of a superconductor in conditions of barrier-free NS interface inside the superconductor and obey the following rule:

$$\frac{\Delta\rho_H}{\rho_L} = \frac{\lambda_s}{L}\cdot\frac{P^2}{1 - P^2}\left[\frac{\xi_N(H)}{L} - 1\right]. \tag{5}$$

From Eq. (5) it follows that if $\lambda_s > L$, i.e. magnetic zone dispersion is maintained throughout the whole area L(F), then, while $\xi_N(H) \geq L$, the value of the spin-dependent contribution will not depend on the magnetic field up to fields at which $\xi_N(H)$ becomes smaller than L. The curve 1 in Fig. 5 behaves in a similar way. From the shape of this curve we may conclude that the condition $\xi_N(H)/L \geq 1$ is violated in the fields exceeded about 2 kOe:

$$\xi_N(H) = \sqrt{2\lambda_{\mathrm{B}}\cdot R_{\mathrm{L}}} \Rightarrow \xi_N(H = 2\times10^3\ \mathrm{Oe}) \approx 2\times10^{-5}\ \mathrm{cm} \approx \lambda_T = L_{(1\ \mathrm{mA})}, \tag{6}$$

where, for LaOFFeAs, λ_{B} and R_{L} are the de Broglie wavelength and the Larmor radius, respectively, and the Fermi velocity $v_{\mathrm{F}} \approx 10^7$ cm/s [23].

Of course, this assumes that in the NS mode the total current is converted into a supercurrent, the probability of Andreev reflection being equal to 1, since, at the current 1 mA, the ideal (barrier-free) NS boundary and the regime $eV(l_{el}/L) \sim 10^{-2}\,\mathrm{K} \ll \Delta_{\mathrm{LaOFFeAs}}$ are realized. Curve corresponding to the expressions (5) and (2) with the previously estimated parameters $P \sim 60\%$ [16] and $\lambda_s \simeq L \approx 2\times10^{-5}$ cm is shown in Fig. 5 as the dashed curve 4 (a *fit* to the experimental curve 1).

At the current 100 mA and $T = 4\,\mathrm{K} \ll T_c$, the voltage $V^* = V(l_{el}/L)$ which specifies the amount of a jump of the distribution function, $eV^*(-\partial f_0/\partial\varepsilon)$, and the gap Δ are very close in magnitude. Consequently, the contribution from the Andreev reflection (spin accumulation) becomes negligible, although, generally speaking, NS mode remains preserved, as well as the spin polarization of the transport current in the area L(F). Close to this situation seems to be the case in the contacts Cu/FeSe at the current of 1 mA, as evidenced by the positive magnetoresistance (see Fig. 2).

Summarizing the above analysis we can conclude that the negative magnetoresistance in the scale represented by curve 1 in Fig. 5, at least two orders of magnitude greater than the expected value of the weak-localization correction, is possible only if the probability of the Andreev reflection is close to unity. This condition is only realized in the mesoscopic heterojunction Cu/LaOFFeAs at the energy of the carriers $(T + eV^*) \ll \Delta$. At the energy $(T + eV^*) \gtrsim \Delta$, a negative contribution to the magnetoresistance of the same magnitude should be absent, as is observed (see Fig. 2 for Cu/FeSe and curves 2 and 3 in Fig. 4 for Cu/LaOFFeAs), due to suppression of the Andreev reflection and vanishing the conditions for spin accumulation at NS boundary. This fact, as well as

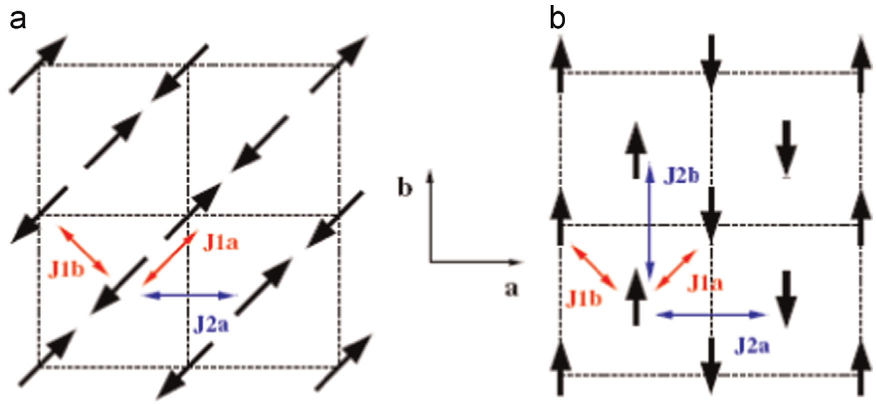

Fig. 6. Spin magnetic structure of iron-based superconductors (parent), (a) oxyarsenides and (b) chalcogenides. Exchange coefficients J1a, J1b, J2a, and J2b refer to AFM, FM, AFM, and FM ordering of the spins of the iron ions, respectively [24,26].

the nonpersistent hysteresis of the magnetoresistance at H=0 observed in all the above energy modes, suggests that the conductivity of the studied superconductors in their normal ground state in the area $L(F)$ is spin-dependent and conditioned by the presence of long-range magnetic order and itinerant magnetism of delocalized conduction electrons due to possible anisotropic s–d exchange interaction between the iron atoms.

2.2. N mode. Positive magnetoresistance

Figs. 2, 3 and 7 show that the magnetoresistance in the NN mode, without being related to the dynamics of charge carriers ($\omega\tau \ll 1$), is a quadratic function of the magnetic field, which may also be due to spin-dependent character of their scattering. Accordingly, we propose the following alternative explanation for the observed behavior. However, it cannot be ruled out that this positive magnetoresistance manifests the intrinsic magnetic nature of FeSe itself.

Since the investigated systems are very critical to the conditions for occurrence of superconductivity (such as the ferromagnetic Stoner instability that leads to spin fluctuations [24], or structural transitions, and doping [3]), we can assume that arising anisotropic magnetic structure of the local magnetic moments is metastable and inclined to metamagnetism even in low magnetic fields. In these conditions, anisotropy of the exchange interactions is usually described by spin-dependent part of the Heisenberg Hamiltonian. In this case, the corresponding potential of spin interaction can be written as

$$U_m = -\,(J_m/n_m)\sum_i \mathbf{s}_e\mathbf{S}_i f(\mathbf{r}-\mathbf{R}_i), \tag{7}$$

where J_m are the anisotropic coefficients of the m-exchange interaction responsible for the processes of ferromagnetic (J_1) and antiferromagnetic (J_2) exchange between the spins of the magnetic ions $\mathbf{S}$ and those of the conduction electrons $\mathbf{s}_e$; $n_m = N_m/\mathcal{V}$; N_m is a number of ions in the stripes with m-exchange interaction (see Fig. 6) and $\mathcal{V}$ is a volume [25]. Under these conditions, taking into account the percolation nature of random walks of electrons between stripes with spin ordering of different types, the total scattering amplitude of electron spins at ion spins could not remain constant when you change both the direction and magnitude of low magnetic fields.

As a result, the spin-dependent part of the conductivity could be represented as

$$\overline{\sigma_{\text{spin}}} = \sigma_{J1} + \sigma_{J2}, \tag{8}$$

and the corresponding resistance as

$$\overline{\rho_{\text{spin}}} = \rho_{J1}\rho_{J2}/(\rho_{J1} + \rho_{J2}). \tag{9}$$

As is well known [18,27], other things being equal, ρ_{J_2} âª¢ ρ_{J_1} since AFM scattering ($J_2 < 0$) allows the spin-flip processes, thereby increasing the scattering amplitude. This fact suggests that the component ρ_{J_1}, corresponding to FM exchange, prevails. Since the resistance is proportional to the square of the scattering amplitude, which, in turn, according to Eq. (4), is proportional to $-(J_m/n_m)(\mathbf{s}_e\mathbf{S})_{s'_e s_e}$, then after summing over the final spin orientations and averaging over initial orientations, we can write down the component ρ_{J_1} in the first Born approximation as [25]

$$\rho_{J_1} = \frac{3\pi m}{2e^2\hbar\varepsilon_F} S(S+1)J_1^2/n_1. \tag{10}$$

Here, m and e are the mass and charge of an electron; ε_F, the Fermi energy. It follows that if a magnetic field reorients a part of spins in the stripes, reducing, in particular, n_1, it will lead to the following dependence of the magnetoresistance on a magnetic field:

$$\frac{\Delta\overline{\rho_{\text{spin}}}}{\rho_0} \sim J_1(n_1)^{-1} \sim f_{ev}(H) \sim H^2, \tag{11}$$

where $f_{ev}(H)$ is an even function of a magnetic field, in agreement with experiment.

In Figs. 2 and 7, the solid lines show the behavior of the magnetoresistance corresponding to this expression with $(n_1)^{-1} \sim H^2$. Note that this result obtained in the first Born approximation predicts positive magnetoresistance, hysteresis, and a different magnitude of $\Delta\rho_H/\rho_0$ in compounds FeSe and LaOFFeAs in the normal state in the mode $(T + eV^*) \gtrsim \Delta$, as observed.

3. Conclusion

In conclusion, we investigated non-ballistic NS heterocontacts, Cu/FeSe and Cu/LaOFFeAs, with a defect-free NS boundary inside the iron-based superconductors. We studied magnetoresistance of the contacts in moderate external magnetic fields, depending on the energy conditions of the experiment, temperature and bias voltage at the contact, which determine the energy of charge carriers, as well as on the magnetic field of the transport current, which determines the initial size of the non-superconducting region of superconductors in the ground state. It was found that when a probability of the Andreev reflection at the NS boundary is close to unity ($r_A \approx 1$), the conductivity increases beginning with the fields of order of 10^3 Oe. The value of the negative magnetoresistance is more than an order of magnitude greater than the

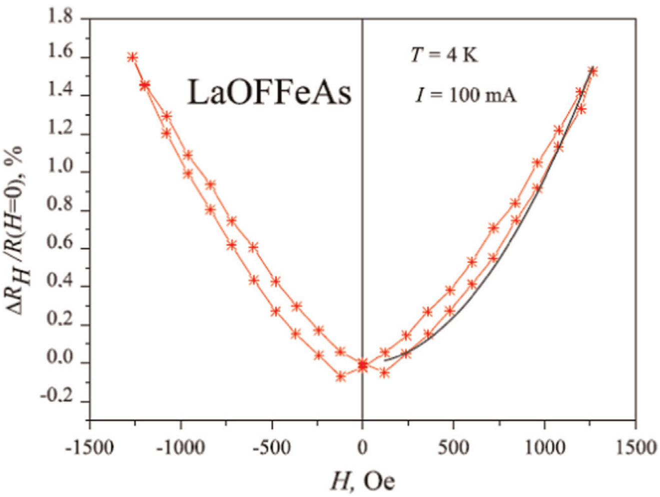

Fig. 7. Magnetoresistance with hysteresis of heterocontact Cu/LaOFFeAs normalized to the total contact resistance: asterisks are experimental data taken at $[(T + eV^*) \sim \Delta]$; solid curve shows spin-dependent magnetoresistance in accordance with Eq. (11).

magnitude of the possible negative contribution of weak-localization nature.

Since this effect only occurs when a probability of the Andreev reflection is nonzero, it points directly to the spin-dependent restrictions of that reflection (spin accumulation at the NS boundary) which are possible only in the presence of the dispersion of the spin subbands in the initial ground state of the superconducting contact side. In particular, we found that the maximum value of the measured accumulative addition to the resistance in FeSe, achieved in zero field at $r_A \approx 1$, corresponds to the polarization in the spin subbands exceeding 50%. The behavior and magnitude of the magnetoresistance under $r_A \approxeq 0$ also confirm the spin-dependent nature of transport due to band magnetism. Positive and even (with respect to a magnetic field) magnetoresistance observed in this regime may be a consequence of the ferromagnetic Stoner instability, where the amplitude of the spin scattering may depend on the number of nematic ferromagnetically oriented local moments in the stripes with the ferromagnetic interaction of local spins with the spins of itinerant electrons.

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