Controllable supercurrent in mesoscopic superconductor-normal metal-ferromagnet crosslike Josephson structures

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Abstract

A nonmonotonic dependence of the critical Josephson supercurrent on the injection current through a normal metal/ferromagnet weak link from a single domain ferromagnetic strip has been observed experimentally in nanofabricated planar crosslike S-N/F-S Josephson structures. This behavior is explained by 0–π and π–0 transitions, which can be caused by the suppression and Zeeman splitting of the induced superconductivity due to interaction between N and F layers, and the injection of spin-polarized current into the weak link. A model considering both effects has been developed. It shows the qualitative agreement between the experimental results and the theoretical model in terms of spectral supercurrent-carrying density of states of S-N/F-S structures and the spin-dependent double-step nonequilibrium quasiparticle distribution.

Keywords: Josephson junction, mesoscopic structures, spin-polarized current, ferromagnetism

(Some figures may appear in colour only in the online journal)

1. Introduction

The interplay between spin-singlet superconductivity and ferromagnetism in mesoscopic hybrid structures leads to a variety of novel effects actively investigated in previous decades. The most remarkable experiments were carried out using nonlocal methods of detection of the spin accumulation and injection in normal metals and superconductors [1–3], coherent effects of crossed Andreev reflection and elastic cotunneling [4–8], Zeeman splitting in superconductors with adjacent ferromagnetic insulators [9], charge and spin imbalance [10–14] and specific thermoelectric effects [15–17].

An unusual Josephson effect characterized by the inverse current-phase relation I = −Ic sin φ, the so called π-state of a Josephson junction, was observed in quite macroscopic trilayered SFS systems with a weak ferromagnetic interlayer [18, 19]. There the temperature induced 0–π transition was demonstrated. Experimentally feasible lateral superconductor (S)-normal metal (N)-ferromagnet (F) Josephson junctions manifesting the π-state under certain conditions were studied theoretically, in detail [20]. Implementation of such structures as submicron-scale π-phase shifters is of particular interest for superconducting and quantum electronics [21], which has already been demonstrated with sandwich-type SFS Josephson junctions incorporated in superconducting logical schemes [22] and in the qubit loop [23]. The future
improvement is associated with the system size reduction by means of the fabrication of submicron lateral hybrid structures. The driving out of equilibrium conditions makes it possible to achieve 0–π transitions even without ferromagnets as it was predicted [24, 25] and demonstrated [26–28] for controllable SNS Josephson junctions. In such diffusive systems (i.e. when the elastic mean free path is much shorter than the length of the weak link) the supercurrent is carried by a continuous density of states [24, 25]. The transition into π-state occurred there at a certain value of the control voltage across the N-barrier, which corresponds to a sign change in the spectrum of supercurrent-carrying states \( \text{Im}[J(z)] \). The latter is characterized by the strongly damped oscillations with positive and negative parts which is cut out by the double-step-like electron distribution function or smeared by the thermal distribution function (see figure 2 in [27]).

It is predicted that for similar mesoscopic structures with ferromagnets [29] (or under an applied magnetic field [30]) the spectral supercurrent is shifted due to the presence of the exchange or the Zeeman field \( h \) which leads to the redistribution of current-carrying states. The redistribution results in the suppression of the Josephson current in equilibrium. The recovery of the supercurrent by applying a suitable nonequilibrium distribution of quasiparticles was proposed. The recovery was predicted both for spin-independent [30] and for spin-dependent nonequilibrium quasiparticle distribution [31]. The proper spin-dependent quasiparticle distribution is the most efficient way to recover the supercurrent. Moreover, 0→π transitions driven by the nonequilibrium quasiparticle distribution can be observed [30, 32, 33].

In this work, we study the effect of spin-polarized current injection on the Josephson supercurrent in the mesoscopic crosslike S–N/F–S (Al–Cu/Fe–Al) structures. A nonmonotonic dependence of the critical Josephson supercurrent on the injection current with two pronounced dips was observed. This behavior is explained by the double 0–π transition. We claim that this effect is due to spectral supercurrent modification in the presence of the effective exchange field \( h \) in the hybrid weak link and controllable nonequilibrium distribution of quasiparticles. The corresponding calculations for the geometry of our structures and the parameters obtained from the measurements show qualitative agreement with the experiment.

2. Samples and experiment

In the investigated structures Al, Cu and Fe were used as a superconductor, a normal metal, and a ferromagnet correspondingly. Figure 1(a) shows a scanning electron microscopy (SEM) image of one of our samples, together with the measurement scheme, figure 1(b) illustrates a schematic sketch of the structure with its geometrical dimensions. The submicron-scale crosslike S–N/F–S junctions were fabricated by means of electron beam lithography and in situ shadow evaporation. First, a thin (10–15 nm) iron layer was deposited onto an oxidized silicon substrate at the first angle to form a ferromagnetic injector. Then a copper layer of 60 nm (or 30 nm) thickness was evaporated at the second angle to create a complex N/F-weak link in the intersection area of N and F layers. Finally, a thick (100 nm) layer of aluminum was deposited at the third angle to form superconducting banks of the junction and electrical contacts to the perpendicular Fe electrode. All these technological steps were executed without breaking the ultra high vacuum, so that the FN and NS interfaces did not appear to contain significant contaminations and were reproducible from sample to sample. The geometrical dimensions are the same for all structures, i.e. the distance between superconducting banks is 200 nm, the width of the iron strip is 160 nm, the width of the copper strip is 200 nm (figure 1 (b)). Since the resistance of the iron film with the specific resistance \( \rho_F = 70 \, \mu\Omega \times \text{cm} \) and thickness \( d_F = 10 \, \text{nm} \) is much larger than the resistance of the thick copper film \( (\rho_N = 4.5 \, \mu\Omega \times \text{cm}, d_N = 60 \, \text{nm}) \), the main part of the current flows through the N layer.

The transport measurements were performed in a shielded \(^3\)He cryostat at temperatures down to 0.3 K. Low-pass RC filters were incorporated into DC measurement lines directly on the sample holder in order to eliminate the external noise. The current–voltage characteristics of crosslike S–N/F–S junctions were measured by using the standard four-terminal configuration in presence of the injection current via the iron electrode as it is shown in figure 1(a). The dimensions and thickness of the ferromagnetic strip have provided a single domain state.
with the practically uniform magnetization aligned parallel to the strip, as it was demonstrated in our previous work [34].

The Josephson supercurrent was observed only for samples with the thickness of copper layer \( d_N = 60 \) nm. In comparison with a reference S–N–S (Al–Cu–Al) Josephson junction with the same geometrical dimensions (the only difference was the absence of a perpendicular iron strip) the critical current of hybrid S–N/F–S structures was strongly suppressed. The temperature dependencies of the critical currents for both structures are shown in figure 2. The suppression of the Josephson supercurrent in the case of S–N/F–S structures is explained by the proximity of the ferromagnetic layer in contact with the copper layer in the weak link. Although the area of the intersection of the N and F layers in the cross-shaped S–N/F–S structures is much less than in the layer-on-layer weak link [34], the F layer still considerably affects the transport superconducting coherence properties. The effective spin polarization is induced into the N layer due to the relatively large spin diffusion length in Cu (\( \lambda_N = 1 \mu\text{m at } 1 \text{ K} [35] \)) in comparison to the dimensions of the Cu strip in the weak link (figure 1). A mechanism of the supercurrent suppression in such systems has already been proposed in theoretical works [29, 30] and it is related to the modification of equilibrium spectral functions by their shifting with the effective exchange energy or Zeeman field \( h \) in comparison with the normal metal case.

The main result of our experiment on the planar S–N/F–S Josephson junction with the ferromagnetic injector is shown in figures 3(a) and (b). Figure 3(a) represents the dependence of the superconducting critical current versus the injection current. The current–voltage (I–V) characteristics of the crosslike S–N/F–S junction were measured for different values of the injection current \( I_{\text{inj}} \) across the junction (inset in figure 3(a) and figure 3(b)). For determination of the critical current \( I_c \) we use \( V = R_n \sqrt{I^2 - I_c^2} \) 1–V curve fitting and the averaging of several current–voltage characteristic measurements at each value of the \( I_{\text{inj}} \). \( R_n \) is the normal state resistance of the weak link. This is applicable in our case even though we take into account effects of thermal fluctuations and electromagnetic noise on the decay of the Josephson state [36], since the activation parameter \( \gamma = 2E_J/k_BT \) for our structures is greater than 10 and electromagnetic noise is effectively filtered. Here \( E_J \) is the Josephson energy and \( k_B \) is the Boltzmann constant. One can see a clear nonmonotonic dependence of the critical current versus the injection current. The inset in figure 3(b) shows the dependence of voltage across the junction versus the injection current at zero bias current. It is seen that the resistive state characteristics do not depend on the injection current sign.

Generally, the \( I_c(I_{\text{inj}}) \) dependence manifests the critical current decrease with the increase in the injection current and two local dips at \( I_{\text{inj}(1)} = 0.25 \) \( \mu \)A and \( I_{\text{inj}(2)} = 1.4 \) \( \mu \)A. We suppose that the observed behavior is due to transitions between 0- and \( \pi \)-states at node values \( I_{\text{inj}(1)} \) and \( I_{\text{inj}(2)} \). As noted above, it was predicted that the different types of Josephson junctions with a complex N/F weak link can be in the \( \pi \)-state even in equilibrium conditions [20], however, the \( \pi \)-state is also possible.

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**Figure 2.** Temperature dependencies of the critical current \( I_c \) for the Al–Cu–Al (blue circles) and Al–Cu/Fe–Al (black triangles) Josephson junctions together with the fits (solid lines) described in the discussion.

**Figure 3.** (a) Critical current \( I_c \) of the crosslike Al–Cu/Fe–Al S1 junction as a function of the injection current \( I_{\text{inj}} \) across the junction at \( T = 0.3 \) K. Inset: Voltage vs current of the Al–Cu/Fe–Al S1 junction for selected values of the injection current \( I_{\text{inj}} = 0 \) (black symbols), \( I_{\text{inj}} = 1 \) \( \mu \)A (open symbols), \( I_{\text{inj}} = 1.7 \) \( \mu \)A (red symbols), the black line corresponds to the Al–Cu/Fe–Al S2 junction with the thickness of the Cu layer 30 nm. (b) The color-scaled voltage drop \( V \) as a function of injection current \( I_{\text{inj}} \) and bias current \( I \) of the Al–Cu/Fe–Al S1 junction. Inset: voltage vs injection current of the Al–Cu/Fe–Al S1 junction at zero bias current.
in controllable SNS systems with non-equilibrium electron distribution due to current injection [26]. In our work, we combine both approaches.

3. Discussion

3.1. Quasiparticle distribution in the interlayer

We associate the mechanism of the \( \pi \)-state formation with the redistribution in occupied fractions of positive and negative supercurrent-carrying density of states (SCDOS) [26, 29, 30, 32]. For the case under consideration an effective exchange field is induced in the normal layer due to the proximity with the ferromagnet [20]. It provides more complicated SCDOS in the interlayer than for the case of a conventional S/N/S Josephson junction (see detailed discussion below). In its turn this richer structure of SCDOS makes the Josephson current more sensitive to the spin redistribution allowing for observation of the double-transition behavior.

At first we describe the nonequilibrium quasiparticle distribution, which is formed in the normal part of the interlayer due to the current injection from the ferromagnet in our system depicted in figure 1. For simplicity, we suppose that no transverse current enters into the superconducting banks of the junction (since the low energy process taking place at energies much less than the superconducting gap of aluminum \( \Delta = 180 \mu \text{eV} \) is considered, and, apart from this, the \( S \) parts are shifted away from the \( F \) part and have no intersection with it). We can consider our crosslike N/F system as F/N/F spin valve in parallel configuration (figure 4) since the main part of the injection current flows through the N layer, as it was noted above.

The quasiparticle distribution in the \( F \) layers can be described in terms of the different electrochemical potentials \( \mu_{\sigma, F} \) [37], while for the \( N \) layer such description is inappropriate because the \( N \) layer length \( L \) is shorter than all the inelastic relaxation lengths \( \lambda_{0} = 1 \mu \text{m} [35], L_{0} = 1.2 \mu \text{m} [38] \) and the Fermi distribution is not formed here. The spin relaxation length for Cu greatly exceeds the \( N \) layer length \( L = 200 \text{ nm} \), as it was noted above. Therefore, the spin relaxation term can also be neglected in the kinetic equation [25], which can be written for the distribution function \( \varphi_{\sigma} \) for the spin subbands separately and takes the form:

\[
\partial_{t}^{2} \varphi_{\sigma} = 0. \tag{1}
\]

This equation should be supplemented by the Kuprianov-Lukichev boundary conditions [39] at \( x = 0, L \):

\[
\partial_{x} \varphi_{\sigma} \bigg|_{x=0,L} = \frac{G_{\sigma}}{\sigma_{N}} \left( \tanh \frac{\varepsilon - \mu_{\sigma, F}^{L}(x = 0, L)}{2T} - \varphi_{\sigma} \right), \tag{2}
\]

where \( \mu_{\sigma, F}^{L}(x = 0, L) \) are electrochemical potentials for left (right) ferromagnets at the F/N interfaces, respectively, and \( G_{\sigma} \) is the conductance of F/N interfaces for the spin subband \( \sigma \). The solution of equations (1) and (2) takes the form:

\[
\varphi_{\sigma} = \frac{1}{2} \left( \tanh \frac{\varepsilon - \mu_{\sigma, F}^{L}(x = 0, L)}{2T} + \tanh \frac{\varepsilon - \mu_{\sigma, F}^{R}(x = 0, L)}{2T} \right) + \frac{G_{\sigma}}{2\sigma_{N}(1 + \frac{\varepsilon - \mu_{\sigma, F}^{L}(x = 0, L)}{2T})} \left( \tanh \frac{\varepsilon - \mu_{\sigma, F}^{R}(x = 0, L)}{2T} - \tanh \frac{\varepsilon - \mu_{\sigma, F}^{L}(x = 0, L)}{2T} \right), \tag{3}
\]

where \( \mu_{\sigma, F}^{L} \) and \( \mu_{\sigma, F}^{R} \) are taken at the corresponding N/F interfaces. For the case under consideration an effect was obtained when \( \mu_{\sigma, F}^{R} \) is at the level of \( \mu_{\sigma, F}^{L} \), which can be written for the distribution function. The direction of the injection current flow is indicated by arrows.

We use the expression for the distribution allowing for observation of the double-transition behavior.

\[
\varphi_{\sigma} = \frac{1}{2} \left( \tanh \frac{\varepsilon - \mu_{\sigma}^{L}}{2T} + \tanh \frac{\varepsilon - \mu_{\sigma}^{R}}{2T} \right) + \frac{G_{\sigma}}{2\sigma_{N}(1 + \frac{\varepsilon - \mu_{\sigma}^{L}}{2T})} \left( \tanh \frac{\varepsilon - \mu_{\sigma}^{R}}{2T} - \tanh \frac{\varepsilon - \mu_{\sigma}^{L}}{2T} \right), \tag{3}
\]

where \( \sigma \) is the spin subband index, \( \sigma = \pm \) for the up (down) subbands, respectively. Constants \( A, C \) and \( D \) are found to be from the condition of the continuity of the electric current at the N/F interfaces for each of the spin subbands separately. The electric currents \( j_{\sigma} \) in the ferromagnets can be calculated as \( j_{\sigma} = (\sigma \phi / e) \partial_{x} \mu_{\sigma} \), while in the normal interlayer it should be calculated according to:

\[
j_{\sigma}^{N} = \frac{\sigma_{N}}{4e} \int_{-\infty}^{\infty} d\varepsilon \partial_{x} \varphi_{\sigma}(\varepsilon). \tag{6}
\]

Then the condition \( j_{\sigma}^{F} = j_{\sigma}^{N} \) at \( x = 0, L \) gives us constants \( A, C \) and \( D = -C \), and the electrochemical potentials \( \mu_{\sigma}^{L} (x = 0) \) and \( \mu_{\sigma}^{R} (x = L) \) entering equation (3) take the form:

\[
\mu_{\sigma}^{L} \equiv \mu_{\sigma} = \frac{j_{\sigma}^{L}}{1 - \kappa_{\sigma}}, \quad \mu_{\sigma}^{R} = -\mu_{\sigma} = -\mu_{\sigma}, \tag{7}
\]
Below we describe the calculations of a supercurrent in the S–N/F–S contact. We consider S as an ordinary superconductor in equilibrium with the superconducting gap $\Delta$, complex N/F weak link as a normal metal with non-equilibrium distribution and Zeeman splitting $h$ and the depairing parameter $\Gamma$. The latter parameter accounts for the leakage of the superconducting correlations into the ferromagnet and depairing there [43]. $d$ is the length of the N/F area (the distance between superconducting banks), $G_{\text{SF}}$ is the specific conductance of the S–N/F boundaries, $R_{\text{SF}}$ is the normal state resistance of the N/F area, $\sigma_{\text{NF}}$ is the conductivity and $D_{\text{NF}}$ is the diffusion coefficient. The calculation is performed in the framework of Usadel equations for Green’s functions in the Keldysh technique. We linearize the Usadel equation in the interlayer region assuming that the S–N/F interfaces are low transparent. The assumption works quite well as it is indicated by further numerical estimates of the interface transparency. The critical current can be expressed via the SCDOS and the distribution function as follows:

\[ J_{c,\sigma} = \frac{d}{8\varepsilon R_{\text{NF}}} \int_{-\infty}^{\infty} d\varepsilon \sum_{\sigma} (\varphi_{\sigma}(\varepsilon) + \varphi_{\sigma}(\varepsilon)) \text{Im}[J_{\varepsilon,\sigma}], \]

where $\text{Im}[J_{\varepsilon,\sigma}]$ is the SCDOS for a given spin subband with

\[ J_{\varepsilon,\sigma} = \frac{(G_{\text{SF}}/\sigma_{\text{NF}})^2 (k_{\text{B}}T)^2 - 1}{\lambda_{\sigma} (\sinh(\lambda_{\sigma} d) + 2 G_{\text{SF}} \sigma_{\text{NF}} \cosh(\lambda_{\sigma} d)).} \]

In general, $\varphi_{\sigma}(\varepsilon) = -\varphi_{-\sigma}(-\varepsilon)$. In our case, due to the antisymmetry of the distribution function this leads to $\varphi_{\sigma}(\varepsilon) + \varphi_{\sigma}(\varepsilon) = \varphi_{\sigma}(\varepsilon) + \varphi_{\sigma}(\varepsilon)$, i.e. the effective quasiparticle distribution, which "occupies" the SCDOS in equation (9), does not depend on spin. Therefore, only the energy nonequilibrium quasiparticle mode $f_{\varepsilon}$ is relevant for the current situation. We can introduce the spin-independent SCDOS $J_c = \text{Im}J_{\varepsilon,\uparrow} + \text{Im}J_{\varepsilon,\downarrow}$ and then

\[ j_c = \frac{d}{8\varepsilon R_{\text{NF}}} \int_{-\infty}^{\infty} d\varepsilon (\varphi_{\varepsilon}(\varepsilon) + \varphi_{\varepsilon}(\varepsilon)) J_{\varepsilon}, \]

where

\[ \lambda_{\sigma} = \sqrt{-2 i (\varepsilon + \sigma h + \Gamma^2)/D_{\text{NF}}}. \]

The SCDOS corresponding to the parameters of the Al–Cu–Al and Al–Cu/Fe–Al junctions are shown in figures 6(a) and (d). The plots correspond to the parameters $G = G_{\text{SF}}/\sigma_{\text{NF}} = 0.13$, $d = 1.76\xi_0$, and several values of $h$ and $\Gamma$, where $\xi_0 = \sqrt{D_{\text{NF}}/\Delta} \approx 190$ nm. These parameters are found by fitting the experimental data presented in figure 2. $d$ is an effective length of the normal interlayer, it does not exactly coincide with the actual length of the Cu region because the Cu regions underneath the Al leads and Cu regions between the Al leads and the Fe strip are partially proximitized by the Al superconductivity. Fitting is carried out using equation (11). We take $\varphi_{\varepsilon} = \varphi_{\varepsilon} = \tanh(\varepsilon/2T)$, that is the Fermi distribution function, because data in figure 2 are

\[ \text{Figure 5. Characteristic form of the distribution function plotted according to the first spatially constant term of equation (3).} \]
related to the case without the injection. At first, we fit the temperature dependence of the critical current for Al–Cu–Al junction and obtain parameters $G$ and $d$. Then from the data for Al–Cu/Fe–Al the parameters $\Gamma$ and $h$ are obtained.

Figures 6(b) and (c) are aimed to demonstrate how the SCDOS evolves from the normal interlayer shown in figure 6(a) upon increase of the exchange field $h$. SCDOS for the Al–Cu–Al junction (figure 6(a)) manifests standard characteristic features at energies $\epsilon = 0, \pm \Delta$. In the presence of $h$ the zero-energy feature splits into two features at $\epsilon = \pm h$. When $h$ becomes larger than $\Delta$, positions of the features are still located at $\pm h, \pm \Delta$, but the SCDOS near the coherent peak changes sign. Also some additional small oscillation arise. The parameter $\Gamma$ acts as magnetic impurities and results in smearing of the SCDOS (figure 6(d)).

The SCDOS for the N/F interlayer (figure 6(d)) should be compared to the SCDOS for a usual N interlayer corresponding to $h = 0, \Gamma = 0$ (figure 6(a)), but for the unaltered other parameters. It is seen that the SCDOS is a sign changing function. This is the reason for providing the possibility for 0–$\pi$ transitions driven by an external parameter controlling the quasiparticle distribution because the distribution function $\varphi^\uparrow(\epsilon) + \varphi^\downarrow(\epsilon)$ is always positive for $\epsilon > 0$. For the case of only one zero-crossing point at $\epsilon > 0$, as it takes place for the SCDOS in the N interlayer (figure 6(a)), no more than one 0–$\pi$ transition driven by injection, which results in the double-step or overheated quasiparticle distribution, is possible. This situation has been realized experimentally [26]. On the contrary, the SCDOS for our system manifests two zero-crossing points at $\epsilon > 0$ due to the Zeeman splitting. They are located at $\epsilon \approx \Delta, h$. This results in the possibility of two 0–$\pi$ transitions driven by injection.

The evolution of the distribution modes $f_L$ and $f_{L3}$ upon increasing of the injection current is presented in figures 7(a),b, respectively. As it was discussed above for the problem under consideration, the critical current is only determined by $f_L$. At zero temperature it manifests a four-step structure as a function of energy. The steps occur at $\epsilon = \pm \mu_L, \pm \mu_L$. According to equation (5), the electrochemical potentials are proportional to the injection current $j$. Therefore, $\mu_{\downarrow, \uparrow} = \alpha_{\downarrow, \uparrow} J_{\text{inj}}$, where taking the parameters of our F/N/F structure $(\sigma_p^\downarrow - \sigma_p^\uparrow)/\sigma_p = 0.45$ [44, 45], $G_{NF} = G_T + G_1 = 0.15 \sigma_{NF}, (G_T - G_1)/G_{NF} = 0.2$, $\lambda_E = 8.5$ nm [46] we obtain $\alpha_{\downarrow} = 1.549 \Delta (\mu/\mu_A)^{-1} = 279$ eV A$^{-1}$ and $\alpha_{\uparrow} = 1.563 \Delta (\mu/\mu_A)^{-1} = 281$ eV A$^{-1}$. It is seen that $\mu_{\downarrow}$ and $\mu_{\uparrow}$ are very close for the particular parameters of the structure. As a result, the spin-energy mode $f_{L3}$ is rather small here, as it is demonstrated in figure 7(b) and the four-step structure is very close to the double-step structure even at $T = 0$. Due to nonzero temperatures this step structure is smeared. The temperature smearing is further increased because of the Joule heating by the injection current, which is modelled by $T \rightarrow T + \beta J_{\text{inj}}^2$ with $\beta = 0.5 K (\mu/\mu_A)^{-2}$. Parameters $G_{NF}$ and $\beta$ are obtained by fitting experimental results presented in figure 3 by using equations (3), (7) and (11).

As it is seen from figure 7(a), upon increasing the injection current the quasiparticles are redistributed to higher energies.

Figure 6. Evolution of the spin-independent SCDOS according to equation(10). (a) SCDOS for a normal interlayer of the Al–Cu–Al junction; (b) and (c) SCDOS for the N/F interlayers corresponding to intermediate values of $h$ and $\Gamma$ between (a) and (d); (d) SCDOS for the N/F interlayer of the Al–Cu/Fe–Al junction. $h$ and $\Gamma$ are indicated in the corresponding panels in units of $\Delta, d = 1.76 \xi_0$ and $G_{SF}/\xi_0/\sigma_N = 0.13$ for all the panels.

This leads to gradual turning off of the low-energy parts of the SCDOS. Therefore, the main part of the SCDOS contributing to the critical current changes sign upon increasing the
Figure 7. Quasiparticle distribution: nonequilibrium modes (a) $f_L = (\phi_\uparrow + \phi_\downarrow)/2$ and (b) $f_{L,3} = (\phi_\uparrow - \phi_\downarrow)/2$ calculated for the current experiment. $(\sigma_\uparrow - \sigma_\downarrow)/\sigma_0 = 0.45$, $G_{NF} = G_\uparrow + G_\downarrow = 0.15 G_{SF}$, $(G_\uparrow - G_\downarrow)/G_{NF} = 0.2$. $T = 0.3$ K, $\beta = 0.5$ K ($\mu$A)$^{-2}$.

Figure 8. Critical current of the S–N/F–S Josephson junction calculated as a function of the injection current. The parameters of the junction correspond to SCOS shown in figure 6(b) and the distribution function presented in figure 7.

4. Conclusion

To conclude, we have studied experimentally the Josephson effect in the crosslike S–N/F–S junctions driven in nonequilibrium by applying an injection current across the complex weak link. The superconducting critical current upon increasing the injection current manifests the nonmonotonic behavior with two pronounced dips, which are supposed to be due to the double 0–$\pi$ transition. We ascribe this effect to the appearance of two zero-crossing points in the supercurrent-carrying density of states (SCDOS) caused by the Zeeman splitting of the superconducting correlations in the N/F interlayer. The model taking into account SCDS of a S–N/F–S structure and spin injection into the N layer is developed to describe the observed effect. It has been concluded that the nonequilibrium in our case is not thermal, mainly described by the energy mode with a small amount of the spin-energy nonequilibrium mode without a contamination of charge and spin imbalance. Thus, we have shown that the Zeeman splitting due to N/F proximity has provided the origin of two nodes of the alternating SCDS, which is practically impossible to realize in simple SNS structures without the F-sublayers used in the pioneering works [26, 27]. In our particular case, the spin-energy mode turned out to be negligible. To demonstrate the spin-energy mode manifestations, it is necessary that the distribution function has a spin splitting (i.e. the difference between $\mu_\uparrow$ and $\mu_\downarrow$ curves in figure 5) significantly exceeding its temperature smearing. Our consideration can be applied for a general situation with the step-like distribution function by fabricating an appropriate structure and further temperature decrease, which, in particular, can be used for determination of the effective exchange field of the hybrid S–N–F structures with different transparency of interfaces.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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