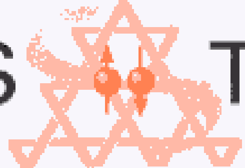
TOWARDS THE CONTROLLABLE QUANTUM STATES



Mesoscopic Superconductivity and Spintronics

Editors
Hideaki Takayanagi
Junsaku Nitta

Atsugi, Kanagawa, Japan 4 – 8 March 2002

TOWARDS THE CONTROLLABLE QUANTUM STATES

Mesoscopic Superconductivity and Spintronics

Editors

Hideaki Takayanagi
Junsaku Nitta
NTT Basic Research Labs, Kanagawa, Japan

World Scientific
New Jersey • London • Singapore • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: Suite 202, 1060 Main Street, River Edge, NJ 07661
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

TOWARD THE CONTROLLABLE QUANTUM STATES
Proceedings of the International Symposium on Mesoscopic Superconductivity and Spintronics (MS+S2002)

ISBN 981-238-169-4

Printed by FuIsland Offset Printing (S) Pte Ltd, Singapore

TOWARDS THE
CONTROLLABLE
QUANTUM STATES

Mesoscopic Superconductivity
and Spintronics

The realizations of physical systems whose quantum states can be directly manipulated have been pursued for experiments on fundamental problems in quantum mechanics and implementations of quantum information devices. Micro-fabricated superconducting systems and electronic spins are among the most promising candidates. This book contains the newest and most advanced research reports on such materials, called "Mesoscopic Superconductivity" and "Spintronics." The former includes superconductor-semiconductor hybrid systems, very small Josephson junctions, and micron-size SQUIDs. The latter includes the control of spin transports in semiconductor heterostructures, nano-scale quantum dots, and spin injections. Superconductor-ferromagnetic metal hybrid structures are covered by both of the topics.

World Scientific
www.worldscientific.com
5104 hc

ISBN 981-238-169-4
9 789812 381699

MECHANISMS OF 0 - π TRANSITION AND CURRENT-PHASE RELATIONS IN SFS JOSEPHSON JUNCTIONS

A. A. GOLUBOV

Department of Applied Physics, University of Twente, P.O.Box 217, 7500 AE Enschede, The Netherlands
E-mail: a.golubov@tn.utwente.nl

M. Y. KUPRIYANOV

Nuclear Physics Institute, Moscow State University, 119899 Moscow, Russia
E-mail: mkupr@pn.sinp.msu.ru

Y. V. FOMINOV

Department of Applied Physics, University of Twente, P.O.Box 217, 7500 AE Enschede, The Netherlands
and L. D. Landau Institute for Theoretical Physics RAS, 117940 Moscow, Russia
E-mail: fominov@landau.ac.ru

Quantitative theory of the Josephson effect in SFIFS junctions (S denotes bulk superconductor, F — metallic ferromagnet, I — insulating barrier) is presented in the dirty limit. Fully self-consistent numerical procedure is employed to solve the Usadel equations at arbitrary values of the F-layers thicknesses, magnetizations, and interface parameters. Various types of the current–phase relation $I(\varphi)$ in superconductor–ferromagnet–superconductor (SFS) point contacts and planar double-barrier junctions are studied within the quasiclassical theory in the limit of thin diffusive ferromagnetic interlayers. The physical mechanisms leading to highly nontrivial $I(\varphi)$ dependence are identified by studying the spectral supercurrent density. These mechanisms are also responsible for the 0–π transition in SFS Josephson junctions.

1 Introduction

Josephson structures involving ferromagnets as weak link material are presently a subject of intensive study. The possibility of the so-called π-state (characterized by the negative sign of the critical current I_C) in SFS (S denotes bulk superconductor, F - ferromagnet) Josephson junctions was predicted theoretically in [1,2,3,4,5,6,7,8] within different models. The first experimental observation of the crossover from 0- to π-state was reported in [9] and explained in terms of temperature-dependent spatial oscillations of induced superconducting ordering in the metallic F layer. Oscillations of the proximity induced density of states and supercurrent in SIFS junctions as a function of F-layer thickness were observed in [10].

Many other novel phenomena are possible in S/F hybrid structures, in particular in junctions with more than one magnetically ordered layers or in structures with constricted geometry. The enhancement of the Josephson critical current by the exchange field in SFIFS junctions (I is insulating barrier) for antiparallel magnetization directions was predicted in [11,12,13] and the crossover to the π-state was predicted in [12] for the parallel case even in the absence of order parameter oscillations in thin F layers. Still physical explanation of these effects and accurate calculation of their magnitude have not been given so far. Further, interesting modifications of current-phase relation $I_S(\varphi)$ are possible in structures with metallic ferromagnets which have not been fully explored yet.

In the present paper we we give a summary of quantitative theory of the Josephson effect in SFS structures in the dirty limit. Several practically interesting cases are considered: (1) low transparent insulating barrier I is placed into F region (SFIFS junction), (2) SFS junction has a planar or point contact geometry and SF interfaces have finite (but not small) transparency (SIFIS structure). Fully self-consistent numerical procedure is employed to solve the Usadel equations at arbitrary values of the F-layers thicknesses, magnetizations, and interface parameters.

For SFIFS structures with antiparallel magnetizations of F layers the effect of the critical current I_c enhancement by the exchange field H is demonstrated while in the case of parallel magnetizations the junction exhibits the transition to the π-state. In the limit of thin F layers, we study these peculiarities of the critical current analytically and explain them qualitatively; the scenario of the 0-π transition in our case differs from those studied before. The effect of switching between 0 and π states is demonstrated.

For SFS structures with transparent interfaces the anomalous current-phase relation $I_S(\varphi)$ is predicted. We show that in planar geometry the maximum of $I_S(\varphi)$ is shifted to $0 < \varphi < \pi/2$. Even stronger modifications of $I_S(\varphi)$ take place in the point contact geometry where $I_S(\varphi)$ changes sign at a certain value of phase difference j in the range between 0 and π. As a result, the junction is in a superposition of 0- and π-states. We discuss separately the cases of ballistic and diffusive point contact and formulate the criteria for observation of $I_S(\varphi)$ anomalies in terms of an exchange field magnitude and parameters of the FS interfaces.

The spectral supercurrent, $ImJ_S(E)$, and the local densities of states (DoS) in F layers are studied by analytical continuation from Matsubara frequencies to the real energy E. This allows one to identify the physical mechanisms of the above effects in terms of splitting of Andreev bound states in a junction by an exchange field. In particular, we show that zero-energy crossing of Andreev bound states is responsible for $I_S(\varphi)$ sign change, which also survives averaging over distribution of transmission eigenvalues in a diffusive point contact. The logarithmic divergency of SFIFS junction I_C in antiparallel orientation is due to the shift of the peak in DoS to zero energy, similarly to the Riedel singularity of ac supercurrent in SIS tunnel junctions at the gap voltage.

2 Results and Discussion

We start with a model structure composed of two decoupled superconducting SF bilayers. We assume that the S-layers are bulk and that the dirty limit conditions are fulfilled in the S- and F-metals. For simplicity we also assume that the parameters of the SF interfaces γ and γ_B obey the condition

$$\gamma \ll \max(1, \gamma_B), \gamma_B = R_B \mathcal{A}_B / \rho_F \xi_F, \quad \gamma = \rho_S \xi_S / \rho_F \xi_F, \tag{1}$$

where R_B and $\mathcal{A}_B$ are the resistance and the area of the SF interfaces; $\rho_{S(F)}$ is the resistivity of the S (F) material, and the coherence lengths are related to the diffusion constants $D_{S(F)}$ as $\xi_{S(F)} = \sqrt{D_{S(F)}/2\pi T_c}$, where T_c is the critical temperature of the S-material. We shall consider symmetric structure and restrict ourselves to the limit when the thickness of the F-layers is small:

$$d_F \ll \min\left(\xi_F, \sqrt{D_F/2H}\right), \tag{2}$$

where H is the exchange energy in the F-layers.

Under the condition (1) we can neglect the suppression of superconductivity in the S-electrodes by the supercurrent and the proximity effect, and reduce the problem to solving the Usadel equations [14] in the F-layers

$$\xi_F^2 \frac{\partial}{\partial x}\left[G_F^2 \frac{\partial}{\partial x}\Phi_F\right] - \frac{\widetilde{\omega}}{\pi T_c} G_F \Phi_F = 0, \tag{3}$$

with the boundary conditions at the SF interfaces ($x = \mp d_F$) in the form [15]

$$\pm\gamma_B \frac{\xi_F G_F}{\widetilde{\omega}} \frac{\partial}{\partial x}\Phi_F = G_S\left(\frac{\Phi_F}{\widetilde{\omega}} - \frac{\Phi_S}{\omega}\right), G_S = \frac{\omega}{\sqrt{\omega^2+\Delta_0^2}}, \Phi_S(\mp d_F) = \Delta_0 e^{\mp i\varphi/2}. \tag{4}$$

In the above equations the x axis is perpendicular to the interfaces with the origin at the constriction; $\omega = \pi T(2n+1)$ are Matsubara frequencies; $\widetilde{\omega} = \omega + iH$; and Δ_0 is the absolute value of the pair potential in the superconductors. The function Φ parameterizes the Usadel functions G, F, and $\bar{F}$:

$$G_F(\omega) = \frac{\widetilde{\omega}}{\sqrt{\widetilde{\omega}^2 + \Phi_F(\omega)\Phi_F^*(-\omega)}}, \quad F_F(\omega) = \frac{\Phi_F(\omega)}{\sqrt{\widetilde{\omega}^2 + \Phi_F(\omega)\Phi_F^*(-\omega)}} \tag{5}$$

and $\bar{F}_F(\omega) = F_F^*(-\omega)$. Under the condition (2) the spatial gradients in the F-layers arising due to the proximity effect and current are small. Then we can expand the solution of Eqs. (3)–(5) up to the second order in small gradients, arriving at

$$\Phi_{F1,F2} = \Phi_0 \exp(\mp i\varphi/2), \quad \Phi_0 = \Delta_0\widetilde{\omega}/W, \tag{6}$$

where

$$W = \omega + \widetilde{\omega}\gamma_{BM}\Omega, \qquad \Omega = \sqrt{\omega^2+\Delta_0^2}/\pi T_c, \gamma_{BM} = \gamma_B d_F/\xi_F, \tag{7}$$

and the indices 1, 2 refer to the left and right SF bilayers, respectively.

In order to calculate supercurrent we start with the ballistic point contact when two SF bilayers are connected by a clean constriction with transparency D (the size of the constriction a is much smaller than the mean free path l: $a \ll l$). The supercurrent is given by the general expression [16]

$$I = \frac{4\pi T}{eR_N} Im \sum_{\omega>0} \frac{(\bar{F}_1 F_2 - F_1\bar{F}_2)/2}{2 - D\left[1 - G_1G_2 - (\bar{F}_1F_2 + F_1\bar{F}_2)/2\right]}, \tag{8}$$

where R_N is the normal-state resistance of the junction. Inserting Eq. (6) in this expression we obtain

$$I = \frac{2\pi T}{eR_N} Re \sum_{\omega>0} \frac{\Delta_0^2 \sin\varphi}{W^2 + \Delta_0^2\left[1 - D\sin^2(\varphi/2)\right]}. \tag{9}$$

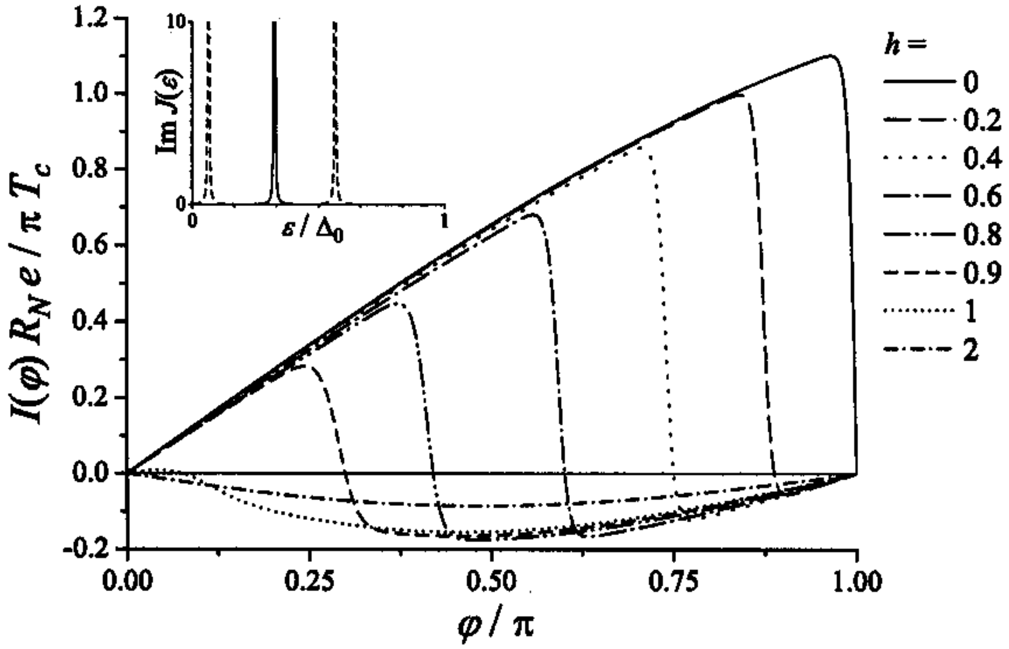


Figure 1. Current–phase relation in clean SFcFS junction with ideally transparent constriction ($D = 1$) at $T/T_c = 0.01$, $\gamma_{BM} = 1$ for different values of the normalized exchange field h. Inset: spectral supercurrent density at $\varphi = 2\pi/3$ for $h = 0$ (solid line) and $h = 0.4$ (dashed line).

At small ω the function $I(\varphi)$ changes its sign at finite phase difference $\varphi_c = 2\arcsin\sqrt{[1-(\gamma_{BM}h)^2]/D}$ if the exchange field is in the range $1 - D < (\gamma_{BM}h)^2 < 1$; here h is the normalized exchange field, $h = H/\pi T_c$. The results for $I(\varphi)$ are shown in Figs.1,2 and can be understood by considering the spectral supercurrent density $ImJ(\varepsilon)$. The latter is obtained by the analytical continuation in Eq. (9) and is given by a sum of delta-functions $\delta(\varepsilon - E_B)$ where E_B are energies of the Andreev bound states. At $\gamma_{BM} = 0$ the well-known result $E_B = \pm\Delta_0\sqrt{1 - D\sin^2(\varphi/2)}$ is reproduced, while at finite γ_{BM} the exchange field split each bound state into two (see inset in Fig.1). At $\varphi = \varphi_c$ one of these split (positive) peaks crosses zero leaving the domain $\varepsilon > 0$, and simultaneously a negative peak moves from the region $\varepsilon < 0$ into $\varepsilon > 0$ reversing the sign of the supercurrent.

The sign-reversal of the supercurrent (the 0–π transition) can be also achieved at *fixed* H due to nonequilibrium population of levels. This phenomenon has been studied in long diffusive SNS [17,18,19] and SFS junctions [20,21].

To get the $I(\varphi)$ relation for the diffusive SFcFS point contact ($l \ll a \ll \xi_F$) we integrate $\int_0^1 \rho(D)I(D)dD$, where $I(D)$ is given by Eq. (9) for the clean case (note that $R_N \propto D^{-1}$ in this equation) and $\rho(D)$ is Dorokhov's density function [22] given by $\rho(D) = 1/2D\sqrt{1-D}$. The resulting expression coincides with the direct solution of the Usadel equations and yields $I(\varphi)$ dependencies similar to those for the clean point contact, with less sharp transition from 0- to π-state [23].

We have also studied a double-barrier SIFIS junction (I denotes an insulating barrier) — this structure is easier for experimental implementation than an SFcFS junction. The current-phase relation and spectral supercurrent was calculated by

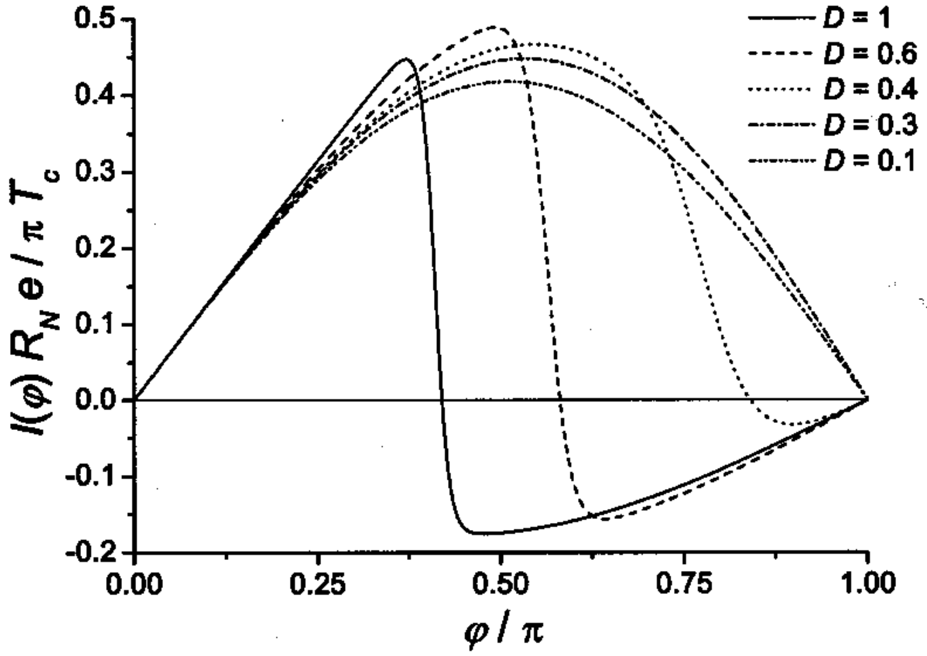


Figure 2. Current–phase relation in clean SFcFS junction at $T/T_c = 0.01$, $\gamma_{BM} = 1$, $h = 0.8$ for different values of the barrier transparency D.

solving the Usadel equations [23]. In this case $I(\varphi)$ is strongly modified by finite H, especially at low temperatures. An increase of H results not only in suppression of the critical current, but also in the shift of the $I(\varphi)$ maximum from $\varphi_{\max} \approx 1.86$ at $H = 0$ to the values smaller than $\pi/2$, however the sign change of $I(\varphi)$ is not realized in SIFIS junctions. In the limit of large exchange fields, $h \gg \gamma_{BM}^{-1}$, $I(\varphi)$ returns to the sinusoidal form.

The phenomena studied in this work may be used for engineering cryoelectronic devices manipulating spin-polarized electrons and in qubit circuits.

Acknowledgments

We acknowledge stimulating discussions with J. Aarts, N.M. Chtchelkatchev, K.B. Efetov, M.V. Feigel'man, V.V. Ryazanov, and M. Siegel. The research of M.Yu.K. was supported by the Russian Ministry for Industry and Technology. Ya.V.F. acknowledges financial support from the Russian Foundation for Basic Research, project 01-02-17759, and from Forschungszentrum Jülich (Landau Scholarship).

References

1. L.N. Bulaevskii, V.V. Kuzii, and A.A. Sobyanin, Pis'ma Zh. Eksp. Teor. Phys. **25**, 314 (1977) [JETP Lett. **25**, 290 (1977)].

2. A.I. Buzdin, L.N. Bulaevskii, and S.V. Panyukov, Pis'ma Zh. Eksp. Teor. Phys. **35**, 147 (1982) [JETP Lett. **35**, 178 (1982)].
3. A.I. Buzdin, B. Vujičić, and M.Yu. Kupriyanov, Zh. Eksp. Teor. Phys. **101**, 231 (1992) [Sov. Phys. JETP **74**, 124 (1992)].
4. Y. Tanaka and S. Kashiwaya, Physica C **274**, 357 (1997).
5. L. Dobrosavljević–Grujić, R. Zikić, and Z. Radović, Physica C **331**, 254 (2000).
6. M. Fogelström, Phys. Rev. B **62**, 11812 (2000).
7. N.M. Chtchelkatchev, W. Belzig, Yu.V. Nazarov, and C. Bruder, Pis'ma Zh. Eksp. Teor. Phys. **74**, 357 (2001) [JETP Lett. **74**, 323 (2001)].
8. Yu.S. Barash and I.V. Bobkova, Phys. Rev. B **65**, 144502 (2002).
9. V.V. Ryazanov, V.A. Oboznov, A.Yu. Rusanov, A.V. Veretennikov, A.A. Golubov, and J. Aarts, Phys. Rev. Lett. **86**, 2427 (2001).
10. T. Kontos, M. Aprili, J. Lesueur *et al.*, Phys. Rev. Lett. **86**, 304 (2001); preprint cond-mat/0201104.
11. F.S. Bergeret, A.F. Volkov, and K.B. Efetov, Phys. Rev. Lett. **86**, 3140 (2001).
12. V.N. Krivoruchko and E.A. Koshina, Phys. Rev. B **63**, 224515 (2001); **64**, 172511 (2001).
13. A.A. Golubov, M.Yu. Kupriyanov, and Ya.V. Fominov, Pis'ma Zh. Eksp. Teor. Phys. **75**, 223 (2002) [JETP Lett. **75**, 190 (2002)].
14. K.D. Usadel, Phys. Rev. Lett. **25**, 507 (1970).
15. M.Yu. Kupriyanov and V.F. Lukichev, Zh. Eksp. Teor. Phys. **94**, 139 (1988) [Sov. Phys. JETP **67**, 1163 (1988)].
16. A.V. Zaitsev, Zh. Eksp. Teor. Fiz. **86**, 1742 (1984) [Sov. Phys. JETP **59**, 1015 (1984)].
17. A.F. Volkov, Phys. Rev. Lett. **74**, 4730 (1995).
18. F.K. Wilhelm, G. Schön, and A.D. Zaikin, Phys. Rev. Lett. **81**, 1682 (1998).
19. J.J.A. Baselmans, A.F. Morpurgo, B.J. van Wees, and T.M. Klapwijk, Nature **397**, 43 (1999).
20. S.-K. Yip, Phys. Rev. B **62**, R6127 (2000).
21. T.T. Heikkilä, F.K. Wilhelm, and G. Schön, Europhys. Lett. **51**, 434 (2000).
22. O.N. Dorokhov, Solid State Commun. **51**, 381 (1984).
23. A.A. Golubov, M.Yu. Kupriyanov, and Ya.V. Fominov, preprint cond-mat/0204568.