PHYSICAL REVIEW B **76**, 115313 (2007)

Andreev reflection and strongly enhanced magnetoresistance oscillations in $Ga_xIn_{1-x}As/InP$ heterostructures with superconducting contacts

Igor E. Batov,[1,2,3,*] Thomas Schäpers,[2] Nikolai M. Chtchelkatchev,[4] Hilde Hardtdegen,[2] and Alexey V. Ustinov[1]

[1]*Physikalisches Institut III, Universität Erlangen-Nürnberg, Erwin-Rommel-Strasse 1, 91058 Erlangen, Germany*

[2]*Institute of Bio- and Nanosystems (IBN-1) and cni-Center of Nanoelectronic Systems for Information Technology, Research Centre Jülich GmbH, 52425 Jülich, Germany*

[3]*Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia*

[4]*L. D. Landau Institute for Theoretical Physics, Russian Academy of Sciences, 117940 Moscow, Russia*

(Received 23 April 2007; published 13 September 2007)

We study the magnetotransport in small hybrid junctions formed by high-mobility $Ga_xIn_{1-x}As/InP$ heterostructures coupled to superconducting (S) and normal metal (N) terminals. Highly transmissive superconducting contacts to a two-dimensional electron gas (2DEG) located in a $Ga_xIn_{1-x}As/InP$ heterostructure are realized by using a Au/NbN layer system. The magnetoresistance of the S/2DEG/N structures is studied as a function of dc bias current and temperature. At bias currents below a critical value, the resistance of the S/2DEG/N structures develops a strong oscillatory dependence on the magnetic field, with an amplitude of the oscillations considerably larger than that of the reference N/2DEG/N structures. The experimental results are qualitatively explained by taking into account Andreev reflection in high magnetic fields.

DOI: 10.1103/PhysRevB.76.115313 PACS number(s): 73.23.−b, 74.45.+c

I. INTRODUCTION

Mesoscopic systems consisting of superconductor/semiconductor hybrid structures have attracted considerable attention in recent years.[1–3] The carrier transport in superconductor/normal metal or superconductor/semiconductor structures can be described in the framework of Andreev reflection.[4] During an Andreev reflection process, an electron that travels from the semiconductor on a superconductor/semiconductor interface is retroreflected as a hole. Simultaneously, a Cooper pair is created on the superconductor side. A number of interesting phenomena based on Andreev reflection had been studied in the past, e.g., gate control of a Josephson supercurrent,[5,6] superconducting quantum point contacts,[7] control of the supercurrent by hot carrier injection,[8,9] and supercurrent reversal in a quantum dot.[10]

A two-dimensional electron gas (2DEG) in a semiconductor offers the advantage of ballistic transport in the semiconductor part. A fascinating regime occurs in high magnetic fields as soon as the transport across the superconductor (S)/2DEG is governed by the Landau quantization in the 2DEG.[11–16] Microscopic calculations[13–16] revealed conductance oscillations in S/2DEG junctions as a function of magnetic field. It was theoretically shown by Hoppe *et al.*[14] that the current flow along the S/2DEG interface can be described in the framework of Andreev bound states formed by electron and hole edge state excitations. At lower magnetic fields, one can view this process in a semiclassical picture, in which carrier propagation is maintained by skipping orbits of electrons and holes along the interface.[17–21] In mesoscopic S/2DEG contacts where the phase coherence is maintained during the quasiparticle propagation, the interference between electrons and Andreev-reflected holes can lead to the magnetoconductance oscillations which are based on an Aharonov-Bohm type effect.[17–20] The semiclassical theory of the charge transport through the S/2DEG interface at large filling factors was developed in Refs. 19 and 21. Apart from the orbital effects, a magnetic field can also be employed to induce Zeeman energy splitting in the 2DEG. This opens up the possibility to study spin-related effects in combination with Andreev reflection.[16,22–24]

From the experimental point of view, it is challenging to fabricate highly transmissive superconducting contacts to a 2DEG using superconductors with high critical magnetic fields.[25–27] Recently, Eroms *et al.*[28] found enhanced oscillations in the magnetoresistance of a Nb/InAs structure for magnetic fields below the critical field of Nb.

In this work, we report on the magnetotransport across a NbN/Au/2DEG interface. The choice of the NbN/Au system was motivated by our previous studies, where a Au interlayer helped to achieve a high S/2DEG interface transparency while maintaining a high critical field of the superconductor.[29] Complementary to the work of Eroms *et al.*,[28] we observe a suppression of enhanced oscillations in the magnetoresistance when a dc bias current across the junction exceeds a critical value or the temperature is increased above a critical temperature.[29] We compare our measurements of the NbN/Au/2DEG structures to those of similar structures with normal metal electrodes connected to the 2DEG. Our interpretation of the experimental findings is based on recent theoretical models describing Andreev reflection across a S/2DEG interface in the presence of a magnetic field.

II. EXPERIMENT

The strained $Ga_xIn_{1-x}As/InP$ heterostructure was grown on a semi-insulating InP substrate by using metal organic vapor phase epitaxy. Figure 1 shows the corresponding layer sequence. The 2DEG is located in the strained $Ga_{0.23}In_{0.77}As$ layer. From Shubnikov–de Haas measurements on Hall bar samples, a carrier concentration of $n=6.3\times10^{11}$ cm^{-2} and a mobility of $\mu=250\,000$ cm^2/V s were extracted at 0.3 K.

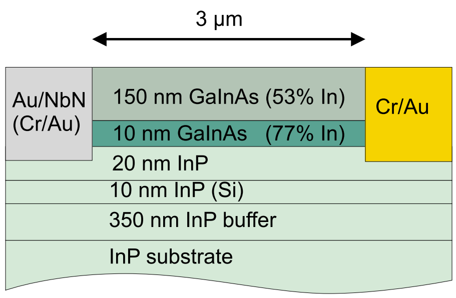

FIG. 1. (Color online) Schematics of the sample cross section. The size of the mesa is 3×3 μm^2. For the first type of structures, a superconducting Au/NbN electrode and a normally conducting Cr/Au electrode face each other. For the second sample type, two Cr/Au electrodes were used.

Analysis of the temperature-dependent Shubnikov–de Haas oscillations yielded an effective electron mass $m^*=0.036m_e$, which is in good agreement with previously reported results.[30] Based on the values given above, a transport mean free path l_{tr} of 3.3 μm and a Fermi energy E_F of 42 meV were determined.

We used a three-step electron beam lithography process to fabricate the samples. First, the mesa was defined by CH_4/H_2 reactive ion etching, using a Ti layer as an etching mask. The etching depth of 170 nm was well below the depth of the $Ga_{0.23}In_{0.77}As$ channel layer. In the second step, the superconducting electrodes (S) contacting the 2DEG at the mesa sidewalls were defined by electron beam lithography. We used Ar plasma cleaning to remove residual atoms on the surface. Subsequently, a 10 nm thin Au interlayer followed by a 100 nm thick NbN layer were deposited *in situ* by dc magnetron sputtering. After the lift-off, the sample was annealed at a temperature of 400 °C for 10 s. The Au interlayer and the annealing were introduced to improve the interface transparency.[29] By the final electron beam lithography step, the normally conductive Cr/Au electrodes (N) (5 nm/100 nm) were deposited by electron beam evaporation. Figure 1 shows a sketch of the sample cross section. The size of the 2DEG mesa was 3×3 μm^2. The S/2DEG interface length L in our samples was 3 μm. Two types of structures were prepared. In the first type (S/2DEG/N), a superconducting Au/NbN electrode and a normal conductive electrode were facing each other, whereas for the second type (N/2DEG/N), a normal conductive material (Cr/Au) was used for both electrodes.

All measurements were performed in a He-3 cryostat in a two-terminal configuration. The sample resistance was measured by employing the current-driven lock-in technique with an ac excitation current of 10 nA. In order to add an additional dc bias voltage across the sample, a dc current I_{dc} was superimposed for some measurements.

III. RESULTS AND DISCUSSION

At the magnetic fields investigated ($B<0.6$ T), the two-terminal measurements showed a positive magnetoresistance

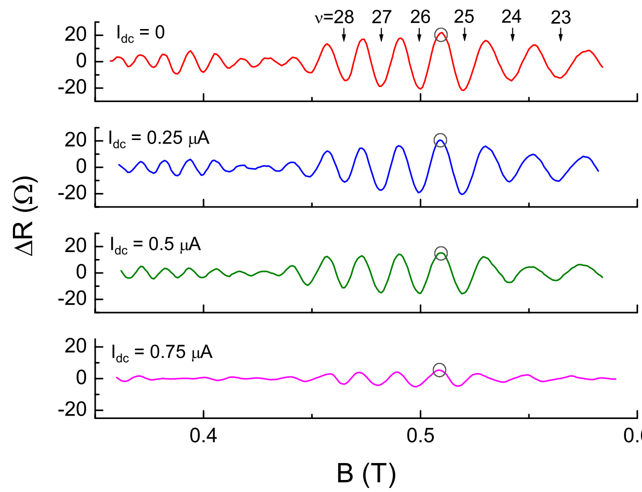

FIG. 2. (Color online) Magnetoresistance oscillations ΔR of the S/2DEG/N sample for various dc bias currents I_{dc}: 0, 0.25, 0.5, and 0.75 μA at a temperature of 0.5 K. The oscillation amplitude was extracted for Fig. 3 at the magnetic field value of 0.51 T indicated by a circle. The filling factors ν are indicated by arrows.

with superimposed oscillations in all samples.[39] In Fig. 2, we display data obtained for a S/2DEG/N structure after subtracting the slowly varying positive magnetoresistance background.[40]

At low dc bias currents, the S/2DEG/N structure reveals clear resistance oscillations as a function of magnetic field. Figure 3 shows the dependence of the amplitude of the resistance oscillations on the dc bias current at 0.51 T, extracted from the data plotted in Fig. 2. For comparison, the corresponding oscillation amplitudes for the reference N/2DEG/N sample are also shown in Fig. 3. It can be seen that within the bias current range $I_{dc}\lesssim0.5$ μA, the oscillation amplitude in the S/2DEG/N structure is substantially enhanced over that of the N/2DEG/N structure. At zero dc

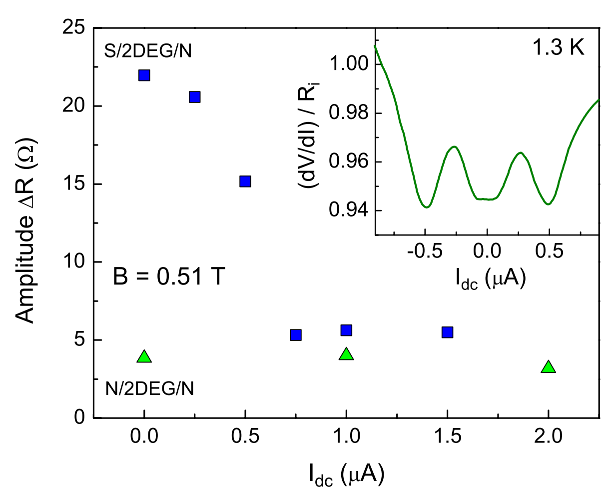

FIG. 3. (Color online) Oscillation amplitude ΔR at $B=0.51$ T as a function of the dc bias current I_{dc} for the S/2DEG/N sample (squares) and for the N/2DEG/N structure (triangles). The inset shows the normalized differential resistance $(dV/dI)/R_i$ of the S/2DEG/N structure as a function of I_{dc}.

bias current, the oscillation amplitude in the S/2DEG/N structure is larger by a factor of about 5.

The magnetoresistance oscillation amplitudes in the S/2DEG/N samples show two distinctly different regimes as a function of I_{dc}. As can be seen in Fig. 3, in the range $0 \leqslant I_{dc} < 0.75$ μA, the amplitude of the magnetoresistance oscillations ΔR decreases monotonously with increasing bias current, comprising a sharp drop for currents exceeding 0.5 μA. At currents $I_{dc} \geqslant 0.75$ μA, the amplitude of the resistance oscillations shows only a very weak bias current dependence. In strong contrast, in the N/2DEG/N reference structures, the magnetoresistance oscillation amplitude depends only weakly on the dc bias current in the whole range from zero up to 2 μA, as shown in Fig. 3.

As can be seen in the inset of Fig. 3, at low temperatures, the differential resistance $(dV/dI)/R_i$ of the S/2DEG/N sample, normalized to the resistance R_i at 1.5 μA, shows a decrease within the range of dc bias currents of ± 0.8 μA. In order to consider the contribution of the S/2DEG interface only, we subtracted the resistance of the 2DEG/N interface deduced from the N/2DEG/N reference structure. Our previous measurements of S/2DEG single junctions prepared in the same processing run revealed that the decrease in the differential resistance is related to the superconducting energy gap.[29] This suggests that the enhanced magnetoresistance oscillations detected at low dc bias currents are most likely due to the Andreev-reflection contribution to the interface conductance.

The decrease of the differential resistance at low dc bias currents indicates that the barrier at the S/2DEG interface is relatively low. A transmission coefficient $T_N=0.74$ was estimated from the ratio of the resistances at zero bias and large bias currents, following the Blonder-Tinkham-Klapwijk model.[31] The high transmission probability results from the Au layer introduced between the NbN layer and the 2DEG.[29] The finite interface barrier can be attributed partly to the Fermi velocity mismatch between the metallic layer and the 2DEG, and partly to contamination at the interface. The specific shape of the $(dV/dI)/R_i - I_{dc}$ characteristics can be associated with the presence of the Au interlayer. Due to the proximity effect between the superconducting NbN layer and the Au layer, a gap in the density of states is induced in the normal conducting Au film, resulting in the maxima in the differential resistance $(dV/dI)/R_i$ observed at approximately ± 0.27 μA.[29]

Figure 4 shows magnetoresistance oscillations of the S/2DEG/N structure at different temperatures in the 0.5–3 K range. The data are taken at zero dc bias current after subtracting the background resistance. The oscillation amplitudes are found to decrease with increasing temperature. Our experiments indicate that the magnetoresistance oscillations are very sensitive to temperature. With the assumption that the conventional effective mass approach is applicable,[32] we attempted to determine the effective mass from the temperature dependence of the oscillation amplitude. However, consistent with the results of Eroms *et al.*,[28] the fit was poor. Below we will show that the experimental temperature dependence of the oscillation amplitudes can be explained within the model of the phase-coherent transport of electrons and Andreev-reflected holes in S/2DEG junctions in a ballistic regime.[17–20]

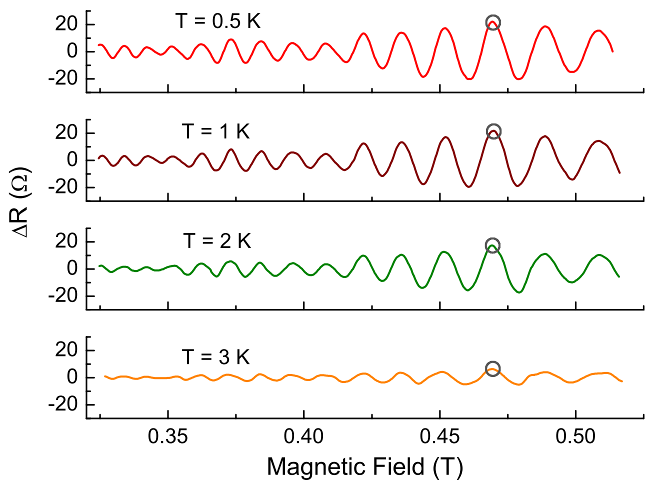

FIG. 4. (Color online) Magnetoresistance oscillations ΔR of the S/2DEG/N sample at $I_{dc}=0$ for various temperatures: 0.5, 1.0, 2.0, and 3.0 K.

The magnetoconductance of S/2DEG junctions in high magnetic fields was theoretically studied in Refs. 13–20. In Refs. 17–20, it has been shown that the magnetoconductance oscillations appear in the high-field regime in a ballistic junction when the Andreev reflection is not perfect at the interface and the diameter of the cyclotron motion of quasiparticles is smaller than the width of the junction. The mechanism of the novel magnetoconductance oscillations has been revealed in Refs. 18 and 20, based on the phenomenology of the Aharonov-Bohm type interference effect, and can be explained using a semiclassical description of a charge trans-

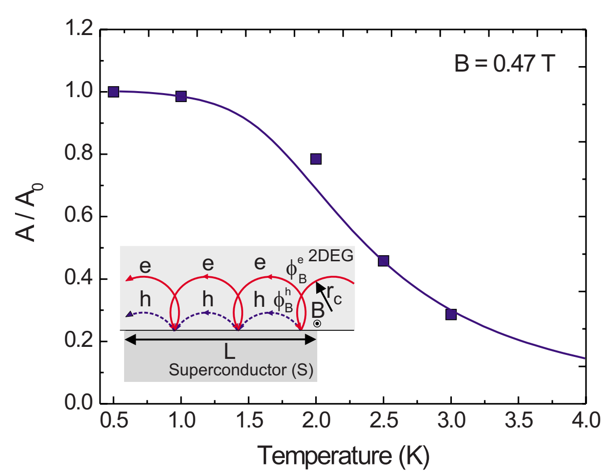

FIG. 5. (Color online) Normalized amplitude A/A_0 as a function of temperature at $B=0.47$ T (squares). Here, A_0 is the amplitude at $T=0.5$ K. The solid line represents the calculated amplitude according to Ref. 19. The inset shows the schematics of the Andreev-reflection process at S/2DEG interface, with a magnetic field applied perpendicular to the plane of the 2DEG. The electrons and holes acquire phase shifts ϕ_B^e and ϕ_B^h, respectively, between two successive Andreev reflections. The quantities r_c and L denote the cyclotron radius and the length of the S/2DEG interface, respectively.

port in the S/2DEG junction. Figure 5 (inset) illustrates a semiclassical picture for the Andreev-reflection process at a finite magnetic field. In the case of a barrier at the S/2DEG interface, an electron impinging at the interface is reflected to a certain probability as an electron or as a hole. The magnetic field forces the quasiparticles to circular motion. Due to the opposite effective mass and the inverse charge, the electron and hole orbits do have the same chirality, as shown in Fig. 5 (inset). Thus, both quasiparticles propagate in the same direction along the interface. Depending on whether an electron or a hole is Andreev reflected at the interface, a Cooper pair is formed or removed from the superconductor, respectively, resulting in a net current across the S/2DEG interface. The electron (hole) wave acquires a phase shift ϕ_B^e (ϕ_B^h) on the path between two scattering processes at the interface, due to the magnetic field, during the circular motion in the 2DEG. It has been shown that the phase difference between the pair of the waves $\phi_B^e - \phi_B^h$ is independent of the incident angle of the electron and proportional to the magnetic flux encircled by the single complete cyclotron orbit.[18,20] This results in the Aharonov-Bohm type interference of quasiparticles at the interface.[17–20] As a consequence, the zero-bias conductance oscillates as a function of magnetic flux encircled by the cyclotron orbit in units of $\phi_0 = h/e$. The magnetoconductance oscillations are periodic as a function of the inverse magnetic field.[18,20] In order to establish periodic oscillations, the length L of the S/2DEG interface must be larger than the cyclotron diameter $2r_c = 2\hbar\sqrt{2\pi n}/eB$ and smaller than the transport mean free path l_{tr}. This ensures that the quasiparticles impinge at the interface at least twice, in order to allow for interference. In our case, the largest possible cyclotron diameter is 880 nm, corresponding to the lowest magnetic field of 0.3 T considered here. In addition, the length of the S/2DEG interface L is smaller than l_{tr}. Thus, both conditions are fulfilled. Note that the theoretical analysis[17–20] presented above is not valid at very high magnetic fields when the filling factors ν are in the order of unity. In this case, the electron and hole propagation can be described in terms of Andreev edge states.[14–16] Similar to the results reported in Refs. 13 and 17–20, analytical calculations within the edge channel picture showed the pronounced magnetoconductance oscillations periodic in $1/B$ for the case of a finite barrier at the interface or a mismatch of the Fermi velocity.[14–16] The amplitude of the magnetoconductance oscillations as a function of the dc bias voltage was studied numerically in Refs. 13 and 20. It has been shown that the pronounced magnetoconductance oscillations can also be seen at the finite bias voltage $V < \Delta_0/e$. The oscillations are suppressed at $V > \Delta_0/e$, since the amplitude of the Andreev reflection is significantly reduced for $eV/\Delta_0 > 1$.

In accordance with the theoretical predictions cited above, we found pronounced oscillations in the magnetoresistance of the S/2DEG/N structure. However, a similar oscillation period in $1/B$ (Shubnikov–de Haas oscillations) is expected for the magnetoresistance of the 2DEG as well. We, therefore, have to make sure that the enhancement of oscillations observed in our experiment can, indeed, be attributed to Andreev reflection at the S/2DEG interface. The first evidence is that a considerably larger oscillation amplitude is found for the S/2DEG/N sample compared to the N/2DEG/N structure (see Fig. 3). An enhanced oscillation amplitude for the magnetoresistance of a S/2DEG structure at bias voltages V less than Δ_0/e was theoretically predicted in the case of a finite interface barrier.[13,20] As can be seen in Fig. 3, the large-amplitude oscillations are preserved up to dc bias currents $I_{dc} \sim 0.75$ μA. At bias current I_{dc} above this value, the bias voltage V exceeds the voltage Δ_0/e related to the superconducting gap energy Δ_0, as indicated by the measurement of the differential resistance. A similar behavior was found in the calculations by Asano and Kato[20] and Takagaki.[13] There, an abrupt decrease of the oscillation amplitude was observed at $eV/\Delta_0 > 1$. The experimentally observed dependence of the oscillation on the bias current is in strong contrast to the findings regarding the N/2DEG/N structure, where the oscillation amplitude remains constant for the entire range of I_{dc}.

Our interpretation is supported further by the measurements of the magnetoresistance as a function of temperature. Here, a strong decrease of the oscillation amplitude with increasing temperature was observed at temperatures below the superconducting transition temperature T_c in our samples. Based on the semiclassical model for the current transport in a ballistic S/2DEG junction,[19] we have estimated the temperature dependence of the magnetoresistance oscillation amplitudes. In the calculations, the normal and Andreev-reflection coefficients are approximated by the Blonder-Tinkham-Klapwijk model.[31] The superconducting energy gap $\Delta(T)$ in the superconductor is assumed to follow the BCS temperature dependence.[33,34] The differential conductance at zero bias $dI/dV(T)$ is evaluated by integration over energy of the spectral conductance[19,21] multiplied by the energy derivative of the Fermi distribution function. In Fig. 5, we show our calculated results of the temperature dependence of the oscillation amplitude. In the simulations, for the semiconductor region, we used parameters characteristic of our GaInAs/InP heterostructures. The interface barrier-strength parameter Z was estimated from the experimental data, and the superconducting energy gap parameter Δ_0 was chosen to adjust the experimental temperature dependence of the oscillation amplitude. The calculated results are found to be in good agreement with the experimental data for values of the Δ_0 parameter close to the superconducting energy gap in the sample measured by the differential resistance versus bias voltage characteristics. Thus, the model of the phase-coherent transport of carriers at the S/2DEG interface in strong magnetic fields[17–20] appeared to be consistent with our experimental data. In Ref. 29, we have analyzed finite temperature zero-field current-voltage characteristics of NbN/Au/GaInAs-InP junctions within a model based on the quasiclassical Green-function approach.[35–38] At present, however, the theoretical description of the conductance oscillations at a S/2DEG interface in a magnetic field based on this approach has not yet been developed.

A similar temperature behavior of the magnetoresistance was found by Eroms *et al.*[28] They attributed the enhanced oscillation amplitude to the higher backscattering contribution in the 2DEG due to the combined occupation of the edge channels by electrons and holes in the case of Andreev reflection at the interface. Giazotto *et al.*[16] studied theoretically the effect of Zeeman splitting on the Andreev reflection at the S/2DEG interface. It is predicted that the effect of Zeeman splitting should be visible as a double-step feature in the conductance of transparent S/2DEG interface. However, at magnetic fields investigated here, these corrections are small and, thus, the effect of the Zeeman splitting could not be resolved in our experiments.

IV. CONCLUSIONS

In summary, we have investigated the magnetotransport in S/2DEG/N structures at various dc bias currents and temperatures. We have found that the amplitude of oscillations of the magnetoresistance is considerably enhanced at low bias currents. The observed behavior is interpreted using the framework of phase-coherent Andreev reflection in the presence of a magnetic field.

ACKNOWLEDGMENTS

The authors thank U. Zülicke (Massey University, New Zealand), A. A. Golubov (Twente University, The Netherlands), and I. S. Burmistrov (Landau Institute, Moscow) for fruitful discussions. This work was supported by the Deutsche Forschungsgemeinschaft (DFG).

---

*Present address: Scuola Normale Superiore and NEST CNR-INFM, I-56126 Pisa, Italy; batov@issp.ac.ru

[1] B. J. van Wees and H. Takayanagi, in *Mesoscopic Electron Transport*, edited by L. L. Son *et al.* (Kluwer Academic, The Netherlands, 1997), pp. 469–501.
[2] H. Kroemer and E. Hu, in *Nanotechnology*, edited by G. L. Timp (Springer, Berlin, 1999).
[3] T. Schäpers, *Superconductor/Semiconductor Junctions*, Springer Tracts on Modern Physics Vol. 174 (Springer-Verlag, Berlin, 2001).
[4] A. F. Andreev, Zh. Eksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].
[5] H. Takayanagi and T. Kawakami, Phys. Rev. Lett. **54**, 2449 (1985).
[6] Y.-J. Doh, J. A. van Dam, A. L. Roest, E. P. A. M. Bakkers, L. P. Kouwenhoven, and S. D. Franceschi, Science **309**, 272 (2005).
[7] H. Takayanagi, T. Akazaki, and J. Nitta, Phys. Rev. Lett. **75**, 3533 (1995).
[8] A. F. Morpurgo, T. M. Klapwijk, and B. J. van Wees, Appl. Phys. Lett. **72**, 966 (1998).
[9] Th. Schäpers, J. Malindretos, K. Neurohr, S. G. Lachenmann, A. van der Hart, G. Crecelius, H. Hardtdegen, H. Lüth, and A. A. Golubov, Appl. Phys. Lett. **73**, 2348 (1998).
[10] J. A. V. Dam, Y. V. Nazarov, E. P. Bakkers, S. D. Franceschi, and L. P. Kouwenhoven, Nature (London) **442**, 667 (2006).
[11] M. Ma and A. Y. Zyuzin, Europhys. Lett. **21**, 941 (1993).
[12] M. P. A. Fisher, Phys. Rev. B **49**, 14550 (1994).
[13] Y. Takagaki, Phys. Rev. B **57**, 4009 (1998).
[14] H. Hoppe, U. Zülicke, and G. Schön, Phys. Rev. Lett. **84**, 1804 (2000).
[15] U. Zülicke, H. Hoppe, and G. Schön, Physica B **298**, 453 (2001).
[16] F. Giazotto, M. Governale, U. Zülicke, and F. Beltram, Phys. Rev. B **72**, 054518 (2005).
[17] Y. Asano, Phys. Rev. B **61**, 1732 (2000).
[18] Y. Asano and T. Yuito, Phys. Rev. B **62**, 7477 (2000).
[19] N. M. Chtchelkatchev, Pis'ma Zh. Eksp. Teor. Fiz. **73**, 100 (2001) [JETP Lett. **73**, 94 (2001)].
[20] Y. Asano and T. Kato, J. Phys. Soc. Jpn. **629**, 1125 (2000).
[21] N. M. Chtchelkatchev and I. S. Burmistrov, Phys. Rev. B **75**, 214510 (2007).
[22] E. V. Bezuglyi, A. S. Rozhavsky, I. D. Vagner, and P. Wyder, Phys. Rev. B **66**, 052508 (2002).
[23] G. Tkachov and K. Richter, Phys. Rev. B **71**, 094517 (2005).
[24] D. Frustaglia, F. Taddei, and R. Fazio, Phys. Rev. B **72**, 125321 (2005).
[25] H. Takayanagi and T. Akazaki, Physica B **249-251**, 462 (1998).
[26] D. Uhlisch, S. G. Lachenmann, Th. Schäpers, A. I. Braginski, H. Lüth, J. Appenzeller, A. A. Golubov, and A. V. Ustinov, Phys. Rev. B **61**, 12463 (2000).
[27] T. D. Moore and D. A. Williams, Phys. Rev. B **59**, 7308 (1999).
[28] J. Eroms, D. Weiss, J. De Boeck, G. Borghs, and U. Zülicke, Phys. Rev. Lett. **95**, 107001 (2005).
[29] I. E. Batov, Th. Schäpers, A. A. Golubov, and A. V. Ustinov, J. Appl. Phys. **96**, 3366 (2004).
[30] Th. Schäpers, J. Knobbe, and V. A. Guzenko, Phys. Rev. B **69**, 235323 (2004).
[31] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
[32] D. R. Hang, C.-T. Liang, C. F. Huang, Y. H. Chang, Y. F. Chen, H. X. Jiang, and J. Y. Lin, Appl. Phys. Lett. **79**, 66 (2001).
[33] J. R. Schrieffer and M. Tinkham, Rev. Mod. Phys. **71**, S313 (1999).
[34] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1996).
[35] K. Neurohr, A. A. Golubov, Th. Klocke, J. Kaufmann, Th. Schäpers, J. Appenzeller, D. Uhlisch, A. V. Ustinov, M. Hollfelder, H. Lüth, and A. I. Braginski, Phys. Rev. B **54**, 17018 (1996).
[36] A. A. Golubov and M. Yu. Kupriyanov, Physica C **259**, 27 (1996).
[37] W. Belzig, C. B. F. K. Wilhelm, G. Schön, and A. Zaikin, Superlattices Microstruct. **25**, 1251 (1999).
[38] A. A. Golubov, M. Yu. Kupriyanov, and E. Il'ichev, Rev. Mod. Phys. **76**, 411 (2004).
[39] The beating pattern of the magnetoresistance can be attributed to the presence of the Rashba effect, see, e.g., Th. Schäpers, G. Engels, J. Lange, Th. Klocke, M. Hollfelder, and H. Lüth, J. Appl. Phys. **83**, 4324 (1998).
[40] The background resistance contribution was gained by fitting a polynomial curve to selected measurement points being midway within the oscillating resistance contribution.