PHYSICAL REVIEW B VOLUME 52, NUMBER 12 15 SEPTEMBER 1995-II

Andreev reflection at the superconductor–two-dimensional-electron-gas interface by a quantum point contact

Hideaki Takayanagi and Tatsushi Akazaki
NTT Basic Research Laboratories, 3-1, Morinosato-Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

(Received 11 May 1995; revised manuscript received 30 June 1995)

Andreev reflection in a split-gate-fitted superconductor–normal-metal–superconductor junction is studied with retro property of Andreev reflection. As the normal metal, the junction uses a two-dimensional electron gas (2DEG) in a semiconductor heterostructure in the ballistic-transport regime. The differential resistance-voltage characteristics, measured as a function of gate voltage, show a clear change from current-deficit to excess-current characteristics. This change is attributed to the Andreev-reflected holes being focused on the quantum point contact defined in the 2DEG by the split gate.

It is well known that at the interface of a normal-metal (N) and a superconductor (S) there occurs Andreev reflection; that is, an electron (hole) incident from the normal-metal side is reflected as a hole (electron).[1] Andreev reflection (AR) has three interesting characteristics: the excess current, the retro property, and the phase interaction (i.e., the Andreev-reflected hole undergoes the macroscopic phase of the superconductor). We proposed a quasiparticle interferometer[2] that could be used to confirm this phase interaction experimentally and recently the quasiparticle interferometer was achieved.[3] The excess current and the retro property are related in that the Andreev-reflected hole (electron) moves back in the direction from which the incident electron (hole) came and this results in the excess current. van Son, van Kempen, and Wyder ultilized this retroreflection for studying the proximity effect at the S-N interface by using a point contact on the N side.[4] Nishino *et al.*[5] also used a coplanar-point contact and observed that the Andreev-reflection probability of the total system increased with decreasing point-contact width. These experiments also showed that Andreev reflection can be used to study the S-N system spectroscopically, and the backfocusing of hole waves in a S-N-S junction with a quantum point contact has recently been studied by computer simulation.[6]

In the work reported in this paper we experimentally evaluated the differential resistance-voltage characteristics of a superconductor–normal-metal–superconductor junction with a split gate. This kind of junction is called a superconducting quantum point contact[7,8] (SQPC) and can be used to study AR systematically.

In a SQPC the normal-metal electrodes of a quantum point contact[9,10] are replaced by superconducting electrodes, and the fabricated SQPC is shown schematically in Fig. 1(a). As the normal metal we used an InAs-inserted-channel $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure grown by molecular-beam epitaxy on an Fe-doped semi-insulating InP substrate. The details of the fabrication process are reported elsewhere.[11] The two-dimensional electron gas (2DEG) is confined in the inserted 4-nm InAs layer and has a high mobility and a high carrier concentration.[12] Two superconducting Nb electrodes are coupled with the 2DEG. The distance L between the two Nb electrodes was 0.2–0.6 μm and the width W of the electrode was 10 μm. At 4.2 K the carrier concentration N_S, the mobility μ, and the effective mass m^* of the 2DEG used in this study were determined by Shubnikov–de Haas measurement to be 2.3×10^{12} cm^{-2},

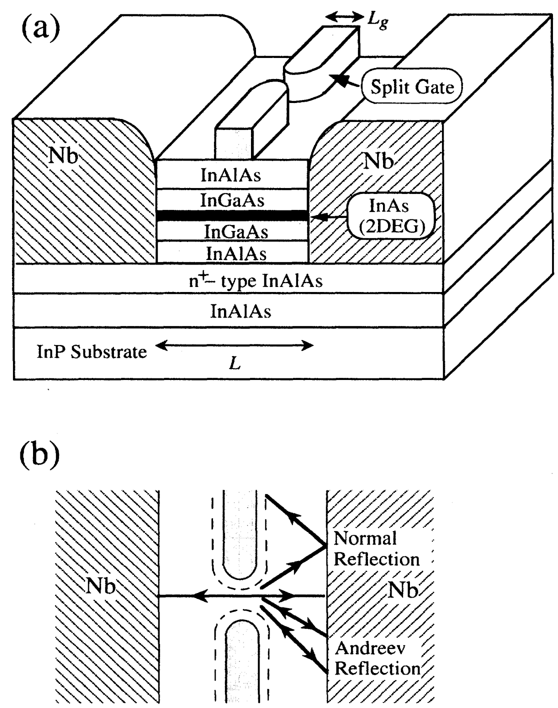

FIG. 1. Structure of a split-gated junction (SQPC). (a) Cross-sectional view. Both the normal current and the supercurrent flow through the two-dimensional electron gas (2DEG) formed in the InAs layer and are changed by gate voltage. (b) Top view. An applied gate voltage generates a depletion layer around the gate electrodes and this layer defines a constriction (a quantum point contact) in the 2DEG. The depletion boundary is shown by the dashed curves. Andreev reflection leads to the reflected holes being focused in the point contact.

111 000 cm^2/V s, and $0.045m_e$, where m_e is the free electron mass. From these values, the coherence length $\xi_N = \hbar v_F/2\pi k_B T$ in the clean limit and the mean free path l were calculated to be 0.28 μm at 4.2 K and 2.8 μm, respectively, where v_F is the Fermi velocity of the 2DEG. Therefore, the junction belongs to the clean limit ($l > \xi_N$) with ballistic transport ($l \gg L$). As shown in the figure, the junction has a split gate with a very short gate length L_g of less than 0.1 μm. This gate configuration made it possible to vary the N_S and μ of the 2DEG underneath the gate by changing gate voltage V_g. This resulted in changes in both the superconducting critical current I_C and the normal resistance R_N of the junction. When the absolute value of the applied gate voltage V_g is small, I_C and R_N show oscillations as a function of V_g (i.e., as a function of N_S).[13] This is explained by Fabry-Pérot interference of the quasiparticles.[14] When the absolute value of the applied gate voltage is large ($V_g < -1$ V), the 2DEG underneath the gate electrode is pinched off and this results in one-dimensional subbands in the constriction. It was predicted theoretically that the superconducting critical current (the maximum supercurrent) in a SQPC is quantized when the constriction works as a quantum point contact,[7,8] and this quantization as well as the quantized conductance was recently confirmed experimentally.[15] The clean-limit and ballistic-transport characteristics are essential for observing both Fabry-Pérot interference and a quantized critical current in a SQPC.

For V_g values from 0 to -1.3 V, the measured differential resistance dV/dI of the junction with $L = 0.3$ μm and $L_g = 0.08$ μm is shown in Fig. 2 as a function of the voltage across the junction V. The measured dV/dI is normalized by R_N, the resistance at $V > 2\Delta/e$ (where Δ is the gap energy of Nb), because R_N is not effected by Andreev reflection. When the supercurrent flows through the junction, extremely sharp peaks of dV/dI appear near $V=0$, and these peaks sometimes hide other dV/dI structures. Therefore, a magnetic field of about 26 G was applied to the junction to suppress the supercurrent. However, a small dip due to the small supercurrent is still evident in each dV/VI-V characteristic. It is clear in Fig. 2 that as the absolute value of V_g increases, dV/dI-V characteristics change from increasing with decreasing V to decreasing with decreasing V. That is, the I-V characteristics change from the current-deficit state to the excess-current state. Four junctions were studied and every junction showed the same change as that shown in Fig. 2.

The observed change in dV/dI-V characteristics can be explained as follows. When $V_g = 0$, the current flows through the overall 2DEG between the two Nb electrodes. The I-V characteristics or dV/dI-V characteristics for $V < 2\Delta/e$ are strongly dependent on the Nb/2DEG interface characteristics. At the interface, the electrons are either transmitted, ordinarily reflected, or Andreev reflected. When the reflected electrons and holes go back to the other electrode, the reflected electrons result in an increase of the resistance and the Andreev-reflected holes (i.e., the excess current) result in a decrease in the resistance. The dV/dI-V characteristics are determined self-consistently through these three processes, which are energy dependent. The transmission, ordinary reflection, and Andreev-reflection probability are characterized by the barrier strength $Z = H/\hbar v_F$, where H is the strength of the δ-function potential at the interface.[16] Calculation by Octavio, Tinkham, Blonder, and Klapwijk[17] (OTBK) showed that a S-N-S junction with two interfaces of $Z > 0.75$ has current-deficit characteristics and a junction with two interfaces of $Z < 0.75$ has excess-current characteristics. The dotted curve in Fig. 2 shows the calculated characteristics based on the OTBK theory[17,18] in which the I-V characteristics of a S-N-S junction were calculated by a Boltzman-equation approach and showed subharmonic gap structures due to multiple Andreev reflections (MAR's) between two S-N interfaces. In the theory all elastic scattering is assumed to occur at the S-N interface, and no energy relaxation is assumed in the N region. The studied junction satisfied these assumptions, since it belongs to the ballistic-transport regime ($l \gg L$) and as discussed later, the contract resistance is much higher than the sheet resistance of the 2DEG. Therefore, the OTBK theory can be used to analyze the experimental data for $V_g = 0$. At $V=0$ the experimental and calculated curves coincide, except for the sharp peaks measured at $V \approx \pm 0.1$ mV. These peaks are not due to the supercurrent, since the supercurrent was suppressed by a magnetic field. They grew rapidly at temperatures lower than 2 K and are thought to reflect the bound state generated in the 2DEG because of Andreev reflection. The experimentally observed details of these peaks will be reported elsewhere.[19] In the calculation $\Delta = 1.5$ meV was assumed. From the calculated results, we can evaluate $Z = 0.85$ for $V_g = 0$.

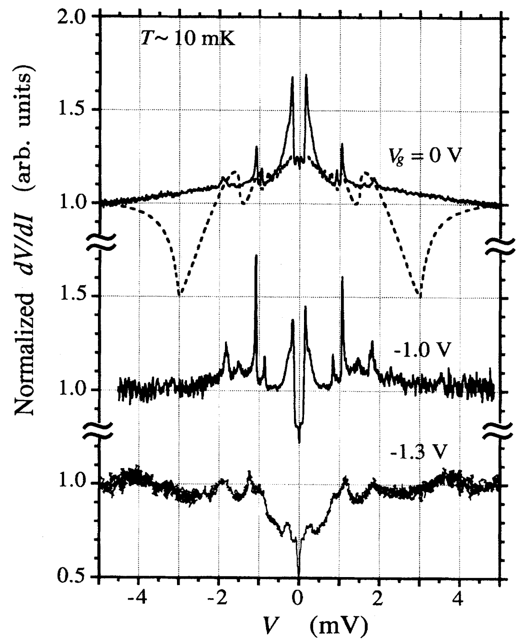

FIG. 2. Measured differential resistance-voltage (dV/dI-V) characteristics as a function of gate voltage V_g. The dV/dI is normalized by the junction normal resistance R_N and is unity at $V = \pm 5$ mV. The dotted curve represents the calculated one based on the OTBK theory.

The current-deficit characteristics of the junction for $V_g=0$ indicate that the electrical contact between 2DEG and Nb is not good from the viewpoint of normal and superconducting transport. The measured R_N for $V_g=0$ was 58.7 Ω, and the calculated sheet resistance of the 2DEG ($R_{NS}=L/eWN_S\mu$) is 0.73 Ω. Therefore the contact resistance R_{NC} of one interface is about 29 Ω. The superconducting critical current I_c of the junction was 1.2 μA at 1 K. The R_{NC} and I_c values of the junction can be compared to $R_{NC}=16$ Ω and $I_c=3.2$ μA at 1 K for the junction with the same L and W but with a Z of about 0.65.

When $V_g=-1.3$ V, the measured R_N was 1.68 kΩ and the resistance of the constriction $R_C=1.68-0.058=1.622$ kΩ, which corresponds to the resistance of 1.6133 kΩ at the eighth quantized conductance step in a quantum point contact, which shows the quantized conductance in units of $2e^2/h$.[9,10] The 2DEG underneath the gate electrode is pinched off and the current flows only through the constriction. As shown in Fig. 1(b), in this case the reflected electrons almost do not return to the constriction but the reflected holes return to it because of the retro property. The returning holes are measured as a decrease in the resistance. In Fig. 2 this can be seen in the dV/dI-V characteristics for $V_g=-1.3$ V.

In this case, R_C is dominant in the total resistance R_N and the reflected electrons, which contribute to building up the total distribution of holes traveling to the opposite direction in the OTBK theory, do not return to the constriction. Therefore, the OTBK theory can no longer be used for a S-N-S junction with a quantum point contact. To analyze such a junction we have to develop a model based on the trajectory method.[20] In a new model the elastic scattering at the interface and the disappearance of the reflected electrons should be taken into account.

In the intermediate state, between $V_g=0$ and -1.3 V, gate voltage makes a barrier underneath the gate electrode and the barrier height is determined by the gate voltage. The transmission probability of the barrier is almost the same for the electron and Andreev-reflected hole except for the case in which the energy of electron or hole at the interface is very close to the Fermi energy (in this case the transmission probability for the Andreev-reflected hole is enhanced because of so-called reflectionless tunneling[21]). Therefore, when V_g is small, for instance -0.5 V, dV/dI-V characteristics almost never change. As the asbsolute value of V_g (i.e., the barrier height) increases, the parallel conductance of the constriction gradually contributes more to the total conductance. Therefore, dV/dI-V characteristics change gradually from current-deficit to excess-current characteristics. The OTBK theory cannot be used in this case, since there is elastic scattering in the N region.

On the measured dV/dI-V characteristics for $V_g=-1.3$ V dip structures were observed at $V\approx 2\Delta/ne$ for up to $n=3$, and it is suggested by comparing the measured and calculated characteristics that these structures are due to MAR. Moreover, some sharp peaks observed on the measured dV/dI-V characteristics for $V_g=0$ and -1.0 V are also thought to be due to MAR, since their voltage positions are the same as those of the structures for $V_g=-1.3$ V. However, deep dip structures predicted theoretically are not evident for $V_g=0$ and -1.0 V. Similar dV/dI-V characteristics were also observed for other junctions. Figure 3 shows dV/dI-V characteristics for another junction. This junction also showed a clear change from the current-deficit to the excess-current state by changing the gate voltage. We cannot explain that dip structures, especially those at $2\Delta/e$, do not appear for both junctions in Figs. 2 and 3. This is not due to high value of Z for the junctions. We observed clear dip structures for a junction with $Z=0.85$ at 4.2 K,[22] and the structure of that junction was almost the same as that of the junction studied here. There are some structural differences between them, but the most important difference is that of the carrier concentration of the 2DEG, which was 3×10^{12} cm^{-2} for the previous junction and was 2.3×10^{12} cm^{-2} for the junction studied here. To explain the obtained results, some modifications to the previous theory are needed.

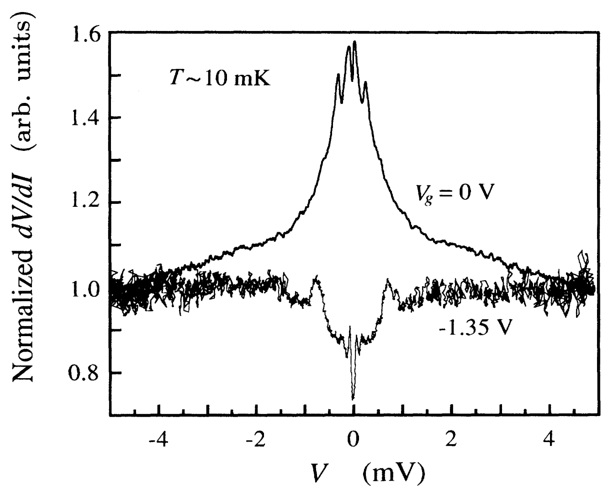

FIG. 3. Measured dV/dI-V characteristics for another junction with $L=0.3$ μm. The resistance of the constriction R_C obtained from the measured R_N for $V_g=-1.35$ V corresponds to the seventh quantized conductance step in a quantum point contact.

In conclusion, we have fabricated a superconductor–normal-metal–superconductor junction using an $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure as the normal metal. The junction has a split gate that defines a quantum point contact by applying a gate voltage. With decreasing negative gate voltage, the measured differential resistance-voltage characteristics showed a change from current-deficit to excess-current characteristics. This change results from Andreev reflection leading to focusing the Andreev-reflected holes, which can be measured as the excess current at the quantum point contact. The measurement method described here will lead to an effective spectroscopy of the S-N interface characteristics, which are very important for understanding transport in a S-N or S-N-S junction.

We thank Dr. Y. Ishii, Dr. K. Arai, and Dr. T. Enoki for discussions on the electron transport in the heterostructure, T. Ishikawa for the molecular-beam-epitaxy growth, and Professor T. M. Klapwijk, Dr. J. Nitta, and Dr. H. Nakano for discussions of Andreev reflection. We also thank Dr. T. Ikegami and Dr. N. Matsumoto for encouragement throughout this work.

[1] A. F. Andreev, Zh. Éksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].
[2] H. Nakano and H. Takayanagi, Solid State Commun. **80**, 997 (1991); Phys. Rev. B **47**, 7986 (1993).
[3] A. Dimoulas, J. P. Heida, B. J. v. Wees, T. M. Klapwijk, W. v. d. Graaf, and G. Borghs, Phys. Rev. Lett. **74**, 602 (1995).
[4] P. V. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **59**, 2226 (1987).
[5] T. Nishino, M. Hatano, H. Hasegawa, T. Kure, and F. Murai, Phys. Rev. B **41**, 7274 (1990).
[6] H. De Raedt, K. Michielsen, and T. M. Klapwijk, Phys. Rev. B **50**, 631 (1994).
[7] A. Furusaki, H. Takayanagi, and M. Tsukada, Phys. Rev. Lett. **67**, 132 (1991); Phys. Rev. B **45**, 10 563 (1992).
[8] C. W. J. Beenakker and H. van Houten, Phys. Rev. Lett. **66**, 3056 (1991).
[9] B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988).
[10] D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).
[11] H. Takayanagi and T. Akazaki, Jpn. J. Appl. Phys. (to be published).
[12] T. Akazaki, J. Nitta, H. Takayanagi, T. Enoki, and K. Arai, Appl. Phys. Lett. **65**, 1263 (1994).
[13] H. Takayanagi, T. Akazaki, and J. Nitta, Phys. Rev. B **51**, 1374 (1995); Jpn. J. Appl. Phys. **34**, 4552 (1995).
[14] A. Chrestin, T. Matsuyama, and U. Merkt, Phys. Rev. B **49**, 498 (1994).
[15] H. Takayanagi, T. Akazaki, and J. Nitta (unpublished).
[16] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
[17] M. Octavio, M. Tinkham, G. E. Blonder, and T. M. Klapwijk, Phys. Rev. B **27**, 6739 (1983).
[18] F. Flensberg, J. Bindslev Hansen, and M. Octavio, Phys. Rev. B **38**, 8707 (1988).
[19] H. Takayanagi, T. Akazaki, and H. Nakano (unpublished).
[20] T. M. Klapwijk, G. E. Blonder, and M. Tinkham, Physica **109&110B**, 1657 (1982).
[21] C. W. J. Beenakker, B. Rejaei, and J. A. Melsen, Phys. Rev. Lett. **72**, 2470 (1994).
[22] J. Nitta, T. Akazaki, H. Takayanagi, and K. Arai, Phys. Rev. B **46**, 14 286 (1992).