# Observation of Maximum Supercurrent Quantization in a Superconducting Quantum Point Contact

Hideaki Takayanagi, Tatsushi Akazaki, and Junsaku Nitta
*NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi-Shi, Kanagawa 243-01, Japan*
(Received 2 June 1995)

We have confirmed the quantization of the critical current in a superconducting quantum point contact consisting of a split-gate superconductor-(two-dimensional electron gas)-superconductor junction. The critical current and conductance show stepwise changes as a function of the gate voltage. We also observed resonant structure resulting from quantum interference of quasiparticles at the step edge.

PACS numbers: 74.80.Fp, 72.20.Jv, 74.50.+r, 74.60.Jg

Along with recent progress in nanofabrication technology, interest is increasing in the quantum transport of superconducting structures coupled with mesoscopic-scale normal metals or semiconductors [1]. In the dirty regime of the normal metal, mesoscopic fluctuations of the maximum supercurrent (the critical current $I_c$) and interaction effects associated with Anderson localization on the critical current have been confirmed experimentally [2,3]. In the clean regime of the normal metal, quantization of the critical current was predicted theoretically in a superconducting quantum point contact (SQPC) [4–6], by analogy with a quantum point contact showing quantized conductance [7,8]. Attempts to achieve a SQPC [9–11] have not yet met with success. This Letter reports on the quantization of the critical current in a SQPC consisting of a split-gate superconductor (*S*)–normal metal (*N*)–superconductor (*S*) junction using a two-dimensional electron gas (2DEG) in the semiconductor heterostructure as the normal metal.

To obtain a SQPC, we used a semiconductor $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure grown by molecular beam epitaxy on an Fe-doped semi-insulating InP substrate. Figure 1(a) shows a schematic of the fabricated SQPC. The details of the fabrication process are reported elsewhere [12]. A two-dimensional electron gas is well confined in the 4-nm-thick InAs channel and has high mobility and carrier density [13]. Two superconducting Nb electrodes are coupled with the 2DEG; both a supercurrent and a normal current flow through the 2DEG. The distance $L$ between the two Nb electrodes is 0.2–0.6 $\mu$m, and the width $W$ of the electrodes is 10 $\mu$m. As shown in the figure, the junction has a split gate with a very short gate length $L_g$ of less than 0.1 $\mu$m. This gate configuration makes it possible to vary the carrier density and mobility of the 2DEG underneath the gate by changing the gate voltage. This results in changes in both the critical current $I_c$ and the normal resistance $R_N$ of the junction.

We determined the carrier density $N_S$ to be $2.3 \times 10^{12}$ cm$^{-2}$, the mobility $\mu$ to be 111 000 cm$^2$/V s, and the effective mass $m^*$ of the 2DEG to be $0.045 m_e$ at 4.2 K by Shubnikov–de Haas measurement. Here, $m_e$ is the free electron mass. From these values, we calculated the coherence length $\xi_N = \hbar v_F / 2\pi k_B T$ (where $v_F$ is the Fermi velocity) in the clean limit to be 0.28 $\mu$m at 4.2 K and the mean free path $\ell$ to be 2.8 $\mu$m. Therefore the junction belongs to the clean limit regime ($\ell > \xi_N$) with ballistic transport ($\ell \gg L$). Though $\xi_N$ does not satisfy the clean limit condition ($\ell > \xi_N$) at a low temperature, the system can be considered to be in the clean limit also in the case of $L < \xi_N$ [14].

The critical current is measured as a function of the gate voltage $V_g$ at a low temperature of about 10 mK.

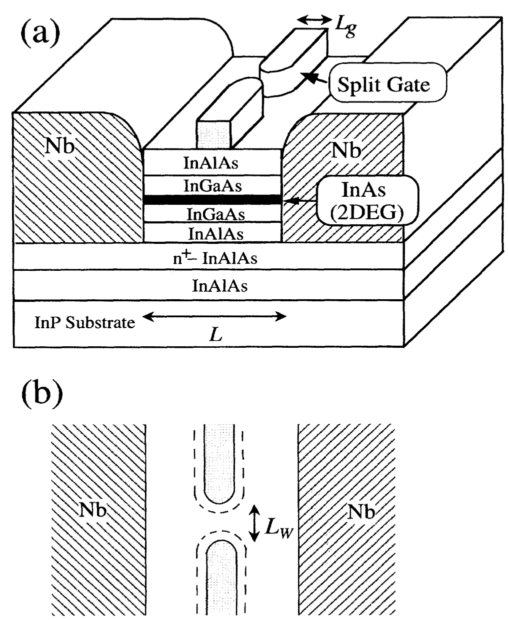


FIG. 1. (a) Cross-sectional view of the superconducting quantum point contact (SQPC). A supercurrent flowing through the 2DEG is changed by the gate voltage. (b) Top view of the SQPC. An applied gate voltage generates a depletion layer around the gate electrodes: this layer defines a constriction in the 2DEG. The depletion boundary is shown by the dashed curve. By increasing the negative gate voltage, the constriction width $L_W$ can be reduced from its original value of about 0.1 $\mu$m to almost zero.

  

When the absolute value of $V_g$ is small ($V_g > -0.8$ V), $I_c$ shows oscillations due to Fabry-Pérot interference of quasiparticles [15]. When the absolute value of $V_g$ is large ($V_g < -1$ V), the 2DEG underneath the gate electrode is pinched off. As the absolute value of the gate voltage increases, the constriction width $L_w$ is reduced gradually by the depletion regions [Fig. 1(b)]. When $L_w$ becomes comparable to the Fermi wavelength of the 2DEG, $\lambda_F \approx 16$ nm, one-dimensional (1D) subbands are generated in the constriction and both the normal and the superconducting current flow through them. The number of subbands is given by $2L_w/\lambda_F$ and may be changed one by one by the gate voltage. For a quantum point contact, this gate control provides the so-called quantized conductance in units of $2e^2/h$ [7,8]. For a SQPC, it should also give rise to quantization of the critical current [4–6].

The $I_c$ of this type of junction structure is very sensitive to a magnetic field. However, when the absolute value of $V_g$ was large, the $I_c$ of the junction became insensitive to a magnetic field, since the supercurrent flows through a very small width of the order of $\lambda_F$. After measuring $I_c$, we measured the total conductance of the junction $G$, using a 10-nA excitation current in a 26-G magnetic field, since the supercurrent was an obstacle for measuring the conductance precisely. As discussed before, a relatively strong magnetic field was needed to suppress the supercurrent that flows through the narrow constriction. However, we confirmed that the applied magnetic field did not reduce the probability of Andreev reflection.

When the conductance of the constriction $G_c$ was calculated, the contact resistance $R_C$ at the Nb-2DEG interface was taken into account in the relation $1/G_c = 1/G - 2R_C$. $R_C$ was calculated to be about 20 $\Omega$ from the relation $2R_C = R_N - R_{\mathrm{Sh}}$, where $R_N$ is the junction resistance at the voltage across the junction $V > 2\Delta_{\mathrm{Nb}}/e$ (where $\Delta_{\mathrm{Nb}}$ is the energy gap of Nb) and $R_{\mathrm{Sh}}$ is the Sharvin resistance of the 2DEG. $R_N$ was measured as 61 $\Omega$ and $R_{\mathrm{Sh}} = (h/2e^2)(\lambda_F/2W)$ was calculated to be 20.7 $\Omega$.

Figure 2 shows the measured critical current and the $G_c$ thus obtained in a SQPC with $L = 0.3$ $\mu$m as a function of gate voltage at a temperature of about 10 mK. It is clear that both the critical current and the conductance undergo stepwise changes as a function of gate voltage and that the behavior of the critical current is similar to that of the conductance. These data prove—as predicted by theory—that the critical current flowing through a SQPC is quantized in magnitude by the number of 1D subbands in the constriction. Beenakker and van Houten [4] calculated the step height of the critical current $\Delta I_c$ for a SQPC that is shorter than the coherence length $\xi_0 = \hbar v_F/\pi\Delta_0$. They showed that $\Delta I_c$ at $T = 0$ is given by $e\Delta_0/\hbar$ and is independent of the junction parameters, where $\Delta_0$ is the energy gap of the bulk superconductor. However, the junction studied here does not satisfy this condition $L \ll \xi_0$, since $\xi_0$ is calculated to be 0.43 $\mu$m for the junction. Furusaki *et al.* calculated $\Delta I_c$ in the opposite case [5] and gave a more detailed description of the dc Josephson effect of the SQPC than did previous studies [6]. The theory of Beenakker and van Houten is included in this theory as a special case of a very short point contact. According to this theory, in the case of $L > \xi_0$, $\Delta I_c$ is not universal but depends on junction parameters such as $L$ and the barrier strength $Z$ at the $S$-2DEG interface (i.e., the Andreev reflection probability at the interface) [6]. To evaluate $Z$ for the junction, we measured the differential resistance-voltage ($dV/dI$-$V$) characteristics and obtained $Z = 0.85$ by comparing with the calculation, taking multiple Andreev reflections into account [16].

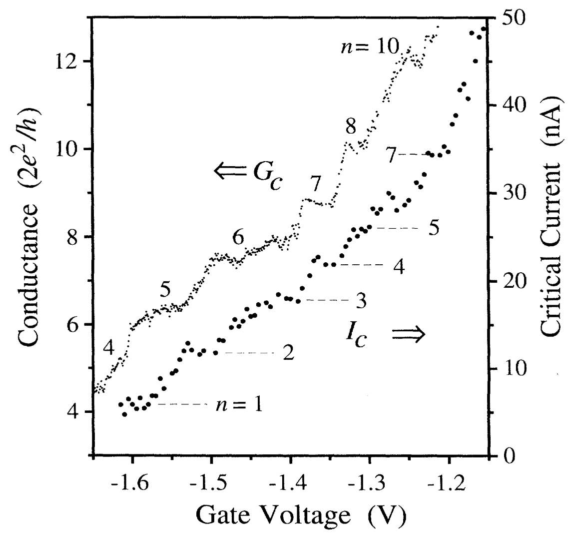


FIG. 2. The critical current $I_c$ and the constriction conductance $G_c$ as a function of the gate voltage $V_g$. All measured critical-current steps from the first to the seventh step are shown as well as the corresponding conductance steps from the fourth to the tenth.

$\Delta I_c$ in Fig. 2 was about 5 nA. In Refs. [5,6] the calculation for $\Delta I_c$ was done for the inversion layer of $p$-type InAs, which has $0.024m_e$, $N_S = 5 \times 10^{11}$ cm$^{-2}$, and $\mu = 5000$ cm$^2$/V s. Therefore the experimental value seems to be much smaller than the theoretical value of $\Delta I_c$ calculated for this junction. The small value of observed $\Delta I_c$ is due mainly to the small value of the critical current of the junction, $I_c = 1.8$ $\mu$A at 10 mK. The theoretical $I_c$ value of about 13 $\mu$A is evaluated for the junction with the same 2DEG and $Z = 0.85$ [14]. The reason for a small $I_c$ of this junction is not clear. However, it is clear that the small $\Delta I_c$ is explained by the small $I_c$. This is supported by the results shown in Fig. 3, which show $I_c$ and $G_c$ for another SQPC with $L = 0.3$ $\mu$m and $Z \sim 0.65$ as a function of $V_g$. This SQPC had $I_c = 3.3$ $\mu$A and $\Delta I_c$ of about 10 nA at 10 mK; both values are almost twice the values of the SQPC for Fig. 2. We note that $\Delta I_c$ in Fig. 2

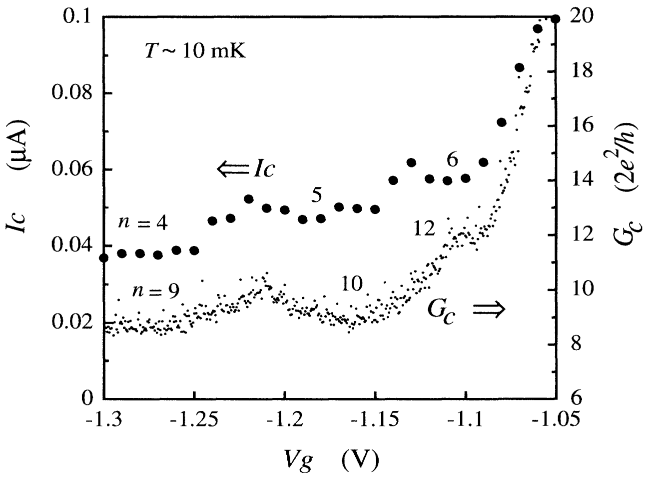


FIG. 3. $I_c$ and $G_c$ of another SQPC as a function of $V_g$. Resonant structures are seen at the edge of the fifth and sixth current steps.

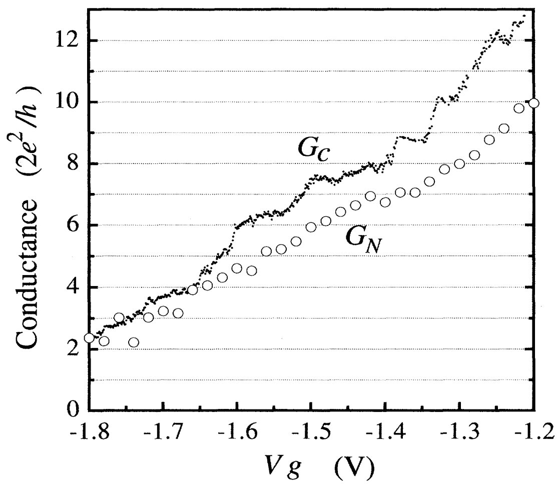


FIG. 4. The constriction conductance $G_c$ measured at $V = 0$ and the conductance $G_N$ measured at a high voltage are shown as a function of $V_g$.

decreases from about 6 to 4 nA as the step order increases from the first to the seventh. This agrees qualitatively with the theoretical prediction [6].

In Fig. 2 the conductance steps do not appear at the expected quantized values of $n \times 2e^2/h$ ($n = 1, 2, 3, \ldots$), and the step height is a bit larger than $2e^2/h$. This results from single and multiple Andreev reflections between the two $S$-2DEG interfaces. It has been shown theoretically that the conductance of the quantum point contact that faces a $S$-$N$ interface is quantized in units of $4e^2/h$ (i.e., the doubling of the conductance step) [17]. In this theory, the Andreev reflection probability is assumed to be 1 at the $S$-$N$ interface (i.e., $Z = 0$). But the observed behavior of the conductance is not yet well understood, since there is no theory for conductance in a SQPC consisting of two $S$-$N$ interfaces with nonzero $Z$ value.

If the Andreev reflection probability becomes zero, conductance steps will appear at the quantized values of $n \times 2e^2/h$ and the step order can easily be determined. One method of determining the step order is to apply a strong magnetic field–enough to suppress the effect of Andreev reflection. We have confirmed that $G_c$ showed a monotonic decrease and conductance steps gradually approached the expected value of $n \times 2e^2/h$ as the applied magnetic field increased. Another method is to compare $G_c$ with $G_N$. This is defined as $1/G_N = R_N - 2R_C$. $G_N$ is the constriction conductance measured at $V > 2\Delta_{\rm Nb}/e$; in this voltage region the conductance (or resistance) is not affected by Andreev reflection. On the other hand, $G_c$ is the constriction conductance determined at $V = 0$. Figure 4 shows $G_c$ and $G_N$ of the SQPC for Fig. 2 as a function of $V_g$. The orders of the conductance steps in Fig. 2 were determined by comparing $G_c$ and $G_N$ in Fig. 4. $G_N$ did not show clear steps since the exciting current (bias current) was very high, at about 1–5 $\mu$A. It can be clearly seen that $G_c$ is always larger than $G_N$, because of Andreev reflection. This increase in the constriction conductance from a large voltage to $V = 0$ can also be seen in the $dV/dI$-$V$ characteristics measured by changing $V_g$. The $dV/dI$-$V$ characteristics showed a clear change from current-deficit to excess-current characteristics [18]. We attribute this change to the Andreev-reflected holes being focused on the quantum point contact defined in the 2DEG by the split gate (retro property of Andreev reflection).

There are resonance structures at the edge of some steps, e.g., at the second and fourth current steps in Fig. 2 and at the edge of the fifth and the sixth current steps in Fig. 3. Furusaki *et al.* also predicted theoretically that the resonant structure appears at the edge of the current step due to quantum interference of quasiparticles that traverse the 2DEG many times due to normal reflections. This effect is very interesting in that the interference of individual electrons, originating from the phase of a single-electron wave function, influences the Josephson effect, which has its origin in the phase of the condensate, i.e., Cooper pairs. There are two kinds of normal reflections that induce the interference effects on the supercurrent: a reflection at the exit of the constriction and one at the $S$-2DEG interface. The first reflection is remarkable when the constriction width changes suddenly. The quantum interference due to the latter reflection can be seen when the $S$-2DEG interface has nonzero $Z$ value and $L$ is much shorter than $\ell$. The reflection probability at the exit of the constriction for the measured SQPC may be small, since the edge of the split gate is rounded, as shown in Fig. 1(b). Therefore, we think that the observed resonant structures are due to the normal reflection at the $S$-2DEG interface, although the possibility of resonant structures due to the impurity scattering cannot be ignored.

Finally we note that, surprisingly, the order of the critical current step is different from that of the corresponding conductance step in Fig. 2. The difference between them is three, and the same kind of difference is also observed in Fig. 3. This suggests that several lower-order subbands do not contribute to the critical current. The present theory predicts an agreement between the order of the two kinds of steps. Further theoretical work along with more experimental data are required before the origin of this phenomenon can be clarified.

In summary, the critical current as well as the conductance in a split-gate semiconductor-coupled Josephson junction showed stepwise changes as a function of the gate voltage. This result is evidence that the critical value of dc Josephson current is quantized in magnitude by the number of 1D subbands in the quantum point contact. Also, we confirmed the resonance structures resulting from quantum interference of quasiparticles to be at the edge of the critical current steps, as predicted. Recently the ac Josephson effect of one-dimensional junctions has been studied [19]. The behavior of ac Josephson current in a SQPC is also very interesting and will be studied in the junction described in this Letter.

We thank Dr. A. Furusaki and Professor M. Tsukada for valuable discussions of transport in a superconducting quantum point contact, and Dr. Y. Ishii, Dr. K. Arai, and Dr. T. Enoki for discussions on electron transport in the heterostructure, T. Ishikawa for MBE growth. We also thank Dr. T. Ikegami and Dr. N. Matsumoto for encouragement throughout this work.

[1] T. M. Klapwijk, Physica (Amsterdam) **197B**, 481 (1994).

[2] H. Takayanagi, Y. B. Hansen, and J. Nitta, Phys. Rev. Lett. **74**, 166 (1995); Physica (Amsterdam) **203B**, 291 (1994).

[3] H. Takayanagi, Y. B. Hansen, and J. Nitta, Phys. Rev. Lett. **74**, 162 (1995).

[4] C. W. J. Beenakker and H. van Houten, Phys. Rev. Lett. **66**, 3056 (1991).

[5] A. Furusaki, H. Takayanagi, and M. Tsukada, Phys. Rev. Lett. **67**, 132 (1991).

[6] A. Furusaki, H. Takayanagi, and M. Tsukada, Phys. Rev. B **45**, 10 563 (1992).

[7] 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).

[8] 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).

[9] J. Nitta, T. Akazaki, H. Takayanagi, and K. Arai, Phys. Rev. B **46**, 14 286 (1992).

[10] C. J. Muller, J. M. van Ruitenbeek, and L. J. de Jongh, Phys. Rev. Lett. **69**, 140 (1992).

[11] K.-M. Lenssen, M. Matters, C. J. P. M. Hermans, J. E. Mooji, M. R. Leys, W. van der Vleuten, and J. H. Wolter, IEEE Trans. Appl. Supercond. **3**, 1961 (1993).

[12] H. Takayanagi and T. Akazaki (to be published).

[13] T. Akazaki, J. Nitta, H. Takayanagi, T. Enoki, and K. Arai, Appl. Phys. Lett. **65**, 1263 (1994).

[14] A. Chrestin, T. Matsuyama, and U. Merkt, Phys. Rev. B **49**, 498 (1994).

[15] H. Takayanagi, T. Akazaki, and J. Nitta, Phys. Rev. B **51**, 1374 (1995); Jpn. J. Appl. Phys. **34**, 4552 (1995).

[16] F. Flensberg, J. B. Hansen, and M. Octavio, Phys. Rev. B **38**, 8707 (1988).

[17] C. W. J. Beenakker, Phys. Rev. B **46**, 12 841 (1992).

[18] H. Takayanagi and T. Akazaki, Phys. Rev. B (to be published).

[19] D. Averin and A. Bardas (unpublished).