Localization effects on the critical current of a superconductor-normal-metal-superconductor junction

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Localization Effects on the Critical Current of a Superconductor–Normal-Metal–Superconductor Junction

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Interaction effects associated with Anderson localization are confirmed for the critical current in a superconductor–normal-metal–superconductor junction using p-type InAs as the normal metal. In the weak localization regime and with decreasing temperature the critical current shows a saturated temperature dependence which agrees well with a theoretical prediction. In the strong localization regime the critical current decreases with lowering temperature.

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Quantum transport in superconducting structures coupled with mesoscopicscale normal metals or semiconductors has been leading to new developments in mesoscopic physics [1]. Interesting theoretical predictions have been reported for this superconducting transport in superconductor–normal-metal–superconductor (S-N-S) junctions. In a dirty regime of the normal conductor Al'tshuler and Spivak [2] and later Beenakker [3] have calculated mesoscopic critical current fluctuations with the same physical origin as that of the universal conductance fluctuations (UCF). Recently, the authors of this Letter have experimentally confirmed these mesoscopic fluctuations [4].

One of the theoretical works looks at the relationship between superconductivity and Anderson localization. Fukuyama and Maekawa studied the proximity effect of interacting electrons in a dirty two-dimensional metal and showed that localization effects reduce the critical current [5,6]. This Letter reports on localization effects on the critical current in an S-N-S junction using p-type InAs as the normal metal. The temperature dependence of the critical current is measured in the weak and strong localization regimes.

A schematic cross-sectional view of the three-terminal sample is shown in Fig. 1. Two superconducting Nb electrodes separated by the junction length L couple with the surface inversion layer of p-type InAs substrate. The Nb film is about 100 nm thick. The junction has a metal-insulator-semiconductor gate. The gate insulator consists of a 70 nm thick anodic oxide film of Nb and InAs and 100 nm of electron beam deposited SiO film.

The supercurrent flows through the two-dimensional electron gas system (2DEG) in the inversion layer forming a junction with Josephson characteristics [7]. Four junctions were studied with the junction length L varying between 2.5 and 0.3 μm. In Fig. 2 the measured critical current and the normalized sheet resistance $R_\square/R_Q$ for the $L = 0.4$ μm junction as a function of the gate voltage at 20 mK are shown. $R_\square$ was obtained from the relation $R_\square = R_N W/L$, where R_N is the junction normal resistance, and $R_Q = h/4e^2$ the quantum resistance. As we will discuss later, with increasing the gate voltage, $R_\square$ clearly shows a large increase, indicating that the electronic states of the 2DEG are shifting from the weak localization regime to the strongly localized one.

At the same temperature two current-voltage (I-V) characteristics of the same junction are presented in Figs. 3(a) and 3(b) for $V_g = 0$ and -19.9 V, respectively.

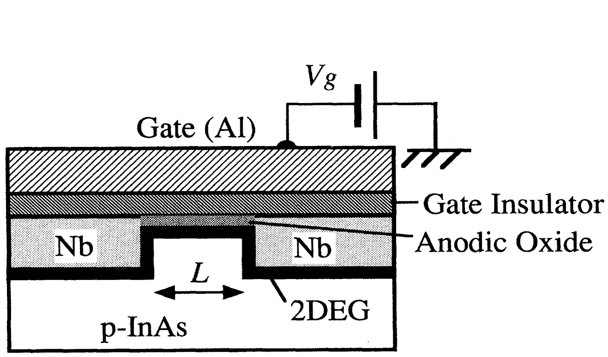

FIG. 1. A schematic cross-sectional view of the junction. The supercurrent flows through the 2DEG formed in the inversion layer of p-type InAs.

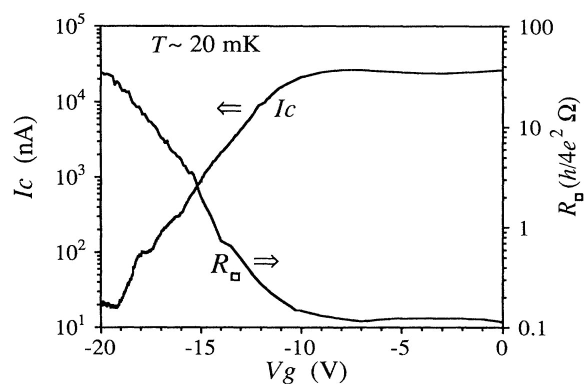

FIG. 2. Critical current and the normalized sheet resistance $R_\square/R_Q$ for a junction with $L = 0.4$ μm as a function of the gate voltage at $T = 20$ mK. $R_\square$ shows a large change by increasing the gate voltage, indicating that the 2DEG shifts from the weak localization regime to the strongly localized one.

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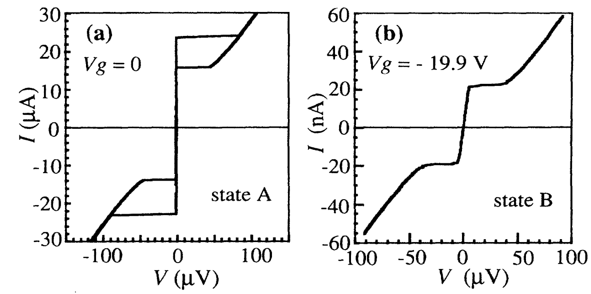

FIG. 3. I-V characteristics for the junction at 20 mK for (a) $V_g = 0$, state A (high conductance state), and (b) $V_g = -19.9$ V, state B (low conductance state).

As seen, by changing V_g, the critical current varied over 3 orders of magnitude. I_c was about 20 nA at V_g -19.9 V. (Hereafter, the junction state at $V_g = 0$ will be referred to as state A and that for $V_g = -19.9$ V state B.) The cryostat with heavily filtered leads was placed in an rf-shielded room. A sharp transition from the superconducting state to the normal one [like the one seen in Fig 3(b)] indicates that the level of the external noise was negligible even at low temperatures. We note that the supercurrent branch in Fig. 3(b) is tilted. This branch has a resistance R_0 of about 250 Ω while R_N is about 1.2 kΩ. This phenomenon can be explained by macroscopic quantum tunneling (MQT) [8]. It will be discussed elsewhere [9].

The temperature dependence of the critical current was measured for both states. First, the experimental results for state A (i.e., the "high conductance" state) are discussed in terms of weak localization. Figure 4(a)

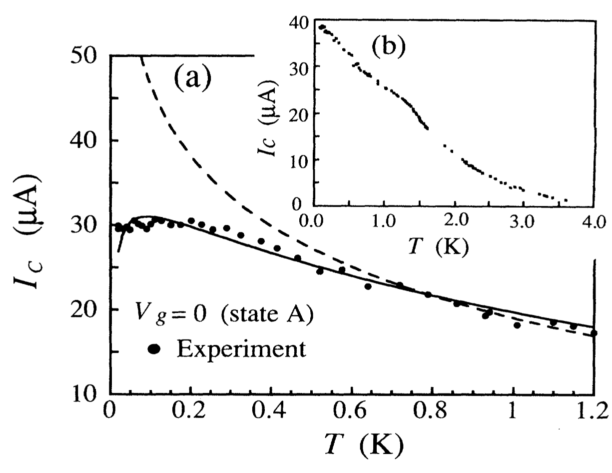

FIG. 4. Temperature dependence of the critical current for (a) the junction in state A and (b) a reference junction coupled with a 2DEG in the clean limit. In (a) the solid line represents the I_c-T curve with localization effects calculated from Eq. (3). The dotted line shows the I_c-T curve without localization effects.

gives the temperature dependence of the I_c for state A. The I_c of this type of junction structure is very sensitive to a magnetic field. For each temperature the maximum value of I_c was therefore found by carefully optimizing I_c with the help of a small magnetic field applied perpendicular to the 2DEG. As shown in the figure, I_c showed a saturation below ~0.3 K. Whereas the junction normal resistance R_N exhibited a small change between 4.2 K and 20 mK. An S-N-S junction with $\xi_N(T_c) \gg L$ (such a junction is called an ideal junction) and a constant R_N against temperature usually shows this kind of saturation at $T \leq 0.2T_c$ [10], where ξ_N is the normal coherence length given by $(\hbar D/2\pi k_B T)^{1/2}, T_c$ is the critical temperature of the superconductor and D is the diffusion constant of the normal metal. Shubnikov-de Haas measurements were taken in order to evaluate ξ_N, the carrier concentration N_s, and the mobility μ in the 2DEG. The results obtained for N_s and μ at 4.2 K were 8.9×10^{15} m^{-2} and 0.61 m^2/V s, respectively. The measurements were made for the same surface inversion layer covered by a 70 nm thick InAs anodic oxide. ξ_N is given as $(\hbar^3 \mu N_s/2k_B Tem^*)^{1/2}$ for a dirty 2DEG [7], where m^* is the carrier effective mass. By substituting the above values for N_s and μ and $m^* = 0.024m_e$ into this equation, $\xi_N = 0.57$ μm at 0.2 K and 0.1 μm at $T = T_c \approx 6$ K are obtained, where m_e is the free electron mass. With $L = 0.4$ μm, this junction therefore does not satisfy the condition $\xi_N(T_c) \gg L$ for which the I_c of an S-N-S junction exhibits saturation at low temperatures.

Another explanation for this saturation is the effect of localization on the proximity effect as predicted by Fukuyama and Maekawa (FM) [5,6]. They introduced interaction effects associated with Anderson localization into the proximity effect in an S-2DEG-S junction as

$$I_c \propto \Delta^2 \zeta(T)^2 \sqrt{D(T)/T} \exp[-L/\xi_N(T)], \qquad (1)$$

where

$$\xi_N(T) = [\hbar D(T)/2\pi k_B T]^{1/2},$$
$$D(T) = D(1 + \lambda \ln \pi k_B T\tau/\hbar)(1 + \lambda \ln k_B T\tau/\hbar), \qquad (2)$$
$$\zeta(T) = 1 + (\lambda/4) \ln k_B T\tau/\hbar \ln(D\kappa^2)^2 \hbar\tau/k_B T,$$
$$\lambda = \hbar/2\pi\varepsilon_F\tau,$$

and Δ is the pair potential at the interface. $D(T)$ and $\zeta(T)$ are the modified diffusion constant and the renormalized overall amplitude caused by the localization effect, respectively. τ and ε_F are the lifetime and the Fermi energy of the 2DEG. κ is the inverse screening radius given as $m^* e^2/\varepsilon_0 \varepsilon \pi \hbar^2$, where ε is the dielectric constant. Equations (1) and (2) hold for $\lambda \ll 1$ (i.e., weak localization regime) and $g < 0$ or g is very small. Here g is the interaction between electrons in the 2DEG. $D = 5.4 \times 10^{-2}$ m^2/s, $\tau = 8.3 \times 10^{-14}$ s, and $\lambda = 1.4 \times 10^{-2}$ are obtained by using the measured N_s, μ, and $m^* = 0.024m_e$. The 2DEG in state A belongs to the weak localization regime and Eq. (1) is used to discuss the temperature dependence of I_c in this state. This is because $\lambda \ll 1$ and g of the inversion layer are considered to be zero or small enough to be neglected. However, since Eq. (1) is derived from the Ginzburg-Landau equation, it is only valid close to T_c. Therefore we have to use an I_c -T equation which is valid at low temperatures instead of Eq. (1). Kresin calculated the temperature dependence of the critical current density J_c for an S-2DEG-S junction by using the thermodynamic Green's function [11]. In the calculation the proximity effect in the 2DEG is treated as the perturbation. By combining the effect of localization on the proximity effect and Kresin's result for a dirty junction, we obtain

$$J_c = \gamma \pi \hbar k_B T \zeta(T)^2 \sum_{k=-} (-1)^k \sum_{\omega_n > 0} \frac{\Delta^2}{\omega_n^2 + \Delta^2} \times \frac{1}{2|\omega_n| + \hbar D(T)(\pi k/L)^2}, \quad (3)$$

where γ is the transparency of the S-N interface, ω_n is the Matsubara frequency given by $(2n + 1)\pi k_B T$, and Δ is the pair potential of the superconductor at the interface. In general Kresin's result holds for $L \gg \xi_N$. For the measured junction, we have $\xi_N \sim 0.6$ μm at 0.2 K so this condition is not satisfied. Nevertheless, if γ is small, Kresin's result is still valid also for $L \ll \xi_N$, i.e., Eq. (3) is valid for our junctions at low temperature [11]. The $I_c R_N$ product of the $L = 0.4$ μm junction was about 60 μV at 1.2 K. This is small compared with the theoretical value of about 1.4 mV, as predicted by Likharev [10]. It was shown theoretically that the $I_c R_N$ product of an S-N-S junction becomes smaller as the transparency of the S-N boundary becomes lower [12]. Therefore we will use Eq. (3), assuming that γ is small, even though it is not clear that Eq. (3) can be used at very low temperatures around 20 mK.

The definitions of $\zeta(T)$ and $D(T)$ are the same as those in Eq. (2). In Eq. (3) the change of R_N is self-consistently taken into account in terms of $D(T)$. R_N is given as $\pi\hbar^2 L/e^2 m^* W D(T)$ from the relation $D(T) = \pi\hbar^2 N_s \mu/em^*$ and $R_N = L/eWN_s\mu$, where $W = 80$ μm is the width of the Nb electrode. The expression for $D(T)$ in Eq. (2) gives the ratio of R_N (20 mK)/R_N (4.2 K) = 1.18 when we use the values of D, τ, λ given above. R_N was measured at 4.2 K and 20 mK, and the results were 3.65 and 4.38 Ω, respectively, giving a measured ratio R_N (20 mK)/R_N (4.2 K) of 1.2 in good agreement with the theoretical value. This indicates that one can discuss the temperature dependence of I_c by using Eq. (3), without paying attention to the change of R_N in the weak localization regime.

The solid line in Fig. 4(a) is the data obtained by using Eq. (3). In this calculation the values of D, τ, λ obtained earlier were used as well as $\varepsilon = 14.55$ for InAs and $\Delta = 1.5$ meV for Nb. The calculated and the experimental data coincide at $T = 0.8$ K, and the experimental results agree well with the calculated ones. The dotted line in the figure is the calculated temperature dependence of I_c without including the localization effects, i.e., the equation obtained from Eq. (3) by replacing $\zeta(T)$ and $D(T)$ with 1 and D. As shown in the figure, the discrepancy between the experimental results and the dotted line becomes larger as temperature becomes lower.

For comparison, we also measured the temperature dependence of I_c for a low λ ("clean") Nb-2DEG-Nb junction by the same measurement system. Figure 4(b) shows the temperature dependence of I_c for a junction using the 2DEG in an InAs-inserted-channel InAlAs/InGaAs heterostructure [13]. In this structure the 2DEG is well confined in a 4 nm thick InAs layer and has $N_s = 2.0 \times 10^{16}$ m^{-2}, $\mu = 7.4$ m^2/V s, and $m^* = 0.05 m_e$ at 4.2 K. These values give $l = 1.7$ μm, $D = 0.71$ m^2/s, and $\lambda = 5.2 \times 10^{-4}$. Because of this small λ value the localization effects on I_c is negligibly small. The clean junction with $L = 0.4$ μm and $W = 80$ μm had almost the same I_c as that of the "dirty" junction shown in Fig. 4(a), but did not exhibit any saturation of I_c below 0.2 K. Taken together, these results indicate that the saturation of I_c at low temperatures in state A (i.e., the high conductance state) of the dirty junction can be explained by the weak localization effect and is not due to external noise or poor heat sinking.

Next we discuss the temperature dependence of the critical current in state B (i.e., the "low conductance" state). Figure 5(a) shows the measured temperature dependence of the critical current and the junction normal resistance R_N. Using a derivative technique R_N was measured carefully from the I-V curve by applying a comparatively

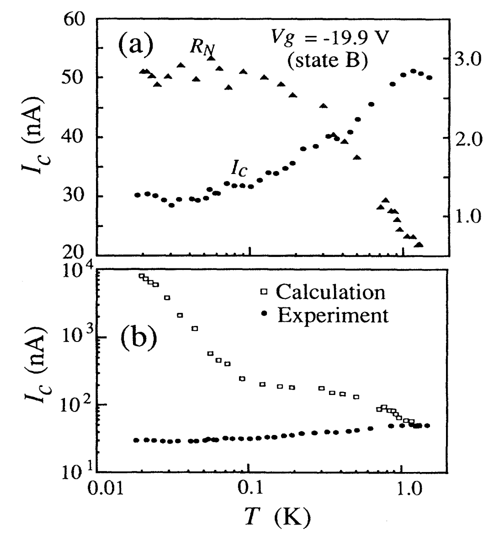

FIG. 5. (a) Measured temperature dependence of the critical current and normal resistance for state B. (b) Temperature dependence of the measured and the calculated critical current for state B.

large magnetic field to suppress the supercurrent to zero. In the measurement a very low excitation current of up to $\sim$20 nA was used to prevent heating effects on the 2DEG by the excitation current. With decreasing temperature R_N first shows an increasing dependence and then saturation. As will be discussed later, state B belongs to a strong localization regime. It is not clear to what extent the weak localization theory can be used in the strong localization regime. Therefore the R_N behavior is not discussed here from the viewpoint of localization effects.

In Fig. 5(a) the critical current I_c is the optimized maximal critical current. As shown in the figure, with decreasing temperature the critical current first increases and then decreases. The values for N_s and μ in the 2DEG in state B are important parameters, but direct measurement of them is difficult. The N_s μ product is $\sim 6.3 \times 10^{13}/\mathrm{V\,s}$ as obtained from the relation $R_N = L/eWN_s\mu$, where $R_N \sim 500\ \Omega$ is the resistance of the 2DEG before localization occurs. This value results in $\lambda = 1.2$ and $D = 6.3 \times 10^{-4}\ \mathrm{m^2/s}$ from the relations $\lambda = e/2\pi^2\hbar N_s\mu$ and $D = \pi\hbar^2 N_s\mu/em^*$. These values indicate that the 2DEG in state B at low temperatures belongs to the strong localization regime and cannot be modeled by the weak localization theory.

Since the variation of R_N with temperature in this case is very large, as compared with that in state A, and I_c in general is reduced when R_N increases in an S-N-S junction, the measured temperature dependence of I_c should be compared with the calculated temperature dependence which does not include the localization effects but does take the change of R_N into account. This temperature dependence is obtained using Eq. (3) with $\zeta(T)$ replaced by 1 and a value of $D(T)$ obtained at each temperature from the measured R_N as shown in Fig. 5(a). In this regime Kresin's result can be used at temperatures down to 20 mK, since ξ_N at 20 mK is calculated to be 0.19 μm which satisfies $L > \xi_N$. The temperature dependence of I_c found in this way is shown in Fig. 5(b) as well as the measured one. The calculated data are made to coincide with the experimental data at 1.5 K, assuming that the localization effects are so weak that they may be neglected at this temperature. Even though R_N increases large factor with decreasing temperature, there is still a huge discrepancy between the experimental and the calculated values of I_c at low temperatures. This shows that in state B localization effects strongly modify the superconducting transport properties of the 2DEG. This behavior of I_c and R_N is not yet well understood, since there is no theory for this regime. Further theoretical developments along with more experimental data are required before the origin of these phenomena is clarified.

In summary, interaction effects associated with Anderson localization were observed in the critical supercurrent of a three-terminal device, based on a 2DEG formed in the inversion layer of p-type InAs. Both a weak and a strong localization regime were accessed by changing the carrier density of the 2DEG with the gate voltage. In the weak localization regime, the critical current showed a saturated temperature dependence at low temperatures which agreed well with theoretical predictions. The critical current decreased with lowering temperature in the strong localization regime.

Recently the effect of phase coherent scattering on the conductance of an S-N interface has been discussed theoretically and experimentally [1]. This effect is not considered in the FM theory used in the present work. Numerical results show that this effect should be considered only when the Andreev reflection probability is small [14]. This problem should be addressed in future works.

For the S-2DEG-S structure investigated in this work, the characteristic variation of the critical current with temperature gives clear evidence of the localization effects on the transport phenomena at low temperature. The results obtained, especially in the strong localization regime will be helpful in advancing the studies of Anderson localization in mesoscopic systems.

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