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Carrier reflection at the superconductor-semiconductor boundary observed using a coplanar-point-contact injector

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The Andreev reflection of carriers at the boundary between a superconductor and a semiconductor has been studied by measurement of the differential resistance of a *n*-type-Si–Nb point contact with a coplanar structure. The boundary condition of the pair potential in the Si-Nb proximity system is obtained from these measurements. A carrier-concentration dependence of the pair potential at the boundary is observed. The pair potential in the Si at the boundary increases with increasing carrier concentration.

Cooper pairs can diffuse, by the proximity effect, into a normal metal in contact with a superconductor.[1] A semiconductor also can be employed as the normal metal.[2–7] For example, the existence of a pair potential, the product of the pair amplitude and the electron-electron interaction potential, has been observed by tunneling into a Si membrane backed with a Pb-alloy film.[7] More detailed studies of the spatial dependence of the pair potential in the normal layer of a proximity-effect sandwich are possible by measurements of the Andreev reflection in the normal metal.[8,9] Such measurements can enhance our understanding of the boundary conditions for the proximity effect. In this Rapid Communication, we describe the results of such a study in a superconductor-semiconductor system.

Andreev reflection is a special process that is due to the superconducting pair potential.[10] It is sensitive to the magnitude of the pair potential near a superconductor–normal-metal boundary.[8] A point-contact technique was used by van Son *et al.* in the first experiments of this type, which showed the existence of the pair potential by differential resistance measurements. We have employed microfabrication technology in an attempt to perform such an investigation in a superconductor-semiconductor system with a thin-film geometry. This method is more suitable for systematic studies of the proximity effect of this system.

In this communication, we describe experimental results of the measurements of quasiparticle reflection at the superconductor-semiconductor boundary. In these measurements, the superconducting pair potential at the superconductor-semiconductor boundary was obtained. We report on experiments which study the carrier-concentration dependence of the pair potential in Si at the boundary.

The specimens used for the measurements were superconductor-semiconductor junctions with a point-contact-like electrode, as shown in Fig. 1. The point contact injects carriers into the semiconductor, a (100)-oriented Si single crystal whose surface was doped with phosphorus in the range from 5×10^{24} to 1×10^{26} m^{-3}. On the Si surface, an opening of a $\mathrm{SiO_2}$ insulating film was made for a contact to the superconductor. After the surface of the Si in the opening was cleaned by heat treatment, a 100-nm-thick Nb film was deposited by evaporation in an ultrahigh vacuum of about 10^{-8} Pa. The Nb superconducting film was patterned by electron-beam lithography and dry etching. The resulting distance between the injector and the other superconductor was in the range 80–120 nm. The electrode widths were 80 nm and 10 μm. For the injector electrode, the typical contact area was 80×50 nm.

Electrons are emitted from the point contact into the semiconductor and reflected at the superconductor-semiconductor boundary. The electron in the semiconductor at the superconductor-semiconductor boundary can be condensed into a Cooper pair creating a hole in the semiconductor which can diffuse back to the injection point. This hole gives an excess current.[8] We believe that the voltage drops at the Nb injector contact.

Electrical measurements were made by employing the high-resolution bridge technique developed by Adler and Jackson.[11] The measured differential resistance at 2 K is shown in Figs. 2 and 3. No superconducting current was observed. The nonlinear dependence of differential resistance on the voltage is due to the superconducting Nb films and the carrier scattering in the semiconductor. At

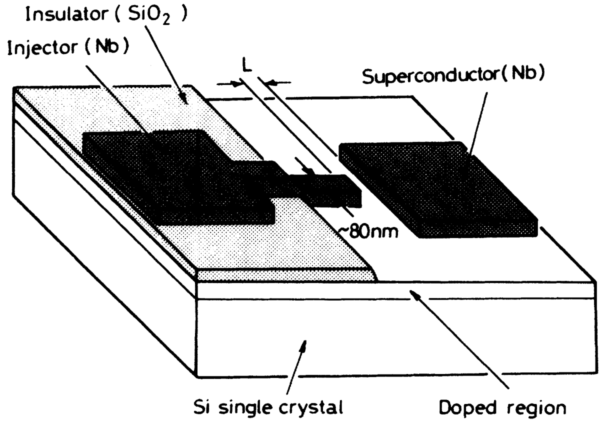

FIG. 1. Structure of specimen with point contact for measurement.

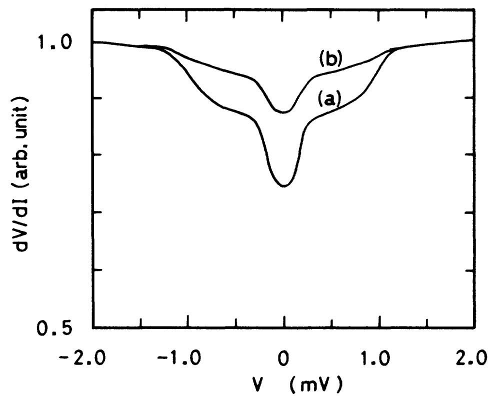

FIG. 2. Relationship between observed differential resistance and junction voltage. Measurement was made at 2.0 K. Doping concentration was 1×10^{25} m^{-3} for two specimens. Distance between injector electrode and superconductor were *a*, 80 nm and *b*, 120 nm.

20 K, above the critical temperature of Nb films, the nonlinearity in the differential resistance is negligible.

In our previous study on specimens in which both superconducting electrodes are the same size, no such structure in the differential resistance was observed.[5] In that study, since the injector is a superconductor, Andreev reflection occurs at the injector as well as the superconducting counterelectrode. No effects due to such a multiple reflection process were observed in the present experiment. There are two possible reasons for this result. First, the front end of the injector may not be superconducting due to damage during the microfabrication process. Second, multiple reflection may not occur due to the inhomogeneous shape of the injector.

In the present experiment, the doping concentration of phosphorus in Si is 1×10^{25} m^{-3}. The superconducting coherence length and the carrier mean free path were estimated to be 18 and about 20 nm, respectively,[5] larger than the distance between the injector and the superconductor, L. The junction characteristics depend on both the probability of Andreev reflection and the probability of inelastic scattering in the semiconductor between the injector and the superconductor. Figure 4 shows the effective length $L_{\rm eff}$ between the injector and the superconductor. The probability of inelastic scattering for the Andreev-reflected carrier increases with increasing distance between the injector electrode and the superconductor. A large decrease in the resistance was observed in the small-length case. This is related to the voltage dependence of the results. The probability of scattering in the semiconductor between the injector and the superconductor is energy dependent, because the effective length $L_{\rm eff}$, between the injector and the superconducting electrode depends on the incident carrier energy. The probability of additional scattering for the once Andreev-reflected carrier is enhanced with increasing distance between the injector and the superconductor. Therefore, the differential resistance is voltage dependent. Andreev reflection of carriers with low incident energy was clearly observed because $L_{\rm eff}$ decreases when the incident energy becomes lower.[8] The spatial change in the pair potential at the superconductor-semiconductor boundary affects the junction excess current, which can be used as a probe to study the spatial change in the pair potential at the superconductor-semiconductor boundary. For the case that L is too large compared to the electron free path, the energy dependence of junction excess current does not reflect the spatial change in the pair potential. For these reasons, the distance between injector electrode and superconductor was chosen to be 80 nm.

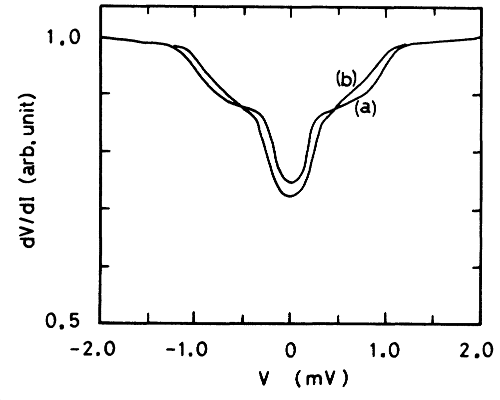

FIG. 3. Relationship between observed differential resistance and junction voltage. Measurement was made at 2.0 K. Distance between injector and superconductor was 80 nm. Doping concentrations were *a*, 1×10^{25} m^{-3} and *b*, 1×10^{26} m^{-3}.

The pair potential has a steep change at the semiconductor-superconductor boundary.[1] This change affects the probability of the Andreev reflection.[8] The change in the pair potential at the superconductor-semiconductor boundary should depend on the electronic properties of the semiconductor. For example, the proximity effect is strongly affected by the carrier concentration in the semiconductor[5,6] and the measurements of the junction excess current were made for various carrier concentrations.

In the energy dependence of differential resistance, we can find two shoulders which are reflected in the second derivative, d^2V/dI^2. The Andreev reflection coefficient depends on the incident carrier energy E. Assuming for simplicity that the coefficient is almost constant in the energy range $0<E<\Delta^0_{\rm Nb}$, where $\Delta^0_{\rm Nb}$ is the value of the pair potential of the Nb film far from the boundary between the *n*-type Si and superconducting Nb,[12] dV/dI depends on the distance L, and the two shoulders correspond to

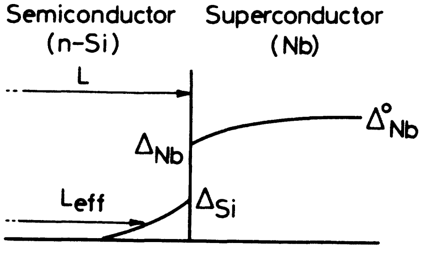

FIG. 4. Illustration of spatial change in the pair potential at superconductor-semiconductor boundary.

$\Delta_{\rm Nb}$ and $\Delta_{\rm Si}$, if the pair potential at the boundary changes more steeply than that in other parts near the boundary. In Fig. 4, $\Delta_{\rm Nb}$ is the pair potential in the Nb near the boundary and the $\Delta_{\rm Si}$ is the pair potential in the Si near the boundary. The differential resistance dV/dI depends on L because the pair potential decays exponentially with the distance from the semiconductor-superconductor interface.[1]

Thus we see evidence for the existence of induced superconducting pairs in the semiconductor due to the superconducting proximity effect. The values of $\Delta_{\rm Nb}$ and $\Delta_{\rm Si}$ obtained from the measured results shown in Fig. 2 are almost constant for the different specimens. These results show that the magnitude of dV/dI depends mainly on the distance L due to the increase of additional carrier scattering, and that the energy dependence of dV/dI reflects the spatial change in the pair potential at the boundary. Though these discussions are too qualitative to conclude that the Andreev-reflection process takes place at the point where the pair potential is equal to the incident carrier energy, the values of the pair potential obtained are independent of the length L. This supports the validity of the idea that the energies of the two shoulders in the dV/dI curve correspond to $\Delta_{\rm Nb}$ and $\Delta_{\rm Si}$.

The relationship between dV/dI and V was measured for the specimens with various phosphorus-doping concentrations, as shown in Fig. 3. Figure 5 shows the carrier concentration dependence of $\Delta_{\rm Nb}$ and $\Delta_{\rm Si}$ for the specimens with phosphorus doping concentration in the range from 5×10^{24} to 1×10^{26} m^{-3}. A 15% enhancement of $\Delta_{\rm Si}$ was observed by the increasing phosphorus doping concentration in Si. On the contrary, the value of $\Delta_{\rm Nb}$ was suppressed. This is due to the enhancement of superconducting proximity effects induced in the Si through the increased carrier concentration. For a low doping concentrations of less than 5×10^{24} m^{-3}, carrier freeze-out effects are significant and the experimental determination of $\Delta_{\rm Si}$ and $\Delta_{\rm Nb}$ was impossible.

In Fig. 5, $\Delta^0_{\rm Nb}$ is the pair potential in the Nb film far from the boundary. The value of $\Delta^0_{\rm Nb}$ decreased by increasing the carrier concentration in the semiconductor. This also results from the suppression of the superconductivity in the superconductor layer by the increase in carrier concentration in the semiconductor,[10] because the Nb film is not thick enough compared to the Nb coherence length. The change in the superconductivity of the double layer is observed as a decrease in the pair potential.

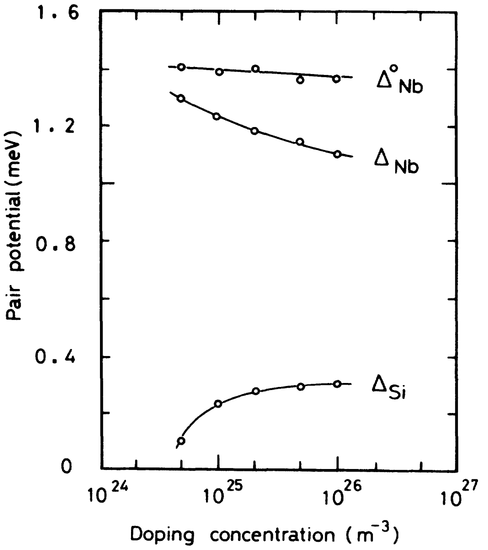

FIG. 5. Observed energies corresponding to pair potential in Si and Nb at boundary for specimens with various doping concentration in Si.

We interpret our experimental results from specimens with coplanar structures in analogy to those obtained from tunneling into a sandwich structure.[8] A difference between those two structures for the electron path is the dimensionality. Further study on the effect of this difference between the experimental results is necessary.

In conclusion, the superconducting proximity effect in Si-Nb junctions was studied by measuring the change in junction resistance due to the Andreev reflection. Point contactlike specimens were prepared using microfabrication technology. The carrier concentration dependence of the pair potential at the boundary between the n-type Si and the superconducting Nb was measured for the first time, and a 15% enhancement of the pair potential in the Si at the boundary was observed by increasing the carrier concentration in Si from 1×10^{25} to 1×10^{26} m^{-3}.

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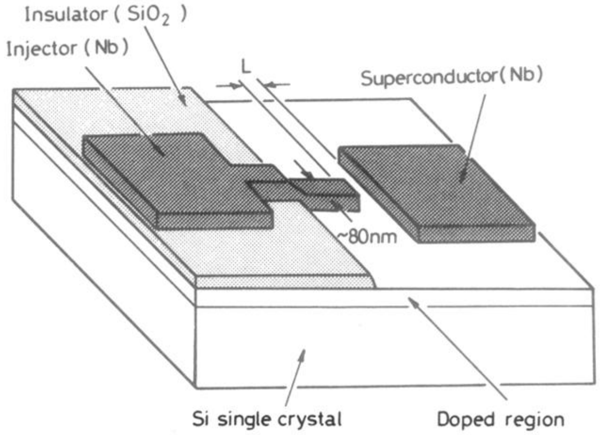

FIG. 1. Structure of specimen with point contact for measurement.