Superconducting Proximity Effect in the Native Inversion Layer on InAs

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A superconducting proximity effect existing in a two-dimensional electron gas in the native inversion layer on a p-type InAs substrate has been confirmed. A supercurrent in the inversion layer was observed for the first time, in addition to an ac Josephson effect, with superconducting electrodes separated by 0.2–0.5 μm. The coherence lengths obtained coincide well with each other, both experimentally and theoretically. A junction with a metal gate electrode showed the controllability of the supercurrent by the gate voltage.

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The superconducting proximity effect has been widely investigated with superconductor–normal-metal–superconductor (SNS) junctions from the viewpoint of the transport properties in proximity-effect systems.[1–4] Recently, the proximity-effect theory was applied to the electron system of n-type InAs[5] with very low carrier concentrations (10^{16}–10^{18} cm^{-3}). n-type InAs has the advantages of light electron effective mass, high mobility, and negative Schottky barrier[6] to study the proximity effect in semiconductors. p-type InAs has the native n-type inversion layer on its surface, and the two-dimensionality of the electron-gas system in the inversion layer has been confirmed.[7] This two-dimensional electron-gas (2DEG) system has been studied from many aspects, e.g., transport properties,[7–9] the possibility of being superconductive itself,[10] subband structures, and Anderson localization.[11]

In few-dimensional physics, much interest has been paid to the relation between superconductivity and localization.[12,13] If the superconducting 2DEG system in semiconductors is realized, it gives new information which can further clarify the relation. The 2DEG system in the inversion layer is suitable for this study, since many different electronic states are realized in this system.

In this Letter, the authors report superconductivity in inversion-layer–coupled (superconductor, inversion layer, superconductor) junctions fabricated on p-type InAs. The 2DEG system became superconductive as a result of the proximity effect. The superconducting characteristics are discussed from the viewpoint of the coherence length of the 2DEG.

A cross-sectional view of the fabricated junction without a gate is shown in Fig. 1(a). Two superconducting Nb electrodes are coupled with the native inversion layer on the p-type InAs substrate. The coupling length L, the separation between two electrodes, was made in the range from 0.2 to 0.5 μm. The thickness of the Nb film is about 100 nm. The electrode width W is about 80 μm. The fabrication process of the junction was almost the same as the process for an Nb-(n-)InAs-Nb junction.[5] The substrates used were p-type, (100)-oriented, Zn-doped InAs single crystals. The carrier concentration and Hall mobility of the substrate were 2.6×10^{17} cm^{-3} and 240 cm^2/V·s at 4.2 K, respectively. The important point in fabrication is to cover the coupling part of the inversion layer [the dotted part in Fig. 1(a)] by electron-beam resist until the final liftoff process of Nb, since the transport property strongly depends on the surface conditions.

Junctions with a metal-insulator-semiconductor gate have also been fabricated to study the controllability of the superconducting characteristics by the gate voltage. In Fig. 1(b) a cross-sectional view of the junction with a metal-insulator-semiconductor gate is shown. After Nb electrodes were deposited, the surfaces of Nb and InAs were anodically oxidized to a thickness of about 20 nm, after which a chemical-vapor deposited (CVD) SiO_2 film with thickness of about 100 nm was deposited subsequently on the anodic oxide films as a gate insulator. Finally, an Au gate electrode was formed on the insulator. [Hereafter, the junction in Fig. 1(a) will be referred to as type A and that in Fig. 1(b) type B.]

The I-V characteristics of a type-A junction at 2 K are shown in Fig. 2. As shown in the figure, the junction showed a clear supercurrent. The supercurrent was observed for L up to ~ 0.5 μm. The junction also

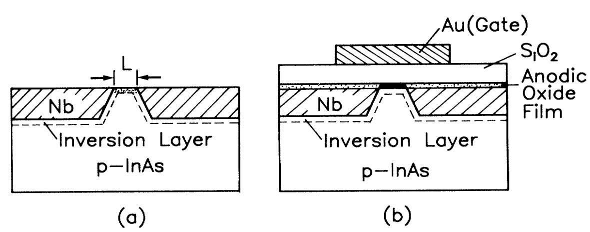

FIG. 1. Schematic of the junction structure: (a) Cross-sectional view of the junction without a gate; (b) cross-sectional view of the junction with a metal-insulator-semiconductor gate.

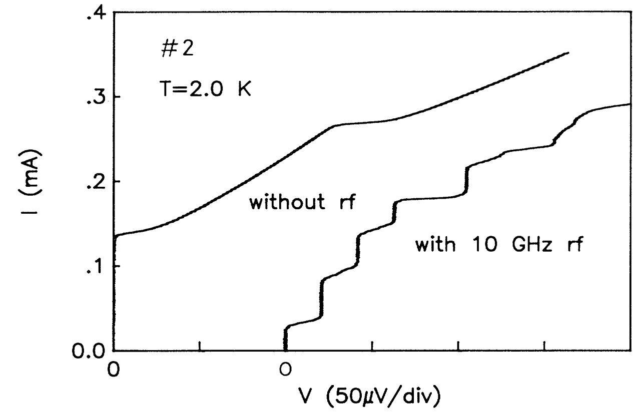

FIG. 2. I-V characteristics of a type-A junction at 2 K. The junction shows clear Shapiro steps, in the right-hand I-V curve under 10-GHz irradiation.

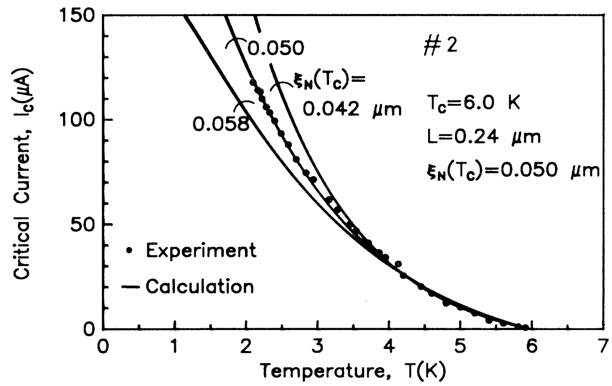

FIG. 3. Temperature dependence of I_c. The solid line is the calculated plot with the expansion of Eq. (1) near T_c.

showed clear Shapiro steps under 10-GHz rf irradiation (ac Josephson effect). These showed that the 2DEG in the inversion layer became superconductive and the junction had Josephson-junction characteristics. Kawaji, Miki, and Kinoshita[14] found a resistivity anomaly of the inversion layer on p-type InAs with high surface-carrier concentration N_s of $\sim 10^{13}$ cm^{-2} below 4 K and estimated the superconducting transition temperature T_c at 2.7 K. Considering N_s and T_c in our system ($N_s \sim 5\times 10^{11}$ cm^{-2}, $T_c \sim 6$ K), however, the superconductivity shown in Fig. 2 is found to be not the superconducting transition of the 2DEG itself but that due to the proximity effect.

Typical I_cR_N products for type-A junctions are from 0.094 to 0.14 mV at 2 K, where I_c and R_N are the critical supercurrent and the normal resistance, respectively. R_N is much lower than the estimated normal resistance because there is normal leakage current between two electrodes with no isolation from the substrate.

According to the proximity-effect theory,[1,15] I_c for an SNS junction is represented as

$$I_c \propto \left(\frac{\Delta_N(T)}{\cosh[L/2\xi_N(T)]}\right)^2 \frac{1}{\xi_N(T)}, \tag{1}$$

where $\Delta_N(T)$ is the induced pair potential of the normal metal at the S/N boundary and ξ_N is the coherence length of the normal metal. The superconducting characteristics of an SNS junction depends on the transport property of the normal metal. For the dirty metal ξ_N can be written as $\xi_N = (\hbar D/2\pi k_B T)^{1/2}$, where D is the diffusion constant of the normal metal.

Seto and Van Duzer[15] extended the proximity-effect theory to semiconductor-coupled junctions as to the coherence length for the three-dimensional, free-electron-gas model. Good agreement between theoretical and experimental results were obtained for n-type InAs[5] and highly doped p-type Si.[16]

The coherence length of the 2DEG in the inversion layer can be obtained by comparison of the measured temperature dependence of I_c with the calculated dependence obtained by expansion of Eq. (1) near T_c. The temperature dependence of I_c was measured for the type-A junction with $L = 0.24$ μm. In Fig. 3 the measured data and the calculated ones are shown. Figure 3 gives a coherence length of 0.060 μm at 4.2 K, with the assumption that the diffusion constant is independent of temperature. Yamaguchi[11] showed that the mobility in the inversion layer on p-type InAs was almost independent of temperature 80 K; therefore this assumption holds in the temperature range of our experiment. The critical temperature T_c, i.e., the critical temperature of the proximity-effect system, was determined to be the temperature at which I_c reduced to zero. T_c was found to be lower than 7.2 K, the critical temperature of Nb used for the electrode.

The coherence length can also be obtained by the coupling-length L dependence of I_c, where the temperature is kept constant. The L dependence of I_c for the type-A junction at 2 K is shown in Fig. 4. The solid line in the figure is the L-dependent part of Eq. (1), $\cosh^{-2}[L/2\xi_N(T)]$. The coupling length L was measured by scanning electron microscopy. The best match between the calculated and experimental data was obtained by setting the coherence length at 0.12 μm. From this value the coherence length at 4.2 K was determined to be 0.083 μm under the assumption that D is independent of temperature. The two coherence lengths obtained by the temperature and the coupling-length dependences of I_c coincide well with each other. This coincidence and the good numerical explanation for the experimental data shown in Figs. 3 and 4 indicate that the superconducting characteristics of the 2DEG in the inversion layer can be explained by the proximity-effect theory.

Although it is supposed that the proximity-effect theory can be used in the inversion-layer–coupled

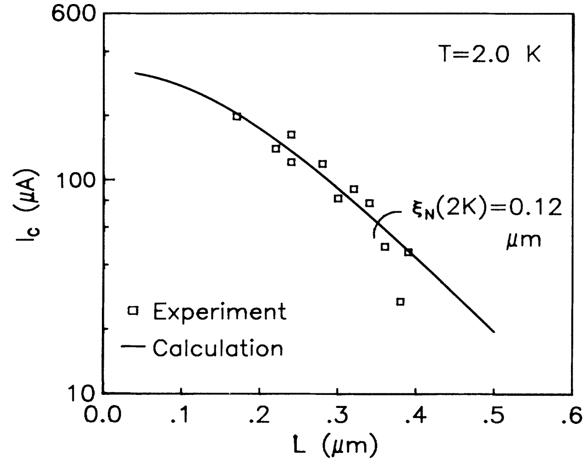

FIG. 4. I_c at 2 K as a function of L. The solid line is the L-dependent part of Eq. (1).

junction as regards the coherence length, the electron system is two dimensional and consequently a modification is needed for the theory. In general, D is represented as $v_F l/d$, where d is the number of dimensions, v_F is the Fermi velocity, and l is the mean free path. With use of the relations $l=\mu v_F m^*/e$, $k_F=(2\pi N_s)^{1/2}$, $v_F=\hbar k_F/m^*$, and $d=2$ in the 2DEG system, the coherence length of the 2DEG is obtained as

$$\xi_N(T)=(\hbar^3\mu N_s/2k_B Tem^*)^{1/2}, \tag{2}$$

where m^* is the carrier effective mass. Many investigations on the transport properties in the inversion layer have been made, especially for Si metal-oxide-semiconductor field-effect transistors.[17] However, few data in the case of a native inversion layer on p-type InAs were available. The transport properties in the inversion layer are very sensitive to the surface conditions. In our experiment, the junction with anodized InAs surface showed no I_c change. However, when a CVD SiO_2 film was subsequently deposited on the anodic oxide film of InAs as a gate insulator to fabricate a type-B junction, the junction showed a reduction in I_c, e.g., one-third of the original amplitude. This suggests that the surface potential, which measures the band bending at the InAs surface, strongly depends on the excess charge in the gate insulator. Kawaji and Gatos[7] obtained $N_s \cong 5\times10^{11}$ cm^{-2} and field-effect mobility $\mu \cong 3000$ cm^2/V·s on the etched surface using p-type InAs with carrier concentration of 2.6×10^{16} cm^{-3}. With substitution of these values of N_s, μ, and $m^*=0.024m_e$ into Eq. (2), a coherence length of 0.07 μm at 4.2 K is obtained, where m_e is the free-electron mass. This calculated value agrees well with the experimentally obtained value of 0.060–0.083 μm. This shows that the coherence length of the 2DEG in the inversion layer is given in Eq. (2).

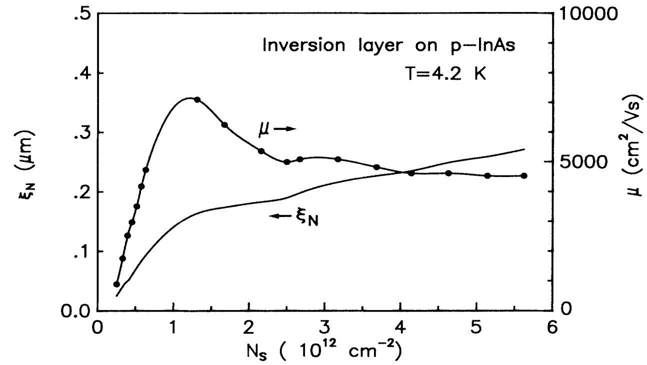

FIG. 5. The coherence length ξ_N(4.2 K) obtained by substitution of the measured N_s and μ (Ref. 11) into Eq. (2). The measured μ as a function of N_s (Ref. 11) is also shown.

The characteristics of the inversion layer also depend on the carrier concentration of p-type InAs. The width of the inversion layer decreases with increasing carrier concentration, and consequently, N_s decreases. Yamaguchi[11] precisely measured the Hall mobility as a function of N_s using 1×10^{17}-cm^{-3} doped p-type InAs metal-insulator-semiconductor field-effect transistors. The results are shown in Fig. 5. The coherence length calculated by substitution of μ and N_s in Fig. 5 into Eq. (2) is also shown in the figure. From the figure, it can be seen that the coherence length of 0.060–0.083 μm yields $N_s=4.4\sim5.8\times10^{11}$ cm^{-2} and $\mu=2900$–4100 cm^2/V·s. These values are considered to be values in the native inversion layer of the present system. They are very close to the values obtained by Kawaji and Gatos.[7] This also verifies that Eq. (2) gives the coherence length of the 2DEG. However, no direct measurement of N_s nor μ of the native inversion layer has been made yet. More investigation of the inversion layer is required.

In Fig. 5, ξ_N varies with the change in N_s and μ. This means that I_c varies with the change in N_s, according to Eq. (1). We could actually change I_c by operating a type-B junction. Figure 6 shows the measured I_c and R_N as a function of the gate voltage V_g that was applied between the gate and Nb electrode. As can be seen from the figure, I_c and R_N vary with V_g. This shows that the superconducting characteristics of the junction can be controlled by changing N_s and μ in the inversion layer. The changes in N_s and μ come from the change in the surface potential. This is the first experimental demonstration that the supercurrent of a Josephson junction is controlled by the electric field, and not by the magnetic field or current injection. Moreover, an increase in I_c and a decrease in R_N are realized in this junction, while in other I_c control methods these are impossible. As shown in the figure, however, the sensitivity of I_c vs V_g, dI_c/dV_g, is very low. This is because the density of

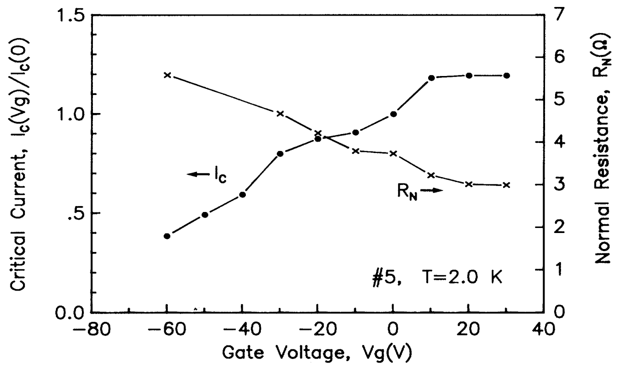

FIG. 6. I_c and R_N as a function of the gate voltage V_g. The data were measured with a type-B junction with $L = 0.26$ μm. An increase in I_c was observed. I_c is normalized by $I_c(V_g = 0)$.

InAs surface states is very high. These states were generated by the formation of insulating films on the InAs surface.

In summary, a supercurrent through the 2DEG in the inversion layer on *p*-type InAs was observed for the first time with a superconductor–inversion layer–superconductor junction. It was shown that superconducting characteristics of the 2DEG were explained by the proximity effect, and the coherence length of the 2DEG was given both experimentally and theoretically. It was also shown that the superconducting characteristics of the 2DEG could be controlled by the gate voltage applied between the gate and the superconducting electrode. The superconductivity in the 2DEG system provides interesting new subjects in few-dimensional physics. Advanced studies on the 2DEG, e.g., the determination of the superconductor-2DEG boundary condition, the change of ξ_N and T_c, and the relation between superconductivity and localization, will be made with a metal-insulator-semiconductor gate fitted junction. The system also appears to be important for basic applications.

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