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Supercurrent transport through a high-mobility two-dimensional electron gas

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We demonstrate that a supercurrent can flow through a high-mobility two-dimensional electron gas (2DEG) between two superconducting contacts 1 μm apart. The $Al_xGa_{1-x}As$/GaAs channel length is over 10 times the proximity-effect-induced coherence length in the semiconductor, and electrons travel ballistically between the contacts. The supercurrent is destroyed when the mobility of the 2DEG is reduced by electron-beam irradiation, suggesting that the supercurrent results from coherent Andreev reflection and ballistic transport between the superconducting electrodes.

Supercurrent transport through a superconductor-semiconductor-superconductor junction requires that the electron-pair phase be continuous between the superconducting electrodes. Transport of this phase in the semiconductor region can be either diffusive or ballistic depending on the mobility of electrons in the semiconductor. Supercurrent transport in semiconductors has been studied in the "dirty" limit[1-9] (where the electron mean free path l_e is less than proximity-effect-induced pair coherence length ξ_n in the normal material), and some experiments[10,11] have been performed in the boundary between the "clean" and dirty limits ($l_e \approx \xi_n$). In these cases the junction length l_j is not more than a few times ξ_n, but as yet the clean limit ($\xi_n \ll l_e$) in long junctions ($\xi_n \ll l_j$) has not been investigated. In this limit, pairs in one superconducting contact are injected into the semiconductor, travel without inelastic scattering, then enter the second contact. Injection at both interfaces and travel in the intervening region must be phase preserving.

Experiments using ballistic weak links where coherent Andreev reflection[12] (a process of charge transport across the superconductor-normal interface) may be possible between the contacts require that the superconducting contacts have extremely thin Schottky barriers to a high-mobility semiconductor. Recently, such contacts have been reported between tin and an $Al_xGa_{1-x}As$/GaAs heterojunction containing a high-mobility two-dimensional electron gas (2DEG),[13-15] where unusual effects have been observed at the interfaces, but no supercurrent has been observed between the electrodes.

We report the observation of supercurrent transport well within the clean limit in a high-mobility 2DEG in an $Al_xGa_{1-x}As$/GaAs heterojunction between two superconducting indium electrodes 1 μm apart. The supercurrent I-V characteristic was changed to an excess voltage below the critical temperature of the electrodes by reducing the mobility of the electron gas by electron-beam irradiation of the weak link.

The weak link was fabricated by deposition of indium electrodes with a gap of 1 μm on the surface of an $Al_xGa_{1-x}As$/GaAs heterojunction with a channel 200 μm wide, shown schematically in Fig. 1. The Ohmic contacts were then formed to the 2DEG, 60 nm below the surface, by sintering the indium at 420 °C for 120 s in a N_2+5%H_2 forming gas.

The carrier concentration and mobility of the 2DEG were determined to be $5.9\times10^{11}\,\mathrm{cm}^{-2}$ and $1.1\times10^{5}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, respectively, at 4.2 K in the dark. The mobility corresponds to an electron elastic mean free path l_e of 1.4 μm.

The coherence length ξ_n in the semiconductor in the clean limit is given by[16]

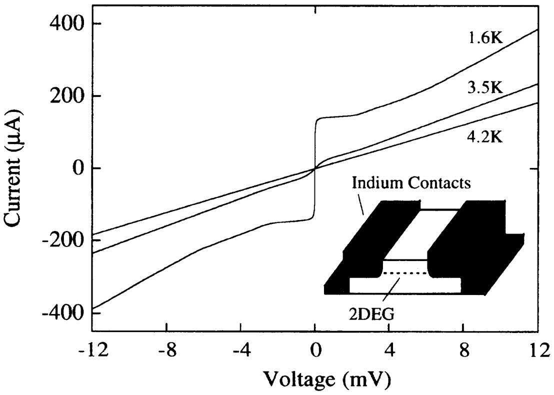

FIG. 1. I-V characteristics for the S-Sm-S junction at a range of temperatures from 1.6 K to 4.2 K. A schematic diagram of the device is shown in the inset.

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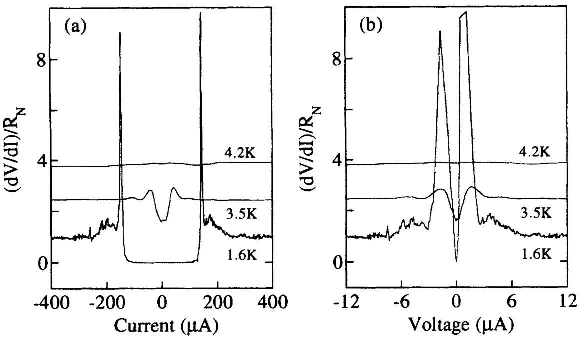

FIG. 2. Differential resistance of the S-Sm-S junction corresponding to the I-V characteristics of Fig. 1 against (a) the current through the junction and (b) the voltage across the junction. The curves have been normalized to R_n at 1.6 K and above 1.6 K have been offset by $dR/R_N = 1$.

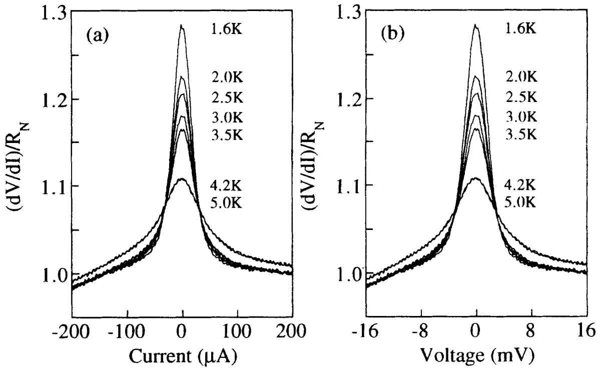

FIG. 3. Differential resistance of the S-Sm-S junction showing an excess voltage characteristic after reducing the electron mobility in the semiconductor by electron-beam irradiation against (a) the current through the junction and (b) the voltage across the junction.

$$\xi_{nc} = (\hbar^2/2\pi m^* k_B T)(2\pi N)^{1/2} \tag{1}$$

in two dimensions, and in the dirty limit by

$$\xi_{nd} = (\hbar^3 \mu/6\pi m^* e k_B T)^{1/2}(2\pi N)^{1/2}. \tag{2}$$

The overall coherence length well within either limit is given by Silvert[17] as

$$\xi_n = (\xi_{nc}^{-2} + \xi_{nd}^{-2})^{-1/2} \tag{3}$$

and at the transition between the limits ($l_e/\xi_n = 1$) by Kleinsasser[11] as

$$\xi_n \cong \xi_{nd}\{1 + [l_e/\xi_{nc}(T_c)]\}^{-1/2}. \tag{4}$$

The coherence length in our device is 90 nm at 4.2 K (less than 1/10 of the gap between the contacts), which makes the ratio $l_e/\xi_n = 15$ well within the clean limit. Transport in the 2DEG of our device approaches the transition between the limits at a temperature of approximately 0.1 K because the normal coherence length increases more rapidly than the mean free path as temperature decreases.

The superconducting contacts have a critical temperature T_c of 4.3 K, higher than that of bulk In (3.4 K). This is probably due to alloying in the contact.

The two-terminal dc I-V characteristics and the differential resistance were measured using a lock-in technique with an alternating voltage less than 10 μV. The normal state resistance at 4.2 K at the start of the experiment was 65 Ω. The I-V characteristics of the device from 1.6 K to 4.2 K are shown in Fig. 1. At 1.6 K and at low currents the I-V curve is vertical; the device has zero resistance. The supercurrent collapses with temperature so that by 3.0 K the device exhibits a small excess current, and is Ohmic at 4.2 K, close to the critical temperature of the electrodes.

The differential resistance of the device from 1.6 K to 4.2 K is shown in Fig. 2. At the critical current I_c of approximately 100 μA the resistance starts to increase slowly from zero, then rises to a large peak before returning to the normal state resistance. The supercurrent characteristic and critical temperature of the electrodes were reproducible after thermal cycling. The application of a magnetic field at 1.6 K causes the device to become measurably resistive at $\approx$10 mT. The resistance then increases gradually until the contacts become normal at 200 mT, above which Shubnikov–de Haas oscillations are observed.

To confirm that conduction of the supercurrent was through the 2DEG, two further experiments were carried out. The first was to determine that the contact sintering process did not result in the formation of conducting channels between the electrodes and, hence, a parasitic path for supercurrent transport between the electrodes. We fabricated and measured the characteristics of almost identical junctions with In contacts on semi-insulating GaAs, rather than the heterojunction. Gaps between the contacts ranged from 2 μm down to 0.4 μm. The resistance of all devices regardless of the contact gap was $> 10\,\text{M}\Omega$. This confirmed that parasitic conducting channels are not formed by interdiffusion of the In contacts on or below the surface of the GaAs, even when the gap is submicrometer size, for our sintering conditions.

The second experiment was to determine that the supercurrent flows between the contacts directly as a result of the high mobility in the semiconducting region between the contacts. To show this, it is necessary to reduce the mobility of the 2DEG without significantly depleting the carrier concentration between the electrodes, or damaging the interfaces.

It has been shown that the high mobility of a 2DEG can be reduced by electron-beam irradiation.[18–20] At electron energies of approximately 10 keV the reduction in the mobility is maximum for a 2DEG which is around 60 nm deep. The reduction in mobility is most likely caused by the charging of defects and trap sites close to the 2DEG region, as the electron energy is too low to cause atomic defects. We have reduced the mobility of our device by irradiating with an electron beam of energy 10 keV with a dose of approximately $1\times10^{-8}\,\text{C}\,\mu\text{m}^{-2}$, over two orders of magnitude greater than the dose used in Refs. 18–20.

The differential resistance of the device in the range 1.6 K to 5.0 K after irradiation is shown in Fig. 3. The supercurrent and excess current have been completely eliminated and are replaced by an excess voltage that rapidly develops below the critical temperature. The normal state resistance of the device at 4.2 K has risen from 65 Ω to 80 Ω.

Assuming the interface resistance to remain approxi-

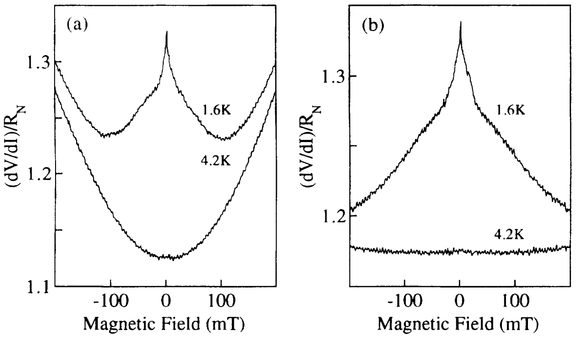

FIG. 4. Magnetoresistance of the S-Sm-S junction after electron-beam irradiation showing the collapse of the excess voltage below the critical temperature of 4.3 K in (a) a perpendicular magnetic field and (b) a parallel magnetic field.

mately constant before and after electron-beam damage (no atomic rearrangement takes place in the semiconductor during the irradiation process, and the interfaces below the surface are screened from electron penetration by the metallic electrodes at the surface), then most of the increase in the normal resistance is due to the increased resistivity of the 2DEG. The carrier concentration of the 2DEG was measured and found to be the same before and after irradiation, which is consistent with previous studies,[18,19] so the increase in resistivity results from a decrease in the 2DEG mobility.

The increase in resistivity of the 2DEG is approximately 30 times (before irradiation the 2DEG resistance was $\approx 0.5\,\Omega$; after irradiation this had increased to $\approx 15\,\Omega$), which indicates that the mobility has been reduced from $1.1\times 10^5\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ to $3.7\times 10^3\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$, changing the ratio l_e/ξ_n from 15.2 to 1.2 from well within the clean limit to the clean-dirty transition (Kleinsasser's[11] expression for ξ_n has been used at the transition). The new mean free path (47.5 nm) is now over 20 times shorter than the distance between the two superconducting contacts.

To confirm that the measured excess voltage was directly due to the superconducting contacts we applied a low magnetic field first perpendicular and then parallel to the junction. The magnetoresistance is shown in Fig. 4 at and below the critical temperature of the electrodes. The sharp peak around zero bias appears just below the critical temperature with a width of approximately 40 mT, outside which the superconductivity is extinguished from the electrodes. There may be small residual islands of superconductivity persisting to higher fields, which causes the more gradual decay of the magnetoresistance up to 200 mT as in Fig. 4(b). This central peak could also be explained by increased weak localization at the normal-superconductor interfaces, which has been predicted by Marmorkos *et al.*,[21] and observed by Lenssen *et al.*[22] The temperature dependence can be seen to change sign at ±3 mV, as the enhanced weak localization is suppressed.

We believe that the interfaces in this device are highly transparent (a very thin Schottky barrier), which allows the measurement of coherent Andreev reflection with ballistic electron transport between the superconducting electrodes. This results in a single electron-pair phase between the electrodes and thus a measured supercurrent. After electron-beam irradiation, an excess voltage was measured because the device became a superconductor-disordered semiconductor-superconductor system with transparent interfaces. Marmorkos *et al.*[21] have recently shown that an excess voltage characteristic can be observed in a superconductor-disordered normal junction even when the interface itself is highly transparent.

The critical current-normal resistance product I_cR_n, known as the critical voltage V_c, is an important figure of merit for weak links. The measured V_c for our device ($I_c = 100\,\mu\mathrm{A}$, $R_n = 35\,\Omega$ at 1.6 K) is 3.5 mV, and the energy gap in the indium electrodes is 1.5 meV [calculated using the experimental expression for indium $2\Delta(0) = 4.1k_BT_c$]. The value of R_n has been determined from the high bias linear asymptote in the I-V characteristics, where the resistance is constant with no significant further curvature. V_c is unusually large as it exceeds by a factor of 2 the total energy gap of the two superconducting electrodes.

The temperature dependence of the normal state resistance between 1.6 K and 4.2 K is mostly due to the Ohmic contacts. The 2DEG resistance is $\approx 0.5\,\Omega$, so R_n is dominated by conduction in the diffused contacts. Close to T_c the contacts are in an intermediate state with some normal and some superconducting areas. It is this mixture of states that progressively increases the normal state resistance until at T_c the contact is entirely normal. There appears to be a difference in the resistance of the contacts for the voltage carrying state and the normal state resistance above T_c.

The Ambegaokar-Baratoff[23] result $[\pi\Delta(0)/2e]$ has traditionally been used as an upper bound to V_c and in this case is 1.02 mV. V_c for our device is over four times larger than this result, but the Ambegaokar-Baratoff system is a tunnel junction and is not directly applicable to transparent contacts.

The critical voltage has been derived for a junction in the clean limit by Kulik and Omelyanchuk,[24] and is given as

$$I_sR_n = \pi\Delta/e\,\sin(\phi/2)\tanh[\Delta\cos(\phi/2)/2k_BT], \tag{5}$$

where ϕ is the superconducting phase across the junction. This expression shows that V_c is dependent on the ratio T/T_c and can occur at a phase $\phi < \pi$ when $T > 0$ K. In our experiment $T/T_c = 0.37$, so $V_s(\max) = V_c = 1.81$ mV at a phase of $\phi = 2.08$ rad. This result was also derived for a very short junction where $l_j \ll \xi_n, l_e$, for a continuous metal weak link. It may be possible that if Andreev reflection at the contacts is taken into account, then this value may be increased by a factor of 2.

The previous theoretical results did not consider a normal region of different effective mass and Fermi velocity from the electrodes, so the results were not dependent on the properties of the normal region. Bardeen and Johnson, and very recently Golub and Horovitz[25,26] extended a theory by Ishii[27] to calculate V_c for a superconductor-normal-superconductor and show how this varies with length ($l_j \gg \xi_n$) and temperature. Scattering in the normal region is neglected, but thermal equilibrium of carriers in the normal region is assumed, rather than ballistic transport. The calculated V_c (Ref. 25) is $\approx 4.5\,\mu\mathrm{V}$, clearly much smaller than measured. This is because the maximum critical current density in the calculation is limited by the density of electron states in the normal region. For ballistic transport, the density of states is not limited to the thermal equilibrium value.

The previous results show that V_c is more likely determined by the properties of the Andreev coupling at the electrodes combined with ballistic transport in the normal region. Therefore, the result of Kulik and Omelyanchuk seems more applicable to our device.

In conclusion, we have demonstrated that it is possible for a supercurrent to flow through a 2DEG between two superconducting Ohmic contacts that are separated by more than ten times the normal coherence length. The supercurrent is carried via ballistic electrons and Andreev reflection at both interfaces, leading to pair coherence across the device, and a large I_cR_n product of 3.5 mV. This large V_c cannot be easily explained using the models currently available as the geometry, the two dimensionality, the ballistic transport, and the multiple Andreev reflection are not addressed in any one model; however, it is evident that the observed phenomenon and the large V_c are directly caused by ballistic transport between the electrodes. Electron-beam irradiation of the device permanently destroys the supercurrent by making transport in the 2DEG diffusive.

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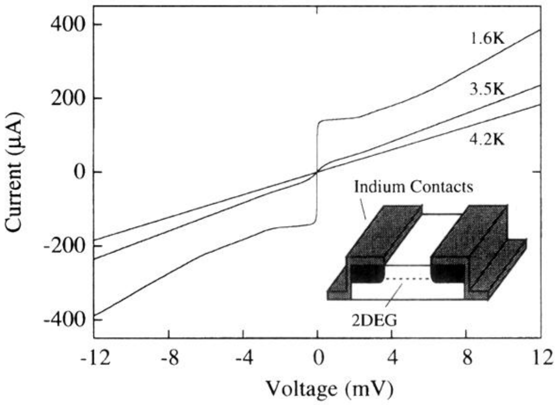

FIG. 1. I-V characteristics for the S-Sm-S junction at a range of temperatures from 1.6 K to 4.2 K. A schematic diagram of the device is shown in the inset.