Observation of Pair Currents in Superconductor-Semiconductor Contacts

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An excess low-voltage conductance is observed in Nb-InGaAs contacts at low temperatures and interpreted as being due to a pair current across the superconductor-semiconductor interface. This is the first observation of a pair current, a nonequilibrium manifestation of the proximity effect, in junctions having one electrode which is not a superconductor. A model is presented which accounts for the observed behavior. In addition to the pair current, it is demonstrated that these junctions exhibit excess conductance due to Andreev scattering.

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Contacts between superconductors (S) and semiconductors (Sm) have received considerable attention as a consequence of interest in hybrid devices [1]. The naturally occurring Schottky tunnel barrier at an SSm interface has a transmittance which is variable over many orders of magnitude by varying the Sm doping. The bulk of the semiconductor is a normal metal (N) and the Schottky barrier an insulator (I), so an SSm contact is an SIN junction. Ordinarily current is carried through the interface by tunneling of quasiparticles with energies exceeding the superconducting gap Δ. In high transmittance contacts, Andreev reflections contribute additional current at low energies [2,3], resulting in excess low-bias conductance and excess large-bias current, as observed in $SSmS$ junctions [4].

Most investigations of SSm contacts have dealt with $SSmS$ junctions. The behavior of such junctions is more complicated than that of two series SSm contacts due to nonequilibrium transport in Sm [4,5] and the possibility of supercurrents [1]. For these reasons, we investigated single SSm interfaces [6]. In this paper, we describe measurements on Nb-InGaAs junctions which reveal a temperature- and magnetic-field-sensitive excess conductance in high transmittance junctions which we attribute to a pair current due to the proximity effect. Although pair currents have been predicted [7,8] and observed [9] in SIS' junctions in which S' is a superconductor above its transition temperature, we know of no reports of supercurrents in SIN structures with N normal. We present a model which accounts for our observations, including the fact that the effect is much larger in junctions with an Sm, as opposed to a metal, electrode. In addition, these junctions exhibit the expected increase in the Andreev current as the contact transmittance is increased by raising the doping in the InGaAs layer [4], and a new method for studying such currents is presented.

For high contact transmittance, low barrier height E_B and effective mass m^* are desirable. Therefore Nb-$n^+In_{0.53}Ga_{0.47}As$ ($E_B = 0.2$ eV, $m^* = 0.044 m_e$) junctions were used in this work. First, a 50-nm-thick layer of $n^+In_xGa_{1-x}P_yAs_{1-y}$ ($n = 5\times10^{18}$ cm^{-3}) was grown epitaxially on an n^+InP substrate by organometallic chemical vapor deposition. Composition was graded from InP to $In_{0.53}Ga_{0.47}As$ for lattice matching to InP and to avoid a potential barrier at the substrate. Next, a 100–300-nm-thick $n^+In_{0.53}Ga_{0.47}As$ layer with n between 10^{18} and 2.5×10^{19} cm^{-3} was grown. To provide an oxide-free Nb-InGaAs interface, the sample was heated in a second UHV chamber to 600 °C under an As flux of 10^{-7}–10^{-6}-Torr beam equivalent pressure to remove the oxide, using reflection high-energy electron diffraction (RHEED) to determine the point of oxide desorption. Upon cooling to room temperature, a 50-nm-thick As cap was deposited to protect the surface from oxidation. In a third chamber, the sample was then heated to 450 °C to remove the As cap, cooled to below 100 °C, and 200 nm of Nb was deposited by sputtering. A typical Nb film had a transition temperature of 9.28 K and a residual resistance ratio of 4.5.

The conductance of 20×20-μm^2 devices was measured using a conventional four-terminal lock-in technique with two leads on the Nb electrode and two leads attached to separate neighboring devices or to the back of the substrate. Some resistance in series with the Schottky barrier of interest is unavoidable due to the contribution of the substrate. However, the series resistance was less than 0.1 Ω and the predominant voltage drop was across the Schottky barrier in all cases. Series resistance is ignored in the discussion here since its inclusion does not affect our conclusions.

Figure 1 shows the conductance-voltage characteristics at 1.2 K, normalized to the normal-state zero-bias conductance, for two typical devices with InGaAs doping levels of 1×10^{18} and 2.5×10^{19} cm^{-3} and normal-state resistances of 2.8 Ω (1.1×10^{-5} Ω cm^2) and 0.26 Ω (1.1×10^{-6} Ω cm^2), respectively. The 10^{18}-cm^{-3} sample behaves as a conventional SIN tunnel junction except for two features: (1) the characteristic is asymmetric due to the shape of the Schottky barrier and (2) the low-temperature subgap conductance is too large to be attri-

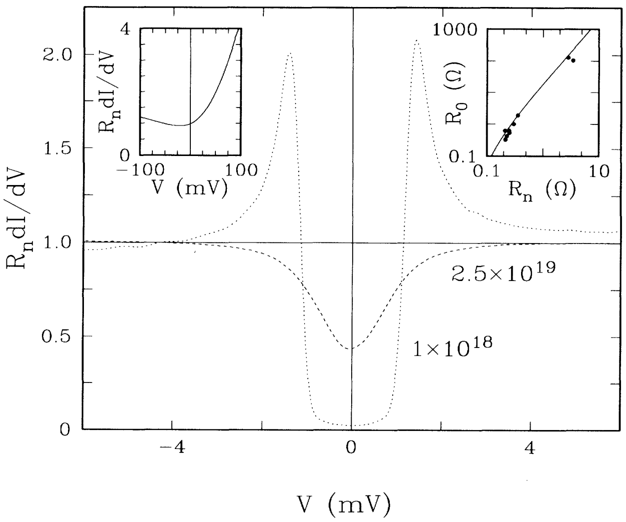

FIG. 1. Normalized conductance-voltage characteristics at 1.2 K for two Nb-InGaAs diodes with carrier densities of 1×10^{18} (R_n=2.8 Ω) and 2.5×10^{19} cm^{-3} (R_n=0.26 Ω). It was necessary to apply a field of 100 mT in the plane of the junction to obtain these data for the 2.5×10^{19}-cm^{-3} sample, as discussed in the text. Left inset: Normalized conductance at 10 K for the 10^{18}-cm^{-3} sample. Right inset: Low-temperature zero-bias resistance R_0 vs normal-state resistance (points) for several devices with different doping levels. The curve represents Eq. (1), with R_n^0=0.1 Ω.

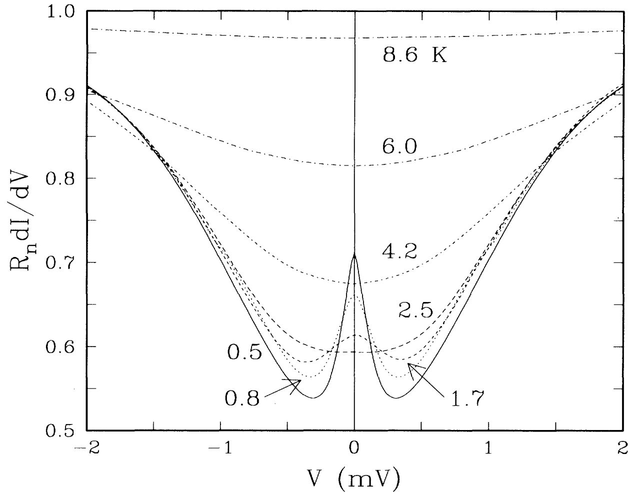

FIG. 2. Normalized conductance-voltage characteristics at temperatures of 8.6, 6.0, 4.2, 2.5, 1.7, 0.8, and 0.5 K and zero magnetic field for a 2.5×10^{19}-cm^{-3} device (R_n=0.27 Ω).

buted to *SIN* quasiparticle tunneling. The high-bias normal-state conductance is shown in the left inset of Fig. 1. It is consistent with tunneling through a 0.2-eV Schottky barrier [10] with a donor density of 10^{18} cm^{-3}. At low temperatures the zero-bias quasiparticle resistance of an ideal *SIN* junction increases as $\exp(\Delta/kT)$. It grows to $10^4 R_n$ in an ideal Nb junction at 1.2 K, as opposed to $46R_n$ in our sample, where R_n is the normal-state junction resistance. The 2.5×10^{19}-cm^{-3} sample in Fig. 1 has a much larger normalized low-bias conductance.

We now show that the mechanism for the large subgap conductance in our junctions is Andreev reflection at the *SSm* interface [2,3], even though our junctions were too resistive to exhibit the excess currents at large voltages usually associated with this process [2–4]. Since Andreev reflection is a second-order process involving two traversals of the interface, ordinary tunneling and Andreev currents vary as D and D^2, respectively, where D is the interface transmittance. Quasiparticle current is negligible at low temperatures and voltages, so Andreev current dominates in very transmissive junctions. For both point contacts [2,3] and planar tunnel junctions [11] the normal resistance R_n and the low-temperature zero-bias resistance due to Andreev reflection R_0 are simply related to the junction transmittance, and therefore to each other. Combining Eqs. (17) and (18) of Ref. [3], in the limits of zero voltage and temperature,

$$R_0=(2R_n-R_n^0)^2/2R_n^0\,, \qquad (1)$$

where R_n^0 is the limiting normal resistance of a highly transmissive contact. Data for samples of various dopings are consistent with this relationship (right-hand inset, Fig. 1), confirming the role of Andreev currents in these junctions.

Figure 2 shows the conductance of a 2.5×10^{19}-cm^{-3} device at several temperatures in zero magnetic field. As expected for quasiparticle tunneling, when the temperature is reduced below T_c the low-voltage conductance decreases. Surprisingly, a conductance peak at voltages below ~0.5 mV also emerges at temperatures below 2 K, becoming more pronounced at lower temperatures and continuing to increase even below 30 mK. Figure 3 shows the conductance of a 2.5×10^{19}-cm^{-3} device at 0.4 K for fields up to 89 mT. The low-temperature conductance peak is dramatically affected by small magnetic fields and is eliminated by fields well below 100 mT. The characteristics in 100-mT fields can be attributed to quasiparticle and Andreev currents; however, the low-field behavior, which was seen in over 40 devices, cannot. This excess conductance is not a zero-bias anomaly [12], since it completely disappears in very small magnetic fields. In the following discussion we argue that this phenomenon strongly suggests the presence of a supercurrent induced by the proximity effect.

Most theoretical treatments [2,3,11] of *SIN* junctions ignore the proximity effect, although it is essential to the function of a number of *SSm* devices [1]. Virtually all investigations of the proximity effect deal with *SN* contacts in equilibrium. Recently, however, the possibility of supercurrents in *SIN* contacts has been the subject of

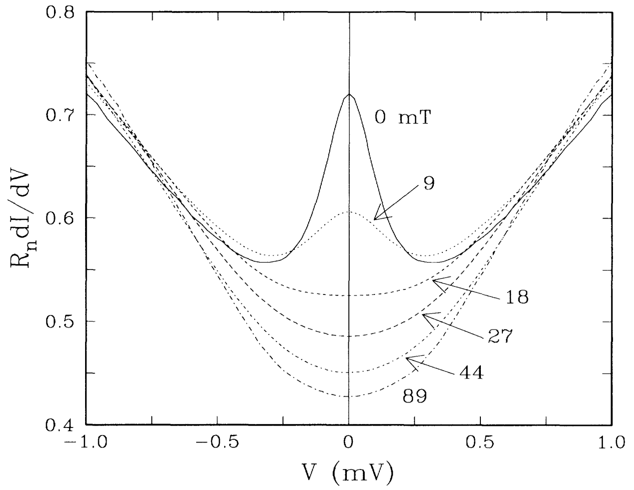

FIG. 3. Normalized conductance-voltage characteristics at 0.42 K in parallel magnetic fields of 0, 9, 18, 27, 44, and 89 mT for a 2.5×10^{19}-cm^{-3} device ($R_n=0.24$ Ω).

some controversy [13,14]. It is known that pair currents can flow in SIS' junctions with S' in the normal state [7–9] ($T_{cn}<T<T_{cs}$, where the s and n identify the superconducting and normal electrodes, respectively). Such currents exist only at low (but nonzero) voltages, low magnetic fields, and temperatures within 1% of T_{cn}, and are a manifestation of the proximity effect [15–17]. Some discussions [13,15] of this phenomenon imply that it can occur in SIN junctions in which N is not a superconductor, although this is not clear from a recent microscopic treatment [16], which predicts no effect for the case $T_{cn}=0$ (actually zero electron-electron interaction; an effect is predicted for the case of electron-electron repulsion). All experiments to date have involved SIS' junctions.

We propose that the current in our SSm contacts consists of a "normal" component (quasiparticle tunneling and Andreev reflection) and a pair current which is eliminated by small magnetic fields. The junction characteristic near 100 mT is representative of the normal current alone, and an additional pair current accounts for the low-field characteristics. An expression for the proximity-induced pair current density J_p in an SIS' junction in the limit of a thin normal film S' ($d_n \gg \xi_n$, where d_n and ξ_n are the normal layer thickness and coherence length, respectively) has been obtained by several authors [8,17], for arbitrary magnetic-field values. Making a phenomenological extension of similar expressions [7,15] obtained in the thick normal film for zero magnetic field, the voltage dependence of the pair current, J_p, can be expressed as

$$J_p=J_0\frac{[(1+v^2)^{1/2}-1]^{1/2}}{[(1+h^2)^2+v^2]^{1/2}}\,, \tag{2}$$

where $v=V/V_0$ and $h=H/H_0$. $V_0=\hbar/2e\tau_\Delta$, where τ_Δ is the order-parameter relaxation time, and $H_0=\phi_0/2\pi\xi_n(\lambda_s+d_n/2)$, where ϕ_0 is the flux quantum and λ_s the penetration depth in S. The zero-bias pair conductance is $(s^{-1/2}J_0/V_0)(1+h^2)^{-1}$. The pair current is linear in voltage at small voltages, but falls off for voltages above $3^{1/2}V_0$ and in magnetic fields $H_0\sim 10$ mT.

The magnitude of the supercurrent, for $T_{cn}<T\ll T_{cs}$, is

$$J_0=\frac{2}{\pi^2}\frac{1}{r_n}\frac{\rho_n\xi_n}{r_n}\frac{kT}{e}\ln^2\frac{T_{cs}}{T}\,, \tag{3}$$

where r_n is the specific resistance of the junction and ρ_n is the resistivity of the normal film. The normal coherence length $\xi_n=(\hbar D_n/2\pi kT)^{1/2}$ in the limit $T_{cn}\to 0$, where D_n is the electron diffusion constant in S'. To obtain an expression applicable in the limit of thick normal layers [7], we used the clear derivation of Kadin and Goldman [17], replacing d_n by $\pi\xi_n$.

In the situation of interest to us, S' is truly normal ($T_{cn}\to 0$). Equations (2) and (3) predict a proximity-effect-induced supercurrent which resembles our excess low-bias current. The relative magnitude of the pair current r_nJ_p is proportional to r_n^{-1}, indicating a second-order effect occurring only in very transmissive contacts. It is also proportional to ρ_n and is thus 3–4 orders of magnitude larger in SSm junctions than in metal SIN ones (having the same r_n), accounting for the almost 100% enhancement of zero-bias conductance we observed in SSm junctions, in contrast to the tiny effect reported earlier in SIS' ones [9].

The zero-bias pair conductance ($dJ_p/dV=2^{-1/2}J_0/V_0$) varies with temperature as $T\xi_n\tau_\Delta\ln^2(T_{cs}/T)$. The supercurrent peaks at a voltage $V_0=3^{1/2}\hbar/2e\tau_\Delta$, where $\tau_\Delta=\pi\hbar/8k(T-T_{cn})$ near T_{cn}. For $T_{cn}\to 0$, however, $\tau_\Delta=\pi\hbar/8kT$ and $V_0\propto T$ are not valid. Our data are consistent with a supercurrent peak position V_0, roughly the position of the conductance minima, that varies only slowly with temperature. The size of V_0 is somewhat less than Δ/e for Nb. We surmise that the appropriate relaxation time τ_Δ is $\sim\hbar/\Delta$ with Δ appropriate for the Sm layer. Since V_0 varies only slowly with T, we shall make the convenient *ad hoc* assumption that $\tau_\Delta\propto T^{-\alpha}$, with $\alpha\ll 1$. Then the zero-bias pair conductance varies as $T^{-\alpha+1/2}\ln^2(T_{cs}/T)$.

Figure 4(a) shows the temperature dependence of the zero-bias conductance of a 2.5×10^{19}-cm^{-3} device. In the 100-mT field the temperature dependence is consistent with Andreev currents [2,3]. We used a curve fitted through these data to represent the normal current in the device. Adding a pair conductance of the form $G_s=0.08R_n^{-1}T^{-\alpha+1/2}\ln^2(T_{cs}/T)$ with $\alpha=\frac{1}{6}$ resulted in a rather good fit to the zero-field data. The size of the prefactor is consistent with Eqs. (2) and (3) to within the accuracy to which we know the device parameters. The procedure worked equally well on other devices. In Fig. 4(b), the magnetic-field dependence at 51 mK of a

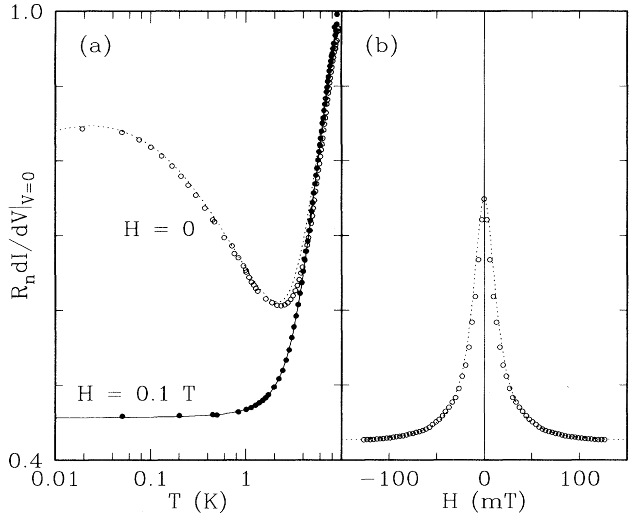

FIG. 4. (a) Normalized zero-bias conductance vs temperature in parallel magnetic fields of 0 and 100 mT for a 2.5 $\times 10^{19}$-cm^{-3} device ($R_n = 0.24\ \Omega$). The curves are fits to the data described in the text. (b) Normalized zero-bias conductance vs magnetic field for a similar sample ($R_n = 0.25\ \Omega$) at 51 mK. The fit is described in the text.

2.5×10^{19}-cm^{-3} device with $R_n = 0.26\ \Omega$ is shown. The data are well fitted by Eq. (2), using $G = G_n + G_p$ with G_n a field-independent normal conductance and $G_p = G_{p0}[1+(H/H_0)^2]^{-1}$. G_n and G_{p0} are 1.63 and 1.25 S, respectively, and $H_0 = 14.9$ mT, consistent with expectations.

In summary, we have observed an excess conductance in heavily doped Nb-InGaAs contacts in addition to the conductance due to Andreev reflection. We attribute this conductance to a pair current induced by the proximity effect. We have presented a model which extends the theory of pair currents in *SIS'* junctions to *SIN* and *SSm* junctions, accounting for the temperature and magnetic-field dependences of the excess conductance and for the large magnitude of the effect compared with that reported in *SIS'* junctions [9]. Our result appears to be in keeping with early theoretical discussions [13,15], although a recent microscopic calculation [16] predicts no effect for $T_{cn} = 0$. This pair current makes a significant contribution to the conductance of these devices and may be important in *SSmS* devices. It would be interesting to extend this work to even higher transmittance junctions to study the possibility of proximity-induced Josephson effects [14,15].

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