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Excess voltage and resistance in superconductor-semiconductor junctions

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We report the observation of excess voltage in Nb-$In_xGa_{1-x}As$ superconductor-semiconductor contacts (at large biases, the voltage in the superconducting state significantly exceeds that in the normal state). In addition, we describe an unusual temperature-dependent large-bias dynamic resistance, including a sudden increase as temperature decreases through the superconducting transition, a steady decrease with decreasing temperature below T_c, and a second smaller increase as temperature decreases through the onset temperature for the recently reported proximity-effect-induced pair current [A. Kastalsky *et al.*, Phys. Rev. Lett. **67**, 3026 (1991)]. These phenomena are discussed in terms of the rapidly evolving theory of superconductor-normal contacts with finite interface transmittance.

Superconductor-semiconductor (S-Sm) contacts behave as superconductor-insulator-normal (S-I-N) tunnel junctions in which the interfacial Schottky barrier is the insulator and the bulk semiconductor the normal metal.[1] The behavior of S-Sm contacts was long believed to be simple, with current carried only by quasiparticle tunneling.[2] However, it has been demonstrated[3] that Andreev reflection[4] contributes additional current in very transmissive contacts, resulting in a wide range of characteristics. More recently, a proximity-effect-induced pair current was observed in Nb-$In_xGa_{1-x}As$,[5] and subsequently in Nb-Si,[6] contacts. Such pair currents have been studied in S-I-N junctions in which N is a superconductor just above its transition temperature (T_c),[7] but early theories predicted no such effect if N is a nonsuperconductor. Recent microscopic theoretical treatments of S-I-N contacts,[8,9] however, support the pair current hypothesis. Thus, current is carried across an S-Sm contact by quasiparticles, by pair-quasiparticle conversion, and by pairs. Such contacts are the subject of considerable theoretical and experimental interest.

In this paper we report the observation of several phenomena in transport studies of the same heavily doped S-Sm contacts in which the proximity-induced pair current was first observed.[5] Two effects, an excess voltage (for fixed large-bias currents, the voltage in the superconducting state exceeds that in the normal state by a fixed amount) and an unusual temperature-dependent large-bias dynamic resistance, are not clearly related to the existence of a proximity effect or pair current across the interface. However, a sudden dynamic resistance jump at a temperature close to that at which the pair current becomes measurable, appears to be connected with its appearance.

The devices investigated were 20×20 μm^2 Nb–n^+-type $In_{0.53}Ga_{0.47}As$ Schottky diodes, described in an earlier publication.[5] The current-voltage (I-V) characteristic at 0.5 K of a device with $n = 2.5\times10^{19}$ cm^{-3} is shown in Fig. 1. The I-V becomes linear above roughly 3 mV but is displaced from the normal-state characteristic. As shown in Fig. 1, the difference between the superconducting and normal-state I-V's tends to a constant excess voltage. In contrast to the pair current,[5] this excess voltage is insensitive to fields small enough to leave the superconducting energy gap unperturbed. It is doping dependent, occurring only in low-resistance (high-transmittance) contacts. In high-resistance contacts (e.g., contacts with $n \sim 10^{18}$ cm^{-3}), the superconducting and normal characteristics coincide at large voltages.

Another feature observed in the heavily doped samples ($n \sim 10^{19}$ cm^{-3}) is a temperature-dependent dynamic resistance at large bias. Figure 2 is a plot of dynamic resistance at a bias of 6 mV, with magnetic fields of 0 and 0.1 T in the plane of the junction. This resistance exhibits a *sharp jump* (which is bias independent up to at least

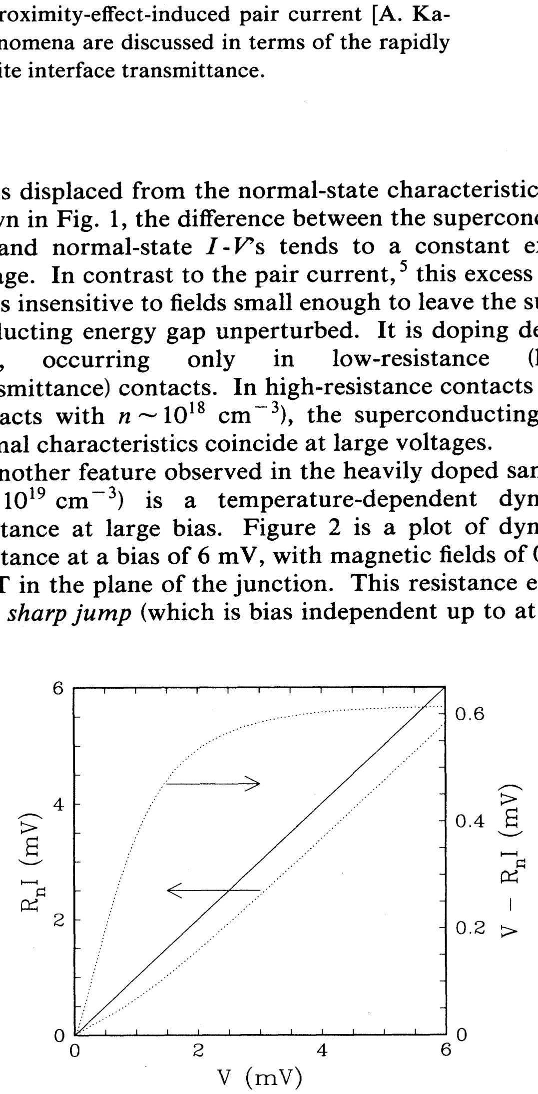

FIG. 1. Left axis: I-V characteristic (dotted curve) of a junction with $n = 2.5\times10^{19}$ cm^{-3} at 0.5 K. Also shown is the normal-state I-V (solid line). The device resistance is 0.26 Ω. Right axis: Difference between the voltage in the superconducting and normal states. The high-voltage limit is the excess voltage.

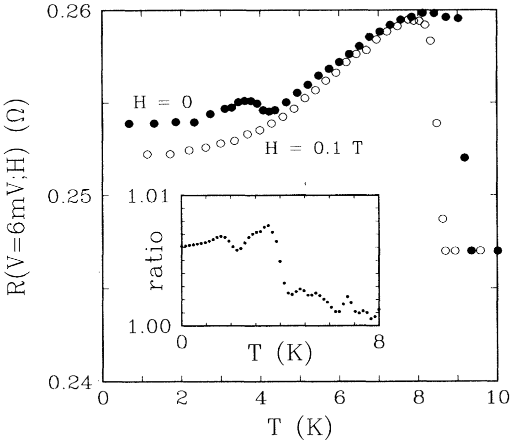

FIG. 2. Dynamic resistance at a bias of 6 mV vs temperature for zero magnetic field and 0.1 T in the plane of the junction. Note the sudden increase of $\simeq 5\%$ as T decreases through T_c in both cases and the second smaller jump at $\simeq 4$ K in the $H = 0$ case. Inset: Ratio of dynamic resistance at 6 mV for $H = 0$ and 0.1 T.

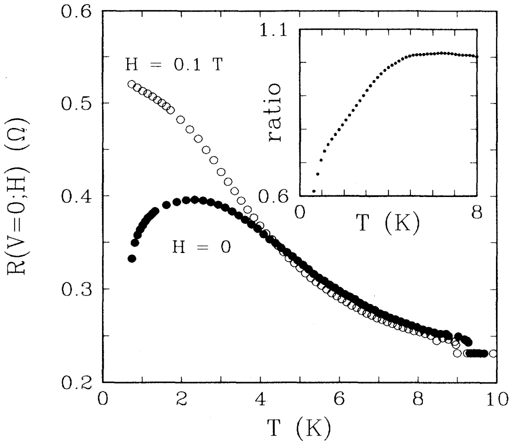

FIG. 3. Zero-bias resistance vs temperature for $H = 0$ and 0.1 T. Inset: Ratio of zero-bias resistance for $H = 0$ and 0.1 T. Note that ratio begins to change noticeably at around 4 K.

6 mV) as temperature decreases through T_c as well as a monotonic decrease as temperature decreases below T_c, at least down to $\simeq 4$ K. In this temperature range, device I-V characteristics are substantially unaffected by magnetic-field changes except near the field-dependent T_c. The magnitude of the resistance jump at T_c, $\sim 5\%$ of the total resistance of the sample, does not change with magnetic field. It is a large effect, $\sim 5 \times 10^{-8}\ \Omega\,\text{cm}^2$, which exceeds the resistance of the entire Nb film in the normal state or the resistance of a ~ 1-μm-thick layer of $\text{In}_x\text{Ga}_{1-x}\text{As}$. Thus it appears to be tunneling related. The jump is constant for voltages varying from 0 to values much larger than the low-temperature gap voltage.

Also shown in Fig. 2 is a *sharp increase* in the large-bias dynamic resistance as temperature decreases through ~ 4 K. This jump disappears in magnetic fields of a few tens of mT. The sharpness of this jump is better illustrated in the inset to Fig. 2, a plot of the ratio of the 6-mV dynamic resistance in zero magnetic field to its value in a 0.1-T field. (The sample was cooled in ^{3}He vapor; the resistance change is not connected with immersion in liquid ^{4}He.)

Figure 3 is a plot of the zero-bias resistance for the same device. The inset shows the ratio of zero-bias resistances at 0 and 0.1 T. The pair current reported in Ref. 5 (which disappears in fields of a few tens of mT) is seen in the zero-field curve as a decrease in resistance at low temperatures and in the ratio curve as a departure from $\simeq 1$. It is interesting that its onset temperature is, to within experimental error determined largely by heating effects, the same temperature as that of the small jump in high-voltage dynamic resistance shown in Fig. 2. (Note that heating is not a large effect, as shown by the lack of a substantial shift in apparent T_c with bias.)

In summary, we have described three effects in heavily doped S-Sm contacts which are relatively insensitive to moderate magnetic fields: (1) An excess voltage, or offset of the I-V from the normal state one at large voltages. (2) A resistance jump of several percent as T decreases through T_c. (3) A decrease in the large-bias dynamic resistance with decreasing temperature below T_c. We note that it is unusual that the dynamic resistance at large voltages changes at all at the low temperatures of this experiment. An additional effect was destroyed by magnetic fields of a few tens of mT: (4) A resistance jump at approximately the same temperature at which pair current appears.[5] This resistance jump, like the one at T_c, is suggestive of a phase transition. The pair current and the excess voltage can be understood in terms of the rapidly evolving theory of S-Sm contacts. An understanding of the dynamic resistance behavior, which appears to be connected with these effects, will require further investigation.

Excess voltages were reported earlier in Nb-$\text{In}_x\text{Ga}_{1-x}\text{As}$ S-Sm-S weak links[3] having contact resistances similar to that of the device of Fig. 1. A simple model can account for excess voltages in such S-I-N-I-S structures.[10,11] The nonequilibrium carrier distribution in N which results from multiple elastic scattering events at the two S-I-N interfaces in the absence of significant inelastic scattering is responsible. The observed dependence of the excess voltage on contact resistance was in qualitative accord with the predicted behavior[11] (in fact, the excess voltage was negative in very low-resistance devices, consistent with the onset of significant Andreev scattering). Similar behavior has been observed in Nb-Si-Nb structures.[12,13]

Excess voltages are predicted only in structures which contain two contacts. Thus, the similarity of the excess voltage we observe in single S-Sm contacts to that observed in S-Sm-S devices is remarkable. This similarity is clearly demonstrated in Fig. 4, a plot of the temperature dependence of excess voltage for the device of Fig. 1 and an Nb-$\text{In}_x\text{Ga}_{1-x}\text{As}$-Nb weak link[4] having similar contact resistance. The excess voltage per contact is the same. The temperature dependence of this excess voltage is decidedly different from that predicted by the simple S-I-N-I-S models,[10,11,14] which yield excess voltages (or

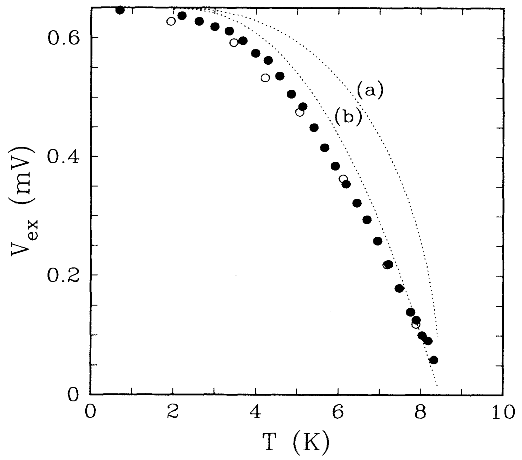

FIG. 4. Excess voltage vs temperature for the S-Sm contact (closed circles) and S-Sm-S weak link (open circles) having similar contact resistances; the latter values were scaled by a factor of $\frac{1}{2}$ because there are two contacts in series. The curves are proportional to (a) $\Delta(T)$ and (b) $\Delta^2(T)$.

currents, depending on contact transmittance) that are proportional to $\Delta(T)$, the electrode energy gap. Inclusion of inelastic scattering in the S-I-N-I-S model[12] can result in a different temperature dependence, but the deviation from $\Delta(T)$ is not large in devices exhibiting significant excess voltage. In Fig. 4, curves proportional to $\Delta(T)$ and $\Delta^2(T)$ are included for purposes of illustration; our data more closely resemble $\Delta^2(T)$. We conclude that excess voltage is an *intrinsic property* of S-Sm interfaces in the doping range of our devices which does *not* depend on the existence of more complex S-Sm-S structures and cannot be accounted for by the simplest models.[14]

Zaitsev[15] has performed microscopic calculations of the I-V characteristics of S-I-N-I-N devices, taking into account the proximity effect, which was ignored in earlier studies. He predicted a low-voltage excess current as well as an excess voltage (or current, depending on interface transparency) at large bias. The temperature dependence of this excess voltage can be substantially different from $\Delta(T)$. The excess voltage evidently has the same physical origin as that in the simple nonproximity effect models,[10,11] and is a property of the full S-I-N-I-N structure. The low-voltage excess current is due to the proximity effect.[16] It is evidently the same pair current predicted for single contacts[8] and observed in our earlier experiment.[5] In fact, Volkov[9] has obtained an expression for the magnetic-field dependence of the low-voltage excess current similar to that which we reported.[5]

Our observations of both the low-bias excess current and the high-bias excess voltage in the same single S-Sm contacts have resulted in suggestions[16,17] that *no second junction is required* in order to produce the nonequilibrium state responsible for the excess voltage. These two phenomena observed in the S-Sm contacts are evidently the result of the proximity effect at the S-Sm interface in conjunction with a perturbed region adjacent to the interface in which only elastic scattering takes place. Effectively there is a second junction an inelastic scattering length away from the interface,[18] and an excess or deficit voltage is present depending on the transmittance of this region. These ideas are extremely attractive for discussing the behavior of S-Sm contacts, and our demonstration that important aspects of the behavior of S-Sm-S devices are properties of single S-Sm contacts makes this direction in the evolving theory of such structures necessary.

We mention for completeness another model which predicts excess voltages in S-Sm contacts. Devyatov and Kupriyanov,[19] predicted such an effect in S-I-N junctions in which transport is dominated by noninteracting localized centers in the barrier. Such centers may be of interest in considering S-Sm contacts with thin Schottky barriers. However, the temperature dependence of the excess voltage[20] is $\Delta(T)$, at least near T_c. Also, the strong pair-breaking Coulomb repulsion at the localized centers invoked for this calculation is seemingly inconsistent with the pair current observed in these junctions. Thus this model does not appear to be consistent with both pair current and excess voltage.

We are aware of no theory which accounts for the behavior of the dynamic resistance of our devices. Unexplained resistance anomalies at or near T_c have been reported recently in various structures undergoing superconducting transitions,[21-23] but these observations are not connected to ours in any obvious way. It is conceivable that our resistance jump at T_c is the result of current redistribution. It is well known that the apparent four-terminal resistance (actually voltage-to-current ratio) of a crossed-strip thin-film junction can be considerably smaller than the barrier resistance if the electrode is resistive enough (it can even be negative). This can result in an increase in apparent resistance when an electrode becomes superconducting. Typical one-dimensional problems are easily solved.[24] The current flow in our devices is inherently two-dimensional and difficult to evaluate precisely due to the multiple semiconductor layers, however, we were unable to account for a 5% resistance jump by current redistribution alone. We point out that the resistance jump was present independent of changes in the configuration of the leads, but further experiments would be required to conclusively rule out current redistribution in explaining this effect. It should be noted that the other effects we describe occur with the S electrode in the superconducting state; they are unaffected by this possibility.

There is a considerable literature on the interface resistance of S-N (Ref. 25) and S-I-N (Ref. 26) junctions, in which the resistance diverges due to charge imbalance as T_c is approached from below. This could account for the temperature dependence of the dynamic resistance below T_c. However, this effect, which is due to penetration of electric fields into the superconductor, cannot contribute a resistance exceeding that in the normal state, so it cannot account for our resistance jump, which is too large to be due to a voltage in either the superconductor or semiconductor. Another process has been predicted[27] and apparently observed[28] which does result in a higher resistance in the superconducting state, due to an upper limit on the acceptance angle for Andreev reflected electrons. However, rather than a sudden jump, the resistance is predicted to grow as $(1-T/T_c)^{3/2}$. Finally, the resistance jump at ~4 K is significant in that it is evidently connected with the appearance of the pair current. At present we have no explanation for this effect. Overall, the behavior of the large-bias dynamic resistance of our samples demonstrates the importance of further theoretical analysis of S-I-N and S-Sm structures, including studies of interface resistance.

In this work we have described several new phenomena, and phenomena known previously to exist only in more complex device structures, in the electrical characteristics of high-transmittance S-Sm contacts. These contacts continue to exhibit a far wider range of behavior than ever suspected in the past. Some of our observations (excess voltage and pair current[5]) appear to be in accord with the developing microscopic theory of S-I-N interfaces.[8,9,15] In fact, experiments like this one have stimulated renewed theoretical interest in this subject. The unusual dynamic resistance behavior of our devices is evidently connected to these phenomena, but the subject requires further investigation. It would be interesting to look for these effects in high-transmittance S-N contacts and S-I-N tunnel junctions as well as in other S-Sm contacts.

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