Anomalous Andreev Conductance in InAs-AlSb Quantum Well Structures with Nb Electrodes

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The differential conductance of InAs-AlSb quantum wells with superconducting Nb electrodes exhibits a sharp single peak at zero bias, followed by a drop *below* the normal conductance at voltages an order of magnitude higher than the gap voltage, before returning to the normal value at yet higher bias. The behavior is interpreted in terms of Andreev reflections, modified by multiple normal reflections of both electrons and Andreev holes between the Nb electrodes and the bottom barrier of the quantum well, in the presence of a nonuniform potential along the well.

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In an earlier paper, we demonstrated superconducting weak links with high critical current densities, using an InAs-AlSb quantum well (QW) as the normal channel [1]. In the present work, we study the properties of similar structures in the temperature range $4.2 \leq T \leq 9.2$ K, above the onset of induced superconductivity for the interelectrode spacings employed (≥ 1 μm), but below the critical temperature T_c of the Nb electrodes. The objective is the study of the manifestations of Andreev reflections for such structures and in that temperature range, along the lines of earlier work by Kleinsasser *et al.* [2] and Kastalsky *et al.* [3], for different structures and at lower temperatures. We find a sharp single peak at zero bias in the differential conductance, followed by a drop *below* the normal conductance at voltages an order of magnitude higher than the gap voltage, before returning to the normal value at yet higher bias. The behavior is interpreted in terms of Andreev reflections, modified by multiple normal reflections of both electrons and Andreev holes between the Nb electrodes and the bottom barrier of the quantum well, in the presence of a nonuniform potential along the well.

Compared to our earlier devices, the devices used in the present work differ principally by use of modulation doping with δ sheets of Te, to achieve higher electron concentrations, up to 8×10^{12} cm^{-2}, while retaining low-temperature mobilities approaching 10^5 cm^2/V s. The growth and characterization of these wells have been described elsewhere [4]. The electron sheet concentrations and mobilities for such heavily doped samples, determined by Hall measurements, are essentially temperature independent below 20 K. For the specific but typical sample discussed in the present paper, they were 6.4×10^{12} cm^{-2} and 81 000 cm^2/V s, corresponding to an electron mean free path of about 2.2 μm. However, the effects reported here were observed in *all* samples (more than twenty) with similarly high electron concentrations and similar structure.

The Nb electrodes, deposited by electron beam evaporation and lift-off, are in direct contact with the InAs layer. Their length in the current flow direction was 200 μm, their perpendicular width, 50 μm. The transition temperature T_c of the Nb electrodes was 9.2 K, determined by a sharp transition in the measured resistance of the device. Various interelectrode spacings were employed, including a few samples with spacings much larger than the electron mean free path. The sample singled out here has a spacing of 1 μm; its resistance just below T_c was about 3.2 Ω, but only a small part of this, about 0.2 Ω, can be attributed to the resistance of the InAs normal channel between two Nb electrodes; the rest is due to a non-negligible specific contact resistance, measured independently by the transmission line method to be about 5×10^{-6} Ω cm^2.

For devices with a spacing greater than 0.7 μm between the Nb electrodes we observe no supercurrent in the temperature range investigated (>4.2 K). However, at temperatures below T_c, the differential conductance of *all* samples with sufficiently high electron concentrations exhibits the overall behavior shown in Fig. 1, characterized by three features: (a) At very low voltages, the samples exhibit a sharp *single* conductance peak, as in the inset of Fig. 1. (b) The *base* of the conductance peak extends to voltages larger than the superconducting gap of the Nb electrodes (≈ 3 mV). (c) The differential conductance then drops smoothly *below* the normal-state conductance, forming a dip at voltages an order of magnitude larger than the superconducting gap voltage. The normal conductance itself, used for normalization of the data in Fig. 1, was determined by measurements at 10 K, slightly above T_c. The resistive contribution from the Nb contact pads having "gone normal," assumed to be equal to the discontinuity in the overall resistance at the transition, was subtracted from the overall sample resistance.

Both the height of the central peak and the voltage of the dip are temperature dependent; Fig. 2 shows the temperature dependence of the latter, a dependence qualitatively similar to that of the Nb gap, but on a much larger voltage scale. The voltage at which the dip occurs contains a contribution from the series resistance of the InAs channel between the Nb electrodes. In the device with the 1.0-μm channel reported here, the latter was less than 7% of the external voltage; the rest occurs underneath the electrodes. For samples with longer channels (>5 μm)

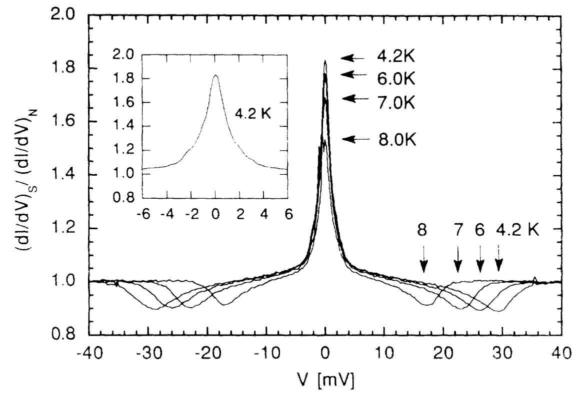

FIG. 1. Normalized differential conductance of a device with 1-μm Nb electrode spacing, as a function of bias voltage, at 4.2, 6.0, 7.0, and 8.0 K, showing a sharp zero-bias conductance peak, followed by a below-normal broad dip. The curves were obtained by direct differential measurements at the temperature stated, divided by the same measurement just above the critical temperature (9.2 K) of the Nb electrodes, with the normal lead resistance subtracted. Inset: The central conductance peak at 4.2 K on an expanded voltage scale.

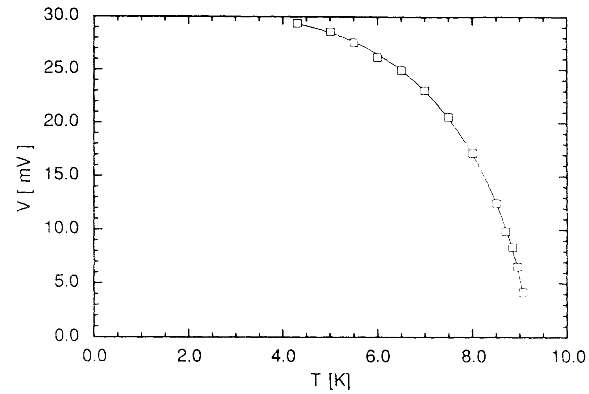

FIG. 2. Voltage position of the conductance dip as a function of temperature.

the dip occurs at higher voltages. The overall phenomenon persists for channels much longer than the electron mean free path.

Above T_c, all three features disappear, and the differential conductance shows a very slight downward cusp ($\approx 3\%$) at zero bias (not shown), which becomes smaller with increasing temperature and vanishes above 80 K, suggesting the presence of a shallow (≈ 10 meV) remaining barrier at the Nb-InAs interface, which depends sensitively on the treatment of the InAs surface prior to the deposition of Nb, and which is presumably responsible for the residual specific contact resistance.

Sharp single conductance peaks at zero bias—at lower temperatures—have been previously reported in Nb-(Ga,In)As structures by Kleinsasser *et al.* [2] and Kastalsky *et al.* [3], but the rest of the behavior seen by us is believed to be a new observation. Following Kleinsasser *et al.* [2], we attribute the sharp peak to Andreev reflections. However, such an interpretation must reconcile the sharp *single* peak at zero bias with the well-established theory by Blonder, Tinkham, and Klapwijk [5] (BTK) and by Arnold [6]. The BTK theory predicts, for superconductor-normal (S-N) point contacts with finite *normal* scattering at the interface, that the differential conductance should exhibit a *pair* of conductance peaks at bias voltages of $\pm 2\Delta/e$ (for two S-N junctions in series), and that it should merge with the normal-state conductance outside this voltage range. Such a predicted behavior has been experimentally observed by some authors [7,8], but the behavior of our QW junctions is clearly different.

In their work, Kastalsky *et al.* [3] attribute their single-peak enhancement of the zero-bias differential conductance to a "precursor of a supercurrent," that is, to pair current transport through the semiconductor. But such pair transport would be extremely unlikely to persist up to the critical temperature of the Nb electrodes, and over spatial distances in excess of 1 μm. We also discount the possibility of the zero-bias conductance peak being due to multiple Andreev reflections between the two superconducting electrodes [9]. We have also observed the effect in samples with electrode spacings > 10 μm, much wider than the electron mean free path.

We believe instead that the single-peak structure in our data is the result of a different kind of multiple reflection, between the super-semi interface and the AlSb back wall of the InAs quantum well, opposite to the Nb electrode. Recently, van Wees *et al.* [10] have interpreted the observations of Kastalsky *et al.* [3] in terms of elastic scatterers *inside* the semiconductor, which causes the electrons and holes to be scattered back to the super-semi interface. The authors show that the constructive quantum interference that results from the phase conjugation of electrons and their associated Andreev holes enhances the zero-bias differential conductance above its normal value, rather than leading to the BTK double-peak structure. Whatever the applicability of this theory to the data of Kastalsky *et al.* [3], we believe that the AlSb back wall of the InAs quantum well is a pronounced case of the kind of elastic scatterer invoked by van Wees *et al.* [10], and we propose that the theory of those authors provides the explanation of the narrow *single*-peak structure seen in our work.

To elaborate on this point, we note that the zero-bias conductance at 4.2 K is more than 1.8 times the normal-state value at 4.2 K. In the absence of multiple reflections, this would require a high *single*-event Andreev-reflection (AR) probability (> 0.5), which is unlikely in the presence of the residual barriers at our interfaces: Kastalsky *et al.* [3] have observed a *decrease* of the low-bias dI/dV in Nb-(Ga,In)As junctions that had contact resistances as low as 1.1×10^{-6} $\Omega\,\mathrm{cm}^2$. This is much less than the contact resistance of our devices, for which an incident electron should be even more likely to be normally reflected than Andreev reflected. The situation changes when strong multiple reflections occur. Consider the positive-bias half of the device, where the local chemical potential in the InAs layer is *higher* than that of the superconducting electrode. As illustrated in Fig. 3(a), an electron in the InAs channel normally reflected from the Nb-InAs interface can be reflected from the lower AlSb barrier and become again incident on the Nb-InAs interface. This process continues until the electron either suffers a large-angle backscatter (due to impurities, interface roughness, etc) or undergoes AR. Considering the long electron mean free paths in our QWs, over 100 times the thickness of the well, the electron can undergo a very large number of reflections, and even a low *single*-event AR probability of only a few percent can lead to a very high *cumulative* AR probability. The same reasoning applies for incident holes at the other electrode.

Turning to the broadened base of the conductance peak, and to the subsequent dip, we believe that they, too, are the results of multiple reflections of both the electrons and the Andreev holes, but modified by the presence of a spatially nonuniform *local* bias at overall voltages exceeding the superconducting gap voltage. Associated with the lateral current flow inside the InAs is a lateral potential drop, which results in a continuous decrease in the chemical potential difference between the InAs layer and the Nb electrode, as shown schematically in Fig. 3(b). For a sufficiently large overall bias, there will exist a crossover plane at a distance x_c from the Nb edge, to the left of which the local potential difference exceeds the gap parameter Δ. With increasing bias this point recedes farther from the Nb edge. The AR current generated to the right of x_c is not affected by this displacement; its path is simply shifted farther to the right. To the left of x_c, most of the current flowing across the contact interface consists of quasiparticles injected into the superconductor, but the AR current persists in this region, and its total magnitude should continue to increase, roughly proportionally to the width x_c of that region, which itself should increase roughly logarithmically with bias voltage. This behavior is seen in Fig. 4, which shows the excess current caused by the AR process, obtained by integrating the experimental differential conductance data. Note that the excess currents continue to increase for voltages much larger than the Nb gap voltage, before decreasing again in the region of the conductance dip.

The strong temperature dependence of the position of this dip rules out interactions with optical phonons as a possible explanation. We can also rule out explanations in terms of sample heating: To put an upper limit on the difference between the temperature of the device and of the bath, we have measured the total resistance of the structure at high bias, beyond the conductance dip, as a function of temperature. We do not observe a rise in the measured resistance until the bath temperature reaches 8.9 K, only 0.3 K below the measured critical temperature of our Nb electrodes. Such a small sample heating is

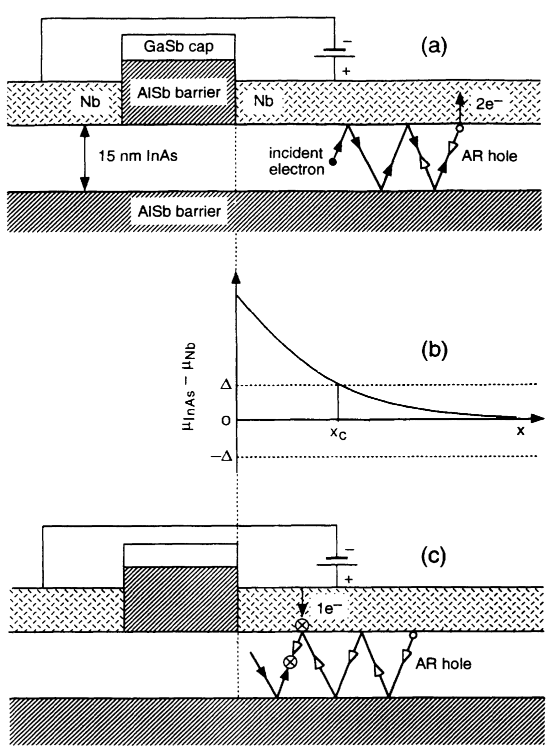

FIG. 3. (a) Schematic cross section of the device, illustrating an electron (solid arrow) undergoing Andreev reflection after multiple normal reflections. The hole travels backwards (open arrow) along the same path as the electron. (b) Local chemical potential difference between the InAs layer and the positive superconducting electrode. (c) Two possible recombination processes for an AR hole with subgap energy in the InAs layer. The hole can recombine with a bulk electron inside the InAs, or with a quasiparticle electron inside the electrode.

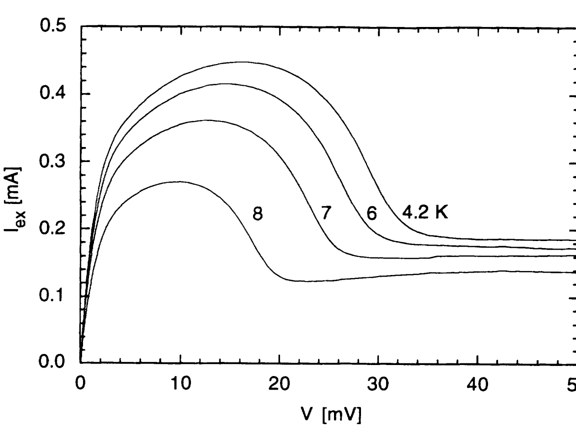

FIG. 4. Excess current as a function of bias voltage for the device of Fig. 1, obtained by integrating the experimental differential conductance data.

insufficient to explain the much stronger conductance dip at temperatures significantly below T_c. In fact, although the voltage at which the dip occurs is much larger than the Nb superconducting gap, its temperature dependence is *qualitatively* similar to that of the gap, suggesting a mechanism related to the existence of the gap.

We propose that this drop in excess current is the result of the *recapture* of backward-traveling multiply reflected AR holes by the Nb electrode, before the holes had an opportunity to recombine with bulk electrons inside the InAs. The process, postulated to take place at sufficiently large bias in the expanding region to the left of x_c, is illustrated schematically in Fig. 3(c). Note that, for $x < x_c$, Andreev holes can no longer undergo Andreev reflections themselves, but only normal reflections, because of the upward shift of the chemical potential on the semiconductor side, which causes the states energetically required for hole pairing to be occupied by electrons. The holes can be recaptured by the superconductor only by recombination with quasiparticle electrons inside the superconductor. These are normally not present in concentrations to make such a recapture likely, and the AR holes will instead recombine with bulk electrons with the InAs, thereby completing the excess current loop. However, at bias voltages sufficiently far above the gap voltage, a copious injection of quasiparticle electrons takes place to the left of x_c. We propose that the electrons injected into the superconductor recapture an increasing fraction of the multiply reflected AR holes. The net result is a reduction of the current excess relative to the normal state of the Nb electrode, not by a reduction of the AR hole current itself, but through a cancellation of that current by a reduction of the injected quasiparticle current. There will of course always be some AR holes, particularly those originating to the right of x_c, which will recombine in the InAs layer, rather than be recaptured. Hence the excess current does not entirely vanish at high bias.

The temperature dependence of the recapture process via injected quasiparticles should be related to that of the gap, as is indeed observed in the temperature dependence of the conductance dip.

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