Crossover from tunneling to metallic behavior in superconductor-semiconductor contacts

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We describe current-voltage measurements on superconducting Nb/InGaAs junction field-effect transistors which reveal a crossover from tunneling-dominated to Andreev scattering-dominated transport at the superconductor-semiconductor contacts as Schottky barrier thickness decreases with increasing interfacial dopant concentration. These measurements are the first demonstration of such a crossover in a thin-film structure, and are of interest for investigations of hybrid superconductor-semiconductor devices, proximity effect boundary conditions, and transport in ohmic contacts to semiconductors.

The behavior of hybrid devices,[1] such as semiconductor-coupled weak links, superconducting field-effect transistors (FETs), and super-Schottky diodes, is sensitive to the quality of the superconductor-semiconductor contacts, and techniques which allow direct measurements of contact properties are therefore of interest. In this letter, we describe measurements which demonstrate dramatic qualitative changes in the source-drain current-voltage (I-V) characteristics of superconducting FETs as the transmittance of the superconductor-semiconductor contacts is improved by increasing the interfacial dopant concentration. These changes are caused by a crossover from normal tunneling to Andreev reflection-dominated transport at the contacts. This work is the first demonstration of such a crossover in a thin-film structure. In addition to connecting superconducting device performance with ohmic contact quality, measurements of this type are of interest for fundamental studies of the proximity effect and of transport in ohmic contacts to semiconductors.

The superconducting junction FETs (JFETs) used in this work are described elsewhere.[2] The device structure is illustrated schematically in the inset to Fig. 1 . Nb source and drain contacts are separated by 0.5–1 μm. The substrate is InP, the channel is lattice-matched n-InGaAs, and the channel conductance is controlled by the bias applied to the p-InGaAs gate. The Nb/InGaAs ohmic contacts are of crucial importance. In the extreme cases of low or high contact transmittance the devices act as back-to-back super-Schottky diodes[3] or as gated Josephson junctions, respectively. In the latter case, a long coherence length and highly transmissive nonalloyed ohmic contacts have made record gated supercurrents[2] possible. This work, however, deals with single particle currents in the semiconductor, and supercurrents are suppressed by applying a magnetic field or a gate voltage.

Since the semiconductor channel acts as a normal metal, the contacts are SN interfaces (in this letter, S, N, Sm, and I denote superconductor, normal metal, semiconductor, and insulator, respectively). There is ample evidence for a proximity effect between superconductors and semiconductors,[1,4,5] but it is well known that even a thin tunnel barrier at an SN interface destroys the proximity effect.[6] The Schottky barriers at most SSm contacts make them SIN tunnel junctions, or super-Schottky diodes.[3] The thickness (and thus the transmittance) of the Schottky barrier at an SSm interface is determined by the dopant concentration near the surface of the semiconductor. We varied this doping in order to study the expected crossover from SN to SIN character. This resulted in changes in the I-V characteristics, as illustrated in Fig. 1 and discussed below. A crossover from SN to SIN behavior has been studied in Cu-Nb point contacts,[7] and these earlier experiments demonstrated the validity of a simple theoretical picture;[8] however, this sort of crossover has not been studied previously in a thin-film structure.

The I-V characteristics of a SIN contact are influenced by two scattering processes.[8] Figure 2 (a) shows an electron (I) incident on the interface from the N side at a subgap energy. It cannot propagate into the superconductor so it reflects, either as an electron ($R1$) contributing zero junction current, or as a hole ($R2$) with a Cooper pair ($T2$) propagating in the superconductor (Andreev reflection) and contributing twice the current expected from Ohm's law. Above the gap energy, both normal tunneling and Andreev scattering contribute current. For a highly

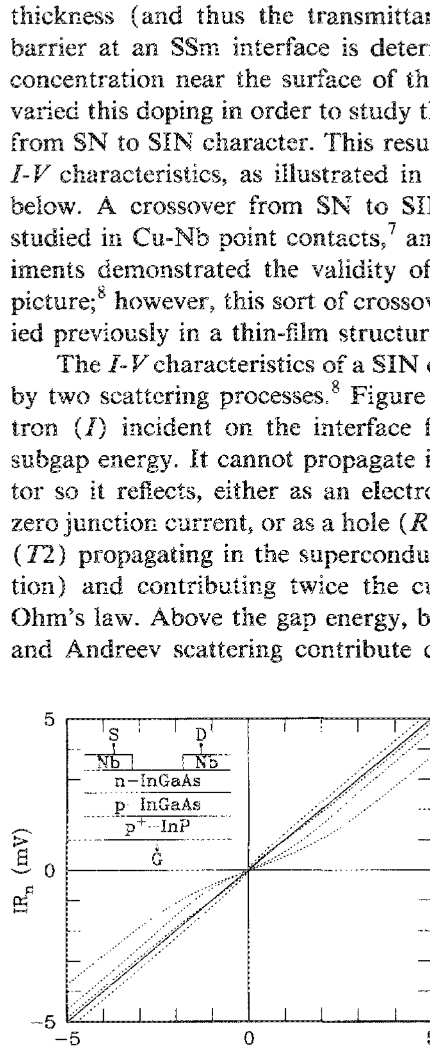

FIG. 1. Source-drain characteristics at 4.2 K of several JFETs without gate bias (dashed curves). The transmittance of the Nb/n-InGaAs contacts was varied using different doping levels in top few nm of the InGaAs. The lowest curve (in the first quadrant) corresponds to the lowest doping and the uppermost curve to the higest doping. The solid line represents the normal state (R_n is the device resistance). Inset: Schematic of the JFET structure. S, D, and G are the source, drain, and gate terminals, respectively.

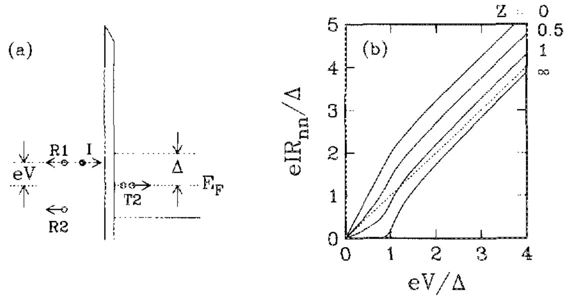

FIG. 2. (a) Scattering processes at a SN contact. A low-energy electron (I) incident from N reflects as an electron ($R1$), or Andreev reflects as a hole ($R2$) with a Cooper pair ($T2$) propagating into S, contributing zero or two units of current, respectively, rather than one. (b) I-V characteristics of an SN contact at $T = 0.1T_c$. $Z = 0$ and ∞ are the thin and thick limits for the interfacial tunnel barrier. $Z = 0.5$ and 1 are intermediate cases. The dashed line represents a normal junction (after Ref. 8).

transmissive barrier, the relative contributions of these processes determines the form of the I-V characteristics, which thus contain information about interface transmission probability. This is shown in Fig. 2(b), which qualitatively resembles Fig. 1. With no barrier ($Z = 0$, Z being a dimensionless parameter characterizing the amount of interfacial scattering), there is a conductance peak at subgap voltages and an excess current (the I-V curve at large voltages extrapolates to a finite current at zero voltage). There is a gradual crossover to the thick barrier extreme ($Z = \infty$), in which case there is a conductance minimum at subgap voltages and no excess current. In the absence of a barrier the Andreev process dominates. However, Andreev scattering involves two traversals of any tunnel barrier, and is thus second order in the transmission probability. Normal tunneling is first order, and dominates for thick barriers.

In the present experiment there are two superconducting electrodes, so that the structure is SNS or SINIS. Both SN interfaces are involved in the scattering processes described above, with significant effects on device behavior. The I-V characteristics at 2 K of a device with high doping in the contact region are shown in Fig. 3 (a). This device had doping levels of $\simeq 10^{19}$ cm^{-3} in the top 5 nm and 10^{18} cm^{-3} in the next 70 nm. The channel thickness was $\simeq 50$ nm. Above 9.2 K, the I-V curve was linear at low voltages, with a normal resistance consistent with estimates based on doping, mobility, and device dimensions which assumed a very small contact resistance ($< 10^{17}$ Ω cm^2). All such low-resistance devices exhibited two features visible in Fig. 3, the effects being largest in the lowest resistance devices: (1) an excess current and (2) a sharp peak in the dynamic conductance at low voltages. This peak was never wider than 2Δ, and was considerably sharper at low temperatures in the lowest resistance devices. At voltages beyond $\simeq 2$ mV the conductance approached the normal-state value. We identify as "SNS-like" devices which exhibit these features.

For devices in which the top 5 nm of the InGaAs film (the contact region) had a doping level between $\simeq 10^{19}$ cm^{-3} and 10^{18} cm^{-3} (the doping level in the channel),

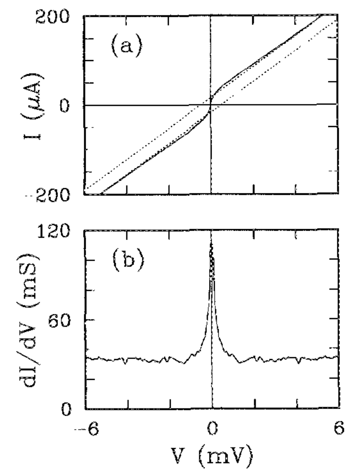

FIG. 3. (a) I-V characteristics at 2 K of a low-resistance device which exhibits SNS-like behavior. The excess current is shown by the dashed lines extrapolated from large voltages ($|V| > 20$ mV). (b) Dynamic conductance of the same device.

the resistance was considerably larger, due to the exponential dependence of tunneling current on barrier width (device resistance becomes increasingly dominated by the contacts as interface doping is reduced). These devices exhibit what we term "SINIS-like" behavior, as shown in Fig. 4 . Clearly visible are (1) a deficit current/excess voltage (the current extrapolated from voltages many times the energy gap voltage has a negative intercept) and (2) a low-voltage minimum in the dynamic conductance with a full width of $\simeq 4\Delta$. This minimum resembles that expected for two series SIN junctions; however, the zero-bias conductance does not fall exponentially at low temperatures. This is consistent with very transmissive tunnel barriers. Again, the I-V curves above the Nb transition temperature were linear at low voltages, and the low-temperature conductance approached the normal-state value for voltages above $\simeq 5$ mV.

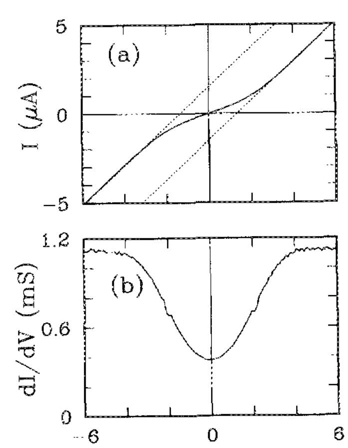

FIG. 4. (a) I-V characteristics at 4.2 K of a high-resistance device which exhibits SINIS-like behavior. The deficit current is shown by the dashed lines extrapolated from large voltages ($|V| > 20$ mV). Dynamic conductance of the same device.

We observed a gradual crossover from SNS-like to SINIS-like behavior, with a transition from excess to deficit current and from a sharp subgap conductance peak to a broader conductance minimum, as the doping level in the contact region was reduced to roughly that of the channel. There were two major differences between this behavior and that of SN or SIN junctions[8] (our samples consist of two junctions in series): (1) the "SNS-like" conductance peak was considerably sharper than the Nb energy gap and larger in amplitude than twice the normal conductance of the device, and (2) the "SINIS-like" devices not only had no excess current, they also exhibited deficit currents. We believe that these features are inherent in SNS (or SINIS) structures.

Most of the work aimed at extending the theory for SN and SIN contacts[8] to SNS and SINIS structures[9,10] has tried to explain the subharmonic gap structure observed in various types of Josephson weak links (in the case of high critical current density tunnel junctions, the basic correctness of this approach has been established[11]). The most recent work[10] also predicts just what we are reporting: an excess current and a sharp (compared with Δ) conductance peak for devices with high transmittance interfaces, a deficit current, and a conductance minimum of (full) width 4Δ for devices with low transmittance barriers, and a gradual transition between these extremes. The model treats SNS and SINIS structures with all (elastic) scattering lumped into two δ function potential barriers at the SN interfaces, with no scattering within the normal material. Our devices had electrode separation well in excess of the elastic mean free path, but the inelastic scattering length is considerably longer. Evidently the model contains the essential physics behind the behavior of our JFETs as long as inelastic scattering is not important.

In principle, the form of the *I-V* characteristic at a given temperature determines the value for the interface parameter[8,10] Z, and therefore the contact transmission coefficient. However, the present model is limited by the use of δ-function barriers. Nevertheless, the fact that *I-V* measurements such as these might be used to determine the transmission probability of a metal (superconductor)-semiconductor contact makes them interesting for ohmic contact studies, since transport measurements of high transmittance normal ohmic contacts are complicated by the parasitic resistance of the semiconductor.

For devices with apparent Z values exceeding approximately unity, the temperature dependence of the characteristics (e.g., the zero-bias conductance) agrees with the model predictions, with Z as a fitting parameter. Such comparisons have not been made for devices having Z values less than unity. At present, the analysis is limited by the fact that the voltage between superconductor and semiconductor is not constant along the contact, washing out the *I-V* characteristic. This does not affect the excess or deficit currents, whose temperature dependences appear to scale with the energy gap as expected. We observed no subharmonic gap structure in our devices. Such structure occurs in the model due to multiple Andreev reflections, but is presumably washed out in these devices due to the spatially varying voltage drop across the interface and to the proximity effect, which results in a graded energy gap in both the superconductor and the normal material.

The measurements described here allow relationships to be established between weak link (and FET) critical currents and ohmic contact transmittance. What is now required is to perform these types of measurements on well-characterized samples spanning various materials systems and contact schemes, and to further improve the theory in this area. It would also be desirable to know the value of the boundary condition for the superconducting order parameter at the contacts, since this quantity is proportional to the critical current of a weak link. Transition temperature[4] and tunneling measurements[5,12] on SSm bilayers can provide such information. SSm samples offer a much wider range of boundary conditions for proximity effect studies than do the more familiar SN ones, allowing further generalization of earlier investigations.[13] Finally, our results imply limits on the specific resistance of super-Schottky diodes, since increasing barrier transmittance results in degraded characteristics (increased subgap currents).

In conclusion, we have described a dramatic crossover in the *I-V* characteristics of gated semiconductor-coupled weak links as the contact transmittance is varied. These measurements are important for understanding hybrid superconductor-semiconductor devices, for fundamental studies of transport in ohmic contacts, and for improving our understanding of the proximity effect.

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