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LETTER TO THE EDITOR

The above-gap structure in normal-metal–superconductor junctions

A Vaknin and Z Ovadyahu

The Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

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Abstract. We report on the observation of zero-bias anomalies and above-the-gap structure in the current–voltage characteristics of Au–InO_x–Pb tunnel junctions. The above-gap modulations appear at energies that scale with the superconductor gap. Following thermal anneals these energies shift randomly in the range 4–20 mV. The conductance changes associated with these anomalies also vary in a non-systematic way and are typically of the order of 10–100 e^2/h.

Charge transport through the interface between a normal metal (N) and a superconductor (S) is controlled by two processes: single-particle (Giaever) tunnelling and two-particle (Andreev) tunnelling [1]. Giaever tunnelling is the dominant mechanism when there is a significant barrier at the SN interface and results in current–voltage characteristics such that $R_N/R_0 \ll 1$. Andreev tunnelling becomes important when the interface is 'transparent' and leads to $R_N/R_0 = 2$. R_0 and R_N are the interface resistance at zero voltage and in the normal state respectively. Both types of process have a characteristic voltage scale of Δ, the superconducting energy gap. For voltages $V \gg \Delta$ the I–V characteristics are essentially independent of whether S is in the superconducting or in the normal state. In several cases, however, rather systematic above-the-gap structures appear in SN contacts. Nguyen *et al* [2] and Xiong *et al* [3] reported on resistance peaks at voltages that were considerably bigger than Δ and scaled with $\Delta(T)$. In both cases the S electrode was Nb.

In this letter we report on the appearance of above-the-gap modulation in SIN devices where N is Au, I is amorphous indium oxide, and S is lead. We show that in addition to resistance peaks there are also resistance minima. Both features appear at voltages that scale with $\Delta(T)$. These anomalies exhibit mesoscopic, sample specific behaviour in the sense that their position and associated conductance swings vary following thermal cycling.

The Au–InO_x–Pb samples were prepared by first depositing a gold strip, 100 μm wide and 400 Å thick onto a room-temperature glass slide. A 600 Å layer of InO_x was e-beam evaporated on top of the Au electrode, and a cross strip of Pb 70 μm wide and 2000 Å thick completed a standard four-terminal device. The entire process was completed in the same vacuum run using a rotatable mask holder. Fuller details of sample preparation, structural study, and measurement techniques are reported elsewhere [4, 5]. In the following we focus on the dynamic resistance $\mathrm{d}V/\mathrm{d}I$ characteristics measured following eight consecutive thermal cycles on a single device.

Figure 1 shows the characteristics of the as-prepared sample (i.e., the initial cool-down, within 20 min of fabrication) along with the first three stages of thermal cycling during which the sample was warmed to room temperature and was allowed to anneal for several hours. One notes the following main features (common also to all other annealing stages):

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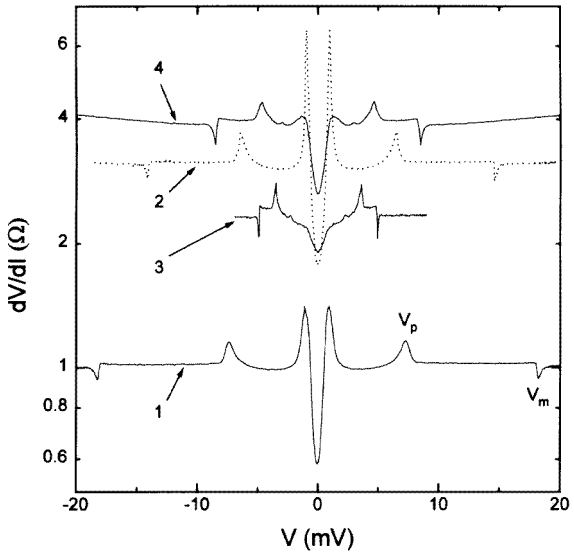

Figure 1. Dynamic resistance against voltage for the as-prepared NIS sample (labelled 1) and the first three samples resulting from consecutive anneals (2–4 respectively). The specific above-gap structure discussed in the text is indicated as V_p and V_m for the first sample. Data shown were taken at $T = 4.11$ K.

(i) a zero-bias anomaly (ZBA) characterized by a resistance dip that extends over a voltage range $V = \pm 1.5$ mV (this voltage is close to Δ of Pb) and

(ii) above-gap modulations that typically appear as a peak and a minimum in $\mathrm{d}V/\mathrm{d}I$ at V_p and V_m respectively. V_p, V_m, and the junction resistance R_N vary randomly from one annealing stage to the next. No correlation amongst these values could be identified. At the same time both V_p and V_m follow the temperature dependence of Δ. As shown in figure 2 $V_{p,m} = A_{p,m}(1 - T/T_c)^{2/3}$ which scales like the BCS $\Delta(T)$. Only one parameter (A_p or A_m) was used in the fit. For the other parameter, T_c, we used the bulk value of the transition temperature in Pb, $T_c = 7.19$ K.

All these features were affected by the application of a magnetic field H but to different degrees. As shown in figure 3, the effect of H is much more pronounced for the resistance minimum at V_m than for the other modulations in $\mathrm{d}V/\mathrm{d}I$. In particular, the ZBA is essentially unaffected by small H, suggesting that this anomaly is not due to 'proximity effects' [3].

The ZBA is commonly associated with prominent Andreev processes [1]. The above-gap structure, on the other hand, is as yet unexplained. Xiong *et al* [3] suggested that these anomalies might be related to the local destruction of superconductivity when a critical current is exceeded. This explanation does not apply in our case. In the first place it conflicts with the observation of the new feature at V_m which reflects a transition to a *smaller* resistance occurring at currents *higher* than the resistance peak at V_p. More importantly, the scaling with Δ of both V_m and V_p suggests a voltage rather than current controlled mechanism.

In the following we wish to explore a different scenario that generically leads to the appearance of a structure at $V = C\Delta$ with $C > 1$. The process we are considering is schematically described in the inset to figure 2. We focus on N-to-S tunnelling via an

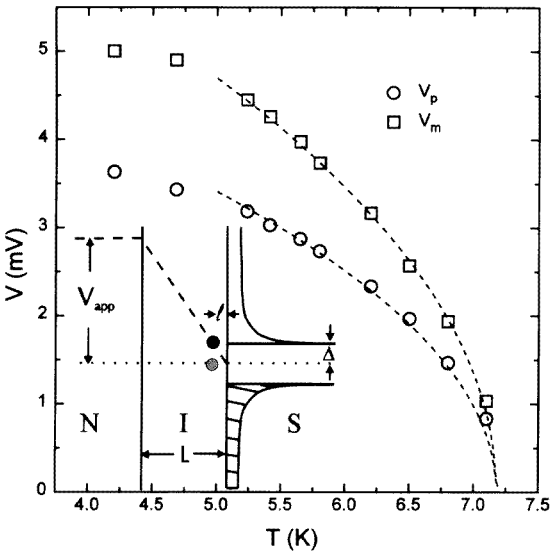

Figure 2. The temperature dependence of the above-gap structure (for sample 3 in figure 1). The dashed lines are theoretical fits to the BCS expression (see the text). V_p and V_m are the sharp peak and minimum respectively observed in the $\mathrm{d}V/\mathrm{d}I$ scans. Inset, the energy-space diagram used to illustrate the origin of the above-gap structure. The dotted and dashed lines are the potentials across the Au–InO_x–Pb (NIS) heterostructure for zero bias and when V_{app} is applied respectively. The intermediate state is depicted as a circle. Also drawn are the filled (hatched region) and empty single-particle density of states in S.

intermediate site i positioned at a distance l from S, and the overall extent of the I region is L. When the applied voltage V_{app} across the junction increases so does the position in energy of i relative to available energy states in S. The geometry of the problem leads to an apparent voltage amplification which is a function of L/l. Clearly, to sweep the state i across, say, Δ, δV_{app} would be considerably bigger than (and scale with) Δ if i is sufficiently close to S. The position in energy of such a channel of (indirect) tunnelling scales with Δ in a natural way. It is also reasonable to expect that thermal cycling changes L/l which, in turn, may explain the observed random variation of V_p and V_m in the samples. These considerations, however, do not address the nature of the processes that lead to the structure at V_p and V_m.

The conductance swings associated with the above-gap structure vary non-systematically in the series of studied samples. The transition at V_m, which is particularly well defined, amounts to a conductance change ΔG that varies between 8 e^2/h and 96 e^2/h in the various annealing stages. These values are much larger than the single-channel quantum conductance and therefore i must be associated with a multi-channel or highly correlated state of the system. It is interesting to note that similar values of ΔG appear in the I–V characteristics of normal point contacts [6]. The correlated nature of these states was ascribed by Ralph and Buhrman to a Kondo-like effect associated with the presence of a two-level system [7]. Such a picture has some obvious merits in the present case. Being an Anderson insulator virtually guarantees a strong coupling between electrons and the two-level system within the InO_x barrier. The observation that the above-gap structure is washed out in the normal state may suggest that the correlated nature of the i state is controlled by Δ [8] or that it is due to interface states near the S electrode. In view of the

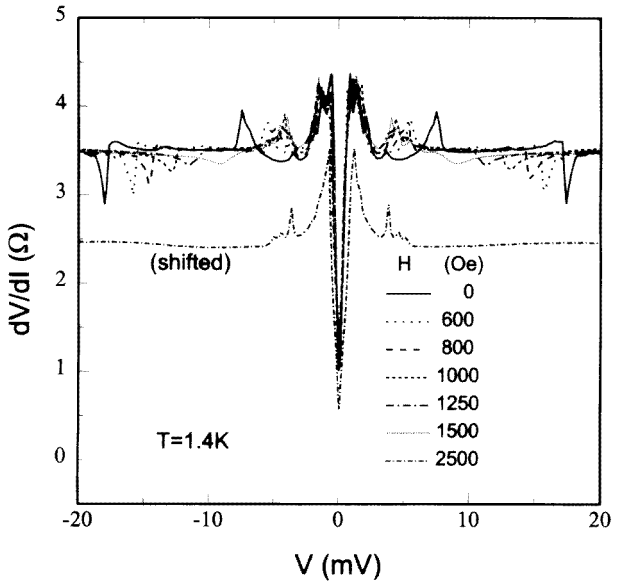

Figure 3. The magnetic field dependence of the dynamic resistance against voltage for a typical sample. Note the different sensitivity to field of various components. In particular, the trace for $H = 2500$ Oe (down-shifted by 1 Ω for clarity) shows that the structure at V_m is completely washed out while the ZBA is barely affected.

high sensitivity to small magnetic fields these states could be 'proximity-effect induced', unlike the ZBA, which is hardly affected by H. In the Ralph–Buhrman experiments, unlike ours, the anomalous structure disappeared after a brief thermal anneal. This difference is probably due to the fact that our system (InO_x) is an amorphous structure that maintains its amorphicity even for more extended annealing periods than employed here [9].

In summary, we have studied the effects caused by thermal anneals and magnetic field on above-gap structure observed in NIS devices. Some of the features in these experiments seem to suggest that in-barrier defects could be involved in these phenomena but the underlying mechanism has not been identified.

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References

[1] Blonder G E, Tinkham M and Klapwijk T M 1982 *Phys. Rev.* B **25** 4515
[2] Nguyen C, Kroemer H and Hu E L 1992 *Phys. Rev. Lett.* **69** 2847
[3] Xiong P, Xiao G and Laibowitz R B 1993 *Phys. Rev. Lett.* **71** 1907
[4] Frydman A and Ovadyahu Z 1996 *Europhys. Lett.* **33** 217
[5] Frydman A and Ovadyahu Z 1997 *Phys. Rev.* B **55** at press
[6] Ralph D C and Buhrman R A 1992 *Phys. Rev. Lett.* **69** 2118
[7] Zawadowski A 1993 *Phys. Rev.* B **28** 1564
[8] Zawadowski A 1980 *Phys. Rev. Lett.* **45** 211
[9] Ovadyahu Z 1993 *Phys. Rev.* B **47** 6161