Excess conductance in normal-metal/Anderson insulator/superconductor junctions

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The current-voltage characteristics of Au/InO_x/Pb tunnel junctions exhibit peculiar zero-bias anomalies. At low temperatures the zero-bias resistance attains saturation values that are smaller than the normal-state resistance by a factor that often exceeds 2. This zero-bias anomaly (ZBA) is also characterized by voltage $\delta \leqslant \Delta$, where Δ is the energy gap of lead. δ depends on the thickness of the InO_x layer. In the presence of a microwave field the ZBA features are affected in a nontrivial way. The possibility that these features arise from the nature of the barrier being an Anderson insulator is discussed.

I. INTRODUCTION

Charge transport through the interface between a normal metal (N) and a superconductor (S) is controlled by two processes: single-particle (Giaever) tunneling, and two-particle (Andreev) tunneling. Giaever tunneling is the dominant mechanism when the transmission coefficient of the N/S interface is small and results in current-voltage characteristics such that $R_0^N/R_0^S \ll 1$. Andreev tunneling becomes important when the interface is ''transparent,'' and in the limiting case of a ''perfect'' interface may lead to $R_0^N/R_0^S = 2$. R_0^S and R_0^N are the interface resistances at zero voltage in the superconducting state and the normal state, respectively. Both types of processes have a characteristic voltage scale of Δ, the superconducting energy gap. Blonder Tinkham and Klapwijk (BTK)[1] showed that the interplay between the two mechanisms leads to a resistance versus voltage (R-V) curve, that is characterized by a double-dip structure at $V = \pm\Delta$ and a peak centered at $V=0$. The double-dip feature is the hallmark of the BTK model, which has been successful in providing a method to extract the transmission coefficient of S/N contacts based on experimental R-V curves.

The BTK theory ignores disorder and quantum interference effects. Over the past few years it has been observed[2,3] that when the N region of extent L near the interface with S is ''dirty,'' and $L < L_\varphi$, where L_φ is the phase-breaking length, a sharp resistance dip occurs around $V=0$. This zero-bias anomaly (ZBA) has been attributed to a constructive interference process between the electron and hole trajectories in the normal region.[4,5] This mechanism increases the value of R_0^N/R_0^S, but the value for this ratio is still limited to a factor of 2. Indeed, the majority of experiments are in agreement with this upper bound. Note, however, that these theories are based on a single-particle picture in which interactions are not taken into account. In this paper we report on the small-bias I-V characteristics in *NIS* devices where N is Au, I is amorphous indium-oxide, and S is lead. The characteristics of these devices exhibit R_0^N/R_0^S ratios which often exceed a factor of 2. In fact, in these samples, a factor larger than 2 is the rule rather than the exception. In addition, the voltage scale δ of the ZBA depends systematically on the barrier length L. For relatively large L (400–500 Å), δ is of the order of Δ. But as L decreases δ becomes much smaller than Δ. These features cannot be accounted for by the current theories of Andreev reflections in S/N contacts. It is also shown that in the presence of a microwave field the ZBA features are modified in a systematic way, which is distinctly different than the effects obtained by raising the sample temperature. The sensitivity to microwave radiation is peculiar to *NIS* samples, and it is not observed when the Anderson-insulating layer is eliminated from the structure. We raise the possibility that the results are due to the combined effects of electronic interactions and disorder, which are particularly important when the barrier is an Anderson insulator (such as the indium-oxide barrier in our samples). It is argued that the large R_0^N/R_0^S values may result from a proximity effect at the I/S interface, which changes the effective barrier. We offer a heuristic picture to explain how the above-mentioned features may arise from tunneling through localized states.

II. EXPERIMENT

The Au/InO_x/Pb samples used in this study were prepared by depositing a gold strip, 100–500 μm wide and 400–500 Å thick, onto a room-temperature glass slide. Then a layer of InO_x (thickness L ranging from 90 to 600 Å) was e-beam evaporated on top of the Au electrode. The InO_x layer was evaporated from a 99.999% pure In_2O_3 target at a rate of 0.5 ± 0.2 Å/S in an O_2 ambience (a partial pressure of 0.3–0.7 m Torr). Such InO_x layers reached a physical continuity at a nominal thickness of 30 Å.[6] The room temperature resistivity of the films (based on in-plane measurement) varied between 10 and 100 Ω cm depending on the preparation conditions. Finally a cross strip of Pb 30–100 μm wide and 2700–3000 Å thick completed a standard four-terminal device. More details of the sample fabrication and characterization are described elsewhere.[7,8]

The samples were mounted onto a probe, and in most cases measured in a sorption-pumped ^{3}He rig equipped with a superconducting magnet. This enabled variable temperature measurements in the range 300 mK to 300 K, and application of magnetic fields up to 9 T. For each sample we measured dV/dI versus V employing standard four-terminal ac techniques. Special care was taken in measurements performed at $T < 1$ K in terms of filtering out high frequency signals for the sample leads, and reducing the ac excitation currents. The ac derivative measurements could be used to

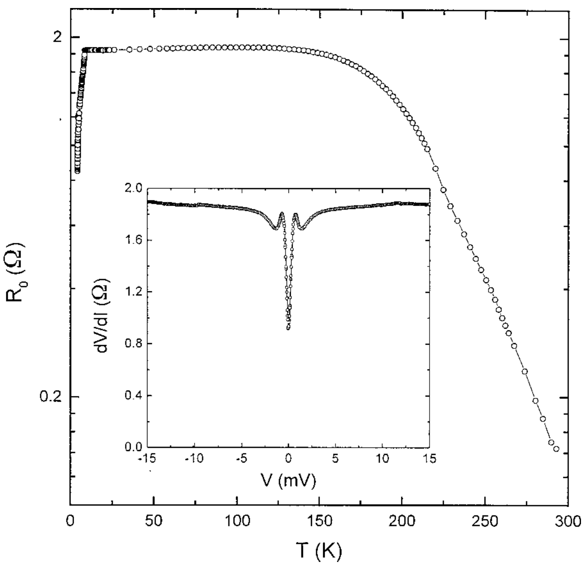

FIG. 1. Temperature dependence of a typical Au/InO_x/Pb sample with $L = 245$ Å. The inset shows the dynamic resistance vs voltage of this sample at $T = 4.11$ K (note the dips at $V = \pm\Delta$).

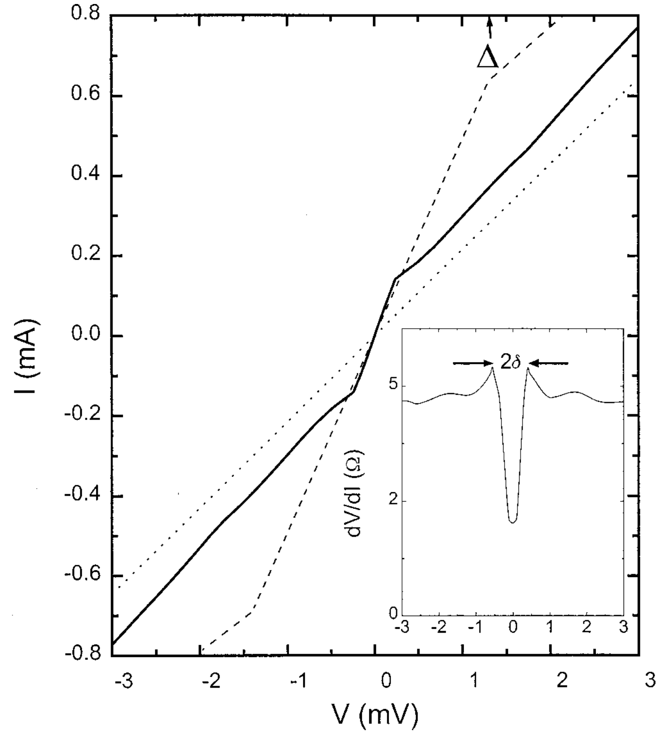

FIG. 2. I-V characteristics of a typical Au/InO_x/Pb sample with $L = 180$ Å in the superconducting state (full line), and in the normal state induced by $H = 0.5$ T (dotted line). Data shown were taken at $T = 4.11$ K. The dashed line curve depicts the I-V characteristics for ''ideal'' Andreev tunneling (see text). The inset shows the dynamic resistance of this sample and the definition of δ.

construct the I-V characteristics by integration. These curves were verified by performing dc measurements on several of the samples.

For the application of microwave radiation we used a 20-GHz Gunn diode. The samples were mounted at the bottom of a cylindrical stainless-steel tube, which formed a waveguide for the microwave field. The maximum microwave power at the bottom of the probe was measured to be about 0.5 mW. Different levels of the microwave power were achieved by using a screw attenuator. The microwave experiments reported here were carried out with the samples immersed in a liquid ^{4}He storage dewar. Hence these experiments were limited to a constant temperature of $T = 4.11$ K.

III. RESULTS AND DISCUSSION

The *NIS* samples described below had a low-temperature normal-state resistance R_0^N in the range 0.8–5 Ω. On cooling down from room temperature the junction resistance *of all samples* increased sharply by a factor of 2–20 depending on the batch of InO_x. A typical case is shown in Fig. 1. Below 10 K the junction resistance in the normal state (obtained when necessary by quenching superconductivity with a magnetic field) was temperature independent in all cases. This behavior is consistent with transport through a thin Anderson insulator (i.e., the indium-oxide layer).[9]

Upon cooling below $T = 7.2$ K (the critical temperature of Pb) the zero-bias resistance, R_0^S started to drop, and the I-V characteristics exhibited a resistance minimum at zero bias. A typical I-V curve measured by dc is shown in Fig. 2. This is compared with the I-V curve expected for an ''ideal BTK'' junction, namely, one having a unity Andreev coefficient. In the latter case $(dI/dV)_S = 2(dI/dV)_N$ for $V < \Delta$ and $(dI/dV)_S = (dI/dV)_N$ for $V > \Delta$. For $V > \Delta$, $(I\text{-}V)_S$ is characterized by a constant ''excess-current'' I_S-I_N.[1] S and N subscripts are used here to designate measurements in the superconducting and normal states, respectively. By comparison, the experimental $(I\text{-}V)_S$ curve shows $(dI/dV) \approx 2.3(dI/dV)_N$ for $V = \pm 0.25$ mV, and has a smaller excess current at higher bias than the ''ideal.''

The ratio R_0^N/R_0^S increases sharply below the transition temperature T_C of the Pb electrode, and it saturates at low temperatures as illustrated in Fig. 3. In this temperature regime, R_0^N was obtained by applying a magnetic field $H \cong 0.15$ T parallel to the sample plane to quench superconductivity (at higher fields, up to 3 T, R_0^N was essentially unaffected by H). R_0^N and R_0^S in Fig. 3 were taken from the respective dV/dI plots at zero bias, always making sure that the excitation current was small enough. Within our experimental error R_0^N obtained by quenching superconductivity with a magnetic field was identical with the zero-bias R measured just above T_C or that measured at $V \gg \Delta$. There is therefore no reason to believe that the large value of R_0^N/R_0^S reported here is due to overestimating the value of R_0^N. The majority of our samples (more than 80 samples altogether) had R_0^N/R_0^S values between 2 and 4. Three samples had R_0^N/R_0^S of 4–5. Only five of the samples had $R_0^N/R_0^S < 2$.

No correlation was found between R_0^N/R_0^S and R_0^N, or with the thickness of the Anderson insulator L. In particular, in a series of samples prepared at the same deposition run, where L was typically 200, 400, and 600 Å, R_0^N/R_0^S was essentially the same for all three junctions.[8]

On the other hand, there is a statistic correlation between L and the range of voltages, δ, over which the anomalous excess conductance is observed. It turns out that the smaller L is, the narrower this range. Figure 4 compares the dynamic

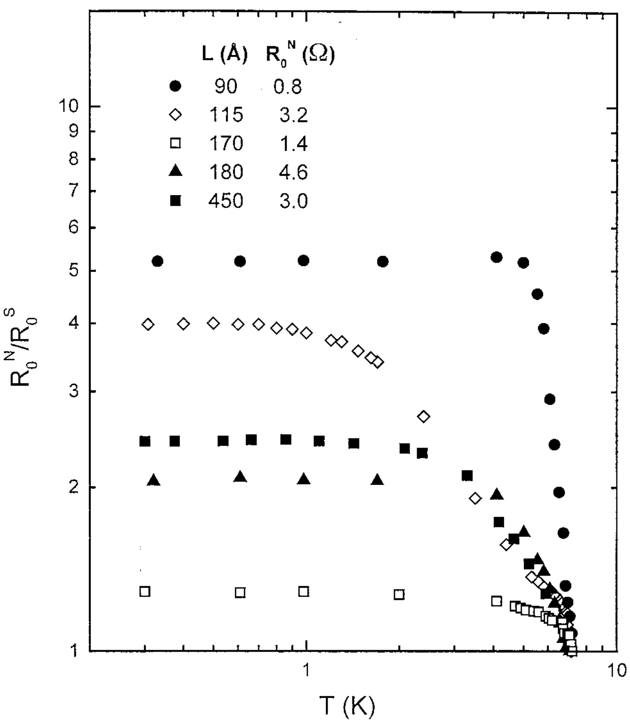

FIG. 3. Temperature dependence of the resistance ratio R_0^N/R_0^S for representative *NIS* samples, with different barrier lengths L and normal state resistances R_0^N.

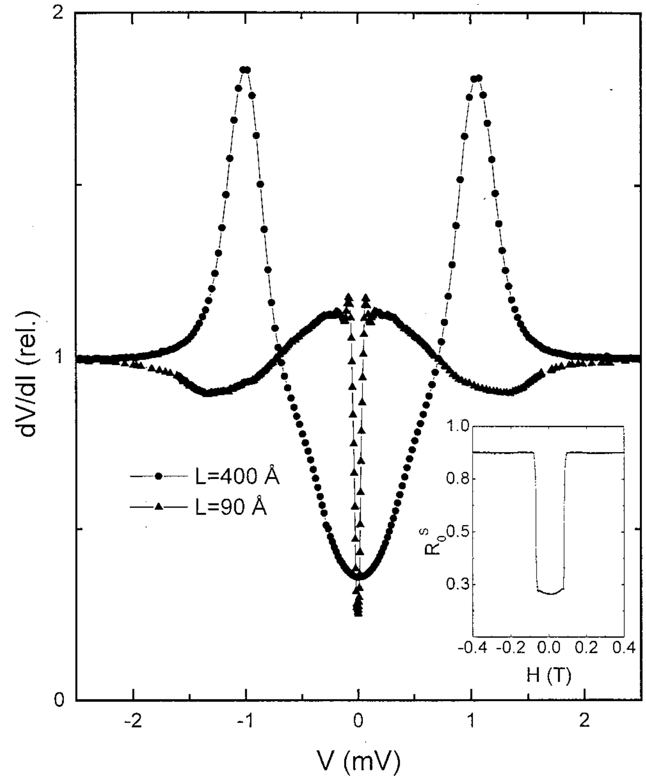

FIG. 4. Dynamic resistance (normalized to the value at 2.5 mV) vs V for *NIS* samples with small and large L (measured at 4.11 K). Note the dips at $\pm\Delta$ for the $L=90$ Å sample. The inset shows the dependence of R_0^S on magnetic field H for the $L=90$ Å sample.

resistance curves versus bias voltage for a small L sample with a larger L sample illustrating this point. A convenient measure of δ is the position of the peak in the dV/dI vs V plot (cf. the inset in Fig. 2).[10] The dependence of δ on L is shown in Fig. 5. Although there is a considerable scatter in the data, the overall trend is clear. No such correlation could be identified between δ and R_0^N. Samples with identical L but with quite different junction areas (and therefore different R_0^N) exhibit similar δ. Moreover, although on average R_0^N does increase with L, the overall range of R_0^N in the samples studied is smaller by a factor of 2 than the respective variation in terms of δ. So, the dependence of δ on L is nontrivial. Current models for the origin of the ZBA in S/N contacts[4] are based on the understanding that the Andreev coefficient at the N/S interface is enhanced by disorder due to constructive interference between the electron and hole. This enhancement effect persists up to a critical voltage V_C given by $\hbar/e\tau_\varphi$ (τ_φ is the phase-breaking time of the disordered region at which the particle is ''trapped'' near the interface). For $N/N'/S$ junctions (where N' is a ''dirty'' normal region of extent L) this should lead to a zero-bias anomaly with a voltage width that *decreases* with L, as was experimentally demonstrated.[11]

The two main findings reported here, i.e., $R_0^N/R_0^S>2$ and the increase of δ with L, are scarcely observed in ''clean'' S/N contacts. That these features are observed so systematically in samples that employ InO_x as the barrier material motivated us to focus attention on the properties of this barrier layer. Since transport through indium-oxide films is very sensitive to the application of microwave radiation,[12] we have studied the effect of microwaves on the I-V character-

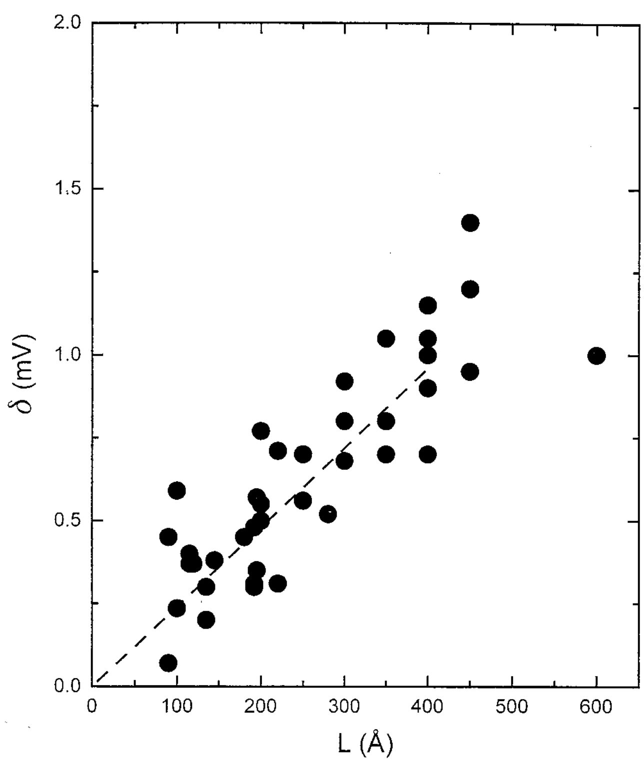

FIG. 5. The value of δ as a function of L for 50 of the studied *NIS* samples (only samples with $0.8\Omega<R_0^N<4.6\Omega$ are included).

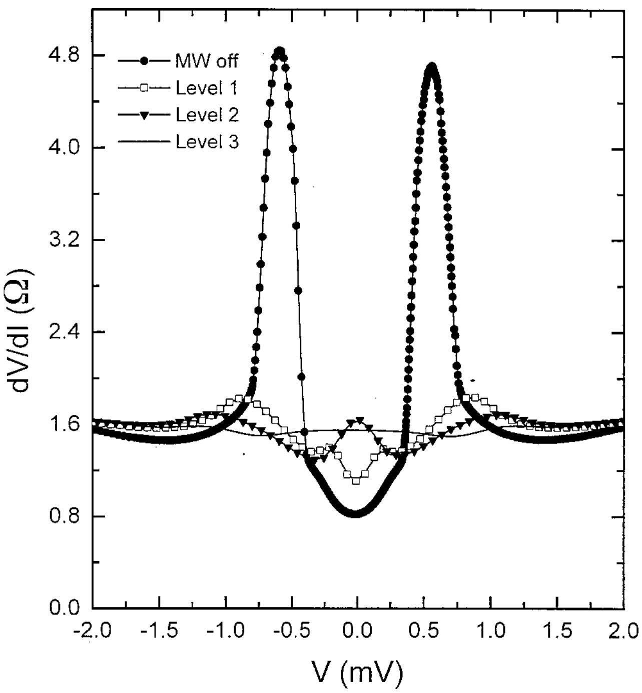

FIG. 6. The evolution of the ZBA features for various microwaves radiation intensities (which increase as the level increases). Note that, if anything, δ increases with the microwaves power (compare with Fig. 8). $L=275$ Å and $T=4.11$ K.

istics of Au/InO_x/Pb junctions. Figures 6 and 7 show the dV/dI curves of two samples in the presence of microwave radiation with different intensities. It is seen that as the power of the microwave increases, the zero-bias resistance R_0^S increases and approaches R_0^N. At sufficiently high level of the microwaves the ZBA features were wiped out almost completely while the Pb electrode remained superconducting. It is natural to suspect that this effect may be due to heating of the sample by the ac field. Raising the sample temperature does increase R_0^S (Figs. 8 and 9). When the temperature is raised the amplitude of the ZBA is progressively decreased, and in this regard the effect is indeed the same as in increasing the microwave power. There are, however, clear differences between the two results. First, the width of the ZBA *increases* continuously with the microwave power, while it *decreases* with temperature. Second, at high enough microwave power the I-V curve is characterized by a local *maximum* around $V=0$, which resembles a typical BTK feature. Increasing the sample temperature never reproduced such a behavior (more than 20 samples were studied in this regard). Finally, even the maximum microwave power we used had a negligible effect on the sample temperature, as can be realized by monitoring the ''above-gap'' structure (c.f. Fig. 9). The latter is a specific modulation that frequently appears at $V>\Delta$. While the origin of this phenomenon is not yet understood, it has been established in several systems[3,13] that this modulation appears at a sample-specific voltage that scales with $\Delta(T)$. Thus, for a given sample, the change of the temperature can be empirically monitored. As illustrated at the bottom of Fig. 7, a substantial change in R_0^S can be affected by the microwave without any observable shift in the position of the above-gap structure. Raising the temperature to reproduce a comparable change of R_0^S evidently causes an appreciable shift in the above-gap structure (Fig. 9). Obviously then, although some heating probably results from the ac field, the sensitivity of Andreev processes in our samples to the microwave field *must* involve more than just heating.[14]

Qualitatively, the zero-bias anomalies we observe have the features expected of N/S contacts in which Andreev processes are dominant and interference effects are important.[1,4,5] It was suggested[7,8] that large Andreev coefficients in *NIS* samples could result from barriers that are Anderson insulators, and thus include a high density of localized states near the chemical potential. Such a medium may contain channels that are nearly resonant due to rare realizations of localized-state configurations. Lifshitz and Kirpichenkov (LK) discussed such ''optimal'' trajectories, and showed their relevance for transport through disordered media.[15] As pointed out by Frydman and Ovadyahu,[8] it is difficult to distinguish LK channels from metallic filaments connecting the S and N regions through, say, pinholes in the barrier. This point will be dealt with further later on. For the time being we focus on the observation of the feature $R_0^N/R_0^S>2$, which seems to be inconsistent with the current theories for N/S contacts. The factor of 2 bound is based on the assumption that each conduction channel that is characterized by a transmission coefficient t_i and contributes $t_1(e^2/h)$ to $(R_0^N)^{-1}$ contributes $2t_i^2(e^2/h)/(2-t_i)^2$ to $(R_0^S)^{-1}$. Therefore, even if all transmission channels are perfect ($t_i=1$) the value of R_0^N/R_0^S is limited to a factor of 2. This limitation is equally valid whether the Andreev processes take place via metallic ''filaments'' or via LK trajectories.

Breaking the factor 2 bound may be possible if one takes into account electronic interactions. A normal region in contact with a superconductor exhibits finite pair amplitude due to the proximity effect. If the N region is endowed with a nonzero electron-electron interaction, the proximity effect induces a finite *pair potential* in the normal metal. Andreev reflections would then occur at a distance ξ_N from the interface with the superconducting electrode. ξ_N is the normal metal coherence-length (either $\hbar D/kT$ or the phase-breaking length). In that case, R_0^N and R_0^S are associated with *different* t's, and the ratio between the two resistances could be much greater than 2. In fact, this ratio should diverge as T goes to zero (or at $T=T_{\rm CN}$, the critical temperature of the N metal, in case the interaction in N is attractive).

The correlation of the ZBA features with the appearance of superconductivity in the Pb electrode (cf. Figs. 3 and 4) is indeed consistent with a proximity effect. However, the fact that R_0^N/R_0^S saturates at low temperatures (Fig. 3) suggests a cutoff for this process. As mentioned in Sec. II, care was taken to ensure that this saturation is not due to experimental artifacts. The ac excitation current was varied over three orders of magnitude without any change in R_0^N/R_0^S. The results were also insensitive to magnetic and rf fields with levels that are larger than those nominally present. The saturation of R_0^N/R_0^S is therefore a real effect. This makes it hard to believe that the proximity effect involves *diffusive* channels, because then the saturation implies that the penetration of pairs is limited by a length ξ_N such that $\xi_N<L$. This is a more severe problem than that discussed in Ref. 16, whose

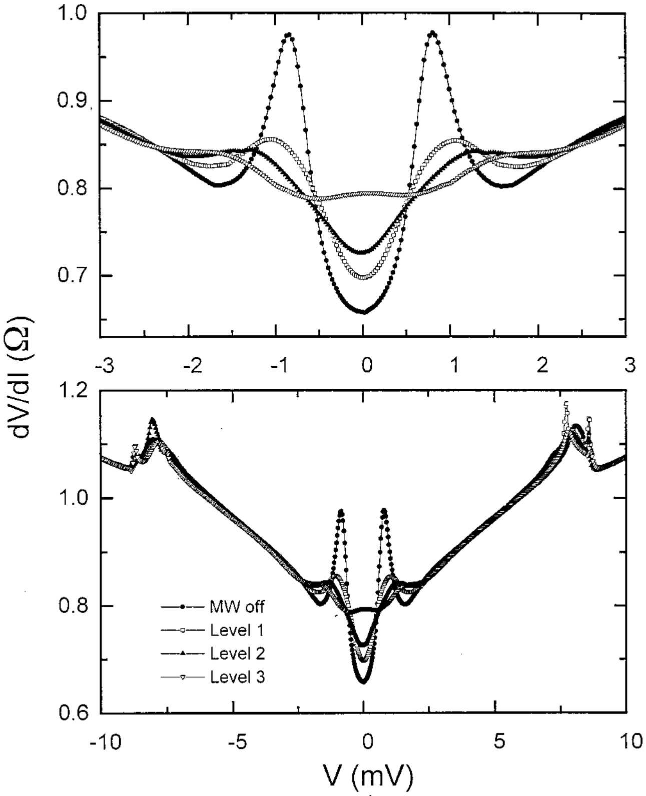

FIG. 7. Same as in Fig. 6 for a $L=375$ Å sample (top graph). The bottom graph shows how the positions of the above-gap structure vary with the microwave power (which increases as the level increases). Note that the voltage position of the above-gap feature (the peaks at $V\approx\pm 8$ mV) is practically independent of the microwave intensity, in contrast with the effect due to temperature (Fig. 9).

authors found a saturation length of the order of few microns which is much larger than our L. As explained below, this problem is alleviated if one considers the role played by the Anderson insulator in this problem.

The role of the Anderson insulator, which forms the barrier material in our samples, must be considered if only for the reason that it is there. As mentioned in Sec. II, R_0^N in our samples always increases steeply upon cooling down from room temperatures, suggesting activation processes consistent with the presence of the Anderson insulator.

At low temperatures however, R_0^N becomes temperature independent. One might then argue that the only function of the Anderson insulator is to sustain accidental metallic ''filaments'' through which the current flows while transport through localized states is irrelevant. The latter is certainly not the case. Note first that elastic tunneling processes evidently take place in our samples. In dV/dI plots of Pb/InO_x/Pb devices we observed[6] a dip at $V=\pm 2\Delta$, and prominent modulations at $V=\pm 4.5$ and ± 8.5 mV, the phonon energies of lead.[17] These two features are clear evidence for Giaever tunneling. In the *NIS* devices this tunneling channel manifests itself as a dip in dV/dI at $\pm\Delta$ which can be clearly seen in samples with $L\leqslant 150$ Å (cf. Figs. 1 and 4). These (single-particle) processes are associated with tunneling paths with $t_i\ll 1$, which arguably exist in Anderson insulators, but are incompatible with transport through metallic shorts.

Likewise, some of the features associated with Andreev processes imply the role of the Anderson insulator. In particular, the unique sensitivity of the ZBA to an ac field (Figs. 6 and 7) hinges on the presence of the Anderson insulator. In Au/Pb and Cu/Pb samples we tested (namely, in samples where the InO_x barriers were deliberately eliminated), *no* effect due to an applied microwave field was observed. Not surprisingly, such samples had a very small R_0^N (typically smaller than 1 mΩ) but they could still be driven normal by high enough currents. Due to the problem of the spreading resistance they cannot be used for a quantitative analysis. Nonetheless, it is still significant that the application of microwaves had no effect on the *I*-*V* characteristics of ''shorted'' samples, while it has a marked effect on the *NIS* samples. Indeed, due to *k*-selection-rule consideration, the InO_x layer, being a highly disordered system, is a more natural candidate for microwave absorption than the clean metals (the Au and Pb layers) used as the electrodes. The sensitivity of transport in InO_x films to an applied microwave field has been demonstrated in Ref. 12. Presumably, the microwave introduces intraband transitions involving the localized states in the Anderson insulator, thereby causing a nonequilibrium occupation of the electronic states. Since the application of microwave power has a nontrivial effect on the ZBA features, it appears that the Anderson insulator *must* play a significant role in the Andreev processes in our junctions.

While it is impossible to rule out the presence of metallic ''filaments'' by any direct experiment, we believe that most of the observed findings can be qualitatively explained without them. Transport through a *NIS* junction is different than that of the N/S system in an essential way. To see that, consider semi-infinite S and N layers separated by a layer of an Anderson insulator I of extent L along the Z axis, such that the S/I interface is at $Z=0$ and the N/I interface at $Z=L$. The electronic states in I are localized on scale ξ (the

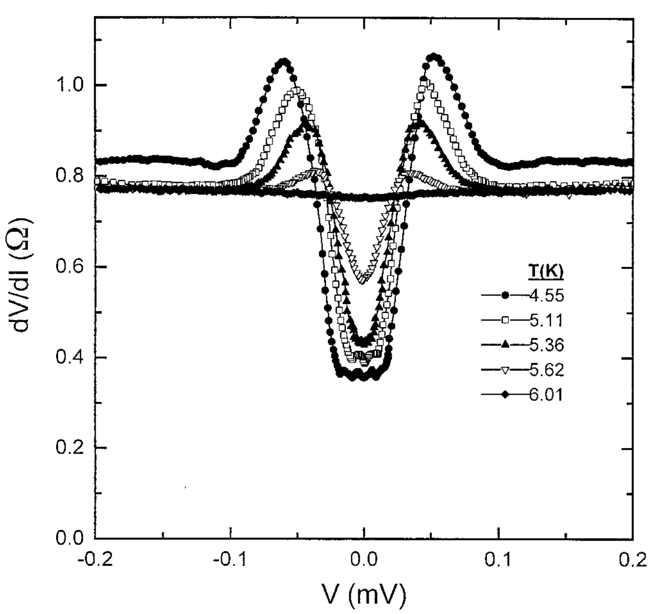

FIG. 8. The evolution of the ZBA features as a function of temperature for a typical *NIS* sample ($L=90$ Å). Note that δ decreases when T increases.

localization length), typically much smaller than L. This introduces a natural hierarchy in the problem. Charge transport from N to S must proceed by tunneling, as, by assumption, no diffusive channel is available. However, it is still possible that the effective barrier for tunneling is different when the S electrode is in the superstate than when it is normal. Tanaka and Fukuyama,[18] using a formal calculation, predicted a proximity effect in Anderson insulators. These authors found that pair amplitude can be induced into an Anderson insulator, and that the penetration depth is limited by the localization length ξ. The physics involved can be understood as follows. Localized states with $Z \leqslant \xi$ are strongly coupled to the superconductor. On a length scale that is smaller than ξ, there is no distinction between an Anderson insulator and a disordered normal metal. Therefore, it is plausible that superconductivity may be induced in this region by the proximity effect. This in turn may lead to a ZBA, with $R_0^N/R_0^S > 2$, as discussed earlier. The difference between the metallic "filaments" and the Anderson-insulator scenarios becomes now clear: The "leakage" of superconductivity into a normal metal occurs on a scale of the normal-state coherence length, which is temperature dependent. In the Anderson insulator, on the other hand, there is a limiting length, ξ which does *not* depend on temperature.[18] This could be the reason for the saturation of R_0^N/R_0^S at low temperatures, as seen in Fig. 2. To be consistent, such interpretation must involve the assumption of a nonzero interaction in the interface layer. By itself, it is natural to expect that in an Anderson insulator such interaction is repulsive due the lack of electronic screening. But the proximity of this thin layer to the S metal may reduce this problem through the induced image charges. However, it should be emphasized that it is sufficient that the interaction in the ξ layer is nonzero, and it might well be negative.

Another question concerns the impact of a proximity layer of extent ξ on R_0^N/R_0^S. This clearly depends on the ratio ξ/L. A typical value for the localization length, based on in-plane transport measurements of InO_x films, is[19] 10–20 Å, which means $\xi/L \ll 1$. In a diffusive transport scenario this will give a negligible enhancement. For tunneling through an Anderson insulator, on the other hand, where R_i for a given channel i should scale like $\exp[L/\xi]$, a significant enhancement may be obtained. In the simplest scenario one divides the tunneling channels into two groups: channels with $t_1 \ll 1$ and channels with $t_1 = 1$. The first group controls the single-particle transport, and contributes practically nothing to pair tunneling. The only significant contribution to $(R_0^S)^{-1}$ then comes from the exponentially rare[20] LK channels with $t_i = 1$. As a crude assumption let us set all the t's to be identically "zero" and "1" for the first and second groups, respectively. Then R_0^N and R_0^S are uniquely determined by the number of resonant channels m. The ratio R_0^N/R_0^S will then be given by $2(m_S/m_N)$, where $m_{S,N}$ are the respective number of LK channels in the superconducting and normal states. Since the probability to find a resonant channel increases when L is replaced by $(L-\xi)$, m_S will be larger than m_N, and R_0^N/R_0^S can then exceed 2. If, as is not implausible, the probability to find a resonant channel is exponential, i.e., $m \propto \exp[-L/\xi]$, the enhancement is a considerable factor of $e \approx 2.8$, *independent* of L and ξ, giving a maximum value of 5.6 for R_0^N/R_0^S. We note that both features are consistent with the data. Whether these considerations can account quantitatively for the experiments remains to be seen.[21] In any event it is evident that the one-to-one association $t_i \to 2t_i^2/(2-t_i)^2$ on which the factor 2 bound hinges, is no longer valid.

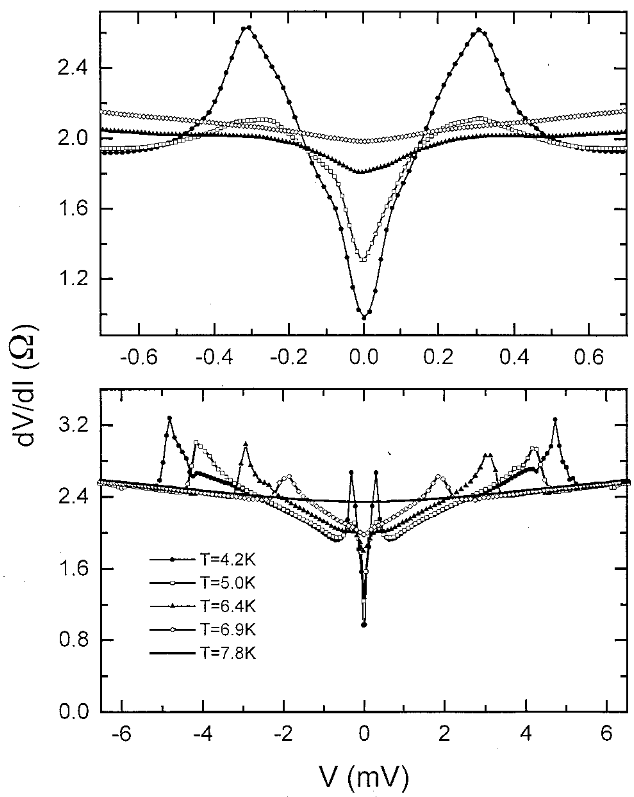

FIG. 9. Same as in Fig. 8 for an $L = 220$ Å sample (top graph). The bottom graph shows how the positions of the above-gap structure vary with temperature.

The suppression of the ZBA feature at small voltages (i.e., at $\delta \approx \Delta$) may be now interpreted in the following way: As the applied voltage V increases, so does the current through the junction. At some point ($V \approx \delta$) this current (I_C) would be large enough to suppress superconductivity in the proximity layer. The pair potential in this layer is then quenched, and Andreev reflections are shifted back to the interface with the Pb, which results in a reduction in the Andreev process. In other words, we associate δ with the voltage that drives I_C through the proximity layer. I_C is probably much smaller than the critical current of the Pb electrode due to two reasons. First, the induced superconductivity is naturally "weaker." Second, the current *density* in the proximity layer is obviously much larger than in the bulk Pb electrode. In the regime $V > \delta$ Andreev reflections are thus still possible (albeit with a smaller Andreev coefficient than in small bias) and lead to the excess current observed (Fig. 2). In this picture the reason for the $\delta \alpha L$ observation is ascribed to the on-average increase of the resistance of the relevant[22] conduction channels with L.

But in addition to destroying the proximity-layer when the current it induces exceeds I_C, the applied V may affect the shape of the ZBA at $V < \delta$. The small bias dV/dI we observe is ''pointed'' rather than ''BTK like,'' and in this aspect resembles the feature observed by Kastalsky *et al.*[2] As alluded to in Sec. I, such a ZBA shape is ascribed to an interference effect.[4] In our samples this interference presumably occurs in the Anderson insulator on a scale $L \gg \xi$. Quantum coherence in this medium is well known[23] to extend on scales much larger than ξ. In fact, quantum effects are cut off by the hopping length, which is typically a few hundred Å at liquid-helium temperatures, and thus comparable to L in our samples. Note that this is consistent with the saturation of R_0^N at low temperatures. However, transport through Anderson insulators is very sensitive to electric fields.[24] A typical field associated with $V \approx \delta$ is $F \cong 250$ V/cm (estimated from the straight line in Fig. 4). Fields of these magnitudes are sufficient to appreciably reduce quantum-coherent effects associated with ''forward-scattered'' tunneling paths in Anderson insulators.[25] Andreev processes are even more sensitive to electric fields than single-particle processes, because the electron and hole acquire different phases upon traversing it. Such a mechanism should also be sensitive to a magnetic field, as it was in the experiment of Kastalsky *et al.* Applying a field H indeed increases R_0^S in our samples (cf. the inset in Fig. 4). But the effect is rather small and the field necessary to appreciably affect R_0^S is considerably larger than that in the experiment of Ref. 2. This difference may be related to the effective coherent area involved in the two systems. In the case of Kastalsky *et al.* the disordered region was a diffusive system for which the relevant area is L_φ^2. For $L_\varphi \approx 1\ \mu$m this area is of the order of $10^{-8}\ \mathrm{cm}^2$. In Anderson insulators the relevant area is set[26] by $r^{3/2}\xi^{1/2}$ where r is the hopping length, which in the present case is effectively L. Taking $L = 100-600$ Å, and $\xi = 10-100$ Å as possible values, this yields an area smaller than $1 \times 10^{-11}\ \mathrm{cm}^2$. The associated field is then much larger than that necessary to quench superconductivity in the Pb electrode.

While a magnetic field is ineffective in this case, an ac field of frequency comparable to τ_φ^{-1} should be a dephasing agent. As shown in Figs. 6 and 7, exposing the sample to a 20-GHz microwave radiation considerably modifies the ZBA. It reduces $(R_0^S)^{-1}$, and the ZBA reverts to a shape that resembles the BTK feature. Such a behavior is consistent with a picture in which the microwave radiation causes electron-hole dephasing, thus suppressing the van-Wees enhancement[4] to the Andreev processes.

IV. SUMMARY

We have presented transport and tunneling experiments performed on a large number of *NIS* junctions employing Anderson-insulating InO_x barriers. While the details of the I-V characteristics may differ from sample to sample, they systematically exhibit common features. These include a large ratio of R_0^N/R_0^S (typically larger than the ''ideal'' factor 2), that saturate at low temperatures, and nontrivial effects due to an ac field. Leaving open the possibility that accidental point contacts are present, we offered an alternative picture that implicates the role of the Anderson insulator in giving rise to these anomalies. In particular, we argued that the coexistence of tunneling channels with $t_i \ll 1$ and channels with $t_i \approx 1$ are inherent in transport through a thin Anderson insulator. Also, both the sensitivity of the ZBA to microwaves radiation and the saturation of R_0^N/R_0^S are more naturally explained in our picture.

A fuller understanding of these phenomena must await a detailed theoretical treatment of transport in such systems. In particular the nature of the proximity effect in Anderson insulators needs to be better understood. We hope that the present results will motivate such studies.

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[21] Note that the ξ derived from the in-plane transport is an *average* value. It is not necessarily the appropriate value to be used in estimating either ξ_N or the decay of m_S with L. These considerations depend in a complicated way on the nature of the ξ distribution, which is not generally known.

[22] As L increases the number of the resonant channels presumably decreases. Therefore, the current that flows through a given proximity layer is effectively smaller, and higher bias should be applied to reach I_C. By ''relevant'' we mean those $t_i \approx 1$ channels that are mainly responsible for the Andreev processes. The *measured* resistance of the sample (R_N) is not necessarily a faithful criterion in this regard, for reasons explained in Ref. 15.

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