# Tunneling of current carriers in niobium nitride junctions

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(Submitted 3 May 1982; resubmitted 27 September 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 9, 313–316 (5 November 1982)

The characteristics $\sigma_e(V)$ and $d\sigma_e(V)/dV$, where $\sigma_e$ is the even part of the conductivity of a tunnel junction, are investigated for NbN-I-Pb and NbN-I-Ag (I is an Nb oxide) junctions in the voltage range $V-(\Delta_{\rm NbN}+\Delta_{\rm Pb})/e = 0\text{–}30$ meV and $V-\Delta_{\rm NbN}/e = 0\text{–}31$ meV, respectively ($\Delta_{\rm NbN}$ and $\Delta_{\rm Pb}$ are the superconducting energy gaps). The positions of peaks in the electron-phonon interaction (EPI) function are determined in the energy range 0–26 meV.

PACS numbers: 74.50. + r

Electron tunneling in S-I-N and S-I-S systems ($S$ is the superconductor, $N$ is the normal metal, and $I$ is the insulator) gives information on EPI in superconducting electrodes.[1] The usual elastic single-particle current, as well as the inelastic part of the current, contribute to $\sigma_e(V)$; multiparticle effects, both intrinsic energy effects and interference effects (related to the nonorthogonality of the elastic and inelastic processes), are included in $\sigma_{H_0}$ ($\sigma_{H_0}$ is the odd part). Separating $\sigma_e$ eliminates the effect of these multiparticle processes.[2] For S-I-N junctions, the energies of minima in the elastic part $d\sigma_e/dV$ coincide with the energies of the peaks in EPI. For S-I-S junctions, there is no such simple relation. However, if the peaks in EPI of both superconductors are separated, then the relation indicated above is approximately satisfied. The advantage of S-I-S junctions is the large magnitude of the effect. For the inelastic part of the tunneling current $d\sigma_e/dV>0$ and the peaks in the phonon density of states or impurity vibrations correspond to peaks in $d\sigma_e/dV$. Thus, if min $d\sigma_e/dV<0$, then it could be related only to the usual elastic tunneling and its position determines the energy of peaks in EPI. The reverse assertion could be incorrect due to increased transparency of the barrier with increasing $V$.

In this paper, we present the results of investigations of $\sigma_e(V)$ and $d\sigma_e/dV$ of NbN-I-Pb and NbN-I-Ag (I is an Nb oxide) tunnel junctions.

NbN films were prepared by the method of reactive cathodic sputtering.[3] The second electrode was deposited after exposing the films to air for 10–720 hours. The area of the tunnel junction was $1.0\times0.1$ mm$^2$ and the resistance was $R=0.7\text{–}8.7\ \Omega$. The I–V characteristic (I is the tunnel current) and $dV/dI$ were measured at $T=1.9$ K. The values of $dV/dI$ were inverted and smoothed, after which $\sigma_e\equiv(dI/dV)_e$ and $d\sigma_e/dV$ were calculated. All calculations were performed on a WANG 2200 computer.

A series of tunnel junctions was prepared. Two junctions were chosen from this series: one junction was NbN-I-Pb and the other was NbN-I-Ag, which have the highest superconducting parameters of the NbN film and only a single superconducting gap in the NbN film.[1)] The parameters of the NbN films in the NbN-I-Pb and

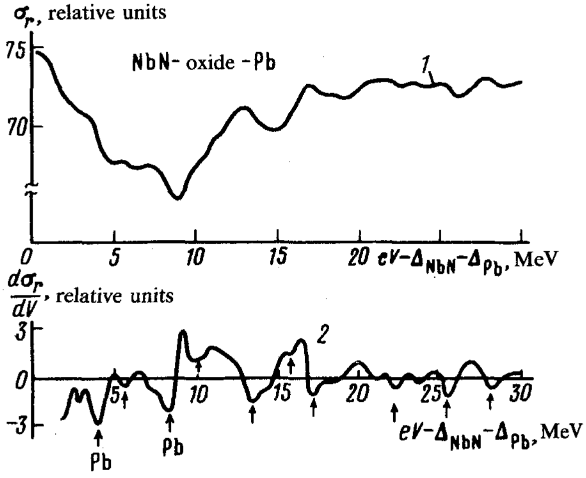

FIG. 1. NbN-I-Pb junction: $T = 1.9$ K, 1) $\sigma_e(V)$,2) $d\sigma_e(V)/dV$.

NbN-I-Ag junctions were equal to, respectively, $T_c = 15.6$ K and $T_c = 14.6$ K, $\Delta = 2.9$ meV and $\Delta = 2.6$ meV, and $R = 8.7\ \Omega$ and $R = 1.5\ \Omega$. Here $T_c$ is the superconducting transition temperature, defined relative to the center of the jump in resistance. The junctions indicated were repeatedly measured and analyzed using the algorithm presented above. The results of all measurements were averaged for each specimen.

Figures 1 and 2 show the dependences $\sigma_e(V)$ and $d\sigma_e(V)/dV$ for both junctions. Figure 1 corresponds to the junction NbN-I-Pb. The measurement along the abscissa axis for each polarity was made from the sum of the gaps $\Delta_{\text{NbN}} + \Delta_{\text{Pb}}$. Figure 2

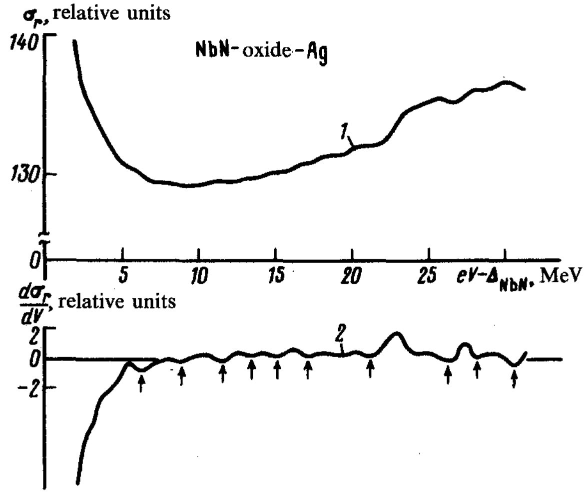

FIG. 2. NbN-I-Ag junction: $T = 1.9$ K, 1) $\sigma_e(V)$, 2) $d\sigma_e(V)/dV$.

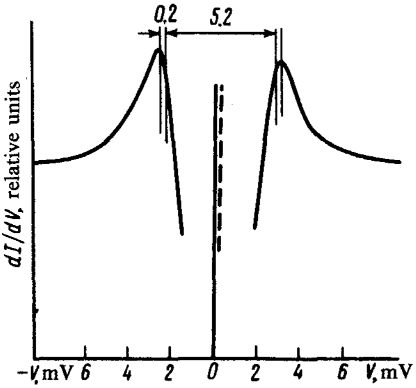

FIG. 3. Correction for the displacement of a peak in the conductivity $\sigma$ relative to the position of $\Delta_{\rm NbN}$ for both polarities for an NbN-I-Ag junction. The correction was made following Ref. 4. The sign of $V$ corresponds to the polarity of Ag.

corresponds to NbN-I-Ag. The measurement along the absciassa axis for each polarity was made from the gap $\Delta_{\rm NbN}$. A correction was introduced for the shift in the position of the peaks in $dI/dV$ relative to $\Delta_{\rm NbN}$, calculated using the method in Ref. 4. The position of $\Delta_{\rm NbN}$ for both polarities is indicated in Fig. 3. It is not possible to normalize $\sigma_e$ to the corresponding values of the conductivity of the normal metal, since in the normal state the resistance of an NbN film is much greater than the resistance of the tunnel junction. It is evident from Figs. 1 and 2 that the functions $d\sigma_e/dV$ have a complex structure which contains a number of minima. The main minima in the figures are indicated by the arrows. The energies corresponding to them are presented in Table I. An analogous picture was also observed for other junctions. The deviation of the positions of the minima from those presented in Table I were in the range from several tens meV to a single meV. The spread is apparently related to the different structure of the films,which not only shifts the minima but also changes the superconducting parameters.

In order to interpret the characteristics obtained, additional information is necessary. NbN has an NaCl-type structure which contains two atoms in a unit electronic cell. Its phonon spectrum contains three acoustical and three optical branches. We are

TABLE I. Position of peaks in the function $d\sigma_e(V)/dV$, meV.

| No. | NbN-Pb | NbN-Ag | No. | NbN-Pb | NbN-Ag |
|---|---|---|---|---|---|
| 1 | 4.0 | – | 7 | 15.8 | 15.0 |
| 2 | 5.6 | 6.2 | 8 | 17.2 | 17 |
| 3 | 8.4 | – | 9 | 21–23.6 | 21 |
| 4 | 9.8 –10.6 | 8.8 | 10 | 25.4 | 26.2 |
| 5 |  | 11.5 | 11 | 28.0 | 28.2 |
| 6 | 13.4 –14.4 | 13.4 | 12 | — | 30.5 |

not aware of any published data either from neutron measurements of the phonon density of states in NbN or from corresponding tunneling investigations. As a first approximation, we can use the data obtained for Nb. Sharp[5] performed neutron studies of the phonon density of states in Nb. The quasilongitudinal branch has a peak at 23.7 meV and the quasitransverse branches have two peaks: a wide peak in the range 18.1–21 meV and a narrower peak at 16.1 meV. Vedeneev, Golyamina, and Pogrebnyakov[6] obtained the energies of the main peaks in the EPI function at 21–23.5 meV and 15.5–16.7 meV and, in addition, they obtained the energies of two low-frequency peaks in the regions 6.0–6.3 meV and 9.5–10.5 meV. The peaks indicated correspond to minima in $d^2I/dV^2$. We can expect that the peaks in the EPI function for the acoustical branches of NbN will occur approximately in the same region. As far as the optical branches are concerned, we have no indications of the energy interval corresponding to them. We assume that in the interval 0–24 meV the main minima in $d\sigma_e/dV$ for the NbN-I-Ag junction determine the peaks in EPI of the acoustical branches of NbN. The data for the NbN-I-Pb junction agree with these results. The errors can be estimated from the spread in the values obtained for different specimens. This is indicated above.

As follows from Fig. 2 and Table I, NbN has three soft modes with energies 6.2, 8.8, and 11.5 meV. The presence of soft modes is also confirmed by investigations of an NbN-I-Pb junction, but the positions of the corresponding singularities are slightly distorted by the presence of strong singularities related to Pb. Minima of $d\sigma_e/dV$ are observed at high energies 3.3, 15, 17, and 21 meV. The minima corresponding to them are also observed for NbN-I-Pb junctions. As far as the structure of $d\sigma_e/dV$ at $V > 24$ meV is concerned, additional data are required for their interpretation.

[1)] In a number of cases, the NbN films with high values of $T_c$ had two gaps. Such films were not used.

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Translated by M. E. Alferieff
Edited by S. J. Amoretty