Single-particle tunneling through an EuS barrier

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The differential current-voltage characteristics of the tunnel structure NbN–EuS–Pb were found to contain features that are associated with the existence of nonadditive components of single-particle tunneling through a ferromagnetic semiconductor barrier. These features could be caused by the phonon generation at the semiconductor–(ferromagnetic semiconductor) boundary.

It was in shown in Ref. 1 that nonadditive components of single-particle tunneling can be observed on the current-voltage characteristics of a multilayer structure with tunnel barriers with a high penetration probability. In addition to the normally expected gap features of the edges and their total contributions, the I–V characteristic of the structure Sn–I–Sn–I–Pb was found to have a feature of the difference type ($\Delta_{Pb}-\Delta_{Sn}$). This feature actually appeared only in the case of phonon injection from the base junction Pb–I–Pb, on which all subsequent layers enumerated were formed. This result is important not so much because a nonadditive component was found on the I–V characteristic of the multilayer structure as because of the identification of its mechanism, which apparently is attributable to the penetration of the tunnel barrier. Before this results was obtained, data from tunneling investigations of superlattice structures[2] and the newly developed three-level tunneling device—the quinteron[3] with its amplification capability—provided the only indications of the possibility of barrier penetration.

The observation of a nonadditive contribution to the I–V characteristic of a tunnel structure containing a barrier layer, consisting of the ferromagnetic semiconductor EuO:NbN–EuO–Pb, apparently was first reported in Ref. 4, but the mechanism responsible for the contribution was not specified. Nonetheless, it was shown in Ref. 5 that the phenomenon of spin uncoupling of quasiparticles, expected at the superconductor–(ferromagnetic semiconductor) boundary in such a structure, is accompanied by increasing penetration of the ferromagnetic semiconductor barrier for tunneling electrons whose spin orientation corresponds to the magnetization of the barrier. Since this phenomenon should also be accompanied by phonon generation, it is obvious that the difference gap features ($\Delta_1 - \Delta_2$) on the I–V characteristics in Refs. 1 and 4 are ultimately determined by the same mechanism.

In this paper this conclusion is confirmed by the results of an experimental study of the differential I–V characteristic $[R_d \equiv \partial V/\partial J\,(V)]$ of the tunnel structure NbN–EuS–Pb. These results previously could not be adequately explained and were not published.

The tunnel structure was formed on a single-crystalline silicon substrate by sputtering the corresponding superconducting layers up to 0.5 μm thick with an EuS

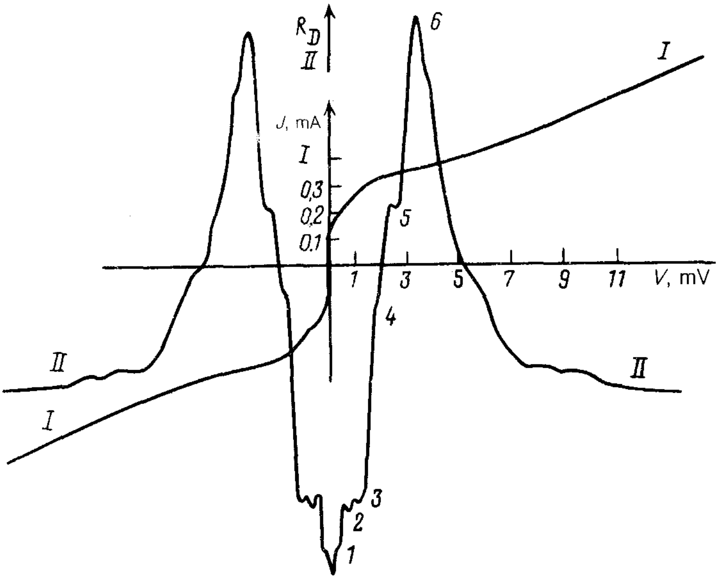

FIG. 1. I–V characteristic of a NbN–EuS–Pb tunnel junction (I) and its derivative $\partial V/\partial J$ (II) at $T = 4.2$ K [the origin of the coordinates of the $R_d(V)$ curve is shifted along the ordinate].

TABLE I. Numerical values of the biases at anomalous points on the I–V characteristic of a NbN–EuS–Pb tunnel junction and their correspondence to the gap features (according to the data of Fig. 1).

Points on the I–V characteristic Bias and correspondence to the gap features	1	2	3	4	5	6
mV	0.35	0,75	1,25	1,80	2,10	3.3 ÷ 3.4
mV	$\frac{\Delta_{NbN}-\Delta_{Pb}}{2}$	$\Delta_{NbN}-\Delta_{Pb}$	Δ_{Pb}	$\frac{\Delta_{NbN}+\Delta_{Pb}}{2}$	Δ_{NbN}	$\Delta_{NbN}+\Delta_{Pb}$

barrier between them. The barrier was more than an order of magnitude thinner. The structure contained several tunnel junctions, whose area was <1 mm^2. The normal resistance of the junctions varied over a range of several tens of ohms. The I–V characteristics were measured by detecting the harmonics at a temperature of 4.2 K, using the four-probe method. Under these conditions the barrier layer exhibited spontaneous magnetization, and its Curie temperature was $T_C \simeq 16$ K (Ref. 6).

The experimental results in Fig. 1 show that the dependence $R_d(V)$ of the junction contains a number of features, which are numbered 1–6. Comparison of the numerical values of the corresponding biases with the known gap parameters of the base superconducting edges (see Table I) shows that, in addition to the usually observed features or the I–V characteristics of the S_1–I–S_2 junctions, which in this case refer to $e^{-1}\Delta_{\rm Pb}$ (point 3), $e^{-1}\Delta_{\rm NbN}$ (point 5), and $e^{-1}(\Delta_{\rm Pb}+\Delta_{\rm NbN})$ (point 6), the I–V characteristic possesses a feature equal to the half-sum of the gaps (point 4) and also the corresponding nonadditive contributions $e^{-1}(\Delta_{\rm NbN}+\Delta_{\rm Pb})$ (point 2) and their half-difference (point 1). The application of an external longitudinal magnetic field to the junction (Fig. 2) changes the shape of the I–V characteristic: The features associated with $e^{-1}\Delta_{\rm Pb}$ (in fields up to 1 kOe) are smoothed out, and the slope of the I–V characteristic with zero bias at the junction (in fields >1 kOe) reverses sign.

Finally, another structural feature, also noted in Ref. 4, of this I–V characteristic is that it does not exhibit hysteresis upon reversal of the polarity of the bias on the structure, including that in a magnetic field.

In summary, our results and those presented in Ref. 4 show that the presence of a

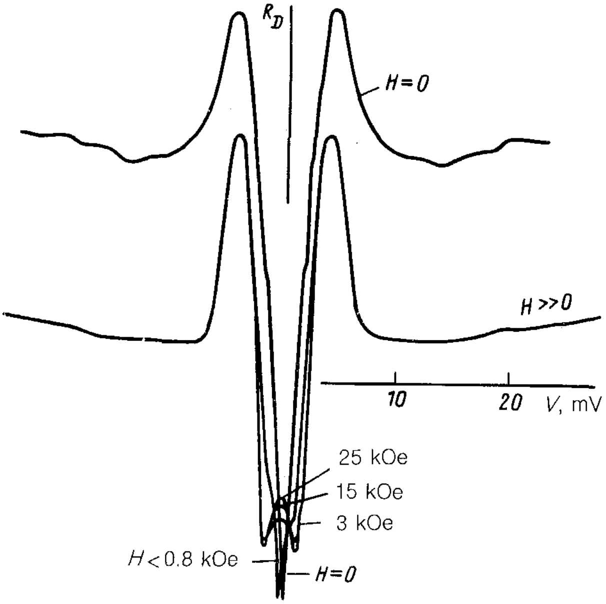

FIG. 2. Variations of the I–V characteristics of a junction in an external magnetic field. $T=4.2$ K.

barrier layer, which consists of a ferromagnetic semiconductor, in a superconducting tunnel junction is associated with the appearance of structural features on the I–V characteristic of the junction, which correspond to nonadditive components of single-particle tunneling through such a barrier. According to the data of Ref. 1, the appearance of these contributions can be attributed to phonon injection (generation), whose origin in this case must reflect the presence of a superconductor–(ferromagnetic semiconductor) boundary in the junction and the associated spin orientation of the quasiparticles. The existence of these phenomena at the (ferromagnetic semiconductor)–semiconductor boundary and their contributions, in particular, to magnetoplasma absorption, was recently demonstrated in Ref. 7. Since the degree of such spin orientation is determined by the size of the magnetic energy barrier, which is equal to $AS/2$, where A is the exchange parameter, and S is the spin of the magnetic ion, the rated frequency of the predicted phonon generation from the designated boundary must be $\omega_0 \simeq 10^{14}$–$10^{15}\ \mathrm{s}^{-1}$. These frequencies include the near-IR region. This frequency region is of practical interest at the junction of the microwave and optical regions, which constitutes one of the possible directions for further research of such tunnel structures, including structures whose edges are high-T_c superconductors.

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