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BAND STRUCTURE OBSERVED IN THE CURRENT-VOLTAGE CHARACTERISTICS OF SINININIS-TYPE JUNCTIONS

I.P.Nevirkovets[+*1], *J.B.Ketterson*[+]

[+]*Northwestern University, Department of Physics and Astronomy*
Evanston IL 60202, USA

[*]*Institute for Metal Physics, National Academy of Sciences of the Ukraine*
252142 Kiev, Ukraine

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Band structure in the conductivity of 4-barrier Nb/Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Nb (SINININIS) tunnel junctions is observed at low temperatures. This structure is explained in terms of the interference of quasiparticle waves in a periodic barrier.

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Until recently, it was thought that the phase-coherent effects between the external S electrodes are negligibly small at non-zero voltage in SINIS-type junctions (here N is either normal metal or a superconductor with an energy gap, Δ_N, considerably smaller than that in S; I is an insulator) with not having high-transparency barriers [1]. Later, it was shown experimentally and theoretically that such effects may be observed in the current-voltage cheracteristics (CVC) of SINIS junctions due to the interference of quasiparticle waves which are Andreev- and normally reflected at the tunnel barriers [2,3]. However, the coherent effects observed so far in the CVC of double-barrier junctions comprised of a metallic thin-film N electrode, manifest themselves either as a zero-voltage supercurrent enhancement [2], or as an increase of the conductivity at non-zero voltages [3]. At the same time, the minima in the conductivity were reported for mesoscopic S-Sm-S junctions in the subgap voltage region (here Sm denotes a doped a semiconductor) [4], and very recently, in the conductivity of the HTSC-based junctions [5].

In this Letter, we present experimental data showing that coherent coupling exists between S electrodes in multi-barrier SINININIS junctions involving low-T_c superconductors. As a result, a band structure in the conductivity appears with minima nearly periodically positioned in voltage.

We have fabricated and investigated four-barrier Nb/Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Nb junctions. We have used the fabrication procedure that is now standard for Nb/Al-AlO$_x$-Al-AlO$_x$-Nb junctions, but included a slight deliberate contamination of a part of internal Al layers by oxygen [6]. The thickness of the external Nb electrodes was approximately 100 nm, whereas the thickness of the Al layers was 7 nm. The junctions were patterned in a two-terminal configuration, so that the CVC could be measured only between the bottom and top S electrodes. The CVC of a 10 μm × 10 μm device (sample 1) measured at $T = 4.2$ K and $T = 1.8$ K are shown in Fig.1 (curves *a* and *b*, respectively). The overall shape of the curves is similar to that of a SIN-junction; i.e., the current rise begins at a voltage $V = \Delta_{Nb}/e$, and not at the voltage $V = 2\Delta_{Nb}/e$ (here Δ_{Nb} is the superconducting energy gap of Nb), as might intuitively be expected. We observed this behavior also in SINIS junctions involving a thick middle N layer (with the thickness,

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[1] e-mail: i-nevirkovets@nwu.edu

d_N, exceeding the electron mean free path). The nature of this feature will be considered elsewhere. Here we only note that the shape of the CVC does not correspond to the simple series connection of the junctions that are involved in the system, i. e., the SINININIS system behaves as a single junction of a new type.

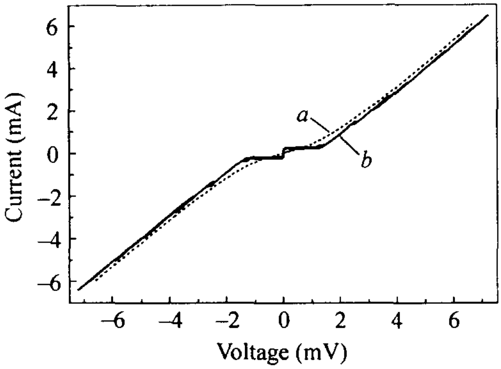

Fig.1. Typical CVC of the Nb/Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Al-AlO$_x$-Nb junction (sample 1) at $T =$ $= 4.2$ K (a) and $T = 1.8$ K (b)

The CVC measured at $T = 4.2$ K is smooth, while that measured at $T = 1.8$ K reveals step-like features accompanied by voltage "jumps". The features are nearly periodically spaced by the voltage $V \simeq 1.2$ mV and persist up to $V \approx 6$ mV, which is higher than the gap sum voltage (even if a reasonable gap, $\Delta_{\rm Al} \approx 0.2$ meV, is assigned to the Al N-layers [6]). The first feature appears near zero voltage as a high-conductivity resistive branch (see Fig.1). This nearly periodical structure will be referred to as band structure.

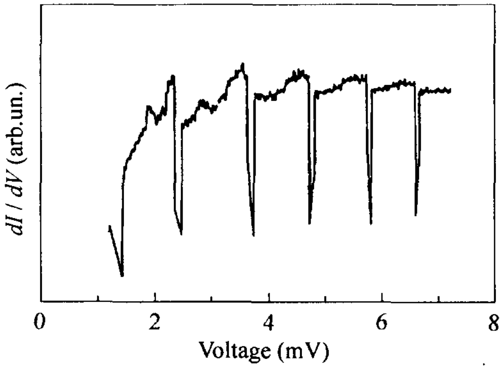

Fig.2. The first derivative, $dI/dV(V)$, of the CVC measured for the 4-barrier junction (sample 2) at $T = 1.8$ K. The derivative was numerically calculated from the branch of the CVC recorded for increasing current

The band structure can be more clearly seen from the first derivative, $dI/dV(V)$, of the CVC (see Fig.2). The derivative was numerically calculated from a branch of the CVC recorded for increasing current (at $T = 1.8$ K) for a sample *2* identical to sample *1* (cf. Fig.1). One can see that below the deep minima, there are maxima in the conductivity. This is evidence that the features appear in the density of the electronic states; i. e., some states are displaced from the mini-gaps to the maxima.

The new features are sensitive to a parallel applied magnetic field. They are significantly washed out at a field $H \sim 300$ G. The voltage and the current at the positions of the voltage "jumps" also depend on the magnetic field. Fig.3 shows two of the features: A (at $V \approx 2$ mV) and B (at $V \approx 1.2$ mV) on an expanded scale for the sample *2*. Currents I_1 and I_2 denote the onset of the forward and backward voltage "jumps", respectively, associated with the feature A. The inset in Fig.3 shows field dependences of the currents

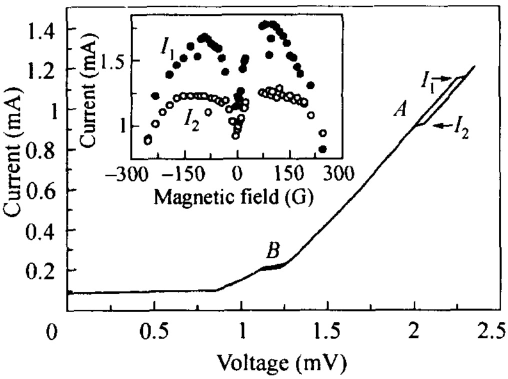

Fig.3. Initial part of the CVC of sample 2 at T = 1.8 K showing the two features (A and B). Currents I_1 and I_2 denote the onset of the forward and backward voltage "jumps", respectively, for the feature A. The inset shows the field dependence of the currents I_1 and I_2 (solid and open circles, respectively)

I_1 and I_2, which have a minimum at $H = 0$, and resemble the field dependence of the height of the Fiske steps in ordinary SIS Josephson junctions [7]. This dependence is typical of the features under consideration. In fact, the magnetic field shifts the band structure along the V axis, so that, at some value of H, a new feature (C) appears at a low voltage $V \approx 1$ mV (see Fig.4). Also, the resistive branch D near zero voltage is clearly seen. This resistive branch is often masked by the Josephson current in the absence of an applied magnetic field (cf. Fig.3).

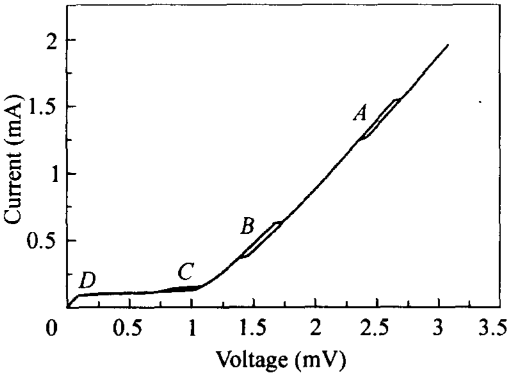

Fig.4. Initial part of the CVC of sample 2 at T = = 1.8 K in parallel applied magnetic field H = = 95 G. Two additional features (C and D) are displayed (cf. Fig.3)

Sensitivity to a weak magnetic field is strong evidence that the effect is related to the phase-coherent current. On first sight, it may be taken for the Tomash or Rowell – MacMillan effect [8 – 10]. However, these effects should be ruled out as possible explanations of the observed band structure due to the following major reasons: (i) we have fabricated and measured many double-barrier SINIS devices with the same geometry of the S and N electrodes, but the effect was not present for such junctions. Therefore, it is apparently associated with the multiple-barrier structures; (ii) both the Tomash and Rowell – McMillan effects produce oscillations of the junction conductance above the gap energy, Δ_S, of the S electrode, and conductance peaks due to bound states below that energy (the last statement is for the Rowell – McMillan effect only, because the Tomash oscillations are not present at the subgap energy). Unlike these effects, we observe a band structure that is a sequence of narrow conductivity hollows rather than peaks or nearly harmonic oscillations, and has essentially the same form both below and above the Δ_S energy.

We suppose that the band structure is due to coherent transport between the external S electrodes through the INININI barrier, and suggest the following interpretation of the new effect. It is known that a band structure may appear in the conductivity of the systems involving a periodic potential [11]. In practical normal-metal–insulator multilayers this structure, to our knowledge, was not observed experimentally so far. Probably this is due to the fact that it is difficult to fabricate homogeneous multilayers with very thin (a few atomic planes) films and perfect (on the atomic scale) interfaces to satisfy the interference conditions for very short wave length, $\lambda_N \sim 1/p_F$, of the normal electrons (here p_F is the Fermi momentum). In the SINI...NIS structure with not too low transparency of the insulating barriers, there is a finite probability of the Andreev reflection at the SIN and NIS interfaces. For the Andreev reflection, one may introduce a wave length $\lambda_s \simeq 2\pi/q_s$ with $q_s = p_e - p_h << p_F$ (where p_e and p_h are quasi-electron and quasi-hole momentum, respectively) [2]. The value of λ_s is of the order of the coherence length in the superconductor, ξ, and is much longer than the wave length of normal electrons. Therefore quasiparticle interference is possible in N films with a thickness of order ξ. This condition is satisfied in our experiments. For similar SINIS devices, we have observed coherent effects that may be associated with the quasiparticle interference [3]. It is important (for the case described in [3] and the case considered here) that the tunnel barriers in the system are of "intermediate" strength, so that both Andreev and normal reflections take place. These two types of reflections give rise to the constructive interference effects that may increase the conductivity of the devices at certain energies. However, even for a simple SINIS case, the electron spectrum of the system strongly depends on the particular setup and, in general, cannot be derived analytically. The situation is more complicated for a multiple INI..NI barrier. Numerical calculations for the INININI barrier were carried out recently by Shafranjuk [12]. It was found that the interference in this case may be destructive [12] and result in a band structure similar to that observed in our experiment. An optical analog of this phenomena may be found in stacks of alternating layers of a semitransparent metal films and a dielectric material, where photonic band gaps were recently observed in transmittance [13].

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