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EFFECT OF DELAY ON THE FORM OF THE TUNNEL CHARACTERISTICS OF SUPERCONDUCTORS

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Yanson, Svistunov, and Dmitrenko [1] observed in an Sn - Sn tunnel structure current peaks at a barrier voltage $v = 2\Delta/n$ (n - integer, Δ - energy gap). A similar phenomenon was observed recently by Marcus in a Pb - Pb structure [2]. In tunnel junctions of the same type as in [2], Rochlin and Douglass [3] observed a more complicated dependence of the current on the voltage. The authors of [1,2] relate the appearance of peaks with tunneling of certain particles [4]. Such processes, however, have low probability and lead to a very rapid decrease of the intensity with increasing peak number, in disagreement with the data of [1,2]. In [3] the complicated dependence of the current on the voltage was attributed to the anisotropy of the electric gap.

We propose in this note another mechanism, which is apparently in good agreement with both the results of [1,2] and the data of [3].

As shown by the author earlier [6], the tunnel current through the junction is

$$I(\vec{r}, t) = \int_0^\infty dr\{K_s(r) \sin[\varphi(t) + \varphi(t - r)] + K_n(r) \sin[\varphi(t) - \varphi(t - r)]\}. \quad (1)$$

The concrete form of the kernels K_s and K_n is immaterial in what follows, and φ satisfies the relations

$$\frac{\partial\varphi}{\partial t} = ev(\vec{r}, t), \quad (2)$$

$$\frac{\partial\varphi}{\partial r} = \frac{8\pi e}{c^2} \lambda_L \vec{j}(\vec{r}, t). \quad (3)$$

Here $\vec{r}$ are the coordinates in the junction plane, λ_L the London depth of penetration ($\lambda_L \gg d$, where d is the thickness of the oxide), and $\vec{j}$ is the current along the surface of the superconductor.

Relations (1), (2), and (3), together with Maxwell's equations, form a closed system. We could therefore, as in [7-9], obtain one equation for φ. As shown in [6], for a point contact this equation has no solutions with $\partial\varphi/\partial t$ = const. This statement holds true also for extended contacts. Consequently, the stationary processes in the system will be either stochastic or periodic, depending on the experimental conditions. We note that singularities of the current-voltage characteristics appeared in [1-3] for structures having both large dc and large ac Josephson currents. To suppress the resonant steps [10-11], a sufficiently large magnetic field, ~10^2 Oe, was turned on. Thus, periodic solutions for the voltages and currents were realized in these experiments.

We write the solution for $\varphi(\vec{r}, t)$ in the form

$$\varphi(\vec{r}, t) = e\bar{v}t + \vec{k}\cdot\vec{r} + \Phi(\vec{r}, t), \tag{4}$$

where $e\bar{v}$ and $\vec{k}$ are the mean values of (2) and (3), respectively, and $\Phi(\vec{r}, t)$ is some periodic function of the time with period T. From the condition for the periodicity of I we find that

$$T = \pi m/e\bar{v}. \tag{5}$$

Here m is an integer determined by the boundary conditions (the question of boundary conditions is considered in [9]).

The average current through the junction is

$$\bar{I} = \frac{1}{T}\int_0^T dt \int_s d^2\vec{r}\, I(\vec{r}, t), \tag{6}$$

where s is the junction area. Using (5), (4), and (1) we obtain after trivial transformations

$$\bar{I}(\bar{v}) = \sum_n c_n I_0[\bar{v}(m + 2n)/m]. \tag{7}$$

Here $\bar{I}_0(\bar{v})$ is the single-particle tunnel characteristic and

$$c_n = \frac{1}{s}\int_s d^2\vec{r}\,|A_n(\vec{r})|^2; \quad \sum_n c_n = 1,$$

where

$$A_n(\vec{r}) = \frac{1}{T}\int_0^T dt\, \exp[\Phi(\vec{r}, t) - (2e\bar{v}/m)nt].$$

In calculating (7) we used the fact that the experiments of [1-3] were made in strong magnetic fields, and neglected the terms of order $e\bar{v}/|\vec{k}|\bar{c}$ ($\bar{c}$ is the wave propagation velocity in the tunnel structure).

Expression (7) agrees well with the data of [1,2] if we put m = 2. This describes correctly the form obtained empirically in [2] for the peaks [1)]. As to the peak amplitude c_n, it must be determined by the concrete experimental conditions. In the author's opinion, the data of [3] also agree well with formula (7) if m = 7.

In conclusion we consider also the case when $\Phi \ll 1$, and the junction is exposed to an external high-frequency field of frequency Ω. We then obtain for the voltage region $e\bar{v} \gg \Omega$

$$\bar{I}(\bar{v}) = \sum_n I_n^2(ev_0/\Omega)\bar{I}_0(\bar{v} + n\Omega/e). \tag{8}$$

Here I_n - Bessel function and v_0 - amplitude of the high-frequency oscillation. We see from

(8) that peaks will appear on the current-voltage characteristic at $e\bar{v} = 2\Delta \pm n\Omega$. This phenomenon was observed experimentally by Dayem and Martin [12].

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OSCILLATIONS OF THE MAGNETORESISTANCE OF TELLURIUM

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It was observed in an investigation of the effect of a strong pulsed magnetic field on the electric conductivity of tellurium, that the plot of the magnetoresistance against the field intensity H is an oscillating curve with extrema that are periodic in the reciprocal field 1/H. Such a singularity, observed in a nondegenerate semiconductor, may be evidence of magnetophonon resonance, the phenomenon predicted by V. L. Gurevich and Yu. A. Firsov [1] and studied in detail in n-InSb [2]. In magnetophonon resonance the oscillation amplitude should decrease with decreasing temperature, and the period $\Delta(1/H)$ should be independent of the density and determined by the carrier effective mass m^* and by the frequency ω of the optical oscillations of the crystal:

$$\Delta(1/H) = e/m^*\omega c.$$