

Oscillatory effects connected with electromagnetic radiation in inelastic tunneling of electrons

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It is shown that the previously observed oscillations of the derivative of the conductivity with respect to pressure (CDO) of N-I-N junctions are due to excitation of transverse-electric (TE) waves by the tunneling electrons in the region of the barrier.

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Recent experimental studies⁽¹⁻³⁾ have revealed oscillations of the derivative of the conductivity with respect to voltage (CDO) in *N-I-N* tunnel junctions. We show in the present paper that the onset of CDO is due to electromagnetic radiation of the tunneling electrons. We consider a symmetrical *N-I-N* junction in which the thickness d of the dielectric liner is much less than the linear dimensions L_y and L_z in the junction cross section. The contribution made to the derivative of the conductivity $G(\Omega)$ (see⁽⁴⁾) by inelastic tunneling with photon emission is

$$G(\Omega) \approx 2e |T|^2 \sum_{\mathbf{k}} \int \frac{d\omega}{2\pi} F(\omega - \Omega) B(\mathbf{k}, \omega).$$

Here $\Omega = eV/\hbar$ (V is the voltage on the junction), $|T|^2$ is the square, averaged over the Fermi surface, of the modulus of the matrix element that describes inelastic electron tunneling with emission of photons, $B(\mathbf{k}, \omega)$ is the spectral intensity of the photon with frequency ω and two-dimensional wave vector $\mathbf{k}(k_y, k_z)$, and the quantity $F(\Omega) = z(z \coth z - 1)/\omega \sinh^2 z$ ($z = \hbar\omega/2\Theta$) tends to a δ -function as $\Theta \rightarrow 0$.

In cases when the local approximation (LA) can be used for the dielectric constants $\epsilon_m(\omega)$ of the metal and $\epsilon_i(\omega)$ of the insulator, the spectral intensity of the photons of this system are obtained by the technique developed in the book.⁽⁵⁾ The applicability of the LA (this question was discussed in detail by Economou⁽⁶⁾) limits the region of the admissible frequencies

$$l/\lambda_p \ll \omega \tau_m [1 + (\omega \tau_m)^{-2}]^{3/4}, \quad (1)$$

where l and τ_m are the length and time of the free path of the electrons in the metals, $\lambda_p = \omega_p/c$, ω_p is the electron plasma frequency in the metals, and c is the speed of sound.

Further calculations are carried out with allowance for the next two circumstances. In addition to the limitation imposed on the frequency by the inequality (1), we shall consider the voltage region for which $\Omega \ll \omega_p$. Second, we assume that one of the dimensions in the junction cross section is much smaller than the other (e.g., $L_y = L \ll L_z$). The tunneling electron will then excite TE waves that propagate along the z axis. If we neglect the losses of the TE waves to radiation from the edges of the junction in the y direction, then the only TE waves that can be excited in the tunnel junction are those with $k_y = \pi n/L$ ($n = 0, 1, \dots$). The foregoing stipulations make it possible to express $G(\Omega)$, after laborious but trivial calculations, in the form

$$G(\Omega) \sim \frac{\phi}{2\pi} + 2 \sum_{n=1}^{\infty} \left\{ \frac{e^{-\gamma n}}{\sqrt{\pi n \chi'}} \left[\frac{\pi n \Theta \beta}{\text{sh}(\pi n \Theta \beta)} \right]^2 \cos \left[n \chi - \frac{\pi}{4} - \frac{\phi}{4} \right] \right\} \quad (2)$$

where quantities ϕ , χ , γ , and β are functions of Ω , expressed in terms of $\epsilon_i(\Omega) = \epsilon' + i\epsilon''$ and $b(\Omega) = [1 + (\Omega r_m)^2]^{1/2}$ with the aid of the complex quantities $a(\Omega) = a' + ia''$

$$a' = \epsilon' + \xi(\epsilon' \sqrt{b+1} - \epsilon'' \sqrt{b-1}) / \sqrt{2} b;$$

$$a'' = \epsilon'' + \xi(\epsilon'' \sqrt{b+1} + \epsilon' \sqrt{b-1}) / \sqrt{2} b;$$

$$\xi = 2\lambda_p/d; \quad \phi = \arctg(a''/a'); \quad \beta = \chi / \hbar \Omega;$$

$$\chi = \sqrt{2} L \Omega \sqrt{a' + |a|} / c; \quad \gamma = \sqrt{2} L \Omega a'' / c \sqrt{a' + |a|}.$$

In the derivation of (2) we used the standard expression for the transverse permittivity of the metals, in the form $\epsilon_m(\Omega) = 1 - \omega_p^2 \tau_m / \Omega (\Omega \tau_m - 1)$, which is convenient for simple metals in the region where the inequality (1) is satisfied. In addition, it was assumed that $\chi \gg 1$. The latter means that we are considering voltages at which the excited photons have sufficiently short wavelengths ($d \ll \lambda \ll L$, λ is the photon wavelength).

In the analysis of (2) we confine ourselves to some concrete form of the function $\epsilon_i(\Omega)$. It appears that greatest interest attaches to the case when $\epsilon_i(\Omega)$ relaxes in accordance with the expression

$$\epsilon_i(\Omega) = \epsilon_{\infty} + \frac{\epsilon_0 - \epsilon_{\infty}}{1 - i\Omega \tau_i}, \quad (3)$$

where ϵ_0 and ϵ_{∞} are the static and optical dielectric constants, and τ_i is the characteristic relaxation time of the polarizability in the oxide.

In experiment, as a rule, the situation is such that $\max\{\gamma, 2\pi\Theta\beta\} > 1$, so that only one term with $n = 1$ need be retained in the sum of (2). We consider first the case of a "dirty" metal, when the condition $\Omega \tau_m \ll 1$ is satisfied in the region accessible to the

measurements. We assume that the insulating liner is likewise not of very high grade ($\Omega\tau_i \ll 1$). Oscillations will then appear, with a voltage period

$$\Delta\Omega = \pi c / L \sqrt{\epsilon_0} (1 + \xi \sqrt{\Omega\tau_m/2})^{1/2} \quad (4)$$

and with an amplitude that depends little on the voltage in the region where the inequality $2\pi\Theta\epsilon_0(1 + \xi\sqrt{\Omega\tau_m/2}) > \hbar\Omega[(\epsilon_0 - \epsilon_\infty)\Omega\tau_i + \xi\sqrt{\Omega\tau_m/2}]$ is satisfied. As soon as this inequality is violated, the CDO attenuate exponentially rapidly. If the oxide between the "dirty" electrodes is of sufficiently high grade ($\Omega\tau_i \gg 1$), the period of the CDO changes only because ϵ_0 in (4) is replaced by ϵ_∞ . On the other hand, the region of voltages in which undamped CDO appear is determined by a different inequality, $2\pi\Theta[1 + \sqrt{2/\xi}\sqrt{\Omega\tau_m}] > \hbar\Omega$. Finally, if the electrodes of the contact are made of a pure metal ($\Omega\tau_m \gg 1$), then the CDO period is given by

$$\Delta\Omega = \pi c \sqrt{2}/L \sqrt{(1 + \xi)(\epsilon' + |\epsilon_i|)}. \quad (5)$$

In this case the CDO amplitude changes only in proportion to $\Omega^{-1/2}$ in the temperature region $2\pi\Theta\epsilon_\infty > \hbar\Omega(\epsilon_0 - \epsilon_\infty)$.

We note in conclusion that the proposed mechanism explains the entire aggregate of facts connected with the CDO, namely, it gives the correct order of magnitude of ΔV ($\Delta V \approx 10[1 + \xi](\epsilon' + |\epsilon_i|)^{-1/2}$ meV for $L \approx 10^{-2}$ cm, which agrees with the period observed in Ref. 3), leads to a very weak dependence of the amplitude and period of the oscillations on V , and, finally, agrees well with the fact that the CDO vanish after annealing at room temperature. The point is that annealing causes the metal atoms to diffuse into the dielectric liner and this results in a sharp decrease of τ_p , which leads to a suppression of the CDO on account of the growth of γ .

¹I.K. Yanson, B.I. Verkin, L.I. Ostrovskii, A.B. Teplitskii, and O.I. Shklyarevskii, Pis'ma Zh. Eksp. Teor. Fiz. **14**, 40 (1971) [JETP Lett. **14**, 26 (1971)].

²J.F. Adler and J. Straus, Phys. Rev. B **13**, 1377 (1976).

³O.I. Shklyarevskii, Issledovanie kolebatel'nykh spektrov tonkikh poverkhnostnykh sloev i adsorbiruyemykh molekul metodom tunnel'noi spektroskopii (Investigation of vibrational spectra of thin surface layers and of absorbed molecules by the method of tunnel spectroscopy), Dissertation, 1977, Khar'kov.

⁴Yu. M. Ivanchenko and Yu. V. Medvedev, Fiz. Nizk. Temp. **2**, 141 (1976) [Sov. J. Low Temp. Phys. **2**, 69 (1976)].

⁵A.A. Brikosov, L.P. Gor'kov, and I.E. Dzyaloshinskii, Metody kvantovoi teorii polya v statisticheskoi fizike (Quantum Field Theoretical Methods in Statistical Physics), Moscow, 1962, p. 347 [Pergamon, 1965].

⁶E.N. Economou, Phys. Rev. **182**, 539 (1969).