# EXPERIMENTAL OBSERVATION OF PHONON GENERATION IN POINT CONTACTS

I.K. Yanson and N.I. Bogatina
Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

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It was shown in [1] that the current-voltage characteristics of point contacts produced by breakdown of tunnel structures (Fig. 1) are essentially nonlinear in the 0 - 100 mV voltage interval. The nonlinearity sets in at voltages corresponding to the Debye energies for the investigated metals (Pb, Sn), and cannot be attributed to heating of the metal in the contact region. It was proposed in [1] that this nonlinearity is due to intense phonon generation by fast electrons whose drift velocity is equal to or exceeds the speed of sound.

The purpose of the present study was a direct observation of the characteristic singularities of the phonon spectrum of a metal as revealed by the dependence of the resistance of the point contact on the voltage or current. It turns out that the kinks appear on the second derivative of the current-voltage characteristic at voltages corresponding to the characteristic energies of the transverse and longitudinal phonons in the metal. At low temperatures we have observed a new effect, namely oscillations of the differential resistance of the contact in the region of the nonlinear properties. The possible mechanism of this effect is interference of the coherent phonons emitted by the supersonic electrons moving in the channel 3, of length L, which joins the two metallic films 1 of the tunnel structure (Fig. 1).

The objects of the investigations were short-circuited tunnel structures of lead, in which the barrier layer contained in addition to the oxide a small amount of organic molecules (uracil). The average thickness of the barrier layer was of the order of 50 Å, so that the tunnel resistance prior to the short-circuiting ranged from hundreds of kiloohms to dozens of megohms. After the breakdown, the resistance dropped to several tenths of an ohm, so that the contribution of the tunnel current through the barrier could be completely neglected and it could be assumed that the entire observed current flows through the short circuit. It must be emphasized that the structure of the connecting channel remains unknown. All that can be stated is that its characteristic length is approximately equal to the thickness L of the barrier layer. The channel radius r determined by us (300 - 500 Å) depends on the assumed model of the point contact [2], in which the connection between the radius and the resistance $R_0$ at zero voltage is given by the formula $R_0 \simeq \rho\ell/r^2$ ($\rho\ell = 10^{-11}$ ohm-cm$^2$ for Pb). The choice of lead as the electrode material was dictated by the strong electron-phonon interaction in this metal and by the simple form of the phonon spectrum, which consists of two clearly pronounced peaks corresponding to transverse ($h\omega_1$ = 4.5 meV) and longitudinal phonons ($\hbar\omega_2$ = 8.5 meV) [3]. The experiments were performed at temperatures 1.5 - 4.2°K in a magnetic field H = 5 - 15 kOe perpendicular to the films. This field served to suppress the superconductivity of the lead. The characteristics given below did not depend on the variation of the field in the indicated limits.

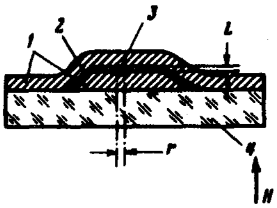

Fig. 1. Schematic diagram of short-circuited tunnel contact:
1 - metallic films,
2 - barrier layer,
3 - short circuit,
4 - glass substrate.

Figure 2 shows the current-voltage characteristic (Fig. 2a) and its first and second derivatives (Fig. 2b), which were registered automatically with an x-y recorder. We see that the differential resistance remains constant up to V ≈ 4 mV, after which it begins to increase. At 4.2°K, the second derivative $d^2V/dJ^2$ is first equal to zero, and then contains kinks at the voltages $V_1 \simeq 5$ mV and

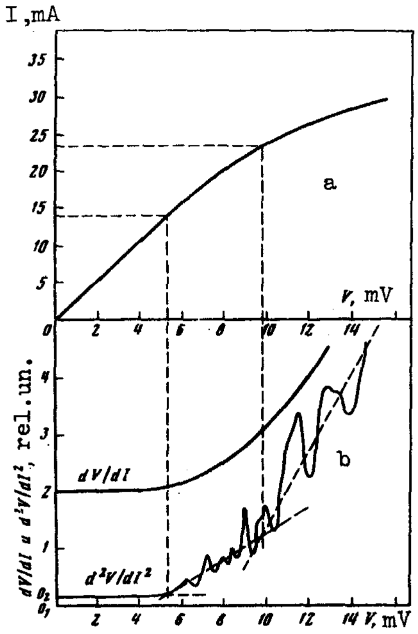

Fig. 2. a) Current-voltage characteristic of Pb-Pb contact, radius $r \approx 500$ Å, $R_0 = 0.39$ ohm. b) First and second derivatives of the current-voltage characteristics of this contact. Continuous curve - automatic plot; the dashed curves correspond to the average lines on the different sections of the curve. $0_1$ and $0_2$ correspond to the positions of the zeroes on the ordinate axes for the first and second derivatives. $T = 1.5$°K, $H = 10$ kOe.

$V_2 \approx 9.5$ mV, which correspond approximately to the energies of the transverse and longitudinal phonons in the lead. By projecting the positions of the observed kinks on the current axis we obtain the values of the current density $j_2 = J_2/S = -1.35 \times 10^9$ A/cm$^2$ ($S = \rho\ell/R_0$) and the corresponding threshold drift velocity $v_2 \approx 2.6 \times 10^5$ cm/sec for longitudinal phonons. The latter coincides with the velocity of the longitudinal sound in lead [4]. For transverse phonons, as expected, we obtain approximately double the values of $j_1$ and $v_1$. In our opinion, the observed singularities have a direct bearing on the effects predicted in the theoretical paper [5], namely the manifestation of the phonon spectrum in the third and fourth derivatives of the current-voltage characteristics of the metal in the strongly-nonlinear regime, since the kinks noted above on $d^2V/dJ^2$ obviously become resonant spikes on the fourth derivative $d^4V/dJ^2$. It is remarkable that in a point contact the threshold values of the drift velocities $v_1$ and $v_2$ correspond to voltages $V_1$ and $V_2$ which are close to the limiting phonon frequencies $\omega_1$ and $\omega_2$. Indeed, for the drift velocity of the electrons we can write $p_0 v \approx eV$ ($p_0$ is the Fermi momentum), hence $p_0 v_1 \approx q_0 v_1 = \hbar\omega_1 \approx eV_1$ ($q_0$ is the Debye quasimomentum of the phonons).

When the temperature is lowered to 1.5°, the second-derivative kinks described above are more clearly pronounced (the dashed lines in Fig. 2b). At the same time a new effect appears in the form of two series of oscillations superimposed on the above-described background. The oscillations occur after the drift velocity reaches the first threshold $v_1$, and their average period increases by approximately 2 times after the drift velocity reaches the second threshold value $v_2$. We note an important detail: the distance between the first maximum in the first series and the remaining five is approximately 1.5 times larger than the average distance between the latter. The average voltage period in the first series is $\approx 0.6$ mV, which is of the order of several times $kT$ at the given temperature. When the temperature is raised, the oscillations vanish gradually, and only the background remains at 4.2°K. The last circumstance shows convincingly that there is practically no overheating in the contact region. A possible explanation of the effect lies in the interference of the coherent phonons emitted by the electron as it moves along the channel. By considering the Cerenkov phonon emission from the supersonic electrons on a finite path segment $L$, we arrive at a dependence of the phonon-radiation intensity on the velocity in the form $I = I_0(\sin^2\phi/\phi^2)$, where $\phi = \omega L(v - s)/2sv$ and $s$ is the speed of sound. This gives two discrete values of the threshold velocity, $v_{n,1}$ and $v_{n,2}$, corresponding to transverse and longitudinal phonons; these reflect correctly the positions of the above-described oscillations on the J and V axes. The calculated length of the channel is ~90 Å, and for the period of the oscillations in the first series we obtain the value $\Delta v_1 \approx v_1 a/L = 0.45$ mV, where $a = 5$ Å is the Pb lattice constant. Both values are in reasonable agreement with experiment.

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# SPECTRAL BROADENING IN SELF-FOCUSING OF SINGLE ULTRASHORT LIGHT PULSES IN GLASSES

A.P. Veduta, N.B. Fedotov, and N.P. Furzikov
P.N. Lebedev Physics Institute, USSR Academy of Sciences
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When the radiation from a mode-locked laser is self-focused in a transparent isotropic medium, one usually observes at the output intense scattered radiation with a broad spectrum in the Stokes and anti-Stokes regions [1 - 5]. The frequency-angle diagram of this scattering has characteristic "whiskers" corresponding to conditions of four-field synchronism [1, 2], and a central lobe attributed presumably to phase modulation [1, 4, 5] or to other factors [2]. We present here results of an experimental study of the previously observed [3] frequency structure of the central lobe following pumping by a group of 1 - 3 ultrashort pulses (USP) with decreasing amplitude. The period of the observed structure agrees in order of magnitude with the results of theoretical estimates based on the model of the four-field parametric interaction of amplitude-modulated waves with wave and frequency detuning.

The pump used was a mode-locked neodymium-glass laser. A burn-out mirror separated 1 - 3 pulses with a total energy ~$6 \times 10^{-4}$ J from the complete train of USP.

The filtered infrared radiation was focused with lenses having focal lengths from 20 to 60 cm into glass samples 0.5 - 45 cm long. The power density at the focus of the lens, at an estimated USP duration 5 psec, was $10^{11}$ W/cm$^2$. The scattering was observed only in samples longer than 2 cm. This is apparently due to the action of the self-focusing, which increases the power density to the previously-obtained threshold value $10^{12}$ W/cm$^2$ [1, 2]. There was no additional scattering-intensity gain in longer samples. The anti-Stokes part of the frequency-angle distribution of the scattering was registered with an ISP-51 spectrograph. Typical spectrograms are shown in Figs. a and b, together with a mercury reference spectrum (Fig. c). At a slight excess above the threshold power, the scattering spectrum, with the exception of isolated cases, always had a periodic structure of the type shown in Fig. a (fused quartz 5 cm long). When the input power was increased, this structure became more