Frequency dispersion caused in the conductivity of metal microcontacts by nonequilibrium-phonon relaxation

I. O. Kulik
Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR

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There should be an appreciable frequency dispersion in the nonlinear component of the current-voltage characteristic of a point contact between normal metals in the "background region" (i.e., at bias voltages $eV > \hbar\omega_D$). This dispersion would be caused by the relaxation of a nonequilibrium phonon gas. The observation of this effect will make it possible to directly determine the relaxation frequencies of the Debye phonons of a metal.

A point contact whose diameter d is small in comparison with the electron mean free path l is a unique entity, in which it is possible to achieve nonequilibrium electronic states with a distribution function[1]

$$f_{\mathbf{p}} = f_0\left(\epsilon_{\mathbf{p}} + \frac{eV}{2}\,\mathrm{sign}\, v_z\right), \tag{1}$$

where $f_0(\epsilon)$ is the equilibrium Fermi function. The electron-phonon interaction leads to a nonlinear dependence of the current on the voltage, of such a nature that the second derivative d^2I/dV^2 is proportional to Éliashberg's electron-phonon interaction function $g(\omega) = \alpha^2(\omega)F(\omega)$, where $\omega = eV$, with a K-factor which reflects the electron scattering geometry at the microcontact (microcontact spectroscopy[2]). The phonon gas at a point contact may also become a nonequilibrium gas if there is some mechanism by which the phonons generated by the electron flux are captured (reabsorbed) in the current concentration region. One such mechanism, pointed out in Ref. 3, is the reflection of phonons by the inhomogeneous region which is always present near metal electrodes in contact.

We assume that this effect can be taken into account by introducing an effective pulsed phonon mean free path l_r on the order of (or smaller than) the diameter of the contact d and small in comparison with the energy mean free path (or phonon-electron

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mean free path) of a phonon, $l_{ph} \sim (M/m)^{1/2}\lambda_{ph} \sim 10^{-5}$ cm (λ_{ph} is the wavelength of a Debye phonon). The typical diameters of a point contact are[2] $d \sim 30$–100 Å; i.e., the condition $d < l_{ph}$ holds. The primary relaxation mechanism in this case is the electron-phonon interaction, and the distribution of phonons in the case $l_r < d$ is isotropic in momentum space; i.e., the distribution function depends on the energy and is given by[4]

$$N_\omega(\mathbf{r}) = q(\mathbf{r}) \frac{eV - \omega}{2\omega} \theta(eV - \omega), \tag{2}$$

where q has a value of 1/2 in the plane of the contact and falls off rapidly with distance from the current-concentration region [an electronic deviation from equilibrium, described by expression (1)]. In contrast with the equilibrium (Planck) distribution, function (2) has a sharp edge at $\omega = eV$. Expression (2) corresponds qualitatively to a heating of phonons to an effective temperature (at the center of the contact)[1)]

$$\theta_{ph} \sim eV/4. \tag{3}$$

Since θ_{ph} increases linearly with the voltage, the nonlinear current component is proportional to V^2 at bias voltages $eV > \omega$, explaining the so-called background in point contact spectra[2]: the constant value of d^2I/dV^2 beyond the boundary of the phonon spectrum of the metal.

If the voltage applied to the contact has not only a constant component but also an alternating component with a frequency ω_0,

$$V(t) = V + v\cos\omega_0 t, \tag{4}$$

the number of nonequilibrium phonons can vary in phase with the changes in $V(t)$ only if ω_0 lies below the frequency of homogeneous phonon relaxation,

$$\nu_{ph} \sim \lambda \frac{s}{v_F} \omega, \tag{5}$$

where $\lambda \sim 0.1$–1 is the dimensionless constant of the electron-phonon interaction. For a Debye phonon, this frequency is 10^{10}–10^{11} s^{-1} in order of magnitude, i.e., is in the microwave range. Consequently, point contact measurements in this frequency range may prove a convenient method for studying the relaxation of extremely short-wave phonons in metals (a subject which is not amenable to a study by any other known experimental method).

In the limit of small l_r ($l_r l_{ph} \ll d^2$) the kinetic equation for the phonons reduces to

$$\left(\frac{\partial}{\partial t} + \nu_{ph}\right) N_\omega = q\nu_{ph} \frac{eV - \omega}{2\omega} \theta(eV - \omega), \tag{6}$$

where

$$\nu_{ph}(\omega) = 2\pi N(\epsilon_F) \alpha^2(\omega)\, \omega \tag{7}$$

[$N(\epsilon_F)$ is the electronic-state density at the Fermi level]. At bias voltages $eV > \hbar\omega_{max}$ on the contact, the frequency dependence of the time-averaged increment in the current ($\overline{\delta I}$) and that of the amplitude (I_2) of the second harmonic of the modulating signal caused by the nonlinearity of the I-V characteristic, are given by[4]

$$\overline{\delta I}(\omega_0) = -\frac{4ev^2 d}{\hbar v_F R_0}\langle q\rangle \int_0^\infty g(\omega)\frac{\nu_{ph}^2(\omega)}{\nu_{ph}^2(\omega)+\omega_0^2}\frac{d\omega}{\omega},$$

$$I_2(\omega_0) = \frac{4ev^2 d}{\hbar v_F R_0}\langle q\rangle \left|\int_0^\infty g(\omega)\frac{\nu_{ph}(\omega)}{\nu_{ph}(\omega)+i\omega_0}\frac{d\omega}{\omega}\right|, \tag{8}$$

where the average value is $\langle q\rangle = 0.29$ for the model of a point contact in the form of a circular aperture. Here R_0 is the resistance of the point contact in the ballistic limit.

A determination of the function $\nu_{ph}(\omega)$ from the known behavior $\overline{\delta I}(\omega_0)$, and $I_2(\omega_0)$ falls in the category of "ill-posed problems" of mathematical physics and can thus be carried out only with a limited accuracy. The average value of ν_{ph}, however, is determined unambiguously.

Recent measurements of the frequency dependence of the "background" on the microcontact spectra of copper contacts confirm the effect predicted here and make it possible to estimate the relaxation frequency of nonequilibrium phonons in copper.[7]

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[1)]An analogous expression for the phonon temperature holds in the thermal limit.[5,6]

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