Nonequilibrium-phonon relaxation in metal microcontacts

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A frequency dispersion has been observed in the intensity of the microcontact spectrum of the electron-phonon interaction at bias voltages $eV > h\nu_{\max}$ across the contact. The magnitude of the effect is determined by the relation between the inelastic-relaxation frequency of nonequilibrium phonons and the frequency of the high-frequency radiation incident on the contact.

In the current-carrying state of microcontacts with dimensions smaller than the electron mean free path, the electrons have very nonequilibrium energy and momentum distributions.[1] The distribution functions of the nonequilibrium phonons generated by electrons have received less study. It has been suggested that nonequilibrium phonons are responsible in particular for the background which is usually present in the microcontact spectra of the electron-phonon interaction. The absence of direct experimental data on the behavior of nonequilibrium phonons at a microcontact has obstructed the derivation of a successful theory for the microcontact background, which has so far been taken into account phenomenologically.[1]

Kulik[2] has predicted a frequency dispersion of the phonon component of the microcontact spectrum of the electron-phonon interaction at comparatively low frequencies, $\nu_{\rm ph} \sim \lambda (s/v_F)\nu_{\max} \sim 10^{10}\ {\rm s}^{-1}$, where $\nu_{\rm ph}$ is the average phonon relaxation frequency, λ is the constant of the electron-phonon interaction, s is the sound velocity, v_F is the Fermi velocity, and $\nu_{\max}$ is the maximum frequency of the phonons of the metal.

Our purpose in the present study was to observe a frequency dependence of the background near the characteristic relaxation frequencies of nonequilibrium phonons at a microcontact. It turns out that the magnitude of the background can be lowered substantially by measuring the microcontact spectra of the electron-phonon interaction at microwave frequencies. In several cases, this lowering of the background has revealed some previously hidden structural features in the spectra.

We studied the second derivative of the I-V characteristic of copper microcontacts fabricated by a displacement method and in the needle-plane configuration.[1] As a signal proportional to $(d^2V/dI^2)(eV)$ at the sound frequency we used the second harmonic of the modulating voltage. At microwave frequencies this function is served by the small increment in the constant component of the voltage: the video detection signal. To improve the sensitivity of the measurement apparatus, we modulate the amplitude of the microwave oscillations at a frequency of 2.5 kHz. The measurements are carried out at liquid-helium temperature at several values of the frequency ν: 1–3 GHz, 10 GHz, 50 GHz, and 80 GHz.

Figure 1 shows the spectra of the electron-phonon interaction of the same microcontact according to measurements at the sound frequency (curve 1) and at a microwave frequency (curve 2). The vertical scale is chosen to bring the intensities of the T

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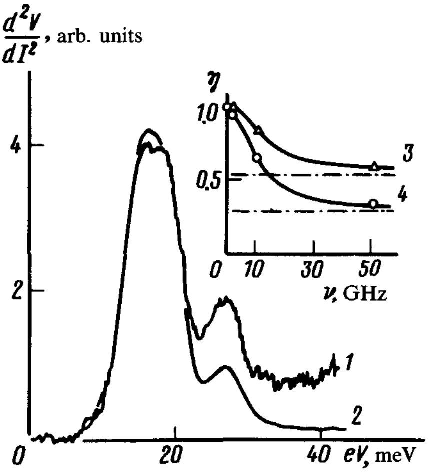

FIG. 1. Microcontact spectra of the electron-phonon interaction in copper obtained at the sound frequency (curve 1) and at a frequency of 80 GHz (curve 2); $R = 6.3\ \Omega$. The inset shows the frequency dependence of the background suppression factor for another contact ($R = 3.6\ \Omega$) for two bias voltages: 3—40 meV; 4—60 meV.

peak, corresponding to transverse phonons, roughly into coincidence. We see that the spectrum of the electron-phonon interaction remains essentially unchanged, but the background in the microwave spectrum at a bias voltage $eV = 40$ meV is several times lower than that on the sound-frequency curve. This lowering of the background at microwave frequencies was observed for all the contacts, but the extent of the lowering varied over a broad range, depending on the frequency of the external radiation and the structural quality and purity of the metal near the constriction, as can be seen indirectly from the shape and intensity of the lines in the microcontact spectrum.[1] With decreasing intensity and increasing background level in the sound-frequency spectrum, the lowering of the background in the microwave spectrum becomes less pronounced, and the "residual" background (which does not disappear with increasing frequency of the radiation) becomes higher. The measurements were carried out at the lowest possible intensity of the external radiation. As this intensity was raised by more than order of magnitude, we observed a linear increase in the rectified signal, independent of the bias voltage across the contact.

The inset in Fig. 1 shows the experimental values of the background suppression factor[1)] $\eta = \gamma_{MW}/\gamma_{SF}$ at various frequencies for one of the contacts for two bias voltages: 40 and 60 meV. The curves are plotted from the equation

$$\frac{\lambda(\nu) - \gamma(\infty)}{\gamma(0) - \gamma(\infty)} = \left[1 + \left(\frac{\nu}{\nu_{\mathrm{ph}}}\right)^2\right]^{-1}.$$

Choosing reasonable values of $\eta(\infty) \simeq \eta$ (80 GHz), shown by the horizontal straight lines, we find $\nu_{\mathrm{ph}} = 12$ GHz and 10 GHz for these two bias voltages, respectively.

An estimate of the frequency of the homogeneous relaxation of phonons with electrons in copper yields $\nu_{\mathrm{ph}} \sim 2.9$ GHz (for $\lambda = 0.14$, $s = 5 \times 10^5$ cm/s, $v_F = 1.6 \times 10^8$ cm/s, and $h\nu_{\max}/k = 315$ K), several times lower than the observed values. Furthermore, the theory[2] has the frequency of the direct phonon-electron relaxation independent of eV at $eV \gtrsim h\nu_{\max}$. Experimentally, we observe a decrease in the

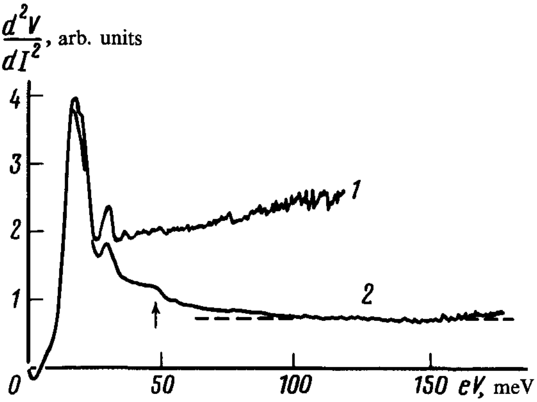

FIG. 2. Microcontact spectra of the electron-phonon interaction in copper at high bias voltages. Measurement frequencies: 1—10^3 Hz; 2—8×10^{10} Hz ($R = 2.97\ \Omega$).

rectification signal in this energy interval in all cases. This decrease reaches saturation only at $eV \sim 100$ meV (Fig. 2).

This behavior can be explained by assuming that the more rapid relaxation of phonons occurs through an intermediate stage of a thermalization of the phonon gas by virtue of phonon-phonon collisions, for which the probability at Debye energies is an order of magnitude higher than the probability for phonon-electron collisions.[3] According to Ref. 4, the phonon temperature at $eV > h\nu_{\max}$ is $\theta = eV/4k$ (despite the fact that the electron gas remains cold, since its relaxation time is very short, $\tau_e \sim d/v_F \sim 10^{-14}$ s, where d is the contact diameter). The rate of change of the number of nonequilibrium phonons is determined by the rate of change of their temperature, which in turn is limited by the phonon heat capacity. This heat capacity increases with increasing θ, causing an increase in the thermalization time, and it tends toward a constant value at $eV > 4k\theta_D \sim 100$ meV (θ_D is the Debye temperature).

The lowering of the background at microwave frequencies is more pronounced at values of eV near that corresponding to the combinational phonon energy $h\nu_T + h\nu_L$, as shown by the arrow in Fig. 2. In addition, the background intensifies at $eV > 100$ meV, because of a progressive shortening of the phonon range with increasing temperature.

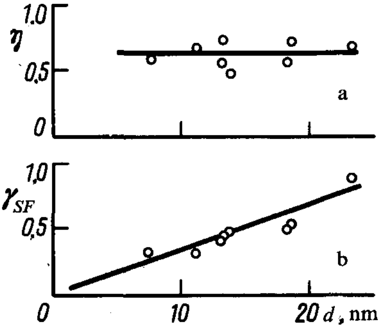

FIG. 3. a—The background suppression factor at microwave frequencies; b—the relative background level at the sound frequency, both versus the contact diameter.

We observed no regular change in the background suppression factor η at the microwave frequencies as the contact resistance R was varied over more than an order of magnitude (Fig. 3a), although it is possible to see the well-known[1] increase in the sound-frequency background, which is proportional to the contact diameter $d = [(16/3\pi)(\rho l/R)]^{1/2}$ ($\rho l = 0.66 \times 10^{-11}\ \Omega\cdot\mathrm{cm}^2$; Fig. 3b). The dimensions of the contacts are probably too large for a substantial inhomogeneous relaxation of phonons.

In summary, the nonequilibrium phonons in these microcontacts are reabsorbed essentially completely by electrons. Over a time $\sim 10^{-11}$ s, phonon-phonon collisions thermalize the phonon gas, which then relaxes among electrons over a time $\sim 10^{-10}$ s.

Preliminary experiments on the mixing of two microwave oscillations with similar frequencies have shown that the background can be reduced even further; the background suppression factor in this case is equal to the square of η during video detection.

We wish to thank I. O. Kulik for useful discussions.

1) The parameter γ is defined as the ratio of the signal at $eV \gtrsim h\nu_{\max}$ to the intensity of the T peak.

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