I. K. Yanson. *Nonequilibrium electrons and phonons in microcontracts.* "Microcontact spectroscopy," a new method for studying the energy spectrum of electrical conductors, has developed rapidly over the past decade. This method is based on effects which arise at electrical contacts whose size d (of the order of several tens or hundreds of angstroms for metals) is small in comparison with the energy relaxation length of charge carriers in a highly nonequilibrium current state. This state differs qualitatively from current states in homogeneous conductors in that all the electrons are separated into two groups near any point near a contact, where the electric field is nonzero. The maximum energies of the electrons in these groups differ by an amount eV, which is the energy corresponding to the bias voltage applied to the contact, under the condition $eV \gg kT$. The electrons belonging to different groups arrive at the given point from distant points on different sides of the contact. The relaxation of a distribution of this sort leads to a nonlinear voltage-current characteristic which has singularities at bias voltages corresponding to the characteristic energies of quasiparticles which scatter electrons inelastically. In metals, these quasiparticles are primarily phonons. Remarkably, the differential resistance of a contact is directly proportional to the rate of electron scattering by phonons, and the derivative of this resistance (i.e., the second derivative of the voltage-current characteristic, called the "microcontact spectrum") is proportional to the microcontact function of the electron-phonon interaction. This electron-phonon interaction function is taken to be the product of the mean square matrix element of the electron-phonon interaction and the density of phonon states. In practice, microcontacts are fabricated, for example, by bringing two pieces of metal into contact at their sharp edges immediately before measurement in liquid helium (Fig. 1). The simplicity and speed of such experiments put them in a class by themselves for studying the phonon spectra of metals, especially spectral functions of the electron-phonon interaction. The price paid for these advan-

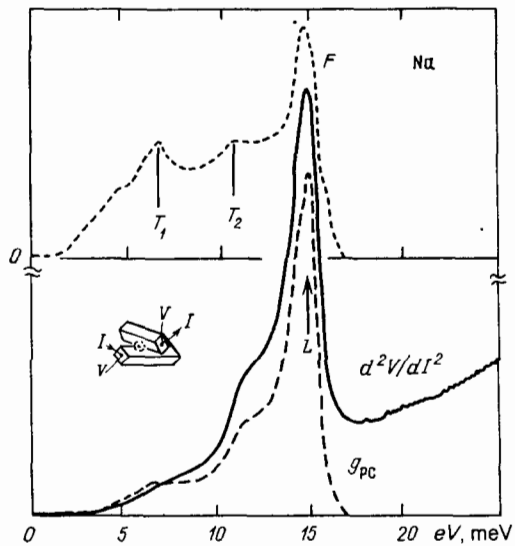

FIG. 1. Phonon-state density (F), microcontact spectrum (d^2V/dI^2), and microcontact function of the electron-phonon interaction (g_{PC}) for sodium. Arrow, T_1, T_2—Maxima in the phonon spectrum; inset—experimental arrangement for microcontact spectroscopy.

tages is that the phonon-state density is multiplied by some function of the energy which includes, in addition to the matrix element of the electron-phonon interaction, a geometric factor which depends on the shape of the contact. Nevertheless, the positions of the main singularities in the microcontact spectrum, and frequently their relative intensities, are the same as those in the phonon spectrum. The agreement between the calculated and measured microcontact functions of the electron-phonon interaction gives us much confidence that the calculated standard function of the electron-phonon interaction, which does not contain a form factor, will also prove to be correct. The microcontact spectra of the electron-phonon interaction have now been studied for more than 30 pure metals, many alloys, and compounds. The use of single crystals makes it possible to study the anisotropy of the electron-phonon interaction.

The energy splitting of the electrons can easily reach the maximum energies of the phonons and even become a significant fraction of the Fermi energy. The current density at the bottleneck reaches 10^9–10^{11} A/cm^2 in the absence of Joule heating. Several interesting phenomena are observed in such an extremely nonequilibrium state. The contact becomes a source of nonequilibrium Debye phonons, and coherent phonons may also be emitted. These phonons are reabsorbed by electrons, giving rise to a background on the microcontact spectra seen as a nonzero signal at bias voltages above the maximum phonon energy (Fig. 1). The frequency dispersion of this background is in the microwave region and can be used to determine the homogeneous relaxation time of phonons in collisions with electrons.

Low-frequency electrical fluctuations, a variety of flicker noise, behave in a nontrivial way in pure microcontacts. As the power dissipated at the contact is increased monotonically, the spectral noise density goes through several extrema (Fig. 2). The positions of these extrema along the energy scale correlate with the energies of certain phonons, which are determined by the shape of the Fermi surface and by the phonon disperison curves for the given metal. The function $S_V(eV)$ thus provides additional information on the electron-phonon interaction, supplementing the microcontact spectra.

Nonphonon quasiparticles which scatter electrons are being studied along with phonons by microcontact spectroscopy. The clearest results are being found in cases in which the spectrum of nonphonon quasiparticles has intense lines on the side of the main peaks in the phonon spectrum. Examples are magnons in Gd and Ho, magnetic excitons in Pr and its compounds, magnetic impurities in a noble-metal matrix (the Kondo effect), and local vibrations.

Another nonlinearity mechanism operates in microcontact compounds with variable valence. In most of the substances which have been studied so far the inelastic scattering length for the scattering of conduction electrons by localized 4f states is so short that the condition $d \ll l_\varepsilon$ does not hold, and the contact undergoes a Joule heating. In $CeNi_5$, however, a cerium ion spends much time in a nonmagnetic Ce^{4+} state, so that electrons can pass through the region with an accelerating potential in a constant-energy fashion. The energy relaxation of the stepped electron distribution results in this case not from inelastic processes but from a resonance scattering of conduction electrons by 4f levels near the Fermi level. These experiments make it possible to determine the position of the 4f levels with respect to the Fermi level and also the width of these levels.

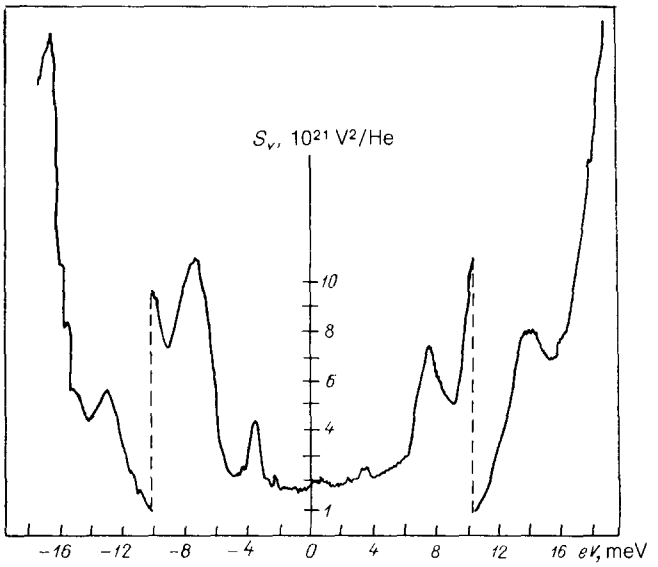

FIG. 2. Spectral density of voltage fluctuations at a sodium microcontact as a function of the energy corresponding to the bias voltage. The frequency is 20 kHz, and the temperature is 1.7 K. The scales for the parts of the curves at the extreme left and right are reduced by a factor of ten.

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Translated by Dave Parsons