PHYSICAL REVIEW B VOLUME 16, NUMBER 4 15 AUGUST 1977

Direct measurement of electron-phonon coupling $\alpha^2F(\omega)$ using point contacts: Noble metals

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(Received 30 December 1976)

A new technique of forming tiny point contacts between normal metals is described. By measuring the voltage derivative of the resistance of such contacts at 1.2 K, structure is found which is consistent with bulk-phonon densities of states. Similar results were reported recently by Yanson using a shorted-film technique. When interpreted, the observed structures yield electron-phonon coupling parameters in close agreement with literature values.

The measurement of the electron-phonon interaction has attracted considerable interest.[1-3] Recently Chaikin and Hansma have estimated the electron-phonon coupling parameter λ in Al and Cu using proximity-effect tunneling,[4] and Hoyt and Mota have estimated λ's for Cu, Ag, and Au using concentration-squared extrapolations based on the McMillian equation and the superconducting critical temperature of α-phase noble-metal–rich alloys.[5] In this paper we report measurements of the voltage derivative of the resistance of junctions formed by tiny contacts between two noble metals, which show deviations from Ohm's law.[6] Structures are seen which coincide well with bulk phonon spectra, and when interpreted yield λ's close to those expected[1-5] for noble metals. Some of our results have been presented qualitatively at the Rochester meeting.[3]

We were stimulated to try our experiments by the work of Yanson.[7,8] He used shorted junctions formed from normal metallic films separated by an insulator. The measured junctions were in the normal state, either because of the Dewar temperature or because of the application of an external magnetic field. His Cu results are in excellent agreement with those presented here. It occurred to us that if we could form tiny *metallic* bridges from sharp points, the resulting junctions would, in the normal state, be Sharvin junctions,[9] and perhaps be simpler to form and control than those formed from shorted films. The major potential disadvantages of such junctions, compared with those formed from films involved questions of mechanical stability.

We formed a sharp tip ($\sim\frac{1}{2}$ μm) on a thin wire ("spear") through an electrolytic etching technique. This was mounted rigidly on a subassembly with a larger wire ("anvil"), cooled to 1.2 K and carefully pressed into the anvil. The separation was first crudely adjusted using mechanical differential screws and then finely adjusted, using a piezoelectric substage. We estimate that the anvil-spear separation could be controlled this way to better than 10^{-6} cm. An individual point contact was made and broken many times until a stable and reproducible value of resistance was achieved. Using the piezoelectric lever arrangement, the resistance of noble-metal point contacts ranged from 2.5 to 60 Ω. Once formed, the point contacts had stable resistances for 3–4 h. The first and second derivative ($\partial V/\partial I$ and $\partial^2 V/\partial I^2$) were recorded using conventional ac modulation, phase-sensitive detection, and lock-in techniques, similar to those used in superconducting tunneling-spectroscopy. The modulation voltage was small, typically 300 μV. The resistance $R(V) = \partial V/\partial I$ was smooth as a function of voltage, but not constant. For applied voltages greater than about 30 mV, the resistance of all such junctions increased linearly with voltage; below 30 mV, the behavior was roughly parabolic. Thus the resistance of the junctions was distinctly non-Ohmic in both regimes, but metallic in the sense that it was a monotonically increasing function of voltage. For a clear discussion on this point we refer to Rowell *et al.*[2]

The voltage dependence of various $(\partial R/\partial V)$ $[\equiv(\partial^2 V/\partial I^2)/(\partial V/\partial I)]$ fell into three distinct types: Those presented here in Fig. 1 ("normal"); those which had a large second derivative peak at less than 5-mV bias ("anomalous"); those which showed structure similar to that in Fig. 1, but with a rapid oscillatory modulation of order 1 mV ("multiple-junction"). Similar effects were seen by Yanson and Shalov[8] in their film experiments. In our experiments the three types divided roughly as 70%, 25%, and 5% of the formed junctions, respectively. In Figs. 1(a)–1(c) typical results are given for $\partial R/\partial V$ of Cu, Ag, and Au as a function of voltage for "normal" junctions. In all cases $R(V)$ was nearly a symmetric function of V and $\partial R/\partial V$ an antisymmetric function of V. Two pieces of structure are seen at voltages less than 30 mV; above this value $\partial R/\partial V$ is constant. In the same figure literature values are given for the phonon density of states $F(\omega)$ for Cu,[10] Ag,[11] and Au,[12] obtained from neutron scattering experiments. The

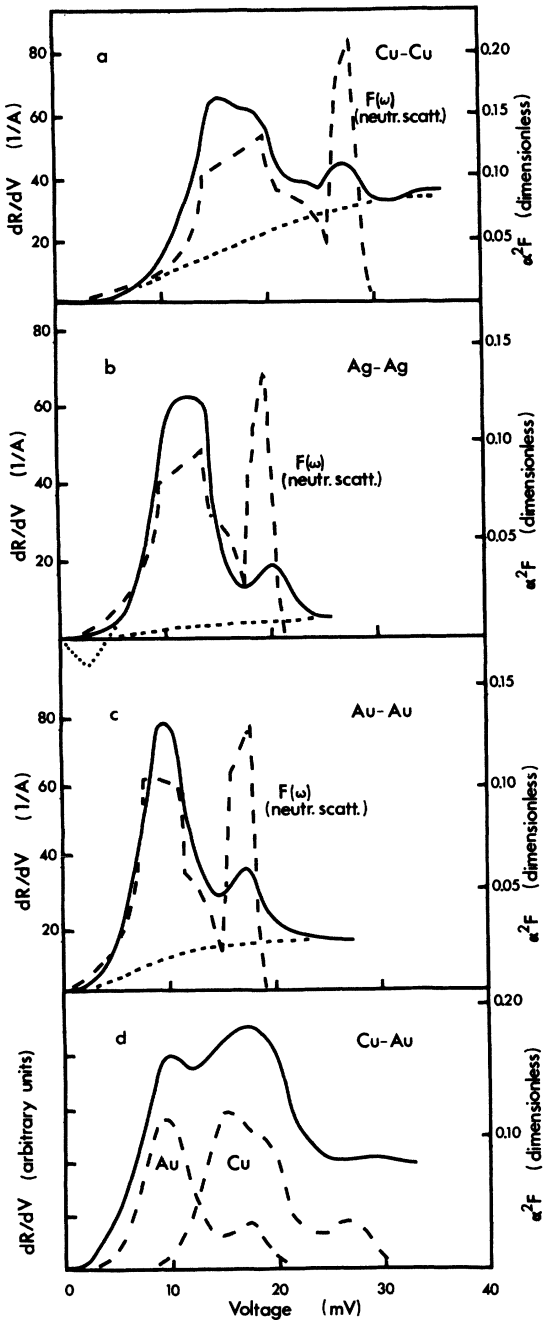

FIG. 1. Measured voltage derivative of the resistance of point contacts as a function of applied voltage of (a) Cu-Cu, (b) Ag-Ag, (c) Au-Au, and (d) Cu-Au, plotted as the solid lines (left-hand scale). The right-hand scale is derived through Eqs. (2) and (3). In (a), (b), and (c) the background functions are shown as short-dashed curves, and phonon density of states from Ref. 12 as long-dashed curves. The dotted line in (b) shows the small measured anomaly at zero bias. In (d) is plotted as long-dashed curves the difference between the measured solid curve and the background function for Au and Cu, respectively.

coincidence of the low voltage peak of our results with the transverse phonon peak is excellent. The higher peak coincides well with the longitudinal peak, with a small disagreement in the case of Ag. We believe, therefore, that bulk phonons play a significant role.

The resistivity ratio (RR) of our samples given in Table I is low and the resistance at zero voltage Ω_0 is high compared with previous experiments on metallic contacts.[6] Estimating the contact radius a_M from $a_M = \rho/2\Omega_0$ (ρ is the resistivity of the metal; Maxwell[13] derived this formula using Ohm's law) and the data of Table I we find values smaller than 0.2 Å. These are far smaller than our estimates of the residual impurity scattering length l_{imp}. Thus the flow of electrons through the contact orifice would have additional impedance due to the Knudsen[14] effect. Wexler[15] has given a detailed treatment of the resistance in the case where the orifice size a is small compared with the scattering length l. He gives

$$R_{\text{int}} = \Gamma(K)/2\sigma a + 4K/3\pi\sigma a\,, \tag{1}$$

where Γ is a slowly varying function of the Knudsen number $K = l/a$ which takes the value 1 at zero and $\frac{9}{128}\pi^2$ at high K and $\sigma = 1/\rho$ the conductivity of the bulk material. The first term in this formula is dominant for small K and similar to the resistive formula of Maxwell.[13] The second term dominates for high K and is similar to the formula of Sharvin.[9] The regime of high K is of interest here and the radii given in Table I are found from $a^2 = 4\rho l/3\pi\Omega_0$. These radii are much larger than our Maxwellian estimates, but the condition $K \gg 1$ is still fulfilled. We assume that only the scattering length l depends on the voltage V (or energy eV). Thus since ρl is independent of l and Γ a slowly varying function of K, the derivative $\partial R/\partial V$ is given by

$$\frac{\partial R}{\partial V} = \frac{\Gamma\rho l}{2a}\,\frac{\partial}{\partial V}\,\frac{1}{l(eV)} \tag{2}$$

and the total scattering length by $1/l = 1/l_{\text{imp}} + 1/l_{\text{ep}}$, where

$$\frac{1}{l_{\text{ep}}} = \frac{1}{v_F\tau(eV)} = \frac{2\pi}{v_F\hbar}\int_0^\infty d\omega\,\alpha^2F(\omega)[2N_0(\omega) + 1 - f_0(eV-\omega) + f_0(eV+\omega)] \tag{3}$$

is the energy-dependent phonon-emission length at energy eV, and α^2F the frequency-dependent electron-phonon coupling constant. Thus at low temperatures we obtain directly α^2F, given as the right-hand scales of Fig. 1. In the theories of electron-phonon coupling reviewed by Zavaritskii and Grimvall,[1] $1/l_{\text{ep}}$ becomes constant at high en-

TABLE I. Experimental parameters for the four point contacts plotted in Fig. 1. Ω_0 is the junction resistance at zero voltage; l_{imp} the 1.2-K resistive scattering length; l_{ep} the 30-meV electron-phonon emission length; a the orifice radius, and K the Knudsen ratio l/a. λ_P is twice the integral of the derived α^2F/ω.

	RR	Ω_0 (Ω)	ρl (10^{-11} Ω cm^2)	l_{ep} (10^{-4} cm)	l_{imp} (10^{-4} cm)	a (10^{-8} cm)	K	λ_G	λ_M	λ_P
Cu-Cu	71	5.7	0.71	0.89	3.25	72.7	96	0.14 ± 0.03	0.16	0.14
Ag-Ag	43	16.3	0.91	1.01	3.26	54.9	140	0.10 ± 0.04	0.16	0.15
Au-Au	23	32.0	1.04	1.16	1.25	37.1	162	0.14 ± 0.05	0.21	0.16
Cu-Au	35	2.5	0.88	...	2.51	122.2	...	...	...	...

ergy, i.e., $(\partial/\partial eV)(1/l_{ep}) \to 0$. We see that our results contain a phonon-emission effect, and another smooth ("background") effect. We have approximated the second effect through the dashed functions presented in Fig. 1, given by

$$B(V) = C \tanh^2(1.5\, eV/k\theta_D), \tag{4}$$

where C is a constant fitted at 30 mV. To compare with other experiments, we integrate to find the λ_P's; λ_G is taken from Grimvall[1] and λ_M from Hoyt and Mota,[5] given in Table I. On the basis of the close coincidence of the structure of Fig. 1 with phonon structures, and the agreement with literature values of λ, we conclude that the voltage derivative of the resistance of small point contacts provides a simple and convenient method to measure $\alpha^2F(\omega)$ in normal metals. The same conclusion was reached by Yanson in his experiments using evaporated films.

We will briefly give some other experimental results and conclusions:

(i) Figure 1(d) tests the possibility of dissimilar junctions—here with a "spear" of Cu and "anvil" of Au. The results suggest that the effect is additive—as was given by Wexler,[15] Eq. (69).

(ii) Using anvils of single crystals, preliminary experiments seem to show that the results do *not* depend on the exposed crystalline face. The form of the variational function of Wexler suggests that the half width at half maximum of the electrons which pass the orifice is 45°. This is 82% of 54.7°, the angle between [100] and [111].

(iii) Plotting all our experimental data, the amplitude of the first peak scales as Ω_0 to the 0.36 ± 0.13 power; this is consistent with the analysis above (0.5 power). The size of the residuals suggest that the internal consistency of the data is of the order of 20%.

(iv) Yanson has defined γ, the ratio of the "background" to the first peak height.[8] γ shows a dependence as Ω_0 to the power -0.54 for Yanson's Cu data and -0.53 for ours. Thus B does *not* depend on Ω_0.

(v) B depends on the residual resistance ratios RR of the anvils as the power -0.52.

(vi) The ratio of the α^2F's of Fig. 1 to the related $F(\omega)$'s shows that α^2 is strongly ω or energy dependent: Transverse phonons couple to the electron gas about four times more effectively than longitudinal phonons in noble metals. This is consistent with the results and conclusions of a theory of Das, who first suggested[16] in a quantitative way, that d electrons were important and strongly umklapp coupled to transverse phonons in noble metals. It is likely that the same is true in transition metals—or "transition-metal compounds."

ACKNOWLEDGMENT

We wish to thank H. W. H. M. Jongbloets for help in setting up the experiments and A. P. van Gelder for helpful theoretical discussions. This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (ZWO).

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