ly if emission arises from an extremely small energy surface or if a band gap occurs near the Fermi surface.[1,2] In the case of molybdenum and tungsten it appears that the energy gap separating the upper and lower Δ_7 bands is the primary factor in producing the deviation in $J(E)$ from the expectations of the Sommerfeld model. The resolution of the band gap in Fig. 1 is not complete presumably because of emission from the Δ_6 and one leg of the Δ_7 band, both of which cross the gap region.

Further substantiation that the lower energy peak in Fig. 2 comes from the lower portion of the Δ_7 band is provided by the increase in relative emission from this band as the field strength is increased (see Fig. 1). This follows from the larger relative increase in transmission with electric field for emission from the lower energy band.

We therefore conclude from these results that field emission TED measurements can be employed to elucidate certain special features of the bulk electronic structure of metals. Also, the close correlation of the TED results with the internal band structure of molybdenum and tungsten suggests that bulk electronic properties are not greatly perturbed by the presence of a nearby physical surface.

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ELECTROMAGNETIC EXCITATION OF TRANSVERSE MICROWAVE PHONONS IN METALS

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We have generated coherent transverse phonons in indium films by direct excitation with microwaves. We have also observed the converse effect, electromagnetic radiation from the surface of indium films when excited by transverse microwave phonons. Just below the superconducting transition temperature T_c the effect rises slightly above the normal-state value, and then on further cooling it decreases rapidly. The experimental results can be explained semiquantitatively if it is assumed that the major coupling mechanism between the lattice and the electromagnetic field is provided by the normal electrons scattering at the boundaries of the film.[1] The condition necessary for the occurrence of the effect in a film or in a semi-infinite metal is that the electronic mean free path be larger than both the microwave penetration depth and the phonon wave number. In that case the two opposing forces exerted on the ions, the electric field and the impact of the colliding electrons, do not cancel each other. In a recent Letter, Houck et al.[2] presented evidence of rf-acoustic coupling near the surface of metals. However, their experiment differs from ours in that it was performed at lower frequencies, 10-40 Mc/sec, and the presence of a dc magnetic field was required. No dc magnetic field was used in this experiment.

The experimental arrangement is illustrated in Fig. 1. The indium films, several thousand angstroms in thickness, were evaporated on an optically polished surface of a high-purity single-crystal germanium rod. The axis of the rod was along the [110] direction and its end faces were polished parallel to 5 sec of arc. The germanium face, with the indium on it, was pressed against the bottom wall of a resonant rectangular microwave cavity. The wall was provided with a 0.5-cm-diam hole so that some of the microwave current flowed through the film. The cavity was excited with 9.3-GHz microwave pulses, 1 μsec in duration, 10-W peak power, and 5×10^{-4}

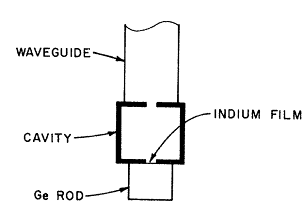

FIG. 1. Schematic of experimental setup.

duty cycle. The reflected power from the cavity was detected by a sensitive microwave detector and displayed on an oscilloscope. Following the initial excitation pulse, several echoes were observed, delayed by times corresponding to the flight of slow and fast shear waves through germanium. The insertion loss, defined as the ratio of the amplitudes of the strongest echo to that of the excitation pulse, was 10^{-13}. In Fig. 2 a recording of the amplitude of one of the echoes is shown as a function of temperature. The thickness of the film in this case was about 2500 Å and the normal dc conductivity $2.3\times10^6\ \Omega^{-1}\ \mathrm{cm}^{-1}$. We conclude from these experimental observations that transverse acoustic waves are generated in the penetration region of the indium film by direct interaction with the electromagnetic field, these waves are propagated in the germanium rod, and the echoes which are reflected back into the indium film emit microwave radiation into the cavity.

To estimate the conversion efficiency of the above process, we consider a plane-polarized transverse electromagnetic wave incident normally on a film bounded by the planes $x=0$ and $x=d$. The bulk mean free path l in the film is assumed to be large compared with d, and the normal conductivity σ_N is determined by diffuse boundary scattering. To compute rigorously the electric field $E(x)$ in the film, a nonlocal theory should be used. However, for the purpose of the present calculation it is assumed that $E(x)$ is determined by the classical skin effect,

$$E(x)=E_0\{\exp[i(Kx-\omega t)]+\gamma\exp[-i(Kx+\omega t)]\}/(1+\gamma), \qquad (1)$$

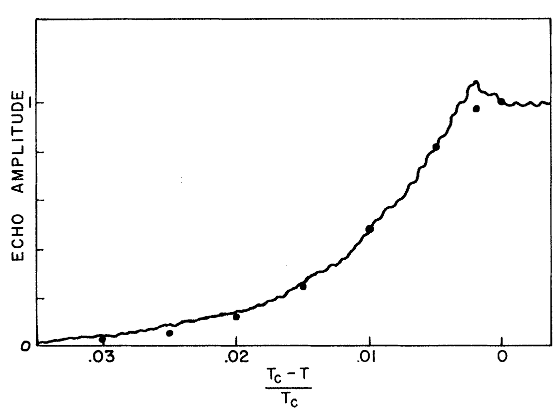

FIG. 2. Echo amplitude versus the reduced temperature, $(T_C-T)/T_C$. The full points are calculated values of α^2 from Eq. (4) with $\lambda_0=600$ Å.

where E_0 is the electric field at $x=0$, ω is the frequency, $K=[4\pi\omega(i\sigma_1-\sigma_2)]^{1/2}/c$ is the propagation constant, σ_1 is the real and σ_2 the imaginary part of the complex conductivity σ, and $\gamma=\exp(2iKd)$. We assume the two-fluid model[3] with $\sigma_1/\sigma_N=(T/T_C)^4$ and $\sigma_2/\sigma_N=[1-(T/T_C)^4]c^2/4\pi\omega\lambda_0^2\sigma_N$, where λ_0 is the penetration depth.

To determine the force exerted on the ions by the electrons scattering at the boundaries, we consider the transverse momentum acquired by an electron in the electric field, $-\int_0^\tau eEdt$, where e is the electronic charge and the integration extends over the time between collisions τ. The majority of the normal electrons transfer this excess momentum to the lattice at the boundaries. This transfer is coherent since the electric field can be taken as stationary ($\omega\tau\ll1$). The momentum transferred by the electrons per unit time and unit area of the boundary represents a shear stress F acting on the boundaries. To calculate F we take into account only the contribution of the normal electrons whose trajectories begin at one boundary and end at the other boundary. The effect of electrons which scatter in the bulk is neglected and superconducting electrons are assumed not to transfer momentum to the lattice. The shear stress F, acting on the two boundaries $x=0, d$ of the film, is then readily calculated to be

$$F=\exp(-i\omega t)E_0en[\ln(l/d)](1-\gamma)/(1+\gamma)2iK, \qquad (2)$$

where n is the density of the normal electrons. The stress F depends only weakly on l and we take $\ln(l/d)=1$ as a reasonable estimate.

The transverse lattice displacement $u(x,t)$ is derived from the wave equation

$$\rho\partial^2u/\partial t^2=C\partial^2u/\partial x^2+Een_0 \qquad (3)$$

and the boundary condition (2). Here en_0 is the ionic charge density. We assume the film to be deposited on a substrate rod which has the same shear stiffness constant C and density ρ as the film and we neglect sound attenuation. The solution for u in the film is given by the superposition of the four waves, $\exp[i(\pm qx-\omega t)]$ and $\exp[i(\pm Kx-\omega t)]$, where $q=\omega/v$ is the phonon wave number and $v=(C/\rho)^{1/2}$ is the velocity of sound. In the substrate u is given by the wave $\exp[i(qx-\omega t)]$. The conversion efficiency α is defined by $\alpha=\int wdf/P$, where P is the microwave power absorbed in the cavity, $w=\frac{1}{2}C\,|\partial u/\partial x|^2v$ is the acoustic flux, $\partial u/\partial x$ is the strain in the substrate, and the integration extends over the area of the film. The insertion loss is given by α^2, because the conversion efficiency of microwaves to sound is equal to that of sound to microwaves. The expression for α can be written in the form

$$\alpha = \frac{c\int H_0^2 df}{8\pi P}\frac{\pi\omega^2 e^2 n_0^2 v}{c^3 C|K|^4}\left|\left(\frac{n}{n_0}\right)(1+\cos qd) - \frac{2Kq}{K^2-q^2}\left(\frac{K}{q}+\frac{2i\gamma^{1/2}\sin qd}{1-\gamma}\right)\right|^2. \qquad (4)$$

We have used the relation $E_0 = H_0\omega(1+\gamma)/(1-\gamma)Kc$ to express E_0 in terms of the magnetic field at the surface H_0. The advantage this has is that H_0 changes only slightly as the film is taken through T_c.

The dimensionless factor $c\int H_0^2 df/8\pi P$ appearing in Eq. (4) represents the enhancement of the field in the cavity. Its numerical value, for the cavity used in the present experiment, was estimated to be about 10. The first term between the absolute value signs in Eq. (4) is due to the normal electrons scattering at the surface and is maximum when the film is normal ($n = n_0$) and when the resonance condition $qd = 2N\pi$ is satisfied (N is an integer). The second term between the absolute value signs results from the electric field driving the ions directly. Using for the indium film the parameters[4] $C = 1.2\times10^{11}$ erg cm^{-3}, $\rho = 7.3$ g cm^{-3}, $q = 4.5\times10^5$ cm^{-1}, $n_0 = 3.8\times10^{22}$ cm^{-2}, and $\sigma_N = 2.1\times10^{18}$ sec^{-1}, we obtain for the normal state ($n = n_0$, $\sigma_2 = 0$, and $\sigma_1 = \sigma_N$) $|K| = 4.1\times10^4$ cm^{-1} and $|K|/q \sim 10^{-1}$. Thus the second term in Eq. (4) is negligible in the present case. When the resonance condition $qd = 2N\pi$ is satisfied then $\alpha^2 = 3\times10^{-12}$. This result is 30 times larger than the experimental value. However, considering the crudeness of the theory and the experimental uncertainties this discrepancy is not considered significant. Some of the discrepancy can probably be accounted for by the acoustic mismatch between the film and the substrate, by departure from the resonance condition, by imperfections in the surfaces, and by sound attenuation.

To calculate the value of α below T_c we assume, according to the two-fluid model, $n/n_0 = (T/T_c)^4$ and we use λ_0 as an adjustable parameter. We obtain good agreement between theory and experiment, with the exception of the small peak just below T_c, if we choose $\lambda_0 = 600$ Å. This value of λ_0 is in reasonable accord with the values for indium of 500 Å by Toxen,[5] and of 600-780 Å by Gittleman, Bozowski, and Rosenblum.[6] At the temperature at which the peak occurs, $(T/T_c)-1 = 2\times10^{-3}$, the energy gap[7] $\Delta(=42\ \mu\text{V})$ is of the magnitude of the energy $\hbar\omega$ of the applied microwaves. This suggests that the peak is due to the breaking up of superconducting pairs by microwaves. Similar effects, due to the BCS coherence factors in the absorption of electromagnetic radiation,[3] have been observed in nuclear magnetic relaxation[8] and have been predicted for transverse ultrasonic attenuation.[9]

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