RESONANT TRANSMISSION OF MICROWAVE POWER THROUGH "THICK" FILMS OF LITHIUM METAL*

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We have been privately informed by Lewis and Carver[1] of their observation of conduction electron spin resonance transmission through films of lithium metal. In this Letter we report the results of independent measurements which confirm their results and, in addition, demonstrate the following significant features: (1) The observed line shape is in good agreement with the results of our detailed calculations; (2) the transmitted fields are circularly polarized; and (3) the signal intensity as a function of sample thickness is exponentially attenuated, with the decay constant expected for diffusing free electrons.

Selective transmission is expected if the distance δ_e that an electron can diffuse in a transverse relaxation time T_2 is much greater than the classical skin depth δ. For free electrons this distance is given by

$$\delta_e = (v\Lambda T_2/3)^{1/2}, \qquad (1)$$

where v is the Fermi velocity and Λ the mean free path. For lithium $T_2 \approx 10^{-7}$ sec, independent of temperature.[2] Room-temperature values for v and Λ give $\delta_e \approx 22\ \mu$, while at 9.4 Gc/sec the classical skin depth is $\delta \approx 1\ \mu$.

Rather than follow the calculation of Azbel' et al.,[3] we have used an approach suggested by Kaplan,[4,5] in which a diffusion term[6] is added to the Bloch equations. The modified Bloch equations, together with Maxwell's equations and appropriate boundary conditions, determine the rf fields in the metal. The solutions are characterized by two wave vectors which, in the approximation $\delta/\delta_e \ll 1$, are given by

$$k_1 = (1+i)/\delta,$$
$$k_2 = (\sqrt{2}/\delta_e)[1 + i(\omega-\omega_0)T_2]^{1/2}. \qquad (2)$$

The first is simply the normal skin effect, while the second gives the slowly damped solution near resonance.

For reasons to be explained below, in order to compare with experiment one must add the transmitted field $H(d)$ to a field H_2 whose phase is θ with respect to the phase of $H(d)$. The solution in terms of the output of a superheterodyne microwave receiver is

$$V_{sig} \propto [1 + (A/H_2)\exp\{-(d/\delta_e)(\rho^2+1)^{1/2}\} \times \sin\{\theta + \varphi/2 + d/\delta_e(\rho^2-1)^{1/2}\}] \qquad (3)$$

where

$$A = \sqrt{2}\, 8\pi k_0 \delta^2 \chi_0 \omega_0 T_2/\delta_e \rho, \quad \rho^4 = 1 + \tan^2\varphi,$$

and $\tan\varphi = (\omega-\omega_0)T_2$. The transmitted line shape computed from Eq. (3) turns out to be roughly independent of the film thickness d, but strongly dependent on θ, as is in fact observed experimentally. Figure 1(a) shows Eq. (3), plotted for $\sqrt{2}d/\delta_e = 2.5$, $\theta = \pi/2$, and Fig. 1(b) shows a tracing of an oscilloscope photograph of the signal from a sample with $d = 45\ \mu$ (corresponding to $\sqrt{2}d/\delta_e = 3.0$ if $\delta_e = 22\ \mu$) with a setting of the microwave phase chosen to give the line shape of Fig. 1(a).

Our experiments were done at room tempera-

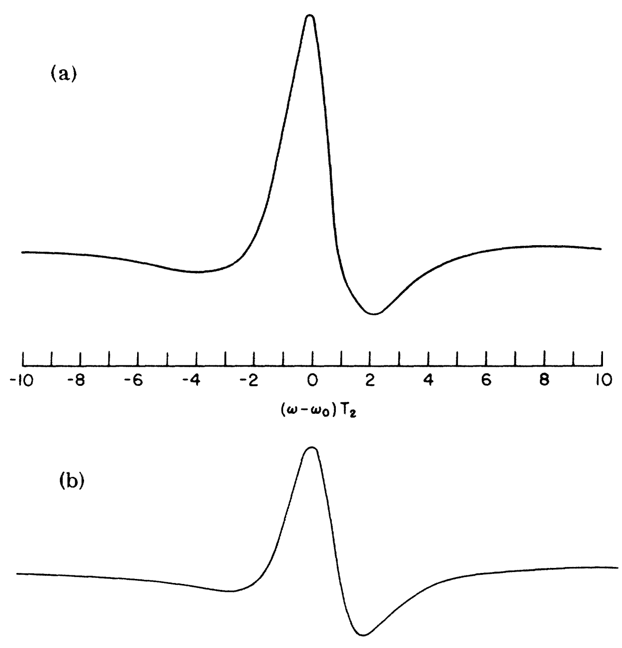

FIG. 1. (a) Equation (3) vs $(\omega-\omega_0)T_2$ for $\sqrt{2}d/\delta_e = 2.5$, $\theta = \pi/2$. The vertical scale is arbitrary. (b) Tracing of oscilloscope photograph for 45μ sample. Horizontal scale only approximately the same as 1(a), vertical scale arbitrary.

ture and at a frequency of 9.5 Gc/sec, with films of lithium ranging in thickness from 45 to 150 μ. Samples were prepared by rolling out, between sheets of oiled waxed paper, slices cut from chunks of the metal as supplied by Fisher Scientific Company. Ordinary resonances, having the characteristic line shape,[2] about 1 Oe wide are observed in these samples. Sheets rolled out to thicknesses much less than 40 μ invariably developed cracks and pinholes.

The samples were arranged so that they formed part of the common sidewall of two adjacent rectangular TE_{101} cavities. This was accomplished by clamping the lithium sheets between two cavities whose adjacent sidewalls contained circular coupling holes 0.200 in. in diameter. The sheets covered and extended well beyond the coupling holes, which were accurately aligned in assembly. Since the sample is many skin depths thick there should be, apart from spurious leakage, no coupling between the two cavities. In a magnetic field, with microwave power incident on one (the "transmitter") cavity, transmission is detected by observing the power coupled into the other (the "receiver") cavity as the field is varied through resonance. This geometry allows the experiment to be performed with H_0 making any angle with respect to the surface of the film. Experimentally little difference was observed between parallel and perpendicular orientations of H_0. Equation (3) is the solution for H_0 perpendicular to the surface.

Since the fields transmitted at resonance are expected to be circularly polarized, provision was made to orient the receiver cavity either parallel or perpendicular to the transmitter cavity, in order to be sensitive to either of the two orthogonal components. The receiver cavity was fixed-tuned, while the transmitter cavity was tunable; each could be matched with a variable coupling device. As in an ordinary resonance experiment, absorption in the transmitter cavity was observed by monitoring the reflected power.

The output of the receiver cavity was detected in a superheterodyne receiver, for which a coherent local oscillator is obtained by coupling a fraction of the signal klystron power into a single-sideband modulator driven at 63 Mc/sec.[7] Ideally the output of the receiver cavity would be zero off resonance so that there would be no i.f. signal to bias the video detector into the linear region. One could then exploit the overall coherence of the system by following the i.f. amplifier with a phase-sensitive detector at 63 Mc/sec. In practice there is always a certain amount of carrier power incident on the receiver owing to incomplete suppression of the carrier in the local oscillator and to small unavoidable leaks in the system. At maximum i.f. gain (120 dB) and with an incident power of 50 mW there was always adequate video detector bias. It is the presence of this carrier power in the receiver that requires that the detected signal be treated as the sum of a transmitted field and a larger field of arbitrary phase.

There is always the possibility that the detected signal may be due to direct leakage, around the sample, and into the receiver cavity, of the absorption signal in the transmitter cavity. To discriminate against this, a sample of 0.03 % Cr^{3+} in powdered MgO was placed on the opposite wall of the transmitter cavity. While the signal from the Cr^{3+}, whose resonance is displaced about 30 Oe, was comparable with that from the lithium in reflection, no signal from the Cr^{3+} was observed in the receiver cavity, even at gain settings 8 × those at which large transmission signals from the lithium were observed.

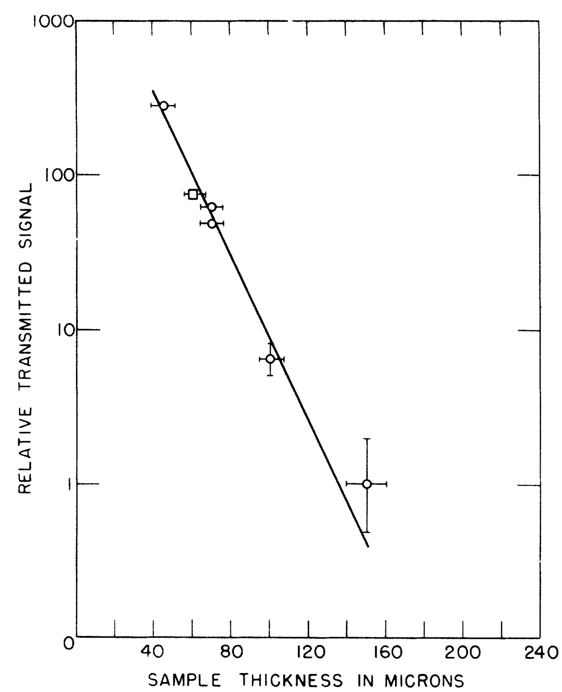

FIG. 2. Signal vs sample thickness on semilog plot. The line drawn through the data has a slope corresponding to $\delta_e/\sqrt{2} = 16\mu$. Circles, parallel cavities; squares, crossed cavities.

Resonances due to transmission were detected in samples up to 150 μ thickness, where the signal to noise after narrow-banding was about 3:1. A plot of the signal intensity versus thickness is shown in Fig. 2, where the slope corresponds to an attenuation length of 16 μ, in excellent agreement with the calculated value of $\delta_e/\sqrt{2} = 15.5\ \mu$. Signals of equal magnitude were observed for both relative orientations of the cavities, verifying that the transmitted fields are circularly polarized.

Observation of spin resonances in metals other than the alkalis and beryllium has frequently been obscured by resonances from static impurities.[2] Resonance transmission should not be sensitive to the presence of static impurities and may aid in the search for spin resonance in other metals at low temperatures. Recent measurements in this laboratory of the relaxation time of conduction electrons in sodium indicate that T_2 may be $\geq 10^{-6}$ sec in the liquid hydrogen range.[8] Transmission experiments on thick samples of sodium may provide an alternative approach to the measurement of T_2. If resonance transmission can be observed in metals having anisotropic Fermi surfaces, transmission experiments on single crystals may possibly be used to measure anisotropies in δ_e.

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THERMAL CONDUCTIVITY AT ELEVATED PRESSURE AND TEMPERATURE

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We report here some results obtained on the thermal transport properties of materials at pressures to 50 kbar and temperatures to 600°C. Phase diagrams of Bi and Te were determined using a differential thermal conductivity analysis[1] (DTCA) and are compared with data taken by other techniques. A theoretical method for determination of thermal conductivity at high pressure and temperature from experimental data is proposed and the results are used to compare qualitatively experimental and theoretical temperature gradients.

Although the idea of determining high-pressure phase boundaries using thermal conductivity changes has been presented before,[1] no method has been proposed which would have general applicability or permit the measurement of thermal conductivity. A coupling of the theoretical analysis and the generally applicable experimental technique reported here will permit simultaneous determination of both high-pressure phase boundaries and thermal conductivities.

Experiments were performed using a tetrahedral anvil high-pressure apparatus and techniques which have been described previously.[2,3] The pyrophyllite tetrahedrons contained a cylindrical graphite heater, inside of which was placed the cylindrical sample and boron nitride container as shown in the inset of Fig. 1(b). A pair of chromel-alumel thermocouples served to monitor the temperature at the center of the sample (T_a) and at a distance b from the center in the boron nitride (T_b). DTCA measurements consist of observation of the temperature difference, $\Delta T \equiv T_b - T_a$, as a function of the center temperature, T_a. If the thermal conductivity of the sample, K_a, differs in magnitude each side of a phase boundary, the transition between phases will be reflected by a discontinuous shift in the temperature dependence of ΔT. Examples of this behavior are shown by the solid curves in Fig. 2. The discontinuities observed correspond to melting