FLUCTUATION EFFECTS IN THE ac CONDUCTIVITY OF THIN LEAD FILMS ABOVE THE SUPERCONDUCTING TRANSITION TEMPERATURE*

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The transmission of microwaves through thin (~100-Å) Pb films indicates considerable excess conductivity at temperatures above the superconducting transition temperature. Both the frequency and temperature dependences of this conductivity are in agreement with a calculation of Schmidt which takes account of the fluctuations of the order parameter for a film of thickness less than the Ginzburg-Landau coherence length. This agreement between experiment and theory supports Schmidt's choice of time-dependent Ginzburg-Landau equations.

Recently considerable attention has been given to the study of superconductors above the transition temperature T_c for situations in which the effective electron mean free path is small compared with the Ginzburg-Landau (GL) coherence length.[1] The excess ac conductivity above T_c due to fluctuations in the order parameter for small mean-free-path superconductors has been investigated theoretically by Schmidt.[2] D'Aiello and Freedman[3] have reported microwave transmission data at 20 GHz on granular Al films which are not in agreement with Schmidt's theory. In this paper we report results of microwave transmission measurements on thin (~100-Å) Pb films which are in very good accord with the results of Schmidt.

Previous experimental studies[4] have demonstrated an excess dc conductivity above T_c for a variety of small mean-free-path films which have been amorphous, dirty, granular, or thin (or combinations of these). In the majority of these studies the resistance varies as

$$R(T)=R_N(1+\tau_0/\tau)^{-1}, \tag{1}$$

where R_N is the normal-state resistance, $\tau=(T-T_c)/T_c$, and τ_0 is a constant. Aslamazov and Larkin[5] first derived Eq. (1) for disordered two-dimensional metallic systems (a superconducting film with thickness less than the GL coherence length should satisfy this condition reasonably well). According to these authors τ_0/R_N should be a universal constant equal to $0.152\times10^{-4}\ \Omega^{-1}$ regardless of the origin of the specimens. More recent theoretical work[6,7] in this area is basically in agreement with that of Aslamazov and Larkin although there are some systems in which discrepancies between theory and experiment have been reported.[7]

For the ac case Schmidt,[2] using the time-dependent GL equations given by Abrahams and Tsuneto,[8] obtains (for a film of thickness d much less than the GL coherence length), for the excess conductivity parallel to the film,

$$\sigma_{\parallel}(\omega, T)=\frac{e^2}{16\hbar d\tau}\left[\frac{2}{\tilde{\omega}}-\frac{2}{\tilde{\omega}}\tan^{-1}\frac{1}{\tilde{\omega}}-\frac{1}{\tilde{\omega}^2}\ln|1+\tilde{\omega}^2|\right], \tag{2}$$

where $\tilde{\omega}=\pi\hbar\omega/16k_BT_c\tau$.

Our measurements at 23.9, 37.2, and 69.6 GHz were made on films prepared from 99.999% purity Pb. The evaporation and subsequent measurements were performed within a microwave cryostat.[9] The Pb was evaporated from a point-source Mo oven and condensed onto Z-cut, optically polished, quartz plates at 77°K. The flux of the evaporating ions was highly collimated to assure uniformity along the large dimension of the film. In order to obtain stable thin films a slow deposition rate (1 Å/min) was used. Hence, in spite of the rather good vacuum ($<10^{-6}$ Torr) the films were probably quite dirty because of absorbed gas molecules. Following the deposition of a given film, it was thermally annealed by allowing the sample block to warm to room temperature. Both dc and microwave measurements were then made simultaneously on the films without breaking the vacuum. Generally, the agreement between the resistance obtained from dc measurements and that computed from the normal-state transmission coefficients was better than 10%, thereby indicating a considerable uniformity in the resistivity and thickness

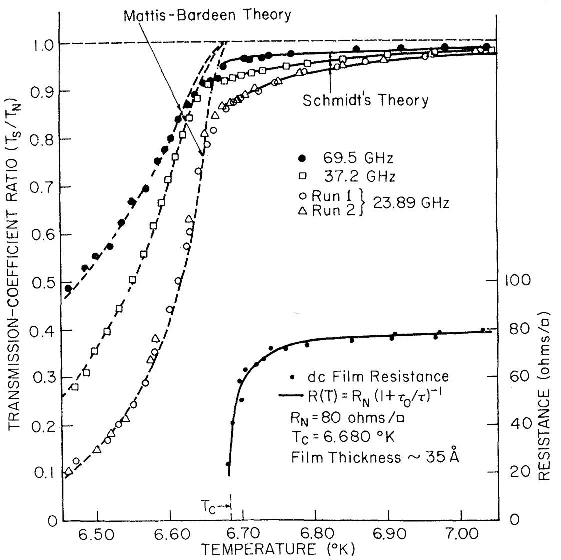

FIG. 1. Microwave transmission-coefficient ratios for a thin Pb film at three frequencies near the superconducting transition temperature. The curve for the dc resistance $R(T)$ was calculated using the R_N and T_c given in the legend and assuming $\tau_0/R_N = 0.152\times 10^{-4}\ \Omega^{-1}$.

over a major portion of the films. The thicknesses of the films as estimated from the residual resistance values ranged from 30 to 150 Å. The effective mean free paths l_{eff} computed in similar fashion varied from 16 to 31 Å. Apparently, the films were well within the criteria for dirty superconductors (i.e., $l_{eff} \lesssim \xi_0$, where ξ_0 is the coherence length in the pure material).

In Fig. 1 the microwave transmission-coefficient ratio T_S/T_N is shown as a function of temperature for a film of 35 Å effective thickness. Because of the possibility of induced currents in the films exceeding critical values near T_c, the microwave power was steadily lowered until the experimental curves showed no dependence upon power level. The microwave power then was further reduced by a factor of 100 to obtain the data presented here. As reported previously,[10] the results below T_c are in good agreement at all three frequencies with the ac conductivity equations derived by Mattis and Bardeen[11] from the BCS theory if 4.5 ± 0.2 is used for $2\Delta_0/kT_c$. From infrared-transmission measurements on Pb thin films similar to ours, Palmer and Tinkham[12] obtain $2\Delta_0/kT_c = 4.5\pm 0.1$.

As can be seen in Fig. 1 the data near and above T_c deviate considerably from those expected on the basis of the Mattis and Bardeen theory. In this temperature region we analyzed the data considering the effects on T_S/T_N of the additional contributions to the dynamic conductivity proposed by Schmidt. In this case, the total conductivity is $\sigma(\omega, T) = \sigma_{\|}(\omega, T) + \sigma_N$, where $\sigma_{\|}(\omega, T)$ is given by Eq. (2) and σ_N is the residual value of the conductivity in the normal state. Thus,

$$\frac{\sigma(\omega,T)}{\sigma_N} = 1 + \frac{e^2 R_N}{16\hbar\tau}\left[\frac{\pi}{\tilde{\omega}} - \frac{2}{\tilde{\omega}}\tan^{-1}\frac{1}{\tilde{\omega}} - \frac{1}{\tilde{\omega}^2}\ln\left|1+\tilde{\omega}^2\right|\right].$$

The transmission-coefficient ratio is given by[9]

$$T_S/T_N = \{n^2[2+Z_g/R_N]^2\cos^2 kl + [n^2+1+Z_g/R_N]^2\sin^2 kl\}\{n^2[(2+Z_g\sigma_1/R_N\sigma_N)^2+(Z_g\sigma_2/R_N\sigma_N)^2]\cos^2 kl$$
$$+[(n^2+1+Z_g\sigma_1/R_N\sigma_N)^2+(Z_g\sigma_2/R_N\sigma_N)^2]\sin^2 kl - n(n^2-1)(Z_g\sigma_2/R_N\sigma_N)\sin 2kl\}^{-1}, \qquad (4)$$

where Z_g is the waveguide impedance, k is the propagation constant in the quartz substrate, l is the substrate thickness, N is the index of refraction of quartz, and σ_1 and σ_2 are the real and imaginary parts of the superconducting complex conductivity, respectively. The solid lines above T_c in Fig. 1 (labeled Schmidt's theory) were calculated using $\sigma(\omega, T)/\sigma_N$ for σ_1/σ_N and $\sigma_2/\sigma_N = 0$ in Eq. (4) above. The agreement of experiment and theory with respect to both temperature and frequency is quite good. It is worth noting that runs 1 and 2 at 23.89 GHz occurred two weeks apart in time.

To allow a more critical comparison between the theory and the experimental results, the temperature and frequency dependence of $\sigma(\omega, T)/\sigma_N$ above T_c, computed from the inversion of Eq. (4), is shown in Fig. 2. The experimental points in Fig. 2 have been multiplied by small normalization factors; for 69.6 GHz the factor was 1.005, for 23.89 GHz it was 1.017 (run 1) and 1.016 (run 2), and for 37.2 GHz it was 1.0185. These factors are of no consequence on the scale of Fig. 1. These normalization factors essentially are corrections to the measured values of T_N. When these measurements were made we were interested primarily in the temperature range below T_c. Consequently, data were not taken at temperatures far enough above T_c to obtain precise values of T_N. Even so, in this type of

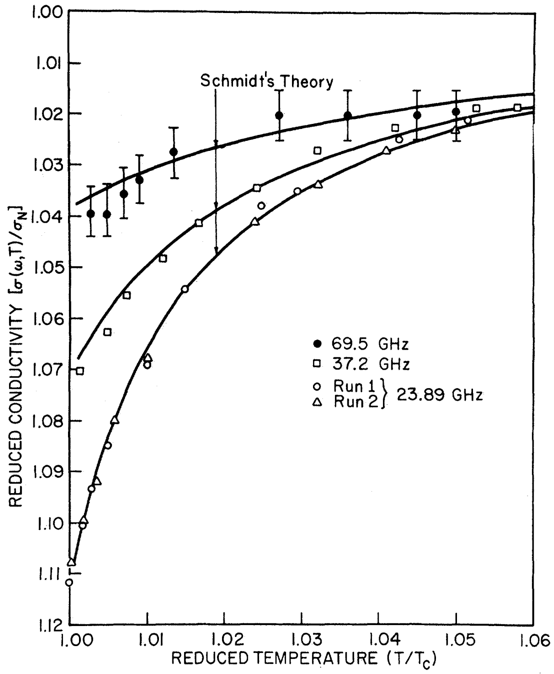

FIG. 2. Reduced ac conductivities calculated from the data shown in Fig. 1. Error bars for the two lower frequencies are about twice the size of the data points.

experiment the limitations imposed by the long-range stability of the microwave measuring equipment would make it extremely difficult to eliminate discrepancies of such small magnitude.

In conclusion, the good agreement between the ac-conductivity theory of Schmidt and the experimental data as a function of both frequency and temperature indicates that the basic assumptions (in particular the form of the time-dependent Ginzburg-Landau equations) and procedures of the theory are satisfactory for thin, dirty Pb films.

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EFFECT OF ELECTRON-LO-PHONON COUPLING ON RAMAN SCATTERING IN CADMIUM SULFIDE

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Enhanced Raman scattering by LO phonons in CdS has been observed when the energy difference between Landau levels in the conduction band is equal to the LO phonon energy at the zone center.

Oscillations in the conductivity due to coupling between electrons and longitudinal optical phonons have recently been observed in several semiconductors.[1-5] In the presence of a transverse magnetic field, minima in the conductivity occur when the energy difference between two