Letters to the Editor

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Cyclotron Resonance in Tin*

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Cyclotron resonance has been observed in single crystals of tin at 24 kMc/sec. The possibility of observing cyclotron resonance in metals was first recognized by Azbel and Kaner,[1] who studied the problem by solving the transport equation. The problem has also been discussed by Chambers.[2] Heine[3] has rederived and extended the results of Azbel and Kaner using the ineffectiveness concept.[4]

Cyclotron resonance in metals is observed under anomalous skin-effect conditions where the electron mean free path is large compared with the skin depth. The static magnetic field and the microwave electric field are applied approximately parallel to the crystal surface and in this case to each other. The electrons contributing to the resonance execute helical motion, rising into the skin depth on each revolution. A resonant absorption will occur when the electrons arrive in the skin depth in synchronism with the microwave electric field or when $H=H_c\equiv m^*c\omega/e$, where H is the applied magnetic field, ω the angular microwave frequency, m^* an effective mass which will be called the cyclotron mass, e the electronic charge, and c the speed of light. In contrast with the situation in semiconductors[5] where the oscillating electric field penetrates uniformly throughout the material, the confining of the electric field to the skin depth makes possible additional resonances at values of $H=H_c/n$, where n is an integer. These subharmonic resonances result from the larger orbits of the electrons in lower magnetic fields for which the electrons complete a revolution and return into the skin depth in n cycles of the microwave electric field.

Coin-shaped single crystals were grown from 99.9999% pure tin obtained from the Vulcan Detinning Company. The surface was electropolished to a mirror finish, and care was taken to avoid straining the sample. The crystal was mounted in the microwave cavity so that its orientation with respect to the applied magnetic field could be varied. All measurements were made at 4°K. Figure 1 shows a typical curve of dR/dH vs H,

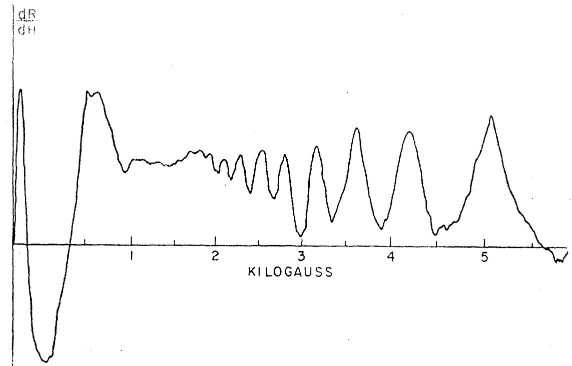

Fig. 1. A typical curve of dR/dH vs H, showing the fifth through the thirteenth subharmonics.

where R is the real part of the surface impedance, as obtained from the microwave losses in the cavity containing the crystal. The fifth through the thirteenth subharmonics are visible.

Fawcett[6] has measured the magnetic field dependence of microwave absorption in single crystals of tin and found a maximum in the absorption which is probably correctly attributed to a cyclotron resonance. In the present work the identification of cyclotron resonance was verified by the observation of the predicted subharmonic resonances with values of n in some cases up to 15, and by the observation of the linear dependence of H_c on microwave frequency. This linear dependence was determined from a 10% variation in frequency. Cyclotron masses from 0.2 to 3 electron masses have been observed. A clearly distinguishable pattern of subharmonics was observed only for certain sample orientations. In some directions the anisotropy was sufficient to give a 50% change in cyclotron mass with a 3° change of orientation of the sample. For many orientations, patterns for two or more masses were superimposed. Curves showing many clearly defined subharmonics have been observed with the magnetic field at an angle as high as 30° from parallel to the crystal surface.

The relatively strong signal at low field is not yet completely understood. Heine[7] has suggested that it is associated with the changeover (at the field H_1 of reference 3) from the usual anomalous skin-effect conditions ($H=0$) to the situation envisaged by Azbel and Kaner. In the latter the curvature of the path in the magnetic field pulls the electrons out of the skin depth and is an important factor in determining the surface current. Samples in which the mean free time τ was evidently too short to allow observation of cyclotron resonance nevertheless exhibited the low-field effect. This might be expected since the requirement on τ for the suggested mechanism is much less than for cyclotron resonance. However, this variation of microwave absorption with magnetic field can be eliminated by etching and cold working the sample. No large anisotropy has been observed in the low-field effect.

The dc resistance of a polycrystalline rod of the tin used was measured and the ratio of resistance at room temperature to that at 4°K was found to be 40 000. The assumption of one electron per atom and an effective mass equal to the electronic mass yields a relaxation time $\tau \sim 30\times10^{-11}$ sec at 4°K. Relaxation times estimated from the resonance results range up to five times this value, implying mean free paths of the carriers involved in the resonance of the order of a millimeter. Experiments are in progress to determine as completely as possible the Fermi surface in tin and to extend the technique to other metals.

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Microwave Measurements of the Energy Gap in Superconducting Aluminum

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DISCOVERY of an exponential temperature dependence of the electronic specific heat in superconductors[1] suggested the existence of a gap in the one-electron energy states of order $\Delta E \sim kT_c$, where T_c is the superconducting transition temperature. This was followed by several electromagnetic experiments[2–4] designed to reveal more of the details of the energy gap by studying the effect on superconductors of photons of energy $h\nu \sim kT_c$. A recently proposed theory of superconductivity[5] has as one of its features a temperature-dependent energy gap. The present paper presents experimental evidence for such an energy gap obtained from microwave absorption studies of aluminum.

An improved version of the apparatus described in a previous paper[3] was used to obtain more accurate measurements of microwave absorption in aluminum (T_c=1.175°K) over an increased wavelength and temperature range. Following convention we have expressed the absorptivity in terms of the surface resistance ratio, $r \equiv R/R_n$ (where R and R_n are, respectively, the surface resistances at a given temperature and in the normal state just above T_c). Measurements of r as a function of the reduced temperature, $t \equiv T/T_c$, at three wavelengths for an annealed, chemically brightened sample (Al 3)[6] are shown in Fig. 1. Unfortunately, the measurements at other frequencies were only made on an unannealed sample of slightly different design (Al 2) which showed a residual absorption at $t=0$. However, by subtracting this residual absorption from the total absorption at $0.65kT_c$ and $2.37kT_c$, the corrected curves for Al 2 were found to be in good agreement with the corresponding curves for Al 3. Thus, we included similarly corrected measurements on Al 2 at $1.23kT_c$ and $1.55kT_c$ in our analysis.

From Fig. 1 it will be seen that the curves do not drop abruptly as t decreases below $t=1$, in contrast to lower frequency measurements, but show a definite rounding which becomes more pronounced as we go to higher frequencies. This marked change in the character of the curves suggests that we are no longer in the region where the behavior predicted by the usual two-fluid model is obeyed but instead have encountered quantum effects associated with the existence of a gap in the electron energy states.

One quantum effect occurs when the photon energy, $h\nu$, exceeds the gap energy, ΔE, and transitions of superconducting electrons are induced across the gap, leading to absorption of energy. Since the proposed energy gap decreases with temperature,[1,5] vanishing at $t=1$, the photon energy required to exceed the gap becomes smaller as t increases. Thus, for each photon energy there exists a particular temperature above which the gap is exceeded and transitions across the gap occur. A second quantum effect associated with an energy gap is the modification of the shielding properties of the superconducting electrons from the London

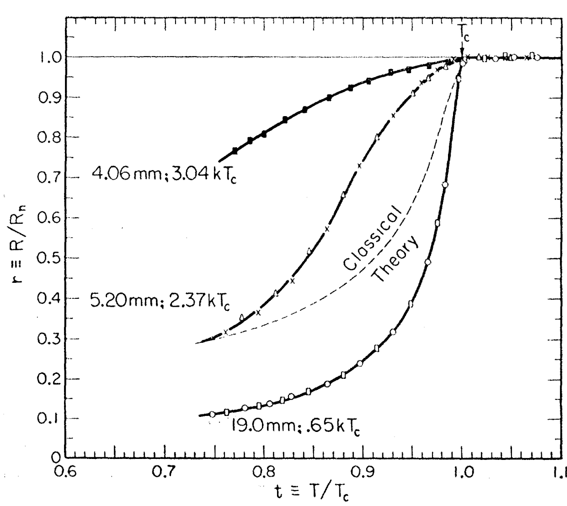

Fig. 1. Surface resistance ratio, r, as a function of reduced temperature, t, at three wavelengths for aluminum. To avoid confusion, some of the experimental data for $t>1$ have been omitted. Different symbols on the same curve indicate runs made on different days. The method by which the dashed curve was obtained is explained in the text.