CYCLOTRON RESONANCE OBSERVATIONS IN CADMIUM

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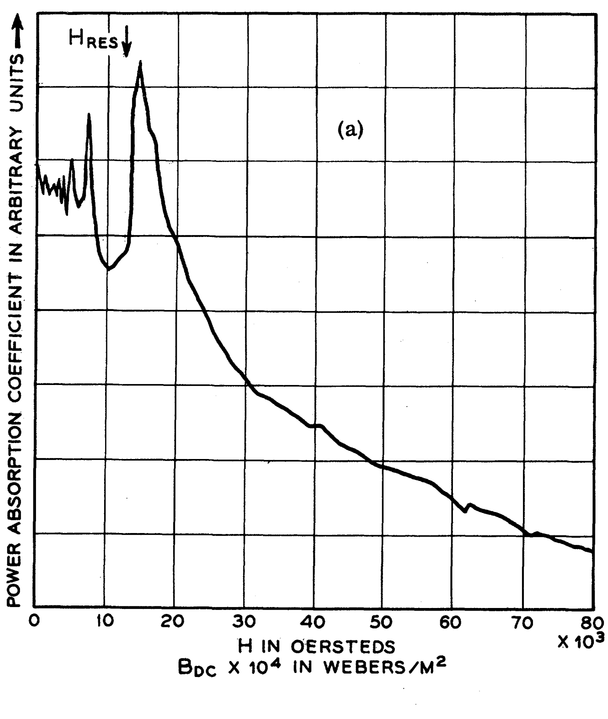
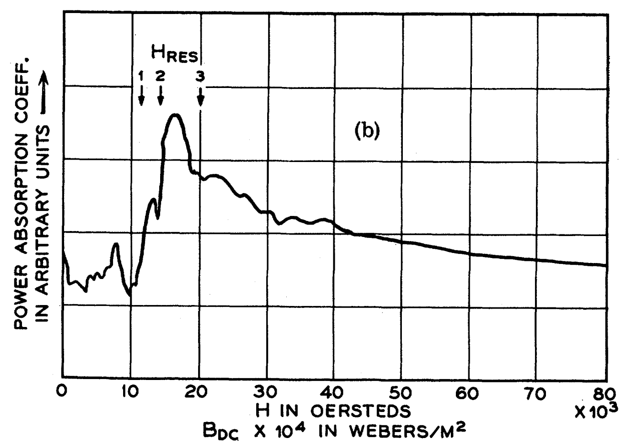
We have observed cyclotron resonance effects in single-crystal samples of cadmium at 1.3°K, or below, and at both 24 000 Mc/sec and 72 000 Mc/sec. We have done the experiment with the magnetic field, B_{dc}, along each of the three principal axes [⟨0001⟩, ⟨11$\bar{2}$0⟩, and ⟨10$\bar{1}$0⟩] and with it both parallel and perpendicular to the sample surface in each case. The effective masses observed range from 0.35 to about 1.5, and are somewhat similar to those observed in zinc, for which preliminary results have previously been reported.[1,2]

The experiments were done using a technique previously reported,[3] and will, therefore, be described only briefly. The crystallographically oriented plane surface of a disk sample is made to form part of the wall of a cylindrical cavity, and a signal proportional to the variation in the power absorption coefficient of the sample surface is observed as a function of applied magnetic field. The radiation incident on the sample is substantially circularly polarized; the part of the radiation with the undesired circular polarization is 15%, or less, in power density of that with the desired circularity.

Single-crystal boules of cadmium were grown from zone-refined raw material in vacuum, using the Bridgman method. Samples cut from these boules showed residual resistance ratios $[R_{300°K}/R_{4.2°K}] \cong 30\,000$. The boules were oriented by means of x-ray techniques, and disk-shaped samples were then cut from them with an acid string saw.

Figure 1(a) shows data taken with B_{dc} along the ⟨10$\bar{1}$0⟩ twofold axis and parallel to the sample surface. Two signals are observed. One is a well-resolved oscillation of the Azbel'-Kaner type[4] whose resonance field corresponds to an





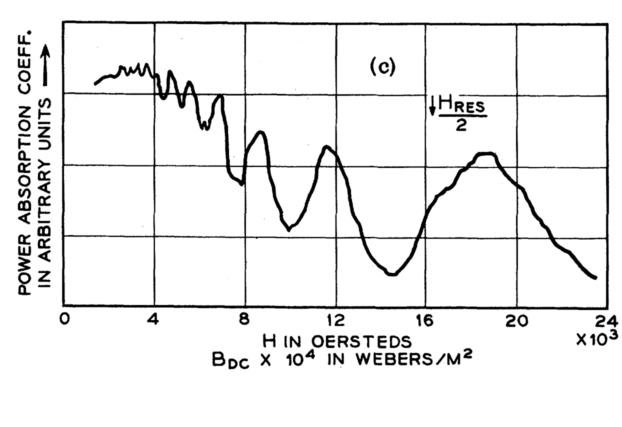


FIG. 1. Cyclotron resonance data at 72 000 Mc/sec and 1.3°K for cadmium. (a) B_{dc} parallel to plane of sample and along a ⟨10$\bar{1}$0⟩ twofold axis; (b) B_{dc} parallel to plane of sample and along a ⟨11$\bar{2}$0⟩ twofold axis; (c) B_{dc} parallel to plane of sample and almost precisely along the ⟨0001⟩ axis.

effective mass $m^* = (0.51 \pm 0.02)m_0$. The other is a much broader signal which suggests to us the presence of a distribution of effective masses which begins at about $m^* = 0.35\, m_0$ and goes up to $m^* = 0.6\, m_0$ and perhaps further.

Figure 1(b) shows data taken with B_{dc} along the $\langle 11\bar{2}0\rangle$ twofold axis and parallel to the sample surface. Here three signals of the Azbel'-Kaner type are discernible, and there is some evidence for an additional signal from a distribution of masses which extends up from about $0.7\, m_0$. The three oscillatory signals interfere with each other so that relatively few harmonics are resolved, but the fundamental resonance fields indicated by arrows in Fig. 1(b) give effective masses $m^* = (0.40 \pm 0.02)m_0$, $m^* = (0.51 \pm 0.02)m_0$, and $m^* = (0.76 \pm 0.04)m_0$.

The data obtained with B_{dc} near the $\langle 0001\rangle$ axis and parallel to the sample surface show great anisotropy. When B_{dc} is sufficiently close to $\langle 0001\rangle$, one oscillatory signal corresponding to a mass $m^* = (1.23 \pm 0.05)m_0$ occurs. Data at the lower magnetic fields corresponding to this condition are shown in Fig. 1(c), although even here the presence of a second signal can be detected. As B_{dc} deviates from $\langle 0001\rangle$, three signals occur; one shows masses which increase rapidly to $1.5\, m_0$ in a degree or so, suggesting that open orbits occur at larger angles, one continues to show a mass near $1.25\, m_0$, and the third shows masses which drop slowly to around $1.1\, m_0$ when B_{dc} is about 8 degrees from $\langle 0001\rangle$.

Figure 2 shows data obtained with B_{dc} along the $\langle 11\bar{2}0\rangle$ axis and normal to the sample surface. These data are obtained under anomalous skin effect conditions, and a satisfactory detailed theory is not available. Nevertheless, a general increase in absorption occurs at the higher fields, and we conclude that the relevant charge carriers are electrons, since this absorption is so much stronger on the side for which electrons resonate (fields labeled negative). The other outstanding feature of the data is a sharp change in absorption which occurs at the field for resonance of carriers of $m^* = 0.51\, m_0$. A smaller but similar change occurs at half this field. This signal is not well understood, but is now thought to be associated with the presence of a group of minority electrons. It has also been suggested that it is a conduction electron spin resonance.[2] A similar effect is observed when this experiment is done with B_{dc} parallel to $\langle 10\bar{1}0\rangle$, but not when B_{dc} is parallel to $\langle 0001\rangle$. We do not show other data observed with the field normal to the sample surface for lack of space.

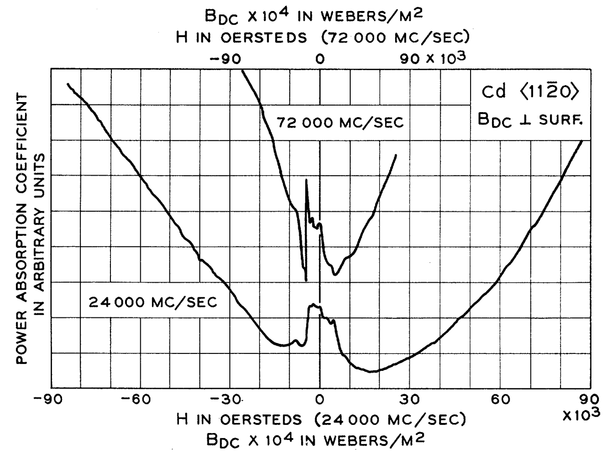


FIG. 2. Cyclotron resonance data at 72 000 Mc/sec and 24 000 Mc/sec at 1.3°K for cadmium with magnetic field normal to sample surface and along a $\langle 11\bar{2}0\rangle$ twofold axis. Field scales are adjusted so that cyclotron resonance fields for both curves are on the same vertical line. Electrons resonate on the negative-field side of the figure, holes on the positive-field side.

Harrison[5] has proposed an approximate band structure in cadmium in which the hole band has a complicated shape which might give rise to the distribution of masses indicated by some of our data, and in which the electron band has discrete sections which might give rise to the discrete masses observed here when B_{dc} is along one of the twofold axes, especially since Fig. 2 indicates that these masses are electrons. More detailed comparisons lead to some difficulties, and it seems likely that two of the signals observed with B_{dc} near $\langle 0001\rangle$ are associated with holes. Quantitatively, Harrison predicts an effective mass $m^* = 0.14\, m_0$ which we do not observe. Berlincourt[6] observes such a mass from temperature dependence of the de Haas–van Alphen effect. We are not able at present to understand the discrepancy between this result and ours; we have done experiments near the orientation mentioned by Berlincourt and failed to see such a resonance. We expect to continue this work with a view toward resolving these problems.

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SUPERCONDUCTING TUNNELING ON BULK NIOBIUM

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Superconducting tunneling experiments on bulk niobium-niobium oxide-lead film sandwiches indicate that the energy gap in bulk niobium is about $3.6\,kT_c$ which is in good agreement with the Bardeen-Cooper-Schrieffer[1] theory.

If two metals are separated by a thin dielectric (50 A), then a potential applied across them results in a current due to electron tunneling. Recent experiments by Giaever[2,3] and Nicol, Shapiro, and Smith[4] have shown that if either or both of the metals are superconducting films, then the tunneling current depends strongly upon the superconducting density-of-states functions. These experiments have provided direct measurements of superconducting energy gaps in films. Bardeen[5] has shown that the dependence of tunneling current on density of states for superconductors can be deduced if tunneling is treated as a many-particle problem.

In the present experiment, plates of commercial grade niobium were mechanically polished and then annealed at 1800°C in vacuum for about six hours. The residual gas pressure during annealing was about 10^{-5} mm Hg for some samples and about 5×10^{-7} mm Hg for others. This annealing procedure was adopted after early experiments on niobium not so treated indicated that the niobium was not superconducting at the surface.

These niobium plates were painted with collodion leaving a narrow unpainted strip at the center. Lead films were evaporated onto these substrates so that they crossed the unpainted strip at right angles, providing a region where the films were separated from the niobium only by the thin niobium oxide which had grown in air. The area of these junctions ranged from 2 mm^2 to 10 mm^2. Using an ammeter and a vacuum tube voltmeter, the tunneling current for these junctions was measured as a function of voltage.

Figure 1 shows the I vs V trace for a typical junction at 4.2°K. The niobium used for this sample was annealed in 5×10^{-7} mm Hg and was polycrystalline with crystallite sizes ranging from 0.2 mm to 1.5 mm across as evidenced by

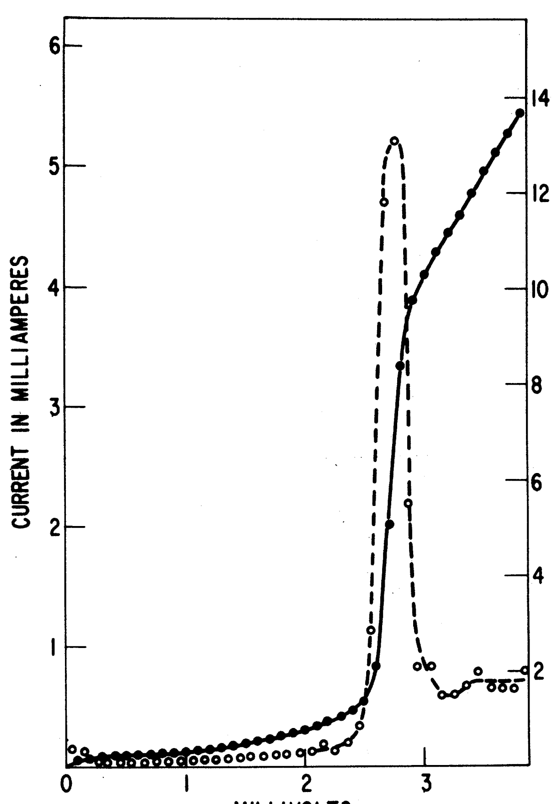

FIG. 1. The solid curve shows the current-voltage characteristic for a typical niobium-lead tunneling junction at 4.2°K. The dashed curve is the first difference ($\Delta I/\Delta V$) of the solid curve. The error in $\Delta I/\Delta V$ increases by a factor of ten over 1 ma.