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Cyclotron Resonance in Cadmium Telluride*

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Cyclotron-resonance experiments were carried out on cleaved samples of high-purity *n*-type CdTe at liquid-helium temperatures and a frequency of 70 Gc/sec. A single well-defined resonance line believed due to electrons was observed under photoexcitation. Rotation of the magnetic field in the (110) plane showed no evidence for anisotropy. An electron effective mass of $m_p=(0.096\pm0.005)m_e$ was obtained. The cyclotron-resonance photosensitivity-versus-wavelength spectrum was found to peak strongly in the vicinity of the direct exciton transition. These results provide data not only for the value of the effective electron mass, but also for additional empirical evidence demonstrating the single-valley behavior of the conduction band of CdTe.

I. INTRODUCTION

CADMIUM telluride is generally believed to be a direct band gap material having a conduction band of standard form. As early as 1955, Herman[1] surmised that the band structure of CdTe is similar to that of InSb, which has been shown to be isotropic. Optical experiments have been described which support this point of view. For example, low-temperature luminescence has been observed[2,3] very close (<0.005 eV) to the direct exciton peak which occurs at 7778 Å (1.595 eV). Recently, absorption constant data on high-purity crystals have been unambiguously interpreted in terms of direct transitions.[4] An electron effective mass of the order of $m=0.1\ m_e$, where m_e is the free electron mass, has been used to analyze this optical work.

A similar value of conduction band mass was determined by analyzing certain free carrier and electron transport measurements. For example, Marple[5] was led to a value of $m/m_e=0.11\pm0.01$ from free carrier Faraday rotation experiments and from the contribution of these free carriers to the dielectric susceptibility. His analysis was based on the assumption of a simple band shape. Segall, Lorenz, and Halsted[6] also used a simple band shape and effective mass of the order of 0.1 to interpret Hall mobility data in the temperature range where optical mode scattering predominates. Theoretical estimates[7,8] of the conduction band mass have been based upon the assumption that the band minimum lies at $\mathbf{k}=0$. Again these calculations yield the result that $m/m_e=0.1$, although this is probably not a highly accurate figure. It would be interesting to have an independent and accurate determination of the mass such as provided by cyclotron resonance.

In spite of the evidence in favor of a direct band gap, there have been several attempts to interpret experiments on CdTe in terms of anisotropic bands and indirect transitions. In 1960, Davis and Shilliday[9] observed the spectral dependence of the optical absorption constant and concluded that indirect transitions occur, beginning at photon energies about 0.1 eV less than the direct transition energy. Similar results have appeared in the literature very recently.[10] It should be pointed out that these absorption measurements are not in agreement with the very careful work previously cited (Ref. 4). Magnetoresistance measurements on *n*-type CdTe [11] have been interpreted in terms of a many-valley conduction band with minima along the ⟨111⟩ directions. Such measurements are quite difficult to carry out at low temperatures and it is possible that contact problems influenced the results, as has been suggested by others.[6]

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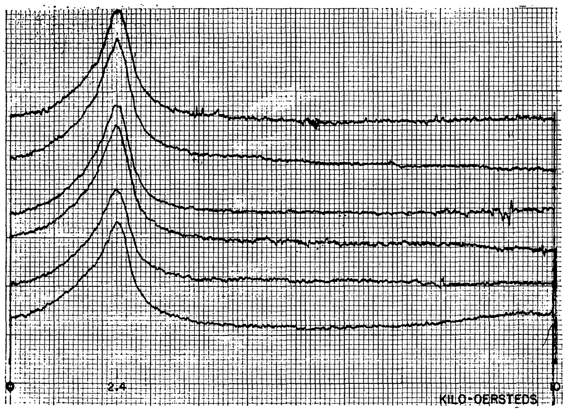

FIG. 1. Cyclotron resonance scans for different directions of magnetic field, reproduced directly from the *X-Y* recorder chart. Changes in the power reflected from the sample cavity are plotted as a function of the magnetic field.

In the present work, the technique of cyclotron resonance was used to accurately determine the conduction band mass and to dispel any lingering doubts about the band isotropy. An isotropic resonance line was observed, although it was necessary to work at a very high frequency (70 Gc/sec) and a low temperature (4.2°K) in order to have well-defined resonance lines with $\omega\tau \gtrsim 2$. The linewidths observed for dark carriers are roughly what one expects from extrapolated electron mobility data. However, with photoexcitation, the linewidths at 4°K depend somewhat on the intensity of illumination.

II. EXPERIMENTAL

A simple reflection-type spectrometer was employed using an Amperex DX-151 reflex klystron as a source of microwave power at a frequency of 70 Gc/sec. The klystron was frequency stabilized on the sample cavity, and the frequency was measured with an absorption-type wavemeter. The tunable sample cavity located at the terminus of a waveguide was operated in the TE_{01n} mode, with n variable between two and four.[12] The power reflected from the cavity was monitored by a bolometer detector.[13] Photoexcitation of carriers at a 142-cps rate was accomplished by illuminating the sample with an AH-6 high-pressure mercury arc lamp, driven by a 71-cps motor-generator. In addition a microwave chopper was incorporated in the guide arm feeding the bolometer to make possible the detection of steady reflected power and losses due to dark carriers. The chopper was, of course, inoperative during photocarrier measurements. A phase sensitive, lock-in system was used to amplify and detect the ac signal components from the bolometer. The magnetic field was produced by a 12-in. electromagnet, and was measured with a calibrated rotating coil gaussmeter. Plots of the changes in reflected power as a function of the magnetic field were obtained directly on an *X-Y* recorder.

The high-purity samples of CdTe were similar to those used in recent transport measurements.[14] They were n-type single crystals, having donor densities of the order of 10^{15} cm^{-3} and Hall mobilities in excess of 5×10^4 cm^2/V-sec at low temperature. A fresh sample was cleaved for each run, and was mounted in the cavity on a nylon support. In most cases the samples were in the form of thin circular disks with diameters about a third of the cavity inside diameter which was 0.250 in. The electric field lines lay in the plane of the disks, insuring an unfavorable geometry for surface depolarization effects.

The cavity and waveguide system were enclosed in a Pyrex jacket into which a small amount of helium gas was admitted for heat exchange purposes. The cavity temperature was monitored with a gold-cobalt: normal silver thermocouple.[15] The radio-frequency power incident on the cavity was increased to a point where a noticeable change in the resonance line shape was observed. Then the power level used for measurements was reduced to values always less than half this value. At this upper limit in power, the electric field in the sample was estimated to be less than one V/cm.

III. RESULTS

Each photocarrier scan was compared to the line shape predicted by the simple theory for cyclotron

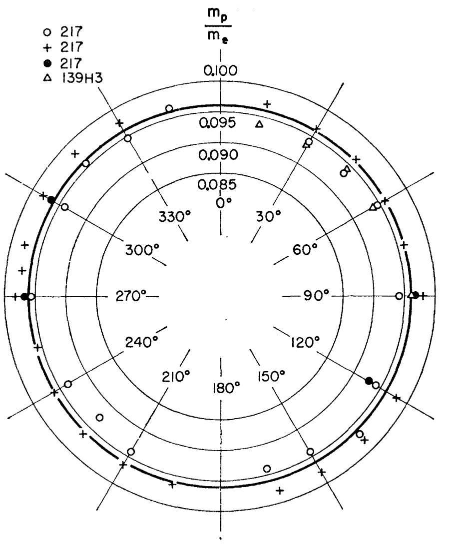

FIG. 2. A polar plot of the effective electron mass as measured by cyclotron resonance. The angle indicates the direction of the magnetic field with respect to an arbitrary fiducial axis in a (110) plane of the sample. Note that the radial scale is expanded in the vicinity of 0.095.

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[12] R. Beringer, in *Technique of Microwave Measurements*, edited by C. G. Montgomery (McGraw-Hill Book Company, Inc., New York, 1947), Radiation Laboratory Series, Vol. 11.

[13] TRG Inc., Boston, Massachusetts.

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[15] R. L. Powell, M. D. Bunch, and R. J. Corruccini, in *Cryogenics* (Heywood and Company Ltd., London, 1961), Vol. 1, No. 3.

resonance. Those appearing to have $\omega\tau \gtrsim 2$ as judged by linewidth, were used to determine the electron effective mass. A few of the scans used for this purpose are shown in Fig. 1. The magnetic field at the absorption maximum was taken to be the resonance field and the mass calculated in the usual way. These measurements yielded the mass value $m_p/m_e = 0.096 \pm 0.005$, where m_p is the polaron mass. This value must be corrected for the polar coupling of the electron to the lattice. Using the relation $m_p = m(1+\alpha/6)$, where the coupling parameter α has the value about 0.4,[6] the resulting band mass $m/m_e = 0.090$ is to be compared with previous mass determinations.

For the mass isotropy study, magnetic field scans were taken at various directions of the magnetic field in the (110) cleavage plane of the sample. The resulting mass values all lie within the experimental uncertainty near the circle whose radius is $m_p/m_e = 0.096$. It is concluded that the mass behaves isotropically, as expected from the band model having its minimum at $\mathbf{k} = 0$.

Since a somewhat unconventional cavity geometry was used, it was felt necessary to demonstrate that the observed phenomena did indeed arise from crossed **E** and **H** fields and corresponded to electric dipole transitions. This was demonstrated as follows. In most of the cyclotron resonance scans using the TE_{01n} cavity (circular disk geometry) with magnetic field in the plane of the disk, a constant background absorption proportional to $[1+(\omega\tau)^2]^{-1}$ is found as discussed elsewhere.[16,17] This effect is due to the components of the electric field which are parallel to the magnetic field. By placing elliptical disks in the cavity, as shown in Fig. 3, the electric field lies predominantly along the major axis of the ellipses. Rotation of the magnetic field in the plane of the figure gives rise to a peak resonance loss which, when corrected for the small component of **E** along the minor axis, should vary as $\sin^2 \times(\theta-\pi/2)$. Figure 3 shows this dependence and gives assurance that the resonance phenomena observed in these experiments arose from crossed **E** and **H** fields.

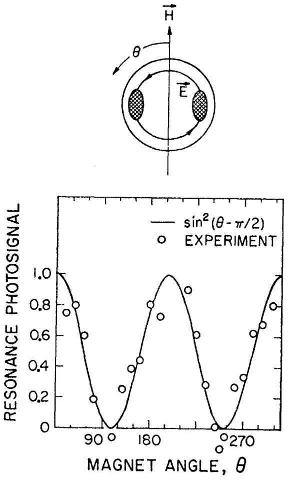

FIG. 3. Upper part: A schematic illustration of the sample geometry used to obtain the data plotted in the lower part of the figure. Lower part: The resonance photosignal as a function of the direction of the magnetic field with respect to an axis in the (110) plane of the sample.

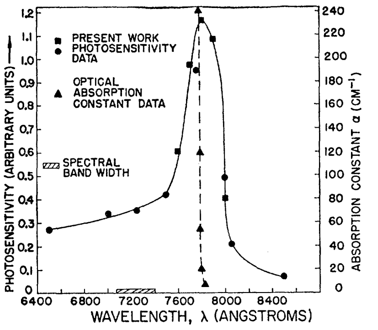

FIG. 4. The cyclotron-resonance photosensitivity at millimeter wave frequencies of CdTe as a function of the wavelength of illumination. Recent absorption coefficient data $\alpha(\mathrm{cm}^{-1})$ for high-purity samples are shown by the dashed line and the right-hand scale (Ref. 4).

Since the Hall mobilities for these samples were known from the work of Segall, Lorenz, and Halsted, it would seem that a clue to the carrier identity could be established by comparing these transport mobilities to the mobilities determined from the width of cyclotron resonance lines. However, effects of the illumination intensity and wavelength on the resonance line shape were observed and tend to make the photocarrier scans unsuitable for such a comparison. For this reason, a comparison was made using dark carrier scans. These scans showed an $\omega\tau$ in the range 0.5 to 0.9, as judged by comparing the observed line shape with a simple, constant τ theory. These dark carrier scans were consistent with the assumption of a mass $m_p/m_e = 0.096$, showing not only the broadening due to the lower $\omega\tau$, but also the shift in the loss maximum to smaller values of H. The fact that dark carrier scans were possible on n-type samples, yielding mass values compatible with the photocarrier scans argues for the identification of the carriers as electrons.

Moreover, using a value of $\omega\tau = 0.7$ for the dark carrier scans, a microscopic mobility of $\mu = (c/H)\,\omega\tau = 3\times10^4$ cm^2/V-sec can be calculated. A linear extrapolation of the low-temperature data of Lorenz and Halsted to $T = 4.2$°K yields a value $\mu_H \sim 1\times10^4$ cm^2/V-sec. This order of magnitude agreement provides further evidence that the carriers involved were electrons.

The cyclotron resonance lines observed at 4.2°K under photoexcitation at high light intensity were narrower than the dark carrier resonances. A study of this effect indicates that it is not due to plasma resonance. It is suggested that steady illumination produces neutral donors and acceptors and consequently fewer charged scattering centers as found in exciton work on the II-VI compounds.[18]

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[17] G. Ascarelli, in *Polarons and Exciton*, edited by C. Kuper and G. D. Whitfield (Oliver and Boyd, Edinburgh, England, 1963).

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In order to obtain the cyclotron resonance photosensitivity excitation spectrum, a Bausch & Lomb grating monochromator was inserted into the light beam. The microwave photosignal was recorded as a function of light wavelength at high magnetic field ($\omega_c/\omega\sim 4$), well away from cyclotron resonance. These data, corrected for the wavelength dependence of the exciting light, are shown in Fig. 4. A few points representative of Marple's data[4] on optical absorption for high-purity samples are also shown. It is seen that, in spite of a rather poor spectral bandwidth, the photosensitivity data peaks strongly in the vicinity of the direct exciton transition at 7778 Å. Cyclotron-resonance scans were taken for each of the points shown in Fig. 4. These scans were consistent with the electron effective mass and $\omega\tau$ discussed above except in the case of the very low level long-wavelength response (wavelengths greater than 8000 Å) which did not show appreciable magnetic field dependence. This long-wavelength behavior was checked by removing the monochromator and instead inserting a 0.050-in. thickness of CdTe as a filter. These scans also did not exhibit a discernible magnetic field dependence.

IV. CONCLUSIONS

Cyclotron resonance has been observed in CdTe at 4.2°K and is almost certainly due to electrons. The measured electron effective mass value was $m_p/m_e = 0.096\pm 0.005$, in fair agreement with values reported previously. By rotation of the magnetic field in the (110) plane of the crystal the mass was found to be isotropic in agreement with a conduction band of standard shape with a minimum at $\mathbf{k}=0$. The resonance due to dark carriers in *n*-type samples of CdTe was also observed and linewidths in approximate agreement with mobility results were obtained. The cyclotron resonance photosignal was observed as a function of wavelength and a strong peak was found in the vicinity of the direct exciton transition.

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