PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PHYSICS OF SEMICONDUCTORS, KYOTO, 1966
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 21, SUPPLEMENT, 1966

V-8. Cyclotron Resonance in Tellurium at Submillimeter Wavelengths†

J. C. PICARD* and D. L. CARTER

Laboratoire de Physique de l'Ecole Normale Supérieure, Paris, France

Magneto-transmission experiments in the Voigt configuration at wavelengths from 730 to 940 μ have been performed on Te single crystals with 2-3$\times 10^{13}$ carriers cm^{-3} and $\mu=5\times 10^4$ cm^2/V sec at 4.2°K, using carcinotron fundamental sources.

The observed cyclotron resonances were fit by a single mass ellipsoid of revolution about the *c*-axis with $m_1=m_2=0.109\,m_0$, $m_3=0.264\,m_0$. An anisotropy in the relaxation time was deduced from the curve shapes which agrees with earlier transport measurement.

§ 1. Introduction

We have developed an experimental method which allows us to observe cyclotron resonance at submillimeter wavelengths and liquid helium temperatures. Operating at wavelengths between the usual microwave spectrometers which currently work down to 2 mm and optical set-ups, it combines elements of both techniques and permits the observation of cyclotron resonance in samples of moderate mobility. At $\lambda=4$ mm (70 Gc/s) for a carrier of effective mass $0.1m_0$ the magnetic field at resonance is $\simeq$3000 gauss and a high resolution ($\omega\tau=\mu B\gtrsim 5$) is realized for samples having mobilities of 170,000 cm^2/V sec. At $\lambda=500\,\mu$ (600 Gc/sec) the required mobility for the same resolution is only 20,000 cm^2/V sec.

Thus short wavelengths are very useful in a study of the cyclotron resonance of Te; samples of high mobility are pathologically sensitive to strains and successive coolings. We have found reproducible results of measurements of effective mass in Te and conclude, as did Mendum and Dexter,[1] that the maximum of the valence band has the shape of an ellipsoid of revolution and have been able to exhibit an anisotropy of the relaxation time.

§ 2. Experimental Set-Up

Successively using three different carcinotrons made by C. S. F., we have performed experiments in the wavelength bands 500-600 μ, 700-800 μ and 900-1000 μ. In Fig. 1 the power output of one of these tubes is shown as a function of carcinotron line voltage and wavelength. The maximum power output is approximately 20 mW. The high voltage power supply for the line voltage is stabilized to 2×10^{-5}. The wave is propagated through an oversized waveguide (a) in Fig. 2, generally a 4 mm guide or a circular tube. The carcinotrons are mounted on a mobile support which enables the polarization direction of the R. F. electric field to be rotated relative to sample crystal axes and magnetic field direction. Using an electromagnet external to the cryostat, fields transverse to the wave-guide (Voigt configuration) up to 28,000 gauss can be applied. Another system which utilizes a superconducting solenoid allows us longitudinal fields (Faraday configuration) up to 60,000 gauss. For transmission experiments, as shown in Fig. 2a, the power transmitted through the sample (b) is detected by bolometer (c) which is in thermal contact with the helium bath (d) and located in

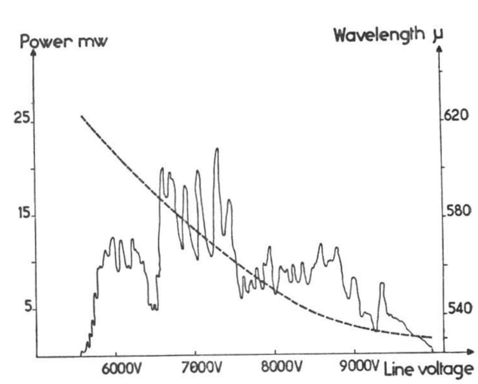

Fig. 1. Power output of carcinotron CO 05 as a function of line voltage and λ.

† Partly supported by the European Office of Aerospace Research (grant AFEOAR 6545).

* Ce travail recouvre partiellement le travail de these de Doctorat d'Etat es Sciences Physiques devant être soutenu a la Faculté des Sciences de Paris en 1966 et enregistré au C. N. R. S. sous le numero 432.

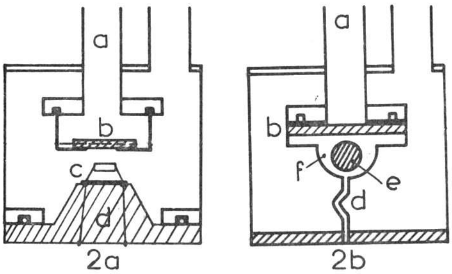

Fig. 2. The experimental arrangements.

a vacuum chamber. In another system (Fig. 2b) sample absorptivity is determined by measuring the sample temperature rise with bolometer (e) shielded (f) from microwaves and in good thermal contact with the sample. Detectors used are carbon resistors at 1.6°K and Ga doped Ge at 4.2°K.

The samples of Te used had mobilities of the order of 50,000 cm^2/Vsec and 2–3$\times 10^{13}$ carriers cm^{-3} at 4.2°K. Samples were small pieces approximately $2\times 4\times 1.5$ mm large.

§ 3. Propagation Conditions

Since the experiments described here on Te were performed in the Voigt configuration we now consider the problem of propagation in this geometry, (Fig. 3). Magneto propagation theory[2] assuming classical skin effect conditions, isotropic mass and relaxation time τ, gives the following expressions for the propagation constants:

$$k_0{}^2=(\omega/c)^2\varepsilon_{/\!/} \quad \text{(ordinary wave)}, \tag{1}$$

for the electric field E polarized along the magnetic field B and

$$k_e{}^2=(\omega/c)^2(\varepsilon_\perp{}^2+\varepsilon_\times{}^2)\varepsilon_\perp{}^{-1}\equiv(\omega/c)^2\varepsilon_e, \tag{2}$$

(extraordinary wave)

for $E\perp B$, where

$$\varepsilon_\perp=\varepsilon_l+\frac{\omega_p{}^2}{i\omega}\left[\frac{i\omega+\tau^{-1}}{(i\omega+\tau^{-1})^2+\omega_c{}^2}\right],$$

$$\varepsilon_\times=\frac{i\omega_p{}^2}{\omega}\,\frac{\omega_c}{(i\omega+\tau^{-1})^2+\omega_c{}^2},$$

$$\varepsilon_{/\!/}=\varepsilon_l-\frac{\omega_p{}^2}{\omega^2}[1-i(\omega\tau)^{-1}]^{-1},$$

where $\omega_p{}^2=4\pi ne^2m^{*-1}$, ω the operating frequency, ω_c the cyclotron frequency and ε_l the lattice dielectric constant.

In the experiments performed on Te $\omega_p<\omega$ and therefore $k_0>0$. Hence, the ordinary wave propagated but gave rise to no cyclotron resonance as there were no tilted orbits.[2] For the extraordinary wave $E_x/E_y=\varepsilon_\times/\varepsilon_\perp\ll 1$ in the experimental conditions, hence there were no screening, longitudinal waves and resonance in k_e occurs for $\omega_c=\omega$. Since under these conditions the variation of the real part of k_e is quite small, the experiment was best carried out by measuring the total transmission. Experimental effects due to standing waves in the sample were observed. These were interpreted theoretically by calculating the power transmission coefficient for an infinite dielectric slab of thickness l,

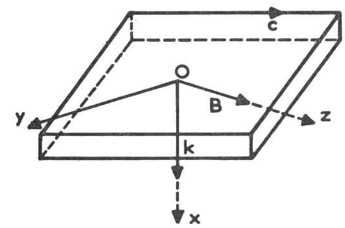

Fig. 3. Orientation of magnetic field and rf electric field in experiments.

$$T=4|2\cos k_el+i(kk_e{}^{-1}+k_ek^{-1})\sin k_el|^{-2}\cdots \tag{3}$$

where k_e is given by eq. (2) and $k=\omega/c$. Equation (3) was computed by machine as a function of four parameters $\alpha=(\omega_p\tau)^2$, $\beta=\omega\tau$ $\gamma=2\pi l/\lambda$ where λ is the free space wavelength and ε_l which was chosen to be 23.6 for $E\perp c$ and 39.7 for $E||c$.[3] The results of calculation are given in Fig. 4 and correspond to $\alpha=1.63$ with $\beta=6$ and a thickness of 1.6 mm.

A small variation in γ approximately corresponds to a small variation of ω. The curve in Fig. 4 ($\gamma=10.32$) which corresponds to approximately 18 half wavelengths in the sample

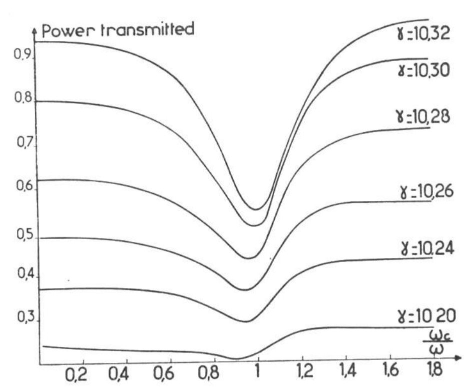

Fig. 4. The results of theoretical calculation of transmission as a function of magnetic field and γ as parameter.

has a nearly pure absorption shape and the total transmission is large. As γ is varied from 10.32 the dielectric effects are magnified by the standing waves and give rise to a diminution of total transmission, a change in shape of the curve and a shift in the minimum of transmission from $\omega_c=\omega$ to different B fields. The transmission has been studied theoretically as a function of carrier density and the periodicity in γ and suggests it will be experimentally possible to measure ε_l and its anisotropy. The values for ε_l used in the calculation are those obtained at $\lambda=6\,\mu$.[3]

§ 4. Experimental Results

The transmission experiments on Te were made for λ between 730 to 940 μ; some results are shown in Fig. 5. Recordings A, B and C

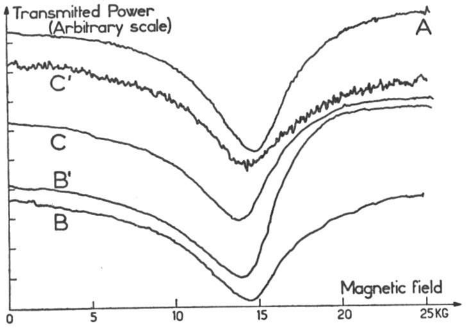

Fig. 5. Experimental transmission records for $\lambda=930\,\mu$ for various different angles of B in a parallel sample (curves A, B, C). B' and C' records are made at the same orientations as B and C but frequency was different by $\sim 0.1\%$.

were made for three different orientations of B in the plane formed by the trigonal (c) and binary axes, ($\equiv$ parallel sample). Recordings B' and C' were made for the same corresponding orientation as in B and C but with the frequency shifted by a few tenths of a percent. The minimum of C' has shifted to higher field and, that of B' to lower field while both curves are distorted from a pure absorption shape. The effective mass deduced from a distorted curve like B' was corrected by comparison with the theoretical curve corresponding to its particular shape. The estimated error in mass due to this procedure is 2%. The effective masses taken from the records for parallel samples and perpendicular samples (B always $\perp c$) are shown in Fig. 6. A single effective mass appears in the results. To within the spread of data for

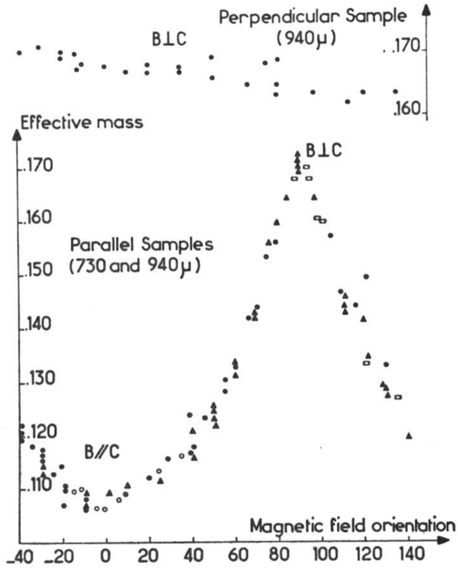

Fig. 6. Experimental cyclotron mass as a function of crystal angle deduced from experiments.

a perpendicular sample one deduces, as was found by Mendum and Dexter,[1] that the valence band maximum can be represented by an ellipsoid of revolution about the c-axis. Thus these ellipsoids probably occur at points M and P in the Brillouin zone according to Hulin.[4] The constants for the mass ellipsoids were found to be

$$m_1=m_2=0.109m_0\pm 0.003m_0$$
$$m_3=0.264m_0\pm 0.008m_0\,.$$

When the magnetic field was along the binary direction, a deformation of the transmission records appeared at low B and is shown in Fig. 7. This might be interpreted as due to a warping of the ellipsoid and a further account of this will be given elsewhere.

The $\omega\tau$ of the experimental cyclotron reso-

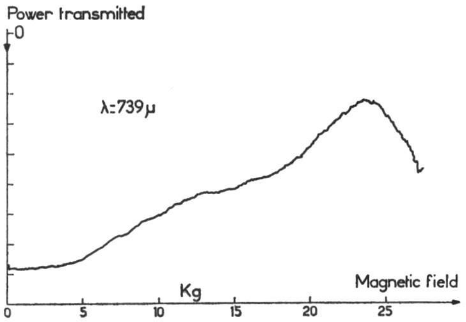

Fig. 7. A deformed resonance curve for B near the binary axis.

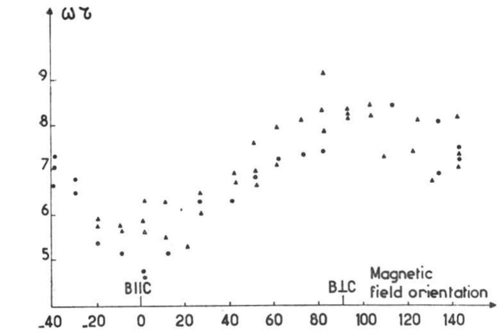

Fig. 8. $\omega\tau$ as a function of the direction of B for a parallel sample obtained from the experimental curve shapes.

nance curves was extracted theoretically by comparison with calculated curves. The $\omega\tau$ as a function of magnetic field direction in a parallel sample is shown in Fig. 8. If one uses the mean of the points to get the anisotropy in τ, one finds that the ratio of $\tau_{\text{cyclotron}}$ $\perp c$ to that $//c$ is 3/2. If one assumes a τ tensor corresponding to an ellipsoid of revolution, then these results predict $\tau_{33} \cong 3\tau_{11} = 3\tau_{22}$ which is in accord with the theoretical τ ratio 2.29 of Dubinskaya and Farbshtein.[5] The spread in points is quite large and one should regard the result with caution. However, if one takes the ratio $\sigma_{33}/\sigma_{11} = (\tau_{33}m_1)/(\tau_{11}m_3)$ of the *dc* conductivity one gets 1.24 as a result using our τ ratio and cyclotron masses which agrees with the experimental value of 1.25 ± 0.15 of Parfen'ev *et al.*.[6]

Acknowledgements

We would like to thank Profs. P. Aigrain and J. Bok for their guidance, Messrs. H. Thomé and B. Delmas for their help in the experiments, Messrs. Convert and Yeouta of C. S. F. for their cooperation, Dr. Y. Kossitchkin and Prof. S. S. Shalyt of the U. S. S. R. Academy of Sciences for the high purity samples and Texas Instruments for the Ge-Ga bolometer assemblies.

References

1) J. H. Mendum and R. N. Dexter: Bull. Amer. Phys. Soc. **9** (1964) 632.
2) G. E. Smith, L. C. Hebel and S. J. Buchsbaum: Phys. Rev. **129** (1963) 154.
3) R. S. Caldwell and H. Y. Fan: Phys. Rev. **114** (1959) 664.
4) M. Hulin: J. Phys. Chem. Solids **27** (1966) 441.
5) L. S. Dubinskaya and I. I. Farbshtein: JETP Letters **2** (1965) 195.
6) R. V. Parfen'ev and A. M. Pogarskii, I. I. Farbshtein and S. S. Shalyt: Soviet Physics —Solid State **4** (1963) 2620.

DISCUSSION

Landwehr, G.: Although our results are not really comparable due to the difference in doping, it might be interesting to note, that both of us see warping in the same section of the constant energy surface, if the second broad line you observed with the magnetic field perpendicular to the trigonal axis is considered as a second harmonic arising from a warped ellipsoid of revolution. Therefore I am inclined to believe that you are dealing with a harmonic and not with a carrier of a different mass.

Picard, J. C.: I agree with you; but our present resolution is inadequate to establish this conclusively. We are now working on samples of higher mobility which should help to clarify the nature of this hump both qualitatively and quantitatively.