

Cyclotron resonance from photoexcited electrons in ZnTe

B. Clerjaud and A. Gélineau

Laboratoire de Luminescence, Université P. et M. Curie, 75230 Paris Cedex 05, France*

D. Galland and K. Saminadayar†

Département de Recherche Fondamentale, Centre d'Etudes Nucléaires, Grenoble, Avenue des Martyrs, Boîte Postale 85, 38041 Grenoble Cedex, France

(Received 23 August 1978)

Electron cyclotron resonance has been observed in ZnTe single crystals (*p*-type semiconductor) at 9.2 and 35 GHz using electron-paramagnetic-resonance equipment. The electrons have been created by illumination of the crystal with light whose energy is larger than the band gap. The signal is isotropic and corresponds to a polaron effective mass $m_p^* = (0.122 \pm 0.002)m_0$. The electron relaxation times are determined from the resonance line shape and the mobility, which is of the order of $10^6 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ at liquid-helium temperature, is deduced. The variation with temperature has been measured.

I. INTRODUCTION

There have been relatively few cyclotron-resonance experiments performed in zinc-blende-structure II-VI compounds. These experiments have been performed mainly on electrons in *n*-type CdTe at millimetric wavelengths^{1,2} and higher frequencies^{3,4} in order to study the polaron coupling. In ZnTe, which is always a *p*-type semiconductor, cyclotron resonance from thermally excited holes has been observed.⁵ This paper describes cyclotron-resonance experiments of photoexcited electrons in ZnTe performed at centimetric wavelengths on samples of high purity.

II. SAMPLES AND EXPERIMENTAL SETUP

The ZnTe single crystals used in these experiments have been grown by B. Schaub LETI (Laboratoire d'Electronique et de Technologie de l'Informatique)-CRM (Centre d'Etudes Nucléaires, Grenoble) using a modified Bridgman method in Te solvent (59.5-at.% Te) in a graphite-coated quartz ampoule. The temperature is 1170 °C and the growth speed is 0.3 mm/h. Mass-spectrographic analysis shows that the concentration of impurities is smaller than 1 ppm for every impurity except Si, 4 ppm, and K, 10 ppm. Capacitance measurements on In-*p*-ZnTe Schottky diodes show that $N_A - N_D$ is in the 10^{15} cm^{-3} range. The samples used in these experiments were unoriented. The crystal is sawed in slices which are mechanically and chemically polished in a solution of bromine in methanol (2%, then 0.2%).

The measurements are made with electron-paramagnetic-resonance equipment. At X-band frequencies (~9.2 GHz) we use a Varian V-4502 EPR spectrometer equipped with a microwave bridge designed in the laboratory.⁶ We use a TE₀₁₂ rec-

tangular microwave cavity in which an ESR-9 Oxford Instruments continuous-flow cryostat is inserted. This cryostat allows measurements between 3.5 K and room temperature. The cryostat is made in such a way that the sample is surrounded by three coaxial quartz tubes; because of the relatively high dielectric constant of quartz (3.8), the cryostat concentrates and bends the microwave electric field lines, so there are components of the microwave electric field perpendicular to the static magnetic field. Our samples being cut as thin slabs, this experimental configuration involves an angular variation of the intensity of the spectra. One of the walls of the cavity is made of a grid allowing light irradiation of the sample.

At Ka-band frequencies (~35 GHz) we use a Varian E-115 EPR spectrometer equipped with a cylindrical cavity resonating in the TE₀₁₁ mode of the type of these described in Ref. 7; this kind of cavity is very convenient for light illumination of the sample. The cavity is immersed in a liquid-helium glass cryostat.

We modulate the magnetic field at 100 kHz and the signal is detected with a phase-sensitive detector; thus we obtain the derivative of the signal.

The irradiation of the sample is carried out with a mercury lamp (Philips S. P. 500) whose light is focused on the sample.

III. RESULTS

When the sample is irradiated with light whose energy is larger than the band gap of ZnTe, a resonance signal is observed in the absorption mode as well as in the dispersion mode. This signal is isotropic (except for the variation of its intensity due to the experimental configuration).

In Fig. 1 the X-band absorption signal at 3.5 K

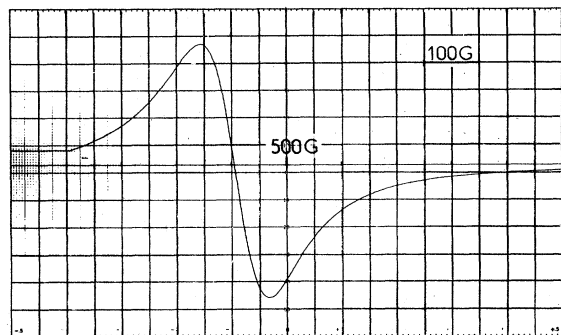


FIG. 1. X-band absorption spectrum at 3.5 K.

$$\frac{\partial P}{\partial B} = \frac{2\omega_c^2 \tau^2 \sigma_0 E^2}{B} \frac{(1 + \omega_c^2 \tau^2 - \omega^2 \tau^2)^2 - 2(1 + \omega_c^2 \tau^2)^2 + 2\omega^2 \tau^2 (2 + \omega^2 \tau^2)}{[(1 + \omega_c^2 \tau^2 - \omega^2 \tau^2)^2 + 4\omega^2 \tau^2]^2},$$

where $\omega_c/2\pi$ is the cyclotron frequency, B is the magnetic field, $\omega/2\pi$ is the microwave frequency, σ_0 is the dc conductivity, E is the amplitude of the microwave electric field, and τ is the relaxation time. In the more realistic case of an electron in a solid, this expression remains the same, but τ becomes a complicated expression⁹ which can be frequency dependent. The fitting of this expression with our experimental spectra at 3.5 K yields $\omega\tau \approx 3.5$. When the temperature increases, the signal broadens out and its dissymmetry becomes more pronounced; when $\omega\tau \leq 1/\sqrt{3}$ the derivative signal does not pass through zero anymore. The electron drift mobility $\mu = e\tau/m_p^*$ can be calculated; $\omega\tau = 3.5$ corresponds to $\mu = 8.5 \times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$. In Fig. 2 we have plotted the variation of τ and μ with temperature. The temperature we measure is the temperature of the helium flow, which can be slightly different from the sample temperature because of its heating by light irradiation. Above 10 K the variation is consistent with the $T^{-3/2}$ law resulting from the lattice scattering by acoustical phonons. At lower temperatures, the scattering by impurities becomes important.

At Ka -band frequencies we observe a cyclotron-resonance signal around 1500 G corresponding to the same effective mass. The signal, corresponding to $\omega\tau \approx 14$, is nearly symmetrical; its width is 125 G at liquid-helium temperature, being slightly narrower than at X band, indicating that the relaxation time is weakly frequency dependent.

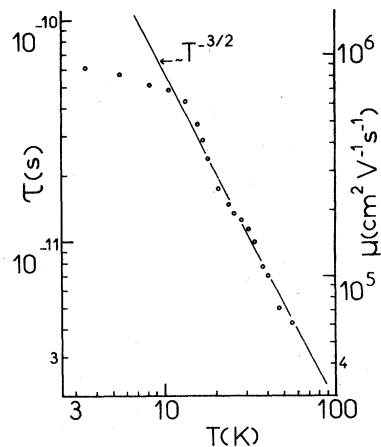
IV. DISCUSSION

There had been several indirect determinations of m_p^* : Riccius and Turner¹⁰ deduced an effective

is represented. The signal is observed around 400 G; its width between the two extrema of the derivative signal is 135 G and independent of the microwave power, incident in the cavity, up to 100 μW ; at higher microwave power the signal is broadened. This signal corresponds to a polaron mass value $m_p^* = (0.122 \pm 0.002)m_0$.

It is possible to deduce the quantity $\omega\tau$ from the line shape. We used the simple line-shape expression obtained for gases, which supposes collision of electrons with neutral gas atoms⁸:

mass of $0.158m_0$ from electroabsorption measurements in ZnTe thin films; from oscillatory photoconductivity experiments, Nahory and Fan¹¹ proposed $0.09m_0$ and Vanacek and Klier¹² proposed $0.107m_0$. Hollis¹³ deduced a large effective-mass value of $0.22m_0$ from exciton energy shifts due to an external magnetic field. Recently, a more direct determination has been performed on identical LETI samples by Dean *et al.*¹⁴ They observed directly optical transitions from the Landau sub-levels, and their results $m_p^* = (0.116 \pm 0.005)m_0$ are consistent with our cyclotron-resonance determination. It should be noted that our experimental value is much smaller than the bare band-edge effective mass ($0.17m_0$ and $0.18m_0$) calculated theoretically by Cardona¹⁵ and Lawaetz¹⁶ by the

FIG. 2. Relaxation time τ and drift mobility as function of temperature.

\vec{k}, \vec{p} . method.

The effective mass we measure is, in fact, the low-frequency polaron mass m_p^* which is related to the bare band-edge effective mass m_B^* by $m_p^* = m_B^*(1 - \frac{1}{6}\alpha + \dots)$ when the electron phonon coupling is not too large (polaron coupling constant $\alpha < 1$).

According to the Fröhlich formula, α should be close to 0.3 for ZnTe. It should be interesting to evaluate more directly α because the Fröhlich formula depends on the static and high-frequency dielectric constants, which are very difficult to determine accurately. Measurements of cyclotron resonance at higher frequencies interpreted with

Larsen's polaron cyclotron-resonance theory^{17,18} should permit a more accurate evaluation of α . In addition, the study of the drift mobility at lower temperatures (< 3.5 K) should give information on the scattering of the electrons by impurities.

ACKNOWLEDGMENTS

We would like to thank Dr. B. Schaub for supplying high-quality ZnTe single crystals, Prof. C. Marti who brought our two groups into contact for that study, and Dr. P. J. Dean who made his results available prior to publication.

*Equipe de Recherche associée au CNRS.

†Also Université Scientifique et Médicale de Grenoble.

¹K. K. Kanazawa and F. C. Brown, *Phys. Rev.* **135**, A1757 (1964).

²A. L. Mears and R. A. Stradling, *Solid State Commun.* **7**, 1267 (1969).

³J. Waldman, D. M. Larsen, P. E. Tannenwald, C. C. Bradley, D. R. Cohn, and B. Lax, *Phys. Rev. Lett.* **23**, 1033 (1969).

⁴C. W. Litton, K. J. Button, J. Waldman, D. R. Cohn, and B. Lax, *Phys. Rev. B* **13**, 5392 (1976).

⁵R. A. Stradling, *Solid State Commun.* **6**, 665 (1968).

⁶B. Clerjaud and B. Lambert, *J. Phys. E* **4**, 619 (1971).

⁷M. Chamel, R. Chicault, and Y. Merle d'Aubigné, *J. Phys. E* **9**, 87 (1976).

⁸B. Lax and J. G. Mavroides, in *Solid State Physics*, Vol. 11, edited by F. Seitz and D. Turnbull (Academic, New York, 1960), p. 261.

⁹G. M. Shmelev, I. A. Chaikovskii, and Ch'ang K'uang Heng, *Fiz. Tverd. Tela (Leningrad)* **19**, 924 (1977) [*Sov. Phys. Solid State* **19**, 538 (1977)].

¹⁰H. D. Riccius and R. Turner, *J. Phys. Chem. Solids* **29**, 15 (1968).

¹¹R. E. Nahory and H. Y. Fan, *Phys. Rev. Lett.* **17**, 251 (1966).

¹²M. Vanecek and E. Klier, *Phys. Status Solidi A* **30**, 441 (1975).

¹³J. F. Scott and R. L. Hollis, *Solid State Commun.* **20**, 1125 (1976).

¹⁴P. J. Dean, H. Venghaus, and P. E. Simmonds, *Phys. Rev. B* **18**, 6813 (1978).

¹⁵M. Cardona, *J. Phys. Chem. Solids* **24**, 1543 (1963).

¹⁶P. Lawaetz, *Phys. Rev. B* **4**, 3460 (1971).

¹⁷D. M. Larsen, *J. Phys. C* **7**, 2877 (1974).

¹⁸D. M. Larsen, *J. Phys. C* **7**, 2890 (1974).