Effective Mass of Electrons in Gallium Arsenide*

L. C. Barcus, A. Perlmutter, and J. Callaway
Department of Physics, University of Miami, Coral Gables, Florida
(Received March 4, 1958)

The effective mass of electrons in a sample of n-type gallium arsenide has been measured by determining the reflectivity in the infrared. The value obtained, $(0.043\pm0.005)m_0$, supports the hypothesis that the minimum of the conduction band is at the center of the Brillouin zone.

INTRODUCTION

MEASUREMENTS of the reflection and absorption of light can provide information concerning the band structures of semiconductors and metals. Recent studies of the optical properties of germanium, silicon, indium antimonide, and indium arsenide[1] in particular, have shown that it is possible to determine the effective mass of electrons in the conduction band. In indium antimonide and indium arsenide, the dependence of the effective mass on carrier concentration, and thus the variation with energy as the band is filled, have also been determined. This note reports an extension of the work of Spitzer and Fan to the case of n-type gallium arsenide.

The basic idea of this work is to determine the contribution of the free carriers to the dielectric susceptibility of the material. The dielectric susceptibility can be determined from the index of refraction and the absorption coefficient. From the susceptibility, the effective mass of electrons can be determined if the carrier concentration is known. The calculation is independent of the relaxation time provided that $(\omega^2t^2)\gg1$. The formula relating the effective mass of the carriers to the measured index of refraction and extinction coefficient is (in mks units)

$$\frac{m^*}{m_0}=\frac{Ne^2}{m_0\epsilon_0\omega^2}\frac{1}{(X_0+K^2-n^2)}, \tag{1}$$

where N is the carrier concentration, ω the circular frequency of the light, X_0 is the high-frequency dielectric constant, n the index of refraction, and K the extinction coefficient. This formula can be obtained immediately from the results of reference 1. The extinction coefficient K can be related to the linear absorption coefficient, α, by

$$\alpha=4\pi K/\lambda. \tag{2}$$

METHOD

A technique devised by Simon was used in the measurements.[2] It is possible to determine both the index of refraction and the extinction coefficient by measuring the percentage of plane polarized light reflected at two angles of incidence from the surface. A complex index of refraction is substituted into the Fresnel equations. Analytic solution is not practical, so it is necessary to construct tables or a family of graphs giving the percentage of reflection for specific angles of incidence and values of n and k. Such curves for 20° and 70° angles of incidence have been given by Simon.[2] In our case, it was found independently that the extinction coefficient is 0.1 or less throughout the wavelength range investigated. Since the extinction coefficient enters as K^2, it can be disregarded and the necessary computations are considerably simplified.

Measurements were made in the region between 0.78 and 22 microns. A Perkin-Elmer model-13 spectrophotometer was used. Light from the monochromator was polarized by passing through a stack of ten AgCl plates arranged at the polarizing angle. It is estimated that greater than 99% polarization was achieved.

Observations were made at three angles of incidence; 30°, 45°, and 60° for each component of polarization. The gallium arsenide sample was n type and polycrystalline with a carrier concentration $N=6.9\times10^{-17}$ cm^{-3} as determined by a Hall effect measurement. The material from which the sample was cut was furnished by Chicago Midway Laboratories.

RESULTS AND DISCUSSION

In Fig. 1 the index of refraction is shown as a function of wavelength. A least-squares fit was made to the

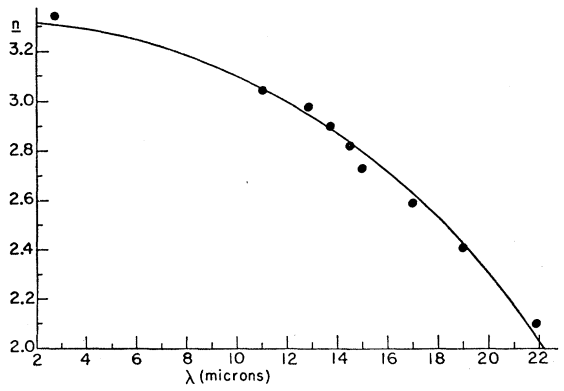

FIG. 1. Index of refraction n as a function of wavelength. The curve is a least-squares fit to the data as described in the text.

* Supported in part by the Air Force Office of Scientific Research and the Office of Naval Research.
[1] W. G. Spitzer and H. Y. Fan, Phys. Rev. **106**, 882 (1957).
[2] I. Simon, J. Opt. Soc. Am. **41**, 336 (1951).

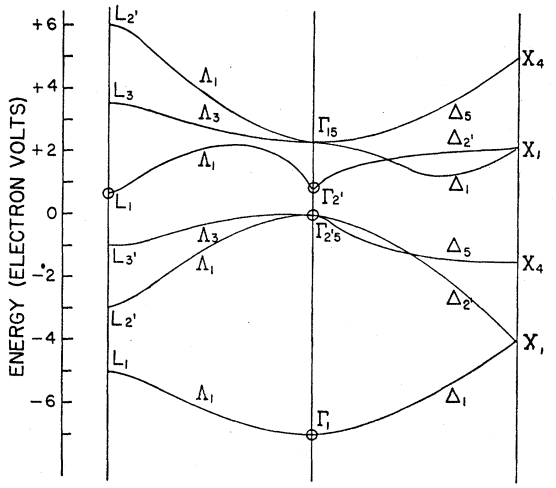

FIG. 2. Band structure of germanium. The curves shown are a synethesis of experimental results and theoretical calculations. The energies of the circled states are known experimentally.

experimental points with an expression of the form

$$n^2 = X_0 - A\lambda^2. \tag{3}$$

The high-frequency dielectric constant X_0 was found to be 11.06 ± 0.14. The value of A was determined to be 0.0143 ± 0.0005. The uncertainties given are one standard deviation in each case.

The quantity m^*/Nm can be found from A after comparison of (3) and (1). It is 6.25×10^{-26}. The mass ratio m^*/m_0 is finally 0.043 ± 0.005. The standard deviation in m^*/m_0 due to scatter of the experimental points amounts to an uncertainty of ± 0.002. Consideration of possible systematic error suggests an over-all uncertainty of ± 0.005. A value of 0.032 was given previously by Barrie *et al.*[3] for a similar carrier density from thermoelectric data. We have made no attempt to determine the variation of effective mass with carrier concentration. Our result can be compared with the effective mass of 0.15 found for germanium by Spitzer and Fan.[1] In the case of germanium, the effective mass determined in this way is an average of the longitudinal and transverse masses pertaining to the ellipsoidal energy surfaces about the face center L in the Brillouin zone. The smaller value of the effective mass in gallium arsenide can be understood as due to a shift of the minimum of the conduction band to the center of the Brillouin zone.

In Fig. 2, the band structure of germanium is shown according to a recent review.[4] The lowest minimum of the conduction band is located at the point L, but there is another minimum at the zone center which is only slightly (0.15 ev) higher. The effective mass around this minimum has been measured to be 0.036 from observation of the oscillatory magnetoabsorption associated with the direct optical transition.[5] This small effective mass is quite close to that found for gallium arsenide. As it is unlikely on theoretical grounds that such a small effective mass could be obtained elsewhere in the zone, it is quite likely that the lowest conduction band minimum is located at the center of the zone. Such a shift is predicted by the theory relating the bands in gallium arsenide to those in germanium.[6]

ACKNOWLEDGMENT

We would like to acknowledge the assistance of Mr. Carl Rice in the operation of the infrared equipment.

[3] Barrie, Cunnell, Edmond, and Ross, Physica **20**, 1087 (1954).

[4] J. Callaway, in *Solid State Physics*, edited by F. Seitz and D. Turnbull [Academic Press, Inc., New York], Vol. 7, (to be published).

[5] Zwerdling, Lax, and Roth, Phys. Rev. **108**, 1402 (1957).

[6] J. Callaway, J. Electronics **2**, 330 (1957).