Infrared Cyclotron Resonance Absorption in *n*-Type GaAs

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Cyclotron resonance of conduction electrons in GaAs at liquid nitrogen temperature has been observed in the far infrared spectral region. The data yield an effective mass ratio of 0.071±0.005 at the bottom of the band.

I. INTRODUCTION

LARGE static and pulsed magnetic fields have made it possible to study infrared cyclotron resonance in several III-V compounds recently. Burstein *et al.*,[1] Keyes *et al.*,[2] and Palik *et al.*[3] have measured infrared cyclotron resonance in InSb. Palik and Wallis[4] have observed cyclotron resonance of conduction electrons in InAs and InP. These measurements have yielded information about the effective mass at the bottom of the conduction band and the nonparabolic nature of the band. Cyclotron resonance in *n*-type GaAs reported in the present paper has given a value for the effective mass ratio at the bottom of the conduction band of 0.071.

II. RESULTS

The detailed experimental techniques are reported elsewhere.[3] Three samples of *n*-type GaAs were used; A with carrier concentration $N\approx 3\times 10^{16}/\text{cm}^3$ and mobility $\mu\approx 5000$ cm^2/v sec, B with $N=1.99\times 10^{16}/\text{cm}^3$ and $\mu=7033$ cm^2/v sec, and C with $N\approx 3\times 10^{15}/\text{cm}^3$ and $\mu\approx 21\,000$ cm^2/v sec at liquid nitrogen temperature. The samples were polycrystalline sections about 35 μ thick mounted on crystal quartz. The effect of sample strain on the present data was not determined. Each sample, about 0.5 cm×1 cm in area, contained several large crystals, the crystallographic orientation of which were unknown. It is probable[5] that the conduction band is spherical and the masses isotropic. Measurements were made in the far infrared using a reststrahlen monochromator to obtain three narrow bands of wavelengths using crystals of KRS-5, CsI, and CsBr. The wave numbers of the wavelengths at which the experiments were performed are KRS-5, 65 cm^{-1}; CsI, 70 cm^{-1}; and CsBr, 85 cm^{-1}. Measurements were made at room temperature and at liquid nitrogen temperature. The experiment consisted of fixing the wavelength and sweeping the magnetic field. The samples were placed in the magnet so that the magnetic field was parallel to the sample surface and the direction of propagation of the radiation was perpendicular to the sample surface. The radiation was plane polarized with electric vector perpendicular to the external magnetic field. Sample A showed no cyclotron resonance, only a gradual increase in transmission with increasing magnetic field. Sample B showed a definite transmission minimum from which an effective mass was calculated using the formula $m^*=eH/c\omega_c$ where H is the magnetic field at minimum transmission and ω_c, the cyclotron frequency, is taken equal to the frequency of the radiation. However, the mass value was somewhat smaller than expected. Also, the transmission at high magnetic field was more than at zero magnetic field. This suggested that magneto-plasma effects were complicating the measurements. The plasma frequency for sample B was calculated to be 48 cm^{-1} so the measurements were being made quite close to ω_p.

There are two effects which can distort the line position as observed in transmission.[4] First, for the orientation used, the pertinent depolarizing factor $L=1$. Then the actual cyclotron frequency ω_c is related to the observed frequency ω by the relation

$$\omega_c=\omega[1-(\omega_p/\omega)^2]^{\frac{1}{2}}, \tag{1}$$

where $\omega_p=(4\pi Ne^2/m^*\epsilon_0)^{\frac{1}{2}}$ and ϵ_0 is the static dielectric constant in the absence of free carriers. Throughout this paper we use unrationalized cgs units. The corrected cyclotron frequency can then be used to determine the effective mass. If this correction is neglected, the apparent effective mass obtained from the raw data is too small. A second effect which distorts the line position is connected with the fact that while the real part of the conductivity peaks at $\omega_c=\omega$ (assuming the first effect is negligible), the extinction coefficient will peak at a lower magnetic field in general. This is due to the dependence of the extinction coefficient on both the real conductivity and the index of refraction, the latter helping to distort the line from the position $\omega=\omega_c$. The transmission of the sample will depend on both the absorption constant and reflectivity. The reflectivity may also vary rapidly and can further distort the line as observed in transmission. The quantitative shift is not readily determinable, but calculations of the sample transmission indicate that the minimum is shifted to lower fields by a few percent. Neglecting this effect gives rise to an apparent effective mass which is too small.

Both of these magneto-plasma effects are probably

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TABLE I. Data obtained from GaAs samples B and C.

	ν_c (cm^{-1})	H (kgauss)	m^*/m	m^*/m, corrected
Sample B	65	31.9	0.046	0.064
	70	38.2	0.051	0.068
	85	55.1	0.060	0.070
Sample C	65	50.0	0.0718	
	70	53.5	0.0712	
	85	66.0	0.0725	

present in the data obtained for sample B. The masses obtained from the raw data for sample B are listed in Table I. These were corrected using Eq. (1) to yield values which are both higher and more nearly equal. No correction has been made for the second effect, although presumably, this correction would tend to further raise and equate the mass values. The corrected masses in Table I are in rough agreement with the value of about 0.076 obtained from Faraday rotation measurements near 20 μ on samples A and B before they were thinned down. Using the Faraday rotation method, Moss and Walton[6,7] obtained an effective mass ratio of 0.074±0.006 for n-type GaAs.

To minimize the magneto-plasma effect, measurements were made on a much purer sample obtained from F. A. Cunnell. For this sample $\omega_p \approx 18$ cm^{-1}. This is sufficiently far removed from ω_p that magneto-plasma effects should be negligible. Also $\omega_c\tau \approx 5$, so that a fairly sharp resonance was observable. The relative transmission vs magnetic field for the three samples for CsI reststrahlen are shown in Fig. 1. The noise has been smoothed out but the signal-to-noise ratio was not less than 15 to 1. The results for sample C are summarized in Table I. The fixed masses obtained with sample C indicate that the plasma frequency complications are probably negligible. No magneto-plasma corrections

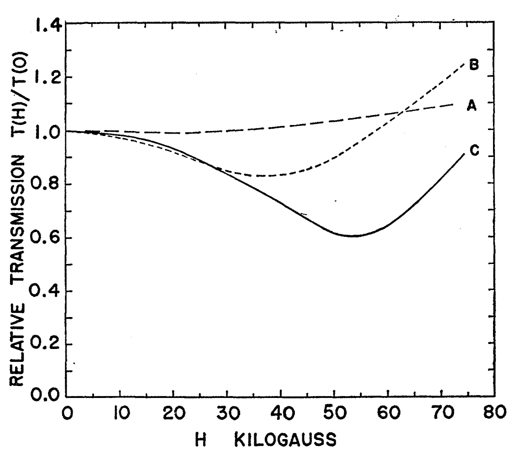

FIG. 1. Relative transmission of three low-temperature samples of GaAs at 70 cm^{-1} as a function of magnetic field.

[6] T. S. Moss and A. K. Walton, Proc. Phys. Soc. (London) **A74**, 131 (1959).
[7] A. K. Walton (private communication).

have been made to the data of sample C, since these corrections are small compared to the experimental uncertainty in wavelength and magnetic field, the uncertainty being about ±7%.

Measurements at room temperature on sample C showed that the room temperature effective mass is the same as the low-temperature mass to within experimental error. The room temperature band was weaker and broader than the low-temperature band.

As described by Palik *et al.*,[3,4] the magnetic field dependence of effective mass for InSb, InAs, and InP can be satisfactorily explained in terms of the nonparabolic nature of the band. The linear dependence of the mass on field which holds well for InAs and InP is given by $m^* = m_0^*[1+(\hbar\omega_c/E_G)(A-B)]$ where m_0^* is the effective mass at the bottom of the band, $\omega_c = eH/m_0^*c$, E_G is the band gap, and A and B depend on m_0^*, E_G, and Δ, the spin-orbit splitting. For GaAs, assuming at liquid nitrogen temperature that $E_G = 1.53$ ev,[6] $\Delta = 0.33$ ev,[6] and $m_0^* = 0.071$, the theoretical straight line given by the above equation has been calculated and is shown in Fig. 2. The experimental effective mass ratio points for sample C given in Table I are also shown as open circles. The cyclotron resonance data, therefore, give an effective mass ratio of 0.071±0.005 at the bottom of the band.

Values of the conduction electron effective mass for GaAs as obtained from optical and electrical measurements are summarized and discussed by Ehrenreich.[5] He concludes that the conduction band is centered at $k=0$ and the effective mass ratio is about 0.072 at the bottom of the band and is isotropic.

An interesting feature of the data for samples A and B is that the samples are more transmitting at high fields than at zero field. This is not readily explained in terms of the magneto-plasma effects discussed above. This increase in transmission may be due to interference effects. Since the reflection and transmission interference fringes are a function of the index of refraction, a change in index due to changing magnetic field will shift the fringes somewhat. Rough calculations of the reflectivity at zero field and high field for sample B (about 35 μ thick) including the effects of interference have been made at a wavelength of 143 μ (CsI reststrahlen). For sample B the calculated indices of refraction at zero and high fields were used. The results indicate that at zero field, the reflectivity is near a maximum, near the top of a fringe. At high field, the reflection decreases as the fringe shifts. Qualitatively, this produces more sample transmission at high fields than at zero field. At intermediate fields, the results would be more complicated since the index of refraction and the extinction coefficient vary considerably through the cyclotron resonance. At best, the changing background due to interference effects would cause only a small distortion in the position of the absorption band.

This same type of interference effect has been observed using a thin section of InAs for similar cyclotron

resonance measurements. In this case, the thin-sample reflectivity as a function of field was measured also. The results are quite striking, showing changes in reflectivity in qualitative agreement with the fact that the changing index of refraction causes the fringes to shift.

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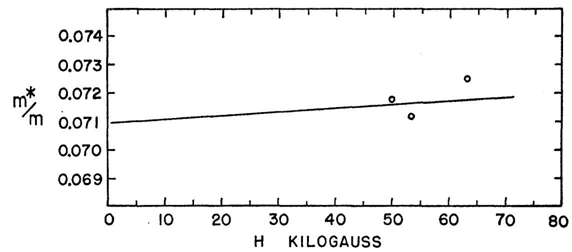

FIG. 2. Cyclotron resonance effective mass ratio vs magnetic field for GaAs at liquid nitrogen temperature.

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Exciton-Induced F-Center Growth in KI and KBr Crystals

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A study has been made at room temperature of the growth in F-center concentration resulting from the absorption of photons in the energy range of the first fundamental band (exciton band) of KI and KBr crystals. The growth in F-center concentration was followed by measuring the fractional change in transmission at the maximum of the F band by an ac method capable of detecting a change in F-center concentration of 10^{11} cm^{-2}. The crystals used in the study of the dependence of F-center production on irradiating wavelength and crystal history were grown both by the Kyropoulos method (seed-pulled) and the Bridgman method (crucible-grown). For seed-pulled KI crystals the F-center growth showed a consistent behavior for irradiation throughout the exciton band. The growth was found to be describable as a volume process for which the F-center density as a function of the number of photons absorbed per unit volume is given by a saturating curve whose shape and initial slope (quantum efficiency) are approximately independent of irradiating wavelength but whose saturation level increases with decreasing wavelength. The F-center saturation density was found to increase from 5×10^{15} cm^{-3} for irradiation in the tail of the band to about 5×10^{17} cm^{-3} at the peak of the band, with the initial quantum efficiency remaining between 0.1 to 0.2 for this wavelength range. While the behavior for seed-pulled KI samples was relatively unaffected by either plastic deformation or previous irradiation in the exciton band, the crucible-grown samples showed large changes due to either of these treatments. Before these treatments the F-center density induced in the crucible-grown samples had predominantly a square-root dependence on the number of absorbed photons; afterwards the behavior was very much like that of the seed-pulled samples. The KBr crystals were found to behave like the seed-pulled KI samples. The results are discussed in terms of the properties of the exciton and its interaction with negative-ion vacancies to form F centers.

INTRODUCTION

THERE are many questions that remain unanswered as to the physical events that follow the absorption of photons in the fundamental optical bands of an alkali halide crystal. The work of Taft and Phillip[1] has at least tentatively answered the question as to where the dividing line between the region of conducting states (electron-hole pairs) and the region of nonconducting states (excitons) lies in the band. While the existence of nonconducting excited states brought about by excitation in the first fundamental band appears to be reasonably well established, there still remain many questions as to the properties of these excited states. For example, does the energy of excitation remain localized in the lattice or can it move? Also, how in detail does this excited state bring about the formation of defect centers,[2,3] ionize F centers,[4,5] and lead to luminescence at low temperatures?[6]

Smakula's study[2] of the formation of F centers in several different alkali halides brought about by excitation in the tail of the first fundamental band (exciton band) indicated that the formation of F centers played a most important part in events leading to the destruction of the exciton; i.e., he found approximately unity efficiency for the conversion of photons absorbed in the band to F centers formed. The objectives of the present study were to repeat Smakula's experiments and to

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