from the disordered phase of the crystal by a single second-order phase transition. Fourth, in those cases where the spin direction or magnitude in a proposed structure is not fixed by the crystal symmetry in the ordered phase it can be expected, in general, to be temperature dependent. Therefore, although the Landau-Lifshitz theory is based on rather general considerations, it makes some definite predictions concerning the symmetry of magnetic structures, and should be useful both in connection with the determination of new structures and in considerations of already proposed configurations in magnetic crystals.

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Infrared Cyclotron Resonance in *n*-Type InAs

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Cyclotron resonance absorption of conduction electrons in InAs has been measured in the infrared spectral region 23–34 μ using magnetic fields as high as 150 kG. The absorption was resolved into three lines, this structure being interpreted on the basis of the changing effective g factor of the conduction electrons.

1. INTRODUCTION

INFRARED cyclotron resonance in *n*-type InAs has been observed by Keyes *et al.*,[1] and Palik and Wallis.[2] The effective mass ratio at the bottom of the band has been found to be about 0.023 at room and liquid-nitrogen temperatures.[2] Also, the mass variation with magnetic field, due to the nonparabolic character of the conduction band, has been measured.

In cyclotron resonance measurements on *n*-type InSb by Palik *et al.*,[3] additional structure was observed in the form of lower frequency satellite lines. These were interpreted as transitions between various Landau levels with unequal spin splittings due to the changing effective g factor. Similar structure should be present in the cyclotron absorption of conduction electrons in InAs but was not observed, probably due to insufficient spectral resolution or lack of sufficiently high magnetic fields.[1,2] The present paper reports the observation of this structure.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Recently, the NRL magnet group has built an air core, solenoidal magnet with a 1.25-in. cylindrical aperture which has produced steady fields in excess of 150 kG. We have used this magnet to study cyclotron resonance in *n*-type InAs and InSb at room temperature and near liquid-nitrogen temperature. The InAs sample, the same one used by Palik and Wallis,[2] was about 20 μ thick mounted on a silicon backing with a thermoplastic cement. It contained $\sim 7\times 10^{15}$ carriers/cm^3 and had a mobility of 70 100 cm^2/V sec at liquid-nitrogen temperature and 23 700 cm^2/V sec at room temperature. The sample transmission was measured at fixed wavelengths in the spectral region 23–34 μ as a function of slowly increasing magnetic field. The transverse sample orientation with direction of propagation perpendicular to magnetic field was used. Some results are shown in Fig. 1. The magnetic field H was varied from 0 to 150 kG. At room temperature two absorption lines are resolved, a strong one at lower field and a weaker satellite at higher field as shown in Fig. 1(a). When the sample was cooled, the strong line sharpened somewhat and split into two lines at high fields, while the satellite essentially disappeared as shown in Fig. 1(b). The positions of the room-temperature and low-temperature lines were about the same.

This structure, similar to structure observed in InSb by Palik *et al.*,[3] has been interpreted as shown in Fig. 2. The Landau levels each have two spin states, the g factor decreasing with increasing energy into the band. The levels are designated $E(l,k_z,\pm)$, l being the Landau quantum number, k_z the propagation constant along the magnetic field, and $\pm$ the spin direction with respect to the magnetic field. Consequently, the transitions $E(0,0,+)\rightarrow E(1,0,+)$ and $E(0,0,-)\rightarrow E(1,0,-)$ will not coincide. Higher transitions will not coincide, either. For a fixed photon energy of 0.0451 eV as the magnetic field is increased, the positions of the low-temperature lines are shown on the energy level dia-

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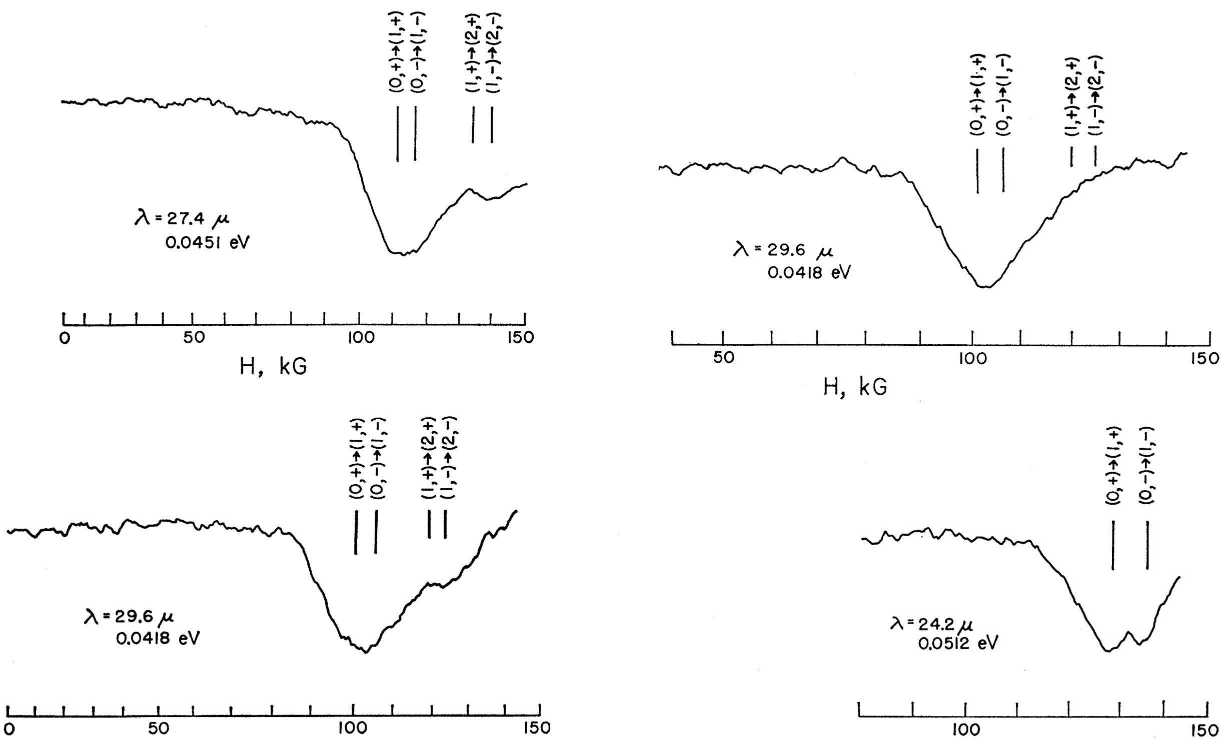

(a) (b)

FIG. 1(a) Observed and calculated cyclotron resonance lines in n-type InAs at room temperature. (b) Observed and calculated lines at liquid-nitrogen temperature.

gram in Fig. 2. These levels were calculated using the theory given by Bowers and Yafet[4] setting $k_z=0$. The fit shown in Fig. 1(b) by the solid lines above the observed absorption lines was obtained assuming $E_G=0.41$ eV, $\Delta=0.43$ eV, and $m_0^*/m=0.024$. No intensity calculations were made, so both solid lines are drawn the same length.

The good agreement at $\lambda=24.2\,\mu$ serves to identify the low-temperature lines as due to the transitions $(0,+)\rightarrow(1,+)$ and $(0,-)\rightarrow(1,-)$. While these two lines are clearly resolved at $24\,\mu$, they gradually blend into one line and are not resolved at $29\,\mu$. The spectral slits varied from 10 to 15 cm^{-1} over the wavelength range studied. The higher transitions, $(1,+)\rightarrow(2,+)$ and $(1,-)\rightarrow(2,-)$, not observed at low temperatures, are indicated also for the $29.6\,\mu$ data.

The two lowest transitions, $(0,\pm)\rightarrow(1,\pm)$, were not resolved at room temperature, but the next transitions, $(1,\pm)\rightarrow(2,\pm)$, were seen as one line as the fit in Fig. 1(a) indicates. In this case the low-temperature parameters given above were also used. This is not quite correct as the effective mass should change slightly as the gap changes from 0.41 eV at 77°K to 0.36 eV at 300°K. No significant change of mass with temperature was observed, however. It was concluded from this that the gap to be used to calculate the mass might be the dilational instead of the experimentally observed gap since the calculations are based on a rigid lattice model and neglect lattice vibrations.[2] The band gap at room temperature, due to dilation only is about 0.39 eV.[5] Assuming the effective mass ratio at low temperature to be 0.024 for a gap of 0.41 eV, the calculated mass for a room-temperature gap of 0.36 eV is 0.021 which is too small to account for the cyclotron resonance results. Using just the dilational gap at room temperature of 0.39 eV gives an effective mass of 0.023 in better agreement with the observed effective mass ratio. However, even in this case, calculations indicated that a fit as good as that shown in Fig. 1(a) could not be obtained using the parameters $\Delta=0.43$ eV, $E_G=0.39$ eV, and $m_0^*/m=0.023$.

This experiment measures the change in g factor for the $l=0$ and $l=1$ Landau levels and not the g factor itself. This latter quantity was calculated using the above parameters in the formulas given by Roth, Lax, and Zwerdling.[6] The result is $g=-15$. This value could be checked by an interband magneto-optical measurement.

In Fig. 3 the mass variation as a function of magnetic field as obtained from the $(0,+)\rightarrow(1,+)$ transition is

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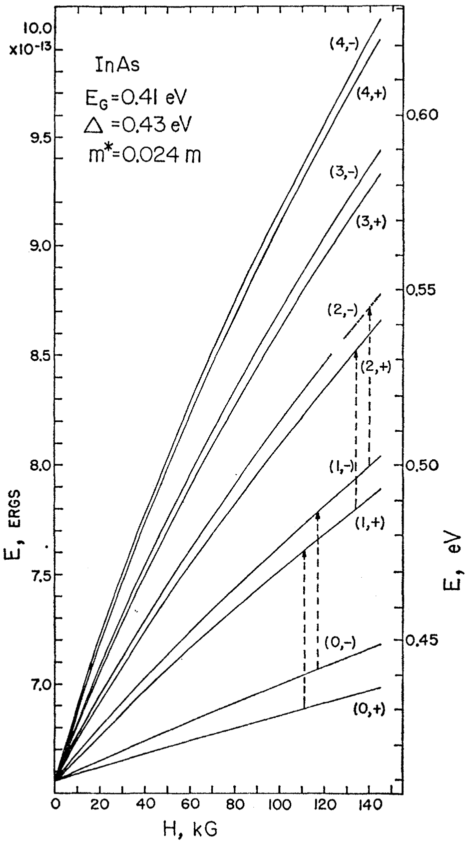

FIG. 2.Conduction Landau levels at $k_z=0$ for InAs as a function of magnetic field.

shown. The low-field, low-temperature data of Palik and Wallis[2] are shown along with the present higher field, low-temperature data. The solid line was determined by calculating the energies of the Landau levels using the theory of Bowers and Yafet.[4] The fit of the present high-field data is reasonable. As can be seen in Fig. 3, we have given more weight to the data points around 50 kG and above 80 kG, and to fit these points, have found it necessary to use an effective mass ratio of 0.024, slightly higher than obtained previously.[2] The lower field points are not weighted as heavily because the cyclotron resonance lines are shifted by depolarizing effects which are somewhat hard to correct for, quantitatively.

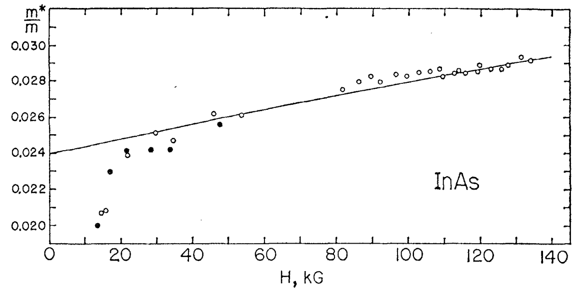

FIG. 3. Effective mass variation with magnetic field obtained from cyclotron resonance data obtained at liquid-nitrogen temperature. The solid line was determined using the theory of Bowers and Yafet and the parameters $E_G=0.41$ eV, $\Delta=0.43$ eV and $m_0^*=0.024\,m$. Open circles indicate data obtained in the transverse orientation, and solid circles indicate data obtained in the longitudinal orientation.

Further support of the energy level scheme in Fig. 2 was obtained using the free-carrier oscillatory absorption technique.[7] In this experiment, oscillations are observed in the free carrier absorption at fixed photon energy which are periodic in $1/H$. The absorption maxima are harmonics of cyclotron resonance due to the breakdown of the selection rule $\Delta l=\pm 1$. We observed the transition $l=0 \rightarrow l=4$ at 12.7 μ when $H=86.8$ kG. The calculated position of this line from Fig. 2 is 86 kG in good agreement with experiment. The sample was 1 mm thick and contained about 5×10^{16} carriers/cm^3 at liquid-nitrogen temperature.

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