can result in a contribution due to spontaneous emission. The ambient pressure measured during this experiment is 5×10^{-6} mm Hg. It is estimated from Pirani gauge measurements that the beam flux is $\sim10^{14}$ molecules per second.[7] If it is assumed that the separation of states in the focuser is ideally efficient, but that all the beam is intercepted by the cavity, this contribution to the noise figure from this source would be $\sim$0.7 db. The correction would be larger if the separation of states were poorer. The present experiment indicates an upper limit to effects of this kind.

In conclusion, it may be said that this experiment justifies the continued belief that maser amplifiers can have very low noise figures.

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[1] J. P. Wittke, Proc. Inst. Radio Engrs. **45**, 291 (1957).
[2] M. W. Muller, Phys. Rev. **106**, 8 (1957).
[3] R. V. Pound, Ann. Physik **1**, 24 (1957).
[4] Gordon, Zeiger, and Townes, Phys. Rev. **99**, 1253 (1955).
[5] R. H. Dicke, Rev. Sci. Instr. **17**, 268 (1946).
[6] M. W. Muller (private communication).
[7] J. C. Helmer, J. Appl. Phys. **28**, 212 (1957).

Infrared Resonant Absorption from Bound Landau Levels in InSb

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In semiconductors of low effective mass and high dielectric constant, the Landau level separation may be greater than the ionization energy of impurities in strong magnetic fields.[1] In this case the bound states may be expressed in terms of the wave functions of the Landau levels modified by the presence of the Coulomb potential of the charged impurity.

We have carried out transmission experiments as a function of magnetic field in the far infrared on thin samples of n-type InSb. These experiments show field-dependent resonant absorption with structure which we ascribe primarily to Landau levels bound to donor impurities.

The experiment was carried out at liquid helium temperatures and extended through the wavelength region from 70 to 120 microns. Monochromatic radiation was obtained from a grating spectrometer with filters of quartz and paraffin. Where necessary, second order spectra were suppressed by the use of KI and CsBr residual ray plates. The bolometer detector also at liquid helium temperatures was mounted immediately behind the sample. By operating at low temperatures, considerable improvement over the best room-temperature thermal detector was obtained. The details of the detector will be given elsewhere.

A recorder trace of the transmission through a 0.01-cm thick sample with excess donor concentration of 2×10^{14} cm^{-3} is shown in Fig. 1. The magnetic field

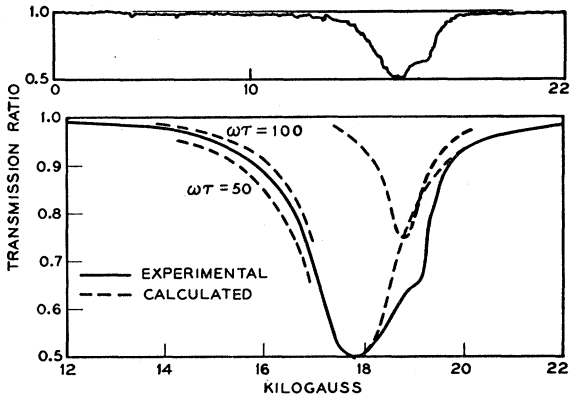

FIG. 1. The relative transmission of an n-type sample of InSb (2×10^{14} carriers/cm^3) as a function of magnetic field at a wavelength of 87 microns.

was in the direction of propagation. The dashed curves to the left correspond to the calculated transmission curves for $\omega\tau$ equal to 50 and 100. This yields a relaxation time of approximately 4×10^{-12} seconds which is in reasonable agreement with mobility measurements on similar samples. The satellite line which appears as a shoulder on the high-field side can be extracted by extrapolation of the low-field line. From this the splitting is estimated to be 1000 gauss. The relative intensity of the two lines is sensitive to temperature, the high-field line increasing in intensity with temperature.

In order to correlate our results with theoretical analysis, we have extended the calculations of reference 1 and estimated the energy of some of the excited donor states. The trial functions used were of the form $\phi(n,l)\exp[-(z^2/4a_{||}^2)]$ where $\phi(n,l)$ is the function corresponding to the motion in the transverse plane of a free carrier with energy $(n+\frac{1}{2})\hbar\omega_c$ and z-component of angular momentum $\hbar(n-l)$.[2] In each case the energy was minimized with respect to $a_{||}$ which is an adjustable parameter determining the z-dependence of the function. From the calculated level scheme at a field of 18 000 gauss shown in Fig. 2, it is seen that the transition in the conduction band from $n=0$ to $n=1$ is very close

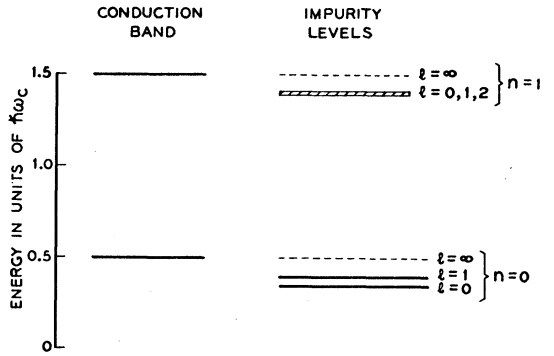

FIG. 2. Energy level diagram for bound and free electrons at a field of 18 000 gauss.

to the transition between the bound states $n=0$, $l=1$ and $n=1$, $l=1$. The transitions between the bound states $n=0$, $l=0$ and $n=1$, $l=0$, 2 is approximately $0.05\hbar\omega_c$ above this in energy. We ascribe the two observed lines to these two types of transitions and the splitting to this difference in their transition energies. The calculated separation of $0.05\hbar\omega_c$ is in excellent agreement with the observed value $0.055\hbar\omega_c$.[3] The relative increases in intensity of the satellite line at higher temperatures is due to an increase in the number of carriers in the excited donor states and in the conduction band.

We have also determined the conduction-band effective mass. Figure 3 shows the results of a series

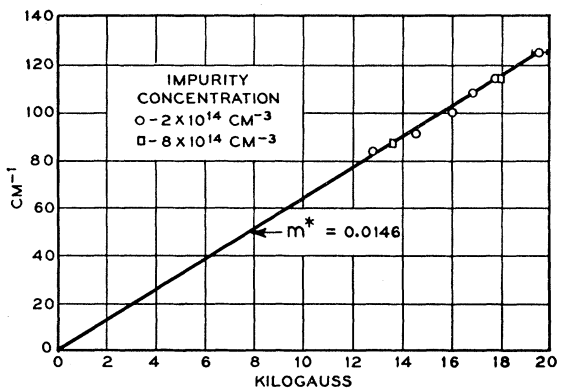

FIG. 3. The resonant frequency for bound electrons plotted against the corresponding magnetic field.

of measurements taken from 70 to 120 microns on two samples of different impurity concentration, the resonant field corresponding to the low-field line. From the slope of this curve we obtain a mass of $0.0146m_0$ for the main transition between donor states. Using the value of the line splitting, we find the effective mass to be $(0.0155\pm0.005)m_0$. This is considerably higher than the value $(0.013\pm0.001)m_0$ obtained from microwave measurements[4] but presumably not beyond the possible error in measurement because of the small value of ω_τ. Our results when combined with previous infrared cyclotron resonance measurements[5] taken at room temperature show a smooth variation of effective mass with magnetic field extending down essentially to the bottom of the conduction band at zero field.

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[1] Yafet, Keyes, and Adams, J. Phys. Chem. Solids **1**, 137 (1956).
[2] M. H. Johnson and B. A. Lippmann, Phys. Rev. **76**, 828 (1949).
[3] Here ω_c is the angular frequency for resonance in the conduction band. The experimentally observed splitting is determined from the ratio of the magnetic fields for the two lines.
[4] Dresselhaus, Kip, Kittel, and Wagoner, Phys. Rev. **98**, 556 (1955).
[5] Keyes, Zwerdling, Foner, Kolm, and Lax, Phys. Rev. **104**, 1804 (1956); Burstein, Picus, and Gebbie, Phys. Rev. **103**, 825 (1956).

Paramagnetic Resonance of Nickel Fluosilicate under High Hydrostatic Pressure*

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A SINGLE crystal sample of $NiSiF_6\cdot 6H_2O$ has been examined by para-magnetic resonance techniques while exposed to hydrostatic pressures up to 10 000 kg/cm² at room temperature. For details of crystal structure and spin Hamiltonian the reader is referred to the literature.[1-4] Analysis of our data taken with the static magnetic field along the trigonal axis leads to the curve of zero-field splitting, D, *versus* pressure shown in Fig. 1, where $\partial D/\partial P=0.834\times10^{-4}$ cm^{-1}/(kg/cm²) at $T=300$°K. The sign of D is not determined by paramagnetic resonance but is known to be negative at atmospheric pressure.[3] That D goes to zero is indicated by the crossing of two transitions at 6200 kg/cm² where a pronounced minimum in the line width of the superposed resonances occurs. The interesting question of exchange narrowing *versus* broadening in this pressure region will be investigated more fully.[5,6] The values of D near 10 000 kg/cm² are assumed to be positive because of the monotonic, linear character of the data up to 6200 kg/cm². The g factor was found to be $g_{11}=2.34\pm0.02$ at all pressures.

Since it is known that D is produced by the trigonal component of the crystalline electric field in conjunction with spin-orbit coupling, we infer that this crystalline field component varies monotonically with P, changing sign at $P=6200$ kg/cm².

This change in the crystalline field is presumably due to anisotropy of the elastic constants of the crystal. Measurements of D *versus* temperature support this view, D decreasing in magnitude with temperature to a constant value of -0.12 cm^{-1} at $T=20$°K.[3,4,7] Bagguley *et al.*[4] ascribe this to anisotropic thermal expansion. Attempts will be made to measure the anisotropy of

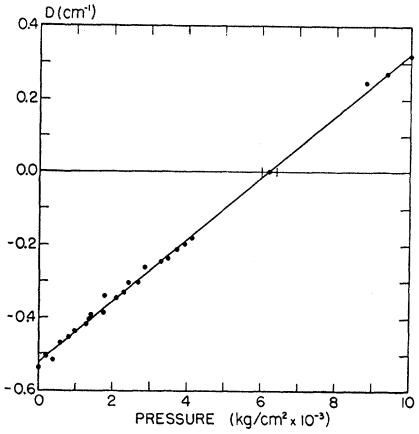

FIG. 1. Pressure dependence of the zero-field splitting in $NiSiF_6\cdot 6H_2O$ at 300°K.