COMBINED RESONANCE AND ELECTRON g VALUES IN InSb*

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Calculations for III-V semiconductors,[1,2] and particularly for InSb,[3-6] yield nonvanishing matrix elements for electric dipole transitions between conduction band states in a magnetic field which differ in both orbital and spin quantum numbers. These so-called "combined resonance" transitions can occur because of the absence of inversion symmetry in the crystal structure[1] or the nonparabolicity of the bands.[2]

This Letter reports the observation of the combined resonance transition $h\nu = h(\nu_c + \nu_s)$ in InSb, where ν_c and ν_s denote the cyclotron and electron-spin resonance frequencies, respectively. In this process the absorption of a single photon induces a transition from the spin-up (lower energy), $L=0$ electron Landau level to the spin-down, $L=1$ Landau level. By observing in addition the usual cyclotron resonance transitions from each of the $L=0$ spin states, a direct measure of the conduction-electron-spin g values for the $L=0$ and $L=1$ Landau levels has been obtained over a wide range of magnetic fields. The data also exhibit a weak absorption at the photon energy $h\nu = h(\nu_c + \nu_{LO})$, where ν_{LO} is the frequency of the longitudinal optical phonons. A similar weak absorption has been observed at lower fields previously.[7]

The experiments were performed on two samples of InSb, cut from the same portion of a single-crystal ingot containing 2×10^{14} carriers/cm^3 with a mobility of approximately 5×10^5 cm^2/V sec at 80°K. A grating monochromator provided fixed-frequency radiation in the spectral region 300 to 650 cm^{-1} and a Bitter magnet generated swept fields from 0 to 110 kG. Synchronous detection was used in conjunction with a conventional chopped light source. The direction of propagation of the radiation was perpendicular to the applied magnetic field $\vec{H}$, so that the use of a wire grid polarizer[8] made it possible to obtain radiation with the electric field $\vec{E}$ polarized along the field direction ($\vec{E}\parallel\vec{H}$) or perpendicular to it ($\vec{E}\perp\vec{H}$). The applied magnetic field was parallel to the (111) plane of the samples.

The transmission of a relatively thick sample (9.25 mm) was studied at temperatures in the range 6 to 80°K. Over this range, the positions of the absorption peaks were independent of temperature within experimental error. Typical spectra are displayed in Fig. 1. The small peak at 54.5 kG occurs at the photon energy $h(\nu_c + \nu_{LO})$ and is observed only for $\vec{E}\perp\vec{H}$. At 78.7 kG the combined resonance transition occurs for $\vec{E}\parallel\vec{H}$.[4] (The doublet structure of this absorption is discussed below.) For $\vec{E}\perp\vec{H}$ the much stronger cyclotron resonance absorption causes the sample to become opaque at about 98 kG and remain so up to somewhat higher fields. In order to observe the cyclotron resonance peaks, the transmission of a thinner sample (0.05 mm) was studied under the same conditions. At 6°K only the spin-up cyclotron resonance peak was observed. When the temperature was raised to 80°K, the spin-down cyclotron resonance peak became observable at higher fields.

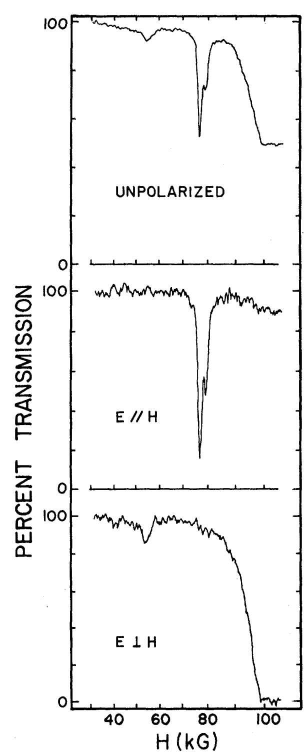

FIG. 1. Transmission spectra obtained at 500 cm^{-1} and 6°K for the 9.25-mm-thick sample of InSb. The doublet structure of the transition appearing at about 78 kG reflects the presence of both free and localized electrons, as discussed in the text.

Both the $h(\nu_c+\nu_s)$ and $h\nu_c$ transitions manifested a doublet structure at sufficiently low temperatures, reflecting the freeze-out or localization of electrons that occurs in high magnetic fields in relatively pure InSb.[9] The localized electrons exhibit an "impurity-shifted" cyclotron resonance at a photon energy slightly greater than $h\nu_c$.[9,10] The relative intensities of the doublet components of both the $h\nu_c$ and $h(\nu_c+\nu_s)$ absorption peaks could be altered experimentally by changing the sample temperature and therefore the degree of carrier freeze-out.

The observed magnetic field dependence of the energies of the transitions $h(\nu_c+\nu_{LO})$, $h(\nu_c+\nu_s)$, $h\nu_c$ (spin-down), and $h\nu_c$ (spin-up) are plotted in Fig. 2. In order to simplify this figure and subsequent discussion, transitions involving localized electrons have been excluded. For a given value of magnetic field, the energy difference between the $h\nu_c$ (spin-down) and $h\nu_c$ (spin-up) transitions yields the quantity $g(0,H)-g(1,H)$, the difference between the $L=0$ and $L=1$ g values. The energy difference between the $h(\nu_c+\nu_s)$ and $h\nu_c$ (spin-up) transitions yields $g(1,H)$ directly, and in conjunction with the quantity $g(0,H)-g(1,H)$, determines $g(0,H)$. These g values are as defined in Eq. (5) of Ref. 9. A plot of the experimentally determined magnetic-field dependence of $g(0,H)$ and $g(1,H)$ at 80°K is presented in Fig. 3. The experimental results are for arbitrary magnetic field direction in the (111) plane. Also shown in Fig. 3 is the calculated dependence of g on $\vec{H}$ for two directions of the magnetic field relative to the crystal axes.[11] Although the agreement between theory and experiment for $g(1,H)$ is satisfactory, the experimental and theoretical values of $g(0,H)$ differ by about 8%. This difference is significantly greater than the estimated limit of 3% systematic error in the experimental results.

Calculations of matrix elements for combined resonance transitions in InSb[4] indicate that electric-dipole transitions should be observable at the frequencies ν_s, $\nu_c+\nu_s$, $2\nu_c-\nu_s$, and $2\nu_c+\nu_s$ with absorption constants in the range 10^{-4}-10^{-5} of that for normal cyclotron resonance in a magnetic field of 20 kG. Of these transitions, only the electric-dipole-induced spin transition ν_s has been observed previously.[12] The observation was made at a field of about 1 kG utilizing a cavity microwave spectrometer; the absorption line was found to be isotropic. In the present work, the ratio of absorption constants of the transitions occurring at the frequencies $\nu_c+\nu_s$ and ν_c was 7×10^{-3} at 80 kG, or about two orders of magnitude larger than calculated.[4] This discrepancy may be because the transitions were observed for magnetic fields in the range 50-100 kG, since

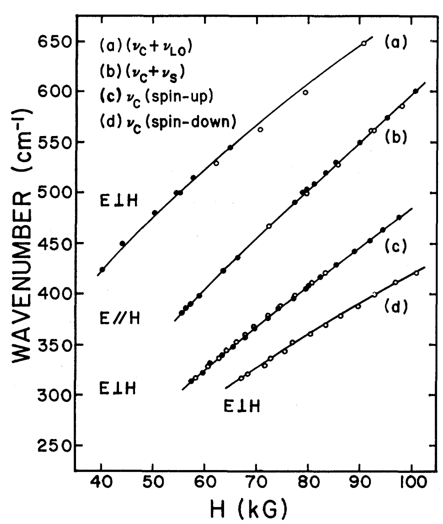

FIG. 2. Magnetic field dependence of the observed absorption peaks. The open data points were obtained at 80°K and the solid data points at 6°K.

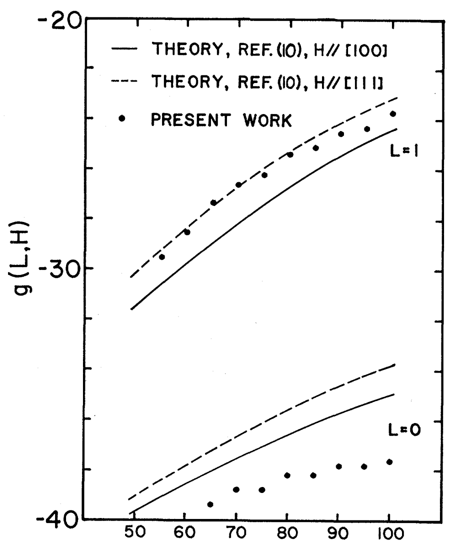

FIG. 3. Comparison of the experimentally determined magnetic field dependence of the g values for the $L=0$ and $L=1$ Landau levels (at 80°K) with the calculated dependence of g on H for two directions of the magnetic field relative to the crystal axes. (Ref. 11).

the absorption constant for combined resonance is expected to increase with increasing field.[2] The experimental results indicate, however, that between 50 and 100 kG the combined resonance strength is only weakly dependent on magnetic field. Preliminary measurements of the absorption strength as a function of the angle between the applied field and the crystalline axes indicate that anisotropy is weak or absent. A search was made for absorption at the frequencies of the other two combined resonance transitions, but neither was found. From the data, an upper bound on the absorption constants of these transitions has been obtained as follows: $2\nu_c+\nu_s$, 0.054 cm^{-1}; $2\nu_c-\nu_s$, 0.38 cm^{-1}. (The latter transition requires population of the $L=0$, spin-down level.)

Both the observed isotropy of the intensities of the ν_s [12] and $\nu_c+\nu_s$ transitions, and the absence in the spectra of the $2\nu_c+\nu_s$ and $2\nu_c-\nu_s$ transitions, indicate that the nonparabolicity of the bands,[2] rather than the absence of inversion symmetry, is responsible for most of the combined resonance intensity. Combination resonance should therefore be observable in crystals possessing inversion symmetry and having nonparabolic bands, such as PbTe, as well as in other III-V semiconductors.

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ULTRASONIC ATTENUATION IN NORMAL AND SUPERCONDUCTING LEAD; ELECTRONIC DAMPING OF DISLOCATIONS*

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In a recent publication[1] it was reported that a maximum is found in the ultrasonic attenuation, as a function of wave amplitude, in normal and superconducting lead at 4.2°K and the normal state at 8°K. At a given temperature the maximum occurs at higher amplitudes in the normal state. These experiments were interpreted in terms of the difference in the damping of dislocation motion due to conduction electrons in a metal.[2]

This Letter reports on some further experiments and gives a more detailed analysis of the results. Specifically, the shift in amplitude at maximum ultrasonic attenuation in normal and superconducting lead was used to determine the parameter B associated with damping of dislocations by conducting electrons in the normal state. The analysis does not involve any *ad hoc* assumptions concerning inaccurately known features of the dislocation network in crystals, and the result is believed to be the first of its kind.

The experimental conditions and techniques used were described in Ref. 1. Figures 1 and 2 show, respectively, the results obtained at frequencies of 10 and 20 Mc/sec. The features relevant to the present consideration are the following: (a) At 10 Mc/sec the amplitude corresponding to maximum attenuation in the superconducting state at 4.2°K is 5 dB lower than