ning rather than being a feature of ideal flux flow.

We would like to thank J. Curnow and D. H. Leslie for their technical assistance.

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# MAGNETO-OSCILLATORY EXCITATION SPECTRA OF SHALLOW ACCEPTOR IMPURITIES IN InSb AND Ge

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The effect of a magnetic field on the excitation spectra of impurities in semiconductors has been the subject of considerable theoretical and experimental interest. In general, this interest has been directed either to the high-field regime $\gamma \gg 1$, or the low-field regime $\gamma \ll 1$, where the field parameter $\gamma \equiv \frac{1}{2}\hbar\omega_c/\mathrm{Ry}^*$ is the ratio of the zero-point energy in a magnetic field to the effective Rydberg energy, Ry*, of the impurity atom, and $\omega_c$ is the cyclotron resonance frequency multiplied by $2\pi$. The present Letter describes an experimental study of acceptor impurity excitations in InSb and Ge that involves simultaneously the high-field and low-field regimes. In addition to yielding information concerning the acceptor impurity states, the experiments provide a useful means of studying the valence-band structure in a magnetic field.

The absorption due to shallow acceptor impurities in InSb and Ge has been measured in magnetic fields up to 100 kG, at temperatures near 4.2°K. The spectral regions of interest extended upward in energy from the ionization energies of the impurities. Impurity-induced photoconductivity has also been observed; however, this work will be described in detail elsewhere. Acceptor concentrations were in the range $10^{14}$-$10^{15}$ cm$^{-3}$. At the higher fields, measurements were made with a grating spectrometer designed for use with the Naval Research Laboratory Bitter-type magnets. Additional spectra were obtained at lower fields by means of an interferometric spectrometer and superconducting solenoid.

Typical transmission spectra for Cd-doped InSb are shown in Fig. 1. The transmission minima were observed with equal strength in the Voigt and Faraday orientations, and in the Voigt orientation with the electric field of the radiation parallel or perpendicular to the ap-

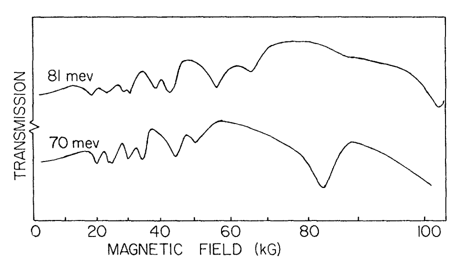


FIG. 1. Transmission spectra obtained at two fixed photon energies for Cd-doped InSb at 4.2°K, using a monochrometer and Bitter-type magnet. The sample was in the Voigt orientation, with the electric field of the radiation parallel to the applied magnetic field.

plied magnetic field. The positions of the transmission minima did not appear to depend on the angle between the magnetic field and the sample crystalline axes. The field dependence of the positions of the transmission minima is shown in the form of a fan chart in Fig. 2; labeling of the minima will be discussed below. Because of the strong lattice absorption and reflection bands in InSb, the spectral region 21-27 meV was inaccessible to transmission measurements. Extrapolation of the fan chart to zero field yields the energy $9.3 \pm 0.6$ meV. Within the experimental error, experiments on Cd-doped and Zn-doped InSb yielded identical results.

Measurements of the spectral absorption due to the acceptor impurities Ga and B in Ge yielded results having the same general features as those described above for shallow acceptors in InSb. However, the transmission minima due to B and Ga in Ge were much sharper than those observed using the InSb samples. It was therefore possible to follow individual minima down to fields as low at 4 kG. The resulting fan charts, which were similar for both impurities in Ge, differed appreciably in slopes and spacing from those obtained for InSb. Furthermore, the zero-field energy intercepts of the fan charts form a narrow band along the energy axis. Figure 3 shows these results for a Ge sample doped with B. It is important to note that the known ionization energy[1] of B acceptors in Ge, $10.97 \pm 0.02$ meV, lies significantly above the band of zero-field intercepts. Observation of this result was not achieved for the InSb spectra because of their poorer resolution relative to that of the Ge spectra, and to the absence of an independent, accurate value of the ionization energy. The Ge spectra also contained additional structure, in the form of weak satellites on the high-energy side of the transmission minima. The field dependence of the positions of four of the most prominent satellites is indicated by the dashed lines in Fig. 3. Within the experimental error, these lines extrapolate linearly to 10.97 meV. While each main transmission minimum in the observed spectra is accompanied by a weak-satellite minimum, nearly half of the latter are obscured to some extent by the former.

In analogy with the theoretical[2-4] and experimental[5] results concerning the high-field donor excitation spectra in InSb, it may be expected that transitions will occur between the $s$-like acceptor ground state and a $p$-like excited state associated with each of the light-hole Landau levels. It is believed that these transitions are responsible for the observed excitation spectra. According to this model, there are four distinct contributions to the energy $\hbar\omega$ of a given transition. The first two are the zero-field acceptor ionization energy $E_I$ and the field-induced shift $\Delta E_g$ of the ground state. Calculations[6] have shown that the acceptor ground state is characterized by a large effective mass; hence $\Delta E_g$ is small even in

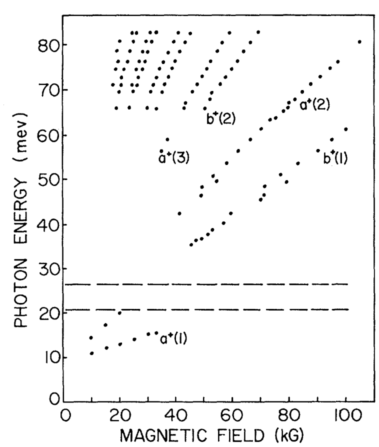


FIG. 2. Field dependence of the observed transmission minima for Cd-doped InSb. The samples were opaque in the region between the dashed lines due to the strong lattice absorption and reflection bands.

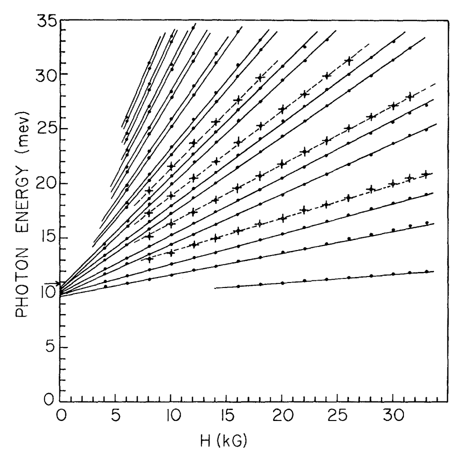


FIG. 3. Field dependence of the observed transmission minima for B-doped Ge. Solid and broken straight lines have been drawn through the data points representing the main and satellite minima, respectively. Only four of the most prominent satellites have been included. The broken lines are found to extrapolate linearly to the photon energy identified by the arrow, which corresponds to the ionization energy of B impurities in Ge (Ref. 1).

high fields, and $\gamma \ll 1$. Using the value $m^* = 0.4m_0$ for the ground-state effective mass in both InSb and Ge, the definition of $\gamma$ given earlier yields $\gamma \sim 0.07$ for a field of $10^5$ G. The third contribution to $\hbar\omega$ is the energy $\epsilon_N^{a,b}$ of the light-hole Landau level involved in the transition, measured from the top of the valence band in zero field, where $a, b$ refer to the two light-hole ladders ladders and $N$ is the Landau quantum number. Finally, there is a contribution $E_{ex}$ equal to the magnitude of the energy separation between the Landau level and the associated $p$-like excited state. For impurity states of this type in InSb, use of the light-hole mass $m^* = 0.015m_0$ leads to the value $\gamma \sim 46$ for a field of $10^5$ G. In Ge the corresponding quantities have the values $m^* = 0.04m_0$ and $\gamma \sim 6.5$. For a given magnetic field, transitions occur at the energies $\hbar\omega = E_I + \Delta E_g + \epsilon_N^{a,b} - E_{ex}$.

In earlier measurements[7] of the photoconductive response of B-doped Ge in a magnetic field, structure similar to that observed in the present work was found. The structure was attributed to transitions between the acceptor ground state and the light-hole Landau levels. That the final states are impurity excited states rather than valence-band levels is indicated by the fact that the zero-field energy intercepts of the fan charts for the Ge samples lie significantly below the known ionization energies $E_I$ of the acceptor impurities. Furthermore, it appears that the weak-satellite minima mentioned earlier, and observed both in transmission and photoconductivity, do represent photoionization transitions from the ground state to the valence-band levels. Photoionization transitions may occur at the intermediate fields,[2] but they are expected[3] to be much weaker than the transitions to impurity levels and to disappear in the extreme high-field limit. The observation of both sets of transitions in the Ge samples makes it possible to determine, for this material, the impurity energy $E_{ex}$ and its dependence on magnetic field, $H$, and Landau quantum number, $N$. $E_{ex}$ is observed to increase monotonically with increasing $H$, and to decrease with increasing $N$ for $N < 7$.

For higher energy Landau levels the data were not sufficiently precise to permit a determination of the dependence of $E_{ex}$ on $N$. These results for Ge lie in the intermediate field range $\gamma \approx 1$. Since existing theories[2-4] assume that $\gamma \gg 1$, a quantitative comparison of theory and experiment for the behavior of $E_{ex}$ cannot be made at present. Qualitatively, however, the observed magnitude of $E_{ex}$ and its dependence on $H$ and $N$ are consistent with theoretical predictions.[2-4]

Assuming $\Delta E_g$ is sufficiently small to be ignored, a precise determination of the light-hole energy levels is possible. Preliminary analysis of the InSb data yields good quantitative agreement, for the light-hole Landau levels, with values determined earlier from interband measurements.[8,9] The notation employed in the latter work has been used to identify the transitions in Fig. 2.

In conclusion, it appears that the experiments described will be useful in studying the valence-band structure in a magnetic field of InSb, Ge, and possibly other materials, as well as impurity states associated with the valence-band levels. In addition, it may be possible to study the effects of the magnetic field on the acceptor ground state.

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