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INFRARED MAGNETOELECTROREFLECTANCE IN Ge, GaSb, AND InSb

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An infrared electroreflectance technique has been used to observe magneto-optical effects associated with direct valence- to conduction-band transitions in Ge, GaSb, and InSb.

Electroreflectance measurements in solids using an electrolyte[1] have proven to be a convenient and sensitive method for obtaining reflectivity spectral structure in the energy range 1 to 6 eV. In this study we have been able to extend the wavelength range of this technique into the near infrared. We also have established the usefulness of the electroreflectance method for studying magneto-optical phenomena and have found that in the configuration of parallel static electric and magnetic fields ($\vec{F} \parallel \vec{H}$), where the effects of $\vec{F}$ and $\vec{H}$ are essentially independent,[2,3] the electric field modulation enhances the normal magnetoreflection spectra. Results are presented here of magnetoelectroreflectance in Ge, GaSb, and InSb associated with direct valence- to conduction-band transitions at $\vec{k}=0$. We have been able to find either new or more accurate experimental values at room temperature for the spin-orbit splitting in InSb, the effective mass of the split-off band in Ge, and the direct energy gap in GaSb. Similar results for Ge have been obtained recently by a piezoreflectance method.[4-6]

The electrolyte technique has been described in Ref. 1 for use to wavelengths of about 1 μ, where the absorption bands in alcohol and water cut off the light transmission. We have been able to use these electrolytes (e.g., a dilute solution of HCl in methyl alcohol) to about 3 μ by reducing the light path through the electrolyte to a few tenths of a millimeter. The experimental arrangement is shown in Fig. 1. The cell was located in the bore of a solenoidal magnet with the electric field $\vec{F}$ produced at the electrolyte-semiconductor interface parallel to the dc magnetic field. Tungsten and globar sources and a PbS detector gave adequate sensitivity. Direct recording of the differential reflectivity, $\Delta R/R$, was accomplished by chopping the light at 1000 Hz and modulating the electric field at 35 or 160 Hz. The 1000-Hz signal was then phase detected and used to operate a servo system which controlled the output of the PbS detector amplifier. A cell window in the form of a wedge was used to prevent reflections from its front surface reaching the detector and causing an error in the measurement of $\Delta R/R$.

Figures 1 and 2 show the results of magnetoelectroreflectance for Ge. Points A and B in Fig. 1 show the onset of direct valence- to conduction-band transitions and spin-orbit split-off valence-band (split-off band) to conduction-band transitions at $k=0$, respectively. The spectrum for $H=0$ is similar to that obtained

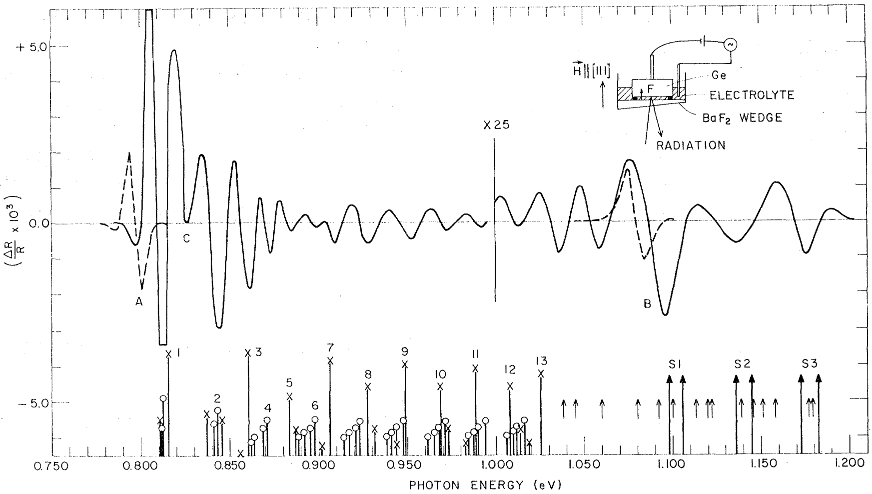

FIG. 1. Interband electroreflectance in Ge for $H=0$ (dashed line) and $H=92.4$ kG (solid line) in the parallel electric and magnetic field configuration, at $T\simeq 300°$K. Theoretical energies and relative strengths are shown for allowed light-hole (×) and heavy-hole (○) to conduction-band transitions up to 1.03 eV. Above this energy the positions of the principal valence- to conduction-band transitions are indicated by small arrows. The relative strengths and positions of all the allowed split-off-band to conduction-band transitions are shown by heavy arrows. A schematic diagram of the experimental arrangement is shown (inset).

by Seraphin and Hess[7] using the transparent electrode technique. With an applied magnetic field, a differential spectrum characteristic of interband transitions between Landau levels (or to their associated exciton states) is observed. In order to determine the position of the resonances in the spectra, we have compared our lower magnetic field data with the room-temperature magnetoabsorption spectra of Zwerdling, Roth, and Lax[8] (where the line shapes are better understood). The best agreement is found by taking the resonance positions at the minima of the differential spectra. A plot of the photon energies of the magnetoelectroreflectance minima versus H together with the resonance positions for $H=35.7$ kG from Ref. 8 is shown in Fig. 2. Vrehen's[2] magnetoabsorption resonance positions measured at 77°K and 96.4 kG (reduced by 0.082 eV to account for the temperature change of the gap) are plotted for comparison with the high-field data. The usefulness of the magnetoelectroreflectance for observing transitions high into the bands is quite apparent. Transitions between the light- and heavy-hole valence bands and the conduction band merge with those between the split-off valence and conduction band at about 1.1 eV. From the experimental points in Fig. 2 it is clear that we observe the first four split-off valence- to conduction-band transitions.

The solid lines in Fig. 2 give the transition energies calculated from effective mass theory.[9] The modification of Pidgeon and Brown,[10] which includes the $\vec{k}\cdot\vec{p}$ interaction between $\Gamma_{2'}$ and $\Gamma_{25'}$ bands exactly, has been used for this computation. We have used the 77°K Ge band parameters[9,2] and then reduced the calculated energies by 0.082 eV to make the theoretical energy gap coincide with the energy of the $H=0$ transition at 0.801 eV. We wish to emphasize that we have used this method to show the overall agreement between theory and experiment for the two sets of transitions and to make an assignment of transitions to the observed spectral structure. We have not made a detailed fitting to these room-temperature data, something which would require more attention to the temperature dependence of the band parameters. Our treatment is a reasonable approximation if, as is likely, the parameters determined by $\vec{k}\cdot\vec{p}$ interactions between bands are only weakly dependent on temperature. A further complication is that the transitions probably involve creation of excitons associated with Landau levels[11]; that the points for the lowest transitions do not extrapolate linearly to the position of the $H=0$ minimum may be evidence of this. We have not plotted the theoretical curves at the highest energies because

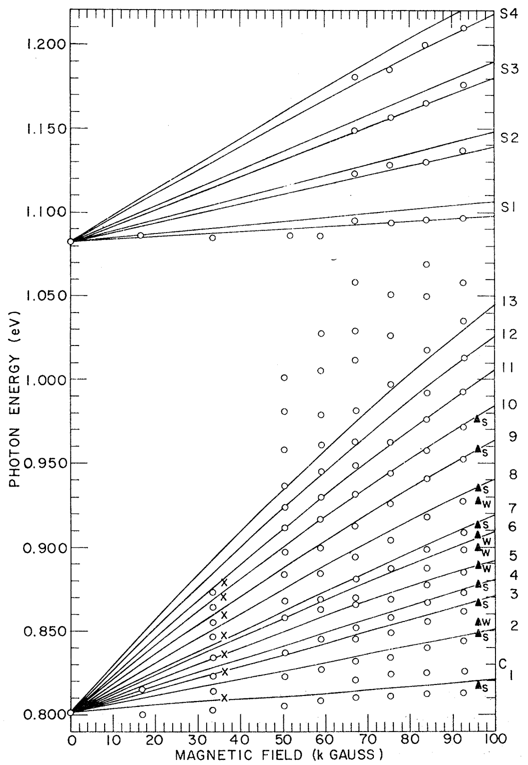

FIG. 2. Plot of the photon energy of magnetoelectroreflectance minima as a function of magnetic field. The circles show the experimental points. The crosses give the positions of magnetoabsorption peaks (i.e., transmission minima) of Zwerdling, Roth, and Lax[7] for $H=35.7$ kG, and the solid triangles, those of Vrehen[2] for $H=96$ kG (S indicates strong feature and W, weak feature). The solid lines give the theoretical energies for the principal allowed valence- to conduction-band transitions labeled 1 to 13. The split-off-band to conduction-band transitions are labeled $S1$ to $S4$.

the allowed transitions bunch together (cf. Fig. 1), and it is not possible to make a theoretical assignment.

As seen in Figs. 1 and 2, the energies of the highest four minima correspond closely to those predicted theoretically for the split-off valence- to conduction-band transitions. The spin splitting of these transitions is shown theoretically but not resolved in experiment. Point C is structure which is not seen in magnetoabsorption and is at present unexplained.

The minima in the $H=0$ spectrum occur at 0.801 eV for the direct gap transitions and at 1.083 eV for the split-off valence- to conduction-band transitions. Seraphin and Hess[7] observe peaks at 0.798 and 1.09 eV and Zwerdling, Roth, and Lax[8] find a direct gap of 0.803 eV. The difference in our $H=0$ energies is 0.28 eV, which is an experimental value for the room-temperature spin-orbit splitting at $k=0$.

We have calculated the room-temperature conduction-band mass at $k=0$ to be $m_c=(0.042 \pm 0.005)m_0$, by subtracting the computed heavy-hole energies from the measured transition energies for the heavy-hole to conduction-band transitions numbered 2 and 4 (Fig. 2). The reduced mass for the split-off valence- to conduction-band transitions, taken from the transition energy differences (Fig. 2), is $m_r \equiv m_c m_{s0}/(m_c+m_{s0})=(0.028\pm0.0007)m_0$. With this and the conduction-band mass, a mass for the split-off band at $k=0$ of $m_{s0}=0.084m_0$ is found with an error largely determined by the uncertainty of m_c. These masses are in reasonable agreement with theoretical estimates[12] and the magnetopiezoreflection data.[5]

In Fig. 3 are shown the electroreflectance of undoped, p-type GaSb near the absorption edge and of intrinsic InSb in the region of the split-off valence- to conduction-band transitions, for zero field and $H=92.4$ kG. Structure due to the onset of direct valence- to conduction-band transitions is clearly seen in GaSb. Again, taking the minimum as the resonance position, we find a room-temperature energy gap of 0.74 eV. The structure sharpens and increases in strength with magnetic field, and a satellite peak is observed, presumably associated with interband Landau-level transitions. The InSb electroreflectance in the region of the split-off valence- to conduction-band separation shows a broad negative peak. In contrast to Ge, this is of opposite sign to the peak associated with transitions at the λ point (inset Fig. 3). If we take the minimum as the onset of split-off valence- to conduction-band transitions, we find a spin-orbit splitting of 0.79 eV, where the room-temperature energy gap of 0.18 eV has been subtracted off the transition energy. Unfortunately, magneto-optical structure associated with these transitions was not observed, probably because of lifetime broadening of the submerged valence band.[13] As seen in the figure there is magnetoreflection structure below 0.8 eV, but this appears to be associated with very high energy valence- to conduction-band transitions. In conventional magnetoabsorption or reflection measurements, Landau-level structure has only been observed up to about 0.6 eV, even at liquid-He temperature.

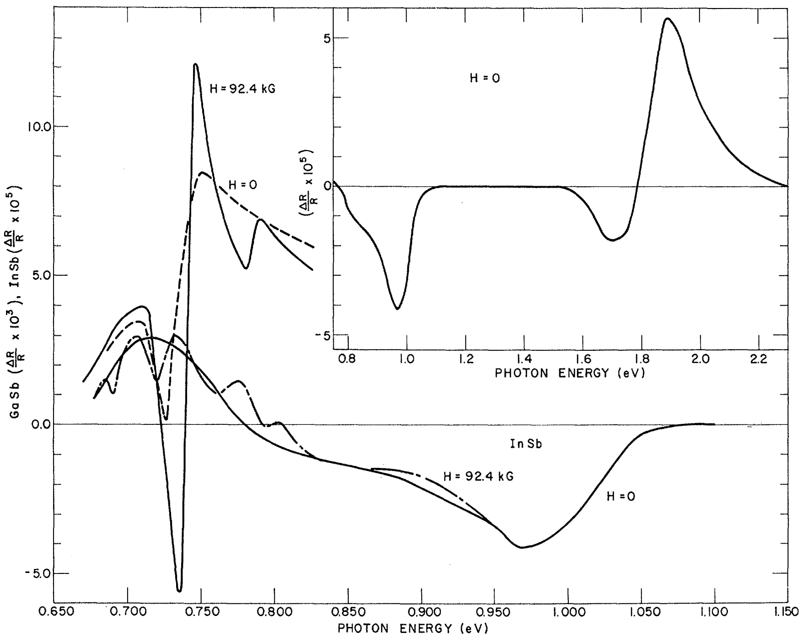

FIG. 3. Electroreflectance in the region of the absorption edge in GaSb, and of the split-off-band to conduction-band transitions in InSb, for $H=0$ and $H=92.4$ kG. Inset is shown the relative magnitude of the electroreflectance associated with the split-off-band transition at $k=0$, and the λ-point transition in InSb.

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