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MAGNETOPIEZO-OPTICAL REFLECTION IN GERMANIUM

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We report the first observation of magnetoreflection for the direct transition in germanium. Among semiconductors, a study of magnetoreflection was first made[1] in InSb but was not successfully extended to other higher energy-gap materials. We have examined the magnetoreflection in germanium by the use of piezoreflection technique reported recently by Engeler et al.[2] In this technique, the sample is mounted rigidly on a piezoelectric transducer. By applying an alternating voltage to the transducer, the sample is subjected to a small sinusoidal strain. The resulting change in reflectivity, ΔR, due to the applied strain, is detected synchronously with driving voltage on the transducer by using a phase-sensitive amplifier. In this manner, it is possible to measure fractional changes in reflectivity, $\Delta R/R$, as small as 10^{-5}. Thus piezoreflection provides a much more sensitive probe for the investigation of magnetoreflection effects in solids. It should be mentioned that one obtains an equally high sensitivity with the electroreflection technique.[3,4] A very high electric field $\sim 10^5$ V/cm has to be applied at the surface of the sample in the latter technique. As pointed out by Vrehen,[5] a high electric field tends to smear out the magnetic structure present at the direct gap in germanium. This is due to the fact that the selection rules for optical transitions are modified and additional transitions occur in the presence of the electric field.[6] Another advantage of the magnetopiezoreflection technique is that it can be applied to metals as well.

We have performed a preliminary experiment for the effect of magnetic field on the piezoreflectance for the direct transition in germanium. A Bitter-type magnet with a 4-in. bore provided magnetic fields up to ~90 kG at 4 MW. The samples were in the Faraday configuration, the direction of light propagation being parallel to the magnetic field. The reflection measurements were made with samples at near-normal incidence using a Perkin-Elmer double-pass grating monochromator equipped with a Bausch and Lomb grating blazed at 1.6 μ. A lead sulfide cell operating at room temperature was used to detect infrared radiation. Samples of single-crystal "web" germanium[7,8] were used in the present investigation. Web material grows in the form of thin flat sheets and, therefore, no polishing and/or etching is needed for sample preparation. Thus web material, whenever available,[9] provides an as-grown surface of high quality necessary for the study of reflection effects.

For the experimental results reported in this Letter, 0.15-mm-thick samples were glued to one face of a 2.5-mm-thick lead-zirconate-titanate transducer using Duco-type cement. The transducer was operated at a frequency of 1000 cps and at a level such that the rms value of the strain, S, in the plane of the sample was $\sim 5\times 10^{-5}$. In the above sample-transducer configuration, the stress on the sample is neither purely hydrostatic nor uniaxial, but a combination of the two types. The contribution of each component is determined by the crystallographic orientation of the sample and the elastic constants of the material. For the (111) germanium samples used in the present case, it can be shown[10] that the dilation, $\Delta V/V$, is equal to $(2-\lambda)S$, where

$$\lambda = 2\,\frac{c_{11}+2c_{12}-2c_{44}}{c_{11}+2c_{12}+4c_{44}} = 0.37.$$

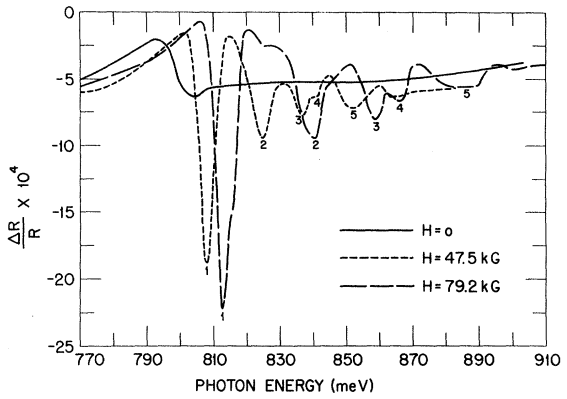

FIG. 1. Magnetopiezoreflectance for the direct transition in germanium at room temperature ($T \sim 296°K$) for various values of applied magnetic field. Both the direction of the light propagation and the magnetic field were along a [111] axis. The zero of $\Delta R/R$ should be considered arbitrary because of the presence of a wavelength-independent signal.

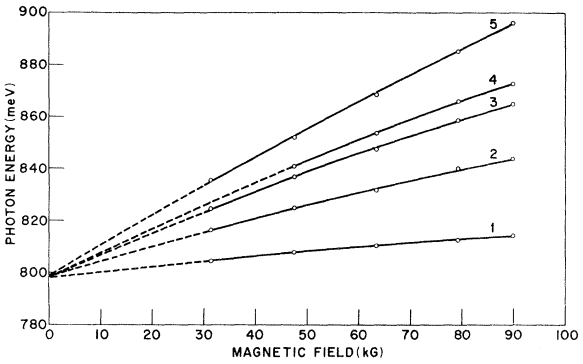

FIG. 2. A plot of the positions of prominent magnetopiezoreflectance minima as a function of the applied magnetic field. Data additional to those shown in Fig. 1 are included in this plot.

The experimental results for piezoreflectance obtained at room temperature ($T \sim 296°K$) for magnetic fields of 47.5 and 79.2 kG are shown in Fig. 1. The piezoreflectance for zero magnetic field is also given in this figure for purposes of comparison. The sign convention for $\Delta R/R$ has been chosen so as to agree with that of Engeler et al.[2] As can be seen from Fig. 1, the magnetic field has a very pronounced effect on the piezoreflectance, and the magnetopiezoreflectance exhibits oscillations. This oscillatory pattern is in good agreement with that observed by Zwerdling, Lax, and Roth[11] in the magnetoabsorption at room temperature. Thus we interpret the observed magnetopiezoreflection spectra as arising from transitions between the Landau levels of valence band and that of the conduction band. It should be mentioned that the position of the magnetopiezoreflectance minima can be determined more accurately than those of other points in the spectrum. The most prominent minima have been labeled serially for the sake of further reference. A plot of the positions of these minima as a function of the magnetic field is shown in Fig. 2. As can be seen from this figure, all the curves extrapolate to the same point. From this common intercept on the frequency axis, one obtains a value of 798 meV for the energy gap at room temperature provided the exciton effects are neglected. This value of room-temperature energy gap is somewhat lower than that of 803 meV as deduced on the basis of magnetoabsorption experiments at lower fields.[11] This small discrepancy in the energy gap may be due to the following reasons: Firstly, the sample temperature may be somewhat higher than the room temperature because of heat dissipation in the transducer, although this is not certain. Secondly, the exciton effects at high magnetic fields may be important even at room temperature because the Coulomb term increases with H.[12] This would have the effect of depressing the Landau ladder to extrapolate below the true gap. A third possibility is that the magnetopiezoreflection minima may not correspond to the magnetoabsorption peaks.

In order to obtain other quantitative results from the magnetopiezoreflection data, one must consider theoretically the effect both of the applied magnetic field and of the stress on the absorptive as well as the dispersive part of the index of refraction. We have made no analysis of this kind. However, when such an analysis is carried out, magnetopiezoreflection experiments are expected to yield very useful information on the band structure of solids. Experimentally, we have demonstrated that magnetopiezoreflection is a powerful tool in the study of reflection effects which are comparatively small. Further experiments on germanium and other semiconductors are in progress.[13]

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ENHANCEMENT OF RAMAN CROSS SECTION IN CdS DUE TO RESONANT ABSORPTION

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We have observed marked resonant enhancement of the Raman cross section for phonons in CdS at frequencies near the absorption edge. The data, taken at 77°K, can be explained on the basis of a simplified model in which the absorption band is replaced by a single effective frequency coinciding with the band edge to within one percent. The experimental technique involved collecting Raman radiation scattered from the surface of the crystal.

Resonant Raman effect in liquids was observed by Tsenter and Bobovich[1] for excitation in the neighborhood of absorption bands. Their experimental data show that the properties of Raman scattering by molecules which have continuous electronic absorption spectra are described satisfactorily by a semiclassical theory. This effect has also been called upon by Worlock and Porto[2] as a device to increase the Raman cross section of F centers. We report in this Letter a striking demonstration of this phenomenon for lattice-vibration Raman effect which we believe has never been observed before.

CdS was chosen for this experiment because its absorption edge at 77°K is quite convenient for resonance with the available lines of the Ar^+ laser. The technique and experimental arrangement are quite similar to the one already described by the authors[3] and recently extended to solids.[4] Because of absorption it was necessary to make the laser beam incident on the crystal surface at a glancing angle of about 5 deg, observation being performed on the same face, and perpendicularly to the incident beam. The CdS crystal was immersed in liquid nitrogen.

Measurements of absolute cross section are difficult, particularly near resonance where the scattering volume and effective excitation intensity are not well known because of absorption. But relative intensity measurements between two Raman-shifted frequencies in the same crystal are a simpler matter as the mentioned difficulties are largely removed.

We chose in the present experiment the one- and two-longitudinal-optical-phonon processes at 305 and 604 cm^{-1}, respectively. The spectrum in Fig. 1 shows the one-, two-, three-, and four-phonon processes. The emissions at 909 and 1200 cm^{-1} are sufficient evidence to ascribe the 604-cm^{-1} emission to the two-phonon process. In general, the frequency shift of a two-phonon process is not exactly twice that of the one-phonon process because phonons allowed by momentum conservation to participate in the former process are restricted to a narrow range of momentum, whereas in the latter, this is not so. Two phonons with opposite propagation directions may satisfy the momentum-conservation rule in a wider range of energy. This can be verified by the