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V-4. Magneto-Piezo-Optical Experiments in Semiconductors

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Preliminary room temperature results are reported of magneto-piezo-reflection experiments in germanium and InSb. It is demonstrated that acoustical modulation of the magneto-reflection enhances the optical structures which are identified with interband transitions. By extrapolation of the magneto-piezo-reflection results to zero magnetic field, the resonance frequency within the piezo-reflection linewidth is determined. In germanium, results are reported for interband transitions across the indirect bandgap and the lowest direct bandgap; and also between the spin-orbit split-off valence band and the $\boldsymbol{k}=0$ conduction band. In InSb, results are presented for interband transitions across the lowest bandgap.

§ 1. Introduction

The piezo-optical technique has proven to be a very useful tool in providing information on the electronic band structure of solids.[1,2] This method has been used to increase the spectral sensitivity in the reflection and absorption experiments in semiconductors and metals.

It is well known that more detailed information on the band structure can be obtained by performing optical experiments in a magnetic field.[3] The application of a magnetic field, H, to the differential piezo-optical technique also results in a marked improvement in the sensitivity of the magneto-optical measurements.

In this work acoustical modulation is applied to the magneto-reflection rather than to the magneto-absorption technique. By making reflectivity measurements, it is possible to operate at energies large compared with the lowest direct bandgap. Above this bandgap, transmission measurements on samples of reasonable thickness are not possible because of the prohibitively high absorption. Furthermore, the magneto-piezo-reflection technique is also applicable to the study of metals, where the absorption coefficients are high even below the lowest direct bandgap.

§ 2. Experimental Method

The magneto-piezo-reflection experiment is similar to the conventional magneto-reflection experiment,[4] except for the addition of acoustical modulation to the optical signal. The acoustically modulated reflectivity signal is synchronously detected using a standard lock-in amplifier. A geometrical arrangement like that described by Engeler *et al.*[1] was also found to be convenient for the magnetic field experiments. The measurements described in this paper have been taken at $T\sim 300°$K and with a modulation frequency of $\sim$1 kc.

The periodic stress effectively modulates the Landau level structure, so that by phase sensitive detection at the applied acoustic frequency it is possible to observe a differential spectrum associated with the interband transitions between Landau levels. The experiments were carried out either at a constant $\hbar\omega$ by sweeping H or at constant H by sweeping $\hbar\omega$. It is convenient

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to use the latter method for surveying a large range of photon energies and the former method for studying detailed structure.

§ 3. Results in Germanium

Although magneto-absorption oscillations associated with interband transitions at $k=0$ have been previously observed in thin germanium samples at room temperature,[3] the corresponding magneto-reflection effect has never been reported. However, by acoustically modulating the Landau levels, a large enhancement of the oscillations results, as shown in Fig. 1. Here we compare the H dependence of the reflectivity itself with the H dependence of the piezo-reflectivity. These recorder traces were taken at 0.826 eV, which lies above the lowest direct gap of germanium. The resonances for interband transitions between Landau levels are indicated by arrows.

The frequency variation of the piezo-reflection in this energy region is shown in Fig. 2 for various values of H. This figure emphasizes the enhancement of the resonant structure by the application of a magnetic field. Above $\sim$20 kG, the amplification is approximately linear with field, as one would expect from density of states considerations. Also seen in Fig. 2 is a shift in the frequency of the piezo-reflection peak. This shift corresponds to the motion of the lowest Landau level with increasing H. By plotting the H dependence of the piezoreflection maxima, minima and inflection points corresponding to the lowest interband transition, it is found that all three positions on the magnetic field resonance line extrapolate to the inflection point of the zero field piezo-reflection line. This result suggests that the energy band gap is determined from the photon energy corresponding to the zero field inflection point.

A summary of the interband transition observed on a (111) face of germanium is given in Fig. 3. Here we have plotted the position in photon energy and magnetic field of the piezo-

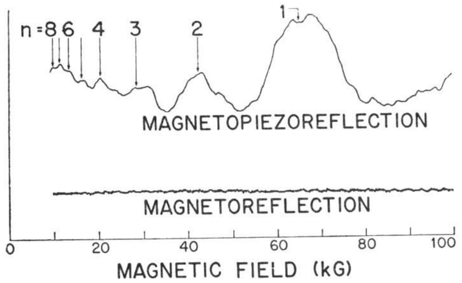

Fig. 1. Recorder traces from (111) face of germanium at 300°K and 0.826 eV.

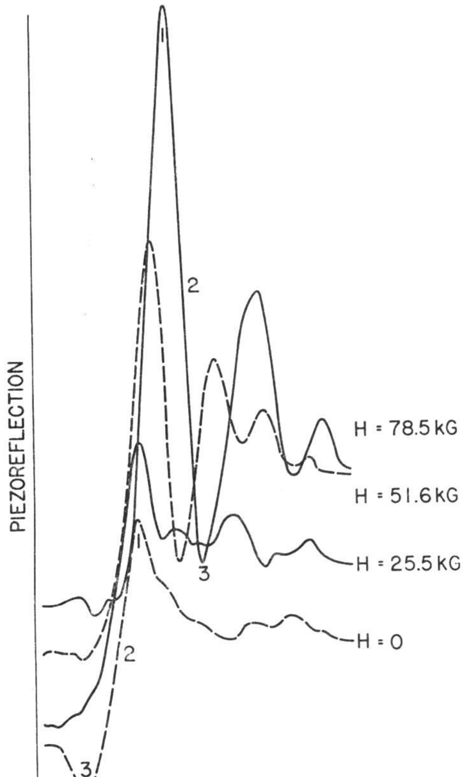

Fig. 2. Piezo-reflection vs. $\hbar\omega$ near the direct bandgap for various values of H. Here $H\perp$ (111) face of germanium at 300°K. The piezo-reflection maxima (1), inflection points (2) and minima (3) which are discussed in the text are indicated both for the $H=0$ and $H=78.5$ kG traces.

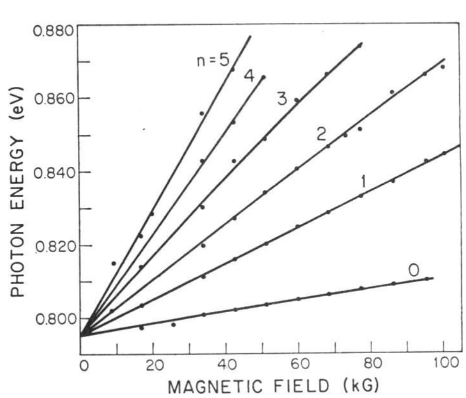

Fig. 3. Interband transitions across direct bandgap for a (111) face of germanium at 300°K by magneto-piezo-reflection technique.

reflection maxima. The value for the direct bandgap obtained from this data is 0.795 eV which is somewhat lower than the value of 0.803 eV obtained from magneto-absorption.[3] Using a value of $m_v^*=0.375m_0$ for the valence band,[5] $m_c^*=0.041m_0$ was found for the conduction band.

An attempt was made to obtain an experi mental criterion for locating the resonance position within the magneto-piezo-reflection linewidth. Curves for the $n=0$ transition were constructed using the piezoreflection maxima, minima, and inflection points and the slopes of these curves were compared with the slope from the room temperature magneto-absorption data for the $n=0$ transition.[3] It is this lowest quantum transition which is most sensitive to the details of the lineshape. The best fit with the magnetoabsorption data of Zwerdling *et al.*[3] was obtained by taking the resonance point at the magneto-piezo-reflection *maxima*. However, since the fit obtained by selecting the magneto-piezo-reflection inflection points was almost as good, this criterion for the determination of the resonance position is not well established. In this paper, the analysis was carried out by selecting these maxima.

Not only it is possible to study with greater sensitivity the structure associated with the direct bandgap, but one is also able to investigate new aspects of the germanium band structure using the magneto-piezo-reflection technique. For example, Fig. 4 illustrates the H dependence of phonon-assisted interband transitions associated with the indirect bandgap of germanium. Previous investigations of the Landau level transitions at the indirect bandgap have been carried out at low temperatures and have therefore involved the emission of a phonon.[3,6] By the magneto-piezo-reflection technique, these transitions can also be observed at room temperature, but, in addition, we observe the corresponding transitions involving the absorption of a phonon (Fig. 4). Here we have shown several traces at fixed values of H of the piezoreflection about the LA_a phonon line first reported by Engeler *et al.*[7] in zero-field piezoabsorption studies. The behavior of this structure was found to be sensitive to the polarization of the light relative to the acoustical stress direction, in agreement with Engeler's results. In Fig. 4, the light is incident on a (111) face and the uniaxial acoustical stress is applied in a $[11\bar{2}]$ direction. The most prominent structure in the magnetic field is labeled 1, and the next largest peak toward higher photon energies is labeled 2, etc.. Other magnetic field structures at lower photon energies are also observed in this figure, but these have not yet been analyzed in detail. A summary of the most prominent piezo-reflection maxima (similar to Fig. 3) shows that these maxima extrapolate in zero magnetic field to 0.635 eV, which corresponds to the inflection point of the zero field piezo-reflection line. The slope of the line corresponding to the lowest quantum number transition compares well with the low temperature result of Zwerdling.[3]

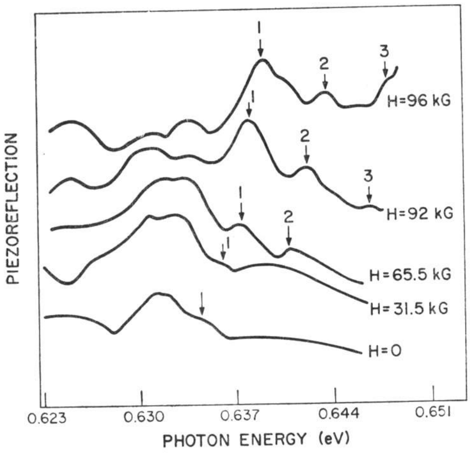

Fig. 4. Piezo-reflection vs. $\hbar\omega$ near 0.63 eV for various values of H. The resonances are identified with indirect transitions involving absorption of a phonon.

The magneto-piezo-reflection technique is also useful in studying interband transitions above the direct energy bandgap. We report here the observation of direct transitions from the spin-orbit split-off valence band at $\boldsymbol{k}=0$ to the lowest conduction band. A recorder trace showing these transitions is given in Fig. 5 for $H\perp$ (100) face of germanium. Arrows pointing downward indicate the location of the resonances expected at 1.13 eV using $m^*/m_0=0.041$ and 0.074 for the conduction and split-off valence bands, respectively. The arrows pointing upward give the corresponding resonance locations for transitions across the lowest direct bandgap. For the $n=2$ transition, the experimental trace exhibits a splitting, which may be associated with the effective g-factors for the pertinent bands. Analysis of traces like that of Fig. 5 yields a value for the spin-orbit split-off bandgap of

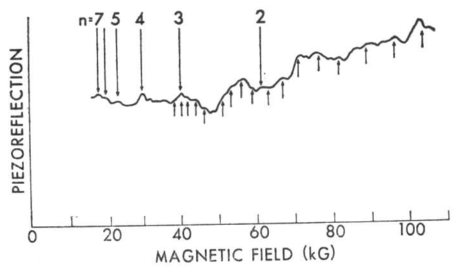

Fig. 5. Magneto-piezo-reflection at 1.13 eV showing resonances associated with direct interband Landau level transitions at $k=0$. The arrows indicate resonance positions calculated from known m^* values.

1.08 eV, which may be compared with the value of 1.09 eV, obtained from electroreflectance studies.[8)]

§ 4. Results in InSb

Since InSb has small effective masses, it has been the subject of numerous magneto-optical investigations.[3,9,10–12)] With the magneto-piezo-reflection technique, an impressive enhancement is found for the resonances identified with interband transitions as seen in Fig. 6, where a comparison is made between the magneto-reflection and magneto-piezo-reflection at 0.253 eV for a (100) face. Of particular interest is the difference in the lineshapes in the two recorder traces of this figure. Magneto-reflection lineshape calculations for the resonances associated with interband transitions between Landau levels[13)] have shown that when the pertinent bandgap $\gg \hbar\omega_p$ (where ω_p is the

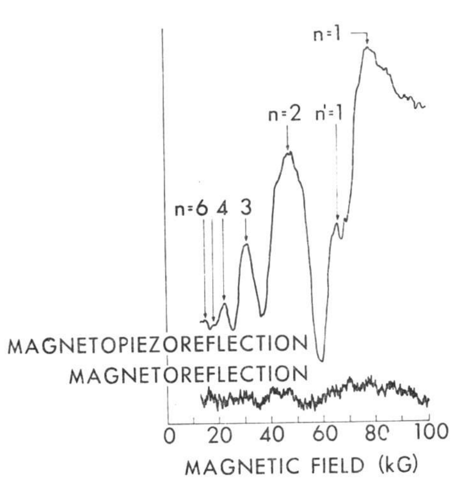

Fig. 6. Recorder traces from (100) face of InSb at $T\sim300$°K and 0.253 eV. To be more easily observable, the vertical scale for the lower trace has been expanded by a factor of 2.

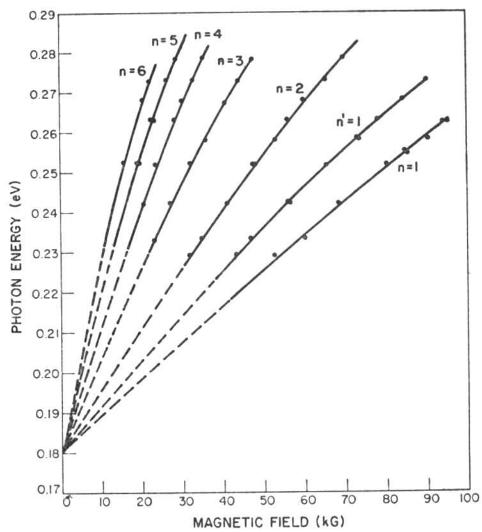

Fig. 7. Interband transitions across lowest bandgap for (100) face of InSb at $T\sim300$°K.

plasma frequency), the resonance positions are in the vicinity of the reflectivity maxima. A comparison between the two traces in Fig. 6 shows that the reflectivity maxima in the magneto-reflection approximately correspond to the maxima in the magneto-piezo-reflection, although this comparison is not definitive because of the broadness of the magneto-reflection resonances. Thus, as in the case of germanium, there is a need for a line-shape calculation to interpret the magneto-piezo-reflection data.

A summary of these piezo-reflection maxima as a function of $\hbar\omega$ and H is given in Fig. 7. The curves have been extrapolated to the room temperature bandgap obtained from magneto-absorption measurements.[3)] The fan chart of Fig. 7 exhibits the non-parabolic-behavior associated with the small m^* and bandgap in InSb.[14)] The curves labeled $n=1, 2, \cdots 6$ are in fairly good agreement with the corresponding curves obtained from magneto-absorption.[3)] The additional $n'=1$ line, which arises from the complexity of the valence band structure of InSb,[14)] has also been observed by the magneto-absorption technique.[11)]

§ 5. Summary

These preliminary measurements on germanium and InSb indicate the power of the magneto-piezo-reflection technique. Most of the effects discussed in this paper have been observed for the first time on reflection and at room temperature. Some of these effects have not been previously reported: as, for example, the magnetic field dependence of the interband transitions across the indirect bandgap involving the absorption of a phonon and the direct Landau level transitions from the spin-orbit split-off band to the conduction band.

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