solution to the homogeneous equation is

$$\varphi_k{}^{lm}\sinh^2\eta_k=\mathbf{k}\cdot\mathbf{A}, \quad (5.5)$$

where $\mathbf{A}$ is an arbitrary constant vector. Since χ_k is an even function of $\mathbf{k}$, $\mathbf{k}\cdot\mathbf{A}$ is orthogonal to χ_k. This differs from the corresponding case for thermal conductivity wherein normal processes cannot be treated alone. (For thermal conductivity the inhomogeneous term is an odd function of $\mathbf{k}$.)

Next consider the scattering due to imperfections alone; then

$$\chi_k=L_2[\varphi_k{}^{lm}]. \quad (5.6)$$

In this case an arbitrary $g(\omega_k)$ is a solution to the homogeneous equation; however, as is apparent from (5.4) only the particular form $g(\omega_k)=\omega_k/\sinh^2\eta_k$ is orthogonal to χ_k. Therefore, one cannot calculate a contribution to the coefficients of viscosity by treating the imperfections as the only scattering mechanism.

Combining the discussion in the preceding two paragraphs, if we wish to treat both anharmonic forces and imperfections, Eq. (5.1), we have the possibilities of either including or not including U processes in the calculation of the viscosity coefficients. It remains for specific applications to determine the relative importance of N and U processes.

PHYSICAL REVIEW VOLUME 138, NUMBER 3A 3 MAY 1965

Fundamental Absorption Edge of Tin Telluride

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(Received 7 December 1964)

Infrared transmission and reflection measurements at room temperature have been made at energies between 0.2 and 0.7 eV on single-crystal p-type SnTe films with carrier concentrations of $\sim 1\times 10^{20}$ cm^{-3}. The absorption spectrum is characterized by a sharp absorption edge commencing near 0.5 eV and extending to higher energies. This rapid rise is believed to be the result of direct transitions between a valence and a conduction band. Because of the Burstein shift of the edge, the separation of the band extrema is expected to be significantly less than 0.5 eV. For energies below 0.5 eV it is shown that the absorption is primarily due to free carriers. This indicates that the observed absorption edge is associated with the smallest direct optical gap between the valence and conduction bands.

RECENT studies of the electrical and thermal properties of p-type SnTe indicate that the material is a semiconductor and that two valence bands play a significant role in determining the transport properties.[1–4] The similarity of the electrical properties of this material to those of lead telluride has been demonstrated[5] and adds additional weight to the belief that the material is a semiconductor. However, the possibility that SnTe is a semimetal[6,7] cannot be definitely ruled out on the basis of existing information. Despite the rather extensive experimental study of this compound during the past few years, little is known about the parameters characterizing its conduction and valence bands. The infrared-absorption measurements which we report here are intended to contribute to this subject since they yield information about the separation of these bands.

The major difficulty in carrying out such measurements in the past has been that extremely thin samples are required because of the large optical absorption existing throughout the infrared region. This absorption is at least partially due to the high concentration of free carriers characteristic of the bulk material now available. Sufficiently thin optical samples could not be prepared by lapping the bulk material without causing undesirable crystal damage. We have overcome this difficulty by preparing large-area, thin single-crystal films of SnTe which are ideal for optical measurements of this kind. These films were grown epitaxially upon cleaved potassium chloride employing, in general, the techniques described previously for making lead sulfide films.[8] Using these films, a sharp absorption edge has been observed in the infrared region near 0.5 eV. We believe this edge is associated with the onset of direct

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[1] R. S. Allgaier and P. O. Sheie, Bull. Am. Phys. Soc. **6**, 436 (1961).
[2] R. F. Brebrick and A. J. Strauss, Phys. Rev. **131**, 104 (1963).
[3] J. A. Kafalas, R. F. Brebrick, and A. J. Strauss, Appl. Phys. Letters **4**, 93 (1964).
[4] B. B. Houston and R. S. Allgaier, Bull. Am. Phys. Soc. **9**, 293 (1964).
[5] R. S. Allgaier and B. B. Houston, *Proceedings of the International Conference on Semiconductor Physics, Exeter, 1962* (The Institute of Physics and the Physical Society, London, 1962), p. 172.
[6] A. Sagar and R. C. Miller, *Proceedings of the International Conference on Semiconductor Physics, Exeter, 1962* (The Institute of Physics and the Physical Society, London, 1962), p. 653.
[7] D. H. Damon, C. R. Martin, and R. C. Miller, J. Appl. Phys. **34**, 3083 (1963).
[8] R. B. Schoolar and J. N. Zemel, J. Appl. Phys. **35**, 1848 (1964); J. N. Jemel, J. D. Jensen, and R. B. Schoolar (to be published).

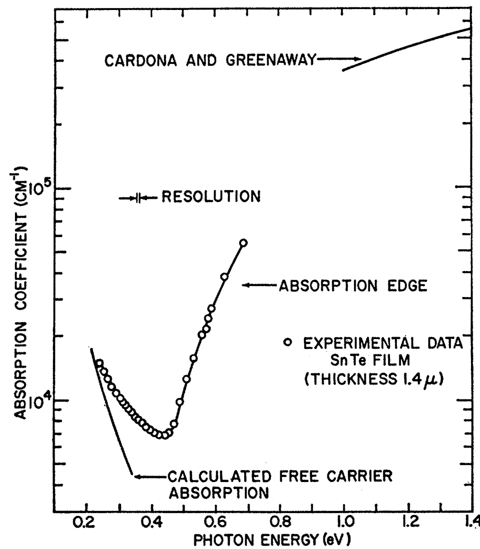

FIG. 1. Optical absorption of p-type SnTe at room temperature for material having a carrier concentration of 1×10^{20} cm^{-3}. The calculated curve is based upon the classical free-carrier model and parameters given in the text.

transitions between a valence and a conduction band.

Our results are shown in Fig. 1. The absorption coefficients were calculated from meaurements of transmittance and reflectance at normal incidence. The analysis of these data took into account the effects of multiple interference and the film backing, as described previously.[9] The results apply to SnTe at room temperature having a hole concentration, N, of 1×10^{20} cm^{-3} and a conductivity mobility, μ, of 350 cm^2/V-sec. These quantities were determined from measurements of the weak-field Hall coefficient R_H and the electrical conductivity σ using the relations $N=0.6/R_He$ and $\mu=R_H\sigma/0.6$.[10] The film thickness of 1.4 μ was obtained from an analysis of interference fringes observed in the reflectance.

On the high-energy side of the minimum shown in Fig. 1 the absorption increases rapidly toward a plateau region indicated by the results of Cardona and Greenway.[11] This behavior is characteristic of a fundamental absorption edge. The increase in absorption on the low-energy side of the minimum is believed to be associated primarily with free-carrier absorption. This assertion is based upon the similarity illustrated in the figure between the experimental data and the curve calculated on the basis of the classical free-carrier model. These calculations were based upon an effective carrier mass of $0.1m_e$, an optical dielectric constant of 50, and the electrical properties described above. The first two quantities are estimates made from the reflectivity data reported by Bis.[12] The uncertainties associated with the input quantities account for the discrepancies between calculation and experiment shown in Fig. 1. This evidence that the low-energy absorption is primarily due to free carriers is of particular significance. It indicates that other absorption edges involving direct transitions between valence and conduction bands do not exist at lower energies.

The energy at which the absorption edge occurs cannot be equated directly to the separation of conduction- and valence-band extrema. The high carrier concentration of our films is expected to produce a Burstein shift of the edge to an energy larger than that separating the extrema. An analysis of our data taking the Burstein shift into account requires detailed information about the conduction and valence bands which is not known. However, estimates based upon plausible models all indicate that the separation of extrema is significantly less than 0.5 eV.

In summary, an absorption edge has been observed which we believe to be associated with the smallest direct optical gap between a conduction and a valence band of SnTe having a hole concentration of 1×10^{20} cm^{-3}. There is a possibility of smaller indirect gaps or overlapping bands. Consequently, our results cannot be used to establish that this compound is a semiconductor. They do serve, however, as important and necessary evidence for this classification.

It is a pleasure to acknowledge helpful discussions with R. S. Allgaier and J. L. Davis. Thanks are due to B. B. Houston, Jr. who furnished the SnTe material for the evaporations and to E. P. Wenzel for making some of the electrical measurements.

[9] R. B. Schoolar and J. R. Dixon, Phys. Rev. **137**, A667 (1965).
[10] B. B. Houston, R. S. Allgaier, J. Babiskin, and P. B. Siebenmann, Bull. Am. Phys. Soc. **9**, 60 (1964).
[11] M. Cardona and D. L. Greenaway, Phys. Rev. **133**, A1685 (1964).
[12] R. F. Bis, Solid State Commun. **2**, 161 (1964).