Infrared Absorption in *P*-Type Germanium*

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Infrared absorption in *p*-type germanium was investigated at various temperatures down to 5°K. The absorption coefficient is proportional to the hole concentration and shows band structure, a strong band beyond 10 microns and two weaker bands at shorter wavelengths. The strong band is shown to be caused by excitations within the filled band because of the presence of holes. The relative strengths of the two weaker bands change with temperature, only one being observable at low temperatures.

THE absorption of infrared radiation ($h\nu$ less than the forbidden energy gap) in *p*-type germanium[1] shows spectral structure in contrast to the case of *n* type, where the absorption increases smoothly approximately λ^2. Figure 1 shows the absorption curves reduced to unit carrier concentration, after subtracting the lattice absorption.[2] The *p*-type curve shows two weak bands[3] at 2200 cm^{-1} and 3500 cm^{-1}, followed by a much stronger band beginning around 1800 cm^{-1}. The smoothly rising *n*-type curve is much lower.

Regarding the mechanism of absorption, the following observations are to be noted. (A) Samples having different hole concentrations with either indium or aluminum as acceptor give approximately the same absorption curve reduced to unit hole concentration. (B) The Fermi level in these samples varied from 0.1 ev to 0.24 ev above the valence band, whereas the strong absorption band corresponds to $h\nu < 0.1$ ev. (C) *P*-type material with fairly high acceptor concentration after being converted to high-resistivity *n* type by adding donor impurities to the melt showed only weak absorption, characteristic of *n* type. It follows from (B) that the strong absorption band cannot be due to excitation of electrons from the valence band to empty levels within the energy gap. Furthermore, in view of (C) it cannot be due to excitation of electrons from localized states to higher excited states. It could only be caused then by excitations within the valence band due to the presence of holes. This indicates an overlapping of bands and complicated band structure. The evidence is not as conclusive, however, for
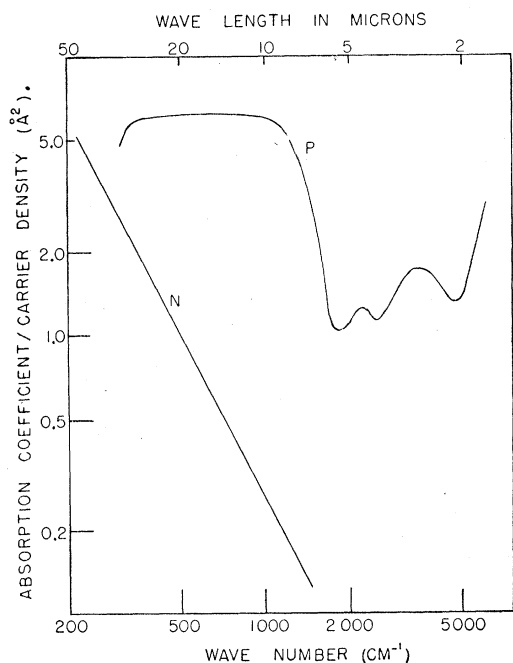

FIG. 1. Absorption coefficient reduced to unit carrier concentration for germanium. The lattice absorption independent of carrier concentration has been subtracted.

[1] R. J. Collins and H. Y. Fan, Purdue Semiconductor Progress Report, June 30, 1953 (unpublished); Kaiser, Collins, and Fan, Bull. Am. Phys. Soc. 28, No. 2, 32 (1953).
[2] R. J. Collins and H. Y. Fan, Phys. Rev. 86, 648 (1952); R. C. Lord, Phys. Rev. 85, 140 (1952).
[3] H. B. Briggs and R. C. Fletcher, Phys. Rev. 87, 1130 (1952).
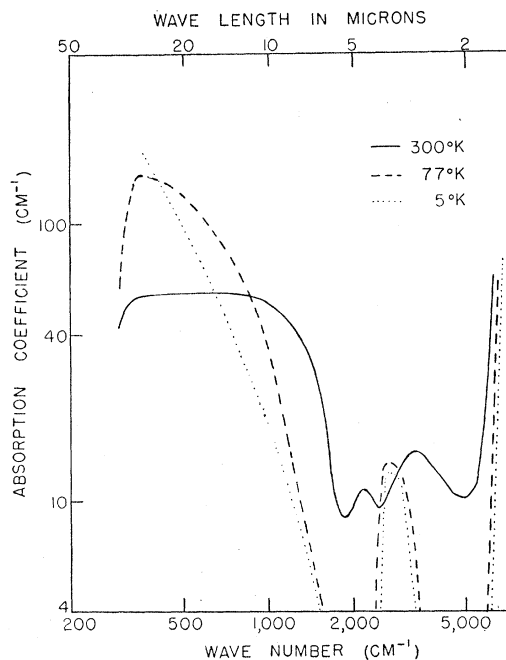

FIG. 2. Absorption coefficient for indium-doped *p*-type germanium with room temperature resistivity 0.07 ohm-cm. The lattice absorption has been subtracted.

the two short wavelength peaks, which correspond to $h\nu$ close to one half of the energy gap.

Figure 2 shows typical absorption coefficient curves for indium-doped samples at 300°K, 77°K, and 5°K. For different samples the low temperature curves are also proportional to the room temperature hole concentrations. At 77°K the hole concentration in these samples is the same as at room temperature. Thus, the mechanism for the strong absorption band seems to be the same as at room temperature. This conclusion is supported by the measurement of gold-doped samples.[4] These p-type samples with an acceptor activation energy of 0.23 ev have very few holes at 77°K. At 300°K the measured absorption is the same as in other samples of corresponding carrier concentration, and at 77°K the absorption becomes negligible.

There is some uncertainty about the interpretation of the absorption at 5°K. Within the limit of measurements the long wavelength absorption has not reached a peak. It is, therefore, uncertain whether we have here the same band observed at the higher temperatures. Furthermore, the Hall coefficient of the samples reaches a maximum at some low temperature, the magnitude and temperature depending on the sample purity, and drops again to about the room temperature value by 5°K. The resistivity at 5°K, on the other hand, can be orders of magnitude higher than at 300°K.[5] Consequently, it is not certain that the measured Hall coefficient gives the true hole concentration in the valence band, and we cannot be sure that the long wavelength absorption is due to the presence of free holes.

Figure 3 shows the absorption curves above 1000 cm^{-1} at various temperatures. Of the two peaks observed at room temperature the one at longer wavelength decreases with decreasing temperature, unseen at 77°K, whereas the one at shorter wavelength increases and shows a shift toward longer wavelength.

[4] Benko, Fan, and Lark-Horovitz, Purdue Semiconductor Progress Report, June 30, 1952 (unpublished).
[5] Measurements by H. Fritzsche [see C. S. Hung and J. R. Gliessman, Phys. Rev. **79**, 726 (1950)].
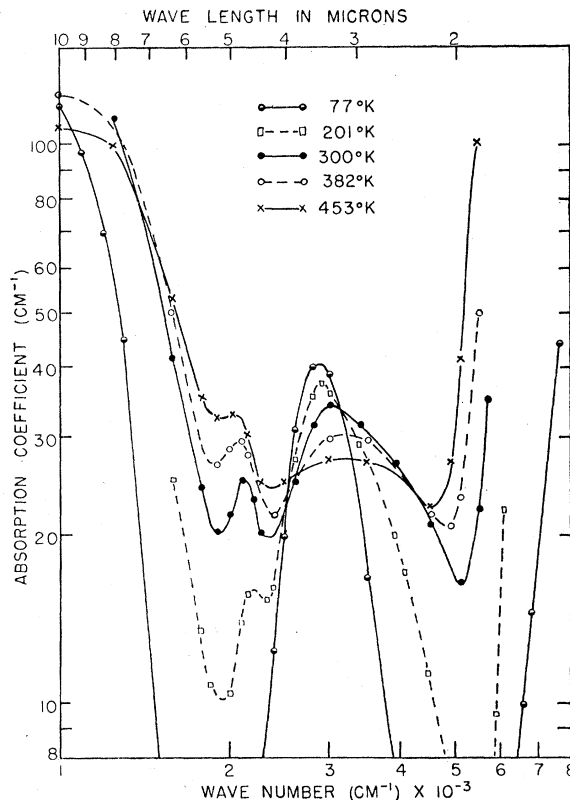

FIG. 3. Absorption coefficient for indium-doped p-type germanium with room temperature resistivity 0.04 ohm-cm.

Up to the highest temperature the sample is in the impurity range, the hole concentration remaining practically constant. A possible explanation for the temperature variation of the two bands might be that the one at longer wavelength is connected with holes of higher energy. It is also possible that the longer wavelength peak involves the absorption of an optical phonon.[6] However, the two peaks are~0.1 ev apart, whereas the strong lattice band in germanium corresponds to only 0.04 ev.[2]

[6] Suggested by Professor J. Bardeen in a private discussion.