Optical Absorption in p-Type Gallium Arsenide

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In p-type gallium arsenide, a number of absorption bands have been observed on the low-energy side of the intrinsic absorption edge. The absorption spectrum has a distinct peak at 0.42 ev, a partially resolved peak at 0.31 ev and the beginning of a strong absorption band setting in at 0.25 ev. The main features of the spectra can be explained in terms of hole-transitions between different branches of the valence band of gallium arsenide. The transitions between light- and heavy-hole bands and a band split off by spin-orbit splitting are identified. The spin-orbit splitting is $\sim$0.34 ev.

IN p-type gallium arsenide, a number of absorption bands have been observed on the low-energy side of the intrinsic absorption edge. Similar structure was found in all p-type samples regardless of the doping agent used to introduce the free-hole concentrations. The evidence is that these bands are associated with free-hole absorption and are not due to the presence of unknown impurities or lattice defects. The main features of the spectra can be explained in terms of hole transitions between different branches of the valence band of gallium arsenide.

The absorption spectrum for p-type gallium arsenide at 295°K with $p=3\times10^{16}$/cm³ is shown in Fig. 1. The hole concentration was determined from a Hall measurement on a sample cut from a slice adjacent to the one used for the optical measurements. The curve shows a distinct peak at 0.42 ev, a partially resolved peak at 0.31 ev, and the beginning of a strong absorption band setting in at 0.25 ev. This sample was specifically doped with zinc. Identical absorption structures were found in cobalt-doped samples. n-type samples of gallium arsenide do not show this type of absorption structure, but instead exhibit a monotonically increasing absorption with wavelength at these carrier concentrations. However, when samples which were initially n-type were converted to p-type by heat treatment, owing to the diffusion of an unknown impurity, optical measurements revealed the same type of absorption spectrum as shown in Fig. 1. In all p-type samples, the absorption constant at a given energy increased with the hole concentration. However, at high carrier concentrations, i.e., $p\sim10^{17}$/cm³, the absorption cross section was not a constant.

The spectral distribution of the absorption in p-type gallium arsenide is strongly reminiscent of the structure seen in p-type germanium,[1] aside from slight differences in the positions of the bands. An analysis of the absorption spectrum shown in Fig. 1, assuming a valence band structure for gallium arsenide similar to that of germanium,[2,3] allows an identification of the interband hole transitions. The band at 0.42 ev is attributed to transitions between band 3, the band split off by spin-orbit interaction, and band 1, the heavy-hole band; the peak at 0.31 ev is attributed to transitions between band 3 and band 2, the light-hole band. The onset of the absorption band at 0.25 ev is then attributed to transitions between the light- and heavy-hole bands. The bands are labeled as in the case of germanium. Since the gallium arsenide lattice lacks a center of inversion, it is expected that the degeneracy[4,5] of the heavy-hole bands would be split. The present measurements indicate that the energy separation between the valence band maxima and the intercept of the heavy-hole bands at $k=0$ is small.

The trough between the 0.42- and 0.31-ev peaks indicates a spin-orbit splitting of $\simeq$0.34 ev for gallium arsenide. The spin-orbit splitting in germanium[2,3] is 0.29 ev. The larger splitting in gallium arsenide is to be expected from considerations of the spin-orbit splitting
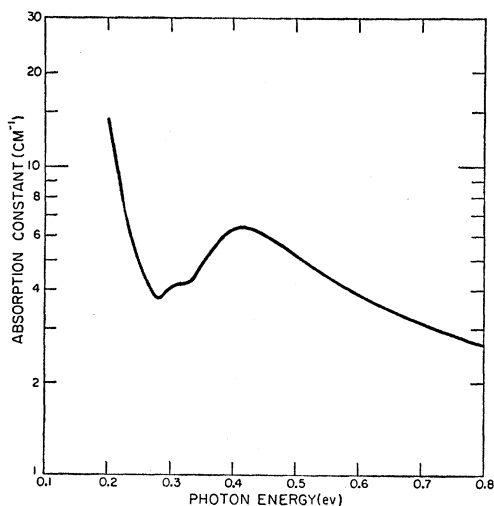

Fig. 1. The absorption coefficient for p-type gallium arsenide at 295°K with $p=3\times10^{16}$/cm³.

[1] H. B. Briggs and R. C. Fletcher, Phys. Rev. 87, 1130 (1952); 91, 1342 (1953).
[2] A. H. Kahn, Phys. Rev. 97, 1647 (1955).
[3] E. O. Kane, J. Phys. Chem. Solids 1, 83 (1956).
[4] R. H. Parmenter, Phys. Rev. 100, 573 (1955).
[5] G. Dresselhaus, Phys. Rev. 100, 580 (1955).

of the atomic p-functions of Ga, As, and Ge; these can be estimated from atomic spectra to be 0.10, 0.30, and 0.20 ev for Ga, As, and Ge, respectively.[6] If we assume the same normalization factor for gallium arsenide, as seems appropriate for germanium in estimating the spin-orbit splitting in the solid from the free-atom value, we find that an electron at the top of the valence

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[6] We wish to thank E. O. Kane for these estimates.

band at $k=0$ spends more time on an arsenic atom than on a gallium atom.

Preliminary measurements of these bands as a function of temperature indicate the same qualitative temperature dependence observed in germanium.[1]

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Simplified Quantum-Mechanical Theory of Pressure Broadening

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Quantum mechanics is used to treat the motion of the perturbers broadening a line. Several simplifying assumptions are made, such as the Born-Oppenheimer approximation, and the assumption of no degeneracy. These assumptions can be removed. Also made is the "impact approximation," which is essential for the validity of the results and cannot be removed. With it, the line has a Lorentz shape, and its width and shift are expressed in terms of the two scattering amplitudes of the perturbers by the atom in its upper and lower state. The case where the perturbers do not interact appreciably with the lower state is particularly simple. Then, the width and shift are proportional to the imaginary part and the real part of the forward scattering amplitude, respectively. A quantity called the "collision volume" is defined. It is shown that the impact approximation is valid only if the collision volume is much smaller than the volume per perturber. There is a second validity condition, which has no classical analog.

1. INTRODUCTION

PRESSURE broadening of spectral lines arises when an atom, molecule, or ion, which is emitting light in a gas, is disturbed by its interactions with the other constituents of the gas, such as other atoms, molecules, ions, or electrons. The study of this phenomenon is necessary for accurate spectroscopic observations, and it can in addition yield useful information about the conditions and concentrations in the gas. With the recent interest in high-temperature ionized gases, much thought has been given to using pressure broadening as a tool for measuring temperatures and ion or electron densities inside the gas. The theory of these effects has received a lot of attention in recent years.[1] Most theoretical work uses the "classical path approximation." It assumes that the "perturbers," i.e., the atoms, molecules, ions, or electrons that disturb the light-emitting object, move like classical particles, and, for simplicity, their trajectories are usually taken to be straight lines. Their effect on the line is then calculated using quantum mechanics. The classical path approximation is sometimes perfectly justified, particularly when the perturbers are heavy (i.e., not electrons).

By a "quantum-mechanical theory," we mean a theory where the motion of the perturbers is treated by quantum mechanics. The need for such a theory arises whenever the classical path approximation breaks down. This will happen, for instance, if the distance between the atom[2] and the nearest perturber is of the same order of magnitude as the wavelength of one or the other. Then, it is not a good approximation to replace the translational wave functions by wave-pockets moving according to the laws of classical mechanics. For light perturbers, like electrons, whose wavelength is therefore relatively large, this breakdown may occur for a sizable fraction of the total number of collisions. Thus, quantum-mechanical effects are important for a theory of electron broadening. Quantum mechanics must also be taken into account whenever the collision of a perturber with the atom is strongly inelastic, i.e., the energy transfer is not small compared to the kinetic energy. This will occur frequently in an ionized gas. Thus, it appears desirable to have a fully quantum-mechanical theory of pressure broadening, even if one is led to find afterwards that, in many cases, the classical path theory constitutes a good approximation to it.

The quantum-mechanical theory in this paper is "simplified" because several important approximations are made. These approximations are not really neces-

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[1] See the following reviews: A. Unsöld, *Physik der Sternatmosphären* (Springer-Verlag, Berlin, 1955), second edition, Chaps. 11 and 13; S. Ch'en and M. Takeo, Revs. Modern Phys. **29**, 20 (1957); R. G. Breene, Jr., Revs. Modern Phys. **29**, 94 (1957).

[2] We shall usually call the light-emitting object in the gas "the atom," even though it may be an ion or a molecule.