by a diamagnetic shift and by magnetic mixing with $P_{z\pm}$. Brevity requires the omission of the discussion of the effect of this mixing on the strengths of $P_{y\pm}$ (where the effect is small) and $P_{z\pm}$ (where the effect is large).

The theory indicates that the sign of $(\vec{k}\times\vec{H})\cdot\vec{z}$ should determine which lines are strong. (One should note that $\vec{z}$ and $-\vec{z}$ are not equivalent directions in wurtzite.) The rotation experiments agree with this theoretical conclusion.

The peculiar band structure[3] of CdS makes A rather small and k_yB unexpectedly large for the states under study. Independent evidence in experiments with H parallel to the c axis indicates that $|k_yB/A| \approx \frac{1}{2}$. If A and B have the same phase, this could lead to a 9:1 intensity ratio of strong $P_{x\pm}$ or $P_{y\pm}$ to weak $P_{x\pm}$ or $P_{y\pm}$ lines, in at least qualitative agreement with experiment.

A second effect, independent of the effect just described, should be observable in magneto-optic experiments because of the finite wave vector of light. A quasi-electric field $(1/c)\vec{v}\times\vec{H}$ should act on excitons in a uniform magnetic field due to the exciton center-of-mass velocity (finite wave vector). In CdS, this field should be approximately 150 volts/cm for $H=30\,000$ gauss. This small electric field is capable of producing observable effects on excitons of large radius (say >100 A) if the excitons can exhibit a linear Stark effect. We have compared experimental results for $\vec{H}\perp\vec{k}$ and $\vec{H}\parallel\vec{k}$ to look for this effect. Unfortunately we have not yet been able to isolate this effect due to other complications which arise. It should be possible, however, to perform exciton mass spectrometry experiments with crossed electric and magnetic fields. By balancing the quasi-electric field with a real field, $\vec{v}$ (and thus the exciton mass) can be determined.

We wish to thank Dr. W. W. Piper of the General Electric Company Research Laboratory for providing the crystals.

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[1] D. G. Thomas, J. Phys. Chem. Solids (to be published).

[2] J. J. Hopfield and D. G. Thomas, J. Phys. Chem. Solids (to be published).

[3] D. G. Thomas and J. J. Hopfield, Phys. Rev. 116, 573 (1959).

PHOTOSENSITIVE ULTRASONIC ATTENUATION IN CdS

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It has been observed in this laboratory that the physical acoustical properties of CdS crystals are influenced by photon irradiation. Upon illumination with white light from an incandescent lamp, the ultrasonic wave propagation measured by the change in ultrasonic attenuation was found to be changed in large single crystal of CdS. Each crystal was prepared for the attenuation measurements by lapping two parallel (within 0.000020 in./in.) faces normal to the c axis (within ± 0.5°). Electroplated indium electrical contacts were attached to opposite sides of the crystals halfway between the lapped faces so that bulk photoconductance measurements could be made simultaneously.

Using the technique of Roderick and Truell[1] the ultrasonic attenuation in CdS was measured as a function of light intensity and wavelength. The effect of light intensity on the ultrasonic attenuation (measured at 5800 A) proved to be linear but of opposite direction in two crystals examined. In crystal A the ultrasonic attenuation of compressional waves was decreased by illumination with white light. In crystal B the attenuation was increased. The attenuation effect in crystal B was about an order of magnitude greater than the opposite effect in crystal A. (See Table I.)

These effects on the ultrasonic attenuation were noted for compressional waves propagated along the c axis over the ultrasonic frequency range from 10 Mc/sec to 200 Mc/sec. No effect was noted for shear waves along the c axis over the same frequency range. In addition, qualitative measurements indicate that the effect is different for waves propagated normal to the c axis. (See Table I.)

The ultrasonic attenuation and the photoconductance were simultaneously measured as a function of wavelength. Figures 1 and 2 show the spectral responses of the ultrasonic attenuation

Table I. The ultrasonic attenuation characteristics for incandescent white light and the physical properties of the CdS crystals used.[a]

Crystal	Attenuation effect, c axis, Compressional	Attenuation effect, c axis, Shear	Attenuation effect, Normal to $\{1,\bar{1},0,0\}$ plane, Compressional	Attenuation effect, Normal to $\{1,\bar{1},0,0\}$ plane, Shear	Impurity content Zn	Impurity content Mg	Impurity content Si	Impurity content Cu	Thickness along c axis and (area of face)	Natural color	Room temperature luminescence (3650A irradiation)
A	Decrease	NE	NE	Small decrease	0.04	0.0001	0.001	0.0004	1.04 cm (2.3 cm^2)	Med. amber	Red
B	Increase	NE	NM	NM	0.01	0.0001	0.001	0.0004	0.63 cm (1.4 cm^2)	Dark amber	Dull red
C	Decrease	NE	NM	NM	ND	0.0001	0.001	0.0002	1 cm (1.2 cm^2)	Light amber	Red-green

[a] ND—not detected; NE—no effect; NM—not measured.

and the photoconductances for the CdS crystals. In both the attenuation and photoconductance measurements, long response times from point to point (as much as a day) were noted. The crystals exhibit the ultrasonic attenuation effect over the same range of light wavelengths as the response region of the photoconductance effect—from the band edge for CdS at about 5100 A up to about 8000 A in the infrared.

In both crystals the phenomenon of infrared quenching of the photoconductance was observed. Similarly the ultrasonic attenuation effect in

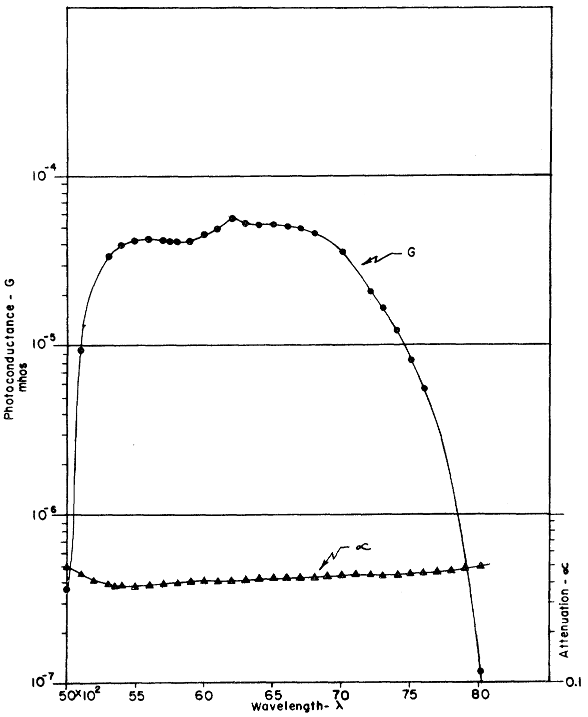

FIG. 1. Photoconductance G and ultrasonic attenuation constant α vs light wavelength in angstroms for CdS crystal A. The ultrasonic attenuation is of the form $I=I_0e^{-\alpha t}$ and was measured at 30 Mc/sec.

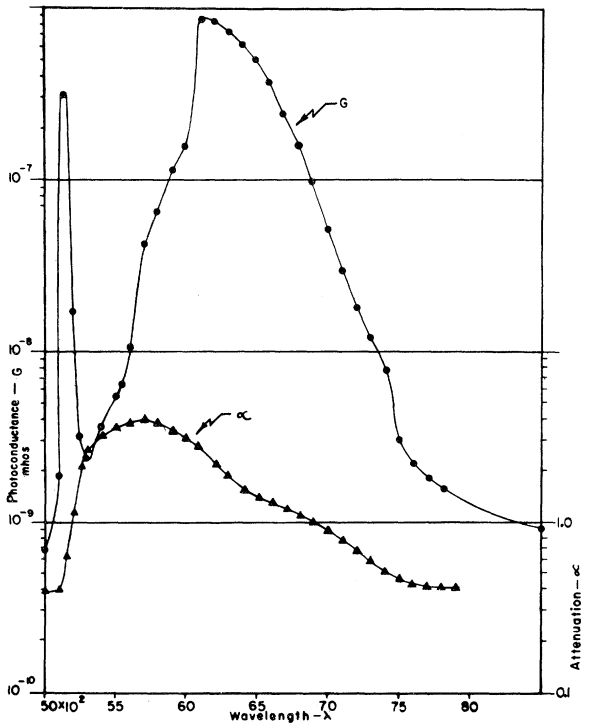

FIG. 2. Photoconductance and ultrasonic attenuation measured at 45 Mc/sec vs light wavelength in angstroms for CdS crystal B.

crystal *B* was quenched to the dark value by infrared but the attenuation effect in crystal *A* was unaffected by infrared.

A semiquantitative spectrographic analysis revealed little difference between the two crystals. In Table I are included some properties of the two crystals *A* and *B* and also those of a third crystal, *C*, upon which qualitative measurements have been made.

Two types of mechanisms are being considered as possible explanations of the ultrasonic attenuation changes: (1) relaxation associated with electron or hole trapping at impurity or vacancy sites, or with electron transitions at sulfur photoactivation sites, and (2) changes in thermoelastic attenuation losses due to heat conduction by photoactivated electrons. It is believed that the ultrasonic attenuation effect may be found in other photosensitive crystals and may be a useful tool for solid state investigation of photoconductors.

The author wishes to thank Norman W. Schubring of this laboratory for many valuable discussions relating to this study. The author also expresses his gratitude to Y. T. Sihvonen and D. R. Boyd of this laboratory who grew the CdS crystals[2] and through whose cooperation the photoconductance measurements were made. The advice of Professor R. Truell and his associates of Brown University in the technique of ultrasonic attenuation measurements is gratefully acknowledged.

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[2] D. R. Boyd and Y. T. Sihvonen, J. Appl. Phys. 30, 176 (1959).

EXPERIMENTAL PROOF OF THE EXISTENCE OF A NEW ELECTRONIC COMPLEX IN SILICON

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Recombination radiation from silicon crystals containing one of the group III or group V elements as an added impurity has recently been examined using a spectroscope of high resolution. Extremely sharp lines appear at low temperatures. It will be shown that these lines can only be interpreted as the radiation produced by the recombination of an electron and a hole both of which are bound in an immobile four-particle complex consisting of an impurity ion and three electronic particles.

Excess electrons and holes were produced in silicon single crystals by illumination with a high-intensity light beam.[1] These carriers recombine in thermal equilibrium with the crystal lattice giving recombination radiation. The intensity of this radiation as a function of photon energy is shown in Fig. 1 for two different silicon specimens at 25°K: (1) a crystal containing a negligible amount of impurity, shown by the dashed line; (2) a crystal containing arsenic added to the melt in the crystal growing process, shown by the solid line.

The dashed trace is essentially all intrinsic recombination radiation produced by the recombination of excitons with simultaneous photon and phonon emission. The energy of the exciton, E_0,

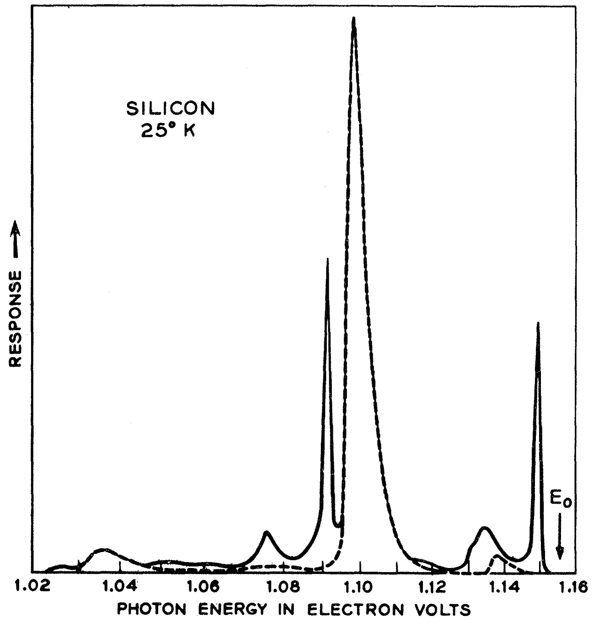

FIG. 1. Spectrometer response (nearly proportional to the number of photons/unit energy interval) as a function of the energy of the photons for two silicon crystals: (1) A specimen containing a negligible amount of impurity, shown by the dashed trace. (2) A specimen containing 8×10^{16} cm^{-3} arsenic atoms, shown by the solid trace.