Measurements were made in the dark to avoid effects of photoconductivity.[9,10] As the CdS crystals were of high resistivity, electrical conductivity effects could be neglected. Since CdS is a piezoelectric material the electrical boundary conditions for the elastic constants have to be specified. In addition the piezoelectric properties cause a "stiffening" of the lattice[11,12] which has to be taken into account when relating the sound velocity to the elastic constants.

Cadmium sulfide crystallizes in the hexagonal system, and thus it has five independent elastic constants c_{11}, c_{12}, c_{13}, c_{33}, and c_{44}. For the determination of the latter eight different propagation modes of the sound are available for velocity determination. These modes together with the relations between the sound velocities and the elastic constants are listed in Table 2. Here the c_{ij}'s are the adiabatic elastic constants at *constant electric field*, the e_{ij}'s and ϵ_i's the piezoelectric and adiabatic dielectric constants respectively, ρ the density, and the conductivity has been assumed to be zero. The convention of axis is that the z axis is parallel to the crystalline c axis, the x axis to the a axis, while the y axis is normal to the x and z axis, the three forming a right handed system.

The sound velocity was measured by the McSKIMIN pulse superposition method.[13,14] The longitudinal and shear waves were generated by X and Y cut crystalline quartz transducers respectively, operating at their fundamental frequency of 15 Mc/s. Over the temperature range of 78–300°K, Canada balsam and Dow Corning DC 200 silicone fluid (viscosity 12,500 cS) were used for bonding the transducer to the crystal, while for the range 4·2–78°K 4-Methylpentene-1 was the bonding agent.

In order to compute the elastic constants at temperatures different from room temperature, a correction for the change in path length and density has to be applied, this correction requiring the knowledge of the thermal expansion coefficient as a function of temperature. Since such data for the range 4·2–3000°K are not available, this coefficient was estimated from the room temperature value,[15] assuming its temperature dependence is a Debye function. For the 45° direction the expansion coefficient was taken as $\frac{1}{2}(\alpha_1+\alpha_3)$ where α_1, and α_3 are the expansion coefficients in the a and c direction, thus neglecting the change in angle with thermal expansion. Since the correction due to thermal expansion is very small, such an estimate is considered to be adequate. As only the room temperatures values of the ϵ_i's and e_{ij}'s for CdS are known,[8] the latter were used over the whole temperature range. This will not introduce an appreciable error as the correction due to the term containing the ϵ_i's and e_{ij}'s adds a correction of

Table 2. The relation between the sound velocity and the elastic constants for CdS *single crystal*

Velocity	Direction of propagation	Mode of propagation	Relation between sound velocity and elastic constants
v_1	$z = \parallel c$ axis	Longitudinal	$\rho v_1^2 = c_{33}+e_{33}^2/\epsilon_3$
v_2	$z = \parallel c$ axis	Shear, polarized in z plane	$\rho v_2^2 = c_{44}$
v_3	$x = \parallel a$ axis	Shear, polarized $\parallel z$	$\rho v_3^2 = c_{44}+e_{31}e_{15}/\epsilon_1$
v_4	$x = \parallel a$ axis	Shear, polarized $\perp z$	$\rho v_4^2 = (c_{11}-c_{12})/2$
v_5	$x = \parallel a$ axis	Longitudinal	$\rho v_5^2 = c_{11}$
v_6	45° to a and c axis	Shear, polarized $\parallel y$	$\rho v_6^2 = (c_{11}-c_{12}+2c_{44})/4$
v_7	45° to a and c axis	Quasi longitudinal	$\rho v_7^2 = (c_{11}^1+c_{55}^1)/2+[(c_{11}^1-c_{55}^1)^2+4c_{15}^1c_{51}^1]^{1/2}/2$
v_8	45° to a and c axis	Quasi shear	$\rho v_8^2 = (c_{11}^1+c_{55}^1)/2-[(c_{11}^1-c_{55}^1)^2+4c_{15}^1c_{51}^1]^{1/2}/2$

$$c_{11}^1 = (c_{11}+c_{33}+2c_{13}+4c_{44})/4+(2e_{15}+e_{31}+e_{33})^2/[2(\epsilon_1+\epsilon_3)]$$
$$c_{15}^1 = (c_{11}-c_{33})/4+(2e_{15}+e_{31}+e_{33})(e_{31}-e_{33})/[2(\epsilon_1+\epsilon_3)]$$
$$c_{55}^1 = (c_{11}+c_{33}-2c_{13})/4+(e_{31}-e_{33})(2e_{15}-e_{31}-e_{33})/[2(\epsilon_1+\epsilon_3)]$$
$$c_{51}^1 = (c_{11}-c_{33})/4+(2e_{15}+e_{31}+e_{33})(2e_{15}-e_{31}-e_{33})/[2(\epsilon_1+\epsilon_3)]$$

about 2 per cent. By analogy with zinc sulfide, the variation of the ϵ_i's and e_{ij}'s is of the order of 2 per cent over the temperature range room—78°K. Thus the neglect of the temperature dependence of the e_{ij}'s and the ϵ_i's will introduce an error of the order of 0·5 per cent.

The ultimate accuracy which can be achieved with the pulse super-position method is of the order of 1 in 10^5. Such an accuracy is however conditioned by a perfect echo pattern. Due to structural imperfection in the crystals, slight misalignment from the true crystalline direction and other disturbances, a perfect echo pattern could not be achieved, and thus the ultimate accuracy of the measuring method could not be realized. It is estimated that the accuracy of the sound velocity determination in the present measurements is about 1 in 1000.

3. RESULTS AND DISCUSSION

The measured eight different sound velocities as a function of the temperature over the range 4·2–300°K are presented in Figs. 1 and 2. The five elastic constants were determined from the measured values of v_1, v_2, v_3, v_4, v_5 and v_8; while v_6 and v_7 served as a check on the consistency of the results. The elastic constants as a function of temperature are shown in Figs. 3 and 4. The former figure presents the diagonal c_{11}, c_{33}, and c_{44}, while the latter showing the cross coupling constants c_{12} and c_{13}, a room temperature density of 4·824 g cm^{-3} being used in the computation. As can be seen the cross coupling constants vary somewhat more with temperature than the diagonal constants. Overall, the variation of the elastic constants with temperature is quite small, which indicates that anharmonic effects in the CdS lattice are small. This is also corroborated by the low values of the thermal expansion coefficient.[15]

Table 3 shows a comparison of the present room temperature elastic constants with results of other investigators. As can be seen the agreement with BOLEF *et al.* for the values of c_{11}, c_{12} and c_{13} is very good while there is a discrepancy for c_{33} and c_{44}. This discrepancy seems to be due to neglect of the

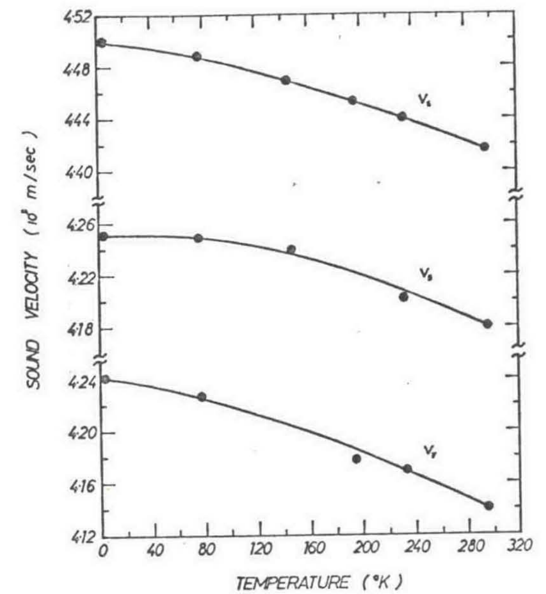

FIG. 1. Sound velocity for longitudinal waves in different crystalline directions as a function of temperature.

piezoelectric correction by BOLEF *et al.* c_{11} and c_{12} are not affected at all by this correction while c_{14} only very slightly.

From the low temperature elastic constants, the Debye temperature at 0°K can be determined.

Table 3. Comparison of the present room temperature elastic constants of CdS *with former work*

	c_{11} 10^{10} N/m²	c_{33} 10^{10} N/m²	c_{44} 10^{10} N/m²	c_{12} 10^{10} N/m²	c_{13} 10^{10} N/m²
BOLEF *et al.*[6]	8·432	9·397	1·489	5·212	4·638
BERLINCOURT *et al.*[8]	9·07	9·38	1·504	5·81	5·10
Present work	8·431	9·183	1·458	5·208	4·567