

# Deformation Potentials of the Indirect and Direct Absorption Edges of AlSb†

LUCIEN D. LAUDE,\* MANUEL CARDONA, AND FRED H. POLLAK

*Physics Department, Brown University, Providence, Rhode Island 02912*

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The splittings and shifts of the phonon-aided indirect exciton edge ( $\Gamma_{15} \rightarrow X_1$ ) of AlSb produced by uniaxial stresses along [001], [111], and [110] have been determined. These measurements were performed at 77°K, using the wavelength-modulation technique. TO-phonon-assisted transitions, not reported previously, have been identified in the spectrum of the stressed materials; they yield a TO-phonon energy at  $X$  of  $42 \pm 3$  meV. These measurements have also yielded the shear deformation potentials of the  $\Gamma_{15}$  valence band ( $b = -1.35 \pm 0.1$  eV and  $d = -4.3 \pm 0.4$  eV) and the  $X_1$  conduction band ( $\epsilon_2 = +5.4 \pm 0.3$  eV). The hydrostatic deformation potential of the indirect edge was found to be  $a_i = +2.2 \pm 0.2$  eV. Electroreflectance measurements at room temperature of the direct edge ( $\Gamma_{15} \rightarrow \Gamma_{1c}$ ) of this material under uniaxial compression along the [110] direction have also been performed. The stress-induced splitting of the  $\Gamma_{15}$  band observed in these measurements agrees with that obtained from the indirect exciton. The hydrostatic coefficient of the direct edge was found to be  $-5.9 \pm 1.2$  eV.

## I. INTRODUCTION

THE III-V semiconductors of small band gap (e.g., InSb, InAs, etc.) are known to have a direct fundamental edge at  $k=0$ .<sup>1</sup> The large-band-gap materials (BP,<sup>2</sup> GaP,<sup>1</sup> etc.) have an indirect fundamental edge which usually corresponds to transitions between the  $\Gamma_{15}$  valence-band maximum and conduction-band minima along [100], at or very close to the edge of the Brillouin zone ( $X$ ).<sup>1</sup> AlSb, with a moderately large absorption edge (1.69 eV at 77°K), is known to be an indirect-edge material.<sup>3,4</sup> The corresponding conduction-band minima occur along [100].<sup>5,6</sup> The exact positions of these minima are not known, but they should occur close to  $X$  if not exactly at  $X$ . The lowest direct gap of this material ( $\Gamma_{15} \rightarrow \Gamma_{1c}$ ) occurs at 2.2 eV.<sup>7,8</sup>

The band structure of AlSb, calculated by the  $k \cdot p$  method with inclusion of spin-orbit interaction,<sup>9</sup> is shown in Fig. 1. The fact that in this figure the conduction-band minimum does not occur exactly at  $X$  is not to be taken as decisive, since a small modification of the parameters of the calculation suffices to bring this minimum to  $X$ . The  $X_1$ - $X_3$  labeling of the con-

duction band states at  $X$  is arbitrary since it is determined by the choice of origin of coordinates. For GaP it is well established that the labeling of Fig. 1 corresponds to taking the phosphorus atom as origin.<sup>10</sup> The lowest conduction band  $X_1$  yields a charge distribution concentrated mainly around the group-V atom. As we shall see in Sec. III, our experiments suggest that the charge distribution of the lowest conduction-band state of AlSb is concentrated mainly around the group-III atom. A number of gaps ( $E_1, E_1 + \Delta_1, E_2$ ) observed in the reflectivity of AlSb<sup>11</sup> are indicated by arrows. In addition, the spin-orbit splitting of the  $\Gamma_{15}$  valence band has been observed in the absorption spectrum of  $p$ -type AlSb.<sup>12</sup>

Modulation techniques have been very helpful in elucidating the optical properties of AlSb. Electroreflectance<sup>7</sup> and thermorefectance<sup>13</sup> measurements have yielded accurate values of the gaps of Fig. 1, and wavelength-modulated absorption<sup>9</sup> has yielded the value of the indirect edge and the energies of phonons (LO, LA, TA) near  $X$ . In this work we have used the wavelength-modulation technique<sup>3,14</sup> to study the effect of uniaxial stress on the indirect edge of AlSb (at 77°K). We have also used the electroreflectance technique (at room temperature)<sup>7</sup> to study the effect of uniaxial stress on the direct edge of this material.

It is known<sup>15</sup> that a uniaxial stress splits the  $\Gamma_{15}$  valence-band state of a zinc-blende-type material. The splitting due to the pure shear component of the stress can be completely described, for an arbitrary stress direction, by two deformation potentials ( $b$  and  $d$ ).<sup>15</sup> A uniaxial stress may also split the equivalent  $X$  conduction-band minima. This splitting is completely

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<sup>1</sup> See, for example, O. Madelung, *Physics of III-V Compounds* (John Wiley & Sons, Inc., New York, 1964).

<sup>2</sup> R. J. Archer, R. Y. Koyama, E. E. Loebner, and R. C. Lucas, *Phys. Rev. Letters* **12**, 538 (1964).

<sup>3</sup> J. E. Rowe, K. L. Shaklee, and M. Cardona, *Solid State Commun.* **7**, 441 (1969).

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<sup>7</sup> M. Cardona, F. H. Pollak, and K. L. Shaklee, *Phys. Rev. Letters* **16**, 644 (1966); M. Cardona, K. L. Shaklee, and F. H. Pollak, *Phys. Rev.* **154**, 696 (1967).

<sup>8</sup> C. A. Mead and W. G. Spitzer, *Phys. Rev. Letters* **11**, 358 (1963).

<sup>9</sup> F. H. Pollak, C. W. Higginbotham, and M. Cardona, *J. Phys. Soc. Japan Suppl.* **21**, 20 (1966).

<sup>10</sup> T. N. Morgan, *Phys. Rev. Letters* **21**, 819 (1968).

<sup>11</sup> T. Fischer, *Phys. Rev.* **139**, A1228 (1965).

<sup>12</sup> R. Braunstein, *Bull. Am. Phys. Soc.* **4**, 133 (1959).

<sup>13</sup> E. Matataqui, A. G. Thompson, and M. Cardona, *Phys. Rev.* **176**, 950 (1968).

<sup>14</sup> I. Balslev, *Phys. Rev.* **143**, 636 (1966).

<sup>15</sup> G. E. Picus and G. L. Bir, *Fiz. Tverd. Tela* **1**, 154 (1959) [English transl.: *Soviet Phys.—Solid State* **1**, 136 (1959)].

described with one deformation potential  $\mathcal{E}_2$ .<sup>16</sup> The indirect edge of stressed AlSb should show these splittings (see Fig. 2) plus a shift due to the hydrostatic component of the stress (deformation potential  $a_i$ ). The direct edge should show the same valence-band splittings plus a hydrostatic shift described by a deformation potential  $a_d$ . The experimental study of these splittings reported here leads to the determination of all these deformation potentials. The selection rules for the various transitions observed experimentally are considered and shown to be in qualitative agreement with the experimental observations. Wavelength-modulated absorption experiments under uniaxial stress have been reported by Balslev for the indirect edge of Ge, Si,<sup>14</sup> and GaP.<sup>17</sup> Electroreflectance measurement under stress (piezo-electroreflectance) of the direct edge of Ge and GaAs have been reported by Pollak and Cardona.<sup>18</sup>

## II. EXPERIMENT

The AlSb used for these experiments was obtained from Bell and Howell Inc.<sup>19</sup> The samples were x-ray oriented to  $\pm 1^\circ$  and cut into parallelepipeds of approximate dimensions  $15 \times 1.5 \times 1.5$  mm, with the length along either the [001], [111], or [110] direction. They were mechanically polished and etched in a solution of Br in methanol. They were then coated with a solution of Lucite in ethylene dichloride so as to slow down tarnishing in air (AlSb is known to be hygroscopic). When not in use, the samples were kept in a desiccator. After several hours of exposure to room air, the transmission of the samples, even when coated, was found to decrease markedly, especially in the vicinity of the fundamental edge. The samples used for the wavelength-modulation studies of the indirect edge were *p* type and had a carrier density of  $9 \times 10^{16} \text{ cm}^{-3}$ . Those used for the electroreflectance work were *n* type (tellurium doped) with  $n = 2 \times 10^{18} \text{ cm}^{-3}$ . The electroreflectance signals obtained with the more lightly doped *p*-type samples were considerably weaker.

The experimental technique used for the wavelength-modulation experiment has been described elsewhere.<sup>20</sup> The wavelength region of interest for the study of indirect excitons in AlSb was narrow enough and the exciton structure sharp enough to make the use of a double-beam system<sup>20</sup> unnecessary with the proper choice of grating and detector. We used a 600-lines/mm grating and a Dumont S-1 response photomultiplier.

<sup>16</sup> H. Brooks, in *Advances in Electronics and Electron Physics*, edited by L. Marton (Academic Press Inc., New York, 1955), Vol. 7, p. 85. We have used script  $\mathcal{E}$ 's to indicate the deformation potentials in order to avoid confusion with the symbol used for energy.

<sup>17</sup> I. Balslev, J. Phys. Soc. Japan Suppl. **21**, 101 (1966).

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<sup>19</sup> Bell and Howell, Inc., Pasadena, Calif.

<sup>20</sup> K. L. Shaklee, J. E. Rowe, and M. Cardona, Phys. Rev. **174**, 828 (1968); K. L. Shaklee, Thesis, Brown University, 1968 (unpublished).

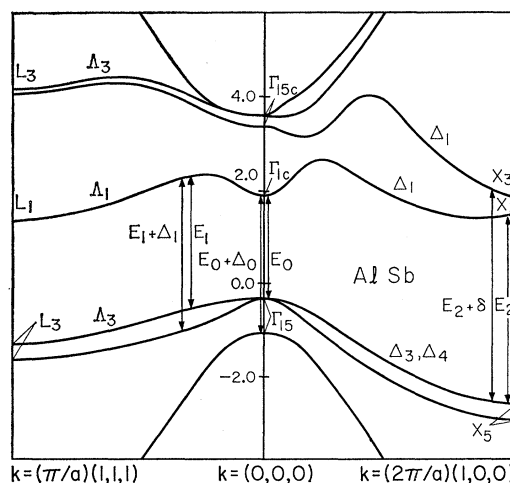


FIG. 1. Band structure of AlSb, as obtained by the  $\mathbf{k} \cdot \mathbf{p}$  method (Ref. 9), in the [100] and [111] directions.

The light source was a Sylvania 600-W quartz-iodine lamp. The modulation unit was a silica plate vibrating at 23 Hz placed inside the monochromator in front of the entrance slit.

Electroreflectance measurements were performed at room temperature only, using as an electrolyte methanol with a few drops of HCl. With this nonaqueous electrolyte, the sample surface was found to be stable over the period of several hours required for the stress measurements. The stress was applied with the stressing apparatus described elsewhere.<sup>18</sup>

## III. SYMMETRY CONSIDERATIONS AND EXPERIMENTAL RESULTS: INDIRECT EDGE

As mentioned in Sec. I, the fundamental edge of AlSb is indirect: Photon absorption is accompanied by

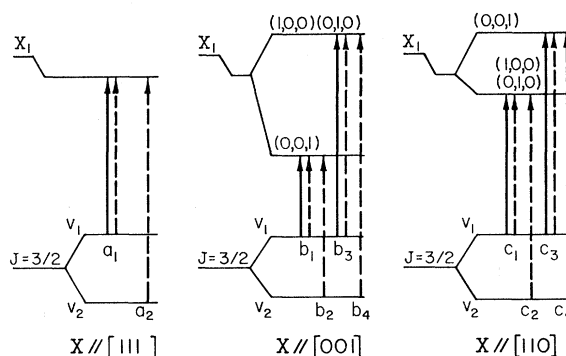


FIG. 2. Schematic representation of the stress-induced splittings and shifts of the  $\Gamma_{15}$  valence bands and  $X_1$  conduction bands for compressive stress along the [111], [001], or [110] direction. The allowed transitions are given for the electric field vector of the incident light,  $\mathbf{E}$ , parallel (solid lines) and perpendicular (dashed lines) to the stress direction. Not shown is the weak transition originating from the  $v_2$  valence band for the case of stress along [110] and  $\mathbf{E} \parallel \mathbf{X}$  (see Table I).

TABLE I. Theoretical expressions for the relative intensities of the LA-phonon-assisted indirect exciton transitions, with  $\Gamma_{1c}$  as the intermediate state, for stress along [111], [001], or [110] with light polarized parallel and perpendicular to the stress axis.

		$E \parallel X$	$E \perp X$
$X \parallel [111]$	$I(a_1)$	$\frac{2}{3}(1+\alpha_1)$	$\frac{1}{6}(1-2\alpha_1)$
	$I(a_2)$	0	$\frac{1}{2}$
$X \parallel [001]$	$I(b_1) = \frac{1}{2}I(b_3)$	$\frac{2}{3}(1+\alpha_0)$	$\frac{1}{6}(1-2\alpha_0)$
	$I(b_2) = \frac{1}{2}I(b_4)$	0	$\frac{1}{2}$
$X \parallel [110]$	$I(c_3) = \frac{1}{2}I(c_1)$	$\frac{2}{3}(1+\alpha_2)$	$\frac{1}{6}(1-2\alpha_2)$
	$I(c_4) = \frac{1}{2}I(c_2)$	$\frac{1}{2}\epsilon^2$	$\frac{1}{2}(1-\epsilon)$
$\epsilon = (\delta E_{001} - \delta E_{111}) / (\delta E_{001} + 3\delta E_{111})$			
$\alpha_1 = \delta E_{111} / \Delta_0$			
$\alpha_0 = \delta E_{001} / \Delta_0$			
$\alpha_2 = (\delta E_{111} / \Delta_0) [1 + (\delta E_{001} - \delta E_{111}) / 4\delta E_{111}]$			

the absorption or emission of a phonon of  $\mathbf{k}$  vector along equivalent  $\langle 001 \rangle$  directions, near  $X$ . For the purposes of this paper, it is reasonable to assume that the conduction-band minima occur at  $X$ . Of the possible intermediate states for the indirect transitions, the  $\Gamma_{1c}$  conduction band (Fig. 1) should give by far the smallest energy denominator and, hence, it is reasonable to assume that it gives the largest contribution to the indirect transition probability. Only phonons at  $X$  which are invariant under the operations of the group of the  $\mathbf{k}$  vector at  $X$  are able to produce  $\Gamma_{1c} \rightarrow X_1$  transitions; these are either the LA or the LO phonons depending on the choice of origin imposed

by the  $X_1$  labeling of the lowest conduction-band minimum.<sup>10</sup> The LA phonon corresponds to the vibration of the heavier atom and, thus, has  $X_1$  symmetry if the origin of coordinates is at the site of the lighter atom. We find experimentally that the strongest indirect transitions are LA-phonon-aided although weak LO-, TO-, and TA-assisted transitions are also observed. This implies that if the  $\Gamma_{1c}$  intermediate state is indeed dominant, the electron density at the lowest conduction-band state must be concentrated around the group-III atom (Al). This conclusion is in contrast to that obtained for GaP<sup>10</sup>: In this material the LA-phonon-aided transitions are also the strongest and, thus, the electron density at  $X$  must be concentrated around the lighter group-V atom. We shall base our determination of deformation potentials on the behavior of the strong LA-emission lines (LA<sub>e</sub>). Weak phonon-absorption lines are also observable for the four phonons at  $X$ .

### A. Stress along [111]

For [111] stress, no intervalley splitting of the [001] conduction bands takes place. The splitting of the indirect exciton edge is expected to be due to the splitting of the top  $\Gamma_{15}$  valence band into the  $(\frac{3}{2}, \frac{3}{2})$  and the  $(\frac{3}{2}, \frac{1}{2})$  bands ( $v_2$  and  $v_1$ , respectively, in Fig. 2). The energies of the split edges are given by<sup>18</sup>

$$\begin{aligned} \Delta(E_x - E_{v_2} \pm E_{\text{phon}}) &= \delta E_H + \frac{1}{2}\delta E_{111}, \\ \Delta(E_x - E_{v_1} \pm E_{\text{phon}}) &= \delta E_H - \frac{1}{2}\delta E_{111} - \frac{1}{2}(\delta E_{111})^2 / \Delta_0, \end{aligned} \quad (1)$$

to second order in the stress.  $\Delta_0$  is the spin-orbit splitting of the valence band. The linear hydrostatic and shear shifts  $\delta E_H$  and  $\delta E_{111}$  are, in terms of the corresponding deformation potentials  $a_i$  and  $d$ ,

$$\begin{aligned} \delta E_H &= a_i(S_{11} + 2S_{12})X, \\ \delta E_{111} &= (d/\sqrt{3})S_{44}X, \end{aligned} \quad (2)$$

where  $S_{11}$ ,  $S_{12}$ , and  $S_{44}$  are the elastic compliance constants and  $X$  is the applied stress. Values of these

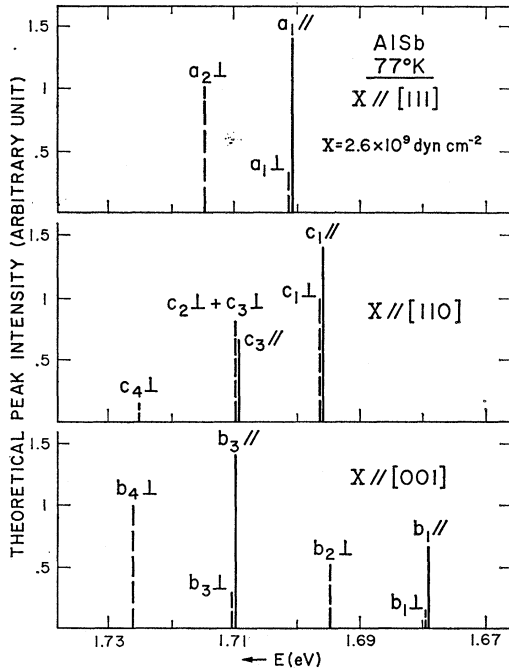


FIG. 3. Theoretical peak intensities of indirect transitions via  $\Gamma_{1c}$  for a stress of  $2.6 \times 10^9$  dyn cm<sup>-2</sup> along [111], [110], or [001].

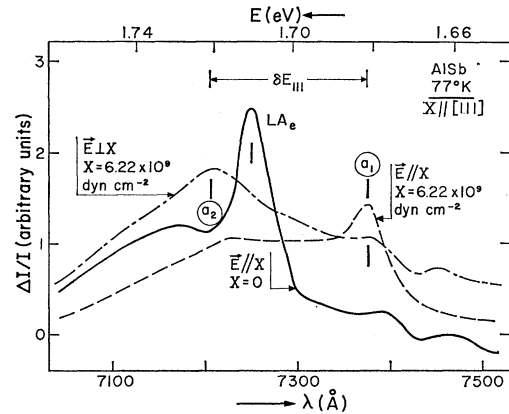


FIG. 4. Derivative transmission spectra for zero stress and for a stress of  $6.22 \times 10^9$  dyn cm<sup>-2</sup> applied along [111] with light polarized parallel and perpendicular to the stress axis.

TABLE II. Deformation potentials obtained in paper for AlSb.

Stress direction	$d$ (eV)	$\delta E_{111}/X = (d/\sqrt{3})S_{44}$ ( $10^{-12}$ eV cm <sup>2</sup> dyn <sup>-1</sup> )	$b$ (eV)	$\delta E_{001}/X = 2b(S_{11}-S_{12})$ ( $10^{-12}$ eV cm <sup>2</sup> dyn <sup>-1</sup> )	$\delta E_{110}/X = \frac{1}{4}[d\sqrt{3}S_{44} + 2b(S_{11}-S_{12})]$ ( $10^{-12}$ eV cm <sup>2</sup> dyn <sup>-1</sup> )		$a_i$ (eV)	$a_d$ (eV)	$\varepsilon_2$ (eV)
					77°K	295°K			
[111]	-4.3 ±0.4	5.9±0.6					+2.2 ±0.2		
[001]			-1.35 ±0.1	5.8±0.6			+1.8 ±0.9		+5.4 ±0.3
[110]					5.5±0.8		+2.7 ±1.3		+5.1 ±0.7
[110] <sup>a</sup>						6.4±1.3		-5.9 ±1.2	

<sup>a</sup> Obtained from room-temperature electroreflectance measurements.

compliance constants are not available at 77°K. However, from the existing data<sup>1</sup> for AlSb at room temperature and the previously reported variation of the elastic compliance constants of GaAs between 77°K and room temperature, we obtained the following values for AlSb at 77°K:

$$\begin{aligned} S_{11} &= 1.634 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2, \\ S_{12} &= -0.552 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2, \\ S_{44} &= 2.38 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2. \end{aligned}$$

The room-temperature values of these constants are

$$\begin{aligned} S_{11} &= 1.661 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2, \\ S_{12} &= -0.549 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2, \\ S_{44} &= 2.410 \times 10^{-12} \text{ dyn}^{-1} \text{ cm}^2. \end{aligned}$$

We assume throughout this paper that the change of the exciton-binding energy with stress is negligible.<sup>14</sup>

The phonon-induced transitions between  $\Gamma_{1c}$  and  $X_1$  are isotropic and, hence, the selection rules for the transition probability reflect exactly those for transitions between the split initial states ( $v_1, v_2$ ) and the intermediate state  $\Gamma_{1c}$ . This would not be true for other intermediate states such as  $\Gamma_{15c}$ .<sup>21</sup> The intensities of the LA-assisted transitions via  $\Gamma_{1c}$  for both normal modes of polarization are given in Table I to first order in the ratio  $\alpha_1 = \delta E_{111}/\Delta_0$ . The intensities of these lines are represented schematically in Fig. 3 for  $\alpha_1 \ll 1$ . If  $\alpha_1$  is not negligible, a change in the intensity of the  $a_1$  lines linear with stress results. This change is produced by the coupling of the  $v_1$  valence band to the lower spin-orbit split component of the  $\Gamma_{15}$  multiplet. This coupling is also responsible for the nonlinear shift of the  $a_1$  line with stress shown in Eq. (1). Figure 4 shows the unstressed LA-phonon emission peak ( $LA_e$ ) and the effect of a [111] compression of  $6.22 \times 10^9 \text{ dyn cm}^{-2}$  for the electric field vector of the incident light ( $E$ ) parallel and perpendicular to the stress. The hydrostatic shift in the average position of the peaks observed for both polarizations appears clearly. The shift with stress of

the various phonon-aided transitions observed is shown in Fig. 5. While the  $LA_e$  peaks can be followed easily as a function of stress, the weaker additional peaks are

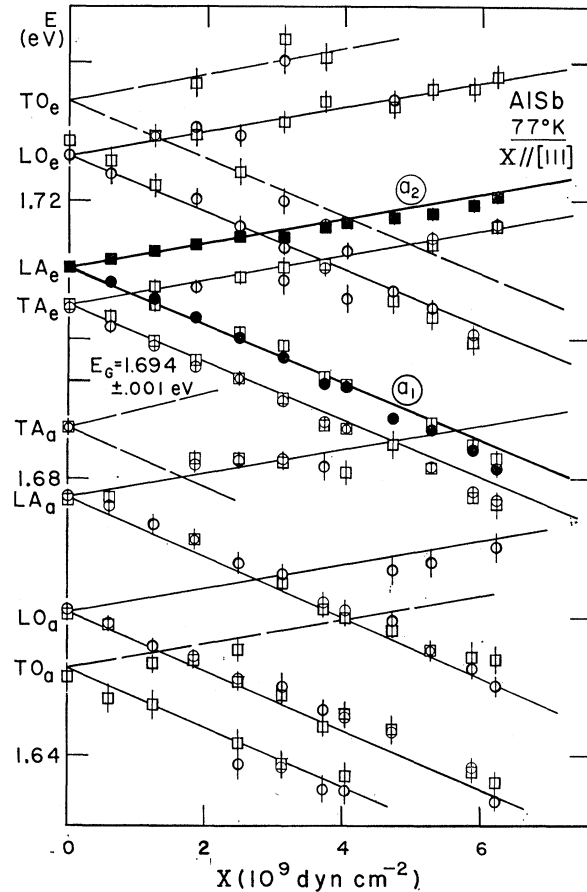


FIG. 5. Stress dependence of the exciton energies as a function of [111] stress for light polarized parallel (circles) and perpendicular (squares) to the stress axis. The solid points show the  $LA_e$  exciton thresholds from which the deformation potentials  $a_i$  and  $d$  have been obtained. The stress-induced splittings of the other excitons were drawn parallel to the  $LA_e$  exciton lines in order to fit the experimental points. The TO phonon energy is found to be at  $(42 \pm 3) \text{ meV}$ .  $TA_e$  excitons were not observed. A value of  $1.694 \pm 0.001 \text{ eV}$  for the indirect gap was obtained from the emission and absorption branches of the spectrum.

<sup>21</sup> E. Erlbach, Phys. Rev. **150**, 767 (1966).

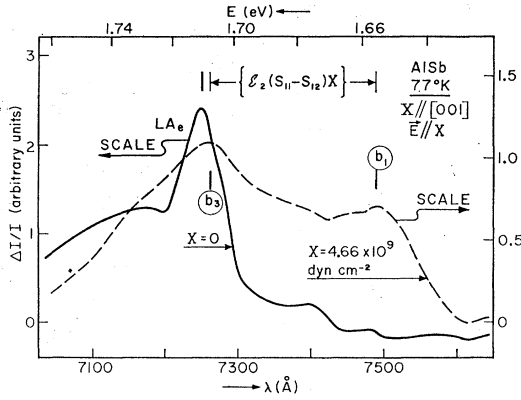


FIG. 6. Derivative transmission spectra for zero stress and for a [001] stress of  $4.66 \times 10^9$  dyn cm $^{-2}$  for light polarized parallel to the stress axis.

best followed by plotting lines from the zero-stress position parallel to the trajectory of the split  $LA_e$  peaks. This figure gives some evidence of the TO-assisted transitions at about 40–45 meV. These transitions were not observed earlier but they were predicted to occur at  $41 \pm 3$  meV.<sup>3</sup> The observed splittings are linear within the experimental accuracy [Eq. (1) predicts a nonlinear shift of 0.8 meV at  $6.3 \times 10^9$  dyn cm $^{-2}$ , too small to be observed]. From the splitting and shift of the  $LA_e$  line we have determined the deformation potentials  $a_i$  and  $d$  listed in Table II.

Figure 4 shows selection rules and intensities in qualitative agreement with Fig. 3 and Table I. In particular, the  $a_2$  line is very weak for  $E \parallel X$ : it is only allowed with  $\Delta_1$  as an intermediate state. A change of intensity of the sign predicted in Table I was observed for the  $a_1$  line. This change is, however, too small for quantitative comparisons.

### B. Stress along [001]

For a stress along [001], the splitting of the valence band is the same as that given by Eq. (1), with  $\delta E_{111}$  replaced by  $\delta E_{001} = 2b(S_{11} - S_{12})X$ . The three equivalent [001] conduction minima now split into a singlet [001] and a doublet [010], [100]. This splitting can be represented by the deformation potential  $\mathcal{E}_2$ ,

$$\begin{aligned} \Delta E_{001} &= \frac{2}{3} \mathcal{E}_2 (S_{11} - S_{12}) X, \\ \Delta E_{100,010} &= -\frac{1}{3} \mathcal{E}_2 (S_{11} - S_{12}) X. \end{aligned} \quad (3)$$

The hydrostatic shift of the indirect gap is independent of stress direction and given by Eq. (2). The expected scheme of splitting is shown in Fig. 2.

Each phonon-aided exciton peak thus splits into four under the action of [001] stress. The selection rules for these four  $LA$ -phonon-aided transitions are easily obtained under the assumption that  $\Gamma_{1c}$  is the dominant intermediate state. As mentioned earlier, the phonon transitions from the  $\Gamma_{1c}$  band to  $X_1$  are isotropic and hence they introduce a factor of 1 for

transitions to the singlet [001] and a factor of 2 for transitions to the doublet [100], [010]. The selection rules for  $\Gamma_{15} \rightarrow \Gamma_{1c}$  transitions are the same as for [111] stress. The expected intensities at  $2.6 \times 10^9$  dyn cm $^{-2}$  ( $\alpha_0 \ll 1$ , where  $\alpha_0 = \delta E_{001}/\Delta_0$ ) are shown schematically in Fig. 3 and listed in Table I.

Figure 6 shows the  $LA_e$ -phonon-assisted exciton peak for zero stress and for a [001] stress  $X = 4.66 \times 10^9$  dyn cm $^{-2}$  with  $E \parallel X$ . Because of the selection rules of Table I, the observed splitting corresponds to the singlet-doublet splitting of the conduction band  $\mathcal{E}_2(S_{11} - S_{12})X$ . The observed intensities are not in agreement with those of Fig. 3, if only peak heights are compared. There are several possible explanations for this discrepancy. For sufficiently close peaks, the overlaps of corresponding signals will distort the shape of the spectrum. Also, external structure (which was observed at 7450 Å only for perpendicular polarized light) made difficult comparison between the spectra for the two different polarizations. However, the  $b_3$  and  $b_4$  lines, which correspond to transitions to the conduction-band doublet, seem to broaden as a function of stress more than  $b_1$  and  $b_2$ . If this broadening is considered, the agreement with the calculated intensities is better. This broadening could be due, in part, to the elastic scattering from the conduction band doublet to the large density of states provided by the singlet. Figure 7 shows the stress dependence of the four  $LA_e$  peaks for [001] stress. As in the case of [111] stress, the non-

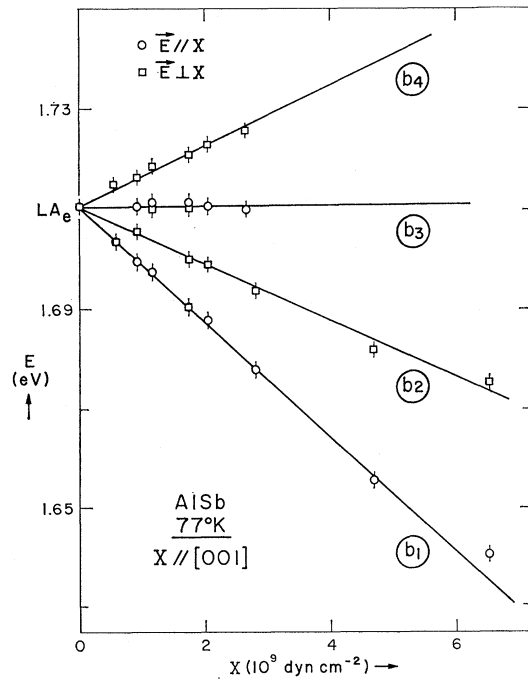


FIG. 7. Stress dependence of the  $LA_e$  phonon-assisted exciton for the case of [001] stress. The split lines are labelled according to Fig. 2. The intensities of the  $b_4$  and  $b_3$  lines were too small to be observed for stresses above about  $3 \times 10^9$  dyn cm $^{-2}$ .

linearities predicted by Eq. (1) are too small to be observed. The deformation potentials  $b$ ,  $\mathcal{E}_2$ , and  $a_i$  obtained from Fig. 7 are listed in Table II. Because of the fourfold splitting for [001] stress, the values of  $a_i$  obtained from these measurements are expected to be less accurate than those obtained from [111] stress. Nevertheless, the agreement between both determinations of  $a_i$  is quite satisfactory.

### C. Stress along [110]

A [110] stress couples both  $v_1$  and  $v_2$  bands to the spin-orbit split band. Hence,  $v_1$  and  $v_2$  should have a nonlinear dependence on stress. The pure shear component of the stress dependence of the energies of the  $v_1$  and  $v_2$  bands is, to second order in  $X$ ,<sup>18</sup>

$$\begin{aligned} \Delta E_{v_1} &= \frac{1}{4}[(\delta E_{001})^2 + 3(\delta E_{111})^2]^{1/2} \\ &\quad + \frac{1}{32}[(\delta E_{001}) + 3(\delta E_{111})]^2/\Delta_0, \\ \Delta E_{v_2} &= -\frac{1}{4}[(\delta E_{001})^2 + 3(\delta E_{111})^2]^{1/2} \\ &\quad + \frac{3}{32}[\delta E_{001} - \delta E_{111}]^2/\Delta_0, \end{aligned} \quad (4)$$

where  $\delta E_{001}$  and  $\delta E_{111}$  have been defined earlier. The measurements for [001] and [111] stress have shown that  $\delta E_{001} \approx \delta E_{111}$ . Under these conditions, Eq. (4) yields a behavior very similar to that found for [001] and [111] stress. We shall write  $\epsilon = (\delta E_{001} - \delta E_{111})/(\delta E_{001} + 3\delta E_{111})$ . By expanding Eq. (4) in power series of  $\epsilon$  ( $\epsilon \sim 0.002$ ) and keeping only first-order terms, we find

$$\begin{aligned} \Delta E_{v_1} &= \frac{1}{2}\delta E_{110} + [(\delta E_{110})^2/2\Delta_0], \\ \Delta E_{v_2} &= -\frac{1}{2}\delta E_{110}, \end{aligned} \quad (5)$$

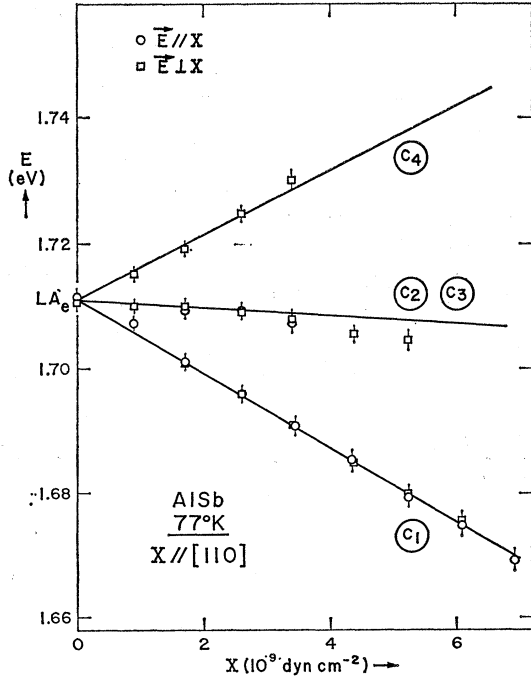


FIG. 8.  $LA_e$  phonon-assisted exciton energies as a function of [110] stress.

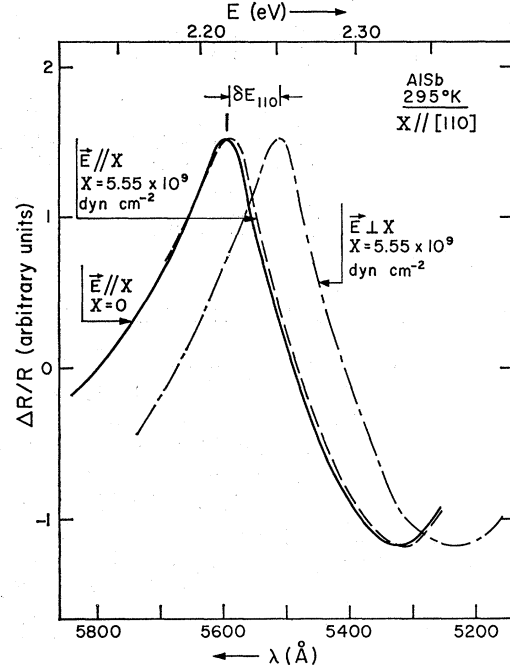


FIG. 9. Electoreflectance spectrum of the  $E_0$  peak ( $\Gamma_{15} \rightarrow \Gamma_{1c}$ ) of AlSb for zero stress and a stress of  $5.5 \times 10^9$  dyn cm<sup>-2</sup> along [110] for both polarizations showing the  $\delta E_{110}$  splitting of the  $P_{3/2}$  multiplet of the  $\Gamma_{15}$  valence band.

where

$$\delta E_{110} = \frac{1}{4}(\delta E_{001} + 3\delta E_{111}) = \frac{1}{4}[2b(S_{11} - S_{12}) + d\sqrt{3}S_{44}]X.$$

The  $X_1$  conduction bands also split under the action of a [110] stress: The pattern of splitting is opposite to that obtained for [001] stress (see Fig. 2). The total splitting is half that obtained for the same [001] stress. Instead of Eq. (3), we obtain

$$\begin{aligned} \Delta E_{001} &= -(\mathcal{E}_2/3)(S_{11} - S_{12})X, \\ \Delta E_{100,010} &= (\mathcal{E}_2/6)(S_{11} - S_{12})X. \end{aligned} \quad (6)$$

The hydrostatic shift of the indirect gap is the same as that found for [001] and [111] stress.

The selection rules for the transitions with  $\Gamma_{1c}$  as intermediate state can be easily written down for  $\epsilon \ll 1$ . They are similar to those for [001] stress, with  $\delta E_{001}$  replaced by  $\delta E_{110}$ . The expected intensities are represented schematically in Fig. 3 (for  $X = 2.6 \times 10^9$  dyn cm<sup>-2</sup>).

The splitting of the  $LA_e$  line alone as a function of [110] stress is shown in Fig. 8. The  $c_2$  and  $c_3$  lines are almost accidentally degenerate. From these data, we can derive  $\mathcal{E}_2 = +(5.1 \pm 0.7)$  eV and  $a_i = +(2.7 \pm 1.3)$  eV. Figure 8 also yields  $\delta E_{110}$  and hence the  $b$  and  $d$  combination

$$\delta E_{110}/X = \frac{1}{4}[2b(S_{11} - S_{12}) + d\sqrt{3}S_{44}]. \quad (7)$$

The value obtained from Fig. 8 for this combination of  $b$  and  $d$  is shown in Table II to agree with that calculated from the [001] and [111] measurements.

TABLE III. Hydrostatic pressure coefficients (in units of  $10^{-6}$  eV bar $^{-1}$ ) of the indirect gaps of Ge, Si, GaP, and AlSb as obtained from uniaxial and hydrostatic stress experiments.

	Ge	Si	GaP	AlSb
Uniaxial	$+3 \pm 1^a$	$-3.8 \pm 0.5^a$	$-4.5 \pm 1.5^b$	$-3.5 \pm 0.3^c$
Hydrostatic	$+5^d$	$-1.5^d$	$-1^d$	$-1.5^d$

<sup>a</sup> I. Balslev, Phys. Rev. **143**, 636 (1966).

<sup>b</sup> I. Balslev, J. Phys. Soc. Japan Suppl. **21**, 101 (1966).

<sup>c</sup> This paper.

<sup>d</sup> Ref. 23.

#### IV. ELECTROREFLECTANCE AT DIRECT EDGE

Figure 9 shows electroreflectance spectra<sup>7</sup> near 2.2 eV of AlSb without stress and with a  $[110]$  stress of  $5.55 \times 10^9$  dyn cm $^{-2}$ . These measurements were performed at room temperature. The peak in Fig. 9 is believed to correspond to the lowest direct edge ( $\Gamma_{15} \rightarrow \Gamma_{1c}$ ) of this material; it should, therefore, exhibit the  $\delta E_{110}$  splitting of the valence band and the appropriate selection rules. The peak for  $\mathbf{E} \parallel X$  should correspond to  $v_1 \rightarrow \Gamma_{1c}$  transitions while that for  $\mathbf{E} \perp X$  should correspond mainly to  $v_2 \rightarrow \Gamma_{1c}$  transitions. The value of  $\delta E_{110}$  obtained on the basis of this interpretation agrees with that found from the measurements of the indirect edge (see Table II). Figure 9 shows also a hydrostatic shift for the center of the two split peaks. From this shift in the center of mass we find the hydrostatic deformation potential of the direct edge:  $a_d = -5.9 \pm 1.2$  eV.

#### V. CONCLUSIONS

We have determined the shear deformation potentials of the  $\Gamma_{15}$  valence band of AlSb and the hydrostatic deformation potentials of its lowest direct and indirect gaps. The pattern of splittings of the indirect edge of this material confirms rather conclusively the  $[001]$  symmetry of the corresponding conduction-band minima. An examination of the evolution of the indirect exciton spectrum with stress has enabled us to identify the TO-phonon-aided peak and, thus, to determine the energy of these phonons at  $X$ . The splitting of the direct edge and its selection rules confirm its previous assignment to  $\Gamma_{15} \rightarrow \Gamma_{1c}$  transitions.<sup>7</sup>

The obtained shear deformation potentials  $b$  and  $d$  are in line with those found for other III-V compounds (e.g., for GaAs  $b = -2.6 \pm 0.2$  eV,  $d = -4.7 \pm 0.3$  eV).<sup>18,22,23</sup> They correspond to splittings

nearly independent of stress direction ( $\delta E_{111} \approx \delta E_{001}$ ). This fact seems to be characteristic of III-V compound since for Ge and Si  $\delta E_{111} < \delta E_{001}$  and for II-VI compound  $\delta E_{111} > \delta E_{001}$ .<sup>22</sup>

The hydrostatic deformation potentials of the indirect gap determined from measurements for three stress directions (Table II) agree within the experimental error. The best accuracy for  $a_i$  [ $+(2.2 \pm 0.2)$  eV], has been obtained for  $X \parallel [111]$ . This deformation potential can be easily converted into the hydrostatic pressure coefficient  $(\partial E / \partial P)_i$ ,

$$\begin{aligned} \left( \frac{\partial E}{\partial P} \right)_i &= -3(S_{11} + 2S_{12})a_i = -(3.5 \pm 0.3) \\ &\times 10^{-12} \text{ eV dyn}^{-1} \text{ cm}^2 \\ &= -(3.5 \pm 0.3) \times 10^{-6} \text{ eV bar}^{-1}. \end{aligned}$$

We notice that this coefficient is considerably larger than that quoted in the literature ( $-1.5 \times 10^{-6}$  eV bar $^{-1}$ ),<sup>23</sup> obtained from optical measurements under hydrostatic stress at room temperature. Similar discrepancies between low-temperature uniaxial stress and room-temperature hydrostatic stress data exist for other indirect gap materials, such as Si, Ge, and GaP (see Table III). While we do not know the source of this discrepancy, one might speculate that the optical measurements of the indirect gap at room temperature are based on a detailed analysis of the changes of the line shape with stress<sup>24</sup> and hence are not very reliable. However, results in agreement with the shift of the indirect edge with hydrostatic pressure have been obtained from radiative recombination at 80°K<sup>25</sup> and from electrical measurements under hydrostatic pressure.<sup>24</sup> We are thus led to conclude that the discrepancy is related to the uniaxial nature of the applied stress in a manner not understood by us.

The hydrostatic pressure coefficient obtained for the  $\Gamma_{15} \rightarrow \Gamma_{1c}$  direct gap is  $(\partial E / \partial P)_d = +(10 \pm 2) \times 10^{-6}$  eV bar $^{-1}$ . This coefficient has not been determined from hydrostatic pressure measurements. However, it is approximately equal to that found for most other materials of this family<sup>25</sup> [ $(\partial E / \partial P)_d \approx +11 \times 10^{-6}$  eV bar $^{-1}$ ].

<sup>23</sup> R. N. Bharagava and M. I. Nathan, Phys. Rev. **161**, 695 (1967).

<sup>24</sup> W. Paul and P. M. Warschauer, J. Phys. Chem. Solids **5**, 89 (1958); **5**, 102 (1958).

<sup>25</sup> R. Zallen and W. Paul, Phys. Rev. **134**, A1628 (1964); **155**, 703 (1967).

<sup>22</sup> A. Gavini and M. Cardona, Phys. Rev. (to be published).