

Piezoresistance in *p*-Type Gallium Antimonide\*

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The piezoresistance effect has been measured in *p*-type gallium antimonide having a hole concentration of approximately  $1 \times 10^{17} \text{ cm}^{-3}$  over a temperature range from 77 to 350°K. At 300°K, the values of the piezoresistance coefficients  $\pi_{11}$ ,  $\pi_{12}$ , and  $\pi_{44}$  are  $5 \times 10^{-12}$ ,  $-2.4 \times 10^{-12}$ , and  $87 \times 10^{-12} \text{ cm}^2/\text{dyn}$ , respectively. A germanium-type valence band structure is shown to be consistent with both the piezoresistance results and previous magnetoresistance results, whereas none of the many-valley models are consistent with both measurements.

## INTRODUCTION

THE valence band structure of gallium antimonide near the band edge is probably<sup>1</sup> similar to germanium, but only a limited amount of experimental information is available. The results of free carrier absorption experiments<sup>2,3</sup> suggest transitions between two overlapping bands. Magnetoresistance measurements<sup>3-5</sup> are also consistent with a germanium-type valence band, but in this case other interpretations are also possible. The problem with the interpretation of magnetoresistance results is that the low-field coefficients *B*, *C*, and *D* follow the symmetry relation  $B+C = -D$  for both a many-valley-type band structure with energy minima along the [100] reciprocal axes<sup>6</sup> and a germanium-type valence band structure.<sup>7</sup> However, the magnetic field dependence of the magnetoresistance and Hall effects at lower temperatures indicates the presence of light- and heavy-mass carriers as in a germanium-type valence band. The purpose of this paper is to present the results of an investigation of the piezoresistance effect in *p*-type gallium antimonide and to use these results to distinguish between the two possible types of band structure indicated by the magnetoresistance results.

## EXPERIMENTAL

Single crystals of gallium antimonide were grown by a horizontal zone leveling technique. The crystals were *p* type as grown and have a hole concentration of approximately  $10^{17} \text{ cm}^{-3}$ . Oriented samples having side-arms for making electrical contacts were ultrasonically cut from these crystals. For the piezoresistance measurements, a tensile stress was applied to the sample by means of cords passing through the enlarged sample ends. The piezoresistance was measured using a con-

stant current dc method. The unstrained sample voltage was balanced out on a Rubicon type B potentiometer and the output of the potentiometer connected to a dc amplifier and recorder. In this manner, the change in voltage due to the applied stress was measured on the recorder. Stresses up to  $5 \times 10^7 \text{ dyn/cm}^2$  were used in the measurements and a linear relation between the applied stress and the voltage change was found on all samples.

From a combination of longitudinal piezoresistance measurements on [100] and [111] oriented samples and transverse piezoresistance measurements on [100] oriented samples, the piezoresistance coefficients  $\pi_{11}$ ,  $\pi_{12}$ , and  $\pi_{44}$  were evaluated. For the orientations used, the relations between the measured change in the sample resistance  $\Delta R/R$  due to an applied stress  $\chi$  and the piezoresistance coefficients are<sup>8,9</sup>:

$$\frac{1}{\chi} \frac{\Delta R}{R} = \frac{1}{3} [(\pi_{11} + 2\pi_{12}) + 2\pi_{44}] + \frac{1}{3} [2S_{44} - (S_{11} + 2S_{12})] \quad \text{[111] long,}$$

$$\frac{1}{\chi} \frac{\Delta R}{R} = \pi_{11} + (S_{11} - 2S_{12}) \quad \text{[100] long,}$$

$$\frac{1}{\chi} \frac{\Delta R}{R} = \pi_{12} - S_{11} \quad \text{[100] trans.}$$

In these equations, the  $S_{ij}$  are the elastic compliance constants which correct for the change in resistance due to dimensional changes in the crystal with stress. The elastic constants for gallium antimonide reported by McSkimin *et al.*<sup>10</sup> have been used in making these

TABLE I. Values of the resistivity, Hall coefficient, and Hall mobility of a typical gallium antimonide sample.

	$\rho$ ( $\Omega$ -cm)	$R$ ( $\text{cm}^2/\text{C}$ )	$\mu_H$ ( $\text{cm}^2/\text{V-sec}$ )
300°K	0.08	57	712
77°K	0.12	375	3150

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<sup>1</sup> H. Ehrenreich, *J. Appl. Phys.* **32**, 2155 (1961).

<sup>2</sup> A. K. Ramdas and H. Y. Fan, *Bull. Am. Phys. Soc.* **3**, 121 (1958).

<sup>3</sup> W. M. Becker, A. K. Ramdas, and H. Y. Fan, *J. Appl. Phys.* **32**, 2094 (1961).

<sup>4</sup> O. N. Tufte and E. L. Stelzer, *Bull. Am. Phys. Soc.* **6**, 426 (1961).

<sup>5</sup> M. Matyáš and J. Škácha, *Czech. J. Phys.* **B12**, 566 (1962).

<sup>6</sup> M. Shibuya, *Phys. Rev.* **95**, 1385 (1954).

<sup>7</sup> J. G. Mavroides and B. Lax, *Phys. Rev.* **107**, 1530 (1957).

<sup>8</sup> C. S. Smith, *Phys. Rev.* **94**, 42 (1954).

<sup>9</sup> R. F. Potter and W. J. McKean, *J. Res. Natl. Bur. Std. U. S.* **59**, 427 (1957).

<sup>10</sup> H. J. McSkimin, W. L. Bond, G. L. Pearson, and H. J. Hrostowski, *Bull. Am. Phys. Soc.* **1**, 111 (1956).

corrections. For the transverse measurement, an arrangement similar to Smith's<sup>8</sup> method B was used. The accuracy of the  $\pi_{12}$  value measured by this technique is estimated to be  $\pm 20\%$ . The accuracy of the  $\pi_{11}$  and  $\pi_{44}$  values is  $\pm 5\%$ .

The electrical conductivity, Hall coefficient, and Hall mobility of a typical sample are given in Table I. The properties of all of the samples used in this investigation are very nearly identical with those given in Table I.

### RESULTS AND DISCUSSION

The coefficients  $\pi_{11}$  and  $\pi_{44}$  have been measured from 77 to 350°K. The results are shown in Fig. 1. Due to the

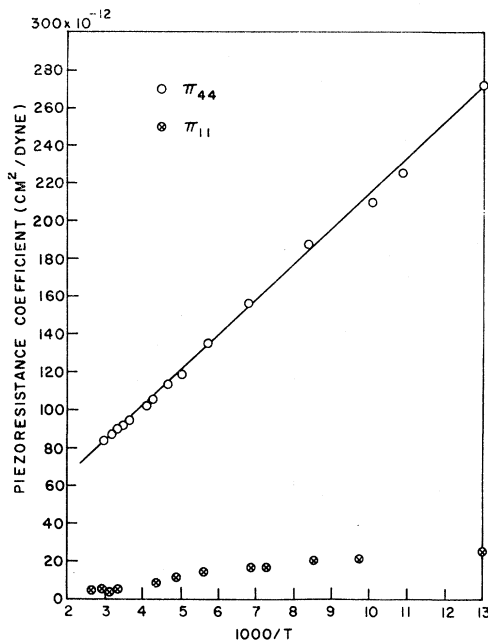


FIG. 1. Variation of the coefficients  $\pi_{11}$  and  $\pi_{44}$  with temperature in *p*-type gallium antimonide. The solid line is a best fit to the experimental  $\pi_{44}$  data points.

small signal obtainable from transverse measurements, the coefficient  $\pi_{12}$  was measured only at 77 and 300°K where constant-temperature baths were used. The measured  $\pi_{12}$  values at 77 and 300°K are  $-8.0$  and  $-2.4 \times 10^{-12}$  cm<sup>2</sup>/dyn, respectively. At 300°K,  $\pi_{12} \approx -\pi_{11}/2$ , in agreement with the hydrostatic pressure results of Paul.<sup>11</sup> The  $\pi_{44}$  values were obtained from longitudinal measurements on [111] oriented samples

<sup>11</sup> W. Paul, J. Appl. Phys. **32**, 2082 (1961).

TABLE II. Values of the piezoresistance and elastoresistance<sup>a</sup> coefficients in *p*-type gallium antimonide at 77 and 300°K.

	77°K	300°K	77°K	300°K
$\pi_{11}$ (cm <sup>2</sup> /dyn)	$24 \times 10^{-12}$	$5.0 \times 10^{-12}$	$M_{11}$	15
$\pi_{12}$ (cm <sup>2</sup> /dyn)	$-8.0 \times 10^{-12}$	$-2.4 \times 10^{-12}$	$M_{12}$	-0.6
$\pi_{44}$ (cm <sup>2</sup> /dyn)	$272 \times 10^{-12}$	$87 \times 10^{-12}$	$M_{44}$	118
				37

<sup>a</sup> The elastic constants given in Ref. 9 were used to calculate the elastoresistance values at both 77 and 300°K.

assuming  $\pi_{11} + 2\pi_{12} = 0$ . Two or more samples were measured for each orientation, and the results on different samples were found to agree within experimental error. The values of the piezoresistance and elastoresistance coefficients at 77 and 300°K are listed in Table II.

The piezoresistance results in gallium antimonide are similar to those found in *p*-type germanium,<sup>8</sup> indium antimonide<sup>12,13</sup> and gallium arsenide<sup>14</sup> in that the coefficient  $\pi_{44}$  is positive and large compared to the  $\pi_{11}$  and  $\pi_{12}$  coefficients. However, a many-valley-type band structure having energy minima along the [111] reciprocal axes could also give piezoresistance results of this symmetry.<sup>15</sup> By combining the piezoresistance results with the previous magnetoresistance results,<sup>3-5</sup> a many-valley-type band structure may be ruled out, since the magnetoresistance results require minima along the [100] reciprocal axes. The results of both measurements are consistent with a germanium-type valence band structure.

The temperature dependence of  $\pi_{44}$  follows very closely a  $T^{-1}$  behavior as shown in Fig. 1. This indicates that the spin-orbit splitting energy in gallium antimonide is large compared to  $kT$  at room temperature, since any carriers excited into the spherically symmetric split-off band would not contribute to the piezoresistance effect. The  $T^{-1}$  dependence also indicates that the gallium antimonide samples used in this investigation are not statistically degenerate, so that the magnitude of the measured piezoresistance coefficients is determined by the valence band structure.

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<sup>14</sup> M. Zerbst, Z. Naturforsch. **17a**, 649 (1962).

<sup>15</sup> C. Herring, Bell System Tech. J. **34**, 237 (1955).