Influence of dislocations on the densities and mobilities of light and heavy holes in *p*-type InSb single crystals at 77.4°K

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The densities and mobilities of light and heavy holes were determined experimentally for *p*-type InSb crystals at 77.4°K before and after plastic deformation. The deformation involved bending of the crystals at 360°C. At this temperature both the light and heavy holes interacted strongly with dislocations generated in the crystals and this was manifested by considerable changes in the hole densities and mobilities, compared with the values obtained for undeformed control crystals. The final results depended strongly on the deformation (strain) rate. At low rates the point centers appearing in a crystal as a result of plastic deformation diffused to the dislocation cores and were activated by the microstrain fields in the crystal lattice near the cores. This enhanced greatly the acceptor effect in the crystal. Changes in the densities in the light- and heavy-hole bands were approximately proportional. The mobilities of both types of carrier then decreased considerably. At high deformation rates there was a direct interaction between carriers and dangling bonds in the cores of the newly formed dislocations, which enhanced greatly the donor effect in the crystal and was accompanied by a considerable reduction in the mobilities of both types of carrier as a result of the scattering of the carriers by the new dislocations. The changes in the densities in the light- and heavy-hole bands were again proportional. All these results were deduced from the dependences of the magnetoresistance on the magnetic field applied to control and to plastically deformed crystals, and from a subsequent analysis of the data carried out using a two-band model and assuming that the relaxation time was independent of the carrier energy. At 77.4°K the two-band approximation was sufficiently accurate for investigations of this type, as demonstrated for a large number of crystals before deformation. Some electrical properties of *p*-type InSb crystals were determined before deformation.

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In earlier papers[1-3] we reported studies on the influence of dislocations on the electrical properties of InSb single crystals. We found that the dislocations which formed in plastically bent InSb crystals interacted strongly with the electron subsystem, causing considerable changes in the carrier densities and mobilities. These results were deduced from an analysis of the Hall coefficient in a strong magnetic field and of the electrical conductivity in the absence of a magnetic field, which gave information on the carrier densities and mobilities in control and in plastically deformed samples. However, one should point out that in the case of *p*-type InSb crystals these measurements can give only the total density of light and heavy holes in a crystal and the corresponding Hall mobility, which are very close to the corresponding values for the heavy holes, because in *p*-type InSb the heavy-hole density is much higher than the light-hole density. This approach fails to give the density and mobility of the light holes. Therefore, it would be interesting to determine separately the properties of the light and heavy holes in order to study independently their interactions with dislocations in plastically deformed crystals.

The aim of the present investigation was to determine the influence of dislocations on the densities and mobilities of both light and heavy holes in *p*-type InSb crystals at the boiling point of nitrogen, $T = 77.4$ °K. The investigation was based on an analysis of the magnetoresistance of control and of plastically deformed samples on the magnetic field considered on the assumption that the relaxation time was independent of the energy.[4] In the case of the undeformed material the dependence of the Hall coefficient on the magnetic field was also analyzed. We used samples bent plastically at very low and very high deformation (strain) rates, which made it possible to observe separately the features characteristic of both mechanisms of the influence of dislocations on the electrical properties of *p*-type InSb crystals.[2,3]

We also carried out a detailed investigation of undeformed *p*-type InSb which gave the densities and mobilities of both light and heavy holes in a wide range of dopant concentrations. Moreover, we carried out a self-consistent comparison of the carrier densities and mobilities obtained from the dependence of the magnetoresistance on the magnetic field with the data deduced from the dependence of the Hall coefficient on the magnetic field. This comparison allowed us to draw conclusions on the mutual consistency of the results obtained by the two (magnetoresistance and Hall effect methods.

1. PRINCIPAL RELATIONSHIPS

The valence band of InSb, like that of Ge, has three components[5]: the heavy-hole band, the light-hole band degenerate with the heavy-hole band at $K = 0$, and a third band separated from the other two by the energy of the spin-orbit interaction which is sufficiently large to allow us to ignore its influence in the interpretation of the results of galvanomagnetic measurements. There are grounds for assuming[5] that the maxima of the heavy-hole band are shifted somewhat from the center

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of the Brillouin zone in the ⟨111⟩ directions. According to Kane's calculations,[6] this shift is of the order of 0.003 of the distance from the center of the Brillouin zone to its boundary. The energy at a maximum exceeds the energy corresponding to $\mathbf{K}=0$ by 10^{-4} eV. Since the carrier energy at 77.4 °K is considerably greater than 10^{-4} eV, we shall assume that the maxima of both bands are located at $\mathbf{K}=0$ and that the constant-energy surfaces are spherically symmetric.

In the case of the p-type material at 77.4 °K only the heavy and light holes participate in the electrical conduction process, because the electron density in the conduction band of InSb is negligible at this temperature. Therefore, we shall consider the magnetic-field dependences of the magnetoresistance and Hall coefficient using a two-band model.

Further simplification is achieved by allowing for the fact that the masses of the heavy and light holes in InSb are very different.[4] It is known[7] that the changes in the magnetoresistance and Hall coefficient with the magnetic field are so large, compared with the corresponding changes due to the thermal scatter of the carrier velocities, that the latter can be ignored because they are effects of higher order. Therefore, irrespective of the carrier scattering mechanism, which depends on temperature and the degree of doping of a crystal, calculations can be carried out on the assumption that the relaxation time is independent of the carrier energy.

Under these assumptions we have[4]

$$\Delta\rho/\rho_0=bH^2/(1+cH^2), \tag{1}$$

$$\frac{\Delta R_H}{R_0}=-\frac{\Delta\rho}{\rho_0}\frac{10^8c^{1/2}}{R_0\sigma_0}, \tag{2}$$

where $\Delta\rho/\rho_0$ is the magnetoresistance of a crystal; R_H is the Hall coefficient in a magnetic field $H(G)$; R_0 is the Hall coefficient in the limit $H=0$; the constants b and c are found from the experimental results. In the case of p-type InSb at 77.4 °K the inequalities $p_1 \gg p_2, \mu_1 \ll \mu_2$ are obeyed.[4] Under these conditions the transport equations in the two-band theory can be solved approximately[4] and the quantities p_1, μ_1, p_2, and μ_2 of interest to us can be expressed in terms of b, c, σ_0, and R_0 determined from the experimental values:

$$p_1=\left(\frac{c}{c+b}\right)^2\frac{\sigma_0}{e(R_0\sigma_0-10^8b/c^{1/2})},\quad p_2=\frac{10^{-8}bc^{1/2}\sigma_0}{e(c+b)^2};$$
$$\mu_1=\left(\frac{c+b}{c}\right)\left(R_0\sigma_0-\frac{10^8b}{c^{1/2}}\right),\quad \mu_2=\frac{10^8(c+b)}{c^{1/2}}. \tag{3}$$

Here, p_1, μ_1, and p_2, μ_2 are the properties of the light and heavy holes, respectively; σ_0 is the electrical conductivity in $H=0$; e is the electron charge.

It follows from the above discussion that the carrier densities and mobilities in our crystals can be determined by two methods.

1. The experimental data on the change in the magnetoresistance with the change in the magnetic field can be used to find the coefficients b and c in Eq. (1), selecting them so that the experimental data satisfy optimally Eq. (1). The knowledge of the coefficients b and c makes it possible to calculate the carrier densities and mobilities using the expressions in Eq. (3).

2. The same results can be obtained from the experimentally determined dependence of R_H on the magnetic field. Substituting Eq. (1) for $\Delta\rho/\rho_0$ in Eq. (2), we obtain an expression for the dependence of R_H on the magnetic field:

$$R_H=R_0-\frac{10^8bc^{1/2}}{\sigma_0}H^2/(1+cH^2). \tag{4}$$

As before, the coefficients b and c are found from the experimental data, in the present case from the magnetic-field dependence of R_H. The carrier densities and mobilities are calculated from the expressions in Eq. (3).

We used both methods. A study of plastically deformed samples involved an analysis of the data on the magnetic-field dependence of the magnetoresistance.

2. EXPERIMENTAL METHOD

We used p-type InSb single crystals grown by the Czochralski method along the ⟨112⟩ axis. The density of the growth dislocations deduced from the etch pits (the etchant was CP-4M-Ref. 8) never exceeded 10^2 cm^{-2}. The initial concentration of the active impurities was determined by the Hall method at the temperature of boiling nitrogen.

Ingots were oriented by an x ray method to within 1° and were cut into plates of 2.2–3 mm thickness and with a suitable orientation; samples used in the electrical measurements were cut from these plates. The planes of the bases of the plates used to investigate the properties of the original material and, consequently, the bases of the samples cut from these plates were perpendicular to the crystal growth axis. The orientation of the samples cut from these plates was not determined apart from the base. The plates intended for plastic deformation and also those from which control samples were cut had the orientation shown in Fig. 1 of Ref. 1. The plates were ground mechanically and etched in CP-4M. They were bent relative to the $[11\bar{2}]$ axis by the four-point method. In the course of bending the plates were kept at 360 °C in a furnace filled with a 90% N_2 + 10% H_2 gas mixture. The samples were loaded dynamically and the deformation rate was constant. Plastic bending of InSb crystals under these conditions[8] should result in the accumulation of an excess of α or β dislocations, depending on the direction of bending. The deformations producing these dislocations were called α and β bending, respectively. It was assumed in Ref. 1 that, for a given orientation of the crystal, the above treatment caused accumulation of edge dislocations directed along the $[11\bar{2}]$ bending axis. The dislocation density was deduced from the measured radii of curvature of the deformed crystals. Two samples were cut from each deformed plate and also from the corresponding control plate: one of them in the direction of the $[11\bar{2}]$ axis (longitudinal sample) and the other at right-angles (transverse sample).

In all cases the samples cut from the plates were in the form of bridges (shown at the bottom of Fig. 1) and

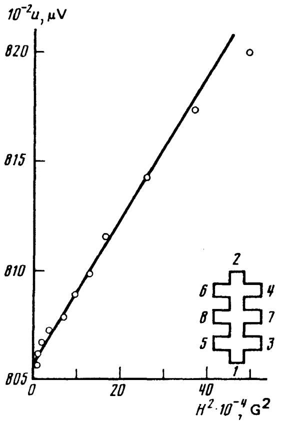

FIG. 1. Dependence of the magnetoresistance emf on the magnetic field obtained in weak fields for sample No. 12; H is the magnetic field and u is the magnetoresistance emf.

their geometric dimensions were such that the ratio of the length of the sample to the width was 7.5 for the original material and 6 for the plastically deformed samples. Before the measurements the samples were ground mechanically and etched in solutions CP-4M and H-100 (Ref. 9).

During measurements of the electrical properties the samples were immersed in liquid nitrogen. A current was passed through contacts 1–2 (Fig. 1). The magnetoresistance emf was measured across contacts 3–4 and 5–6; the Hall emf was determined across contacts 7–8. For each value of the magnetic field the magnetoresistance and Hall emf's were measured twice for the opposite directions of the current. Next, the direction of the field was reversed and the measurements were repeated. All these values were then averaged. The emf's across the contacts were measured by the compensation method employing R-348 potentiometers. The magnetic field intensity was kept constant to within ±3%.

3. DENSITIES AND MOBILITIES OF HOLES IN THE ORIGINAL InSb MATERIAL

The densities and mobilities of the light and heavy holes in p-type InSb single crystals were determined earlier at the boiling point of nitrogen by Champness[4] from an analysis of the magnetic-field dependence of the magnetoresistance. Unfortunately, the limited range of this determination (the results for just three samples were analyzed) and the imperfection of the crystals employed prevented the author from drawing definite conclusions about the results. Moreover, conflict between the data on the magnetoresistance of one of the samples and the data deduced from the Hall coefficient measurements in a field $H = 5000$ G, which was revealed by the analysis of the measurement results, caused Champness to doubt the method employed.

In the present section we shall give the results of our investigation of the carrier densities and mobilities in p-type InSb crystals at 77.4°K, which was carried out on 18 samples with dopant concentrations in the range 5×10^{11}–2×10^{16} cm^{-3}.

The samples prepared for investigating the original material were checked for the homogeneity of the electrical properties. This was done by measuring the Hall coefficient in $H = 700$ G for all three pairs of contacts (4–6, 7–8, 3–5) and the electrical conductivity across the contacts 3–4 and 5–6. The results were used to select the samples with the scatter of the values of $1/eR_H$ and σ_0 not exceeding 10% from the average. The electrical properties of the selected samples are listed in Table I.

The magnetoresistance emf's (emf's across the contact pairs 3–4 and 5–6) and the Hall emf's across the 7–8 contacts were determined for the selected samples in magnetic fields 50–10 000 G (for samples Nos. 15–18 the range was 300–10 000 G). The results of the measurements were analyzed graphically. The values of u_0 (maximum magnetoresistance emf in the limit as $H\to 0$), R_0, b, and c governing the dependences of $\Delta\rho/\rho_0 = (u-u_0)/u_0$ and R_H on the magnetic field in Eqs. (1) and (4) were used to calculate the densities and mobilities of both types of carrier.

The results of the measurements and their analysis will be illustrated by considering sample No. 12. We can easily see from Eq. (1) that in weak magnetic fields such that $cH^2 \ll 1$ the experimental values of u and H^2 should fit a straight line $u = u_0 + u_0 bH^2$ (the quantity H^2 is plotted along the abscissa) and the position of this line can be used to determine the parameters u_0 and b. Figure 1 gives the results of measurements of the magnetoresistance of sample No. 12 in weak fields, showing that the first experimental values of u and H^2 do indeed fit well a straight line. This was true of all 18 samples. The parameters u_0 and b were determined from Fig. 1 using the ordinate of the point of intersection of the H^2 axis relative to this line. The values obtained for sample No. 12 were $u_0 = 80\,561.4$ μV and $b = 5.25\times 10^{-8}$ G^{-2}. The known value of u_0 was used to calculate the experimental magnetoresistance $(\Delta\rho/\rho_0)_e = (u-u_0)/u_0$ for all the values of the magnetic field. The parameter c was found from Eq. (1), where the experimental values of the magnetoresistance corresponding to the magnetic fields 700, 800, and 900 G were substituted for $\Delta\rho/\rho_0$ and the coefficient b was assumed to have the value given above. These results were averaged. For sample No. 12 the value of c found in this way was 7.93×10^{-7} G^{-2}. The parameters u_0, b, and c

TABLE I. Electrical properties of samples.

Sample No.	p, cm^{-3}	σ_0, Ω^{-1}·cm^{-1}	μ_H, cm^2·V^{-1}·sec^{-1}
1	$5.73\cdot 10^{11}$	$1.14\cdot 10^{-3}$	$1.24\cdot 10^{4}$
2	$2.17\cdot 10^{12}$	$3,98\cdot 10^{-3}$	$1,15\cdot 10^{4}$
3	$2,93\cdot 10^{12}$	$5.21\cdot 10^{-3}$	$1,11\cdot 10^{4}$
4	$9.25\cdot 10^{12}$	$1,60\cdot 10^{-2}$	$1.08\cdot 10^{4}$
5	$2,59\cdot 10^{13}$	$4,23\cdot 10^{-2}$	$1,02\cdot 10^{4}$
6	$7.12\cdot 10^{13}$	$1.20\cdot 10^{-1}$	$1,07\cdot 10^{4}$
7	$1.28\cdot 10^{14}$	$2.11\cdot 10^{-1}$	$1,03\cdot 10^{4}$
8	$1,31\cdot 10^{14}$	$2.08\cdot 10^{-1}$	$9,94\cdot 10^{3}$
9	$1,55\cdot 10^{14}$	$2,78\cdot 10^{-1}$	$1.12\cdot 10^{4}$
10	$1,68\cdot 10^{14}$	$2,76\cdot 10^{-1}$	$1,01\cdot 10^{4}$
11	$3,47\cdot 10^{14}$	$6.22\cdot 10^{-1}$	$1,12\cdot 10^{4}$
12	$4.66\cdot 10^{14}$	$7,71\cdot 10^{-1}$	$1,03\cdot 10^{4}$
13	$5.43\cdot 10^{14}$	$9,49\cdot 10^{-1}$	$1.09\cdot 10^{4}$
14	$6,82\cdot 10^{14}$	$9.81\cdot 10^{-1}$	$8.99\cdot 10^{3}$
15	$1.12\cdot 10^{15}$	1,61	$8,96\cdot 10^{3}$
16	$2.83\cdot 10^{15}$	3.28	$7,25\cdot 10^{3}$
17	$2.43\cdot 10^{16}$	13.8	$3.55\cdot 10^{3}$
18	$2.48\cdot 10^{16}$	14.4	$3,63\cdot 10^{3}$

and the expressions in Eq. (3) were then used to determine the carrier densities and mobilities in sample No. 12: $p_1=4.19\times10^{14}$ cm^{-3}; $\mu_1=1.09\times10^4$ cm$^2\cdot$V$^{-1}\cdot$sec^{-1}; $p_2=3.19\times10^{12}$ cm^{-2}; $\mu_2=9.49\times10^4$ cm$^2\cdot$V$^{-1}\cdot$sec^{-1}.

The coefficients b and c allowed us to use Eq. (1) to calculate the theoretical values of the magnetoresistance $(\Delta\rho/\mu_0)_t$ throughout the investigated range of magnetic fields. The values of $(\Delta\rho/\rho)_e$ and $(\Delta\rho/\rho_0)_t$ for sample No. 12 were then compared (Fig. 2). This comparison showed that the values of $(\Delta\rho/\rho_0)_e$ and $(\Delta\rho/\rho_0)_t$ were practically identical for magnetic fields of the order of 2000 G. In stronger fields there was a systematic deviation from the theory: according to Eq. (1), the magnetoresistance should tend to saturate in fields in excess of 2000 G (Fig. 2, curve $(\Delta\rho/\rho_0)_t$, whereas the experimentally observed magnetoresistance continued to rise and there was no tendency for saturation. In a field of $H=10\,000$ G the deviation from the theory was about 150%, which far exceeded the experimental error. A comparison of the results obtained for the other samples established that the point of divergence of the experimental curve representing $(\Delta\rho/\rho_0)_e$ from the corresponding theoretical curve $(\Delta\rho/\rho_0)_t$ was always located near the magnetic field satisfying the condition $\mu_2H\approx1$, so that in the case of heavily doped samples in which the mobility was less the point shifted to the right proportionality to $1/\mu_2$. Bearing in mind that the inequality $\mu H\geqslant1$ defines the range of magnetic fields from which the quantization of the carrier orbits begins in a magnetic field,[7] we assumed that the observed deviation of the magnetic-field dependence of the magnetoresistance from the classical theory was due to the quantization of the light-hole orbits in a magnetic field. One could also explain this discrepancy by postulating the influence of inhomogeneities of the dopant distribution.

We included in Fig. 2 the dependences of $(\Delta\rho/\rho_0)_e$ on the magnetic field obtained for several samples with different dopant concentrations. In the dopant concentration range from $\approx5.73\times10^{11}$ cm^{-3} to $\sim3\times10^{14}$ cm^{-3} for each value of the magnetic field the values of $(\Delta\rho/\rho_0)_e$ were practically identical for all the samples, so that the corresponding magnetic-field dependence of the magnetoresistance was described by a single curve, such as curve 1 in Fig. 2 obtained by averaging of the data for the first ten samples in Table I. An increase in the dopant concentration above 3×10^{14} cm^{-3} reduced rapidly the magnetoresistance, so that the curve followed a lower path. When the dopant concentration was of the order of 2×10^{16} cm^{-3} this reduction in the magnetoresistance reached approximately one order of magnitude (curve 3 in Fig. 2). Figure 2 demonstrates also that in strong magnetic fields the magnetoresistance always depended on the field in accordance with the law $\Delta\rho/\rho_0\propto H^\alpha$, and that for all samples the value of α was approximately the same $\alpha\approx0.84\pm0.02$, irrespective of the doping.

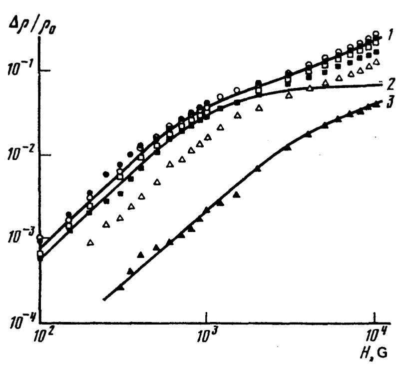

FIG. 2. Dependences of the magnetoresistance $\Delta\rho/\rho_0$ on the magnetic field for undeformed p-type InSb crystals: ○) sample No. 1; ●) sample No. 2; □) sample No. 10; ■) sample No. 12; △) sample No. 16; ▲) sample No. 18. Curve 1 represents the average value of $(\Delta\rho/\rho_0)_e$ for the first ten samples in Table I; curve 2 is the theoretical dependence $(\Delta\rho/\rho_0)_t$ for sample No. 12; curve 3 is the average curve $(\Delta\rho/\rho_0)_e$ for samples Nos. 17 and 18.

As pointed out earlier, the carrier densities and mobilities in the investigated samples could also be obtained by analyzing the magnetic-field dependence of the Hall coefficient. The results of measurements of the Hall coefficient throughout the investigated range of magnetic fields are plotted for sample No. 12 in Fig. 3a. Figure 3b gives the values of R_H as a function of H^2 for the same sample but in weak magnetic fields; it is clear that the first points corresponding to low values of H fit well a straight line. The equation for this line is obtained from Eq. (4) by dropping H^2 from the denominator:

$$R_H=R_0-10^8bc^{1/2}H^2/\sigma_0.$$

This makes it possible to determine graphically both R_0 and $cb^{1/2}/\sigma_0$; having determined R_H at any point in the range of strong fields in Fig. 3a, we can then use Eq. (4) to find the numerical values of the quantities of interest to us: $R_0=2.07\times10^4$ cm^3/C, $b=6.00\times10^{-8}$ G^{-2}, $c=1.05\times10^{-6}$ H^{-2}. The continuous curve in Fig. 3a represents the results of calculations of R_H carried out using Eq. (4), where the parameters b, c, and R_0 have the values just quoted. It is clear from the figure that Eq. (4) describes well the dependence of R_H on the magnetic fields throughout the full range of the latter right up to 10 kG. The carrier densities and mobilities can again be determined from the expressions in Eq. (3): $p_1=4.24\times10^{14}$ cm^{-3}, $\mu_1=1.09\times10^4$ cm$^2\cdot$V^{-1} $\times$sec^{-1}, $p_2=2.43\times10^{12}$ cm^{-3}, $\mu_2=1.08\times10^{15}$ cm$\cdot$V^{-1}

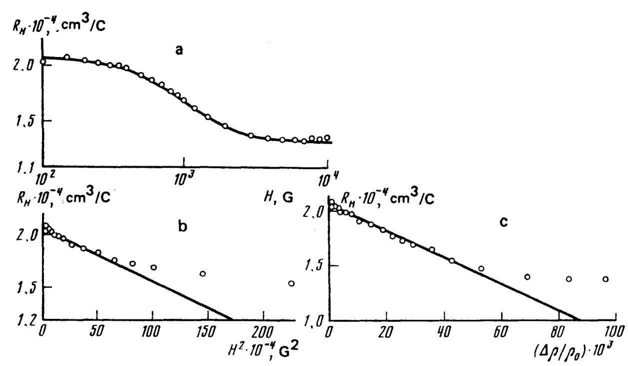

FIG. 3. Dependences of the Hall coefficient R_H for sample No. 12: a) on the magnetic field; b) on the magnetic field in the range of weak fields; c) on the magnetoresistance $\Delta\rho/\rho_0$ in the range of weak fields.

$\times \mathrm{sec}^{-1}$. The good agreement between these values and those obtained earlier from the magnetoresistance data clearly supports the simplfying assumptions formulated at the beginning of the present paper. This is true of all 18 samples in Table I. In all cases the carrier densities and mobilities of the light and heavy holes deduced from the magnetoresistance and Hall coefficient data agree to within ±15% of the corresponding averages.

Champness[4] used Eq. (2) to check the self-consistency of his experimental data within the framework of the theory adopted in the present paper. An analysis of the data for samples R and U (the notation is that of Ref. 4) in a field of $H = 5000$ G gave the value $\Delta R_H/R_0 = 18\%$ for sample R and 36% for sample U. The Hall coefficient data yielded 33 and 38%, respectively, which was satisfactory in the case of sample U but represented a considerable discrepancy in the case of sample R. Hence, Champness concluded that the magnetoresistance data were insufficient to find the correct value of c. In fact, this discrepancy was due to the fact that, as pointed out above, in strong fields (particularly in $H = 5000$ G) the magnetoresistance data cannot be described by the simple theory adopted here. This can easily be seen in Fig. 3c, which gives the measured values of $\Delta\rho/\rho_0$ and R_H. The abscissa represents the values of $(\Delta\rho/\rho_0)_e$ for sample No. 12 and the ordinate gives the corresponding experimental values of R_H. According to Eq. (2), all the experimental points obtained for a given sample should lie on the same straight line. As expected, all the points up to about $H = 2000$ G do indeed fit well a straight line, but in strong fields there is a significant deviation from the adopted theory. We analyzed the data for sample R used by Champness employing the graphical information given for this sample in Ref. 8 and we concluded that the mobilities and densities determined by the two methods described above agreed to within 15% of the corresponding averages.

Figure 4 gives the results of calculations of the carrier mobilities μ_1 and μ_2 and of the density ratio p_2/p_1, representing averages of the magnetoresistance and Hall coefficient data obtained for all 18 samples. We can readily see that in the dopant concentration range from

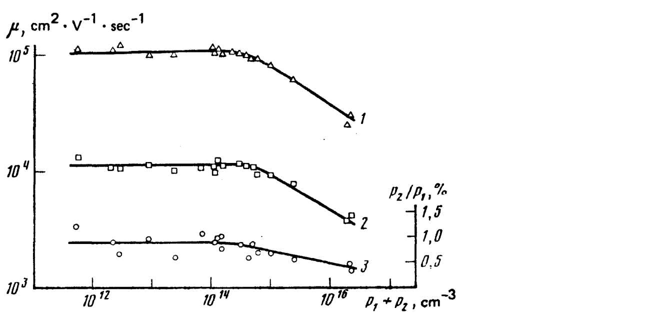

FIG. 4. Dependences of the carrier mobilities and of the ratio of the carrier densities in the light- and heavy-hole bands on the degree of doping: 1) light-hole mobility; 2) heavy-hole mobility; 3) ratio of the carrier densities in the light- and heavy-hole bands; p_1 is the density of carriers in the heavy-hole band and p_2 is the density in the light-hole band.

5.73×10^{11} cm^{-3} to $\sim 3 \times 10^{14}$ cm^{-3} the carrier mobilities in the two bands are essentially constant, which gives us grounds for assuming that the scattering of carriers by the thermal lattice vibrations predominates in this range of the dopant concentrations in the two bands. The average values of the carrier mobilities in this range of concentrations, averaged over the data for the first ten samples of Table I, are $\mu_1 = 1.10 \times 10^4$ cm^2 $\times$ V$^{-1}\cdot$ sec^{-1}, $\mu_2 = 1.07 \times 10^5$ cm$^2 \cdot$ V$^{-1} \cdot$ sec^{-1}, and $\mu_2/\mu_1 = 9.73$. At the dopant concentrations of $\sim 10^{15}$ cm^{-3} or higher the scattering by ionized impurity centers predominates. In this range the mobilities of both types of carrier decreases rapidly on increase in the dopant concentration. The data for p_2/p_1 are not as regular, which is easily explained using the formula $p_2/p_1 = b\mu_1/c\mu_2$ obtained from Eq. (3) by a simple comparison. In fact, if we assume (for the sake of argument) that the error in the determination of b, c, μ_1, and μ_2 is 15%, then the possible error in the ratio p_2/p_1 is 60%. Some reduction in the relative density of the light holes at high dopant concentrations was noted by Champness.[4] Our experiments confirmed this tendency (Fig. 4): in the dopant concentration range 5×10^{11}–5×10^{14} cm^{-3} the ratio p_2/p_1 was essentially constant. There was only some scatter of this quantity relative to the average value, which was 0.93% (average for the first ten samples in Table I). At higher dopant concentrations the ratio p_2/p_1 fell considerably.

It is usually assumed that, in view of the degeneracy of the light- and heavy-hole bands of InSb at $K = 0$, the relaxation times of the carriers in these bands are almost equal.[7] This can be used to determine the light-hole mass. Applying the relationship

$$\mu = e\tau/m^* \tag{5}$$

to each of the bands and assuming that $\tau_1 = \tau_2$, we find that $m_2^*/m_1^* = \mu_1/\mu_2$. Substituting here the above average value $\mu_2/\mu_1 = 9.73$ and the published[5] heavy-hole mass $m_1^* = 0.6 m_0$ (m_0 is the electron mass), we find that $m_2^* = 0.062 m_0$. On the other hand, since in the case of a quadratic band the contribution of carriers to the current is proportional to $m^{*3/2}$, we find that the application of Eq. (5) and reduction in the relaxation time yields

$$\mu_1 p_1/\mu_2 p_2 = (m_1^*/m_2^*)^{3/2}.$$

Substituting here the above average values of μ_2/μ_1 and p_2/p_1, we obtain another value of the light-hole mass $m_2^* = 0.0049 m_0$, which differs by an order of magnitude from that just quoted. This contradiction means that the relaxation times in the heavy- and light-hole bands are different, although they may be of the same order of magnitude. If the relaxation time is not cancelled out, then the above relationships become

$$\frac{\mu_1}{\mu_2} = \frac{m_2^*}{m_1^*}\frac{\tau_1}{\tau_2}, \quad \frac{\mu_1}{\mu_2}\frac{p_1}{p_2} = \frac{\tau_1}{\tau_2}\left(\frac{m_1^*}{m_2^*}\right)^{3/2}.$$

Substituting here the above values of μ_2/μ_1, p_2/p_1, and m_1^*, we now find that $m_2^* = 0.027 m_0$ and $\tau_1/\tau_2 = 2.28$. The new value of the light-hole mass is in good order-of-magnitude agreement with the values obtained by other authors: infrared absorption data are used in

Ref. 11 to show that the order of magnitude of m^* is $0.012m_0$; the cyclotron resonance method at low temperatures is used in Ref. 12 to find that $0.021m_0$.

The good agreement between the light-hole mass obtained in the present study with the value found by the cyclotron resonance method, and the agreement between the carrier densities and mobilities deduced from the magnetoresistance and Hall coefficient measurements as a function of the magnetic field show clearly that the two-band theory and the approximation of independent relaxation times of the carrier energy describe well the electrical properties of p-type InSb crystals at temperatures corresponding to the extrinsic conduction region. Moreover, Eqs. (1) and (4) describe well the observed dependences of the magnetoresistance and the Hall coefficient on the magnetic field in a wide range of the latter. The exception to this rule is only the dependence of the magnetoresistance in strong magnetic fields, where the classical theory is inapplicable. Therefore, in investigating the electrical properties of p-type InSb crystals on the basis of the magnetic-field dependences of the magnetoresistance one should use only the data corresponding to such values of the magnetic field that Eq. (1) is still valid and, consequently, the inequality $\mu_2 H < 1$ is obeyed. It follows from the above treatment that the results obtained are close to the real values of the quantities in question.

4. INTERACTION OF LIGHT AND HEAVY HOLES WITH DISLOCATIONS

In investigating the interaction of carriers with dislocations we shall proceed on the assumption that at $T = 77.4$ °K the process of conduction in plastically deformed p-type InSb crystals and in the original material involves only the light and heavy holes, so that a crystal can be regarded as approximately of the two-band type. This approximation is based on the results of the investigations reported in Refs. 1–3, where it was found that at the boiling point of nitrogen and higher temperatures there is no anisotropy of the electrical conductivity of plastically deformed p-type InSb crystals within the limits of the experimental error, so that the true dislocation conductivity, i.e., the component due to conduction along dislocation cores, is almost completely masked by the change in the bulk conductivity of a crystal caused by the plastic deformation of a sample and there is no significant contribution to the measurements described above. This is independent of the type of conduction in the original material, but it is important that the deformed sample should have p-type conduction. In particular, it follows from Refs. 1–3 that in this range of temperatures the influence of dislocations on the electrical properties of p-type InSb crystals reduces mainly to a considerable change in the carrier densities and mobilities in plastically deformed crystals. Therefore, the purpose of the present investigation on plastically deformed samples is to determine separately the changes in the densities and mobilities of the light and heavy holes as a result of plastic bending of p-type InSb crystals.

We shall also assume that in the case of plastically deformed crystals the inequalities $p_2 \ll p_1$ and $\mu_2 \gg \mu_1$ still apply.

The above assumptions allow us to describe plastically deformed p-type InSb crystals by a simple two-band model using the approximation that the relaxation time is independent of the energy. We can then use the above methods for the analysis of the magnetic-field dependences of the magnetoresistance and the Hall coefficient at temperatures in the vicinity of the boiling point of nitrogen to calculate the quantities p_1, p_2, μ_1, and μ_2 for plastically deformed samples. In the present investigation this was done separately in the calculation of the densities and mobilities of the light and heavy holes in plastically deformed and control p-type InSb crystals at $T = 77.4$ °K. The initial data were the dependences of the magnetoresistance on the magnetic field.

It was also shown in Refs. 1–3 that the electrical properties of plastically deformed p-type InSb crystals depend strongly on the rate of deformation. If this rate is low ($\dot{\varepsilon} \leq 4.5 \times 10^{-6}$ sec^{-1}), the point centers formed in the course of deformation diffuse effectively toward the dislocation cores. They are activated by the microdistortion fields near the cores and form electrically active atmospheres around dislocations; these atmospheres enhance greatly the acceptor effect. At high rates of deformation ($\dot{\varepsilon} \gg 4.5 \times 10^{-6}$ sec^{-1}) these centers cannot reach the dislocation cores in time and the experimentally observed considerable enhancement of the donor action in plastically deformed crystals represents the direct interaction of the dislocation cores with the electron subsystem of the crystal.

In view of this, we shall report separately the results obtained for slowly deformed crystals ($\dot{\varepsilon} = 4.5 \times 10^{-6}$ sec^{-1}) as well as those deformed rapidly ($\dot{\varepsilon} = 750 \times 10^{-6}$ sec^{-1}).

A. Slow bending

Crystals were bent plastically, in accordance with the method described above, at a rate of $\dot{\varepsilon} = 4.5 \times 10^{-6}$ sec^{-1}. A total of eight crystals was deformed. The plates cut from the ingots were grouped in pairs, and the plates in each pair were bent in opposite directions in order to accumulate an excess of α or β dislocations in a plate. The density of the dislocations generated in a crystal was of the order of 1.8×10^7 cm^{-2}. The plates in each pair and the corresponding control plates were all cut from the same ingot. The magnetoresistance of the longitudinal and transverse samples was determined in magnetic fields up to 10 kG. Typical results are plotted in Fig. 5. The results of an analysis of these measurements, made in the two-band model approximation, are listed in Table II.

We can easily see that the magnetoresistance of the plastically deformed samples was considerably less than that of the control samples and this was true throughout the investigated range of magnetic fields. According to Table II, this corresponded to a strong increase in the densities of the light and heavy holes in

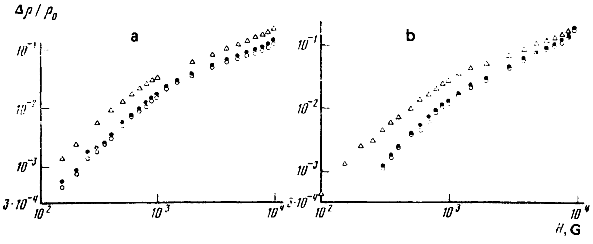

FIG. 5. Dependences of the magnetoresistance $\Delta\rho/\rho_0$ on the magnetic field applied to control and plastically deformed samples. The deformation took place in the α-bending orientation: a) at a low rate; b) at a high rate. The curves were similar for the case of β bending. Δ) Control sample; $\bigcirc$) plastically deformed longitudinal sample; $\bullet$) plastically deformed transverse sample.

the plastically deformed crystals. The occupancy of the dangling bonds corresponding to the density of the heavy holes and implying the direct capture of carriers by these bonds in the dislocation cores was of the order of 10. These results were in good qualitative and quantitative agreement (in the sense of the occupancy by the heavy holes[1]) with the results of Ref. 1, where we reported that under these deformation conditions the plastic bending of p-type InSb crystals was accompanied by a considerable enhancement of the acceptor effect. The changes in the carrier densities in the light- and heavy-hole bands were approximately proportional. The mobilities of the light and heavy holes in the plastically deformed crystals were considerably less than the corresponding mobilities in the control samples. However, these changes were in good agreement with the data of Fig. 4, showing the dependences of the changes in the carrier mobility on the carrier density in the relevant bands in the original material: in both cases the reduction in the mobilities of the light and heavy holes corresponded to a considerable increase in the densities of both carriers in a crystal. Therefore, the electrical properties of slowly deformed p-type InSb crystals were largely similar, from the point of the contributions of the light- and heavy-hole bands, to the properties of undeformed p-type crystals which were doped more heavily than the control samples.

There was no anisotropy of the carrier mobility in the plastically deformed crystals (this was true within the limits of the experimental error).

B. Fast bending

In this case the experiments were carried out exactly in the same way as in the slow bending case, except that the rate of deformation was now 750×10^{-6} sec^{-1}, i.e., it was over two orders of magnitude greater than in the slow bending case. A total of six samples was deformed. In all cases the crystals were bent to a radius of curvature of the order of 1.3 cm, corresponding to the dislocation density of the order of 2.4×10^{7} cm^{-2}. Typical results of measurements and the corresponding results of their analysis on the basis of the two-band model are given in Fig. 5b and Table II.

It is clear from Fig. 5b that the experimental magnetoresistance curves of the rapidly deformed samples are, as in the slow bending case, located much lower

TABLE II. Properties of plastically deformed samples.

Sample No.	Sample	Type of bending	p_1, cm^{-3}	p_2, cm^{-3}	μ_1 cm$^2\cdot$V$^{-1}\cdot$sec^{-1}	μ_2 cm$^2\cdot$V$^{-1}\cdot$sec^{-1}	$\frac{p_2}{p_1+p_2}\cdot100$
			Slow bending				
1	A_1	α	$2.03\cdot10^{15}$	$1.94\cdot10^{13}$	$8.90\cdot10^{3}$	$6.06\cdot10^{4}$	0.9
2	control		$1.44\cdot10^{14}$	$1.06\cdot10^{12}$	$1.10\cdot10^{4}$	$1.04\cdot10^{3}$	0.7
3	B_1	β	$2.20\cdot10^{15}$	$1.27\cdot10^{13}$	$8.13\cdot10^{3}$	$7.24\cdot10^{4}$	0.6
4	control		$1.63\cdot10^{14}$	$1.13\cdot10^{12}$	$1.04\cdot10^{4}$	$1.01\cdot10^{5}$	0.7
			Fast bending				
1	A_2	α	$1.45\cdot10^{14}$	$8.61\cdot10^{11}$	$3.62\cdot10^{3}$	$4.63\cdot10^{4}$	0.6
2	control		$3.89\cdot10^{14}$	$2.08\cdot10^{12}$	$1.03\cdot10^{4}$	$1.04\cdot10^{5}$	0.5
3	B_2	β	$2.85\cdot10^{13}$	$4.70\cdot10^{10}$	$3.93\cdot10^{3}$	$5.54\cdot10^{4}$	0.2
4	control		$4.94\cdot10^{14}$	$3.59\cdot10^{12}$	$7.23\cdot10^{3}$	$8.05\cdot10^{4}$	0.7

than the corresponding curves for the control samples and this is true throughout the investigated range of magnetic fields. However, in the present case this does not represent an increase in the carrier density in the light- and heavy-hole bands, which is true of the slow bending, but it corresponds to a strong reduction in these densities, inplying a considerable increase in the donor effect in the investigated crystals. As in the preceding case, the changes in the carrier densities in the light- and heavy-hole bands were approximately proportional.

It should be pointed out that according to Table I and Fig. 4, the rapidly deformed crystals with much lower carrier densities in both bands (compared with the control samples) should exhibit some increase in the carrier mobilities. However, it is clear from Table I that the carrier mobilities did not increase but decreased, which in the case of the original material would correspond to a dopant concentration of the order of 10^{16} cm^{-3} or higher, in obvious conflict with the true situation. This apparent contradiction is due to the fact that, according to the results of Ref. 3, in the case of rapid bending the diffusion of point acceptor centers to the dislocation cores in the process of deformation is greatly hindered and we are observing a new carrier scattering mechanism corresponding to the direct interaction between the dislocation cores and the electron subsystem of the crystal. This result is in good agreement with the results of Ref. 3 not only in the qualitative but also in the quantitative sense, and this applies to the carrier mobilities and also to the occupancy of the dangling bonds calculated on the assumption that the observed changes in the carrier densities are due to the direct capture of carriers by the dangling bonds in the dislocation cores: in both cases the occupancy assumes a value of the order of unity.

However, it should be pointed out that in all cases, irrespective of whether the deformation is slow or fast, the electrical properties of p-type InSb crystals with excess α and β dislocations bent to the same radius of curvature are the same within the limits of the experimental error.

In strong magnetic fields the magnetoresistance of the plastically deformed samples does not saturate and the magnetic-field dependence of the magnetoresistance in strong fields is approximately the same as in the case of the original material.

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