Electric Field Dependence of Galvanomagnetic Properties in n-Type InSb at 77 °K*

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The electric field dependence of galvanomagnetic properties in n-type InSb has been measured at 77 °K by employing a special method in which the transverse magnetic field $\vec{B}$ is applied parallel or at small angles to the surface of very thin specimens to reduce the influence of inhomogeneities in the impurity concentration. The advantages of this magnetic field orientation are illustrated by comparisons made with measurements done for $\vec{B}$ normal to the surface. It is experimentally determined that (i) quantum effects become noticeable at 2 kG; (ii) impurity scattering is less important in the quantum region; (iii) the electron mobility becomes independent of both impurity concentration and magnetic field at high electric fields; (iv) the electron mobility shows an $E_l^{-1/2}$ (where E_l is the electric field component parallel to the current) dependence in the high electric field region, which is consistent with acoustic-phonon scattering; and (v) time-dependent effects, believed to result from changing surface conditions, are noticed at magnetic fields above 2 kG when $\vec{B}$ is normal to the surface. These spurious effects are not observed when transverse magnetoresistance is measured with $\vec{B}$ parallel to the surface of the specimen, i.e., when the Hall field is along the thin ($\sim 25\,\mu$) dimension.

I. INTRODUCTION

Magnetic and electric field effects in n-type InSb have been studied by many investigators, inasmuch as the very small electron effective mass and consequent high electron mobility give rise to many interesting phenomena. Effects due to quantization of electron orbits can be observed in magnetic fields readily attained from ordinary laboratory magnets. Moreover, the electrons in InSb are easily heated by the electric field because of their small effective mass. Therefore, the importance of quantization of the electron orbits can be controlled by the electric field as well as the magnetic field.

Several investigations, reported earlier in the literature, were done on galvanomagnetic properties in the Ohmic region and in high electric fields at 77 °K where only the electrons in the conduction band contribute to the electric current. In the Ohmic region, experimental data of Sladek[1] and others[2-4] showed a linear dependence of the transverse magnetoresistance in a high magnetic field, which appeared consistent with certain theoretical results for the quantum limit. Saturation of the longitudinal magnetoresistance was found by Huff *et al.*[5] at 77 °K for fields of 4 kG. Work by Herring[6] has, however, cast some doubt on the meaningfulness of high magnetic field experimental data. Herring showed that a linear magnetic field dependence for the transverse magnetoresistance is expected even classically under conditions when certain inhomogeneities in distribution of the impurities in the specimen exist. Other investigators[7-12] have also examined the influence of inhomogeneities on galvanomagnetic effects. As a result, it appears that many experimental results on magnetoresistance in high magnetic fields are of dubious validity.

More recent measurements of Hall effect and resistivity in strong electric and magnetic fields were done by Miyazawa and Ikoma[13] at temperatures ranging from 1.8 to 77 °K. The low-temperature behavior of the Hall coefficient, somewhat reminescent of two-band conduction, was subsequently interpreted by Crandall in terms of temperature variations of the Hall coefficient factor.[14] The data relevant to our studies were taken at 53 and 77 °K and show an initial decrease in resistivity with electric field for all magnetic fields above 0.9 kG, followed by a subsequent increase in ρ with E for $E > 20$ V/cm. This behavior is consistent with the theoretical results of Kazarinov and Skobov.[15] However, Miyazawa and Ikoma were not able to establish the independence of resistivity on magnetic field at high electric fields—which is also predicted by Kazarinov and Skobov.[15] It is likely that inhomogeneities in impurity concentrations in their specimens were responsible for the observed large magnetoresistance at the high electric fields. Large Hall angles augment the effects of inhomogeneities. Therefore their influence becomes more serious in the high electric field region, where increases

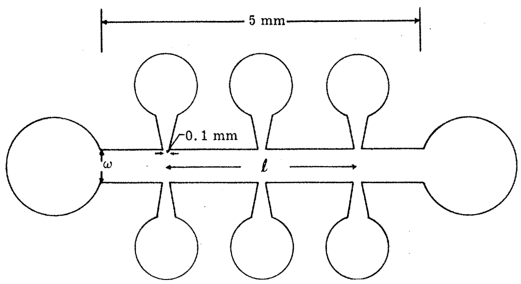

FIG. 1. Geometry of samples.

in mobility and consequently larger Hall angles are expected, as the importance of the quantization is reduced by the heating of the electrons.

The possibility that $\rho(B)$ is independent of B at strong electric fields is suggested by the results obtained by Komatsubara and co-workers,[16,17] although their data fall short of establishing experimentally this independence.

The problem of sample nonuniformity is of major concern when measurements are extended to higher fields. High-quality specimens are essential. In addition, certain special techniques can be used to mitigate effects resulting from material nonuniformities. It is the purpose of this paper to investigate the electric field dependence of galvanomagnetic properties in n-type InSb at 77 °K by employing a special method[18] which reduces the influence of inhomogeneities and surface phenomena, and then to discuss quantum effects and scattering mechanisms. The technique involves the use of specimens that are very thin along the direction of the major component of the Hall field.

II. SAMPLE PREPARATION

Bridge-shaped samples, as shown in Fig. 1, were prepared by photoetching techniques from lapped and etched thin wafers of InSb. One surface was glued to a glass plate with Epoxy resin to reinforce the thin specimens. Both surfaces were chemically etched.

Properties of the four specimens used in the investigation are listed in Table I, along with data on an additional specimen that was used in investigations of possible size effects. The lengths and widths were measured under a microscope. The thickness of the samples was estimated from Hall voltage measurements at room temperature, where the InSb was in intrinsic conduction. The electron concentrations given in the table were determined from the high magnetic field Hall coefficient $R_{H\infty}$ by using the relation $n = 1/eR_{H\infty}$. The Hall coefficient used in these calculations was measured by the conventional method in which a transverse magnetic field is applied perpendicular to the surface. For specimens 35S-1 and 35S-2, the Hall coefficients at 77 °K are essentially constant at magnetic fields of 2 kG and higher, as shown in Fig. 2(a). There is no difficulty in establishing the electron concentration. For specimens 67S-2 and 67S-3, however, the Hall coefficients gradually decrease with increasing magnetic field, even in the high magnetic field region [Fig. 2(b)]. This failure of R_H to saturate became less noticeable as more time elapsed after preparation of the sample, as shown in Fig. 3. This effect can be explained by a surface conduction, which will be discussed in the Appendix. Figure 3 also indicates that the surface effect is negligibly small at magnetic fields below 2 kG. Therefore, the Hall coefficient at 2 kG was regarded as the saturation value and was used to calculate the electron concentrations. Our data indicate such a field to be high enough to approximate the high magnetic field Hall-coefficient plateau and low enough to avoid the surface effects.

The electron mobility μ_0 was calculated from the resistivity ρ_0 and the high magnetic field Hall coefficient $R_{H\infty}$, where μ_0 and ρ_0 are the electron mobility and resistivity in the absence of a magnetic field. Therefore, the mobility μ_0 may be regarded as the conductivity mobility rather than the Hall mobility.

Because of the thinness[19] of the samples, the question may be raised as to whether the properties we measured differ noticeably from true bulk values. To estimate the magnitude of possible size effects, two samples 35S-3 and 67S-2 were thinned by successive etchings. Resistivity was measured both with and without the presence of a magnetic field. In the former case, the field was applied normal to the current, but parallel to the surfaces of the samples for the reasons which will be discussed in Sec. III. Results are shown in Fig. 4. No appreciable change was observed in the resistivity down to around 20 μ for 67S-2 and to around 10 μ for 35S-3. In the case of specimen 67S-2 it is seen that the resistivity increases with decreasing thickness below 20 μ. The precise reason for this behavior was not established. It might be due to size-effect phenomena or other surface effects. It is interesting to

TABLE I. Properties of InSb Specimens at 77 °K.

Specimen No.	Electron concentration n (cm^{-3})	Electron mobility μ_0 (10^5 cm^2/V sec)	Sample dimensions $l \times w \times t$ (mm)
67S-2	6.75×10^{13}	7.06	$3.00\times0.540\times0.0276$
67S-3	7.02×10^{13}	7.24	$3.00\times0.470\times0.0291$
35S-1	4.28×10^{14}	4.52	$3.00\times0.481\times0.0185$
35S-2	3.13×10^{14}	5.19	$3.00\times0.490\times0.0238$
35S-3	4.12×10^{14}	4.59	$3.00\times0.504\times0.0191$

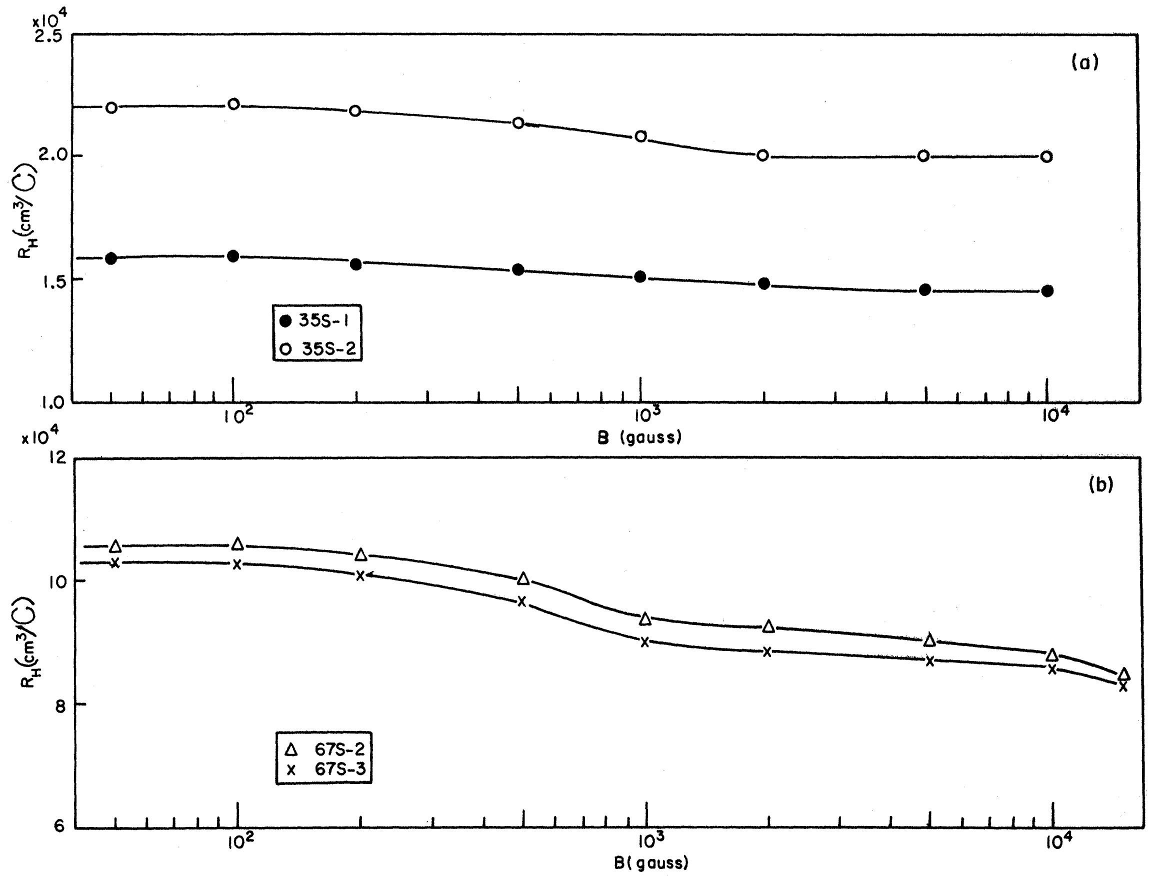

FIG. 2. Magnetic field dependence of Hall coefficient. The transverse magnetic field was applied perpendicular to the surface of the specimen.

note that specimen 67S-2 had also exhibited the time-dependent characteristics which were attributed to surface effects. The important point to be stressed here, however, is that for the specimens listed in Table I, size effects were seen to be small.

III. METHOD OF MEASUREMENT

The magnetic field was applied at small angles to the surface of the specimen and perpendicular

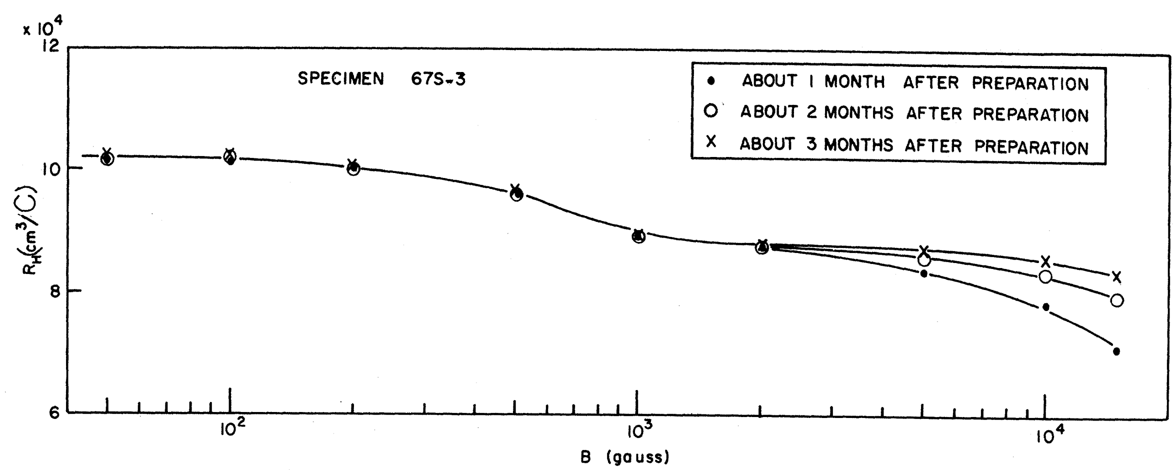

FIG. 3. Variation of Hall coefficient for sample 67S-3 with time elapsed since preparation.

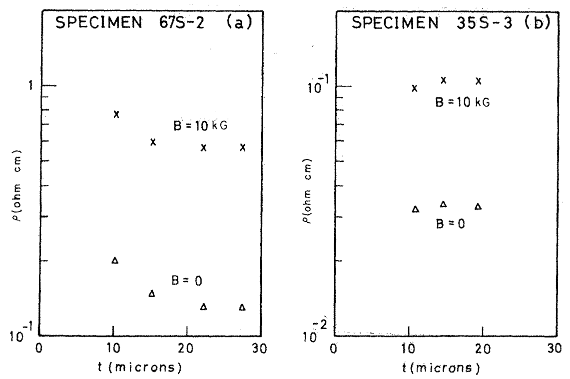

FIG. 4. Thickness dependence of the resistivity of two specimens, with and without magnetic field. The magnetic field was applied perpendicularly to the current and parallel to the surface of the specimen.

to the current, when measuring the electric field dependences of the resistivity and the Hall coefficient. In this arrangement, the Hall electric field is almost normal to the surface of the specimen. Therefore the distortion in current distribution due to a nonuniform Hall electric field may be considered to be small.[20] In addition, since the component of the electric field parallel to the surface is very small, short-circuit effects due to a nonzero surface conductivity are also expected to be minimal. For measurements of magnetoresistance in the Ohmic region, the magnetic field was strictly parallel to the surface. Of course in the case of the Hall coefficient, a nonzero angle with the surface was necessary to obtain a voltage across the Hall probes. It is important to note, however, that this small-angle technique was used only to measure the ratio $R_H/[R_H]_{E\to 0}$—that is, the change in the Hall coefficient with electric field—inasmuch as the setting accuracy (about 0.2°) of the small angles was not sufficient to permit a precise determination of the absolute value of R_H. The absolute value of R_H was measured under a transverse magnetic field perpendicular to the surface of the specimen, as mentioned in Sec. II. For the high electric fields, pulse measurements were employed to avoid Joule heating. The pulse was 2–20 μsec in width with a 15–30 Hz repetition rate. An oscilloscope with differential amplifier was used to measure the voltage difference between two electrodes. All data were taken at 77 °K.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Transverse Magnetoresistance in Ohmic Region

Figure 5 shows the magnetic field dependence of the transverse magnetoresistance in the Ohmic region. The magnetic field was applied parallel to the surface of the specimen and transverse to the current. The magnetoresistance measured in this way did not change with elapsed time after preparation of the sample. On the other hand, magnetoresistance measured in a magnetic field perpendicular to the surface was always larger than that shown in Fig. 5 and had a tendency to decrease with time. This behavior is consistent with the change in the Hall coefficient noted in Fig. 3. The larger magnetoresistance can be attributed to surface conduction and other inhomogeneities.

It is seen in Fig. 5 that the magnetic field dependence of the transverse magnetoresistance undergoes a transition from one characteristic to another in the region between 500 G and 2 kG. This is apparently where effects due to Landau-level spacings became noticeable.

B. Electric Field Dependence of Mobility

Figure 6 shows the electric field dependences of the electron mobility in transverse magnetic fields. The angles between the magnetic field and the surface of the specimen were 10° for 1 and 2 kG, 5° for 5 kG, and 2° for 10 and 15 kG. The electron mobility was calculated from the Hall coefficient and the resistivity by using the relation $\mu = R_H/\rho$. Since the measurements were made in a high magnetic field region ($B \geq 1$ kG), the mobility μ can be considered to be the conductivity mobility. In the absence of a magnetic field, the electron mobility μ_0 was calculated by assuming the electron con-

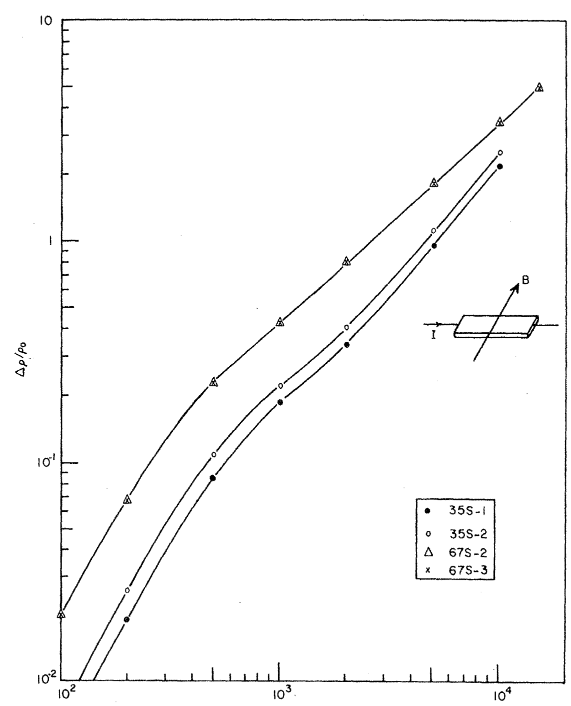

FIG. 5. Magnetic field dependence of the transverse magnetoresistance. The magnetic field was applied parallel to the surface of the specimen.

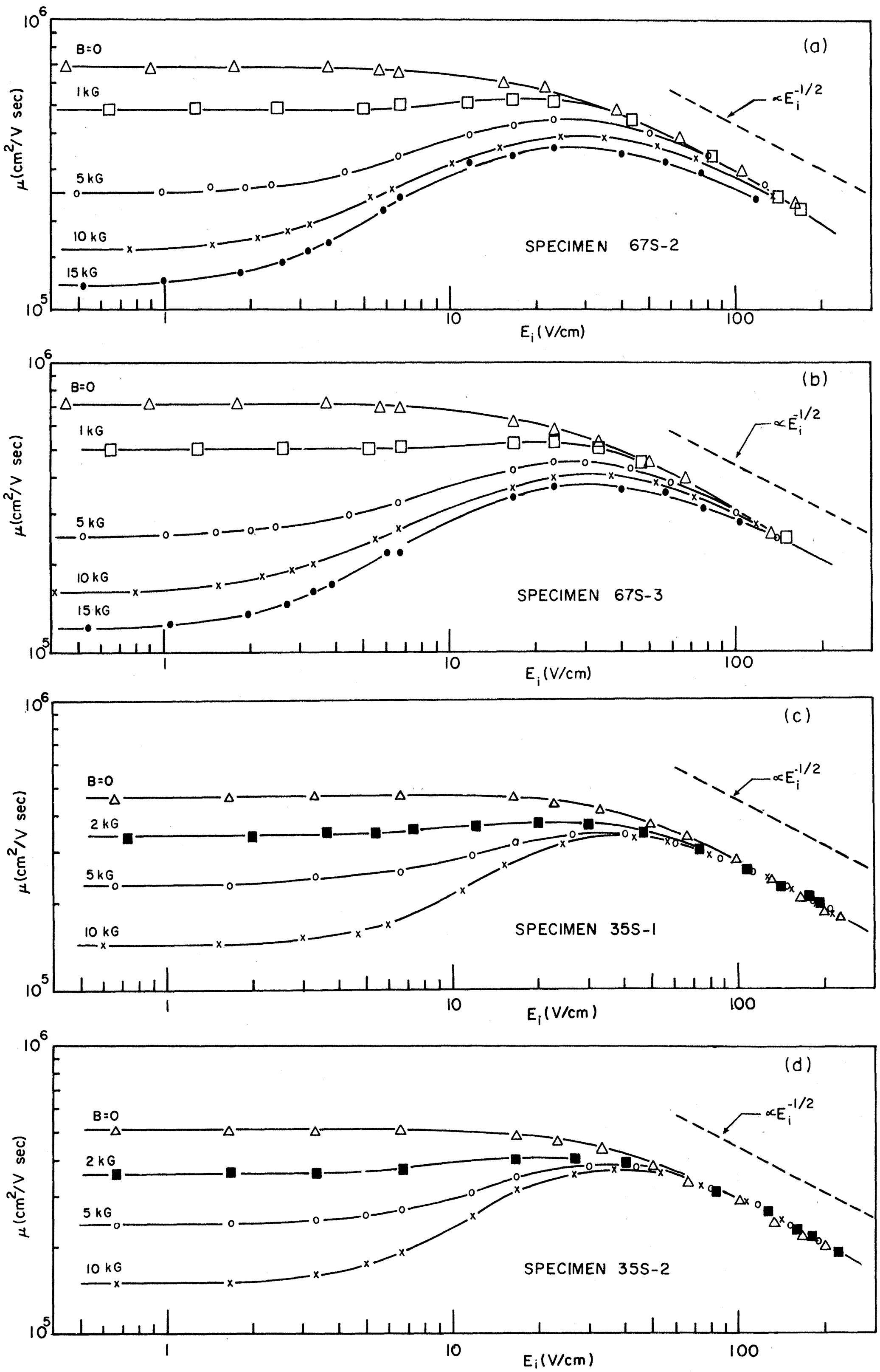

FIG. 6. Electric field dependence of electron mobility under transverse magnetic fields. E_i is the electric field component parallel to the current.

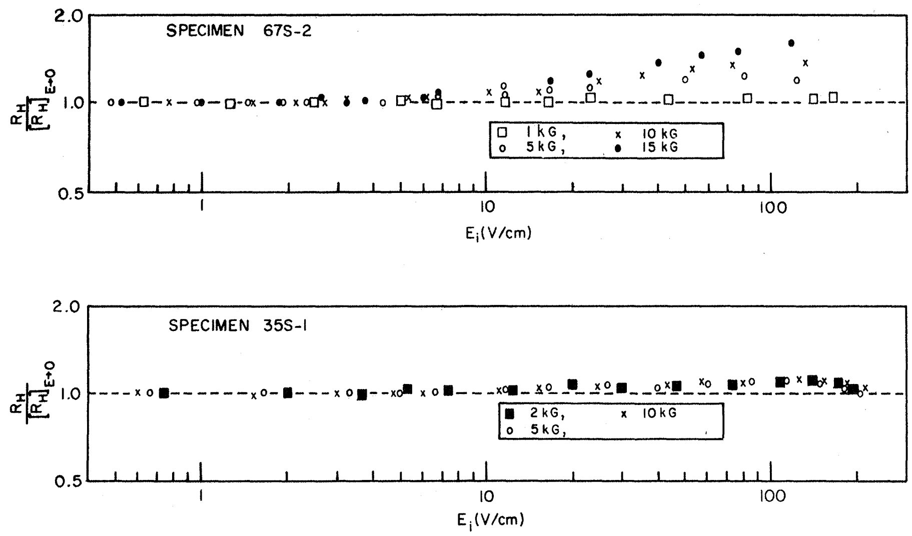

FIG. 7. Electric field dependence of Hall coefficient. E_i is the electric field component parallel to the current.

centration to be independent of the electric field.

When the electric field increases beyond the Ohmic region, the electron mobility in a strong magnetic field is seen to increase. The rate of increase is larger the higher the magnetic field. Two possibilities might be considered to explain such an increase in the electron mobility, namely, a decreased importance of either impurity scattering[21,22] or of quantum effects.[15] The electric field dependence in the absence of the magnetic field, on the other hand, does not show any increase in the electron mobility even in the case of specimens 35S-1 and 35S-2 [Figs. 6(c) and 6(d)] with the larger impurity concentrations, although the importance of impurity scattering is greater in the absence of the magnetic field, as will be mentioned later. Possible mobility increases resulting from decreased impurity scattering would be veiled by decreases due to other scattering mechanisms, such as acoustic phonons, for which the relaxation time decreases with electron energy. Therefore, the initial tendency of the electron mobility under the magnetic field to increase with increasing electric field can be attributed to a decrease in the importance of quantum effects because of heating of the electrons.[15] According to this criterion, we see from Figs. 6(a)–6(d) that quantum effects are already noticeable at fields of 1 or 2 kG. This finding is consistent with results obtained from magnetoresistance data measured under Ohmic conditions (Fig. 5), where the onset of quantum effects is also apparent at around 2 kG.

A further increase in the electric field gives rise to a decrease in the electron mobility. Ultimately, at sufficiently high electric fields, the electron mobility shows an $E_i^{-1/2}$ dependence regardless of the magnetic field, a dependence which is predicted theoretically for acoustic-phonon scattering via deformation potential.[15,23] In addition, the electron mobility becomes completely independent of the magnetic field, although the resistivity still shows a slight dependence. The apparent decrease in the electron concentration, as indicated in Fig. 7, which has not been explained so far, is presumably responsible for the magnetic field dependence of the resistivity. Surface states might play some role in this effect, since the samples are very thin. The disappearance of the magnetic-field dependence of the electron mobility at high electric fields is also predicted by the theory of Kazarinov and Skobov[15] for the region where $\hbar\omega_c \ll kT^*$ (ω_c being the cyclotron frequency and T^* the effective electron temperature). The quantum effects are obscured at high electric fields because of increased electron temperature.

C. Impurity Effect

The electric field dependence of the electron mobility for two specimens having different impurity contents (67S-3 and 35S-2) is shown in Fig. 8. Figure 9 shows the magnetic field dependence of the electron mobility in the Ohmic region. In the absence of a magnetic field, these two specimens have different electron mobilities under Ohmic conduction. The difference decreases with increasing magnetic field. There is almost no difference in the electron mobility at a magnetic field higher than 5 kG. This behavior is consistent with theories appearing in the literature, which predict decreased importance of ionized impurity scattering relative to that by acoustic phonons in quantizing magnetic fields.[24]

As the electric field increases beyond the Ohmic region (Fig. 8), impurity scattering becomes noticeable because of the decreased importance of quantum effects as the electrons are warmed.

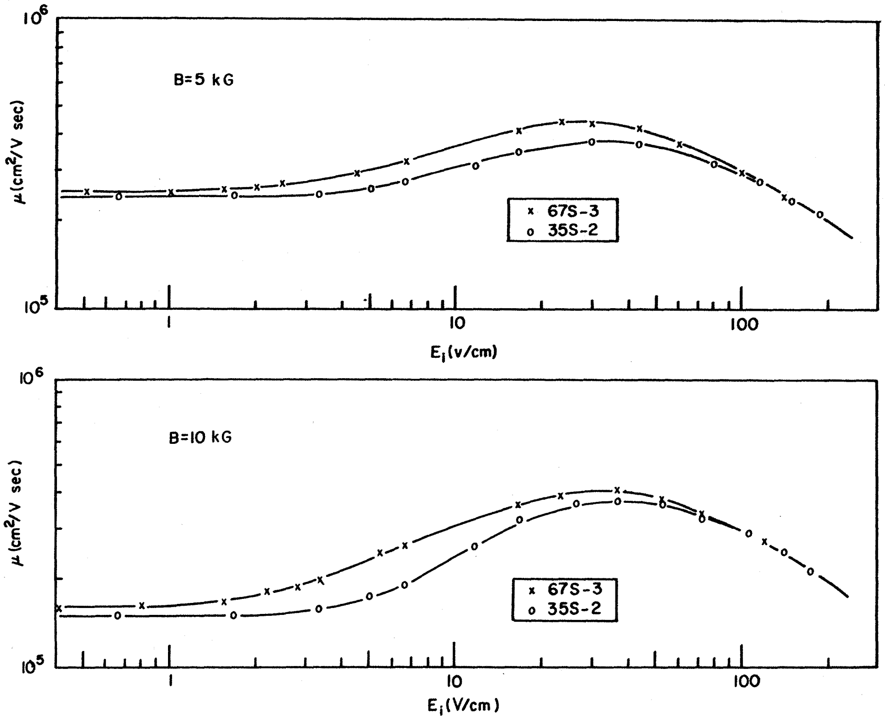

FIG. 8. Comparison of electric field dependence of electron mobility for specimen 67S-3 and 35S-2, having different impurity contents. E_l is the electric field component parallel to the current.

With yet further increases in the electric field, the electron mobility again becomes independent of the impurity concentration, regardless of the magnetic field. This behavior is reasonable, since impurity scattering is not the controlling scattering mechanism for the high-energy electrons.

V. SUMMARY

A special method has been employed to measure magnetic field effects, with reduced influence of inhomogeneities in the impurity concentration, in n-type InSb. In this method, the transverse magnetic field is applied parallel or at small angles to the surface of a very thin InSb sample. Several interesting results were observed in the Ohmic and in the high electric field regions at 77 °K.

In the Ohmic region. Quantum effects seem to be noticeable for magnetic fields higher than 2 kG —at which field $\hbar\omega_c = \frac{1}{4}kT$. In addition, impurity scattering is less significant in the quantum region. At magnetic fields above 5 kG, the electron mobility is almost independent of the impurity concentration.

In the intermediate electric field region. At magnetic fields of 2 kG or higher, an increase in electron mobility with E_l and a dependence of the mobility on impurity concentration can be observed, which is consistent with the decreased importance of quantum effects resulting from an increased electron temperature. The results obtained at intermediate electric fields lead to the same conclusions as in the Ohmic region as regards the onset of quantum effects and the importance of impurity scattering in the quantum region.

In the high electric field region. Impurity scattering is relatively unimportant, because of the increased energy of the electrons. In addition, the high electron temperature minimizes the quantum effects. Therefore, the electron mobility becomes independent of both of the impurity concentration and the magnetic field. Furthermore, the observed $E_l^{-1/2}$ dependence of the electron mobility is an argument for postulating a dominance of acoustic-phonon scattering (via deformation potential) in the high electric field region.

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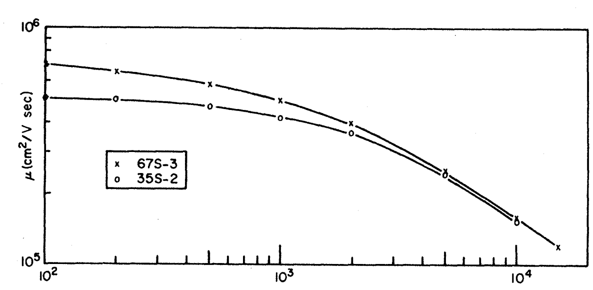

FIG. 9. Magnetic field dependence of electron mobility in Ohmic region for two specimens of different impurity contents.

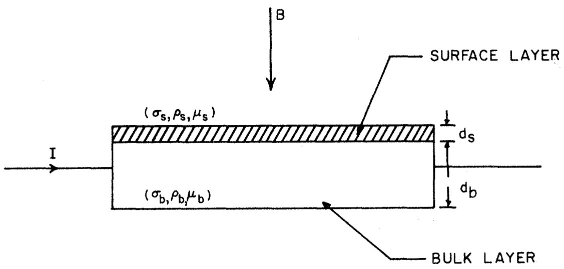

FIG. 10. Two-layer model used to calculate effect of surface conduction.

Columbus for helpful comments, and to H. Yamada of the Electrotechnical Laboratory for useful information which was necessary for preparing the measurement samples.

APPENDIX

The effects of a surface layer on the magnetoresistance and the Hall coefficient were calculated by Wieder.[25] He used a model consisting of two layers, as shown in Fig. 10. For $\mu_b \gg \mu_s$ and $\mu_s^2 B^2 \ll 1$, where subscripts b and s refer, respectively, to values for the bulk material and for the surface, Wieder obtains the following expression for the effective Hall coefficient:

$$R_{H_e} = R_{H_b} \frac{g^2 d/d_b}{(1+g)^2 + \mu_b^2 B^2} \quad , \qquad \text{(A1)}$$

where $g \equiv \sigma_b d_b / \sigma_s d_s$, and the quantities σ, ρ, μ, R_H, and B have their usual meanings. It is to be noted, however, that μ_b is the *Hall* mobility. The dimensions d_b and d_s are the thicknesses of the bulk and surface layers, respectively, and $d \equiv d_b + d_s$.

An expression for the effective resistivity follows at once from Wieder's relations for R_{H_e} and μ_e; namely,

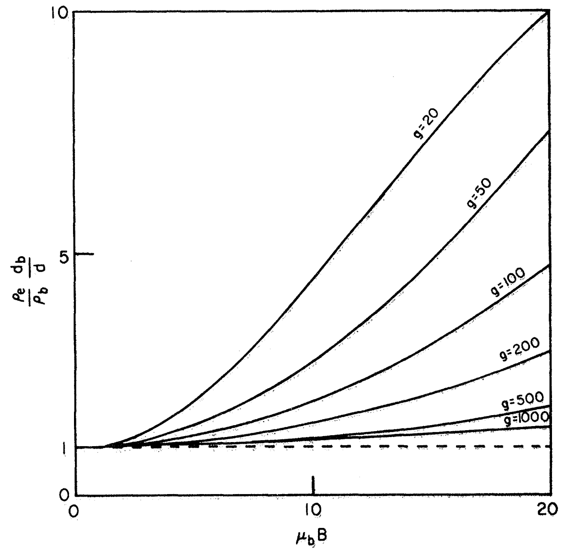

FIG. 11. Effect of surface layer on magnetoresistivity.

$$\frac{\rho_e}{\rho_b} = \frac{d}{d_b} \frac{g(1+g+\mu_b^2 B^2)}{(1+g)^2 + \mu_b^2 B^2} \quad . \qquad \text{(A2)}$$

Equations (A1) and (A2) are valid even if μ_b is magnetic field dependent [i.e., $\mu \equiv \mu(B) \equiv R_H(B)\sigma(B)$] provided, of course, that the proper values of $g(B)$, $R_{H_b}(B)$, and $\rho_b(B)$ are used. It is seen from Eq. (A1) that a significant magnetic field dependence of the measured Hall coefficient can be expected in a high magnetic field region, even if R_{H_b} and R_{H_s} have negligible field dependencies. Still more striking is the magnetoresistance effect. This is shown in Fig. 11, where a plot is presented of Eq. (A2). Even a surface layer with a large value of g can play a very important role in the magnetoresistance if the magnetic field is high enough.

*Work done in part at the Department of Electrical Engineering of The Ohio State University, while H. Fujisada was in residence.

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[18]This method was used by H. Fujisada and S. Kataoka [J. Phys. Soc. Japan 27, 1367 (1969)] in initial measurements which indicated the disappearance of the magnetic field dependence of the electron mobility at high electric fields.

[19]Approximately ten free paths, if the latter are energy independent. A variation in free path with energy would reduce this figure; however, as will be seen later, impurity-scattering effects are quite small in all of the specimens studied.

[20]Under simplified conditions (Ref. 7), the current distortion in the direction of the Hall field can be shown to depend exponentially on $w\beta n^{-1}(dn/dx)$, where dn/dx is the gradient of carrier concentration in the current direction, w is the specimen dimension along the Hall field, and β is the tangent of the Hall angle.

[21]See, for example, E. M. Conwell, Solid State Phys. Suppl. 9, 22 (1967).

[22]J. Yamashita and M. Watanabe, Progr. Theoret. Phys. (Kyoto) 12, 443 (1954).

[23]See p. 165 of Ref. 20 for a theoretical treatment of the zero magnetic field case.

[24]See, for example, the theory of E. N. Adams and T. D. Holstein [J. Phys. Chem. Solids 10, 254 (1959)] which, in the extreme quantum limit, yields $\mu_{ph} \sim H^{-5/2} \times T^{3/2}$ and $\mu_i \sim H^0 T^{3/2}$. Also, the expressions obtained by Kazarinov and Skobov (Ref. 15) give the following ratio for the scattering frequencies in quantizing fields: $\nu_i/\nu_{ph} \sim H^{-2}$.

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Volume Dependence of the Spin-Orbit Splitting in Representative Semiconductors from High-Pressure Electroreflectivity Measurements and Relativistic Orthogonalized-Plane-Wave Calculations

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By means of electroreflectivity measurements at room temperature and at 77 °K performed at pressures up to 10 kbar, we have experimentally determined the volume dependence of the Δ_0 and Δ_1 spin-orbit splittings in CdTe and the Δ_0 spin-orbit splitting in germanium. The volume dependence of the Δ_0 and Δ_1 (at L) spin-orbit splitting has also been obtained for Ge, GaAs, and CdTe from a relativistic orthogonalized-plane-wave (OPW) calculation. Our experimental and theoretical results are in agreement and indicate that the volume dependence of the spin-orbit splitting is considerably smaller than would be expected if the valence-electron density in the core region increased in proportion to the decrease in the crystal volume. These results are interpreted as an indication that the valence-electron density in the core region is little affected by the crystal volume and may be relatively unchanged from that of the free atom. The plausibility of the conclusion and some consequences are discussed. In some cases a reversible change in the electroreflectivity line shape as the pressure is cycled can give rise to erroneous results if the change in line shape is not taken into account. It is shown that all of our experimental results are consistent when reasonable corrections are made for the change in line shape, and it is suggested that such effects may not be accounted for in the experimental results of Bendorius and Shileika on GaAs which disagree with our calculated results.

I. INTRODUCTION

In the past few years, through a combination of experimental and theoretical efforts, the energy-band structure of many semiconducting crystals has become better known. Experimental investigations have usually involved optical studies and have recently been aided in accuracy and information content by the use of various modulation techniques,[1-4] while theoretical calculations[5-8] have made use of better initial models, improved calculational procedures and facilities, and well-established experimental information at isolated points in the Brillouin zone to calculate the optical constants for the crystal as well as the energy-band structure throughout the Brillouin zone.

The work reported in this paper is the result of using improved experimental and calculational techniques to investigate the pressure dependence of the spin-orbit splitting in representative semiconductors. The results are of interest both in terms of assessing which of various calculational