Properties of *p*-Type InSb in Pulsed High Electric Fields

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The results of high electric field experiments on *p*-type InSb at 77°K are described. It is shown that electron-hole pair creation occurs at electric fields greater than 700 volts/cm. When a sufficient number of pairs are created the Hall coefficient changes from positive to negative. The question of whether holes or possible injected electrons initiate the pair creation is examined in detail. An incipient negative resistance effect in transverse magnetic fields and the absence of any self-pinch effects are also discussed.

INTRODUCTION

In earlier communications[1,2] the authors have described the properties of *n*-type InSb in high electric fields. The material used contained 2×10^{14} cm^{-3} electrons initially (in low electric fields), and the experiments showed that the electrons produced additional electron-hole pairs by across-the-gap ionization when electric fields of the order of 200 v/cm were applied. Similar results were observed by Prior[3] and Kanai.[4]

The situation in *p*-type InSb is somewhat different experimentally. The very high electron mobility gives velocities in excess of 10^7 cm/sec at the high fields employed. As a result it is difficult to be sure that the observed effects (using pulses of 0.25-μsec duration) are initiated by the holes initially present, i.e., that injected small densities of electrons play no important role in the observations. The authors have reported the observation[5] of across-the-gap ionization in *p*-type material at electric fields of the same order as those found in *n*-type InSb. However, there have been recent observations in *p*-type material which show[6,7] ionization at lower fields, and Kanai[6] has suggested that very high mobility holes may be responsible. Measurements reported here in more detail than previously show ionization in appreciable intensity at electric fields considerably higher than in *n*-InSb. These effects are due either to injected electrons, or to the holes present. It is concluded that the field necessary for appreciable electron-hole pair production by *holes* is at least 700 v/cm.

EXPERIMENTAL RESULTS

In the present experiments on *p*-InSb, the hole concentration at 77°K was 2.3×10^{16} cm^{-3} in the low electric field region. The low-field hole mobility was ~4000 cm^2/volt-sec at 77°K. Under these circumstances the equilibrium electron concentration would be only 40 cm^{-3}. With such a low concentration, the electrons could be expected to play an insignificant role in the properties of the crystal at low electric fields. Even if a normal amount of background bandgap radiation strikes the crystal (as was the case in some of the experiments) it is believed that the initial electron concentration would not exceed 10^5 cm^{-3}. Hence, in the particular experiments performed, the electrons initially contributed very little to the conductivity even though the electron mobility is much larger than the hole mobility.

Figure 1 shows the current density-electric field characteristic for the *p*-InSb crystal at 77°K. The magnetic fields shown in Fig. 1 were applied transverse to the current in order to make simultaneous Hall effect measurements. Pulses of 0.25-μsec duration (at a repetition rate of 1 per sec) were used throughout in order to avoid heating the crystal. It is seen in Fig. 1 that the current density rises abruptly at rather definite threshold electric fields for each magnetic field intensity used. In Table I the threshold electric field is given as a function of the transverse magnetic field used.

For these data only bridge-type specimens of cross-sectional areas 2.72×10^{-3} cm^2 were used. The earlier

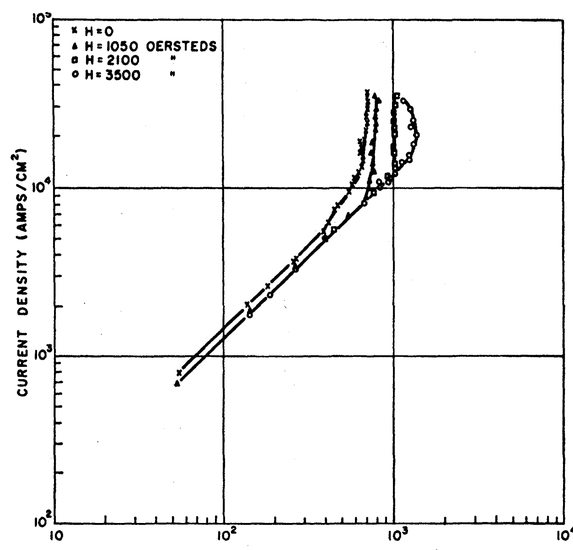

FIG. 1. Current density-electric field characteristics for *p*-InSb at 77°K in various transverse magnetic field strengths.

[1] M. Glicksman and M. C. Steele, Phys. Rev. **110**, 1204 (1958).
[2] M. C. Steele and M. Glicksman, J. Phys. Chem. Solids **8**, 242 (1959).
[3] A. C. Prior, J. Electronics and Control **4**, 165 (1958).
[4] Y. Kanai, J. Phys. Soc. Japan **13**, 967 (1958).
[5] M. C. Steele and M. Glicksman, Bull. Am. Phys. Soc. **3**, 377 (1958).
[6] Y. Kanai, J. Phys. Soc. Japan **13**, 1065 (1958).
[7] J. Bok and R. Veilex, Compt. rend. **248**, 2300 (1959).

experiments[5] with soldered voltage probes had given inconsistent results. This inconsistency was not present in the observations with bridge specimens.

At electric fields slightly higher than the threshold values in Table I it was observed that the Hall coefficient changed sign from positive to negative. This is interpreted as being due to the creation of electron-hole pairs by impact ionization. The Hall data are best represented as a function of current density rather than electric field. In Figs. 2, 3, and 4 are shown plots of the Hall coefficient vs current density for magnetic fields of 1050, 2100, and 3500 oersteds, respectively.

For two mobile carriers the Hall coefficient is given by the expression

$$R_H=(p-b^2n)/e(p+bn)^2, \tag{1}$$

where R_H = Hall coefficient in cm³/coulomb; p = hole concentration in cm⁻³; n = electron concentration in cm⁻³; e = electronic charge (1.6×10^{-19} coulomb); $b=\mu_e/\mu_h$ (the ratio of electron mobility to hole mobility). Clearly, in the low electric field region $p_0\gg b^2n_0$, where p_0 is the initial hole concentration (2.3×10^{16} cm⁻³) and n_0 is the initial electron concentration ($\simeq10^5$ cm⁻³).

TABLE I. Threshold electric field for various applied magnetic fields.

H (oersteds)	E (volts/cm)
0	700
1050	770
2100	1000
3500	1350

Hence R_H will be positive, and have the value

$$(R_H)_0\simeq1/ep_0. \tag{2}$$

As the electric field is increased to such a value that the holes and/or electrons attain enough energy to cause impact ionization across the forbidden gap, the electron concentration will increase. As this process proceeds to increase b^2n in Eq. (1) R_H will decrease, go through zero, and then become negative. The observations confirm such behavior exactly. The manner in which R_H changes with current density can give valuable information about the value of b. To begin with, $R_H=0$ when

$$n\simeq p_0/b^2. \tag{3}$$

After this inversion it is assumed that $p=p_0+n$, so that $-R_H$ will become maximum when

$$n=p_0/(b-1). \tag{4}$$

For this value of n

$$(-R_H)_{\max}=(b-1)^2/4ep_0b. \tag{5}$$

From Eqs. (2) and (5) it follows that

$$b=1+2r+2(r^2+r)^{\frac{1}{2}}, \tag{6}$$

where

$$r=(-R_H)_{\max}/(R_H)_0. \tag{7}$$

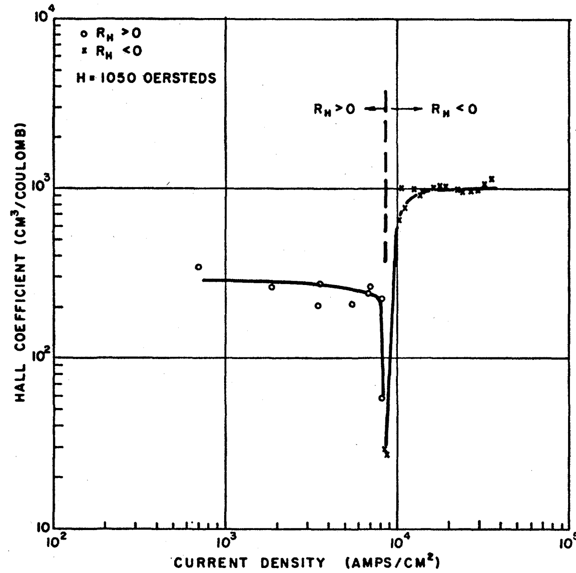

FIG. 2. Hall coefficient vs current density for $H=1050$ oersteds.

At this stage it should be pointed out that for InSb under the conditions of the present experiment, there are actually three mobile carriers involved.[8] These are the electrons, the heavy holes, and the light holes. If proper account is taken of all these carriers the expressions given by Eqs. (1) through (6) would be far more complicated. However, since the impurity concentration of the p-InSb used in this work was at least as large as 2.3×10^{16} cm⁻³, the effect of the light holes will be greatly diminished because of ionized impurity scattering of such light holes. This point, coupled with

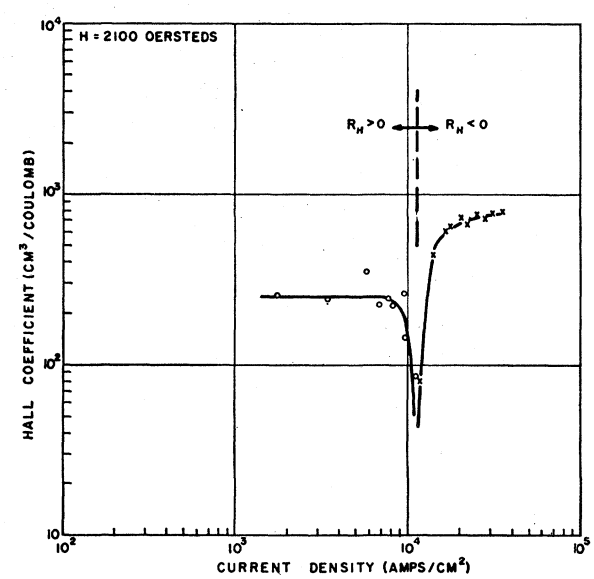

FIG. 3. Hall coefficient vs current density for $H=2100$ oersteds.

[8] H. J. Hrostowski, F. J. Morin, T. H. Geballe, and G. H. Wheatley, Phys. Rev. **100**, 1672 (1955).

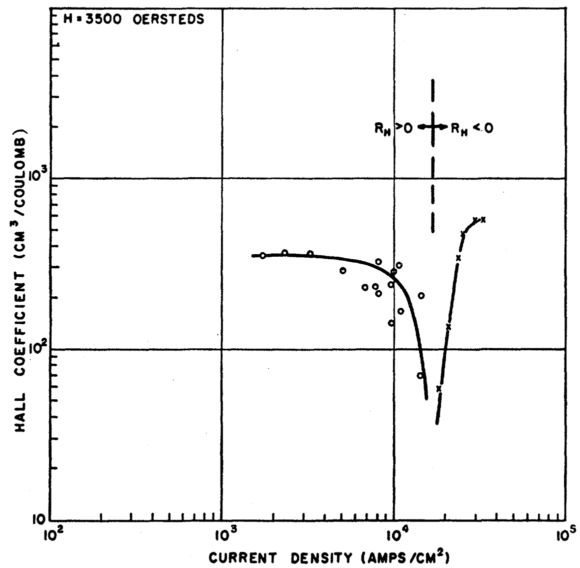

FIG. 4. Hall coefficient vs current density for $H=3500$ oersteds.

the fact that at 78°K and magnetic field strengths higher than 500 oersteds the Hall coefficient of such highly doped *p*-InSb does *not* change with magnetic field,[9] justifies the use of the simple two-carrier model developed above. If much purer *p*-InSb is used (impurity concentrations $\simeq 10^{14}$ cm^{-3}), the effect of the light holes would have to be considered. Under such conditions the expression for the Hall coefficient would follow that given by previous workers.[10]

Therefore, it is possible to compute b from Eq. (6) and the values of r obtained from the experimental data. In Table II are shown the values of b at different magnetic fields. It is recognized that the value of b computed in this way is not the value that would be obtained at low electric fields. Clearly the change in distribution which results from making the carriers "hot" will affect b. In this respect the b which appears in Eqs. (5) or (6) is to be interpreted as an average b under the conditions of approximately equal numbers of electrons and holes.

DISCUSSION

There is an important question in this *p*-type InSb work about the nature of the carrier which initiates the electron-hole pair creation. If the crystal were completely in the dark the initial electron concentration would be too small to play a significant role. Under such conditions, if any impact ionization were observed it would have to be attributed to the holes. Therefore an experiment was performed on the *p*-InSb surrounded by a radiation shield. It showed a current density-electric field characteristic exactly the same as the characteristic seen without the shield, and hence in background bandgap radiation which generated $\simeq 10^5$ cm^{-3} electron-hole pairs. These experiments might suggest that the holes are initiating the ionization.

TABLE II. Data for calculating the value of μ_e/μ_h.

H	$(R_H)_0$	$(-R_H)_{max}$	r	b
1050	270	1050	3.9	17.5
2100	250	800	3.2	14.7
3500	350	570	1.6	8.3

There remains, however, another possible effect that leaves some doubt about such a conclusion. If electrons are being injected into the *p*-InSb, the radiation shield experiment loses its significance. Injected densities in an amount appreciably greater than 10^5 cm^{-3} at some fixed voltage, could be responsible for initiating the ionization. In order that they be capable of doing so their lifetime in the *p*-InSb must be greater than the time needed to initiate the ionization. Prior[3] has reported that 1 to 2×10^{-8} sec are needed for the ionization to occur in *n*-InSb at room temperature. Following Prior, an ionization time $\tau_g(E)$ is defined as the mean time for an electron to create an electron-hole pair. This time is a decreasing function of the electric field E. A recombination time, τ, is also defined. The current will then continue to rise as long as $\tau_g<\tau$. A steady state value will be reached when τ has been reduced to the value τ_g. The reduction in τ can be reasonably assumed to result from the increase in the carrier concentration. Hence if injected electrons in *p*-InSb have $\tau\simeq\tau_g$ there should not be any appreciable ionization. By raising the electric field and hence decreasing τ_g a threshold will be reached at which ionization will occur. It will now be made clear that this threshold field can be much higher for injected electrons in *p*-InSb than for the equilibrium electrons in *n*-InSb. Let $E_{n,n}$ be the electric field threshold for appreciable ionization by the majority carrier electrons in *n*-InSb. Earlier work has shown that $E_{n,n}\simeq 200$ volts/cm. This value should not be dependent on either τ_g or τ. But the shape of the current density-electric field curve beyond $E_{n,n}$ will be very much dependent on both τ_g and τ.

If electrons are injected into the *p*-type material, which in the present experiments is at least ten times more impure than the *n*-type material, it is expected that the recombination time τ will be much lower than in the *n*-type InSb. To see appreciable ionization by these injected electrons, E would then need to be larger than $E_{n,n}$ in order to reduce τ_g to the same value as τ. This could explain the need for a field as high as 700 volts/cm to obtain the sharp rise in current density in *p*-type InSb.

In work with the *n*-type material, effects due to injection of holes were ruled out because of the combination of flat pulse shape and the relatively long transit time of the holes compared to their lifetime.

[9] T. Fukuroi and C. Yamanouchi, Sci. Repts. Research Insts., Tohoku Univ. **9**, 262 (1957).
[10] R. K. Willardson, T. C. Harman, and A. C. Beer, Phys. Rev. **96**, 1512 (1954).

The latter is no longer the case for injection of electrons in p-type material.

There are also physically two difficulties with Kanai's suggestion of ionization by the high-mobility holes. One involves the expectation that, if the holes are producing ionization at fields of the order of 15–20 volts/cm or even lower, once holes are produced in n-type InSb the field necessary to maintain the high density should drop to this value when enough holes are present. This was not observed in the earlier work.[1,4] Secondly, the concept of high-mobility holes is in a sense statistical, since there is expected to be abundant inter-band scattering. If one follows a hole in time, it spends only a small fraction of its time in the high-mobility state. The inter-band scattering time for the light holes is probably the dominant scattering mechanism, and this gives a relaxation time[11] for this process of 10^{-12} sec for 10^5 cm^2/volt-sec and 10^{-11} sec for a mobility 10 times higher. Even this larger "high-mobility-coherence time" is much shorter than what might be expected for the time necessary to produce enough ionization to affect the Hall coefficient. It is recalled that Prior's work[3] showed that $\sim 10^{-8}$ sec was needed to produce a sufficient amount of ionization to see departures from the low-field conductivity. As a result, the light holes are left in a poor competitive position with respect to the electrons, which gain energy over a number of collisions.[3] For a hole of effective mass 0.015 electron mass, the minimum time necessary to gain an energy equal to the band-gap energy of 0.2 ev is $4\times 10^{-9}/E$, where E is in v/cm. At $E=10$v/cm, this is 4×10^{-10} sec, i.e., 40 times the mean free time for the fast holes, if they have a mobility as high as 10^6 cm^2/v-sec. Thus, it appears to be very difficult to have this group of hole states be responsible for the ionization process.

The arguments presented earlier, with respect to the field necessary for a large current increase predict that the threshold field in p-type InSb should be a sensitive function of the total impurity content of the crystal. It would be expected that this threshold should be lower in the purer material (hole densities[6,12] of $\sim 3\times 10^{15}$ cm^{-3}) employed by Kanai[6] and Bok and Veilex.[7] However, to explain the effects they observed at such low fields as 10 v/cm, it is here suggested that the current was being carried by appreciable quantities of injected electrons. As is clear, the Hall effect is very sensitive to quite small injected densities. Thus in order to test the above suggestions, such injection must be kept from occurring in densities sufficient to obscure the electron-hole pairs produced by ionization.

In the experiments reported here, the two alternatives of electron-hole pair production by holes or by injected electrons are available. If the threshold field for production by holes is smaller than that for appreciable effects due to electrons in the p-type material, the electron-hole pair production observed could be due to the holes. If the effects are due to injected electrons, it is clear that the field necessary for electron-hole pair production by the *holes* in this material is at least as large as those observed in the experiments reported here. Thus these experiments show that ionization across the band gap by holes in p-type material requires higher fields than by electrons in n-type material.

There are two other phases of the present work that warrant some discussion. The first one deals with the "incipient" negative resistance which is shown in Fig. 1 for a transverse magnetic field of 3500 oersteds. Unfortunately, there are insufficient data to arrive at even a tentative explanation of such an effect. It would be desirable to extend the measurements to higher current densities and stronger magnetic fields before attempting any analysis. However, it is worth noting that in the p-InSb work of Bok and Veilex,[7] they observed a negative resistance effect in *longitudinal* magnetic fields. To date, there has been no definitive explanation of such a behavior.

The second point involves the question of possible self-pinch effects in the p-InSb. In a recent report[13] the authors presented evidence for plasma pinch effects in n-InSb. Such evidence was *not* observed in the present experiments. The maximum currents in this work exceed 100 amperes. Such currents are about twenty times greater than those needed to produce a self-pinch. However, it is believed that due to collisions the time needed for the plasma to contract would be greater than 0.25 μsec. Since the pulses were 0.25 μsec, no pinch effects should have been observed. It would be significant to extend these measurements to much purer p-InSb and seek the pinch effect. For p-type material with a total impurity content of $\sim 10^{15}$ cm^{-3}, the situation should be as favorable for seeing pinch effects as in the earlier n-type work.[13] However, care has to be taken to avoid injection effects, since it is believed[14] that space-charge effects associated with injection seriously limit the possibilities of pinching.

ACKNOWLEDGMENTS

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[11] The effective mass has been assumed 0.015 the free electron mass, as estimated by E. O. Kane [J. Phys. Chem. Solids **1**, 249 (1957)].

[12] J. Bok (private communication).

[13] M. Glicksman and M. C. Steele, Phys. Rev. Letters **2**, 461 (1959).

[14] M. A. Lampert (private communication).