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Absolute Measurement of the Electron Velocity-Field Characteristic of InSb

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Absolute measurements of the electron velocity in InSb at low and high fields have been made, using the combined Shockley–Haynes and time-of-flight technique. Low-field mobilities of 7×10^5 cm/V sec are reported and negative differential mobility is observed at high fields. By comparing the experimental results with numerical solutions of the ambipolar equations, it is demonstrated that the ambipolar errors are of the order of 10–15%. The experimental results are in good agreement with previous low-field measurements and agree over the whole range with the recent Monte Carlo calculations of Fawcett and Ruch.

I. INTRODUCTION

Drift mobilities of electrons in InSb have in the past been measured by making use of simultaneous pulse conductivity and Hall measurements.[1,2] The number of carriers is determined from the Hall measurement, and hence the mobility can be determined from the conduction current. Absolute measurements like the Shockley–Haynes experiment fail because of the very fast trapping that takes place.[3] By making use of an electron-beam-injection technique, which we have employed previously to measure electron mobility in p-type Ge,[4] we have succeeded in making absolute measurements of the velocity-field characteristics in InSb. This method combines the Shockley–Haynes technique with the time-of-flight method.

Transit times of the electrons in the sample are of the same order or less than the trapping times, and therefore the trapping does not limit the measurement as much as in other techniques. Absolute measurements were obtained in high-resistivity material; in more impure material the trapping is, however, too pronounced, and excessive injection of electrons is required to obtain a waveform that can be used for a measurement. It is demonstrated, however, by solving the nonlinear ambipolar equations numerically, that in general the ambipolar correction is substantially smaller than what would be expected from the linear theory.

Initial experiments were limited to fairly low fields (100–200 V/cm). The observation of Gunn oscillations by Smith *et al.*[5] in unstressed InSb, stimulated interest in the high-field region ($E>400$ V/cm). The existence of negative differential mobility (NDM) was confirmed experimentally, as reported earlier.[6] For both the high- and low-fields regions, there exists good agreement between the Monte Carlo calculations of Fawcett and Ruch[7] and our results.

II. EXPERIMENTAL SETUP AND SAMPLE PREPARATION

The basic technique and experimental setup was essentially the same as for the measurement of germanium, described in the previous paper.[4] High-energy electrons bombard a biased extrinsic (usually p-type) semiconductor and create a thin layer of charge which drifts through the semiconductor. This current "pip" associated with the drifting charge layer is filtered from the equilibrium current, and its duration provides a measure of the transit time of electrons in the sample.

The material used in all experiments was commercially available, high-purity p-type InSb, supplied by Cominco and Monsanto. Samples with resistivities ranging from 5 to 280 Ω cm (at 77 °K) have been used. Since the main problem encountered in the measurement is the occurrence of very fast trapping, care has to be taken to remove all damage that can occur during handling of the samples. InSb in particular is susceptible to damage from cold working, and therefore only the center parts of the slices as obtained from the suppliers were retained, and the rest removed with fine abrasive.

Prior to diffusion the samples were etched in CP_4 for 2 sec. To make p^+ contacts to the samples, Cd was used as a diffusant. Zn and In were also used at an early stage, but the quality of the contacts was much poorer. For Cd, the measurements of Kendall,[8] Wilson and Hearsell,[9] and Boltaks and Sokolov[10] all converge to a value for the diffusion constant $D = 1\times10^{-5} e^{-1.1/kT}$ $(250 < T < 500\,^\circ\mathrm{C})$. The diffusions were carried out in a sealed evacuated quartz tube at 400 °C for about $\frac{1}{2}$ h, which results in a diffused layer about 0.7 μm deep. With 200-Ω cm material, fields up to 200 V/cm could be applied without electron injection from the contacts and up to almost 700 V/cm could be used with 15-Ω cm material. After diffusion, 500 Å of In is vacuum deposited on one face and 7000 Å on the other, and subsequently alloyed at 200 °C. Typical sample dimensions after slicing the samples on the wire saw are 1.5×1.5×0.7 mm. After etching, the broad sides are covered with Mylar tape, and the sides are reetched in CP_4 for 2 sec. The final etching operation usually results in a marked improvement in the breakdown voltage. All measurements on the samples were performed at 77 °K. The Hall mobility of the holes in p-type InSb as quoted by the manufacturer was typically around $(1.0-1.2)\times10^4$ $\mathrm{cm^2/V\,sec}$ at that temperature. Since the hole mobility does not change very much up to the highest fields used in these experiments,[11] the potential distribution can be expected to be uniform, as was confirmed by probe measurements on 15-Ω cm material. Two injection schemes were used, one giving an injection time of about 190 psec, and a four-times-faster circuit giving an injection time of about 50 psec.[4]

III. EXPERIMENTAL RESULTS AT LOW FIELDS

As stated in Sec. II, the main difficulty in the measurement at low fields is the occurrence of very fast trapping. Since the trapped carriers do not contribute to the excess current, the current decays very fast, and a transit-time measurement is nearly impossible. As expected, the trapping tends to be more pronounced in the lower-resistivity material, since this is somewhat more impure. The minority-carrier lifetime itself is expected to be of the order of several hundred nanoseconds, on the basis of the work of Baev,[12] which was, however, done at slightly higher temperature. The observed trapping times are smaller than indicated by his results by two orders of magnitude or more. To alleviate this problem, we tried to illuminate the sample with a laser beam, but as the light is absorbed very strongly in the contact region, no distinct improvement occurred.

In 200-Ω cm material, we have obtained a few samples where the trapping was low enough to provide reasonably strong signals. Some photographs of the observed waveforms are illustrated in Fig. 1. In the 15-Ω cm material, because of the trapping, it was not possible to measure the electron velocity at low injection levels. If the injection level is, however, sufficiently high, an appreciable number of minority carriers will eventually reach the anode. A typical signal observed under such conditions is illustrated in Fig. 2. It is seen that after the arrival of the main pulse, a substantial current keeps flowing, owing to electrons coming out of the traps. In addition, since the injection needs to be fairly high, the difference between the measured velocity of the injected pulse of carriers and the true electron-drift velocity can become significant, as will be discussed later.

The results of the measurements deduced from the time-of-flight data as presented in Fig. 1 are given in Fig. 3. The observations for 200 Ω cm are in good agreement with the data of Glicksman and Hicinbothem[1] and those of Bok and Guthmann.[2] Both these experiments measure the conduction current and carrier concentration in n-type samples. The measured low-field mobility is about 7.5×10^5 $\mathrm{cm^2/V\,sec}$. These and other measurements confirm the soundness of the theory developed by Stratton,[13] who first calculated the velocity-field characteristic under the assumption that the dominant scattering mechanism is polar optical scattering. Indicated in Fig. 4 are the Monte Carlo calculations by Fawcett and Ruch.[7] It is seen that the agreement between the calculations of Fawcett and Ruch and our data is fair, especially if some impurity scattering is included in the calculation.

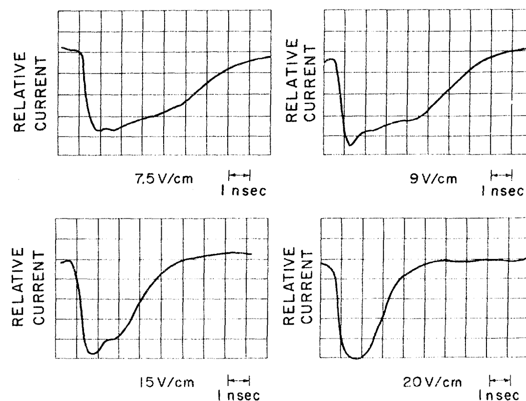

FIG. 1. Observed pulse shape vs field in a 200-Ω cm InSb sample at 77 °K. The transit time is taken as the pulse width at half-height.

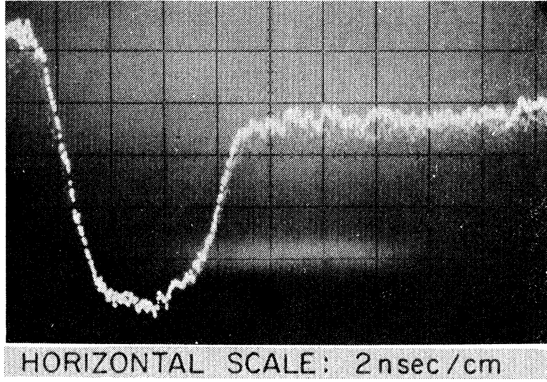

FIG. 2. Observed pulse shape in 15-Ω cm InSb sample The vertical offset in the trace indicates that electrons keep flowing out of the traps after the main pulse is over.

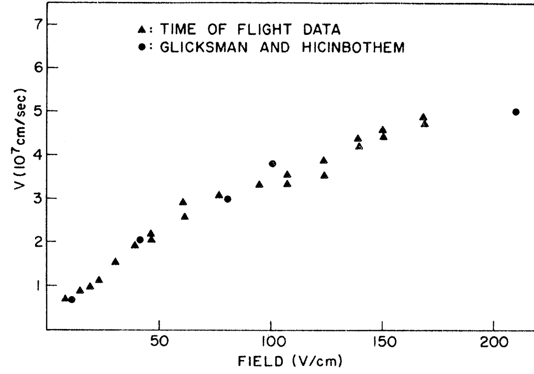

FIG. 3. Velocity-field characteristic measured in 200-Ω cm material; also indicated are data from Glicksman and Hicinbothem.

For the 15-Ω cm material, the results are much less conclusive. This is mainly due to ambipolar effects, as is discussed in the next section.

IV. NONLINEAR THEORY OF AMBIPOLAR EFFECTS

Since the technique is based on the observation of the transit time of electrons moving in p-type material, it is necessary to estimate the magnitude of the ambipolar correction. In particular, since the ratio of the electron mobility to the hole mobility is of the order of 60, one can expect that ambipolar effects will be quite pronounced in InSb.

The behavior of a pulse of electrons in a p-type semiconductor is governed by the equation[4]

$$\frac{\partial \Delta n}{\partial t}=\frac{v_n p(\partial v_p/\partial E)-v_p n(\partial v_n/\partial E)}{-p(\partial v_p/\partial E)+n(\partial v_n/\partial E)}\frac{\partial \Delta n}{\partial x}+\frac{-D_n p(\partial v_p/\partial E)+D_p n(\partial v_n/\partial E)}{-p(\partial v_p/\partial E)+n(\partial v_n/\partial E)}\frac{\partial^2 \Delta n}{\partial x^2}, \qquad (1)$$

where the coefficient of $-\partial\Delta n/\partial x$ gives the effective group velocity $v(n)$, and the effective diffusion coefficient $D(n)$ is given by the coefficient of $\partial^2\Delta n/\partial x^2$. Both $v(n)$ and $D(n)$ are decreasing functions of n as illustrated in Fig. 5.

The large ratio of electron to hole mobilities makes both quantities strongly dependent upon the electron concentration, and hence the equations are substantially nonlinear. This brings in an additional complication. It is proven in the Appendix that if the diffusion coefficient is substantially concentration dependent, Eq. (1) cannot truly represent the propagation of a pulse, as the number of particles is not conserved during propagation. This is in essence due to the fact that Eq. (1) is based on the assumption of complete space-charge neutralization, $\Delta n=\Delta p$, which is not rigorously true. The error is proportional to the derivative $\partial D/\partial n$, which is of course rather large in this case.

Apart from this consideration, the solution of Eq. (1) is not trivial. Herring[14] has given a solution to the ambipolar equation for arbitrary injection levels, in the case of a step injection. For this case (neglecting diffusion), the wave front at some time interval Δt later can be simply found by displacing each point on the original wave front by a distance $v(n)\Delta t$, where $v(n)$ is the concentration-dependent velocity. Particle trajectories of the electrons will not cross in this situation. However, for a short injected pulse, the situation is considerably more complicated, since particle trajectories will cross under these circumstances. No analytic solution exists in this case, and to the authors knowledge, numerical calculations have never been performed.

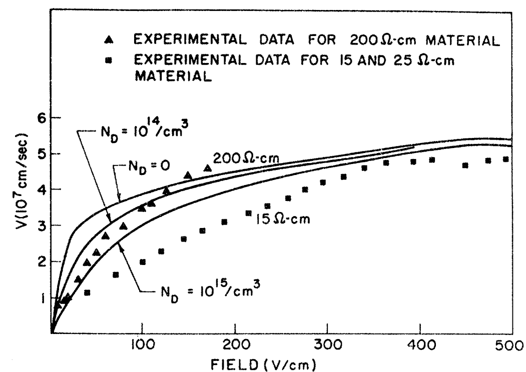

FIG. 4. Measured velocity-field characteristic in 200- and 15-Ω cm material and comparison with the theory of Fawcett and Ruch, for various amounts of impurity scattering.

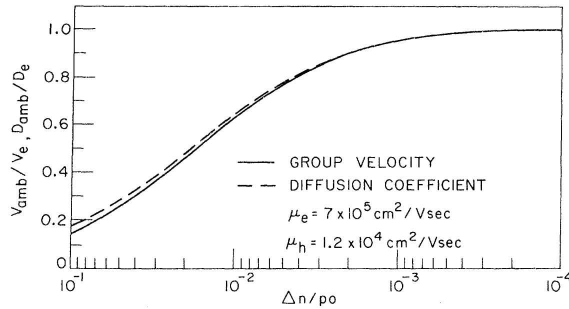

FIG. 5. Variation of the group velocity and the effective diffusion constant as a function of the injected electron density in InSb at 77 °K.

A qualitative picture of the behavior of an injected pulse is, however, possible. Consider, for example, a Gaussian input distribution as illustrated in Fig. 6. Since the velocity of particles at point A in the distribution is faster than in B, the front of the pulse will spread out. Particles at C are moving faster than those at B, and therefore the distribution will gradually get steeper in the back. Diffusion will prevent the wave front from becoming infinitely steep, and in addition, the pulse width will widen so that the concentration becomes lower. This increases the velocity, and makes the equation become more linear. The disturbance therefore propagates with an increasing velocity and with increasing diffusion effects. As the pulse spreads, the electron velocity and effective diffusion coefficient become close to that when the number of minority carriers is infinitesimally small (the true values). To obtain a quantitative picture of this behavior, Eq. (1) was solved numerically on a digital computer for increasing injection levels. All calculations were done at $E = 10$ V/cm, and hole and electron mobilities of 1.2×10^4 and 7.5×10^5 cm^2/V sec, respectively, were assumed. The background hole density p_0 was taken to be 4×10^{13}/cm^3. The input distribution was Gaussian, of the form $e^{-(x/x_0)^2}$, with $x_0 = 20\mu$.

An illustration of the solution corresponding to

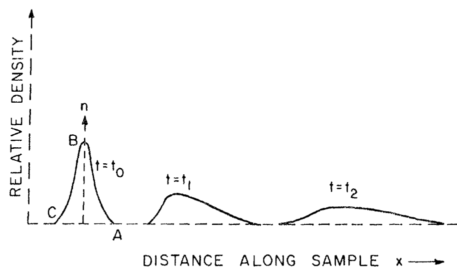

FIG. 6. Schematic solution of a Gaussian input distribution in time.

low injected levels is given in Fig. 7(a). The distribution is redrawn after each 1-nsec interval. Although the maximum electron density at the start was assumed to be 2×10^{11}/cm^3 ($\Delta n/p_0 = 5 \times 10^{-3}$), the actual velocity averaged after 10 nsec was only

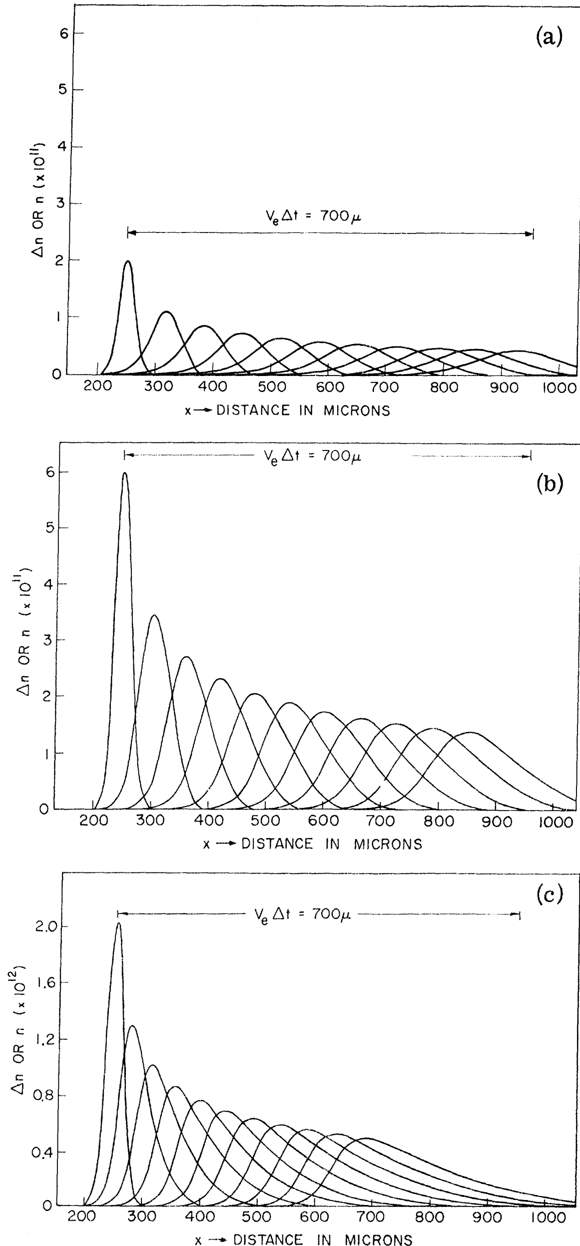

FIG. 7. Numerical solutions for ambipolar pulse propagation in InSb, for various minority-carrier concentrations: (a) $\Delta n_{max} = 2 \times 10^{11}$/cm^3, (b) $\Delta n_{max} = 6 \times 10^{11}$/cm^3, (c) $\Delta n_{max} = 2 \times 10^{12}$/cm^3. The majority-carrier concentration in all cases is $p_0 = 4 \times 10^{13}$/cm^3, and the applied field 10 V/cm. The distribution is redrawn after consecutive 1-nsec intervals. $v_e \Delta t$ is the distance the electron packet would travel if no dispersion took place.

3% less than the true electron drift velocity. This reduction is substantially smaller than that which would be anticipated on the basis of the graph of Fig. 5 (about 20%). The reason for this is the large diffusion and dispersion that is taking place, which rapidly reduces the maximum concentration.

When the injection level is increased to $n = 6 \times 10^{11}/\mathrm{cm}^3$ ($\Delta n/p_0 = 1.5\times 10^{-2}$) it is seen that after 10 nsec the distribution is not at all Gaussian; as expected, the rear end of the injected charge layer has steepened and the front has widened. However, the average drift velocity is only 14% lower than the true electron drift velocity.

Finally, at rather high injection levels $n = 2 \times 10^{12}/\mathrm{cm}^3$ ($\Delta n/p_0 = 5\times 10^{-2}$) the average velocity has been reduced by almost 40%. The charge layer is seen to pick up speed while it moves through the sample; the peak velocity at the anode is almost double what it was at the input. Note also that the effective diffusion constant has been substantially reduced, especially near $t = 0$. The shortcomings of the ambipolar equations are clearly indicated: the area under the curve (or the total number of electrons) has been increased by about 57% in the span of 10 nsec. It would seem reasonable that the actual disturbance velocity would therefore be somewhat higher, but a quantitative guess is hard to make.

From the above considerations, it is possible to make an estimate of the ambipolar correction required for the experimental results. For a 10-mV signal at 1.4×10^7 cm/sec, a minority-carrier density of the order of $5\times 10^{10}/\mathrm{cm}^3$ is required. For 200-Ω cm material, $p_0 = 3\times 10^{12}/\mathrm{cm}^3$ and therefore $\Delta n/p_0 = 1.7\times 10^{-2}$; it would seem, therefore, that the measured velocity could be 10–15% less than the true drift velocity. At higher fields the correction will be less, since the differential mobility is decreased, and also the effective value of the maximum excess carrier density is decreased. This arises because for a fixed injection time, the input distribution will be more spread out at higher fields. That the ambipolar effects are not very pronounced is also proven by the measurement of the diffusion coefficient. [4] The observed experimental value is 5100 cm^2/sec, whereas the expected value from the mobility measurement is 4900 cm^2/sec.

For the lower-resistivity materials (15 and 25 Ω cm), where the injection was larger by a factor of 20–50 to overcome trapping, the correction factor could become of the order of 30–40%, as illustrated in Fig. 7(c), but the situation is more complicated, since carriers are constantly being removed by the traps. It is seen from Fig. 2 that the fall time is not substantially lower than the rise time, as would be predicted from Fig. 7(c). This occurs presumably because electrons are mainly removed from the front end of the distribution by the traps.

It therefore becomes very difficult to make an exact estimate of the correction. Again the correction factor should decrease at high fields and be zero when velocity saturation occurs, as is indeed observed in Fig. 4, where the results are compared with the calculations by Fawcett and Ruch. Three curves are shown for increasing impurity concentrations. It is seen that even at fairly low impurity concentrations, the impurity scattering reduces the low-field mobility substantially because of the very high value of the latter. This phenomenon itself can to some extent explain why the velocities are different in the high- and low-resistivity material.

V. HIGH-FIELD EXPERIMENTS ($E > 400$ V/cm)

In n-type material appreciable electron avalanching takes place at fields slightly above 200 V/cm. In p-type material hole avalanching only becomes appreciable at much higher fields. Steele and Glicksman[11] indicate that hole avalanching becomes appreciable around 800 V/cm, but there seems to be theoretical evidence that this value is much too low. [15]

Electron avalanching in p-type material starts to occur for fields in excess of 400 V/cm. The loss of electrons due to trapping is then compensated for or overcome by the generation of electrons due to the avalanching; in other words, the minority carriers replenish themselves while they travel. Therefore, the injection level can be substantially reduced even in 15- and 25-Ω cm material. In addition, experimental measurements are made easier and more accurate because in the high-field region ($E > 400$ V/cm), the differential mobility is much lower than at low fields, and therefore ambipolar effects are insignificant.

All samples used in the high-fields experiments. were of 15- or 25-Ω cm material, as no contacts could be made to the high-resistivity material that would sustain, without electron injection, fields of 400 V/cm or more for the length of the bias pulse (200–300 nsec). The trapping characteristics varied widely from one sample to the other, even in samples cut from adjacent sites. In some samples, a growing signal would be observed as illustrated in Fig. 8 even at fields below 500 V/cm, while in others the trapping would still not be overcome at fields of almost 650 V/cm. In the absence of external injection no avalanching is observed. The residual electron concentration is very low ($n \approx 10^5/\mathrm{cm}^3$), and although in n-type material at these high fields the generation rate g is very high [$g = (1/n)\,dn/dt = 10^9$ or $n = n_0\, e^{10^9 t}$] this rate will be substantially reduced in p-type material because of trapping.

Smith *et al.* [16] indicate avalanching from these residual electrons at fields of approximately 500 V/cm. Our observations do not show this effect. In our case, using very carefully constructed noninjecting contacts, bias fields of almost 700 V/cm were applied for 200 nsec, without any indication of avalanching.

The velocity measured with the best sample is illustrated in Fig. 9. In this sample, the avalanching would overpower the trapping gradually and the signal would not show a growing tail as in Fig. 8. There is seen to exist a region of substantial negative differential mobility, with values as high as 5×10^4 cm^2/V sec. The agreement with the Fawcett–Ruch calculation is again very good, both in magnitude of the velocities and the magnitude of the NDM. This lends substantial support to their hypothesis that the NDM in InSb is caused by intervalley transfer effects ([000] to [111]) rather than by intraband effects (a calculation by Persky and Bartelink[17] based on the latter assumption is also shown). Smith *et al.* [5] found also from pressure measurements that the assumption of the intervalley transfer effects as the dominant mechanism agrees best with the observed threshold behavior as a function of pressure.

One can argue that the velocity-field characteristic as measured could be affected by the avalanching process. However, the amount of electrons in the sample stays quite small, as seen from the amplitude of the signal. Since the average distance traveled by an electron before trapping is a substantial fraction of the sample length, relatively few collision-trapping events are required to carry one effective minority carrier across the sample. The time required for the avalanche-generated electron to reach its terminal drift velocity is not known with accuracy, but is presumed to be quite small compared to the flight time. No exact data on the electron energy relaxation at 77 °K are

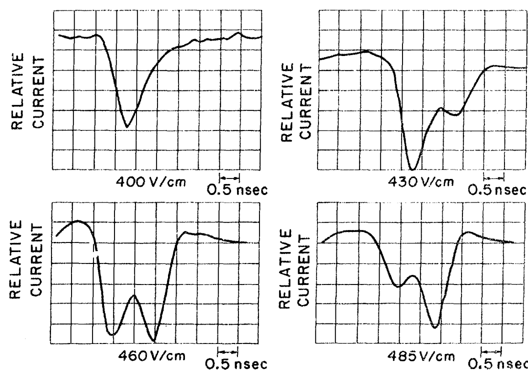

FIG. 8. Growing carrier distribution due to avalanching in low-trapping material. Vertical scale: relative current; horizontal scale: 500 psec/cm.

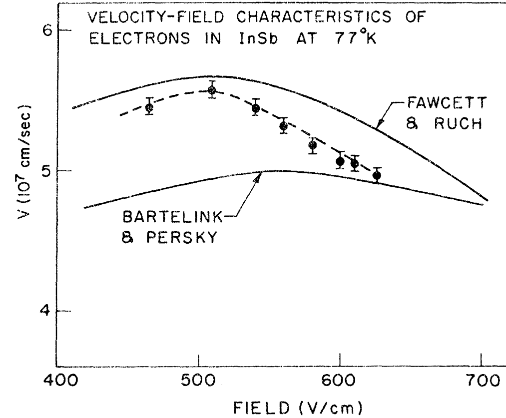

FIG. 9. Velocity-field characteristic of electrons in InSb at 77 °K at high field.

available; at 15 °K the value measured by Whalen and Westgate[18] is 2.5×10^{-8} sec, but their data indicate a very steep decrease with increasing temperature. The experiments of Smith *et al.* [5] also indicate Gunn domain formation well within 200 psec, so that the above time span must be a fraction of 200 psec. Since the process occurs statistically only two to three times during the time of flight, its effects should be small.

It would seem from this experiment that InSb would be a good candidate for electron-beam p-n-junction devices. Norris[19] indicates that the figure of merit for a material in such an application is proportional to the quantity

$$(1/E_{\text{pair}})(v_0/\epsilon)^{1/2},$$

where E_{pair} is the average energy needed to create an electron-hole pair, v_0 the electron velocity, and ϵ the dielectric constant. Since the energy for pair production is almost four times smaller, and the velocity at 77 °K roughly five times larger, an increase in the figure of merit by a factor of almost 9 would seem feasible.

APPENDIX: LIMITATIONS OF AMBIPOLAR WAVE EQUATIONS

It should be pointed out that the ambipolar equation, as derived in Ref. 4, is an approximation based on the fact that we assume $\Delta n = \Delta p$. It can in fact be proven easily that this nonlinear equation cannot represent the true physical situation, because the number of particles is not conserved. If we have an extrinsic p-type semiconductor, then the number of electrons in the disturbance cannot increase and should stay constant and equal to the number that was injected. Consider a finite, x-dependent distribution of electrons. For conservation of charge we require that

$$\frac{d}{dt}\int_{-\infty}^{\infty} n(x,t)dx = 0 \quad \text{or} \quad \int_{-\infty}^{\infty} \frac{\partial n(x,t)}{\partial t}\,dx = 0\,. \tag{A1}$$

The wave equation is of the form

$$\frac{\partial n}{\partial t} = v(n)\frac{\partial n}{\partial x} + D(n)\,\frac{\partial^2 n}{\partial x^2}\,. \tag{A2}$$

Substituting for $\partial n/\partial t$ from (A2), we obtain for condition (A1)

$$\int_{-\infty}^{\infty} v(n)\,\frac{\partial n}{\partial x}\,dx + \int_{-\infty}^{\infty} D(n)\,\frac{\partial^2 n}{\partial x^2}\,dx = 0\,. \tag{A3}$$

Consider the first term:

$$\int_{-\infty}^{\infty} v(n)\,\frac{\partial n}{\partial x}\,dx\,.$$

We define a function $F(n)$ such that $F'(n) = v(n)$. We have then

$$\frac{d}{dx}F(n(x)) = v(n)\,\frac{\partial n}{\partial x}\,.$$

Hence

$$\int_{-\infty}^{\infty} v(n)\,\frac{\partial n}{\partial x}\,dx = F(n(x))\Big|_{-\infty}^{\infty} = 0\,, \tag{A4}$$

since $v(n)$ and $F(n)$ are single-valued functions of n. For the second term we find that

$$\int_{-\infty}^{\infty} D(n)\,\frac{\partial^2 n}{\partial x^2}\,dx = D(n)\,\frac{\partial n}{\partial x}\Big|_{-\infty}^{\infty} - \int_{-\infty}^{\infty} D'(n)\left(\frac{\partial n}{\partial x}\right)^2 dx. \tag{A5}$$

The first term is zero, while in the second term $D'(n)$ is negative as can be verified, but $(\partial n/\partial x)^2$ is always positive. Therefore the total contributions of the right-hand side of Eq. (A5) are positive.

Hence condition (A1) is not satisfied for a wave equation that has a concentration-dependent diffusion coefficient. In cases where the mobilities and hence the diffusion coefficients are not too different for both sets of carriers, the error will be minor. However, for InSb, $D'(n)$ will be much larger, and consequently the equation will not exactly describe the physical phenomena. The number of particles will seemingly increase in time, as has been confirmed in the numerical calculation.

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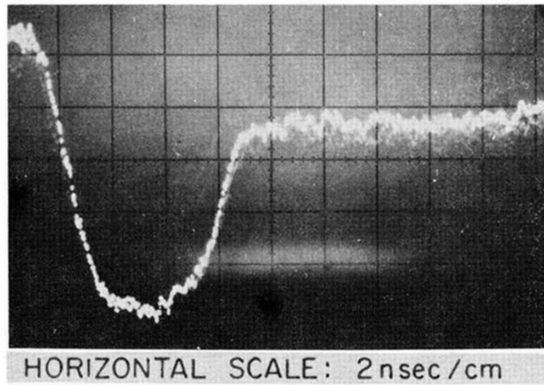

FIG. 2. Observed pulse shape in 15-Ω cm InSb sample The vertical offset in the trace indicates that electrons keep flowing out of the traps after the main pulse is over.