Transport Properties of GaAs†

J. G. RUCH* AND G. S. KINO
Stanford University, Stanford, California 94305
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The transport properties of the electrons in GaAs have been investigated; i.e., the absolute values of the electron drift velocity, the diffusion coefficient, and the trapping time have been measured for the first time as a function of the electric field. To measure the velocity at the electron, the response of a reversed-bias Schottky barrier-I-n^+ GaAs device to a short pulse (0.1 nsec) of high-energy electrons was measured. The incident electrons create a sheet of charges in the semiconductor very close to the cathode. The electrons move across the diode under the influence of the applied electric field and induce a current in the contacts until they reach the anode. The width of the induced current pulse is a measure of the transit time of the electrons. With a knowledge of the width of the field region (I layer), the drift velocity corresponding to the particular bias field can be accurately determined. The specimen used in this experiment consists of a slab of semi-insulating boat-grown GaAs cut in the [100] and [111] directions. Thin contacts were evaporated on each face; one, the cathode contact, less than 1000 Å thick, forms the noninjecting Schottky barrier. The other, the anode, is ohmic. The experimental results are in excellent agreement with the Butcher-Fawcett theory, with a low-field mobility of 7500 cm^2/V sec, a threshold field of 3300 V/cm, and an initial negative mobility of 2600 cm^2/V sec. Signs, but no strong evidence, of the minimum velocity being reached up to the highest field used, 14 kV/cm, were observed. We have also measured by the same method the velocity-field relation over a range of ambient temperatures from 160 to 340°K. From the measurement of the difference between the rise and the fall time of the induced current pulse, which is a measure of the spread of the electron layer created at the cathode by electron bombardment, it was possible to obtain the diffusion coefficient as a function of the electric field. The diffusion coefficient is sharply peaked (900 cm^2/sec) at the threshold field and decreases to a value slightly less than 200 cm^2/sec at high field. The experimental results are in considerable disagreement with the theoretical prediction. This disagreement may possibly be due to the velocity fluctuation arising from the rapid electron intervalley transfers which have not been taken into account in the theory by Butcher and Fawcett. Finally, measurement of the number of electrons trapped during the electron transit time across the specimen yields the variation of the trapping time as a function of the electric field.

I. INTRODUCTION

MICROWAVE current oscillations have been observed[1] in samples of n-type GaAs provided with ohmic contacts and subjected to high electric fields. It is now well established that the mechanism responsible for this effect is the one predicted by Ridley and Watkins[2] and by Hilsum.[3] The mechanism is the transfer of hot electrons from the light-mass, high-mobility valley at the center of the Brillouin zone to the heavy-mass, low-mobility satellite valley (100) 0.35 eV higher in energy.

The magnitude and consequence of hot-electron transfer have been investigated on theoretical grounds by Butcher and Fawcett[4] and by Conwell and Vassel.[5] In particular, they predicted the electric-field dependence of the drift velocity of the electrons and the diffusion coefficient. Butcher and Fawcett's treatment is based on Boltzmann's equation, taking into account electron and polar mode intravelley scattering and deformation potential scattering between the central and satellite valleys. The equations were solved by assuming a displaced Maxwellian electron distribution in each valley. Conwell and Vassel removed this assumption, but neglect the electron-electron interaction and assumed that the polar optical scattering is elastic. As a result their solution is not accurate until a fairly high field is reached, so that the average electron energy exceeds several times the optical phonon energy.

Because space charge causes the field within the semiconductor to be nonuniform, it has been difficult, until recently, to carry out a direct experimental measurement of the negative differential mobility of GaAs.

McWhorter and Foyt[6] measured the rf admittance of a nonoscillating diode and from their results calculated the negative differential mobility of the material, μ_2, using a three-slope piecewise linear model for the velocity-field characteristic.

Chang and Moll[7] studied the response of a reverse-biased Schottky barrier-I-n^+ GaAs photodetector to a step input of light from a pulsed GaAs laser. This method has the advantage that, when insulating material is used, the only space charge present is that due to the induced carriers, which can be kept small enough to allow the fields within the semiconductor to remain essentially uniform. By introducing a phenomenological trapping time τ and assuming that τ is independent of the electric field, they were able to show that the

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* Presently at Bell Telephone Laboratories, Murray Hill, N. J.

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[2] B. K. Ridley and T. B. Watkins, Proc. Phys. Soc. (London) **78**, 293 (1961).

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[6] A. McWhorter and A. G. Foyt, Appl. Phys. Letters **9**, 300 (1966).

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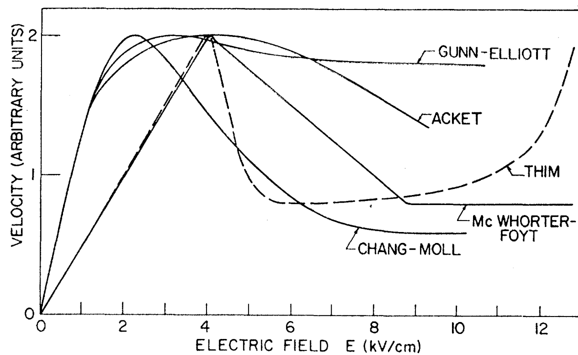

FIG. 1. Velocity-field characteristic in GaAs. The curves are normalized to the same peak value.

photocurrent obtained should be proportional to the drift velocity of the carriers. Thim[8] and Kino *et al.*[9] measured the potential distribution along the surface of nonoscillating GaAs diodes with probes. Thim calculated the velocity-field characteristic from his results, while the later work of Kino *et al.* carried out after much of the work in this paper had been done, was used to show that their results were consistent with the Butcher and Fawcett velocity-field characteristic. Gunn and Elliott[10] measured the current-voltage characteristic of a diode directly, and attempted to avoid the redistribution of charge and the resulting nonuniform field distribution by making the measurement in a time less than the differential dielectric relaxation time. Based on this principle, but using a microwave signal at sufficiently high frequency to prevent buildup of instabilities, Acket[11] and Braslau[12] studied the change in dc conductivity when a large microwave electric field is applied parallel to a small dc field, and were able to derive the velocity-field characteristic from their measurements. The various experimental results are reproduced in Fig. 1.

It will be seen that the experimental data available a year ago were highly conflicting. Consequently, it appeared worthwhile to develop a more direct and accurate method of measurement of the average drift velocity of the electrons as a function of the electric field. The technique we adopt is similar to that of Chang and Moll[7] and was first suggested by Spear,[13] who employed it to determine the variation of the electron drift velocity with field in CdS; it was also used by Norris and Gibbons[14] to measure the field-dependent mobility of Si. In addition we have been able to employ this extremely powerful technique to determine the field dependence of the diffusion coefficient and very small trapping times of the electrons. In our experiment, a nearly uniform electric field E is obtained, as discussed in Appendix A, by reverse-biasing an essentially Schottky barrier-i-n^+ diode in which the width l of the I region is accurately known. However, it was necessary to take the precaution of using a thin layer of insulating material (SiO) under the cathode contact in order to obtain a reliable noninjecting contact to semi-insulating material.

The transit time of the carriers in a uniform field E is determined by measuring the response of the diode to a short pulse (approximately 0.1 nsec) of injected carriers produced by a pulsed high-energy electron beam (approximately 14 kV in most of the experiments) which is passed through the cathode contact. The energy lost by the incident electrons as they come into equilibrium with the lattice produces a thin sheet of electron-hole pairs in the semiconductor approximately within 3 μm of the cathode. This method of pair production has advantages over the use of a pulsed laser in that there are no problems in obtaining sufficiently high current or sufficiently rapid pulses. Of particular importance is the fact that it is possible to turn off the beam pulse as rapidly as it is turned on. The major disadvantage of the technique is, of course, that it is necessary to place the sample in a high-vacuum environment.

The electron sheet produced by the beam is swept under the influence of the nearly uniform bias field towards the anode. As the electrons traverse the field region, a constant current is induced in the external circuit.[14] The induced current persists only as long as the electrons are in the field region. The width of the induced current pulse is then a measure of the transit time of the electrons and the difference between the rise and fall times of the pulse is related to the diffusion constant of the electrons. With a knowledge of the width of the field region, the drift velocity and diffusion constant corresponding to the particular bias field can be accurately determined.

II. EXPERIMENTAL APPARATUS AND SAMPLE STRUCTURE

The experimental apparatus, shown schematically in Fig. 2, consists essentially of an electron gun and a sample mount designed to incorporate the sample as well as possible into a 50-Ω coaxial transmission line system, while exposing its front face to the electron beam. The electron beam is derived from a Hewlett-Packard cathode-ray-tube gun equipped with horizontal and vertical deflection plates. The system is pumped with an 8-liter Vacion pump and fastened with Varian flanges, so that samples can be changed fairly rapidly. The cathode-ray gun and deflection plates are mounted inside a glass envelope and the beam is shielded over its full length from the earth's magnetic field, as well as from stray magnetic fields from the nearby Vacion pump. The oxide-coated cathode of the

[8] H. W. Thim, Electron. Letters **2**, 403 (1966).
[9] G. S. Kino, P. N. Robson, and B. Fay, IEEE Trans. Electron. Devices **ED-14**, 612 (1967).
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[11] G. A. Acket, Phys. Letters **24A**, 200 (1967).
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[14] C. B. Norris and J. F. Gibbons, IEEE Trans. Electron. Devices **ED-14**, 30 (1967).

gun is kept warm in an argon atmosphere every time the system is opened to change the sample. By this means the lifetime of the cathode can be considerably lengthened.

In order to take measurements at different temperatures, the samples can be cooled down by continuously transferring cold nitrogen gas from a nitrogen storage Dewar and heated up by transferring hot nitrogen gas. The temperature during a set of measurements can be held essentially constant. The sample temperature is measured with an iron-constantan thermocouple placed in contact with it.

A thin plane of carriers is created near the front surface of the sample by an electron beam which is rapidly deflected past a disk, in which there is a hole 3 mm in diam, placed in front of the sample. Using the circuit shown in Fig. 2 a sinusoidal signal of approximately 50 MHz is applied to one set of deflection plates and is used to trigger a sampling oscilloscope. The amplitude and frequency of the signal are such that the electron beam sweeps across the specimen in a time shorter than 0.1 nsec. This performance was checked by replacing the sample with a metal plate and observing the pulse of current directly on the sampling oscilloscope, the rise time of the oscilloscope itself being at best 0.06 nsec.

The repetition rate of this short pulse of electrons is controlled by a variable-length pulse signal triggered directly from the sampling output of the oscilloscope or through a countdown circuit from it. This pulse, which is of the order of 1 μsec long with a repetition rate of 100 kHz or a subharmonic integral power of 2 down from this frequency, is applied to the second pair of deflection plates, thus keeping the electron beam away from the hole in the plate most of the time. When both signals go through zero at the same time, an electron burst of the order of 0.1 nsec long is delivered into the sample with a repetition rate equal to that of the microsecond pulse.

It is necessary to apply the reverse bias (the applied field) to the diode on a pulsed basis, since dc bias could result in destruction of the sample. This pulse which is typically of the order of 1 μsec long is also triggered from the circuit described above but is arranged to start before the arrival of the bombarding electron. Appropriate high-pass filter circuits are placed in the output leads of the diode and the rise time of the pulse is made slow enough to protect the sampling oscilloscope which is used to detect the short pulse of current induced in the diode.

The samples to be measured were fabricated from high-purity, high-resistivity n-type GaAs kindly given to us by IBM, and cut in the [100] direction. Measurement on $10^8\,\Omega$ cm Monsanto material cut in the [111] direction have also been performed. The n^+ anode contact was formed by alloying Au-Ge at 500°C. The noninjecting negative contact was obtained by first evaporating a thin layer of SiO (200 Å) covered with 500 Å of Au onto a chemically polished surface of the

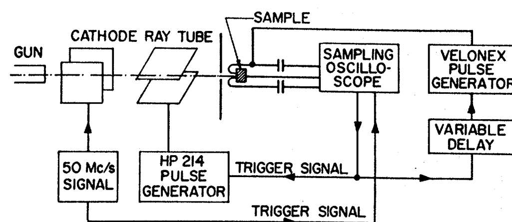

FIG. 2. Schematic of the experimental apparatus.

high-resistivity GaAs. The contact-film thicknesses were chosen to be thin enough so that the bombarding electrons would still have a substantial energy after passage through the contact film, but thick enough to prevent injection of electrons. In our experiment, this energy is such that electron-hole pairs are created within 3 μm from the cathode contact. Typical devices have 3-mm diam active circular areas and the high resistivity layer thickness varied from 250 to 300 μm. The reverse breakdown voltage of these devices was about 500 V.

We have not found it to be experimentally possible to construct a good Schottky barrier on insulating GaAs. Instead, with a gold film applied directly to the material, the sample behaves as a space-charge-limited diode, albeit with trapping. A reasonable approximation to the current-voltage characteristics of this diode could be predicted by using the Butcher-Fawcett velocity-field characteristics and assuming that the diode was space-charge-limited at the cathode contact. Moreover, when such diodes were used to measure the velocity-field characteristics by the method described in this paper, the results obtained were different from those with an insulating layer of SiO between the gold contact and the GaAs. The results obtained in the first case could be predicted from the velocity-field characteristic measured in the latter situation by assuming that there was perfect injection at the cathode contact and hence a nonuniform field in the diode. Results intermediate between the two cases were obtained with very thin layers of SiO 50–100 Å thick.

It should be noted that, because of the SiO layer between the cathode contact and the sample, dc potentials across the diode could not be used. If they were, the high-capacity SiO layer would eventually charge up through the resistance of the diode to a high potential and break down. Under pulsed conditions, because of the relatively low capacity of the sample, there is a negligible voltage drop across the SiO layer.

III. EXPERIMENTAL MEASUREMENTS

The response of a Schottky barrier-I-n^+ device to electron bombardment has been studied in the past assuming a constant electric field in the dipletion region.[14] While in most circumstances this is not strictly true, we have shown in Appendix B that with a minor field variation present within the sample, the carrier

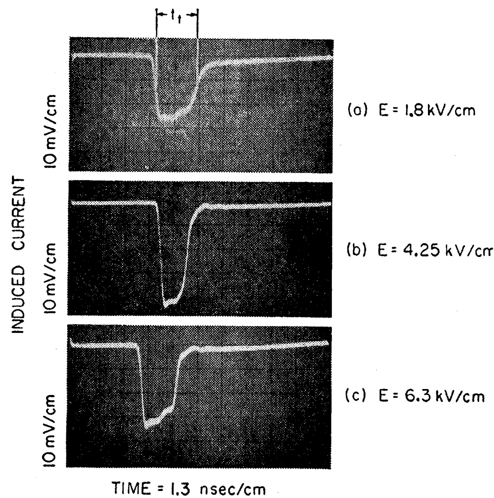

FIG. 3. Typical sample current wave form. The sample thickness is 300 μm and t_t corresponds to the transit time of the electrons across the specimen.

transit time is essentially that corresponding to the average value of the field. Therefore, in the interest of clarity we shall assume in any further discussion that the electric field, and consequently the drift velocity of carriers, is constant in the depletion region. In this circumstance, it can be shown that the current induced in the electrodes by a layer of charge Q moving with a velocity v is $I=Qv/l$, where l is the electrode spacing.[14] Thus, ideally, an infinitesimally thin layer of electrons, introduced instantaneously into the semiconductor at the cathode plane, would travel in the applied uniform field with a constant velocity v until it reached the anode plane, where its velocity would instantaneously drop to zero. We would therefore expect in this ideal situation that there would be a perfect rectangular pulse of current induced in the electrodes. In practice the pulse shape is at best only an approximation to the ideal one, both because of circuit problems and because the charge layer introduced into the semiconductor is neither infinitesimally thin nor invariant in shape or charge during its passage from cathode to anode.

The circuit problems are of two types: First the diode itself has a capacity which can be considered as a lumped element C connected across the 50-Ω coaxial line feeding the sampling oscilloscope. Thus the diode must not be made too large in area or too short, and care must be used to minimize the capacitance of its supports. In our experiment the equivalent capacitance of the diode and supports was less than 2 pF, leading to rise and fall times of the pulse due to this cause of less than 0.1 nsec. A second difficulty is caused by the high surface resistance of the contacts due to the imperfect deposition of the thin evaporated layer required. Such a contact can behave as if there is a resistance in series with the coaxial line, thus causing the rise and fall times of the pulse to be still worse and often as much as 0.2 nsec over-all on good samples.

Some typical experimental pulse current wave forms are shown in Fig. 3. It will be observed that, in addition to the rise and fall times of a pulse being finite, they are not equal and the amplitude of the pulse may decrease with time. Probe measurements carried out on similar semi-insulating samples of GaAs have shown that when the cathode contact is noninjecting, the electric field is uniform and hence the drift velocity of the carriers is constant. Thus we must conclude that trapping or recombination of the carriers is taking place. As will be seen from the wave form, in some instances, there is a pronounced "trail" on the pulse, corresponding to the carriers being released from the traps. We therefore conclude that fast trapping can take place in these materials and have made use of measurements of the time constant of this effect to measure the trapping times. However, as long as the transit time of the carriers is somewhat shorter than the trapping time, the transit time can still be measured directly.

The difference between the rise and fall times of the induced current pulse can be attributed to space-charge and diffusion effects although, in practice, neither one of these effects is dominant. Diffusion spreads the space-charge layer and increases the fall time of the pulse. The space charge of the layer itself causes the field in the front to be higher than that at the back; this field difference can be determined from the space charge in the layer, Q, which in turn can be obtained from the amplitude of the carrier current. It is shown in Appendix C that when the average field corresponds to a region where the differential resistance is positive, electrons on the anode side of the space-charge layer move faster than those on the cathode side, for the field in front is larger. Consequently, the effect of space charge is to spread the charge layer and deteriorate the fall time of the current pulse. Conversely, for fields in the negative differential resistance region, the charge layer tends to decrease in width as it moves through the diode, and the fall time of the pulse is decreased. These space-charge effects have been observed by varying the current in the electron beam and are in fairly good quantitative agreement with our theoretical estimates. The latter effect is, in fact, the process which leads in higher conductivity material to the formation of a domain. Since it is possible to make reasonable estimates of the corrections due to space charge, the diffusion constant can also be measured experimentally, although only with limited accuracy.

A. Velocity-Field Characteristic Measurement

A direct and absolute measurement of the velocity-field characteristic has been obtained up to an electric field greater than 14 kV/cm by measuring the width of the induced current pulse and hence the velocity of the carriers. In order to eliminate the effect of diffusion, this transit-time measurement was taken from the time the electrons at the center of the sheet of carrier (created

at the cathode by electron bombardment) leave the cathode until the time these electrons arrive at the anode, i.e., from the midpoint of the rising edge to the midpoint of the trailing edge of the induced current pulse, as illustrated in Fig. 3.

Carrier velocity determination from data taken on three samples of IBM material is presented by curve a of Fig. 4. The electron drift velocity was measured along the [100] axis of the material.

With the technique we have employed, the accuracy of the data obtained is determined by the precision that is possible in the measurement of transit time, sample thickness, and sample bias. The estimated maximum error in the determination of the absolute velocity and the determination of the electric field is $\pm 5\%$. Measurement of the velocity has only been taken up to 14 kV/cm at which point the samples broke down. Signs, but no strong evidence, of the minimum velocity being reached were observed.

An indirect measurement of the velocity-field characteristic has also been taken along the [111] axis of Monsanto material and is shown as curve b of Fig. 4. In this case, the trapping time of the carriers was somewhat less than the transit time through the diode, as discussed below in Sec. III C. However, the relative drift velocity as a function of the electric field can be obtained thereafter, as shown below, by considering the variation of the amplitude of the carrier current with the electric field.

The charge Q present in the moving charge layer obeys the following conservation equation:

$$dQ/dt = -Q/\tau + GI, \tag{1}$$

where τ is the electron trapping time, I is the beam current incident on the sample, and G is the number of electron-hole pairs induced per incident electron. Since the observed electron release time is larger than the trapping time for the electric field being considered, the release of electrons from traps has been ignored. This equation has the solution

$$Q = e^{-t/\tau} \int_0^t GI\, e^{t'/\tau} dt'. \tag{2}$$

If the time t of carrier injection is somewhat smaller than the trapping time τ, the exponentials may be taken as equal to unity, so that

$$Q \approx \int_0^t GI\, dt'. \tag{3}$$

It follows that the charge induced in the semiconductor is independent of the trapping time, provided that the beam current pulse occurs within a time somewhat less than the trapping time, a condition that can usually be satisfied. Therefore, the current induced in the electrodes Qv/l is initially directly proportional to the velocity of the moving charge layer. In particular, we may use the peak-induced current as a measure of the velocity of the charge layer. The results obtained cannot, however, provide an absolute measure of the drift velocity, but only a relative measure of the variation of this quantity with field.

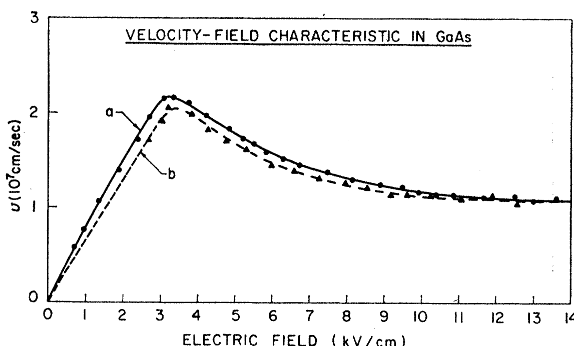

FIG. 4. The measured velocity-field characteristic: (a) Measured along the [100] axis with IBM material. (b) Measured along the [111] axis with Monsanto material.

In order to compare the results taken with Monsanto material with the absolute measurements of velocity taken on the IBM material, it has been necessary to normalize the two against each other. It might be expected, as has been pointed out by Bott and Hilsum,[15] that differences in the low field mobility of different samples of GaAs would be due to impurity scattering. At high fields, where the electron energy is high, impurity scattering should be less important, and so the velocity-field characteristics of different samples of GaAs should tend to be the same at very high fields, but not necessarily at low fields. We have therefore chosen the electron drift velocities in the Monsanto and IBM samples to be identical at the highest field values used (approximately 14 kV/cm).

It will be seen that there is a fairly good match between the two sets of results taken with different materials, the differences being in the expected direction. The measured low field mobility of the IBM material is 7500 cm^2/V sec, and is in good agreement with the Hall-mobility data obtained by IBM for similar higher conductivity material. On the basis of the normalization used, the low field mobility of the Monsanto material would be approximately 6200 cm^2/V sec, a figure in reasonable agreement with the measured Hall mobility on good high-conductivity Monsanto material made by a similar process. The measured negative differential mobility just above threshold is 2400 cm^2/V sec for the IBM material, and 2700 cm^2/V sec for the Monsanto material, results which are in reasonable agreement with those of Foyt and McWhorter.[6] These results have been confirmed using other techniques on 600 and 3000 Ω cm Monsanto material by Kino *et al.*[9]

[15] J. B. Bott and C. Hilsum, IEEE Trans. Electron. Devices **ED-14**, 492 (1967).

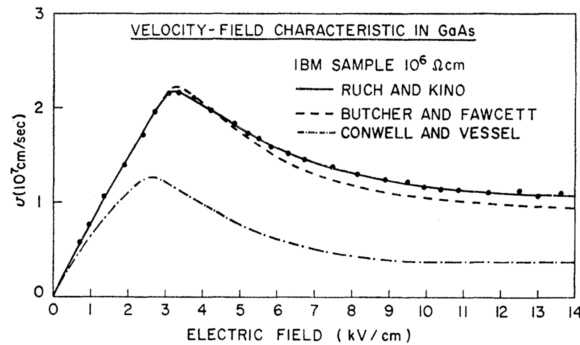

FIG. 5. Measured and theoretical velocity-field characteristics.

The measured threshold field for both types of material is 3.3–3.5 kV/cm. However, experimental work has shown that instability in GaAs appears at a threshold field as low as 2 kV/cm. This apparent contradiction can be explained if we assume that a gradient of impurity can exist, particularly near contacts. This causes a field higher than the average field to be achieved at some point in the specimen, and so domain nucleation becomes possible in this region. Support for this assumption has been given by Copeland,[16] who shows that the minimum average field which can sustain a high-field domain in a sample is a function of the length of the sample and can be substantially smaller than the threshold field for long samples. Moreover, Gunn,[17] by measuring the actual potential distribution at threshold, was able to calculate the threshold field and obtained values as high as 3.8 kV/cm.

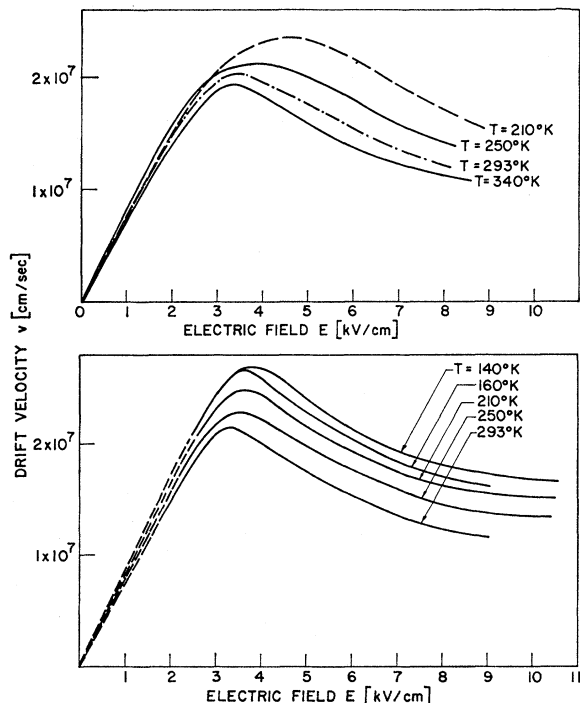

FIG. 6. Temperature dependance of the velocity-field characteristics.

[16] J. A. Copeland, J. Appl. Phys. **37**, 9 (1966).
[17] J. B. Gunn, J. Phys. Soc. Japan **21**, 505 (1966).

The velocity-field characteristics predicted by Butcher and Fawcett[4] and by Conwell and Vassel[5] are compared with the experimental result taken on IBM material in Fig. 5. It will be seen that the agreement between our experimental results and the theory of Butcher and Fawcett[4] is remarkably good.

The velocity-field characteristic has also been measured over a wide range of temperatures; the results taken on two different samples of IBM material are given, respectively, in Figs. 6(a) and 6(b). We observe that the negative differential mobility stays approximately constant when the temperature of the sample is varied. The lattice temperature has a weak influence on the low field mobility, showing evidence that the transport properties of the material were not entirely controlled by phonon scattering; impurity scattering must therefore be playing a fairly strong part. It should also be pointed out that the samples used in this experiment had a fairly high trapping rate, and so the measurements in the low field range are not very accurate; this could explain some of the discrepancies.

One other feature of interest is that it appears there is a monotonic decrease in threshold field as the temperature of the sample is raised. In some experiments carried out by Bott *et al.*,[18] the efficiency of Gunn oscillators increases as the temperature is raised. Such a result could well be explained by a change in threshold field of this type.

B. Measurement of the Diffusion Coefficient

When a plane of carriers created at the cathode by electron bombardment drift across the specimen, the electrons will diffuse because of the concentration gradient. Upon their arrival at the anode, the plane of carrier will be substantially thicker than at the cathode.

We have calculated the diffusion coefficient from the knowledge of the fall and rise time of the induced current pulse assuming that the density distribution of the plane of electrons produced by the beam is Gaussian. There is no real justification for this assumption except that the mathematical manipulation is easier; more sophisticated models have also been considered but give essentially the same result. Hence the injection of electron at one electrode can be visualized as a Gaussian bunch of electrons entering the semiconductor at a time t_1. The centroid of this bunch of electrons will drift across the specimen and leave it at a time t_2 such that $t_2-t_1=T$, the transit time.

By defining the rise and fall time of the induced current pulse as the time it takes for the signal to increase or decrease, respectively, from 5 to 90% of its final value, we show in Appendix C that the following

[18] I. B. Bott and H. R. Holliday, IEEE Trans. Electron Devices **ED-14**, 522 (1967).

expression yields the diffusion constant D:

$$D = v^3(\tau_F^2 - \tau_R^2)/21.6l, \tag{4}$$

where τ_F and τ_R are, respectively, the fall and rise times of the induced current pulse.

The determination of the diffusion coefficient has been obtained from the data taken on only one sample which had a contact resistivity low enough to limit the response time of the system to a value of the order of 0.1 nsec. Measurements were taken along the [100] axis of IBM material. The diffusion coefficient obtained using Eq. (1) is presented in Fig. 7, where the point for $E=0$ is inserted by use of the Einstein relation for D. The results are compared in Fig. 7 with the theoretical prediction of Butcher and Fawcett.[4]

In the technique that we have employed the accuracy of the data obtained is determined by the precision that is possible in the measurement of the rise and fall times of the sample current. Another important source of error could be the inhomogeneity of the material causing the distortion of the plane of carriers injected at the cathode by electron bombardment. In the work reported here it is estimated that the error to be expected in the absolute determination of the diffusion coefficient is $\pm 25\%$ and could be even higher at high electric field. However, such a measurement does give a qualitative estimate of the field dependence of the diffusion coefficient.

We observe that the general behavior of both the experimental and theoretical characteristics is similar, but the numerical agreement between experiment and theory is poor. Better agreement is obtained when the velocity fluctuation arising from the intervalley transfers is taken into account. This is expressed by the expression for diffusion given by Shockley *et al.*[19]:

$$D = n_1 n_2 \tau \Delta^2 + n_1 D_1 + n_2 D_2, \tag{5}$$

where τ is the average time for intervalley transitions, Δ is the difference between the drift velocities of electrons in the upper and lower valleys, and n_1 and n_2 are the fractions of electrons in the lower and upper valleys, respectively.

C. Trapping-Time Measurement

It has already been shown that the decrease in amplitude of the current pulse during the transit of the charge layer through the diode can only be explained in terms of trapping. We report in this section measurements of trapping time as a function of the electric field.

The capture rate for the average electron is given by

$$dn/dt = -n/\tau + N_T^-/\tau_T, \tag{6}$$

where n is the number density of free electrons, N_T^- is the number density of negatively charged traps (assuming that $N_T^- \ll n$ since the material is depleted of its electrons), τ is the electron trapping time, and τ_T is the release time from the traps (assuming that both τ and τ_T are functions of the electric field E and hence of the electron energy).

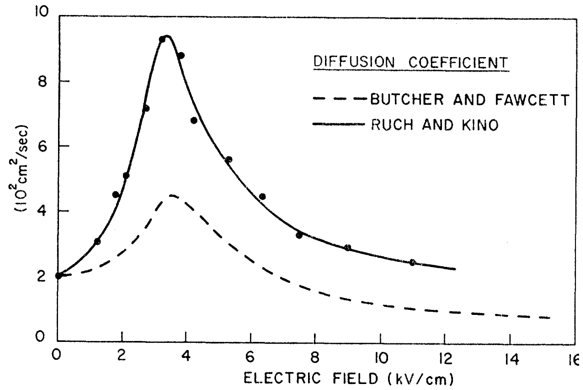

FIG. 7. Measured diffusion coefficient compared with the theoretical prediction of Butcher and Fawcett.

In equilibrium, it follows from Eq. (6) that

$$n = N_{T0}^- \tau/\tau_T, \tag{7}$$

so that, if $n \ll N_{T0}^-$ in equilibrium, then $\tau_T \gg \tau$. Therefore, from Eq. (6), the induced charge density, and hence the charge of the moving layer and the current induced in the electrodes, decreases as $\exp(-t/\tau)$. If $\tau \gg T$ the transit time, it is only a matter of measuring the slope of the current pulse to find τ. Note that a ripple is superimposed over the induced current wave form and extreme care should be taken in the interpretation of this wave form especially for short transit time. This ripple is due to a slight mismatch between the sample mount and the 50-Ω transmission line.

A measurement of trapping time τ, carried out on the sample of IBM material with the longest trapping time that we could find, is shown in Fig. 8. On the best samples of IBM material the trapping times were of the order of 10 nsec and usually longer than 1 nsec for all samples measured. The trapping times observed varied radically for samples taken from different parts

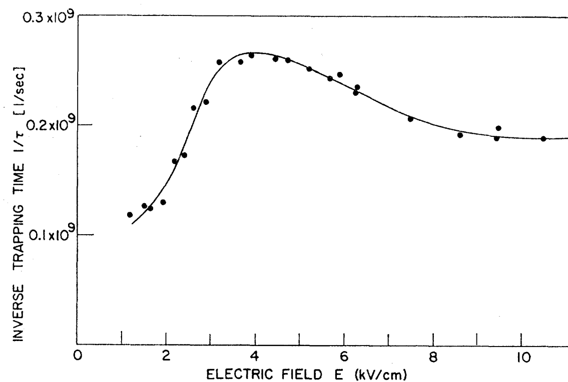

FIG. 8. Electric-field dependance of the trapping time.

[19] W. Shockley, J. A. Copeland, and R. P. James, *Quantum Theory of Atoms, Molecules and the Solid State* (Academic Press Inc., New York, 1966).

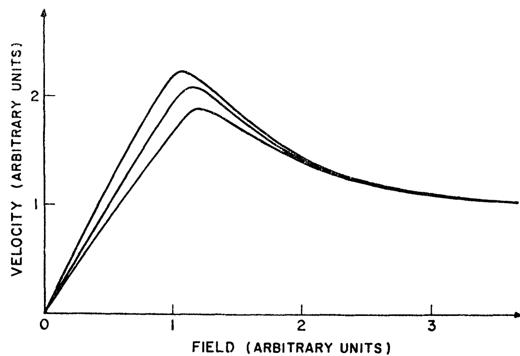

FIG. 9. Qualitative behavior of the velocity-field characteristic as the positive mobility μ varies.

of a slice of the same piece of material, but exhibted a very similar variation with field. Long trapping times were only observed with samples with relatively low etch pit density. However low etch pit density is not a sufficient criterion for a long trapping time, since some samples which satisfied this condition had short trapping times.

We also made approximate measurements of the trapping time variation with field of various samples of Monsanto material. In general all samples of Monsanto material tested had very short trapping times, typically much less than 1 nsec, a time shorter than the transit time of electrons from cathode to anode in the experimental diode used. Since the form of the trapping-time variation with field varied widely from sample to sample, it has not been thought worthwhile to reproduce these results here.

IV. CONCLUSIONS

We have found that the method of producing a thin space-charge layer in a semi-insulating semiconductor by means of a rapidly switched high-energy electron beam provides an extremely powerful technique for determining the velocity-field characteristics, the diffusion constant, and fast trapping times as a function of field. Absolute measurements of the velocity-field characteristics can be made in materials which have a trapping time somewhat longer than the transit time of the electrons. It is still possible to make relative measurements of the velocity-field characteristics independent of the variation of trapping time, provided that the electron beam pulse is somewhat shorter than the trapping time and the trapping time is itself shorter than the transit time of electrons through the sample.

The velocity-field characteristic which has been obtained with semi-insulating GaAs is in good quantitative agreement with the theory of Butcher and Fawcett[4] rather than that of Conwell and Vassel.[5] However, this agreement is rather fortunate when we consider that Butcher and Fawcett described the electron-distribution function in the form of a displaced Maxwellian in each valley with a common electron temperature in the satellite valleys but with a different value in the central valley. It has been shown by Conwell and Vassel[5] that this assumption is not valid in GaAs. However, Conwell and Vassel assume when they determine the electronic distribution from the Boltzmann equation that first-order inelastic scattering with the lattice is dominant. It has been suggested by Sher and Thornber[20] that they have neglected a two-phonon process which is comparable in magnitude to the first-order process and should be included in the Boltzmann equation. This elastic scattering mechanism would have the effect of driving electrons towards a drifted Maxwellian distribution and this would support the assumption, by Butcher and Fawcett, of such a distribution. Furthermore, this would explain the discrepancy of our measurement with the velocity-field characteristic calculated by Conwell and Vassel.[5]

Alternatively, this disagreement could be explained in terms of the observation by Spicer[21] that the ⟨111⟩ valleys may coincide in terms of energy with the ⟨100⟩ valleys. Therefore, the effective mobility of the satellite valleys to be used would be different and probably larger than the mobility of the ⟨100⟩ valleys. Little is known about the scattering mechanism of electrons in the ⟨111⟩ valleys, but the work of Pollak *et al.*[22] has shown that the ⟨111⟩ effective mass is smaller than that of electrons in the ⟨100⟩ valleys.

The variation of the experimentally measured velocity-field characteristics with temperature is somewhat unexpected, for in good quality material we would have anticipated a larger variation of the low field mobility. The results are presumably influenced by the fairly high trap density of the bulk material used. At all events we would expect that the qualitative variagions observed for the dependence of the threshold field and mobility on temperature would hold for different types of GaAs.

It should be noted that all our results have been taken with high-resistivity material, whereas in practical Gunn devices relatively low-resistivity material is used. However, in the presence of phonon scattering only the velocity-field characteristic should be independent of the material. When the impurity scattering becomes important, the velocity-field characteristic should be essentially independent of conductivity, in the high-field range, as has been suggested by Bott and Hilsum.[15] They show that, at high field, where the temperature of the electrons is high, the effect of impurity scattering should be negligible compared with that due to optical phonons unless the impurity density is extremely high. Consequently the velocity-field characteristic at high fields should be essentially independent of doping level, impurities present, and hence conductivity. At low fields the velocity-field characteristic should be de-

[20] A. Sher and K. K. Thornber, Appl. Phys. Letters **11**, 3 (1967).
[21] W. Spicer (private communication).
[22] F. H. Pollak, C. W. Higginsbotham, and M. Cordona, J. Phys. Soc. Japan **21**, 20 (1966).

pendent of the impurity density. However, if we consider two materials of low and high resistivity, respectively having the positive mobility limited to the same common value by impurity scattering, we may expect that the effect of the scattering mechanism will be identical too on the rest of the velocity-field characteristics. Furthermore, the introduction of an additional scattering mechanism will cool down the electrons and hence the threshold field should increase when the positive mobility decreases. In conclusion, all these considerations lead, not to a unique velocity-field characteristic, but to a family of them shown qualitatively in Fig. 9 and from experimental results in Fig. 5, where the variable parameter is the positive mobility. In particular, all materials having the same positive mobility should have the same velocity-field characteristics independently of their resistivity.

This conclusion is supported by the work of Kino *et al.*,[9] who studied the space charge wave propagation and field variation in subcritically doped 600–3000 Ω cm material. They found that the propagation constant varied as predicted from theory, thus confirming that our measured velocity-field characteristic is reasonably accurate in the range from threshold to 11 kV/cm for 600 and 3000 Ω cm material.

The practical effect of using material which has a high impurity content will be to leave the velocity of electrons at high field essentially unchanged but to lower the electron velocity at threshold, thus lowering the so-called "peak-to-valley" current ratio in a given oscillator.[1]

The measurements of diffusion which have been carried out are in good qualitative agreement with the theory by Butcher and Fawcett[4] but indicate higher diffusion rates than the theory predicts. We would expect that both the theory and the experiment would provide more inaccurate estimates of this parameter than of the drift velocity. However, it would appear from the domain theory of Butcher *et al.*[23] and a similar domain theory of Owens and Kino[24] based on the experimental results of this paper, that a higher diffusion rate than the theoretical prediction[4] is required to obtain agreement with measurements of domain shapes[25] in Gunn oscillators.

The method used here makes it possible to measure very fast trapping times in the nsec range. Our results indicate that the trapping time and trapping time variation with field can vary widely from sample to sample of GaAs, even with pieces cut from the same slice of material. In the high-quality IBM bulk material used in most of our experiments, we have found that the trapping rate is maximum near threshold field. Trapping-time measurement has been taken on the Monsanto material used by Chang and Moll.[7] Better agreement with their velocity-field characteristics is obtained where these measurements are used to interpret their data.

The method used here is essentially a modification of the Shockley-Haynes technique for use with semi-insulating material and very rapid pulse times. It can also be used to inject minority carriers into a high-conductivity semiconductor. We are at present involved in carrying out such measurements with other III–V materials, for which the recombination rates are too great to employ the normal Shockley-Haynes technique.

If better quality semi-insulating GaAs material becomes available, it would be interesting to extend these measurements to employ longer samples so as to determine the velocity-field and diffusion-field characteristics more accurately than we have been able to do heretofore.

ACKNOWLEDGMENTS

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APPENDIX A: ELECTRIC-FIELD DISTRIBUTION ACROSS THE SPECIMEN

We have pointed out the importance of having a uniform electric field across the sample or, in other words, a constant drift velocity of the carrier in making accurate measurement of the velocity-field characteristic. The field distribution in the depletion region of a Schottky barrier is easily obtained by integrating Poisson's equation. Assuming that the variation of the electric field is one dimensional and that the space charge producing this variation arises from the presence of a constant net density $N_D{}^+$ of completely ionized donor in the I-GaAs, we obtained

$$E(x)=E_0+E_1(x/l-\tfrac{1}{2})\quad 0\leq x\leq w\,, \qquad \text{(A1)}$$

where

$$E_1=|QN_D{}^+/\epsilon|\,l\,.$$

For the majority of measurements reported here, to have a diode reversed-biased to the point where $E_1 < 0.1E_0$ would correspond to a density of free carriers $n=2\times10^{10}$ cm^{-3} or a resistivity of approximately 4×10^4 Ω cm, assuming that these carriers are provided by a shallow fully ionized impurity. However, high-resistivity GaAs material is obtained by compensating the donor

[23] P. N. Butcher, W. Fawcett, and N. Ogg, in Proceedings of the Institute of Physics and Physical Society Conference on Semiconductors, Manchester, England, 1967 (unpublished); also (private communication).

[24] J. Owens and G. S. Kino (private communication).

[25] I. Kuru, P. N. Robson, and G. S. Kino (to be published).

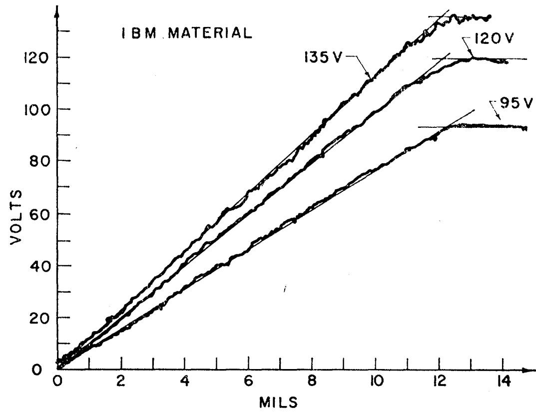

FIG. 10. Voltage distribution along the specimen.

N_D with acceptor N_A and the number of free carriers is $n=N_D-N_A$. Furthermore, according to Blanc and Weisberg,[26] this type of material has not only a shallow but also a deep donor which is not fully ionized at room temperature. Application of a Schottky barrier to such a material may result in the ionization of donors out of the deep level and the number of carriers will exceed N_D-N_A, resulting in large variation of the electric field across the specimen.

For this reason and also because electric-field variation may originate from crystal inhomogeneities or contact defects, the electric field inside the sample has been measured as a function of the distance. The method used, which was first described by Gunn,[27] consists of a measure of the potential distribution $V(x)$ over the plane surface of the specimen, employing a capacitive probe. The probe, consisting of a thin metallic layer insulated from ground plates by two very thin mica sheets, can be moved along the sample by a micrometer stage while the separation of the probe from the surface of the semiconductor is kept small and constant. The specimens were pulsed-biased and the induced voltage which appeared on the probe was measured with a high-input impedance-sampling oscilloscope. When thus measured, it has been shown by Kino[28] that the voltage on the probe V_p is proportional or equal to the potential on the semiconductor averaged over the probe width σx,

$$V_p=k\bar{\psi}, \tag{A2}$$

where the average potential $\bar{\psi}$ on the surface of the semiconductor is defined as

$$\bar{\Psi}(x)=\frac{1}{\sigma x}\int_x^{x+\sigma x}\psi dx. \tag{A3}$$

Probes with a resolution of less than 15 μm have been built and the different materials used in the measurement of the velocity-field characteristic have been investigated. As shown in Fig. 10, we were able to obtain a uniform electric field ($E=-dV/dx$) across the samples as predicted by the theory.

[26] I. Blanc and L. R. Weisberg, Nature **192**, 155 (1961).
[27] J. B. Gunn, in *Proceedings of the Symposium on Plasma Effects in Solids, Paris, 1964* (Dunod Cie., Paris, 1965).
[28] G. S. Kino, Proc. IEEE **55**, 90 (1967).

APPENDIX B: EFFECT OF FIELD NONUNIFORMITY ON CARRIER TRANSIT TIME

The transit time of a plane of carriers created by electron bombardment, drifting with a velocity $v(E)$ through a region of nonuniform electric field $E(x)$, is

$$t_t=\int_0^d \frac{dx}{v[E(x)]}. \tag{B1}$$

Assuming a small field variation $\Delta E(x)$ around an average value E_0, the actual drift velocity is simply obtained using the Taylor formula

$$v[E(x)]=v(E_0)+\Delta E(x)\partial v/\partial E \\ +\tfrac{1}{2}\Delta E^2(x)\partial^2 v/\partial E^2+\cdots, \tag{B2}$$

where, in the particular case considered here, $\Delta E(x)$ is a linear function of the distance

$$\Delta E(x)=(E_1/l)(x-x_0), \tag{B3}$$

and where x_0 is the position of the plane where the electric field E is equal to the average field E_0. Hence we have

$$t_t=\frac{1}{v_0}\int_0^l dx\left(1+\frac{E_1}{lv_0}(x-x_0)\frac{\partial v}{\partial E}+\cdots\right)^{-1}. \tag{B4}$$

Keeping in mind the assumption about $\Delta E(x)$, this expression can be greatly simplified to give

$$t_t=\frac{1}{v_0}\int_0^l dx-\int_0^l \frac{\Delta E}{lv_0}(x-x_0)\frac{\partial v}{\partial E}dx \\ -\int_0^l \frac{dx}{2v_0^2}\left[\frac{\Delta E}{l}(x-x_0)\right]^2\frac{\partial^2 v}{\partial E^2}+\cdots. \tag{B5}$$

If we define t_t^0 to be the transit time in the case of uniform electric field $E=E_0$ across the sample, we have, after integration,

$$t_t/t_t^0=1-[(\Delta E)^2/2v_0]\partial^2 v/\partial E_0^2. \tag{B6}$$

Note that the first-order correction of the velocity has no contribution to the expression for the transit time as long as the field variation is small. Even when this assumption is removed we can show that for GaAs the first-order term is smaller than the second-order one. From the above, we can immediately see that the error in the measure of the transit time is maximum when the average electric field E_0 is equal to the threshold field for which the second-order derivative is maximum and is estimated at 20 cm^3 $(V^2 sec)^{-1}$. In this most extreme circumstance the error on the measurement of

the velocity-field characteristic will be limited to less than 5%. We have then considered $t_t=t_t^0$ in the interpretation of the experimental results.

APPENDIX C: THEORY OF DIFFUSION MEASUREMENT

Consider a plane of carriers which is infinitesimally thin at $x=0$ and has total charge Q. After drifting for time t with the center of the bunch having a velocity v, the linear charge density ρ at a plane x will be[29]

$$\rho=[Q/(4\pi Dt)^{1/2}]\exp[-(x-vt)^2/4Dt]. \qquad (C1)$$

If we regard the cathode as corresponding to the plane $x=x_1$ and the anode to $x=x_1+l$, the current induced by the moving plane of carriers is given by

$$I=\frac{Qv}{(4\pi Dt)^{1/2}l}\int_{x=x_1}^{x_1+l}\exp\left[-\frac{(x-vt)^2}{4Dt}\right]dx. \qquad (C2)$$

It is convenient to make the substitution

$$x=vt+s(4Dt)^{1/2}, \qquad (C3)$$

which yields Eq. (C2) in the following form:

$$I=\frac{Qv}{\pi^{1/2}l}\int_{(x_1+vt)/(4Dt)^{1/2}}^{(x_1+l+vt)/(4Dt)^{1/2}}\exp(-s^2)ds. \qquad (C4)$$

The current pulse falls to zero during a time near $t=(x_1+l)/v$. At this time, the lower limit of the integral can, to a good degree of approximation, be regarded as $-\infty$. In the upper limit of the integral it is reasonable to regard the term Dt as being essentially constant during the fall time of the pulse, and thus replace it by $D(x_1+l)/v$. The time τ_F, the fall time of the pulse, can then be defined as the time for the pulse to fall from 95 to 5% of its full amplitude, and has been measured as such. This time can be evaluated in terms of the integral of Eq. (C4) by using tables of error functions. When this is done we find that

$$v^{3/2}\tau_F/[4D(x_1+l)]^{1/2}=2.32. \qquad (C5)$$

It follows similarly that the rise time τ_R is given by

$$v^{3/2}\tau_R/(4Dx_1)^{1/2}=2.32. \qquad (C6)$$

[29] R. A. Smith, *Semiconductors* (Cambridge University Press, New York, 1961), p. 251.

Combining Eqs. (C5) and (C6), we find that

$$D=(\tau_F^2-\tau_R^2)v^3/21.6l. \qquad (C7)$$

Note that a finite rise or fall time due to the circuitry does not affect, in principle, the evaluation of the diffusion constant. This is because, for an approximately Gaussian rate of rise, the square of the total rise time is approximately the sum of the squares of the individual contributions to it, and similarly for the fall time. Consequently, the circuit rise and fall times tend to cancel out of the expression for the diffusion constant.

It is necessary, also, to correct the fall time of the pulse for the effect of space charge. This is done as follows: The difference in field ΔE on each side of the space-charge layer, produced by electron bombardment, which is essentially the field difference between the points corresponding to 5 and 95% of the charge layer being present, is given by Gauss's law

$$\Delta E=Q/\epsilon A=Il/\epsilon Av, \qquad (C8)$$

where A is the area of the space-charge layer. The difference, due to space charge, in the velocities of the electrons at the two sides of the space charge layer is therefore

$$\Delta v=\Delta E(\partial v/\partial E), \qquad (C9)$$

and so the change in fall time of the pulse due to this effect is

$$\Delta\tau_F=T\Delta v/v=0.9(Il^2/v^3\epsilon A)\partial v/\partial E. \qquad (C10)$$

This correction must be added to the value of τ_F given by Eq. (C5) to give the best possible estimate of the diffusion constant. It will be seen that the correction is large and positive at low field, goes through zero at threshold where the velocity is maximum, and conversely is negative and small above threshold in the range of our experimental measurements.

When there is some trapping present, some of the electrons remain stationary for a time in the material and do not contribute any difference in fields between the front and back of the space charge layer, although they do affect its average velocity slightly. However, since the space charge correction is itself small under the conditions of our experiment, this effect can be neglected.

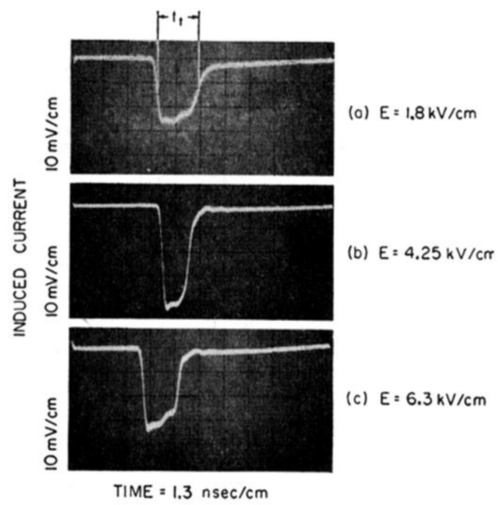

FIG. 3. Typical sample current wave form. The sample thickness is 300 μm and t_t corresponds to the transit time of the electrons across the specimen.