

Properties of a Free, Steadily Travelling Electrical Domain in GaAs

Abstract: Experiments are described on the travelling domains of high electric field which can exist in *n*-type GaAs. A brief discussion of the appearance of stationary domains near the cathode and of the nucleation and transient behaviour of travelling domains is given, but the main topic is the steady-state behaviour of travelling domains. Measurements are reported on the dependence of domain velocity, and of the voltage drop across the domain, on the field E_0 existing outside the domain. It is found that the velocity increases with E_0 , but the voltage decreases. The resulting negative resistance is seen to have important consequences for the stability of the domain in real specimens.

1. Introduction

The microwave oscillations of current which are observed¹ in *n*-type semiconducting GaAs have been shown² to be associated with the motion of domains of high electric field. Each domain is nucleated at a point (usually near the cathode electrode), and grows within a fraction of a nanosecond to an equilibrium form which it maintains as it travels towards the anode. The domain is extinguished when it reaches the anode and, if the applied voltage is high enough, a new one is nucleated at the original point; thereafter the process repeats cyclically. Thus, a key concept in understanding this phenomenon is that of a free, steadily travelling electrical domain. By this is meant a narrow concentration of electric field (Fig. 1), whose effects do not extend to the electrodes, or to any other irregularities in the specimen, and whose motion can be described as a rigid displacement at constant velocity.* In this view, the specimen of semiconductor acts mainly as an environment, characterized by various intensive parameters, permitting the existence of the domain. Extensive parameters, such as the shape, size, and terminal voltage of the specimen, are relevant only to the degree that they affect the intensive ones, as discussed later. In this paper we describe some initial measurements on the properties of such domains.

2. Experimental method

The experimental technique used, a modification of that described in Ref. 2, involved the probing of the time-dependent potential distribution $V(x, y, t)$ over the *xy*

surface of a specimen of GaAs, carrying a pulsed current of a few nanoseconds duration in the *x* direction. This potential distribution, which is assumed to be representative of that in the interior of the specimen, was inferred from the spatial variation of the charge induced on a small rectangular capacitor plate as it was moved parallel to the surface and a few microns away from it (Fig. 2). The plate was narrow (8 or 15 microns) parallel to the applied field, but broad (115 or 320 microns, respectively) transverse to it. A signal proportional to the charge itself (rather than its time derivative²) was obtained by the use of a high-impedance sampling oscilloscope system (Tektronix 4S3/P6038)[†].

After some modifications had been made to the sampling circuit to improve its transient performance under the unorthodox conditions of operation, a step-function response with a rise time of about 0.5 nsec, overshoot of 20%, and decay time-constant of 200 nsec was obtained (Fig. 3). Although the rise time was too long to show the finer details of domain structure, voltage levels could be measured with the desired accuracy, using channel B of the oscilloscope. Simultaneously, the current *I* through the sample was measured with channel A, using the auxiliary circuit shown in Fig. 2; care was taken to synchronize the two channels exactly. The instant t_s , measured with respect to the leading edge of the pulse, at which the current and potential signals were sampled by the oscilloscope, could be scanned over the time interval of

* It has been shown theoretically that such a domain is a solution of the equations describing a semiconductor exhibiting a bulk negative differential resistance,³ provided that an additional effect is included such as a finite response time for the conductivity,⁴ or the diffusion of electrons.⁵ The properties predicted on either of these theories are in general agreement with the present experiments.

† Compared with the previous technique of deriving a signal proportional to $\partial V/\partial t$ and then integrating the output of the sampling oscilloscope electronically, the method gives greatly improved low-frequency noise performance and flexibility in operation, at the expense of some degradation of rise time.

Figure 1 Potential and electric field distribution in a travelling domain (schematic). If the domain travels steadily with velocity c , the potential and field depend only on the moving coordinate ($x - ct$). The potential v_0 serves arbitrarily to define the position of the domain.

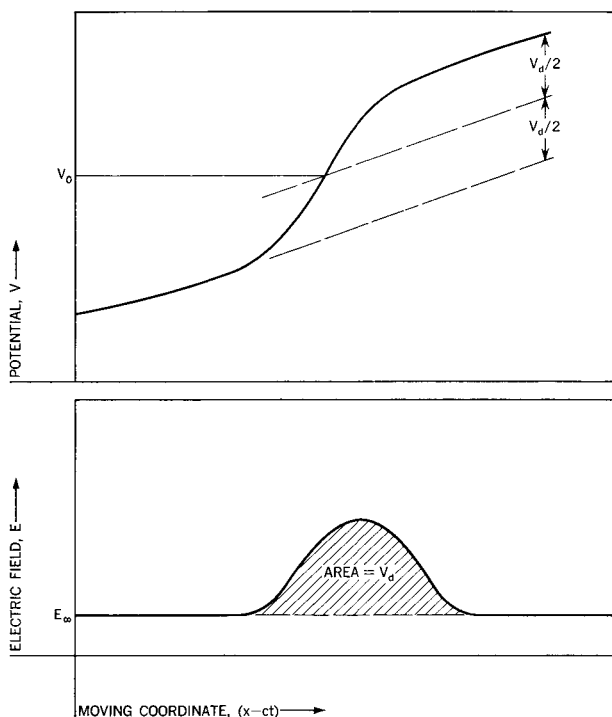


Figure 3 Step-function response of potential probing system (R_1 and P_1 of Figure 2). Time scale: 2 nsec per division.

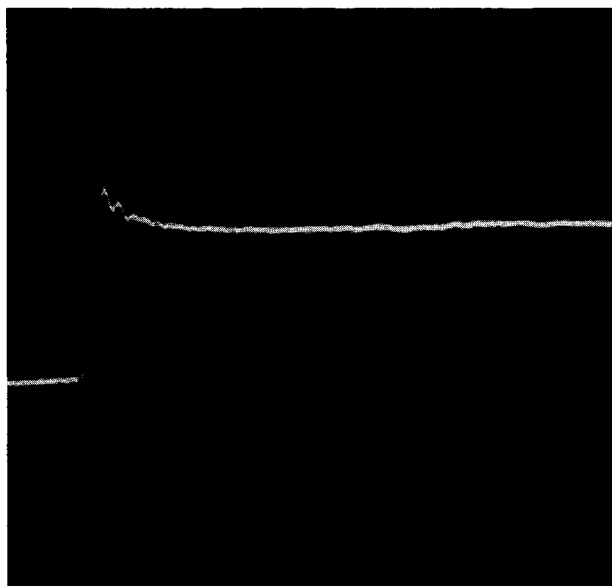
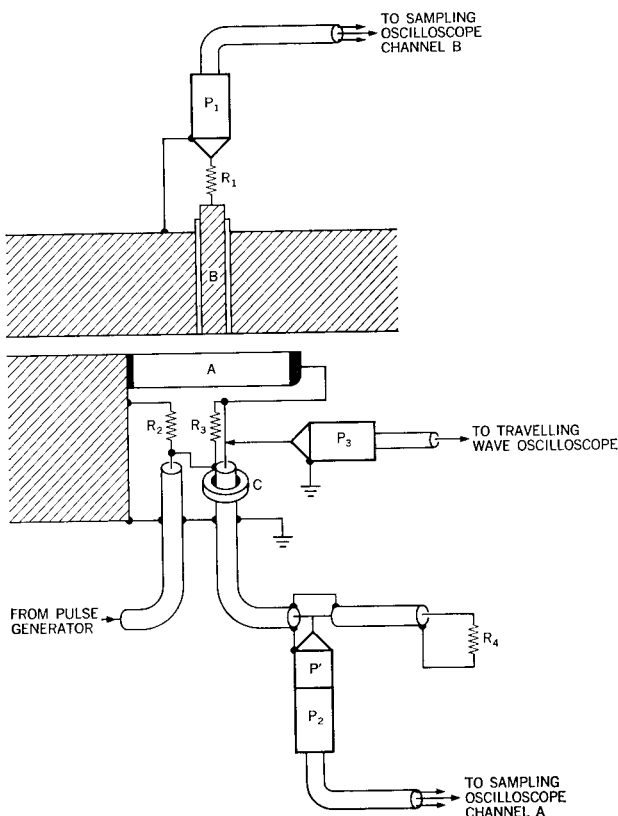


Figure 2 The experimental arrangement.

Legend—A: GaAs specimen; B: Capacitor plate; C: Ferrite core serving to isolate both sides of R_3 from ground.

P_1 and P_2 : High impedance sampling probes; P_3 : $10\times$ attenuator probe (connected only during calibration); P' : $10\times$ attenuator attachment.

R_1 : Damping resistor (100Ω); R_2 : Impedance-limiting shunt resistor (typically 10Ω); R_3 : Current-measuring resistor (typically 2Ω); R_4 : Termination (50Ω).



interest (as in a conventional sampling oscilloscope), or could be varied arbitrarily under the control of an external voltage.

The data on V could be displayed in several ways:

- The capacitive probe could be held fixed at the position x_0, y_0 , while t_s was scanned in the conventional way. This gave $V(x_0, y_0, t)$ and $I(t)$ as displays on the oscilloscope.
- The transverse coordinate y could be held fixed at y_0 , and the sampling time t_s fixed at t_0 , while the probe was scanned mechanically in the x direction. The signal from the sampling oscilloscope was used to give vertical deflection of an auxiliary oscilloscope, whose horizontal deflection was derived from the mechanical motion of the probe. When photographed,* this auxiliary display gave a representation of $V(x, y_0, t_0)$.

* The complete history $V(x, y_0, t)$ could be recorded by photographing this display on cine film, with t_0 increased by a few picoseconds between successive frames. The resulting slow-motion film was valuable in studying the nucleation and extinction of domains.

c) The sampling time t_s could be held fixed at t_0 , while x and y were scanned manually until some predetermined signal level V_0 was found. Thus, the V_0 -contour on a map of $V(x, y, t_0)$ could be traced out.

d) The time t_s could be changed back and forth between fixed values t_0 and $t_0 + \delta t$ on successive pulses, while x and y were held fixed. The output of the oscilloscope then consisted of a dc component, proportional to $\{V(x_0, y_0, t_0 + \delta t) + V(x_0, y_0, t_0)\}$, together with a superimposed square wave of amplitude proportional to $\{V(x_0, y_0, t_0 + \delta t) - V(x_0, y_0, t_0)\}$ and of frequency equal to half the pulse repetition frequency. By phase-sensitively rectifying this square wave, a dc signal proportional to the difference in potential at the times $t_0, t_0 + \delta t$, at a given point was obtained. By making δt large, the difference in potential before and after the passage of the domain could be plotted on an auxiliary oscilloscope against a signal proportional to current. Alternatively, by making δt small, a signal approximating $\partial V / \partial t$ could be obtained; by moving the probe so as to maximize this signal, the position of the domain at the instant $t_0 + \delta t / 2$ could be found with good accuracy.

3. Results

Measurements were made on samples of n -type GaAs of resistivity $\sim 0.7 \Omega \text{ cm}$ (part of Crystal RC28303 of Ref. 1), in the form of polygonal prisms with evaporated and alloyed metallic contacts on their end faces. The length of each sample was approximately 300 microns, and the cross section (uniform for each specimen) was in the range $(1-6) \times 10^{-4} \text{ cm}^2$.

3.1 Sub-threshold behaviour

At low current, the voltage between any two points in the specimen, or between the contacts, was found to be proportional to the current. Further, in most specimens, the distribution of potential was linear with distance, although slight departures were noted in a few cases. Thus it appears that the system (GaAs and contacts) was behaving in an ohmic, homogeneous fashion, without any significant junction potentials. However, when the current exceeded about 0.8 times the threshold value, a *stationary* high field domain appeared in the semiconductor immediately next to the cathode contact. The voltage across this "cathode drop" domain increased very rapidly and nonlinearly with current, and the width of the region could sometimes be seen to increase, as the current was raised to the threshold value. At the latter point the voltage across the 50 microns of material next to the cathode was sometimes as large as that across the remainder of the specimen. After a travelling domain had been nucleated, the cathode drop decreased but did not disappear completely (see Fig. 8, page 304); it was apparently controlled by the current flowing, rather than by the applied voltage. Con-

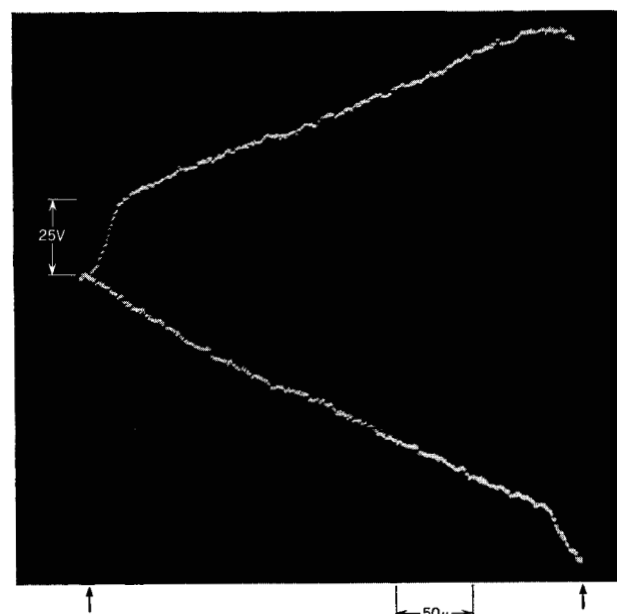


Figure 4 Potential distributions just below threshold, showing "cathode drops." For the upper curve, the cathode and anode are at the positions of the left- and right-hand arrows, respectively. For the lower curve, the connections were interchanged while keeping the specimen fixed.

siderable variation was found between specimens in the magnitude and width of the cathode drop. No similar stationary domain was ever observed near the anode, but when the current through the specimen was reversed, the cathode drop was found to move to the other electrode, in accordance with the reversal of polarity, Fig. 4. The importance of the cathode drop was illustrated by an experiment in which the dependence on current of the voltage between the contacts was compared with that of the voltage measured between the anode and a point 20 microns from the cathode. The results, illustrated in Fig. 5, showed that the bulk of the specimen behaves in a highly linear fashion, and that all of the curvature visible in a conventional I - V characteristic of the sample can be ascribed to the nonlinear behaviour of the cathode drop.

3.2 Nucleation

In almost every case, the nucleation of a travelling domain appeared to take place as an outgrowth of the cathode drop region. If the voltage across the sample was held fixed at the threshold value, the cathode drop region would appear to widen and shortly to divide into two parts, one of which would grow into a steadily travelling domain, while the other part would decrease in voltage and remain attached to the cathode. In one case, however, the travelling domain was found to nucleate near the center of the specimen, in a region of apparently constant

field. Thus the inhomogeneous field produced by the cathode drop is not always necessary for domain nucleation.

A curious dependence of the nucleation process on the rate of change of current near threshold was found in one specimen. If the threshold was crossed rapidly, the new domain formed as a plane parallel to this surface, and travelled steadily to the anode. On the other hand, if the threshold was crossed slowly, the new domain appeared, again in approximately plane form, but at an angle to the cathode. This skewed domain then travelled steadily to the anode, maintaining its orientation unchanged. Thus, by exploring the V_0 contour, it was possible to observe either of two types of domain, parallel or skewed, travelling steadily at the same place in the same specimen under the same conditions of applied voltage, Fig. 6. When a skewed domain was observed using the usual probe electrode, which was narrow in the longitudinal direction and wide in the transverse, and the electrode was set parallel to the cathode, then a distorted view of the potential distribution was obtained. The average potential, as measured by the probe, changed only slowly as the probe was moved over the domain, which consequently appeared to be much wider than it was in reality. When the probe was rotated to correspond with the domain angle, no difference could be observed between the parallel and skewed domains.

3.3 Domain velocity

The velocity of the free, steadily travelling domain was measured by timing its motion between known points in the specimen. These points were established by measuring the movement of the probe relative to the specimen with a

mechanical dial indicator gauge. The occurrence of the maximum value of $\partial V/\partial t$, observed as discussed in Sec. 2 (item d), was arbitrarily taken as marking the arrival of the domain at a given point. The changes in the sampling time t_s required to give this maximum at different points were controlled and measured by a ten-turn potentiometer which had been calibrated against a delay line. Compared with measurements of the period of the current waveform, this method is free from errors introduced by a possible delay in nucleation; as the measured changes in velocity are quite small, such errors could be important.

The voltage applied to the specimen (an extensive parameter) was used as a convenient variable to control the properties of the domain, but is not of fundamental significance. The most significant intensive parameter would appear to be the electric field E_∞ to which the domain is asymptotic (Fig. 1). This field was deduced from the changes in potential measured (see Section 2, item (b)) as the probe was moved over a region of the specimen not including the domain. Considerable care was needed in the choice of this region, particularly when the voltage across the domain was a large fraction of the total specimen voltage. There were two reasons, the first being that the sudden large change in potential which occurred as the domain passed a given point gave rise to an overshoot in the response of the sampling probe. This overshoot, although a small fraction of the change, could be comparable with or larger than the true potential at that point. The error decreased as time passed and the domain moved on, but this fact meant that at a given time t_s , the error was a function of position x_s . Thus an entirely erroneous value

Figure 5 Sub-threshold current-voltage characteristics of the specimen of Figure 4. Curve A: Voltage measured between anode and cathode contacts. Curve B: Voltage measured between anode and a point about 20 microns from the cathode. Note linearity of Curve B up to threshold (end of curve).

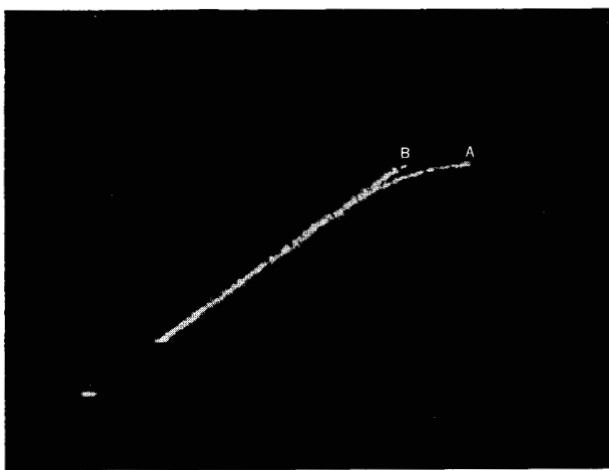
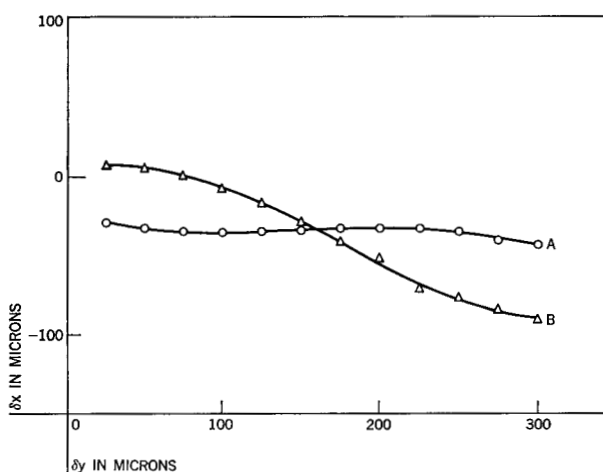


Figure 6 Map in the xy plane of the equipotential V_0 (defined in Figure 1), which locates the electrical center of the domain. Curve A: Threshold passed rapidly. Curve B: Threshold passed slowly. Note rotation by an angle $\sim \sin^{-1} 0.5$ in the latter case.



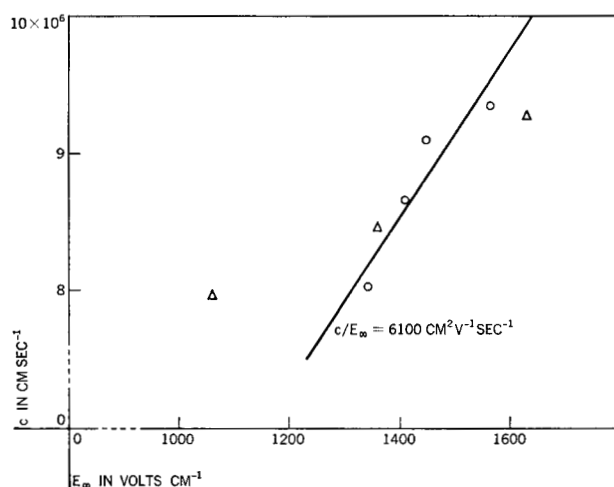


Figure 7 Measured dependence of the velocity c on the asymptotic field E_∞ for two specimens.

of E_∞ might be deduced if measurements were made within 50 microns behind the domain. The second reason was that, if measurements were made on the region of the specimen between the domain and the live (ungrounded) electrode, the large mean potential in this region meant that small changes with distance in the sensitivity of the probe (due to changes in spacing) could give rise to significant variations in the apparent potential. These variations were indistinguishable from those due to the field in this region, and gave rise to a large error. In view of these two difficulties, the most reliable measurements of E_∞ were those made between the domain and the anode when the latter was grounded. The absolute calibration of probe sensitivity was obtained for each run by measuring the signal obtained with the probe next to the live contact, with the other grounded. This was compared with the voltage measured between the live contact and ground with a travelling wave oscilloscope. The latter was used as a null instrument to indicate the equality of the signal and a known dc voltage.

In one specimen, the constancy of the domain velocity c over a major part of the specimen length was checked, at a given applied voltage, by making measurements every 25 microns. The curve of arrival times *vs.* position was found to depart from a straight line by less than 25 psec in a range of about 2 nsec. Subsequent measurements, on this and other specimens, were made by timing the domain only between two positions separated by 100 microns. Results obtained in this way are shown in Fig. 7 for two different specimens. In this figure, the absolute accuracy of the velocity measurements is thought to be quite good, as the measurements of time and distance could be made with good precision in terms of external standards. The values of E_∞ are subject to greater uncertainty (probably $\pm 5\%$) because of the number of inter-

mediate steps required for calibration. For the first set of points (triangles), an additional error may have been introduced, because for this specimen E_∞ could be measured only behind the domain. Overshoot errors, which would tend to magnify the variation of E_∞ , may not have been eliminated completely in this case, even though the measurements were made as far behind the domain as possible. For the second set (circles), E_∞ was measured ahead of the domain, with the anode grounded; thus the accuracy should be improved. However, because of the possibility of residual errors, and the limited range covered in the experiment, no conclusion can be drawn about the proportionality (or otherwise) of c and E_∞ . On the other hand, there is no doubt that dc/dE_∞ is positive. The average value of the "domain mobility" c/E_∞ given by the measurements is about $6100 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$.

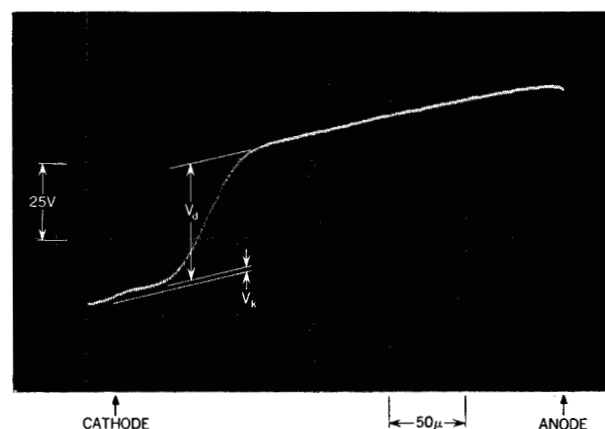
3.4 Domain voltage

A complete description of the electrical properties of the moving domain would require a measurement of the field distribution $E(x - ct)$. Such measurements are, however, beyond the spatial or temporal resolution of the present technique. A related variable which is accessible is the domain voltage V_d , defined by

$$V_d = - \int_{-\infty}^{\infty} (E - E_\infty) d(x - ct).$$

This represents simply the additional voltage across the specimen which is due to the presence of the domain, over that which would exist, in its absence, at the same values of current and E_∞ . Its measured value should be unaffected by the low resolution of the experiment and the overshoot in the oscilloscope transient response should not introduce serious errors. Measurements of V_d were made by two alternative methods on a number of specimens.

Figure 8 Typical potential distribution, showing measurement of domain voltage V_d . Note vestigial cathode drop remaining even above threshold.



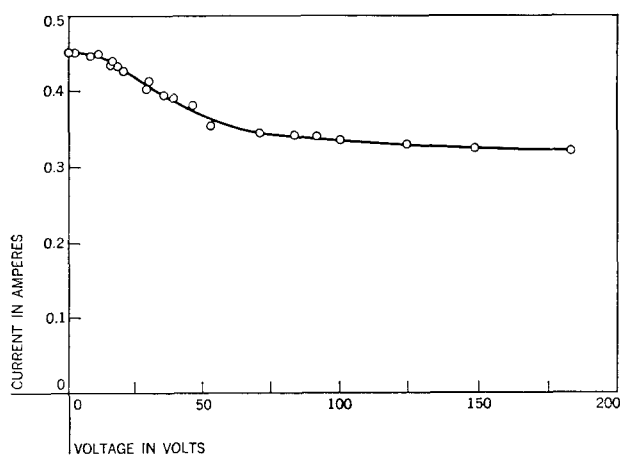


Figure 9 Relation between current and domain voltage V_d , measured by point-by-point technique.

In the first method, the potential distribution $V(x, y_0, t_0)$ was photographed, according to Section 2 (item b), and the current through the specimen at the same instant was measured. The process was repeated for a number of different values* of applied voltage. On each photograph, parallel lines were drawn, asymptotic to the potential distribution on either side of the domain. The vertical distance between these lines gives V_d (Fig. 8). Calibration of the probe was carried out as described in the preceding section, and the values of V_d were plotted against I , as in Fig. 9.

In order to reduce the time involved, and to improve the accuracy of measurement, an alternative method was devised which allowed the relationship between I and V_d to be plotted directly. In it, the probe was fixed in a convenient position, and the value of V_d was obtained from the sudden change in potential as the domain passed by. This change was measured by sampling the potential at two times separated by $\delta t = 1$ nsec; from this was derived a dc signal proportional to the difference, as discussed in Sec. 2 (item d). Simultaneously, the steady current I was measured at the same two instants $t_0, t_0 + \delta t$, with the other channel of the sampling oscilloscope. An auxiliary oscilloscope was arranged to be deflected vertically by the I signal, and horizontally by the V_d signal. When the amplitude of the applied pulse was varied manually, the auxiliary oscilloscope traced out the I - V_d characteristic of the domain, which was photographed (Fig. 10). Calibration was carried out with a known change of voltage, measured as before, which was arranged to occur between t_0 and $t_0 + \delta t$. In order to relate them to a more meaningful variable, the data were also plotted against E_∞ by scaling the current axis according to measurements of the linear

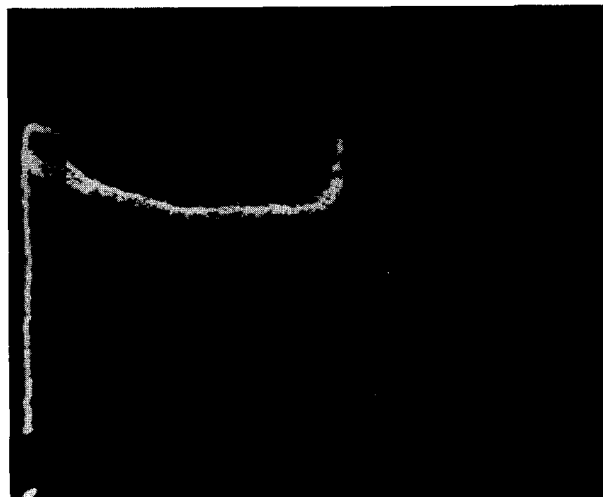
relationship between I and E existing below threshold. It was verified that this scaling applied also to the relationship between I and E_∞ above the threshold.

The agreement between the two methods will be seen to be quite good. Both show that the I - V_d characteristic of the domain is that of a voltage-controlled negative resistance. The current axis has to be regarded as a part of the characteristic, for the absence of a domain ($V_d = 0$) is a perfectly meaningful operating condition for the specimen of semiconductor. In both methods of measurement, it is found that when V_d rises above a certain limiting value V_L , then the motion of the free domain becomes unsteady. At constant applied voltage, the current increases with time, and the domain begins to undergo random changes of shape and velocity. This current increase has been shown by Heeks⁶ to be associated with the onset of light emission from the specimen, and plausibly ascribed by him, following Chynoweth, to an avalanche ionization process. It causes the vertically rising segment shown at the right of the characteristic in Fig. 10. In the present case, the limiting voltage is found to vary from specimen to specimen over the range 115–180 V.

3.5 Domain transients

The data of Figures 9 and 10 describe only the steady-state behaviour of the free domain. To give a description under conditions of changing current and voltage, additional experiments would be needed. Ideally these might consist of measurements of the admittance of the domain

Figure 10 Typical oscilloscope trace, showing direct measurement of domain current-voltage characteristics. The origin for both scales is the spot at the lower left corner. Horizontal sensitivity: 21.7 V per division. Vertical sensitivity: 115 mA per division. The vertical deflection is also proportional to the asymptotic field E_∞ . The scale is 292 V cm^{-1} per division.



* For the lower values of applied voltage, "triggered" operation² was used, in which the applied voltage was reduced to the desired value immediately after the nucleation of the domain at a higher value.

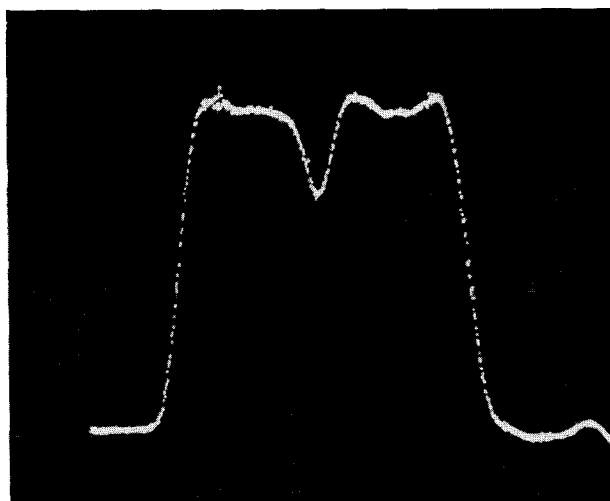


Figure 11 Applied anode voltage pulse with dip. Time scale, 1 nsec per division.

(defined as the complex ratio of the ac component of current to the corresponding component of domain voltage), as a function of frequency. Such experiments were not attempted in the present work, but a preliminary idea of the time constants involved was obtained by applying to the specimen a rectangular voltage pulse with a superimposed spike or dip about 0.5 nsec long (Fig. 11). To eliminate any possible error introduced by displacement currents through stray capacitances in the circuit, or by a lack of synchronization between current and voltage measuring channels, the current was inferred from the variations of voltage between the grounded cathode electrode and a fixed point in the specimen behind the domain. Since these variations were quite small, the change in domain voltage was given approximately by the voltage waveform at a second fixed point ahead of the domain.

Results of this experiment are shown in Fig. 12. The upper trace (A) shows the voltage variation at a point 250 microns away from the cathode; the point corresponding to the dip in applied voltage (Fig. 11) is marked by an arrow. The lower trace (B) in Fig. 12 shows the waveform at a point 100 microns from the cathode. The rise in voltage at this point produced by the rise in current resulting from the decreased domain voltage is again marked with an arrow. There is a definite delay in this case between the current and voltage changes. Measurement by means of the calibrated time-delay potentiometer showed that the current lags the voltage by 0.3 nsec. In the present case, the applied voltage was decreased to the minimum value at which the domain could be revived reliably when the voltage rose again; at any lower value, there was a tendency for a new domain to be nucleated at the cathode. If the minimum voltage was raised appre-

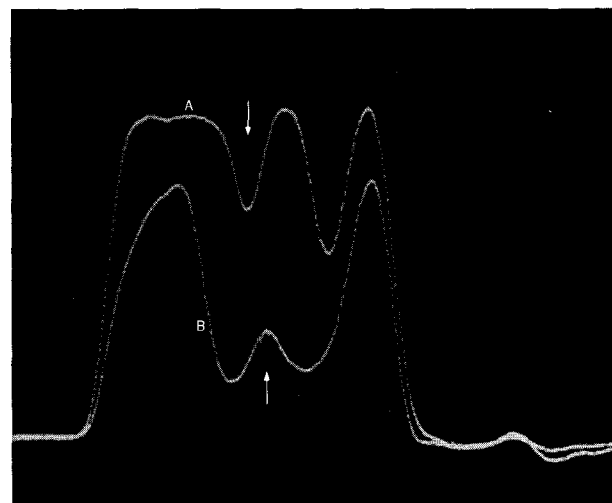
ciably, or if the transient change was made an increase rather than a decrease, the delay in current response became too small to measure. This suggests that the time lag involved decreases as domain voltage increases.

3.6 Aberrations

Apart from the nucleation away from the cathode, mentioned in Section 3.2, other isolated instances of atypical behaviour were observed. In one case, the domain appeared not to fill the whole cross section of the specimen until it reached about half-way to the anode, when it expanded abruptly; at the same time, the current decreased and the domain voltage appeared to rise. When operated with reversed polarity, the same specimen showed no anomalies of domain propagation, but in both directions the rather large cathode drops showed transverse variations. No longitudinal variations of E were observed below threshold. It seems likely that this specimen had large longitudinal and transverse variations in its electrical properties.

In another case, no changes in domain voltage were observed during operation at constant applied voltage, but the current varied as the domain moved. The current waveform was a sawtooth, whose time sequence reversed when the polarity was changed. For one direction of flow, the current fell rapidly when the domain was nucleated, and rose slowly as it approached the anode; for the other, it decreased slowly after nucleation, and rose suddenly as the domain reached the anode. This kind of behaviour

Figure 12 Voltage waveforms measured at 250 microns (A) and 100 microns (B) from the cathode. The dip in Curve A (arrow) corresponds to the dip in the applied voltage pulse (Figure 11); the rise in Curve B (arrow) corresponds to the resulting rise in current. The delay between the two events indicates a lag in the response of the domain, which, at the material time, is between the two measurement points. Time scale: 1 nsec per division.



might be caused by a resistivity gradient which is mainly longitudinal.

None of these atypical specimens was used for the measurement of domain properties.

4. Discussion

4.1 Sub-threshold behaviour

The cathode drop is a new feature whose existence has not previously been recognized. Although in these experiments it has never been found to be absent, it is not known whether it is an inherent property of a low-resistance contact to GaAs, or is in some way the result of certain fabrication techniques. For example, the process of alloying a metal contact might give rise (e.g., by the diffusion of Cu) to a thin layer of increased resistivity material immediately next to the metal. Alternatively, it may be that the current is carried only by a large number of small patches, which together make up something less than the geometrical area of the contact. The resulting concentration of current would bring about an increased electric field, especially when the differential mobility is small. Neither of these mechanisms would, by itself, explain the disappearance of the excess field when the polarity is reversed or explain the changes in its size. Quite probably, free space charge is also involved. More work on this question is obviously needed.

Independently of its origin, the cathode drop may by its presence explain some features of previous work.¹ If it were present in the specimens studied earlier, despite the difference in contact process, then it would be possible to explain both the increase in the apparent value of the threshold field, and the increased curvature of the I - V characteristic, which were observed as the specimen length was decreased. Thus, if the electric fields near the cathode and in the interior of the specimen remain fixed at their threshold values while the specimen is shortened, then the voltage between the contacts will decrease less than proportionately, and the apparent field will therefore increase. As it has been shown in this paper that substantially all of the curvature of the over-all I - V characteristic is due to the nonlinearity of the cathode drop region, it follows that the increasing fraction of the voltage which this region contributes must increase the apparent curvature. Moreover, this result implies that, contrary to the case of germanium,⁷ deductions about the properties of hot electrons in GaAs can be made from measurements on two-terminal specimens only if the contact areas are enlarged.

4.2 Skewed domains

The dependence of domain direction on rate of rise of electric field, which was observed on one specimen, might be explained if a small transverse gradient of electric field were assumed to exist near the cathode. Then, if the applied

voltage rises slowly, the threshold field will be reached first at one edge of the cathode contact, and a domain of small transverse extent will be nucleated there. The additional field in this domain will divert current to neighbouring regions of the cathode, which will in turn cause the field in them to rise above the threshold. Thus the domain will spread across the whole cathode, but with a finite velocity c_t . At the same time, the domain will be moving normally to itself with its usual velocity c , but those parts of the domain which were nucleated first will have travelled furthest from the cathode. Consequently, the domain will leave the cathode at an angle of inclination $\sin^{-1}(c/c_t)$. On the other hand, if the applied voltage rises sufficiently rapidly, the field over the whole cathode surface will be brought above threshold in a time which is short compared with the time required for the domain to spread transversely, and the domain will be nucleated substantially parallel to the cathode surface. From Fig. 6, it may be calculated on the present hypothesis that the nucleation velocity c_t cannot have been greater* than about 2×10^7 cm sec⁻¹ when the skewed domain was nucleated. The existence of skewed domains, and the possible existence of a finite nucleation time, show that it is unsafe to draw detailed inferences about the domain width and velocity from measurements of the specimen current alone.

4.3 Domain velocity

It would be interesting to compare the domain "mobility" (c/E_0) of ~ 6100 cm² V⁻¹ sec⁻¹, deduced from the data of Fig. 7, with the electron mobility in the specimen. Unfortunately, the absolute value of the latter is not known, though it is clear from data like that of Fig. 5 that it is substantially independent of electric field up to the threshold. Measured values of the Hall mobility in GaAs are notoriously variable even on different specimens cut from the same sample, and are frequently less than the theoretically calculated⁸ (and sometimes observed⁹) value of about 9000 cm² V⁻¹ sec⁻¹ for the lattice mobility at 300°K. It does not seem to have been established whether the observed low and variable values are the result of a genuine decrease in the microscopic mobility (e.g., are the result of compensated impurity scattering) or whether they are merely the result of inhomogeneities of resistivity. The latter are known always to decrease the apparent Hall mobility below the true value. Thus if the lattice scattering value is taken for the electron mobility, the domain moves more slowly than the electrons, but if the Hall value, 5500 cm² V sec⁻¹, measured on another specimen from the same crystal, is taken, the domain moves slightly faster. The question must be regarded as open at the present time.

*This is a maximum value, because the angle of inclination measured with the probe represents only the projection of the domain on the lateral surface of the specimen. If there is any inclination to this surface, the true angle will be greater.

A minor but somewhat surprising point is that when the voltage applied to the specimen is increased, V_d increases, but I , and hence E_∞ and c , decrease. Thus the domain travels more slowly as the applied voltage rises.

4.4 Domain voltage and the behaviour of finite specimens

The domain characteristic (the relation between I and V_d) is the key to understanding what will happen when a steady emf V acts in a circuit containing a specimen of length L , and possibly an external resistance R_0 . For V must be equal to the sum of the voltages across the various parts of the circuit, but I is the same for all. Neglecting for the moment the cathode drop, we have

$$V = V_d + LE_\infty + IR_0 = V_d + I(R + R_0),$$

where R is the resistance of the specimen below threshold. Thus it is possible to make a load-line construction by drawing, on a graph of the domain characteristic $I(V_d)$, a line of slope $-1/(R + R_0)$ intersecting the voltage axis at the value V (Fig. 13). The operating conditions are then determined by the intersection of this line with the domain characteristic ODAFBC. If V is small (e.g., V_1 in Fig. 13), the only intersection will be one such as D, on the branch OA, and no domain will be formed. When V is increased, the specimen will continue in a quiescent state until the intersection of the load line with the axis passes above the peak A of the domain characteristic. Then a domain will be nucleated, and the steady operating point will move to B, which thus represents the conditions existing immediately above threshold. The emf will then be given by V_T , and the domain voltage by V_{dT} . If V is increased further, the operating point will move along BC, until finally at C, V_d exceeds the limiting value V_L and the domain motion becomes unsteady. The corresponding value of I is I_L , and of V is $V_{\max}$. During this unsteady motion the current may rise above I_T , and in that case an additional domain can be nucleated at the cathode. On the other hand, if V is decreased, the operating point will move back until the point F is reached, where the load line is tangent to the characteristic. Then V has the lowest value $V_{\min}$ at which a domain can be maintained. Any further decrease will eliminate the intersection of the load line with the branch AC, leaving as the only possible operating point its intersection with OA. The domain is thus extinguished. In the case shown, for which the condition $(R + R_0) > -dV_d/dI$ holds over the region AF, the operating point can never lie in that sector, which is thus inaccessible to measurement.* In sufficiently short specimens, however, the whole domain characteristic may become accessible.

By contrast, if the slope of the load line is decreased, as

* Even if the operating point could be maneuvered into AF, it would, according to the well-known properties of a voltage-controlled negative resistance, be unstable.

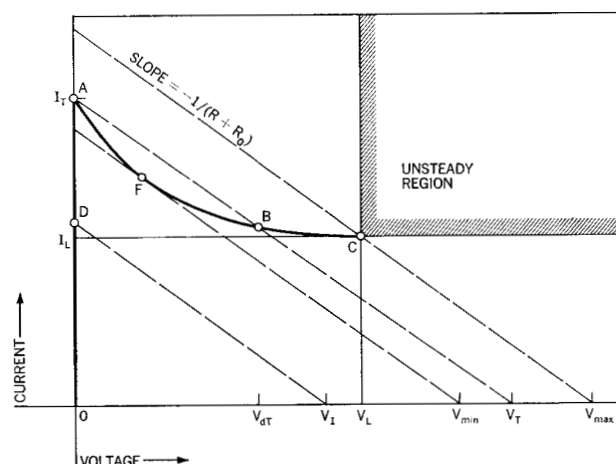


Figure 13 Domain characteristics (schematic) showing load line construction. See text.

a result of increasing either the external resistance or the length of the specimen, then the points B and F will move closer to C. In this process there will come a stage where B passes C and moves into the unsteady region. Then, even at threshold, a steadily travelling domain cannot exist, and the current waveform associated with spontaneously nucleated domains will become incoherent. Coherent triggered operation will still be possible, however, if the operating point can be moved back on to the steady branch by decreasing V below V_T . The inaccessible range AF is increased, of course, and in the limit may coincide with AC. In that case a steadily travelling domain cannot be maintained under any circumstances.

In the absence of cathode drop effects, the criterion for the existence of coherent oscillations under conditions of spontaneous nucleation can be written as follows:

$$R + R_0 < V_L/(I_T - I_L).$$

On making the substitution $R = \rho L/A$, this becomes

$$L + AR_0/\rho < V_L/(E_T - E_L),$$

where A is the cross section of the specimen, ρ is its resistivity, and E_T and E_L are the values of $E_\infty = \rho I/A$ corresponding to I_T and I_L , respectively. Thus there is a maximum length for coherent oscillation, even when R_0 is negligible. From the data of Fig. 10, this length is estimated to be about 0.3 cm, which is considerably greater than the observed value¹ of about 0.02 cm. However, it should be remembered that the existence of resistivity gradients, the cathode drop, or any external impedance, will make the specimen effectively longer. Hence the discrepancy is in the right direction, even though inexplicably large.

The dependence of the quantities V_L , E_T , E_L is not yet known but, in analogy with the behaviour of the avalanche

breakdown voltage of p - n junctions, space charge considerations suggest that V_L should increase with increasing ρ . Support for this idea is found in the comparison of our value of $V_L \sim 150$ V for $\rho = 0.7 \Omega \text{ cm}$ material with the value of 600 V found by Heeks⁶ for $\rho = 3 \Omega \text{ cm}$. If the variation of $(E_T - E_L)$ is less rapid than this, it is possible to understand why, for the higher value of resistivity, steady domain propagation can be observed in longer specimens⁶ than is the case for the lower value.

It should be noted that, according to the present results, V_d is not fixed by the specimen length, but depends also on other variables. Because of the curvature of the domain characteristic, and of the curvature of the load line produced by the cathode drop, even the value of V_{dT} should depend in a complicated way on L . The latter effect may prevent V_{dT} from falling below a limiting value, even in the shortest specimens. These ideas are contrary to those of Ridley,¹⁰ who suggested that V_d should be proportional to L . This last situation would be possible only if I were independent of V_d , and the load-line were straight.

Two results follow from the negative-resistance nature of the domain characteristic. In the first place, since the negative resistance is of the voltage-controlled type, a series connection of two domains will be unstable unless, at the operating point, one of them has a positive resistance which is sufficiently small. If both are in the negative-resistance region of the characteristic, one will grow at the expense of the other until a stable condition is achieved. In the present work, a positive resistance has been observed unambiguously only in the unsteady region, but it is possible that it may exist under other circumstances (e.g., in higher-resistivity material, where V_L is larger). This will explain why two domains seem never to coexist in the same specimen.

Finally, if the motion of the operating point in Fig. 13 is followed as a function of V , it will be seen that a specimen containing a free domain should exhibit an over-all negative resistance across its terminals. This expectation is confirmed by Fig. 14, which shows an ordinary sampled current-voltage characteristic, measured at a time when the domain is about halfway between anode and cathode. Apart from the details of the unsteady branch on the extreme right, the curve was found to be substantially independent of time, and hence of domain position, as long as the domain was free.

e) Domain reactance

The observed delay in the response of the current through the domain to a change in voltage means that, at high frequencies, the domain impedance $Z_d = R_d + jX_d$ is complex. The fact that the current lags the voltage indicates that the phase angle of the impedance is positive, a situation which one normally describes by an equivalent circuit involving an inductance; this is the natural descrip-

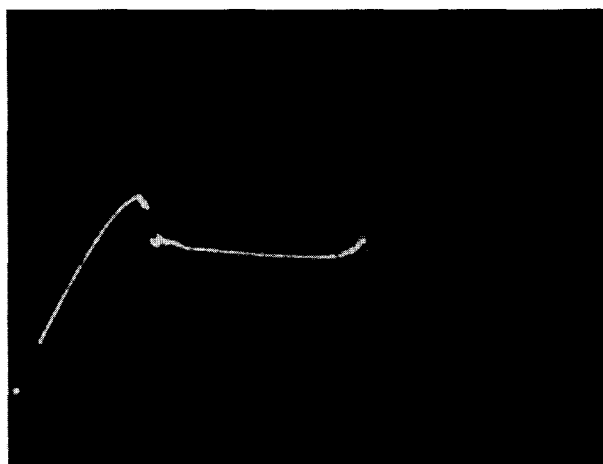


Figure 14 Terminal current-voltage characteristic of a GaAs specimen. The instant of measurement is chosen so that the domain which is formed above threshold is free. Note curvature below threshold due to cathode drop, negative resistance above threshold due to steadily travelling domain, and final rise of current due to unsteady motion. The origin is the spot at lower left. Sensitivity: uncalibrated.

tion of the tendency for the current to remain constant after a sudden change in voltage. Care is needed, however, in dealing with impedances whose real part is negative, since the phase angle is given by $\tan^{-1}(X_d/R_d)$. Thus, if R_d is negative, as here, a positive phase angle implies that X_d is negative. This condition, together with the finite value of R_d at zero frequency, suggests that the equivalent circuit for the domain must involve either a shunt capacitance which is positive, or a series inductance which is negative.

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