NEGATIVE DIFFERENTIAL CONDUCTIVITY

The Gunn effect is only one of several interesting things that can happen when current decreases with increasing electric field in a semiconductor.

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UNIQUE ELECTRICAL BEHAVIOR results when a system operates in a region of negative differential conductivity, where current density falls rather than rises with increasing electric fields. This type of conductivity is not infrequently found in semiconductors, where both factors that determine conductivity—density of carriers and their mobility (drift velocity developed per unit field)—may be easily varied. Under conditions of negative differential conductivity there is a tendency to enhance nonuniformities that would otherwise be damped. One of the many dramatic examples of such behavior is the Gunn effect.

Although negative differential conductivity has been familiar for many decades in certain types of vacuum and gas-discharge tubes, it did not arouse great interest until it was found in semiconductors. When the study of semiconductors was begun in earnest after the Second World War, researchers found that they could change the variation of current density j with field E. One method for doing this, pioneered by William B. Shockley, is by application of a field high enough to produce "hot carriers," that is, carriers with average energy higher than the thermal energy kT at zero field. The magnitude of the field required depends on the material and the lattice temperature, and may be less than 1 volt/cm at 4 K. More typically, however, it is a few thousand volts/cm at room temperature.

The demonstration that carrier heating was possible in a semiconductor, with consequent change in the differential conductivity dj/dE, caused speculation about the possibility of negative differential conductivity (NDC) and stimulated a search for it. However, the greatest prizes, such as the Gunn effect, came to those who were not consciously searching. Part and parcel of the discoveries, and the reason they were accidental, was that NDC causes some unique electrical behavior that had not been appreciated earlier.

More details of the work of Shockley and of other topics to be discussed here may be found in the first three references[1,2,3] and elsewhere. References to original papers are contained in these sources and in several bibliographies.[4]

Figure 1 illustrates the two basic types of negative differential conductivity. The type characterized by the N-shaped curve in figure 1a is called "voltage-controlled" NDC because of its behavior in circuits; the S-shaped curve in figure 1b represents current-controlled NDC.

Growth of nonuniformities

With NDC a departure from equilibrium such as a fluctuation of field or of current will tend to grow rather than dissipate. In a sample with the voltage-controlled type of NDC, consider a small nonuniformity of the field at some point such that the field upstream (as regards current flow) is higher than the field downstream. This nonuniformity may be caused by momentary deficiency of positive charge or accumulation of electrons, or by a permanent nonuniformity in impurity concentration or conductivity. If the differential conductivity of the sample is positive, a higher current will flow into the region than flows out, and any accumulated negative charge will be dissipated. If the differential conductivity is negative, however, a smaller current will flow into the region than out; more negative charge will accumulate and the original field discontinuity will be enhanced.

In a rectangular sample, as is ordi-

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narily used, the equipotentials must be planes perpendicular to the sides of the sample, and the tendency will be to build up a plane of negative charge, an electron accumulation layer, at the discontinuity. If the initial nonuniformity or fluctuation had been of the opposite sign, there would be a tendency for a layer of positive charge, that is, an electron depletion layer, to grow.

Imagine now a fluctuation in a sample with current-controlled NDC such that at some instant two adjacent lateral regions or filaments are carrying different currents. If the differential conductivity were positive, the filament with the higher current would have the higher field. A transverse current would then flow in such a direction as to equalize the currents. In a sample with NDC, however, the filament with the higher current would have the lower field, and transverse current would flow in the direction that increases the difference between the currents. Stability will be reached when the currents in the different filaments all correspond to the same value of electric-field intensity.

Thus different electrical behavior results from negative differential and positive differential conductivity: The field or current distribution tends to be nonuniform for negative and uniform for positive differential conductivity. The nonuniformity may be stationary or, particularly in the voltage-controlled case, time dependent. Time variations of the current may range from simple oscillations at a constant frequency to quite complicated behavior. All of these phenomena have been seen and studied in many materials, notably in cadmium sulfide by K. W. Böer and in gallium arsenide by J. B. Gunn.

In the phenomenon discovered by Gunn the nonuniformity is a high-resistance region or "domain" bounded on one side by positive charge and on the other by negative charge. It is generated at the cathode, moves down the sample with the electron drift velocity and leaves at the anode, thus starting the whole cycle again. These oscillations, observed upon application of a suitably high dc voltage and having a period equal to the length of the sample divided by the drift velocity of the electrons, constitute what is usuallly called the "Gunn effect." Sometimes, however, the term "Gunn effect" is used to describe all of the time-dependent behavior.

Mobility variation

In simple terms voltage-controlled NDC occurs in materials such as gallium arsenide because of the increase in effective mass of electrons at increased field values. These high-mass electrons have less mobility μ and contribute less to the current. Thus as one raises the field and more and more electrons go into the high-mass state one soon reaches a range of field values at which the current begins to decrease. The fundamental theory of band structure helps to explain this phenomenon.

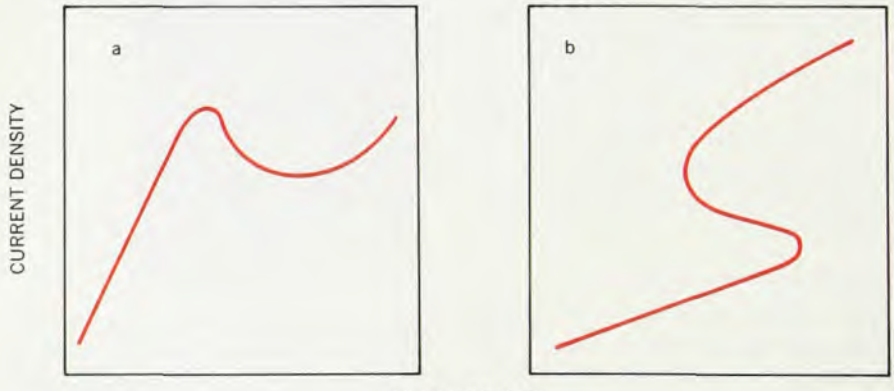
For a free electron the wave function can be taken as a plane wave, $\exp(i\,\mathbf{P}\cdot\mathbf{r}/\hbar)$, where $\mathbf{P}$ is the momentum, $\mathbf{r}$ the spatial coordinate and $\hbar$ is Planck's constant divided by 2π. The energy is then $P^2/2m_0$, m_0 being the free-electron mass. A plot of energy $\mathcal{E}$ versus P is a parabola through the origin. For a conduction electron inside a crystal a plane-wave function $\exp(i\,\mathbf{P}\cdot\mathbf{r}/\hbar)$ may still be used, but this is modulated now by a function having the periodicity of the lattice. The modulating function behaves around each nucleus like an atomic function, its nature depending on P. The quantity P no longer represents the electron momentum; potential variations cause the electron momentum to vary inside the crystal. Nevertheless P retains some properties of a momentum and may be used to characterize the wave function and energy of the electron. It is called the "crystal momentum."

In distinction to the free-electron case, the electron in the crystal has a finite, although very closely spaced, set of allowed values of P that lead to physically different behavior. The volume of P-space, centered at $P = 0$ and containing this set of P's, is called the "Brillouin zone."

The relation between electron energy and crystal momentum[5] interests us in the region accessible to our hot electrons, that is within about 1 eV of the edge of the conduction band. The energy dependence for materials such as gallium arsenide that show the Gunn effect is shown schematically in figure 2. The minimal energy, which will be taken as the zero of our energy scale, is at the center of the Brillouin zone. Around the minimum, the energy dependence is parabolic, resembling the free-electron case. The effective mass is the mass of a free particle with the same energy curve, being 0.07 times the electron mass for gallium arsenide.

At the edge of the Brillouin zone there is another minimum, an energy separation $\Delta\mathcal{E}$ above the conduction-band edge, and another region with parabolic variation of the energy. In this case the parabola is fatter, corresponding to a higher value of effective mass. The difference in mass arises from the difference in the modulating function, resulting in a changed interaction of the electron with the crystal lattice for crystal momenta near the higher minimum. The relation between $\mathcal{E}$ and P must be the same for all P's equivalent under symmetry operations, such as rotations, that leave the crystal in a position indistinguishable from its original position. Thus the energy curve will have the same parabolic region around the minimum at the edge of the zone for momenta in a number of directions.

At low fields essentially all the electrons will be in the central valley. As



NEGATIVE DIFFERENTIAL CONDUCTIVITY is characterized by regions of negative slope in plots of current density against field. The N-shaped curve (a) represents voltage-controlled, and the S-shaped curve (b), current-controlled NDC. —FIG. 1

the field increases and energy is fed to the electrons at a faster rate, they get hot. When an electron has energy greater than $\Delta\mathcal{E}$, where $\Delta\mathcal{E}$ is about 0.4 eV for gallium arsenide, it can make a transition to one of the upper valleys. To do so it must undergo a large change in crystal momentum by interaction with the lattice, usually by absorption or emission of a phonon with large crystal momentum. The transition process is rather probable, particularly when, as is the case here, the upper valleys provide many more states in a small energy range than does the central valley.

Investigating the threshold

Before the discovery of the Gunn effect these facts about the band structure were known and were recognized to imply the occurrence of negative differential conductivity. What was not entirely clear was how high a field would be necessary to cause the transfer of a sizable number of electrons into the upper valleys. Calculations required solution of the Boltzmann equation, which had been done for this system only in a crude approximation. Many, including Gunn, felt that at the threshold for the Gunn effect, about 3 kV/cm, electrons could not possibly be hot enough to get into the upper valleys in substantial numbers. Direct evidence that the upper minima are involved came from two experiments demonstrating that the threshold for the Gunn effect depends on the energy separation between the lower and upper minima.

In the first of these experiments, Andrew R. Hutson and four colleagues at Bell Laboratories[1] applied hydrostatic pressure to decrease the separation between the valleys and found that the Gunn threshold decreased. The electron-transfer mechanism must be working here because, with smaller separation, less energy would be needed for electrons to be transferred into the upper valleys.

The second method of varying the separation between minima took advantage of the fact that gallium arsenide and gallium phosphide form a continuous series of solid solutions. As one goes from GaAs to $GaAs_{0.5}P_{0.5}$, $\Delta\mathcal{E}$ decreases from about 0.4 eV to zero. A group at Stanford[1] found that the threshold voltage for the Gunn effect of a series of $GaAs_xP_{1-x}$ alloys decreased as x decreased from unity. When x was near 0.6, where the two sets of minima should be very close in energy, the oscillations vanished.

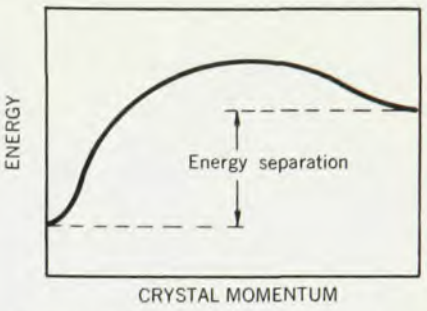
Under the impetus of the Gunn effect and the related experimental activity it engendered, theoretical calculations of electron distributions in high fields made great strides. These calculations, made with the aid of computers, are already greatly enhancing our knowledge of transport and band structure near the conduction- and valence-band edges of semiconductors. With these calculations it has become clear that the reason a substantial number of electrons can attain energies of about 0.4 eV in gallium arsenide at fields as low as 3 kV/cm is that, as long as they remain in the central valley, the electrons are progressively less hindered by the lattice vibrations.

Measuring the conductivity

The negative differential conductivity of a particular system is completely characterized by the variation of current density with field, in other words, by the curves in figure 1. Unfortunately, measurement of this curve is quite difficult, even if one avoids time-dependent behavior. Under almost all conditions, the nonuniform field distribution in the NDC range results in a redistribution of voltage that masks the NDC.[1,6] Observations show that, almost invariably, the current increases with voltage, although usually very slowly in the NDC range.

Various ingenious ways have been suggested to get around the effects of this redistribution of voltage. One way is to measure the current as a function of field in such a short time after the initiation of current flow that the redistribution has not yet taken place. In gallium arsenide, this time is less than a nanosecond. Jacques Ruch and Gordon W. Kino[2] employed a more successful technique, injecting a beam of electrons into a fairly well insulating sample, in which the field remains essentially uniform. They measured the time for the electrons to drift across the sample in a given electric field.

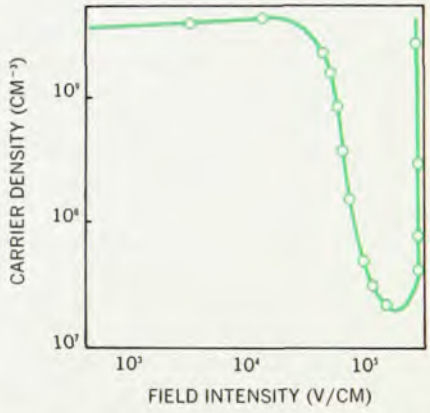
The Gunn effect arising from the electron-transfer mechanism has been found[3] not only in GaAs and $GaAs_xP_{1-x}$ but also in indium phosphide, cadmium telluride, zinc selenide, indium antimonide and $Ga_xIn_{1-x}Sb$. In indium antimonide the effect can be observed only for a nanosecond after the beginning of current flow.



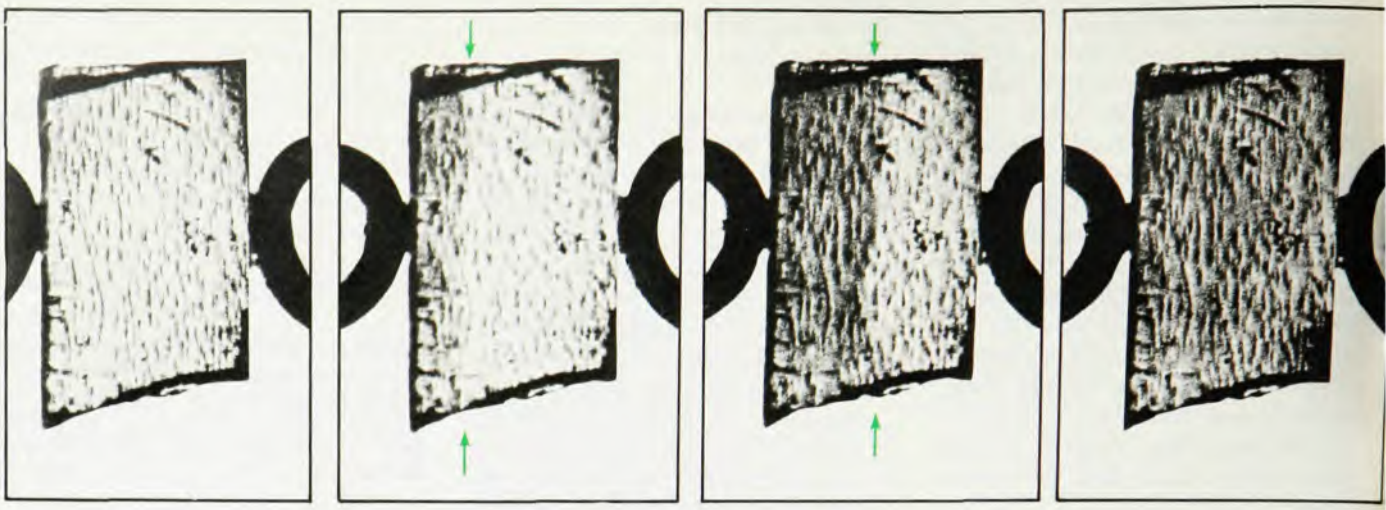
ENERGY DEPENDENCE of electrons shows two minima separated in energy, with lower minimum at zero momentum. Wider parabola at higher minimum means larger effective mass and greater density of states. —FIG. 2

Because the energy gap $\mathcal{E}_g$ between conduction and valence bands in this semiconductor is less than the separation $\Delta\mathcal{E}$, the process of impact ionization of the lattice competes with that of intervalley transfer, and dominates after a short time. Under sufficient hydrostatic pressure, however, the intervalley energy separation can be made less than the energy-band gap, and the Gunn effect predominates at all times.[3]

For similar reasons indium arsenide has displayed the Gunn effect only under uniaxial stress. Uniaxial stress also produces the Gunn effect in p-type germanium.[3] Although p-type germanium has a quite different band structure from the type we have been discussing, under appropriate stress it goes over into one with two sets of valleys, allowing the electron-transfer mechanism to operate.[1] N-type germanium has also shown the Gunn effect under various conditions of temperature and stress. In most of these



DRAMATIC DECREASE in carrier density of cadmium sulfide doped with silver and aluminum is attributed to the mechanism of field quenching. —FIG. 3



ABSORPTION OF LIGHT indicates regions of high field in this sample of doped cadmium sulfide, illuminated with light whose photon energy is less than or equal to the band-gap energy. As the applied voltage increases, the boundary between high- and low-field regions (indicated by arrows) moves across the sample. —FIG. 4

situations, although not all, NDC is clearly attributable to the electron-transfer mechanism.[3]

Carrier-density variation

Negative differential conductivity occurs in some semiconductors because the number of conduction electrons n decreases with increasing electric field. This decrease can occur in the presence of impurities or other defects with a capture cross section that increases with the energy of the carriers. Examples of such impurities are copper and gold in n-type germanium.[1] These centers, in the presence of an appropriate density of shallow donors, such as antimony, acquire two negative charges and therefore repel electrons. Heating the carriers increases their probability of tunneling through the Coulomb barrier to be captured and causes a substantial decrease in the concentration. NDC resulting from electron capture, perhaps mixed with the effects of mobility variation, has also been seen in high-resistivity gallium arsenide.[1]

Carrier density in cadmium sulfide decreases with increasing field E as fast as E^m, where m is greater than unity. Böer and collaborators,[3] attribute this behavior to "field quenching," a mechanism in which the field serves to free holes from hole traps so that conduction electrons can recombine with them. Although the parameters of the various trap levels involved are not well known, extensive study[3] of stationary domains has provided reliable information on the variation of carrier density with field. The variation measured by Böer and collaborators is shown in figure 3. Because the mobility does not vary much over the range of fields shown, figure 3 illustrates essentially the variation of conductivity with field. The same type of field-quenching mechanism may operate to produce NDC in zinc sulfide that has been doped with manganese.[1]

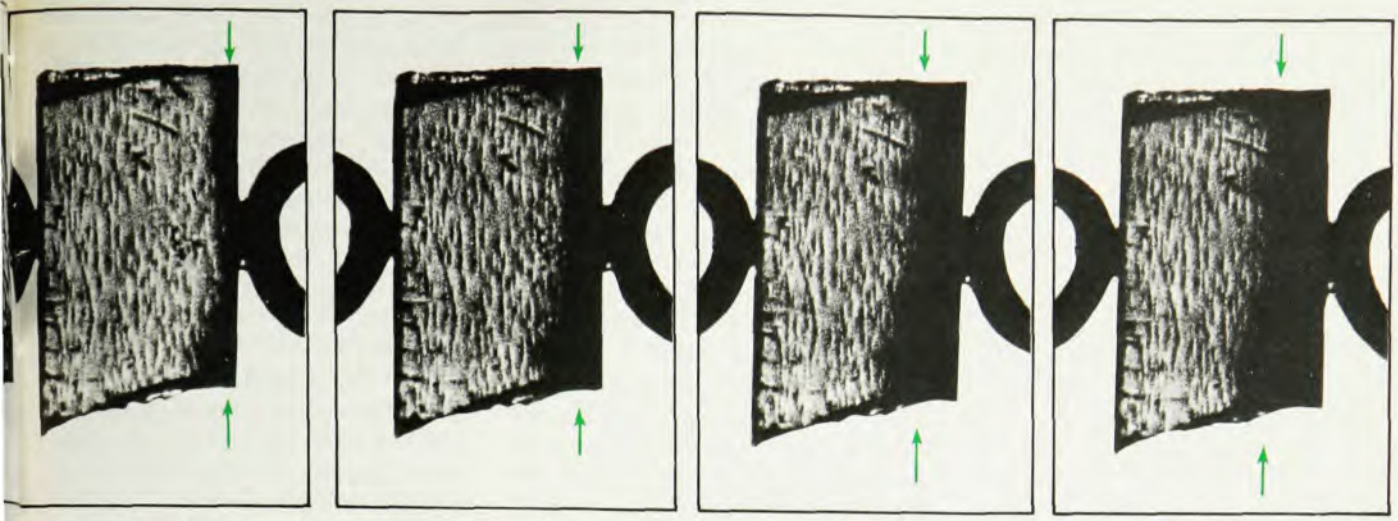
Stationary behavior

A great deal of effort, both experimental and theoretical, has gone into the study of the field nonuniformities and the accompanying nonuniformities in carrier concentration that occur under NDC. The theory has been developed from a rather phenomenological point of view, based on Poisson's equation and the statement that the total current density is the sum of conduction, diffusion and displacement currents.[2] When the carrier density is varied, a complete description requires additional kinetic equations governing the rates at which electrons enter and leave the traps. The equations have been studied extensively and solved numerically for many cases. Because some of the quantities involved, such as boundary values of carrier density and electric field and intervalley scattering rates, are not well known, one can not necessarily match the results of any computer integration with the behavior of any particular sample. The results have nevertheless been quite informative. For gallium arsenide in particular, computer experiments appear to have been as revealing as actual experiments.

The most complete experimental studies of steady-state behavior have been made by Böer and his associates[3] on cadmium-sulfide samples with carrier variation of the sort shown in figure 3. In cadmium sulfide the field inhomogeneities are very easily made visible because the absorption properties change as the field changes. In high fields the energy-band gap is essentially decreased. Thus light of a critical frequency ν such that $h\nu$ is less than or equal to $\mathcal{E}_g$, that would have penetrated fairly well in the absence of a field, is absorbed in the presence of a high field. This effect revealed the existence of layer-like high-field regions in cadmium sulfide many years before it was understood that they were caused by NDC.

Domain formation

Figure 4 is a set of pictures of a cadmium-sulfide sample doped with silver and aluminum taken in light of the critical frequency for different applied voltages. The evaporated gold electrodes used are known to be blocking, that is, the carrier density at the cathode, n_c, is less than the thermal-equilibrium bulk value for zero field. At zero voltage the sample is uniformly lit, indicating that the crystal is relatively homogeneous. At 500 V a shadow, indicating a high-field region or domain, appears at the cathode.



2200 V 2600 V 3000 V 3200 V

With increasing voltage the shadow moves toward the anode, filling the entire crystal at 1750 V. When the voltage is further increased, a darker shadow appears at the anode, indicating a still higher-field region initiated at the anode. With increasing voltage, this domain grows toward the cathode. From the uniformity of the darkening it is clear that the field in either cathode or anode domain remains relatively constant as the domain grows. The field in the anode domain is, of course, higher as is evident from the greater blackening.

If the short transition distance between low- and high-field regions is neglected, one can set up simple linear relationships between the applied voltage, the domain length and the fields in the high-field region and in the low-field region. Böer and collaborators[3] deduced in this way that the field in the cathode domain is 54 kV/cm, that in the anode domain it is 205 kV/cm and that in the low-field region it is 1 kV/cm for this particular crystal. These numbers vary somewhat from crystal to crystal because, as will be seen in the next section, they depend on the boundary conditions at the cathode. As one would expect, during the regime in which a cathode or anode high-field domain exists in a crystal, an increase in voltage will cause little increase in current. One might expect samples with mobility variation to exhibit behavior similar to those with carrier variation because they are governed by similar equations.[7] Indeed, high-field cathode domains have also been found in gallium arsenide[8] with NDC resulting from mobility variation.

Similar investigations have been carried out on cadmium-sulfide crystals with "injecting" contacts, or contacts that supply excess majority carriers so that the electron concentration is larger near the cathode than it is in the bulk. In a definitive set of experiments, Böer and collaborators[3] used a crystal with one blocking (gold) contact and one injecting (indium) contact. With the gold contact as the cathode they obtained cathode and anode domains in succession just as described previously. When the indium contact was the cathode, they did not find a cathode-adjacent high-field domain. They did, however, observe the formation of an anode-adjacent domain that behaved quite similarly to that observed with the gold cathode. Anode-adjacent domains have frequently been seen in germanium, where low-resistance (and therefore low-field) contacts are common. These experiments demonstrate that sample behavior is relatively independent of the downstream contact, the anode in the cases we are discussing.

Conditions at the cathode

The observed domain formation follows readily from the basic equations for uniform samples with the types of cathode specified. What are the conditions required for formation of a stationary cathode domain? If a uniform field of magnitude E_h is to exist over an extended region, the space derivatives dE/dx and dn/dx must be essentially zero over this region. From Poisson's equation, the condition for the former to vanish is that the carrier concentration n_1 have everywhere the value appropriate to the field E_h, that is, $n_1(E_h)$. For a material in which only the mobility μ varies, then $n_1\ (E_h) = n_0$, the thermal equilibrium value of n. The vanishing of dn/dx implies that there is no diffusion current, and therefore

$$j = n_1(E_h)\mu(E_h)\ e\ E_h$$

For the uniform field to start at the cathode and extend into the crystal, the field E_c and carrier concentration n_c at the cathode must match those in the interior, that is

$$E_c = E_h \quad \text{and} \quad n_c = n_1\ (E_h)$$

Thus formation of a stationary cathode domain, for either carrier or mobility variation, or a combination of the two, requires the simultaneous satisfaction, at some voltage, of the conditions

$$n_c \cong n_1\ (E_c) \qquad (1)$$

$$j \cong n_1(E_c)\ \mu(E_c)\ e\ E_c \qquad (2)$$

where the field E_c must be in the NDC range. It may, of course, vary with voltage in any arbitrary way at lower voltages. If these conditions are satisfied for E_c close to the beginning of the NDC range, $n_1\ (E_c)$ or $\mu(E_c)$ is still relatively high and j will also be high. As E_c moves further into the NDC range, the value of j for domain formation decreases. However, these conditions (and in fact the variation of field with distance observed above) do not apply for highly nonuniform samples, which are not at all uncommon. In such samples the nonuniformity rather than the contact conditions determines the behavior.

Space-charge waves

Under certain conditions the behavior described above is not stable. Consider a sample with mobility variation,

having a uniform field in the NDC range. We find mathematically that, provided the electron drift velocity v_d decreases rapidly enough with field, a small perturbation of the steady-state solution in the form of a traveling wave will propagate with velocity v_d and grow. This variation of drift velocity with field, dv_d/dE, can be pictured as a type of generalized mobility. Then the condition for growth may be expressed in terms of a lower limit on the inverse of a generalized dielectric-relaxation time τ_D.

$$\tau_D^{-1} > Dk^2$$

where

$$\tau_D = \varepsilon/4\pi ne\ (dv_d/dE)$$

ϵ is the dielectric constant, D is the diffusion constant and k is the wave vector. In systems with carrier variation, where the basic equations must be supplemented by additional kinetic equations, growing waves of this kind, called "space-charge waves," may also exist. Their propagation rate, however, may be many orders of magnitude less than the drift velocity because it must allow time for electrons to move into or out of traps.

To be more realistic we must consider a situation in which the sample is finite, has a nonuniform field and forms part of a circuit. The nonuniformity means that space-charge waves grow rapidly in some parts or are even attenuated in other parts of the sample. More importantly, only certain frequencies of space-charge waves can propagate for any considerable length of time, that is, over many periods. In the terminology of the electrical engineer, the frequencies that can grow are those for which the resistance is negative. Physically, this signifies that energy is being given to the oscillation at a certain frequency because the component of electron velocity at this frequency is on the average moving against the component of field at the same frequency. (Of course, the energy comes ultimately from the dc supply.) The frequencies for which negative resistance is possible, for mobility variation, are those near v_d/l_-, $2v_d/l_-$ and perhaps higher harmonics, l_- being the length of the sample in the NDC range.[2]

Stability against oscillations

Traveling, growing space-charge waves have been seen in n-type germanium samples at 77K, where $|dv_d/dE|$ is small enough so that the perturbations remain small. The frequencies observed have been one, two and three times a fundamental frequency that is greater than v_d/L, where L is the full length of the sample, because not all the sample was in the NDC range. These waves are not excited in the samples by any outside source, but are manifestations of instability. Their occurrence implies that gain for these frequencies is large enough to overcome losses.

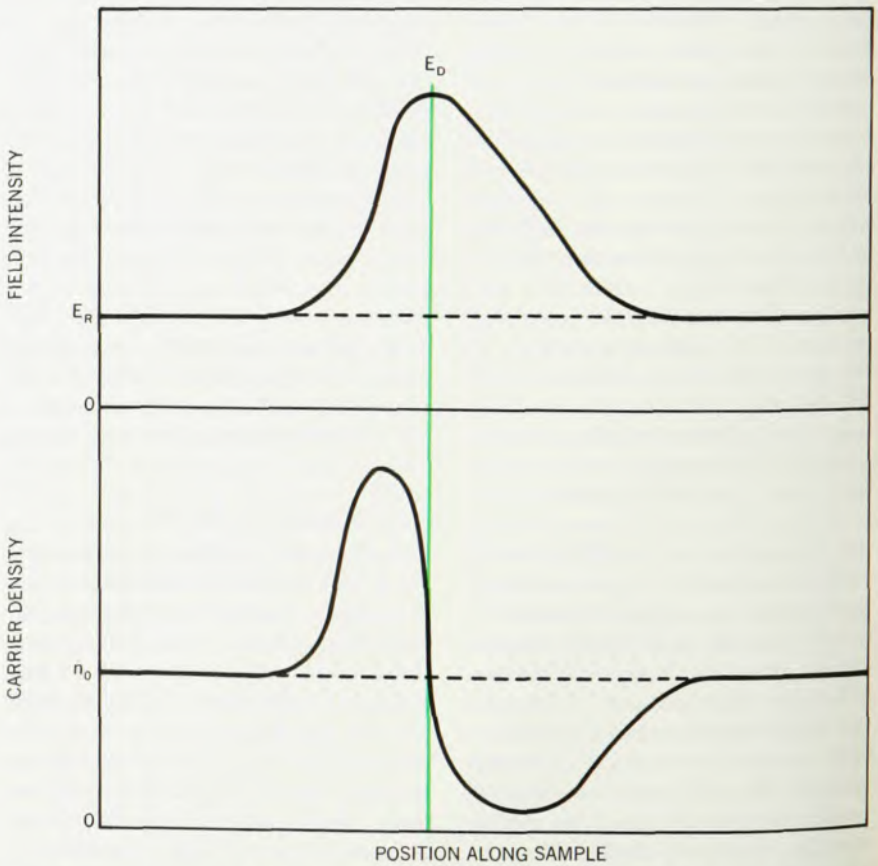
Neglecting losses in the outside circuit, we may write the condition for stability of the sample against such oscillations as an upper limit on the product of n and l_- (or L, if the NDC length can not be determined). This upper limit depends on $|dj/dE|$ and the oscillation frequency.[2] For gallium arsenide the condition for stability[2] against the lowest frequency (approximately v_d/L) is that nL be smaller than $5 \times 10^{11}/\text{cm}^2$. As n is typically greater than or about equal to $10^{15}/\text{cm}^3$, samples with dimensions greater than a few microns are usually unstable. Cadmium sulfide and n-type germanium are more stable, the former because n is much smaller, the latter because $|dv_d/dE|$ is small.

If the nL product is kept below the critical value, space-charge waves will not arise spontaneously. However, if they are excited by an outside electromagnetic field in the right frequency range, they will propagate and grow. This principle has been used to obtain amplification of microwaves.[2]

Moving domains

When the critical nL product is greatly exceeded, a moving domain is likely to form. The period of oscillation is generally given, in the case of mobility variation, by L/v_d. This fact indicates that nucleation of the moving domain occurs commonly at or close to the cathode. Gunn,[8] working on gallium arsenide, and Böer and his colleagues,[3] working on cadmium sulfide, have observed that nucleation generally takes place within a high-field cathode domain.

Computer simulation, carried out by Herbert Kroemer,[9] has provided a detailed description of the nucleation process in gallium arsenide for one



DISTRIBUTION OF FIELD AND CARRIER DENSITY for a stable high-field domain propagating to the right. At the peak field, E_D, the domain is bounded on the left by an accumulation of carriers and on the right by a depletion of carriers, compared to the thermal equilibrium value of carrier density, n_0. —FIG. 5

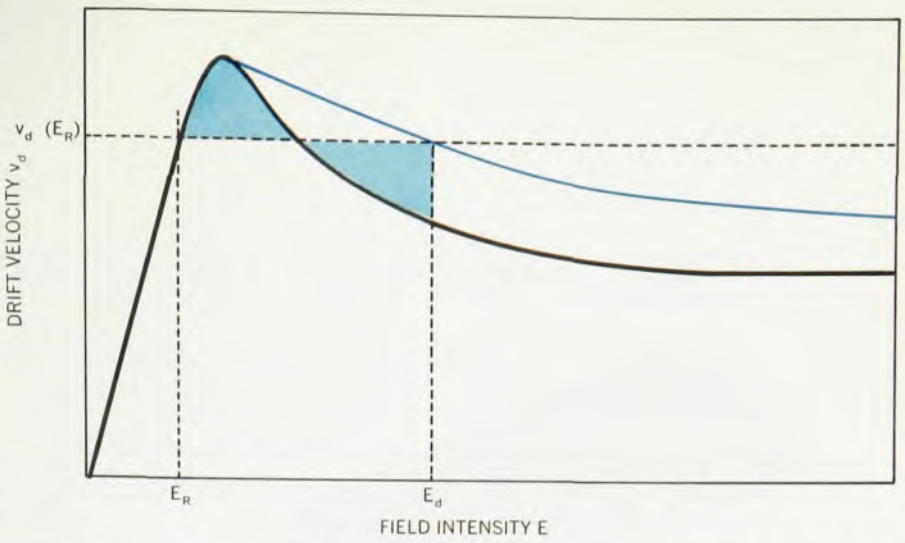
particular case. Briefly, at high enough voltage space-charge waves that arise spontaneously within the cathode domain grow large enough to nucleate an accumulation layer. In turn part of the depletion layer that supports the high field in the domain detaches itself, forming a traveling dipole or domain. Because, as we noted earlier, the current varies slowly with voltage once formation of a stationary domain has begun, satisfaction of equations 1 and 2 (required for formation of a stationary cathode domain) also constitutes a necessary condition for formation at the cathode of a traveling domain. Evidence for the validity of these equations has been obtained by experiments[3] in which the carrier density and the field at the contacts were varied. The same results have also been demonstrated by computer simulations.[7]

At the threshold voltage and just above it, the traveling domain is likely to be unstable and to decay before it reaches the anode. As will be discussed, for the domain to be stable a specified excess voltage is required in addition to the ohmic drop that would normally exist in the region of the domain. This excess voltage may be quite large. Unstable domains have been observed in cadmium sulfide and in gallium arsenide both in real-life and in computer experiments.[3]

Samples with injecting or low-field contacts, which tend to form anode domains, may support space-charge waves in these anode domains. These domains will, of course, never grow into moving domains. In practice, however, a small nonuniformity such as a deficiency in doping anywhere in the sample may act as a pseudocathode and launch a moving domain.[2,3]

When stable moving domains are formed, they propagate at a constant domain velocity v_D, without change in shape. In materials with mobility variation, v_D is of the order of 10^7 cm/sec, approximately equal to the drift velocity of the electrons outside the domain. In materials with carrier-density variation, v_D is typically in the range 10^{-1} to 10^{-5} cm/sec, the exact value depending on the level of light or the carrier density in the sample.

A typical field distribution and the associated carrier-density distribution for a domain in gallium arsenide under fairly high voltage are shown schematically in figure 5. For $n_0 = 10^{14}/cm^3$ and peak domain fields between, for example, 40 kV/cm and 60 kV/cm, the widths of the depletion layer ($n < n_0$) are in the range 35 to 55 microns; the widths of the accumulation layer ($n > n_0$) are somewhat less.



PEAK DOMAIN FIELD E_D is determined graphically from plot of drift velocity as a function of field (solid curve). Dashed line indicates drift velocity when field outside the domain is E_R. Areas (colored regions) of curve above and below this line must be equal. Colored curve shows values of E_D determined in this way. —FIG. 6

A useful rule has been derived[2] for calculating approximately the maximal field E_D in the domain, given the current or the field E_R outside the domain:

$$\int_{E_R}^{E_D} [v_d(E) - v_d(E_R)]\, dE = 0$$

E_D may therefore be determined by the simple construction shown in figure 6. The colored areas above and below the horizontal line at $v_d(E_R)$ must be equal to each other. For gallium arsenide in particular, the E_D values, given by the colored line, get very large as the current decreases. Thus, especially for low currents, even though a domain may be nucleated at a low voltage, it will not be stable until a much higher voltage is put across the sample. In practice there is an upper limit on the maximal field in gallium arsenide of about 10^5 V/cm. Domains with peak fields greater than this are unsteady and undergo random changes in shape and velocity because of the creation of additional carriers by impact ionization.[8]

Possible applications

Although the traveling domain is an interesting phenomenon, and one that appears useful for some applications, the behavior most likely to be technologically important occurs when domain formation is prevented. This can be done by inserting the sample, biased above threshold, into a high-Q resonant circuit in which oscillations have sufficient amplitude to cause the voltage to dip below threshold during part of the cycle. If the circuit frequency is sufficiently higher than v_d/L, space-charge accumulation will be prevented even if the critical nL product is greatly exceeded. When the sample is above threshold, it will act like a homogeneous negative resistance, giving energy to the circuit. Called the "limited space-charge accumulation" mode of operation, this procedure has produced oscillations at frequencies as high as 150 GHz.[10]

References

1. E. M. Conwell, *High Field Transport in Semiconductors*, Academic, New York (1967).
2. P. N. Butcher, Rep. Progr. Phys. **30**, pt. 1, 97 (1967).
3. IBM J. Res. Dev. **13**, no. 5 (1969).
4. T. K. Gaylord, P. L. Shah, T. A. Rabson, IEEE Trans. ED, **ED-15**, 777 (1968) and **ED-16**, 490 (1969).
5. J. C. Slater, PHYSICS TODAY, **21**, no. 4, 61 (1968).
6. E. M. Conwell, IEEE Trans. ED, **ED-17**, 262 (1970).
7. K. W. Böer, G. Döhler, Phys. Rev. **186**, 793 (1969).
8. J. B. Gunn, IBM J. Res. Develop. **10**, 300 (1966).
9. H. Kroemer, IEEE Trans. ED, **ED-15**, 819 (1968).
10. H. Kroemer, IEEE Spectrum **5**, 47 (1968). □