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Bulk negative-resistance semiconductor devices

Negative resistance exhibited by bulk material, such as GaAs, makes possible new devices with high speed and power capabilities. These devices amplify and oscillate, and multi-input versions perform AND and OR functions

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Recent research on semiconductors that exhibit bulk negative resistivity has led to new devices for pulse regeneration, logic function generation, amplification, and millimeter-wave power generation. These are bulk devices in the sense that ac gain is derived from the bulk negative-resistance property of certain uniform semiconductors, rather than from the properties of junctions between different types of semiconductors. Bulk devices are capable of operating with more power at higher speeds and frequencies than conventional junction devices such as transistors.

During the past year the physics of negative resistivity, which appears in n-type GaAs, InP, and CdTe, has become much better understood, and the art of making high-quality GaAs and fabricating GaAs devices has advanced appreciably. The following sections will discuss the theory of operation and the electrical characteristics of a number of developmental devices, including those shown in Fig. 1.

Like charges attract?

The simplest device is a cube of uniform n-type GaAs with ohmic contacts applied to opposite faces, as shown in Fig. 2. When a small voltage is applied, the electric field and conduction current density are uniform throughout the diode. The current is carried by free electrons, which are drifting through a background of fixed positive charge, so no space charge exists within the diode.

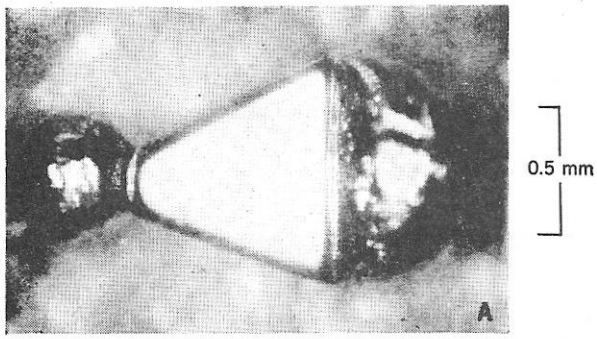
The positive charge, due to impurity atoms that have lost an electron (donors), is sometimes reduced by impurity atoms that have gained an electron (acceptors). As long as the fixed charge is positive, the semiconductor is n-type, since the principal charge carriers will be negative (electrons rather than holes). For simplicity, the density of donors less the density of acceptors will be referred to as the "doping." When there is no space charge, the carrier density is equal to the doping.

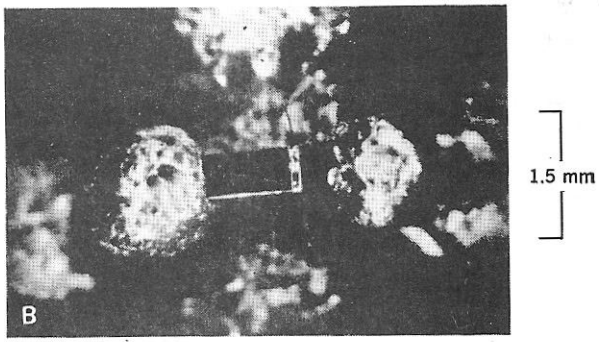
At low voltages, the GaAs is ohmic because the drift velocity of the electrons is proportional to the electric field (voltage/length of diode). Interesting things happen as the voltage on the diode is increased above threshold (about 3000 V/cm × length). The electron drift velocity now begins to decrease as the electric field increases, as shown in Fig. 3, and the material exhibits negative resistivity. When the field was below threshold, a group of excess electrons would disperse, because of electrostatic repulsion, until the negative charge density of the electrons was equal to the positive background charge density—that is, until the space charge disappeared. Above threshold, the excess electrons will not disperse, but pile up at a rapid rate as though they were attracted to each other. This piling-up process occurs because the increased electric field in front of the excess electrons now makes the electron stream slow down, and the decreased field behind makes the electron stream speed up.

Similarly, if there is a region in which there is a deficiency of electrons, so that the space charge is positive, the electron stream will move away from this region faster than it moves toward it and the deficiency will grow. This region may become completely depleted of electrons. As a result of the space-charge growth the diode breaks up into domains (regions) of high and low electric fields separated by layers of space charge that are parallel with the contacted faces. The space-charge layers drift with the carrier stream, which is moving at about 10^7 cm/s (220 000 mi/h).

History and physics

In 1961 Ridley and Watkins discussed the possibility of finding bulk negative resistivity in certain semiconductors, and Ridley later correctly predicted that due to the instability of space charge in such a bulk semiconductor, it would break up into domains of high and low electric fields, which would drift along with the carrier stream, producing oscillations.[1,2] Almost at the same time Hilsum predicted that bulk negative resistivity should exist in n-type GaAs and calculated a threshold field of 2800 V/cm, very close to what is now observed.[3]





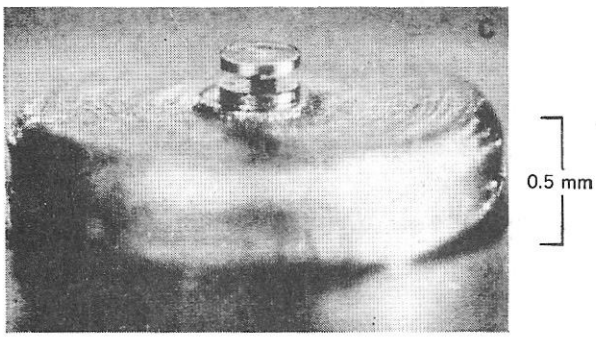
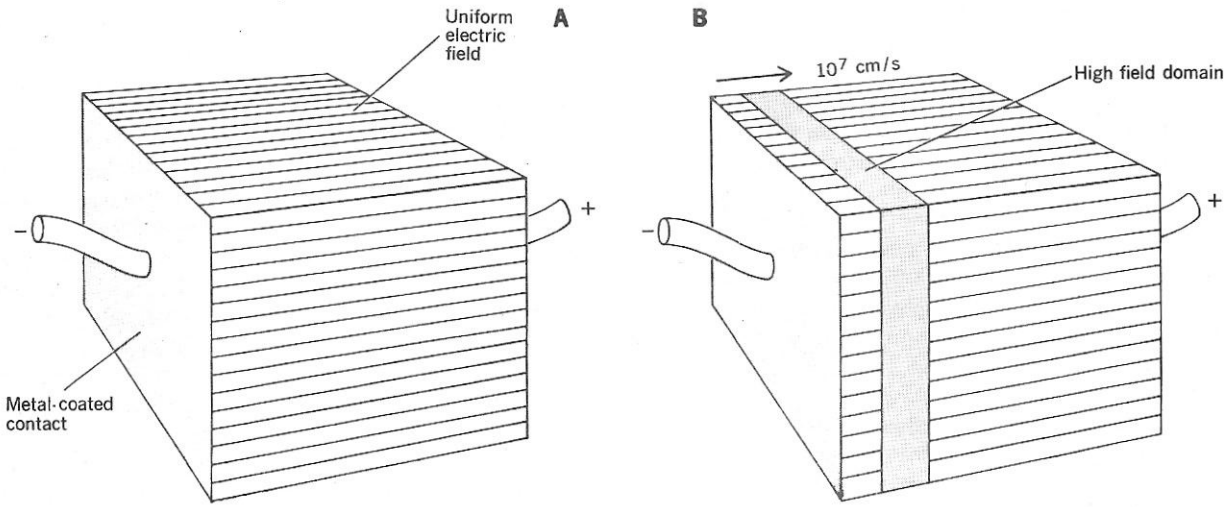


FIGURE 1. Bulk negative-resistance semiconductor devices. A—Sawtooth-wave-function generator and voltage-tunable oscillator. B—Three-terminal AND or OR logic gate. C—Epitaxial diode mounted on heat sink for 90-GHz LSA oscillator.

FIGURE 2. Diode made by contacting opposite faces of a cube of uniform n-type GaAs. A—When the voltage is below the threshold for negative resistivity, the field is uniform. B—Above threshold, a high field domain forms near the negative contact and drifts through the diode.



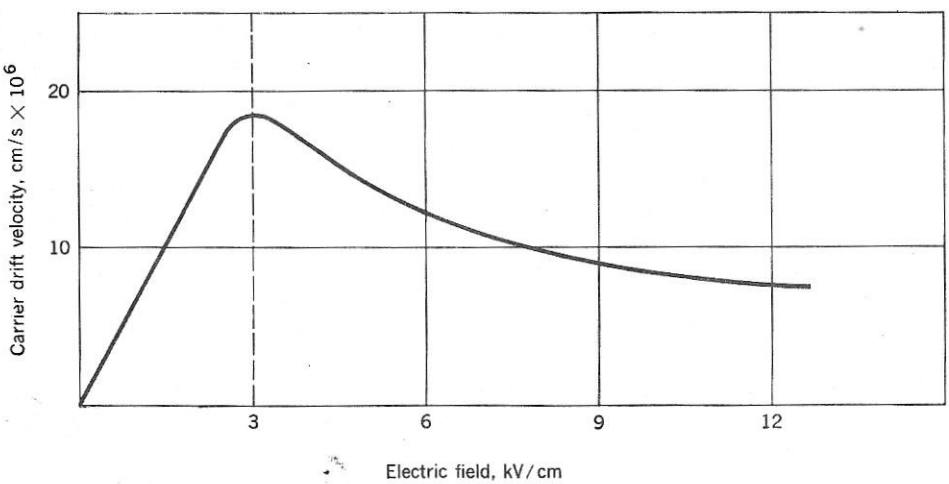


FIGURE 3. Drift velocity of conduction-band electrons in GaAs vs. electric field. The ac resistivity is negative when the electric field is biased above 3000 V/cm.

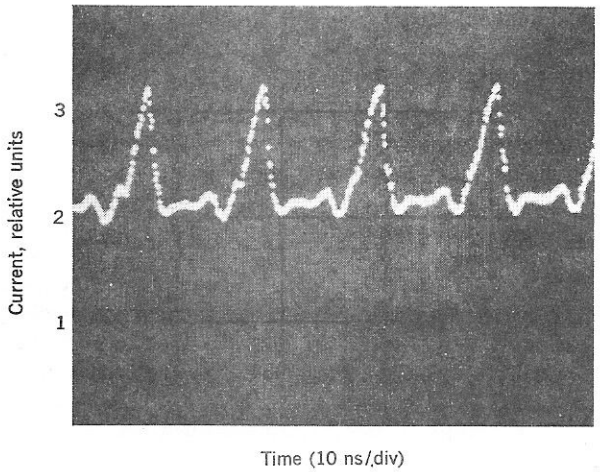
Two years later, while working on electrical noise emitted by semiconductors, Gunn observed that microwave noise powers of the order of a watt were emitted from GaAs and InP when they were subjected to pulsed electric fields of several thousand volts per centimeter.[4] When short samples were used (less than 0.2 mm), the noise changed to coherent oscillation at a frequency with a period close to the time needed for carriers to drift from one contact to the other (transit-time oscillation).

Gunn then developed an elaborate capacitive probe that plotted the electric field distribution within samples while they oscillated. These measurements showed that as the voltage was increased past threshold, a high field domain formed near the cathode that reduced the electric field in the rest of the diode and caused the current to drop to about two-thirds of the maximum value. The high field domain would then drift with the carrier stream across the sample and disappear at the anode contact. As the old domain disappeared at the anode, the electric field behind it increased (to keep the voltage, $\int E\,dx$, constant) until the threshold field was reached and the current had increased back to the threshold value. At this time a new domain would form at the cathode, the current would drop, and the cycle would begin anew.

A current waveform produced by this type of operation is shown in Fig. 4. The flat valley occurs as the domain drifts across the sample. The upward spikes begin as a domain reaches the anode, and a new domain forms at the cathode. The small current fluctuations in the valley occur as a domain passes through regions in the diode of varied doping or cross-sectional area.

At first, many explanations were considered for the phenomena Gunn observed, which soon became known as the "Gunn effect." The usefulness of the effect was immediately apparent, since the transit-time frequency of a 100-μm-thick diode was about 1 GHz, and diodes could be made thinner by an order of magnitude. In 1964 Kroemer pointed out that Gunn's observations were in complete agreement with the earlier predictions of Ridley, Watkins, and Hilsum, whose two-valley theory will be described in the next section.[5]

FIGURE 4. Current waveform due to Gunn-effect oscillations. Current rises each time a domain drifts into anode and drops again as a new domain forms at cathode.



The two-valley model

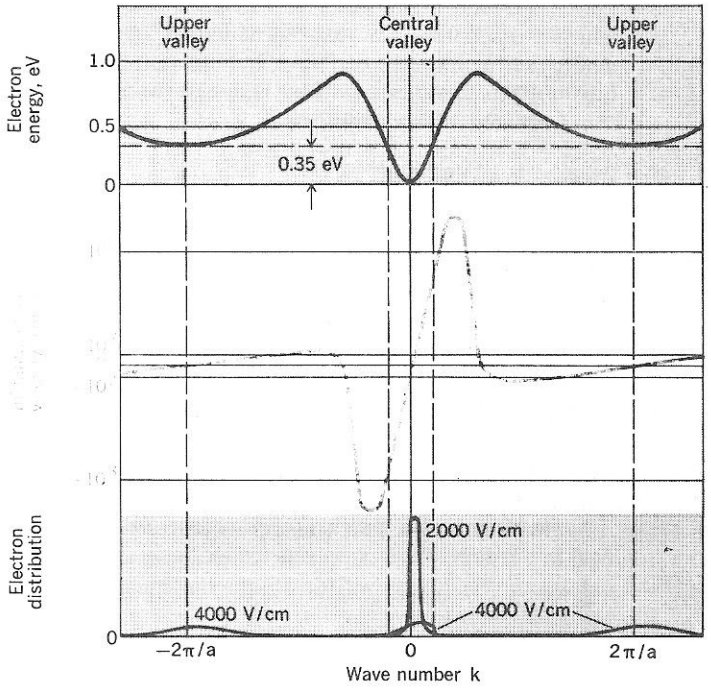
The physical model for GaAs that gives rise to the decrease in average drift velocity at high electric fields is depicted in Fig. 5. At room temperature with no applied electric field, almost all of the electrons are in their low-energy states ($\epsilon \lesssim 0.03$ eV) close to $k = 0$ (the wave number k plays an important role in the quantum mechanics of solids, but need not concern us here). Many electrons have instantaneous velocities of plus or minus a few times 10^6 cm/s due to their thermal motion, but the average drift velocity is zero.

When a small electric field is applied, the electron distribution shifts so that more electrons are moving with the electric field than against it (shown by the slightly shifted electron distribution for 2000 V/cm). The electron stream has an average drift velocity that increases with increasing electric field until the fraction of electrons with energy greater than 0.35 eV begins to increase rapidly. Electrons with energy greater than 0.35 eV transfer to the more numerous states in the upper valleys where they have the same energy but much less average velocity (shown by the electron distribution for 4000 V/cm, which is shifted farther to the right of the valley minima).

At the threshold electric field, about 3000 V/cm, the average electron drift velocity reaches a maximum value of 20×10^6 cm/s. At higher fields the electrons are mostly in the upper valleys and the average velocity decreases to a more or less constant value of 8×10^6 cm/s, as indicated in Fig. 3.

Three criteria on the band structure (energy, ϵ, and k) of a semiconductor must be met in order for the semiconductor to exhibit a negative resistance because of upper valleys: (1) The energy difference between the bottom of the

FIGURE 5. Two-valley model. As the electric field increases, electrons transfer from high-velocity states in the central valley to low-velocity states in ihe upper valleys, causing the average velocity to decrease.



lower valley and the bottom of the upper valley must be several times larger than the thermal energy (about 0.025 eV at room temperature). (2) The energy difference between the valleys must be smaller than the energy difference between the conduction and valence bands, or the semiconductor will break down (become highly conductive because of hole–electron pair formation) before the electrons begin to transfer to the upper valleys. (3) The electron velocities ($d\epsilon/dk$) must be much smaller in the upper valleys than in the lower valley.

Not all of these criteria are met by the two most common semiconductors, silicon and germanium. They do appear to be fulfilled by some compound semiconductors, including gallium arsenide (GaAs), indium phosphide (InP), and cadmium telluride (CdTe), but not by others such as indium arsenide (InAs), gallium phosphide (GaP), and indium antimonide (InSb).[6] The practical uses that are being found for bulk negative resistance should give additional incentive to the present research effort on compound semiconductors.

The energy gap between the conduction-band valleys in GaAs can be varied by putting the material under high pressure or by alloying GaAs with GaP. The measurement of threshold voltage as a function of pressure on GaAs by Hutson, Jayaraman, Chynoweth, Coriell, and Feldman showed that the threshold voltage varies with the intervalley energy gap as predicted by the two-valley model.[7] Similar results were obtained by Allen, Shyam, Chen, and Pearson from alloying experiments.[8] The validity of the two-valley model for GaAs was confirmed by these experiments and by computer-generated movies of domain behavior based on the two-valley model made by McCumber and Chynoweth, which agreed with experimental observations.[9]

There are mechanisms for bulk negative resistance, in addition to the two-valley mechanism, that have been suggested but not yet observed. A closely related phenomenon is the high field domains due to direct interaction between the carrier stream and phonons (quantum lattice vibrations) that have been observed in GaSb, CdS, and in a few samples of GaAs oriented so that current flows along the (111) crystal axis. These domains travel at the speed of sound in the material (about 5×10^5 cm/s), which is much lower than the Gunn domain velocity (10^7 cm/s), and in the case of GaAs, appear at lower fields (about 100 V/cm) than the true bulk negative resistance threshold field (about 3000 V/cm).

Properties of domains

Because of the negative resistivity, space charge grows until it reaches a stable configuration, which usually consists of a single dipole layer (some exceptions to this rule will be discussed later).[10,11] Inside the dipole layer is the high field domain, where the electric field may be greater than 60 000 V/cm. Outside the domain, the field is below threshold (<3000 V/cm) and the resistivity is positive. The shape and behavior of the domain depend on the device doping and size, the bias voltage, and the circuit. Typical field and charge configurations for a domain are shown in Fig. 6. Some general properties of the domain are:

1. A domain will start to form whenever the electric field in a region of the sample increases above the threshold electric field, and will drift with the carrier stream through the device.
2. If additional voltage is applied to a device containing a domain, the domain will increase in size and absorb more voltage than was added and the current will decrease.
3. A domain will not disappear before reaching the anode unless the voltage is dropped appreciably below threshold (for a diode with uniform doping and area).
4. The formation of a new domain can be prevented by decreasing the voltage slightly below threshold (in a nonresonant circuit).
5. A domain will modulate the current through a device as it passes through regions of different doping and cross-sectional area, or it may disappear. The effective doping may be varied in regions along the drift path by additional contacts.
6. The domain's length is generally inversely proportional to the doping, so devices with the same doping × length product will behave similarly in terms of frequency × length, voltage/length, and efficiency.
7. A domain can be detected as it passes a point in the device by a capacitive contact, since the voltage changes suddenly as the domain passes. The presence of a domain anywhere in a device can be detected by the decreased current or by the change in differential impedance.

Properties 3 and 6 are valid only when the length of the domain is much longer than the thermal diffusion length for carriers, which for GaAs is about 1 μm for 10^{16} cm^{-3} doping and about 10 μm for 10^{14} cm^{-3} doping.

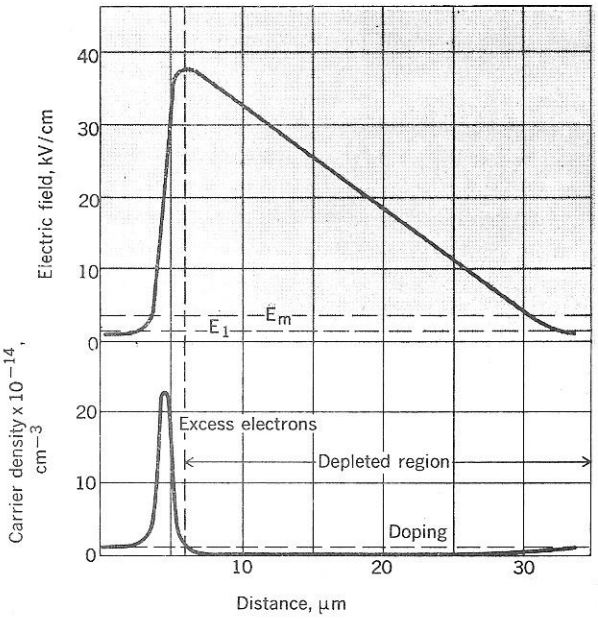


FIGURE 6. Electric field and carrier-density configuration in a high field domain. Outside the high field domain the field E_1 is below threshold E_m.

Two-terminal devices

The foregoing properties can be used to design a more efficient oscillator than the one that produced the waveform of Fig. 4. To increase the power content at the fundamental frequency, the waveshape should be made more symmetrical. If the diode is made shorter, the flat valley of the current waveform will become narrower, because the domain will spend less time traveling through the device, whereas the width of the upward spike will not change.

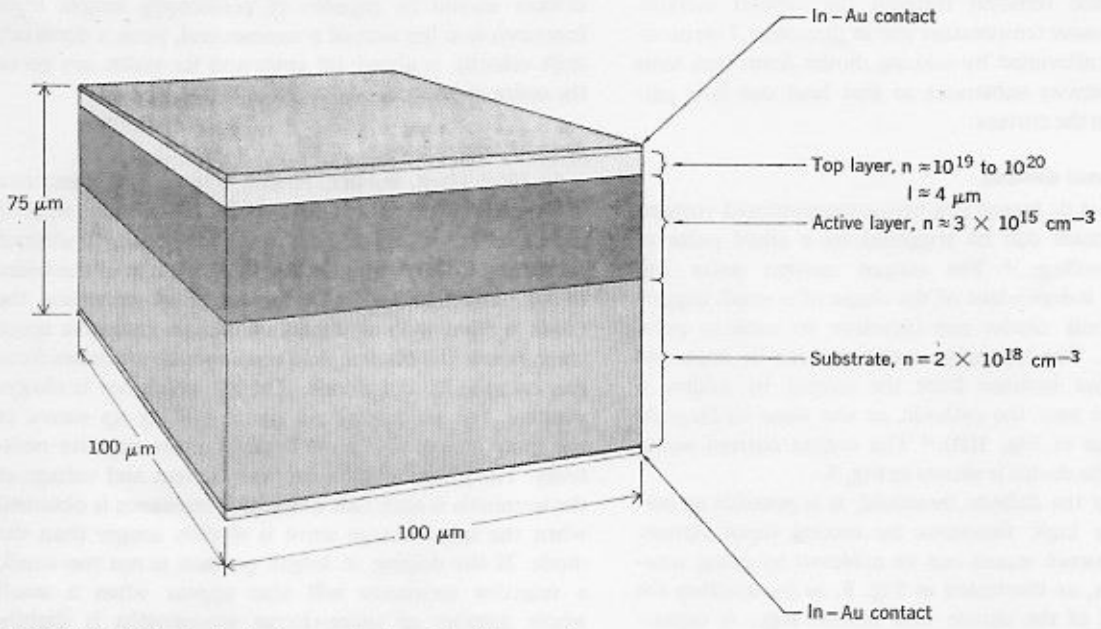


FIGURE 7. GaAs bulk diode, made by epitaxially growing the active layer (doping $n = 3 \times 10^{15}$) on a high-conductivity substrate ($n = 2 \times 10^{18}$). Top layer was highly doped ($n = 10^{19}$ to 10^{20}) before contacting.

By property 5, we could change the waveform in the same manner without changing the frequency, by reducing the doping. This makes the upward spike wider at the expense of the valley because the domain becomes wider and takes longer to build up and disappear. Theoretical calculations indicate that the efficiency of GaAs Gunn oscillators is best when the doping × length product is one to several times 10^{12} cm^{-2}, so the domain is about half as large as the sample and the current approximates a sine wave.

High efficiency could also be obtained from the diode used for Fig. 4 by applying property 4. If the new domain is inhibited from starting for a time equal to the domain transit time, then the waveform will approximate a symmetrical square wave. The highest efficiencies reported, which approach 20 percent, were obtained in this manner by operating diodes in a resonant circuit tuned to half the transit-time frequency. The output power obtained on a pulse basis was approximately 100 watts at 1 GHz.[12]

Even while a diode has a high field domain and is oscillating, it may show a negative resistance at other frequencies due to negative resistance of the domain (property 2). Diodes that are oscillating at 1 GHz or above are frequently observed to modulate themselves at frequencies from a few kilohertz to hundreds of megahertz because of parasitic oscillations due to resonances in the bias circuit. This effect is a nuisance if one wants a clean microwave signal. However, if the microwave oscillations are filtered out, this effect can be used to oscillate, amplify, and generate pulses at frequencies below the transit-time range.

Property 5 results from the tendency of the carrier stream near the domain to move at a constant velocity. If the area of a diode increases as the domain travels through it, then the current will also increase. Further, if the carrier density increases because of increased doping, the current will increase. By physically shaping a diode, the output current waveform can be tailored. The device shown in Fig. 1(A), made by M. Shoji, produces a sawtooth waveform.[13] It is also voltage tunable over a wide frequency range since the domain will disappear before reaching the anode when there is insufficient voltage to sustain both the domain and the increasing *IR* voltage drop over the rest of the device.

By cutting notches in a device that otherwise has uniform doping and cross-sectional area, a desired sequence of pulses can be produced each time a domain passes through. Such sequences can represent binary numbers (zeros and ones), which are used in most computer circuits. Because some impurity atoms can be temporarily ionized (traps) to change the doping, it is also possible temporarily to "write" binary numbers on devices that can be read from the output signal as a domain passes through.

Large Gunn-effect oscillators are produced by cutting wafers (thin disks) and then strips from a piece of bulk-grown material. The contacts are made by alloying balls of indium or tin to the ends, as was done on the devices shown in Fig. 1(A) and (B). For devices with cross-section dimensions greater than their length, the wafer is contacted on both sides by vacuum-evaporating metal films on each end and then it is diced into separate diodes. Diodes with this geometry can be mounted in packages with pressure contacts.

The best devices for practical applications are produced by growing thin films of n-type GaAs on a substrate of either high-conductivity or high-resistivity GaAs. Contacts to the epitaxial film are best made after growing thin high-conductivity layers on the surface. The structure shown in Fig. 7 was used by Brady, Knight, Lawley, and Uenohara for devices with active layer thicknesses of from 20 to 8 μm, which produced 0.1 watt continuously with 3 percent efficiency at frequencies from 6 to 15 GHz (a particular device could be tuned over a 2 to 1 frequency range).[14] The power and efficiency of thinner diodes decreased rapidly at higher frequencies (1 mW and 1 percent at 30 GHz).

For frequencies below 6 GHz, a GaAs diode is too thick for heat removal through the contact surfaces without excessive temperature rise in the center. This problem may be alleviated by making diodes from thin films on high-resistivity substrates so that heat can flow perpendicular to the current.

Multiterminal devices

If a diode is dc biased just below the threshold voltage, a single domain can be triggered by a short pulse of additional voltage.[15] The output current pulse will generally be independent of the shape of a small triggering pulse; bulk diodes can therefore be used as pulse regenerators. The triggering sensitivity can be improved and the input isolated from the output by adding a third contact near the cathode, as was done by Hayashi on the device of Fig. 1(B).[16] The output current waveform from this device is shown in Fig. 8.

Because of the definite threshold, it is possible to perform binary logic functions by mixing input signals. Isolation between inputs can be achieved by using separate contacts, as illustrated in Fig. 9, or by dividing the cathode end of the device into several legs. A capacitive output contact will produce output pulses whose duration is of the order of the time that it takes the domain to pass under the contact, rather than the transit time for the whole device. Ultimately these types of devices should be capable of performing simple logic functions in a fraction of a nanosecond, since a domain's drift velocity is about 10^7 cm/s and its width can be of the order of 10^{-3} cm.

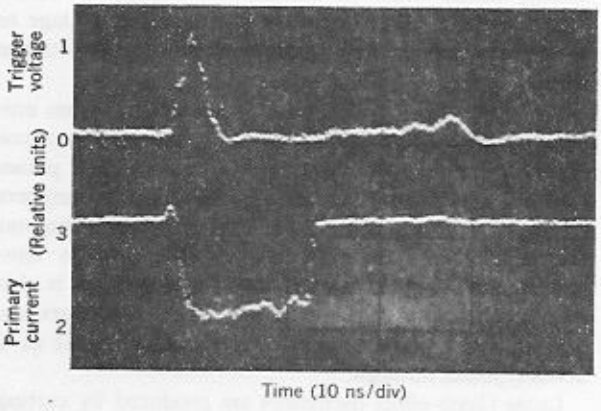
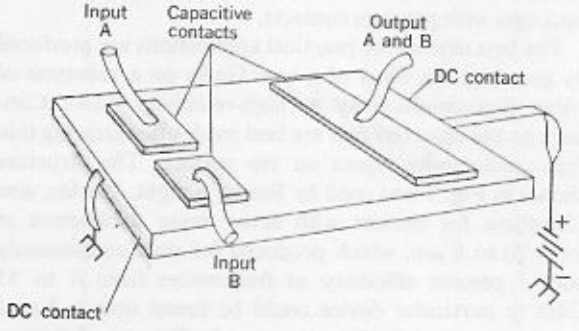


FIGURE 8. Capacitive contact voltage and current through the device shown in Fig. 1(B). This device can be used as a pulse generator or a logic gate.

FIGURE 9. Logic gate using multiple capacitive contacts. When pulses are applied simultaneously to both inputs, a domain forms and creates an output pulse as it drifts under the output contact.



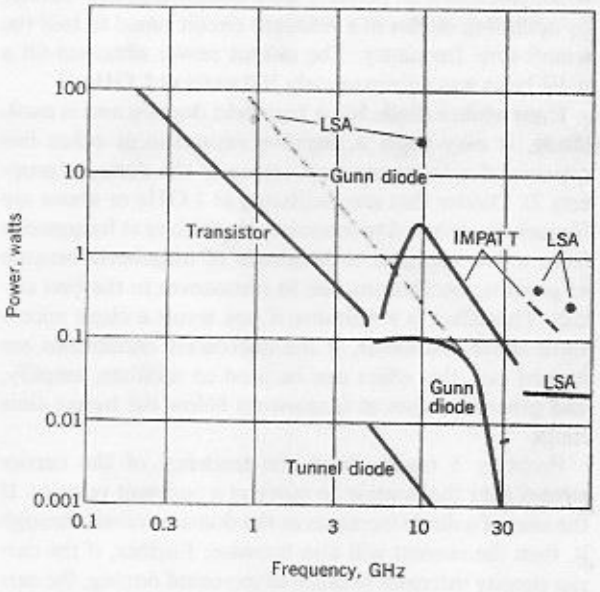
Amplifying diodes

In 1965 Thim, Barber, Hakki, Knight, and Uenohara discovered that an n-GaAs bulk diode can amplify signals in the vicinity of the transit-time frequency without oscillating if the doping × length product is of the order of 10^{12} cm^{-2} or less.[17] In this mode of operation the diode is filled with an excess of carriers (negative space charge) and the electric field continuously increases from the cathode to the anode. The dc resistance is always positive, but an applied ac signal will set up waves in the space charge that grow because of the negative resistivity. The phase relation between current and voltage at the terminals is such that a negative resistance is obtained when the space-charge wave is slightly longer than the diode. If the doping × length product is not too small, a negative resistance will also appear when a small whole number of space-charge wavelengths is slightly longer than the diode. The negative resistivity of the stable bulk diode produces a negative resistance at the diode terminals only for frequencies just below the transit-time frequency and perhaps just below the first few harmonics.

If a stable diode is put into a circuit with sufficient positive feedback at a frequency where the resistance is negative, it will oscillate. It was demonstrated by Hakki that if the oscillation voltage is not so large that it changes the initial space-charge distribution, amplification at nearby frequencies is possible and a single bulk diode can be used as an amplifier, local oscillator, and mixer.[18]

When a bulk diode with a doping × length product

FIGURE 10. Maximum power vs. frequency (1966) for a number of solid-state oscillators. Solid lines are for continuous, room-temperature operation; dashed lines and points (in color) are for pulsed operation. Gunn and LSA results are from bulk n-GaAs diodes.



that is too large for stable amplification oscillates because of the Gunn effect, it exhibits a negative resistance at direct current and at frequencies above and below the oscillation frequency. This result of domain property 2 was used recently by Thim to make amplifiers that are linear until the output power approaches the power that could be obtained from the oscillation. Five-decibel amplification at 6 GHz was achieved with 1-dB compression when the output power reached 60 mW. This is approximately a 15-dB increase in linear range over the stable amplifier diode.[19] The noise figure of these bulk diode amplifiers is about 20 dB above the thermal limit. The noise is largely the result of the internal amplification of thermal noise because of the negative resistivity.[20]

Millimeter-wave power generation

By the proper design of a bulk n-GaAs diode and corresponding resonant circuit, it is possible to prevent domains and other types of space charge from building up within the diode. This mode of operation, called LSA for limited space-charge accumulation, makes it possible to build oscillators with higher frequencies, and with higher power at a given frequency, than can be obtained with a transit-time device.[21]

Devices such as transistors and IMPATT (avalanche) diodes, as well as Gunn-effect oscillators, must be thin enough that carriers can move through the active region during one cycle or less. This means that the thickness and voltage must be decreased to raise the frequency of operation. To maintain a reasonable impedance, the current also must be decreased. The result of these considerations is that the maximum power for a given transit-time or subtransit-time device falls off faster than 1/(frequency)^2, as shown in Fig. 10. The LSA oscillator is the first practical solid-state oscillator that is free of this limitation, since in principle it can be made thick compared with the distance a carrier drifts during one cycle.

For LSA operation of a bulk n-GaAs diode, the voltage must swing below the threshold voltage each cycle long enough to dissipate space charge. Also, the part of each cycle during which the voltage is above the threshold must be too short for space charge to build up and form a domain. Since the speed of space-charge dissipation and growth is proportional to the doping, the ratio of the doping to frequency must be within 2×10^4 to 2×10^5 cm^3/s. The circuit must be lightly loaded to achieve the necessary ac voltage swing. For high efficiency, the doping should be uniform within 10 percent.

Preliminary experiments with epitaxial LSA oscillators [Fig. 1(C)] have produced 0.7 watt and 9 percent efficiency at 50 GHz on a pulse basis and 0.02 watt with 2 percent efficiency at 88 GHz on a continuous basis.[21] Experiments with bulk-grown diodes have yielded 33-watt pulses at 10 GHz and have led to predictions that 250-kW pulses from a single block of n-GaAs are theoretically possible up to 100 GHz.[22] The upper frequency limit for LSA operation of GaAs has not been determined, but it seems certain that an appreciable amount of power can be produced at frequencies of several hundred gigahertz.

The future

Bulk negative-resistance devices offer both opportunity and challenge. The opportunity is to build devices with better combinations of power and speed than is now possible with junction devices. The challenge arises because much of the existing electronics technology concerned with device characterization and circuit design cannot be applied to bulk devices (particularly multiterminal devices), so new techniques must be developed. Also, the materials technology for GaAs is years behind that for silicon and germanium, and is in its infancy for other III–V and II–VI compounds that look promising as bulk negative-resistance semiconductors.

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