LIMITED SPACECHARGE ACCUMULATION MODE

LSA DEVICE

By B.T.G.Tan

A major breakthrough in electronics rivalling in importance that brought about by the transistor has been achieved by recent research on semiconductors. A whole new family of semiconductor devices is being developed, which will in time do for microwave electronics what the transistor has already done for the present-day application of electronics in the domestic and industrial fields. This important development depends on the ability of a semiconducting material, gallium arsenide, to emit microwaves when a voltage is applied to a slice of the material. This concluding article deals with negative resistance and the L.S.A. device used to overcome the problem of high frequency limitations.

LAST month we considered the properties of semiconductor materials and the theory behind the transistor. The high frequency limitation of the latter device was pointed out.

This month we introduce some comparatively new semiconductor devices which overcome these high frequency limitations and thus offer promise of further great advances in semiconductor technology.

A NEGATIVE RESISTANCE DEVICE

The next semiconductor active device of major importance that came on the scene utilised the property of negative resistance.

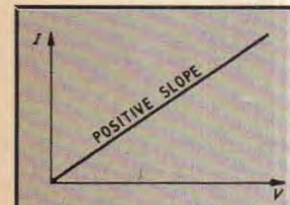

Fig. 21a

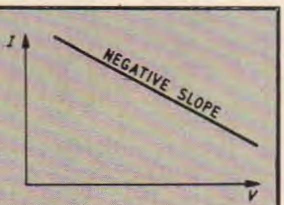

Fig. 21b

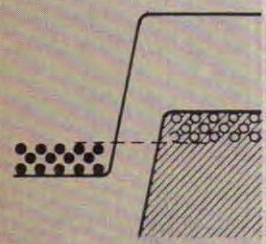

Fig. 22a

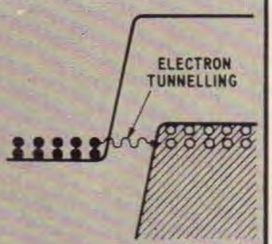

Fig. 22b

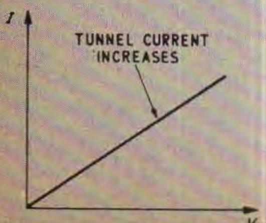

Fig. 23

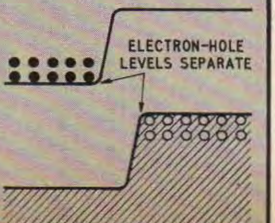

Fig. 24

Ordinary positive resistance is given by the voltage/current ratio for the current flow due to the voltage applied across a resistance. This would be given by the slope of a current-voltage graph as shown in Fig. 21a.

The characteristic of negative resistance on the graph shows a negative (downward) slope as in Fig. 21b, i.e. an increase in voltage resulting in a decrease in current.

Current is determined by the rate of flow of electric charge, so it depends both on the numbers and the velocities of the charge carriers as well as their charge. In normal positive resistance, the number n of charge carriers flowing in a circuit usually stays constant while their velocity increases regularly with increasing applied voltage, so that I increases with V.

If we could somehow decrease n with increasing V sharply enough, there will be a decrease in I and thus negative resistance will occur.

THE TUNNEL DIODE

The tunnel diode, a negative resistance device working in this way, was invented in 1958 by a Japanese physicist, L. Esaki. It consists of a single *pn* junction in which the *p*- and *n*-type regions are very heavily doped. Thus the difference in levels on both sides is so great that the bottom of the conduction band in the *n*-type region is below the top of the valence band in the *p*-type region. This is illustrated in Fig. 22a.

Practically no electrons and holes can flow across the junction and the current is virtually zero. If the junction is biased forward very slightly, reducing the potential difference, the electrons still cannot run uphill into the *p*-type region as the potential difference is still very great. However, they are now brought into levels corresponding with those of the holes opposite them in the *p*-type region. These holes are nothing but absences of electrons.

By the laws of quantum physics, an electron in the *n*-type region is able to "tunnel" through the junction barrier into an empty electron level at the same height in the *p*-type region, i.e. a hole. This surprising effect is allowed a certain small probability by quantum physical laws.

As the number of electrons is so large, some of them do tunnel through and are able to constitute a current across the junction (see Fig. 22b). As the bias is increased, more electron and hole levels are brought opposite one another and the tunnel current increases, see Fig. 23.

As the bias is increased further, the electron and hole levels separate again, and the number of electrons able to tunnel across decreases (Fig. 24). The tunnel current thus decreases with increasing voltage.

The current-voltage graph thus has a negative slope and the junction exhibits negative resistance (Fig. 25). On increasing the bias still further, the junction begins to conduct an appreciable normal forward bias current.

Thus a tunnel diode with an appropriate bias applied to it will behave as a negative resistance. It can be used in an LC circuit to generate electrical oscillations (Fig. 26).

SHORT TRANSIT TIME

The theoretical high frequency response of the tunnel diode should only be limited by the time taken for the electrons to tunnel through the junction. As the tunnelling is an extremely fast phenomenon, this transit time limitation is much less restrictive than that on the transistor, and thus it can work at much higher frequencies. Tunnel diodes can be operated in the lower frequency section of the microwave spectrum. However, the tunnel diode also has its own high frequency limitations.

Like all diodes, it has exposed net charges on either side of the junction. These charges are slightly affected by an external bias, and so the junction has a very small capacitance C_j, which must be added to the C in the LC circuit. The frequency of oscillation is now

$$1/[2\pi\sqrt{L(C + C_j)}]$$

Thus no matter how small we make L or C, the junction capacitance will always impose an upper limit on the frequency of oscillation of the resonant circuit.

However, the tunnel diode is a significant advance on the transistor as a high frequency active device. It has two layers and one junction compared with three layers and two junctions of the transistor, which is a reduction in complexity. Gallium arsenide (GaAs) devices do not depend at all on junction effects for their functioning. Their negative resistance is purely a property of their bulk material, and depends only on the behaviour of the charge carriers in the bulk material.

THE NEGATIVE RESISTANCE PROPERTY OF GaAs

The negative resistance of gallium arsenide depends not on a decrease in n with an increase of voltage, but a decrease in velocity, with n remaining constant. When an n-type GaAs slice is biased to a certain voltage, a further increase in voltage will result in a decrease in the velocity of the electrons. Since it is the electric field (voltage per unit length) across the slice that matters rather than the voltage, a graph of the velocity of the electrons against the applied electric field must be plotted and is shown in Fig. 27.

When the field across the GaAs slice is above about 3,000 volts per centimetre, it starts to exhibit negative resistance, as the current across the slice will decrease due to the decreasing velocity with increasing electric field, i.e. voltage across the slice. A decrease in the velocity of the electrons means that less charge will flow across the slice in a given time, i.e. less current will flow.

THE FIRST GaAs OSCILLATOR

The first GaAs active device functioning as a negative resistance oscillator was discovered by J. B. Gunn in 1964 while he was doing research on the high field properties of semiconductors. A rod of GaAs when biased above 3kV/cm began oscillating electrically and also emitted microwaves, the oscillations being at microwave frequencies.

H. Kroemer then put forward the explanation that the GaAs rod was acting as an oscillator because of its negative resistance property. Kroemer drew attention to the fact that three British physicists, B. K. Ridley, T. B. Watkins and C. Hilsum, had hitherto predicted that GaAs would show the property of negative resistance under these conditions.

FUNDAMENTAL THEORY

To understand why GaAs exhibits negative resistance, it is necessary to refer to fundamental semiconductor physics. Our previous energy level diagrams (see Part 1) only show the energy values of the electrons in a semiconductor, the horizontal axis simply standing for the physical dimensions of the semiconductor bulk.

An energy level diagram can be drawn to show both the energy and momentum of the electrons in the conduction band (Fig. 28a). In this diagram, the horizontal axis stands for the momentum of the electrons. An electron in the conduction band must lie on the curved line, i.e. it can only have the simultaneous values of energy and momentum that the points on the line have. This is because the energy and momentum of a moving object are closely related. This relation involves the mass of the object.

Now, as the electron moves in the semiconductor, its movement is affected by the positive charges of the atomic nuclei in the semiconductor. Thus it does not move in quite the same way as a free electron in space. The effect of these nuclei on the electron can be taken into account by considering the electron as having an effective mass quite different from its actual mass. The

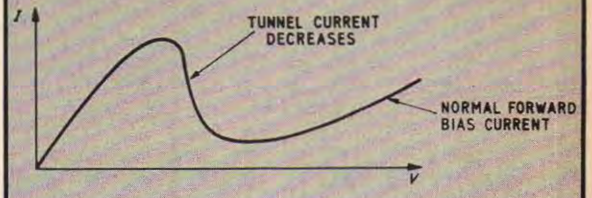

Fig. 25

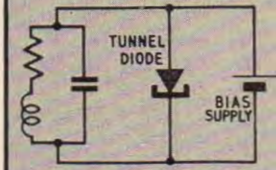

Fig. 26

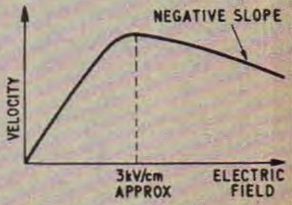

Fig. 27

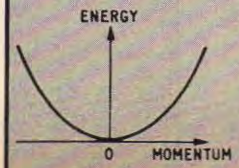

Fig. 28a

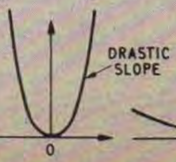

Fig. 28b

Fig. 28c

difference between the effective mass and the actual mass varies with different semiconductors and also with the energy levels of the electron.

Considering the movement of an electron in a semiconductor, using its effective mass instead of its actual mass, the effect of the atomic nuclei on the electron can be taken into account automatically. The effective mass of an electron at any point on the energy-momentum diagram is related to the slope of the curve at that point.

Thus in a semiconductor, whose energy-momentum diagram looks like that in Fig. 28b, the effective masses of the electrons at the bottom of the conduction band is less than those at the bottom of the conduction band of a semiconductor with an energy-momentum diagram of gentler slope like that in Fig. 28c.

ENERGY-MOMENTUM CURVE

Gallium arsenide has an energy-momentum curve with a drastic slope (Fig. 28b). The electrons at the bottom of the conduction band have a small effective mass.

Now, GaAs also has secondary curves of gentler slope higher up in its energy-momentum diagram (Fig. 29a). If we apply a voltage to a GaAs slice, the electrons having a small effective mass are easily moved and the current across the slice increases. As they are accelerated by the voltage, they gain energy and they rise up the curve on the diagram. We show the rise only on one side of the momentum axis as they are accelerated and gain momentum only in one direction—that due to the applied voltage.

As they approach the levels of the secondary curve, they begin to get transferred to the energy levels there. This is because the energy levels there are much more numerous than the energy levels on the main curve at the same height (Fig. 29b).

Once they are on the bottom of the secondary curve, their effective masses are much larger as the slope of the secondary curve is much gentler. As a result, their velocity decreases, since an object with a large mass is harder to move than an object with a small mass. As we further increase the voltage, more and more electrons get transferred to the secondary curve and the overall velocity of the electrons decreases. The velocity-electric field curve thus has a negative slope (Fig. 30).

The electron current will thus decrease with increasing applied voltage, and the GaAs slice exhibits negative resistance.

THE GUNN EFFECT

A slice of gallium arsenide when biased into the negative resistance region should be able to generate electrical oscillations when put into an LC circuit.

When Gunn observed the oscillations in the GaAs rod, what was actually happening was that the rod itself and its mounting made up its own LC circuit and thus oscillated at a frequency determined by its own physical dimensions. As the oscillations were at microwave frequencies, the rod radiated the oscillating electrical energy in the form of electromagnetic waves. This is because a circuit element carrying an oscillation will radiate more and more electromagnetic energy as the wavelength of the oscillation decreases and becomes comparable to the physical dimensions of the element. This is a fundamental of aerial theory.

This microwave emission phenomenon from GaAs was called the Gunn Effect after its discoverer.

ELECTRON BUNCHING

In the Gunn Effect, it was later found that when the GaAs rod is biased into the negative resistance region, and begins to emit microwaves, a bunch of electrons collects at one end of the rod near the contact and travels to the other end. As soon as it reaches the other end, another bunch forms at the first end and the process repeats itself. This occurred in step with the oscillations; in fact, it seemed to determine the frequency of the oscillations.

The electrons in the rod when it is in the negative resistance region do not behave like normal electrons in a normal positive resistance material. In a positive resistance material a bunch of electrons will be dispersed in a short time. In a negative resistance material, as the electrons travel along in the material due to the voltage applied to the material, any slight bunching up leads to a greater accumulation of electrons. This is because the bunching up creates a higher field in the area of the bunch due to the electrons' own charges.

This higher field affects the electrons in and near the bunch, which then slow down because of the negative velocity-field slope. Thus instead of dispersing, a further accumulation of electrons takes place and what is known as a domain forms and travels across the rod.

DOMAIN FORMATION

The actual nature of the domain is an accumulation of electrons preceded by a layer depleted of electrons. The overall number of electrons in the rod remains the same (Fig. 31).

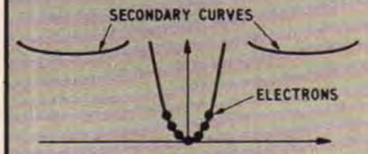

Fig. 29a

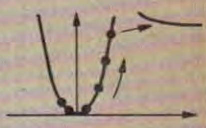

Fig. 29b

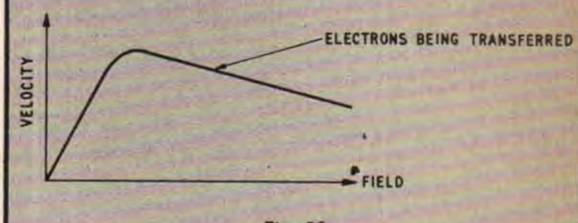

Fig. 30

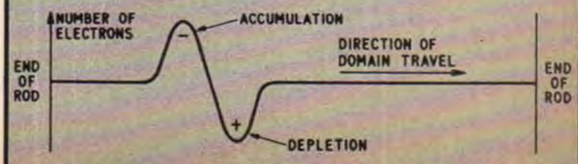

Fig. 31

The result of this domain formation and travel is to limit the high frequency response of the device. The frequency of the oscillations is tied to the transit-time of the domain across the rod. The domains will always form since natural inhomogenities in the GaAs will always result in uneveness in the electron distribution in the rod. This uneveness is most pronounced at the end of the rod where the electrical contacts are made, so that the domains form at the ends. Only one domain is sustained at a time; as the domain consists of electrons, it travels under the influence of the applied field to the other end of the rod. Another domain then forms at the first end and repeats the process.

EFFECTIVE CAPACITANCE

We may look at the high frequency limitation of the Gunn Effect device from another angle. The domain consists of a layer of accumulated electrons having a negative charge relative to the rest of the rod, and a depleted layer having a net positive charge. This is like a charged capacitor because the accumulated charge depends on the external applied field.

Thus like the tunnel diode, the Gunn Effect device is frequency-limited by this effective capacitance. However, it is able to oscillate in the microwave region of the electromagnetic spectrum.

THIN SLICES BY EPITAXIAL GROWTH

Clearly then, the high frequency microwave response is limited by the formation of the domains. In practice, the frequency limit is pushed up by making the domain transit-time as short as possible. This is done by making the distance between the contacts as short as possible, and thin slices of gallium arsenide and not rods are used as microwave oscillators.

These slices are formed by a process known as epitaxial growth, which also gives layers of the very high purity required for this purpose. Thin films of GaAs are deposited onto a heavily doped GaAs substrate which serves as one contact. A further thin film of heavily doped GaAs is deposited on the working layer to serve as the other contact (Fig. 32).

Microwaves of up to about 30GHz have been emitted from such devices. However, the restriction on the thickness of the slice limits the power capability of the device. As higher frequencies are reached by using thinner layers, the power output drops sharply.

THE LSA MODE

Since the frequency limitation is imposed by the moving domains, could we not get rid of them? If we could, such a GaAs slice would be able to function as a pure negative resistance device in an oscillator circuit.

J. E. Carroll, in early 1966, found that by putting a Gunn Effect device in a suitable circuit, the domain could be extinguished before it reached the other end. In the middle of 1966, M. W. Kennedy discovered that he could make a Gunn Effect device oscillate at a frequency far in excess of its usual one determined by the domain transit-time. J. A. Copeland then demonstrated theoretically and experimentally that in this case, the domains were being prevented from forming at all.

Here at last was the major breakthrough. The GaAs was now being used as a pure negative resistance oscillator, Fig. 33a, and the frequency of oscillations was determined by the external LC circuit (actually a cavity at microwave frequencies).

How were the domains prevented from forming? They form only when the GaAs is in the negative resistance region of the velocity-field curve. The GaAs slice was put in a resonating circuit and biased into the negative resistance region. A load impedance in the circuit was of such a value that the oscillating voltage across the load was large enough to bring the voltage bias across the GaAs slice at one end of each oscillatory swing into the positive resistance section of the velocity-field diagram (Fig. 33b).

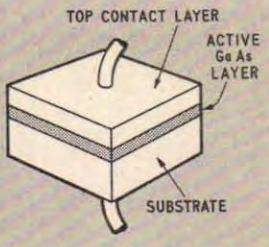

Fig. 32

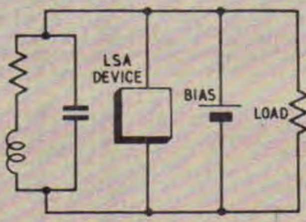

Fig. 33a

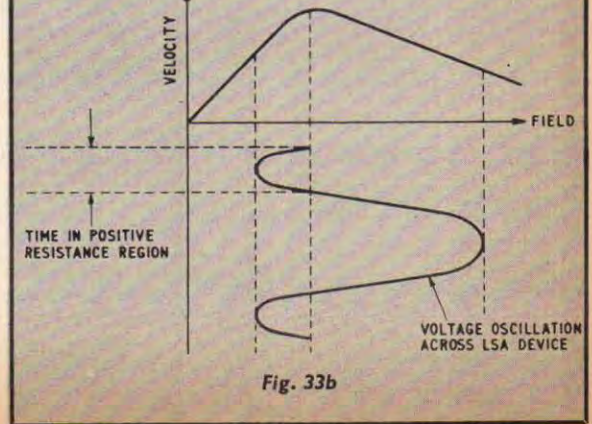

Fig. 33b

While the GaAs is in this section it has a normal positive resistance; thus the electrons do not accumulate to form a domain but will disperse in the normal way. The formation and existence of the domain can only take place between each swing into the positive resistance region, when the GaAs is back in the negative resistance region.

PURE NEGATIVE RESISTANCE

In the quenched domain mode observed by Carroll, the time between swings was long enough to permit domain formation, but short enough to quench the domain before it reached the other end of the slice. Now, if this time, which is determined by the frequency of the oscillation, were even shorter, the domains which take a finite time to form will not even have any chance to do so. Thus the GaAs slice can operate as a pure negative resistance device. This was achieved by Kennedy and Copeland.

The frequency of oscillation which is now determined by the resonant LC network must be high enough to prevent domain formation. This is a good thing, since it is the higher frequencies that we are interested in anyway.

HIGHER POWER POSSIBLE

Because there is no transit-time limitation on the devices, they do not have to be made very thin. They can be fairly long so that they can handle much greater powers than Gunn Effect devices at higher frequencies. Copeland has recommended that they be made long in the direction parallel to the current flow and thin in a perpendicular direction to the flow, so that heat can be easily removed from the sides of the devices (Fig. 34).

This mode of operation of gallium arsenide as a negative resistance material is known as the Limited Space-charge Accumulation (LSA) mode, since the electrons are prevented (limited) from accumulating to form space-charge (bunched charges).

LSA devices are the first true negative resistance devices which depend only on the properties of a bulk material and not on layers or junctions. It is interesting to note this further step in the decrease of the number of layers necessary in a semiconductor active device, compared to the three layers of the transistor and the two layers of the tunnel diode. Furthermore, each progressive step has pushed the frequency limit of oscillation higher.

THE FUTURE OF LSA DEVICES

LSA devices hold exciting promise for the future wider applications of microwave electronics. In the not too distant future one can envisage the commercial production of small portable radar sets.

Using Gunn Effect devices, prototype portable radar sets have been constructed and demonstrated by the Royal Radar Establishment.

The availability of tiny, simple and efficient microwave generators and oscillators at millimetre wavelengths brings nearer the day when the personal portable sound and colour television transceiver for communication with anybody else in the world is a working reality.

At the time of writing, Copeland has obtained 20mW output of c.w. microwaves at 88GHz with GaAs slices operating in the LSA mode. The GaAs slices were thin and originally intended for operation in the Gunn Effect mode. When proper LSA devices to Copeland's design have been constructed, they will undoubtedly be able to generate much higher powers.

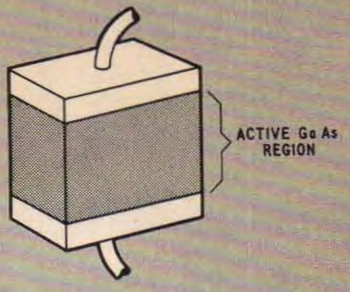

Fig. 34

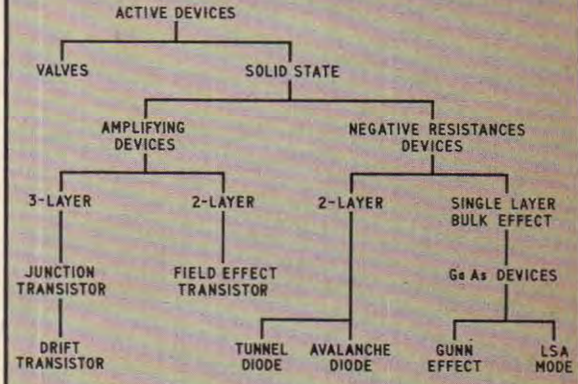

Fig. 35

Even then, the powers already obtained are much higher than those ever generated by previous semiconductor active devices at such high frequencies.

INTENSE RESEARCH

Research on LSA devices is now proceeding intensely in many laboratories and gaining momentum with each week. The writer is certain that by the time this article appears, significant progress will have been made in the practical construction, operation and application of these devices.

As a matter of interest, a chart (Fig. 35) showing the progress of the development, and the relationships of active devices is included. ★

MUSICAL PHASE

In the article *Musical Phase* (September) the name of the co-author M. G. Lewis B.Sc., was inadvertently omitted. Mr. Lewis was in fact responsible for the invention of the Pradge phase generating equipment described in this article.