YBN University, Ranchi, Jharkhand-834010

Unit-3

MICROWAVE TUBE

KLYSTRON

5kW klystron tube used as power amplifier in UHF television transmitter, 1952. When installed, the tube projects through holes in the center of the cavity resonators, with the sides of the cavities making contact with the metal rings on the tube.

A **klystron** is a specialized linear-beam vacuum tube, invented in 1937 by American electrical engineers Russel and Sigurd Varian,[1] which is used as an amplifier for high radio frequencies, from UHF up into the microwave range. Low-power klystrons are used as oscillators in terrestrial microwave relay communications links, while high-power klystrons are used as output tubes in UHF television transmitters, satellite communication, and radar transmitters, and to generate the drive power for modern particle accelerators.

In a klystron, an electron beam interacts with radio waves as it passes through resonant cavities, metal boxes along the length of a tube.[2] The electron beam first passes through a cavity to which the input signal is applied. The energy of the electron beam amplifies the signal, and the amplified signal is taken from a cavity at the other end of the tube. The output signal can be coupled back into the input cavity to make an electronic oscillator to generate radio waves. The gain of klystrons can be high, 60 dB (one million) or more, with output power up to tens of megawatts, but the bandwidth is narrow, usually a few percent although it can be up to 10% in some devices.[2]

A *reflex klystron* is an obsolete type in which the electron beam was reflected back along its path by a high potential electrode, used as an oscillator.

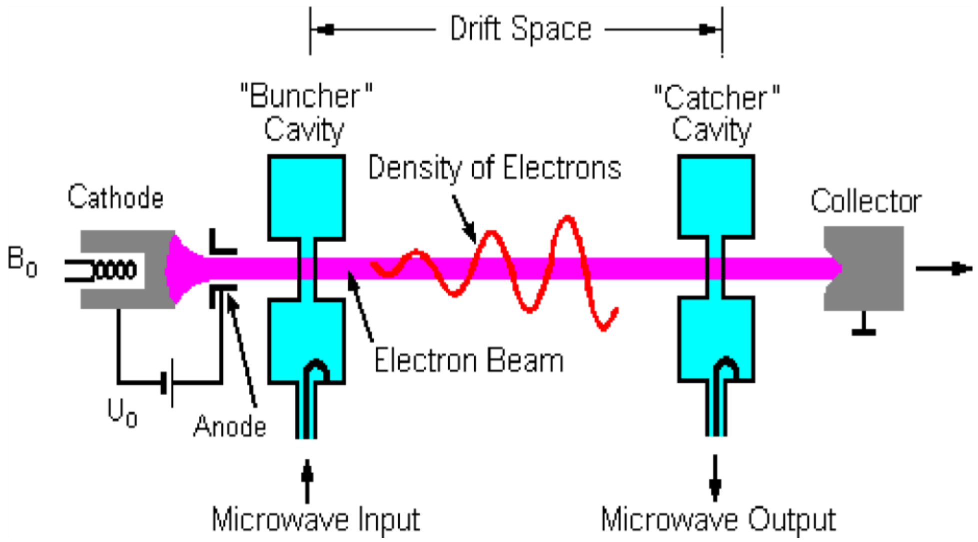
The name *klystron* comes from the stem form κλυσ- (*klys*) of a Greek verb referring to the action of waves breaking against a shore, and the suffix -τρον ("tron") meaning the place where the action happens.[3] The name "klystron" was suggested by Hermann Fränkel, a professor in the classics department at Stanford University when the klystron was under development.[4]

OPERATION

Klystrons amplify RF signals by converting the kinetic energy in a DC electron beam into radio frequency power. A beam of electrons is produced by a thermionic cathode (a heated pellet of low work function material), and accelerated by high-voltage electrodes (typically in the tens of kilovolts). This beam is then passed through an input cavity resonator. RF energy is fed into the input cavity at, or near, its resonant frequency, creating standing waves, which produce an oscillating voltage which acts on the electron beam. The electric field causes the electrons to "bunch": electrons that pass through when the electric field opposes their motion are slowed, while electrons which pass through when the electric field is in the same direction are accelerated, causing the previously continuous electron beam to form bunches at the input frequency. To reinforce the bunching, a klystron may contain additional "buncher" cavities. The beam then passes through a "drift" tube in which the faster electrons catch up to the slower ones, creating the "bunches", then through a "catcher" cavity. In the output "catcher" cavity, each bunch enters the cavity at the time in the cycle when the electric field opposes the electrons' motion, decelerating them. Thus the kinetic energy of

the electrons is converted to potential energy of the field, increasing the amplitude of the oscillations. The oscillations excited in the catcher cavity are coupled out through a coaxial cable or waveguide. The spent electron beam, with reduced energy, is captured by a collector electrode.
To make an oscillator, the output cavity can be coupled to the input cavity(s) with a coaxial cable or waveguide. Positive feedback excites spontaneous oscillations at the resonant frequency of the cavities.

TWO-CAVITY KLYSTRON AMPLIFIER



The simplest klystron tube is the two-cavity klystron. In this tube there are two microwave cavity resonators, the "catcher" and the "buncher". When used as an amplifier, the weak microwave signal to be amplified is applied to the buncher cavity through a coaxial cable or waveguide, and the amplified signal is extracted from the catcher cavity.

At one end of the tube is the hot cathode heated by a filament which produces electrons. The electrons are attracted to and pass through an anode cylinder at a high positive potential; the cathode and anode act as an electron gun to produce a high velocity stream of electrons. An external electromagnet winding creates a longitudinal magnetic field along the beam axis which prevents the beam from spreading.

The beam first passes through the "buncher" cavity resonator, through grids attached to each side. The buncher grids have an oscillating AC potential across them, produced by standing wave oscillations within the cavity, excited by the input signal at the cavity's resonant frequency applied by a coaxial cable or waveguide. The direction of the field between the grids changes twice per cycle of the input signal. Electrons entering when the entrance grid is negative and the exit grid is positive encounter an electric field in the same direction as their motion, and are accelerated by the field. Electrons entering a half-cycle later, when the polarity is opposite, encounter an electric field which opposes their motion, and are decelerated.

Beyond the buncher grids is a space called the *drift space*. This space is long enough so that the accelerated electrons catch up to the retarded electrons, forming "bunches" longitudinally along the beam axis. Its length is chosen to allow maximum bunching at the resonant frequency, and may be several feet long.

Klystron oscillator from 1944. The electron gun is on the right, the collector on the left. The two cavity resonators are in center, linked by a short coaxial cable to provide positive feedback.

The electrons then pass through a second cavity, called the "catcher", through a similar pair of grids on each side of the cavity. The function of the *catcher grids* is to absorb energy from the electron beam. The bunches of electrons passing through excite standing waves in the cavity, which has the same resonant frequency as the buncher cavity. Each bunch of electrons passes between the grids at a point in the cycle when the exit grid is negative with respect to the entrance grid, so the electric field in the cavity between the grids opposes the electrons motion. The electrons thus do work on the electric field, and are decelerated, their kinetic energy is converted to electric potential energy, increasing the amplitude of the oscillating electric field in the cavity. Thus the oscillating field in the catcher cavity is an amplified copy of the signal applied to the buncher cavity. The amplified signal is extracted from the catcher cavity through a coaxial cable or waveguide.

After passing through the catcher and giving up its energy, the lower energy electron beam is absorbed by a "collector" electrode, a second anode which is kept at a small positive voltage.

KLYSTRON OSCILLATOR

An electronic oscillator can be made from a klystron tube, by providing a feedback path from output to input by connecting the "catcher" and "buncher" cavities with a coaxial cable or waveguide. When the device is turned on, electronic noise in the cavity is amplified by the tube and fed back from the output catcher to the buncher cavity to be amplified again. Because of the high Q of the cavities, the signal quickly becomes a sine wave at the resonant frequency of the cavities.

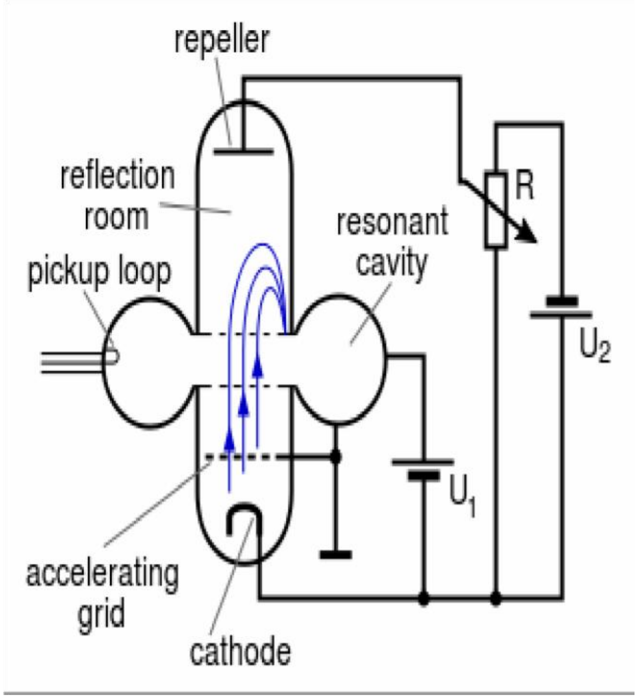
MULTICAVITY KLYSTRON

In all modern klystrons, the number of cavities exceeds two. Additional "buncher" cavities added between the first "buncher" and the "catcher" may be used to increase the gain of the klystron, or to increase the bandwidth.

The residual kinetic energy in the electron beam when it hits the collector electrode represents wasted energy, which is dissipated as heat, which must be removed by a cooling system. Some modern klystrons include depressed collectors, which recover energy from the beam before collecting the electrons, increasing efficiency. Multistage depressed collectors enhance the energy recovery by "sorting" the electrons in energy bins.

REFLEX KLYSTRON

Low-power Russian reflex klystron from 1963. The cavity resonator from which the output is taken, is attached to the electrodes labeled *Externer Resonator*. Reflex klystrons are almost obsolete now.



The reflex klystron (also known as a Sutton tube after one of its inventors, Robert Sutton) was a low power klystron tube with a single cavity, which functioned as an oscillator. It was used as a local oscillator in some radar receivers and a modulator in microwave transmitters the 1950s and 60s, but is now obsolete, replaced by semiconductor microwave devices.

In the reflex klystron the electron beam passes through a single resonant cavity. The electrons are fired into one end of the tube by an electron gun. After passing through the resonant cavity they are reflected by a negatively charged reflector electrode for another pass through the cavity, where they are then collected. The electron beam is velocity modulated when it first passes through the cavity. The formation of electron bunches takes place in the drift space between the reflector and the cavity. The voltage on the reflector must be adjusted so that the bunching is at a maximum as the electron beam re-enters the resonant cavity, thus ensuring a maximum of energy is transferred from the electron beam to the RF oscillations in the cavity. The reflector voltage may be varied slightly from the optimum value, which results in some loss of output power, but also in a variation in frequency. This effect is used to good advantage for automatic frequency control in receivers, and in frequency modulation for transmitters. The level of modulation applied for transmission is small enough that the power output essentially remains constant. At regions far from the optimum voltage, no oscillations are obtained at all.

There are often several regions of reflector voltage where the reflex klystron will oscillate; these are referred to as modes. The electronic tuning range of the reflex klystron is usually referred to as the variation in frequency between half power points—the points in the oscillating mode where the power output is half the maximum output in the mode.

Modern semiconductor technology has effectively replaced the reflex klystron in most applications.

FLOATING DRIFT TUBE KLYSTRON

The floating drift tube klystron has a single cylindrical chamber containing an electrically isolated central tube. Electrically, this is similar to the two cavity oscillator klystron with a lot of feedback between the two cavities. Electrons exiting the source cavity are velocity modulated by the electric field as they travel through the drift tube and emerge at the destination chamber in bunches, delivering power to the oscillation in the cavity. This type of oscillator klystron has an advantage over the two-cavity klystron on which it is based. It only needs one tuning element to effect changes in frequency. The drift tube is electrically insulated from the cavity walls, and DC bias is applied separately. The DC bias on the drift tube may be adjusted to alter the transit time through it, thus allowing some electronic tuning of the oscillating frequency. The amount of tuning in this manner is not large and is normally used for frequency modulation when transmitting.

APPLICATIONS

Klystrons can produce far higher microwave power outputs than solid state microwave devices such as Gunn diodes. In modern systems, they are used from UHF (hundreds of MHz) up through hundreds of GHz (as in the Extended Interaction Klystrons in the CloudSat satellite). Klystrons can be found at work in radar, satellite and wideband high-power communication (very common in television broadcasting and EHF satellite terminals), medicine (radiation oncology), and high- energy physics (particle accelerators and experimental reactors). At SLAC, for example, klystrons are routinely employed which have outputs in the range of 50 MW (pulse) and 50 kW (time- averaged) at 2856 MHz. The Arecibo Planetary Radar uses two klystrons that provide a total power output of 1 MW (continuous) at 2380 MHz.[9]

Popular Science's "Best of What's New 2007"[10][11] described a company, Global Resource Corporation, currently defunct, using a klystron to convert the hydrocarbons in everyday materials, automotive waste, coal, oil shale, and oil sands into natural gas and diesel fuel.

TRAVELING-WAVE TUBE

A **traveling-wave tube** (**TWT**) is a specialized vacuum tube that is used in electronics to amplify radio frequency (RF) signals in the microwave range.[1] The TWT belongs to a category of "linear beam" tubes, such as the klystron, in which the radio wave is amplified by absorbing power from a beam of electrons as it passes down the tube.[1] Although there are various types of TWT, two major categories are:[1]

Helix TWT

> In which the radio waves interact with the electron beam while traveling down a wire helix which surrounds the beam. These have wide bandwidth, but output power is limited to a few hundred watts.[2]

Coupled cavity TWT

> In which the radio wave interacts with the beam in a series of cavity resonators through which the beam passes. These function as narrowband power amplifiers.

A major advantage of the TWT over some other microwave tubes is its ability to amplify a wide range of frequencies, a wide bandwidth. The bandwidth of the helix TWT can be as high as two octaves, while the cavity versions have bandwidths of 10–20%.[1][2] Operating frequencies range from 300 MHz to 50 GHz.[1][2] The power gain of the tube is on the order of 40 to 70 decibels,[2] and output power ranges from a few watts to megawatts.[1][2]

TWTs account for over 50% of the sales volume of all microwave vacuum tubes.[1] They are widely used as the power amplifiers and oscillators in radar systems, communication satellite and spacecraft transmitters, and electronic warfare systems.[1]

A TWT has sometimes been referred to as a **traveling-wave amplifier tube** (**TWAT**),[3] although this term was never widely adopted. "TWT" has been pronounced by engineers as "twit",[4] and "TWTA" as "tweeta".[5]

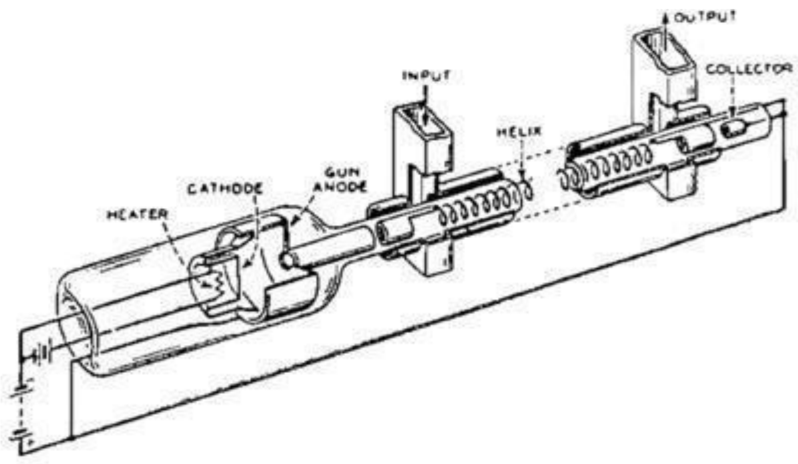


Diagram of helix TWT

BASIC TWT

The TWT is an elongated vacuum tube with an electron gun (a heated cathode that emits electrons) at one end. A voltage applied across the cathode and anode accelerates the electrons towards the far end of the tube, and an external magnetic field around the tube focuses the electrons into a beam. At the other end of the tube the electrons strike the "collector", which returns them to the circuit.

Wrapped around the inside of the tube, just outside the beam path, is a helix of wire, typically oxygen-free copper. The RF signal to be amplified is fed into the helix at a point near the emitter end of the tube. The signal is normally fed into the helix via a waveguide or electromagnetic coil placed at one end, forming a one-way signal path, a directional coupler.

By controlling the accelerating voltage, the speed of the electrons flowing down the tube is set to be similar to the speed of the RF signal running down the helix. The signal in the wire causes a magnetic field to be induced in the center of the helix, where the electrons are flowing. Depending on the phase of the signal, the electrons will either be sped up or slowed down as they pass the windings. This causes the electron beam to "bunch up", known technically as "velocity modulation". The resulting pattern of electron density in the beam is an analog of the original RF signal.

Because the beam is passing the helix as it travels, and that signal varies, it causes induction in the helix, amplifying the original signal. By the time it reaches the other end of the tube, this process has had time to deposit considerable energy back into the helix. A second directional coupler, positioned near the collector, receives an amplified version of the input signal from the far end of the RF circuit. Attenuators placed along the RF circuit prevent the reflected wave from traveling back to the cathode.

Higher powered helix TWTs usually contains beryllium oxide ceramic as both a helix support rod and in some cases, as an electron collector for the TWT because of its special electrical, mechanical, and thermal properties.[6][7]

Coupled-cavity TWT

Helix TWTs are limited in peak RF power by the current handling (and therefore thickness) of the helix wire. As power level increases, the wire can overheat and cause the helix geometry to warp. Wire thickness can be increased to improve matters, but if the wire is too thick it becomes impossible to obtain the required helix pitch for proper operation. Typically helix TWTs achieve less than 2.5 kW output power.

The **coupled-cavity TWT** overcomes this limit by replacing the helix with a series of coupled cavities arranged axially along the beam. This structure provides a helical waveguide, and hence amplification can occur via velocity modulation. Helical waveguides have very nonlinear dispersion and thus are only narrowband (but wider than klystron). A coupled-cavity TWT can achieve 60 kW output power.

Operation is similar to that of a klystron, except that coupled-cavity TWTs are designed with attenuation between the slow-wave structure instead of a drift tube. The slow-wave structure gives the TWT its wide bandwidth. A free electron laser allows higher frequencies.

TRAVELING-WAVE-TUBE AMPLIFIER

A TWT integrated with a regulated power supply and protection circuits is referred to as a traveling-wave-tube amplifier[10] (abbreviated **TWTA** and often pronounced "TWEET-uh"). It is used to produce high-power radio frequency signals. The bandwidth of a broadband TWTA can be as high as one octave,[*citation needed*] although tuned (narrowband) versions exist; operating frequencies range from 300 MHz to 50 GHz.

A TWTA consists of a traveling-wave tube coupled with its protection circuits (as in klystron) and regulated power supply electronic power conditioner (EPC), which may be supplied and integrated by a different manufacturer. The main difference between most power supplies and those for vacuum tubes is that efficient vacuum tubes have depressed collectors to recycle kinetic energy of the electrons, so the secondary winding of the power supply needs up to 6 taps of which the helix voltage needs precise regulation. The subsequent addition of a liberalizer (as for inductive output tube) can, by complementary compensation, improve the gain compression and other characteristics of the TWTA; this combination is called a linear zed TWTA (LTWTA, "EL-tweet- uh").
Broadband TWTAs generally use a helix TWT, and achieve less than 2.5 kW output power. TWTAs using a coupled cavity TWT can achieve 15 kW output power, but at the expense of bandwidth.

USES

TWTAs are commonly used as amplifiers in satellite transponders, where the input signal is very weak and the output needs to be high power.[23]

A TWTA whose output drives an antenna is a type of transmitter. TWTA transmitters are used extensively in radar, particularly in airborne fire-control radar systems, and in electronic warfare and self-protection systems.[24] In such applications, a control grid is typically introduced between the TWT's electron gun and slow-wave structure to allow pulsed operation. The circuit that drives the control grid is usually referred to as a grid modulator.

Another major use of TWTAs is for the electromagnetic compatibility (EMC) testing industry for immunity testing of electronic devices.[*citation needed*]

TWTAs can often be found in older (pre-1995) aviation SSR microwave transponders.

TRAVELING WAVE TUBE

Since Kompfner invented the helix traveling-wave tube (TWT) in 1944 its basic circuit has changed little. For broadband applications, the helix TWTs are almost exclusively used, whereas for high-average- power purposes, such as radar transmitters, the coupled-cavity TWTs are commonly used.

In previous sections klystrons and reflex klystrons were analyzed in some detail. Before starting to describe the TWT, it seems appropriate to compare the basic operating principles of both the TWT and the klystron. In the case of the TWT, the microwave circuit is nonresonant and the wave propagates with the same speed as the electrons in the beam. The initial effect on the beam is a small amount of velocity modulation caused by the weak electric fields associated with the traveling wave.

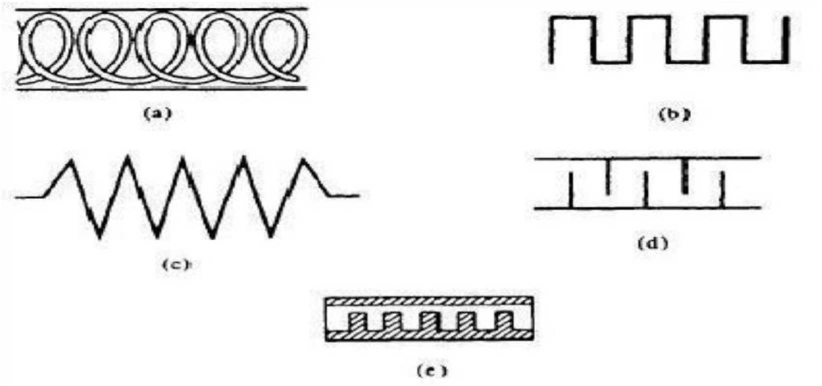
Just as in the klystron, this velocity modulation later translates to current modulation, which then induces an RF current in the circuit, causing amplification. However, there are some major differences between the TWT and the klystron:

The interaction of electron beam and RF field in the TWT is continuous over the entire length of the circuit, but the interaction in the klystron occurs only at the gaps of a few resonant cavities.

The wave in the TWT is a propagating wave; the wave in the klystron is not.

In the coupled-cavity TWT there is a coupling effect between the cavities, whereas each cavity in the klystron operates independently.

As the operating frequency is increased, both the inductance and capacitance of the resonant circuit must be decreased in order to maintain resonance at the operating frequency. Because the gain-bandwidth product is limited by the resonant circuit, the ordinary resonator cannot generate a large output. Several nonresonant periodic circuits or slow-wave structures (see Fig. 9-5-2) are designed for producing large gain over a wide bandwidth.



Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity in a certain direction so that the electron beam and the signal wave can interact. The phase velocity of a wave in ordinary waveguides is greater than the velocity of light in a vacuum.

In the operation of traveling-wave and magnetron-type devices, the electron beam must keep in step with the microwave signal. Since the electron beam can be accelerated only to velocities that are about a fraction of the velocity of light, a slow-wave structure must be incorporated in the microwave devices so that the phase velocity of the microwave signal can keep pace with that of the electron beam for effective interactions. Several types of slow-wave structures are shown in figure.

$$\frac{v_p}{c} = \frac{p}{\sqrt{p^2 + (\pi d)^2}} = \sin \psi$$

MAGNETRON

MAGNETRON OSCILLATORS

Hull invented the magnetron in 1921 [1], but it was only an interesting laboratory device until about 1940. During World War II, an urgent need for high-power microwave generators for radar transmitters led to the rapid development of the magnetron to its present state.

All magnetrons consist of some form of anode and cathode operated in a de magnetic field normal to of the crossed field between the cathode and anode, the electrons emitted from the cathode are influenced by the crossed field to move in curved paths. If the de magnetic field is strong enough, the electrons will not arrive in the anode but return instead to the cathode.

Consequently, the anode current is cut off.
Magnetrons can be classified into three types:

1. *Split-anode magnetron:* This type of magnetron uses a static negative resistance between two anode segments.
2. *Cyclotron-frequency magnetrons:* This type operates under the influence of synchronism between an alternating component of electric field and a periodic oscillation of electrons in a direction parallel to the field.
3. *Traveling-wave magnetrons:* This type depends on the interaction of electrons with a traveling electromagnetic field of linear velocity. They are customarily referred to simply as *magnetrons.*

Cylindrical Magnetron

A schematic diagram of a cylindrical magnetron oscillator is shown in Fig. 10-1-1. This type of magnetron is also called a *conventional magnetron.*

In a cylindrical magnetron, several reentrant cavities are connected to the gaps. The de voltage *Vo* is applied between the cathode and the anode. The magnetic flux density *Bo* is in the positive *z* direction. When the de voltage and the magnetic flux are adjusted properly, the electrons will follow cycloidal paths in the cathodeanode space under the combined force of both electric and magnetic fields as shown in Fig. 10-1-2.

Equations of electron motion. The equations of motion for electrons in a cylindrical magnetron can be written with the aid of Eqs.(l-2-Sa) and (1-2-

Sb) as

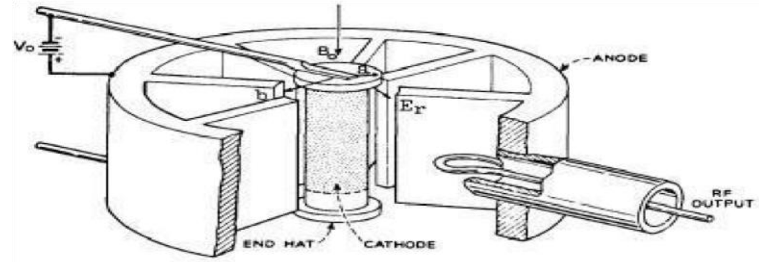


Figure 10-1-1 Schematic diagram of a cylindrical magnetron.

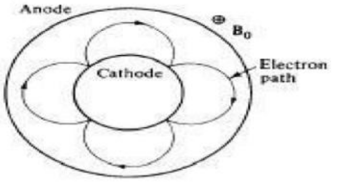


Figure 10-1-2 Electron path in a cylindrical magnetron.

$$\frac{d^2r}{dt^2} - r\left(\frac{d\phi}{dt}\right)^2 = \frac{e}{m}E_r - \frac{e}{m}rB_z\frac{d\phi}{dt} \qquad (10\text{-}1\text{-}1)$$

$$\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\phi}{dt}\right) = \frac{e}{m}B_z\frac{dr}{dt} \qquad (10\text{-}1\text{-}2)$$

where $\frac{e}{m} = 1.759 \times 10^{11}$ C/kg is the charge-to-mass ratio of the electron and $B_0 = B_z$ is assumed in the positive z direction.

Rearrangement of Eq. (10-1-2) results in the following form

$$\frac{d}{dt}\left(r^2\frac{d\phi}{dt}\right) = \frac{e}{m}B_z r\frac{dr}{dt} = \frac{1}{2}\omega_c\frac{d}{dt}(r^2) \qquad (10\text{-}1\text{-}3)$$

where $\omega_c = \frac{e}{m}B_z$ is the cyclotron angular frequency. Integration of Eq. (10-1-3) yields

$$r^2\frac{d\phi}{dt} = \frac{1}{2}\omega_c r^2 + \text{constant} \qquad (10\text{-}1\text{-}4)$$

at $r = a$, where a is the radius of the cathode cylinder, and $\frac{d\phi}{dt} = 0$, constant $= -\frac{1}{2}\omega_c a^2$. The angular velocity is expressed by

$$\frac{d\phi}{dt} = \frac{1}{2}\omega_c\left(1 - \frac{a^2}{r^2}\right) \tag{10-1-5}$$

Since the magnetic field does no work on the electrons, the kinetic energy of the electron is given by

$$\frac{1}{2}m\mathcal{V}^2 = eV \tag{10-1-6}$$

However, the electron velocity has r and ϕ components such as

$$\mathcal{V}^2 = \frac{2e}{m}V = \mathcal{V}_r^2 + \mathcal{V}_\phi^2 = \left(\frac{dr}{dt}\right)^2 + \left(r\frac{d\phi}{dt}\right)^2 \tag{10-1-7}$$

at $r = b$, where b is the radius from the center of the cathode to the edge of the anode, $V = V_0$, and $dr/dt = 0$, when the electrons just graze the anode, Eqs. (10-1-5) and (10-1-7) become

$$\frac{d\phi}{dt} = \frac{1}{2}\omega_c\left(1 - \frac{a^2}{b^2}\right) \tag{10-1-8}$$

$$b^2\left(\frac{d\phi}{dt}\right)^2 = \frac{2e}{m}V_0 \tag{10-1-9}$$

Substitution of Eq. (10-1-8) into Eq. (10-1-9) results in

$$b^2\left[\frac{1}{2}\omega_c\left(1 - \frac{a^2}{b^2}\right)\right]^2 = \frac{2e}{m}V_0 \tag{10-1-10}$$

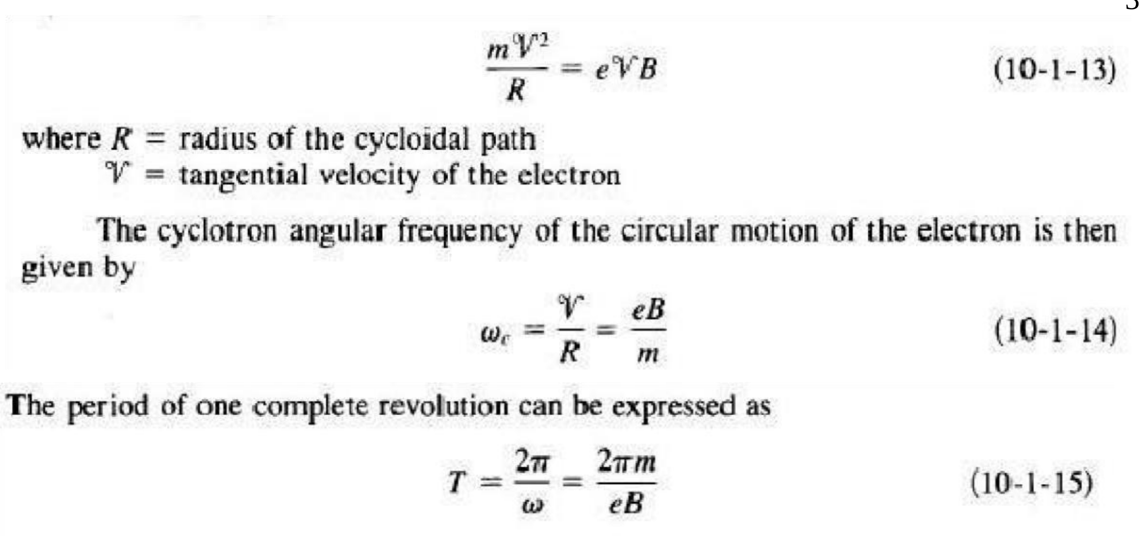
The electron will acquire a tangential as well as a radial velocity. Whether the electron will just graze the anode and return toward the cathode depends on the relative magnitudes of V_0 and B_0. The *Hull cutoff magnetic equation* is obtained from Eq. (10-1-10) as

$$B_{0c} = \frac{\left(8V_0\frac{m}{e}\right)^{1/2}}{b\left(1 - \frac{a^2}{b^2}\right)} \tag{10-1-11}$$

This means that if $B_0 > B_{0c}$ for a given V_0, the electrons will not reach the anode. Conversely, the cutoff voltage is given by

$$V_{0c} = \frac{e}{8m}B_0^2 b^2\left(1 - \frac{a^2}{b^2}\right)^2 \tag{10-1-12}$$

Cyclotron angular frequency. Since the magnetic field is normal to the motion of electrons that travel in a cycloidal path, the outward centrifugal force is equal to the pulling force. Hence



$$\frac{m\mathcal{V}^2}{R} = e\mathcal{V}B \qquad (10\text{-}1\text{-}13)$$

where R = radius of the cycloidal path
$\mathcal{V}$ = tangential velocity of the electron

The cyclotron angular frequency of the circular motion of the electron is then given by

$$\omega_c = \frac{\mathcal{V}}{R} = \frac{eB}{m} \qquad (10\text{-}1\text{-}14)$$

The period of one complete revolution can be expressed as

$$T = \frac{2\pi}{\omega} = \frac{2\pi m}{eB} \qquad (10\text{-}1\text{-}15)$$

Since the slow-wave structure is closed on itself, or "reentrant," oscillations are possible only if the total phase shift around the structure is an integral multiple of 27T radians. Thus, if there are *N* reentrant cavities in the anode structure, the phase shift between two adjacent cavities can be expressed as

$$\phi_n = \frac{2\pi m}{N} \qquad (10\text{-}1\text{-}16)$$

where *n* is an integer indicating the *nth* mode of oscillation. In order for oscillations to be produced in the structure, the anode de voltage must be adjusted so that the average rotational velocity of the electrons corresponds to the phase velocity of the field in the slow-wave structure.

Magnetron oscillators are ordinarily operated in the 7T mode. That is

$$\phi_n = \pi \qquad (\pi \text{ mode}) \qquad (10\text{-}1\text{-}17)$$

$$\beta_0 = \frac{2\pi n}{NL} \qquad (10\text{-}1\text{-}18)$$

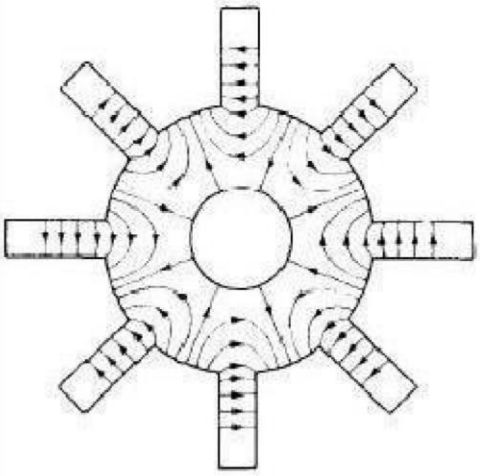


Figure 10-1-3 Lines of force in π mode of eight-cavity magnetron.

Maxwell's equations subject to the boundary conditions. The solution for the fundamental *cf>* component of the electric field has the form [l]

$$E_{\phi 0} = jE_1 e^{j(\omega t - \beta_0 \phi)} \qquad (10\text{-}1\text{-}19)$$

where £ 1 is a constant and *f3o* is given in Eq. (10-1-18). Thus, the traveling field of the fundamental mode travels around the structure with angular velocity

$$\frac{d\phi}{dt} = \frac{\omega}{\beta_0} \qquad (10\text{-}1\text{-}20)$$

where~ can be found from Eq. (10-1-19). When the cyclotron frequency of the electrons is equal to the angular frequency of the field, the interactions between the field and electron occurs and the energy is transferred. That is,

$$\omega_c = \beta_0 \frac{d\Phi}{dt} \qquad (10\text{-}1\text{-}21)$$

TRANSFERRED ELECTRON DEVICES

The application of two-terminal semiconductor devices at microwave frequencies has been increased usage during the past decades. The CW, average, and peak power outputs of these devices at higher microwave frequencies are much larger than those obtainable with the best power transistor. The common characteristic of all active two-terminal solid-state devices is their negative resistance. The real part of their impedance is negative over a range of frequencies.

In a positive resistance the current through the resistance and the voltage across it are in phase. The voltage drop across a positive resistance is positive and a power of (/2 R) is dissipated in the resistance. In a negative resistance, however, the current and voltage are out of phase by 180°. The voltage drop across a negative resistance is negative, and a power of (-/ 2 R) is generated by the power supply associated with the negative resistance. In other words, positive resistances absorb power (passive devices), whereas negative resistances generate power (activedevices).

In this chapter the transferred electron devices (TEDs) are analyzed. The differences between microwave transistors and transferred electron devices (TEDs) are fundamental. Transistors operate with either junctions or gates, but TEDs are bulk devices having no junctions or gates. The majority of transistors are fabricated from elemental semiconductors, such as silicon or germanium, whereas TEDs are fabricated from compound semiconductors, such as gallium arsenide (GaAs), indium phosphide (InP), or cadmium telluride (CdTe). Transistors operate with "warm" electrons whose energy is not much greater than the thermal energy (0.026 eV at room temperature) of electrons in the semiconductor, whereas TEDs operate with "hot" electrons whose energy is very much greater than the thermal energy. Because of these fundamental differences, the theory and technology of transistors cannot be applied to TEDs.

GUNN DIODE

Gunn Effect:

Gun effect was first observed by GUNN in n_type GaAs bulk diode. According to GUNN, above some critical voltage corresponding to an electric field of 2000-4000v/cm, the current in every specimen became a fluctuating fuction of time. The frequency of oscillation was determined mainly by the specimen and not by the external circuit.

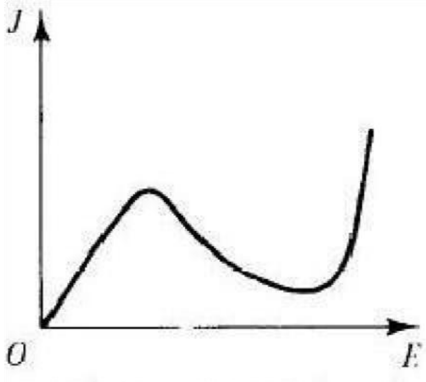
RIDLEY-WATKINS-HILSUM (RWH} THEORY

Differential Negative Resistance

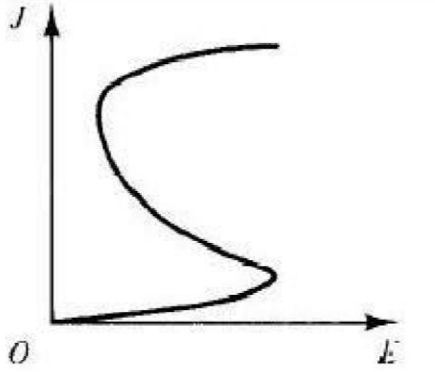
The fundamental concept of the Ridley-Watkins-Hilsum (RWH) theory is the differential negative resistance developed in a bulk solid-state Ill-Y compound when either a voltage (or electric field) or a current is applied to the terminals of the sample.

There are two modes of negative-resistance devices:
i) Voltage-controlled and ***ii)*** **current controlled**

modes as shown in Fig.

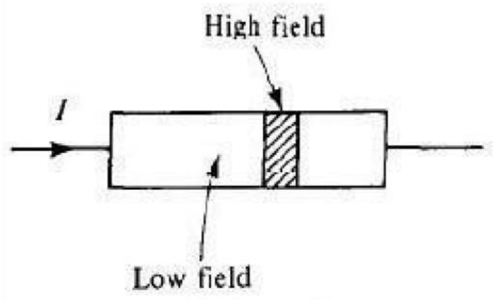


(a) Voltage-controlled mode

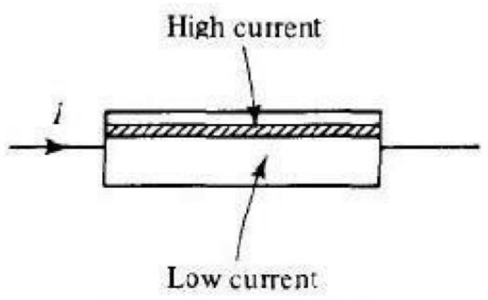


(b) Current-controlled mode

In the voltage-controlled mode the current density can be multivalued, whereas in the current-controlled mode the voltage can be multivalued.



(a) High-field domain



(b) High-current filament

The major effect of the appearance of a differential negative-resistance region in the currentdensity- field curve is to render the sample electrically unstable. As a result, the initially homogeneous sample becomes electrically heterogeneous in an attempt to reach stability.

In the voltage-controlled negative-resistance mode high-field domains are formed, separating two low- field regions. The interfaces separating lowand high-field domains lie along equipotentials;

thus they are in planes perpendicular to the current direction as shown in Fig. 7-2-2(a). In the current- controlled negative-resistance mode splitting the sample results in high-current filaments running along the field direction as shown in Fig. 7-2-2(b).

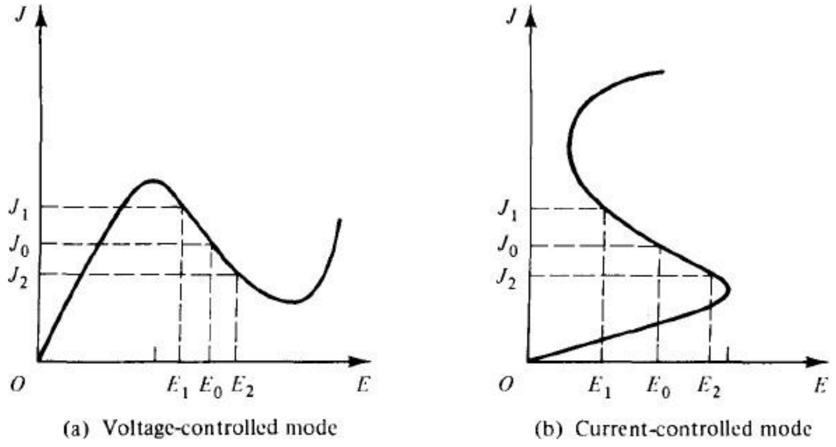
Expressed mathematically, the negative resistance of the sample at a particular region is

$$\frac{dI}{dV} = \frac{dJ}{dE} = \text{negative resistance} \qquad (7\text{-}2\text{-}1)$$

If an electric field *Eo* (or voltage *Vo)* is applied to the sample, for example, the current density is generated. As the applied field (or voltage) is increased to *E2* (or *V2)*, the current density is decreased to *J2.*

When the field (or voltage) is decreased to E1 (or V1), the current density is increased to J1 . These phenomena of the voltage controlled negative resistance are shown in Fig. 7-2-3(a).

Similarly, for the current controlled mode, the negative-resistance profile is as shown in Fig. 7-2-3(b).

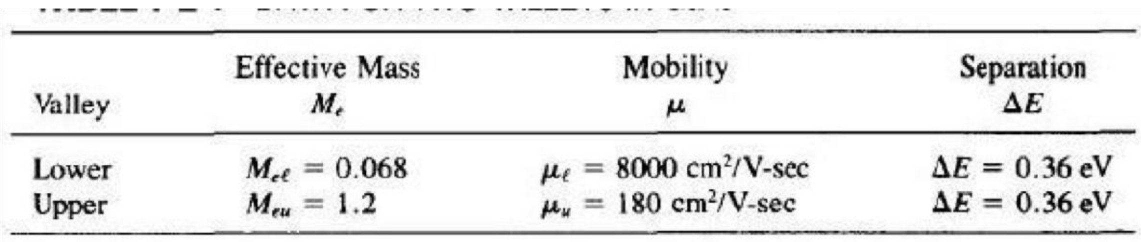


(a) Voltage-controlled mode

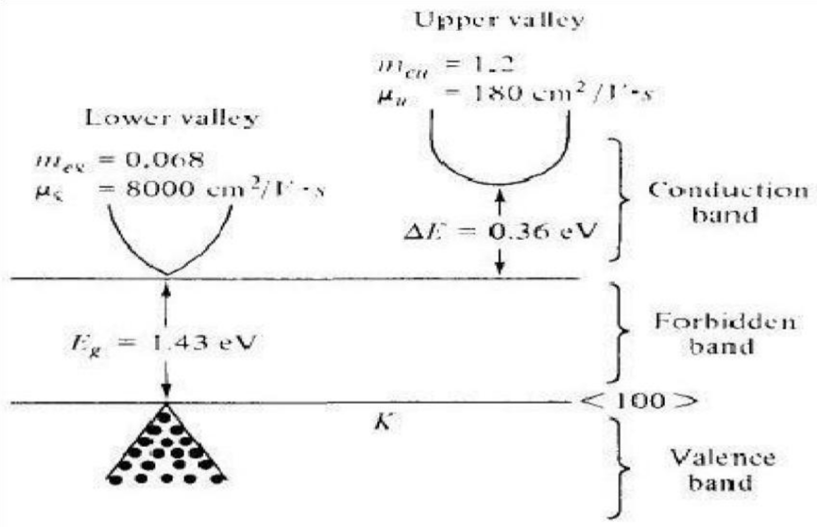
(b) Current-controlled mode

Two-Valley Model Theory

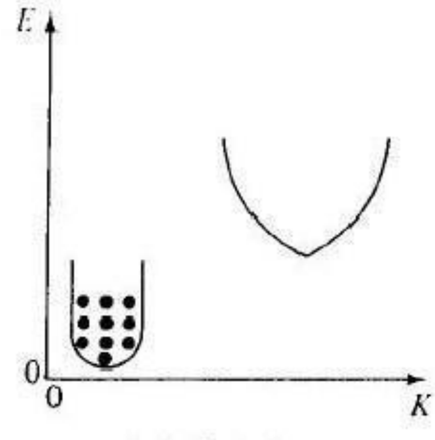
According to the energy band theory of then-type GaAs, a high-mobility lower valley is separated by an energy of 0.36 eV from a low-mobility upper valley



Valley	Effective Mass M_e	Mobility μ	Separation ΔE
Lower	$M_{e\ell} = 0.068$	$\mu_\ell = 8000\ \text{cm}^2/\text{V-sec}$	$\Delta E = 0.36$ eV
Upper	$M_{eu} = 1.2$	$\mu_u = 180\ \text{cm}^2/\text{V-sec}$	$\Delta E = 0.36$ eV

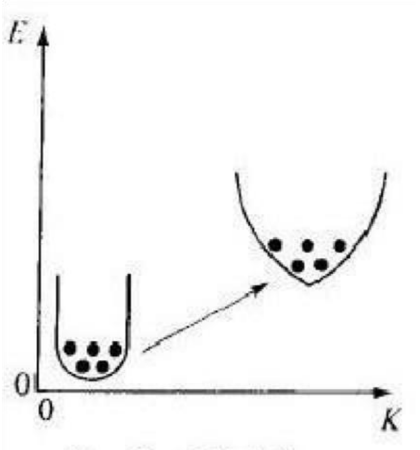


When the applied electric field is lower than the electric field of the lower valley (£ < *Ec)*, no electrons will transfer to the upper valley as show in Fig. 7-2-S(a).



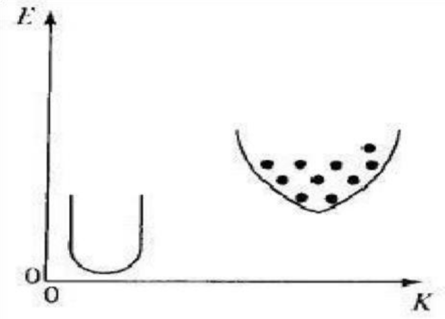
(a) $E < E_\ell$

When the applied electric field is higher than that of the lower valley and lower than that of the upper valley *(Ec < E < Eu)*, electrons will begin to transfer to the upper valley as shown in Fig. 7-2-S(b).



(b) $E_\ell < E < E_u$

And when the applied electric field is higher than that of the upper valley *(Eu < E)*, all electrons will transfer to the upper valley as shown in Fig. 7-2-S(c).



(c) $E_u < E$

If electron densities in the lower and upper valleys are *nc* and *nu* , the conductivity of the *n* -type GaAs is

$$\sigma = e(\mu_\ell n_\ell + \mu_u n_u) \qquad (7\text{-}2\text{-}2)$$

where e = the electron charge
μ = the electron mobility
$n = n_\ell + n_u$ is the electron density

When a sufficiently high field *E* is applied to the specimen, electrons are accelerated and their effective temperature rises above the lattice temperature. Furthermore, the lattice temperature also increases. Thus electron density *n* and mobility *f-L* are both functions of electric field *E*. Differentiation of Eq. (7-2-2) with respect *toE* yields

$$\frac{d\sigma}{dE} = e\left(\mu_\ell \frac{dn_\ell}{dE} + \mu_u \frac{dn_u}{dE}\right) + e\left(n_\ell \frac{d\mu_\ell}{dE} + n_u \frac{d\mu_u}{dE}\right) \qquad (7\text{-}2\text{-}3)$$

If the total electron density is given by *n* = *nt* + *nu* and it is assumed that *f.Le* and */Lu* are proportional to

EP, where *p* is a constant, then

$$\frac{d}{dE}(n_\ell + n_u) = \frac{dn}{dE} = 0 \qquad (7\text{-}2\text{-}4)$$

$$\frac{dn_\ell}{dE} = -\frac{dn_u}{dE} \qquad (7\text{-}2\text{-}5)$$

$$\frac{d\mu}{dE} \propto \frac{dE^p}{dE} = pE^{p-1} = p\frac{E^p}{E} \propto p\frac{\mu}{E} = \mu\frac{p}{E} \qquad (7\text{-}2\text{-}6)$$

Substitution of Eqs. (7-2-4) to (7-2-6) into Eq. (7-2-3) results in

$$\frac{d\sigma}{dE} = e(\mu_\ell - \mu_u)\frac{dn_\ell}{dE} + e(n_\ell\mu_\ell + n_u\mu_u)\frac{p}{E} \qquad (7\text{-}2\text{-}7)$$

Then differentiation of Ohm's law *J* = *aE* with respect *toE* yields

$$\frac{dJ}{dE} = \sigma + \frac{d\sigma}{dE}E \qquad (7\text{-}2\text{-}8)$$

Equation (7-2-8) can be rewritten

$$\frac{1}{\sigma}\frac{dJ}{dE} = 1 + \frac{d\sigma/dE}{\sigma/E} \qquad (7\text{-}2\text{-}9)$$

Clearly, for negative resistance, the current density *J* must decrease with increasing field *E* or the ratio of *dJ!dE* must be negative. Such would be the case only if the right-hand term of Eq. (7-2-9) is less than zero. In other words, the condition for negative resistance is

$$-\frac{d\sigma/dE}{\sigma/E} > 1 \qquad (7\text{-}2\text{-}10)$$

Substitution of Eqs. (7-2-2) and (7-2-7) with/= *nu/ne* results in [2]

$$\left[\left(\frac{\mu_\ell - \mu_u}{\mu_\ell + \mu_u f}\right)\left(-\frac{E}{n_\ell}\frac{dn_\ell}{dE}\right) - p\right] > 1 \qquad (7\text{-}2\text{-}11)$$

AVALANCE TRANSIT TIME DEVICES:

Avalanche transit-time diode oscillators rely on the effect of voltage breakdown across a reverse-biased p-n junction to produce a supply of holes and electrons. Ever since the development of modern semiconductor device theory scientists have speculated on whether it is possible to make a two-terminal negative-resistance device.

The tunnel diode was the first such device to be realized in practice. Its operation depends on the properties of a forward-biased *p-n* junction in which both the *p* and *n* regions are heavily doped. The other two devices are the transferred electron devices and the avalanche transit-time devices. In this chapter the latter type is discussed.

The transferred electron devices or the Gunn oscillators operate simply by the application of a de voltage to a bulk semiconductor. There are no *p-n* junctions in this device. Its frequency is a function of the load and of the natural frequency of the circuit. The avalanche diode oscillator uses carrier impact ionization and drift in the high-field region of a semiconductor junction to produce a negative resistance at microwave frequencies.

The device was originally proposed in a theoretical paper by Read in which he analyzed the negative-resistance properties of an idealized *n+p- i-p+* diode. Two distinct modes of avalanche oscillator have been observed. One is the IMPATT mode, which stands for *impact ionization avalanche transit-time* operation. In this mode the typical dc-to-RF conversion efficiency is 5 to 10%, and frequencies are as high as 100 GHz with silicon diodes.

The other mode is the TRAPATT mode, which represents *trapped plasma avalanche triggered transit* operation. Its typical conversion efficiency is from 20 to 60%. Another type of active microwave device is the BARITT *(barrier injected transit-time)* diode [2]. It has long drift regions similar to those of IMPATT diodes. The carriers traversing the drift regions of BARITT diodes, however, are generated by minority carrier injection from forward-biased junctions rather than being extracted from the plasma of an avalanche region. Several different structures have been operated as BARITT diodes, such as p-n-p, p-n-v-p, p-n-metal, and metal-nmetal. BARITT diodes have low noise figures of 15 dB, but their bandwidth is relatively narrow with low output power.

IMPATT AND TRAPATT DIODE:

Physical Structures

A theoretical Read diode made of ann+ *-p-i-p+* or *p+ -n-i-n+* structure has been analyzed. Its basic physical mechanism is the interaction of the impact ionization avalanche and the transit time of charge carriers. Hence the Read-type diodes are called IMPATT diodes. These diodes exhibit a differential negative resistance by two effects:

1) The impact ionization avalanche effect, which causes the carrier current *lo(t)* and the ac voltage tobe out of phase by 90°

2) The transit-time effect, which further delays the external current *l,(t)* relative to the ac voltage by 90°

The first IMPATT operation as reported by Johnston et al. [4] in 1965, however, was obtained from a simple *p-n* junction. The first real Read-type IMPATT diode was reported by Lee et al.

[3], as described previously.

From the small-signal theory developed by Gilden [5] it has been confirmed that a negative resistance of the IMPATT diode can be obtained from a junction diode with any doping profile.

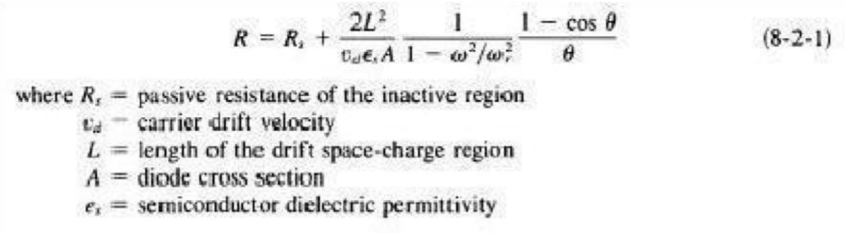
Many IMPATT diodes consist of a high doping avalanching region followed by a drift region where the field is low enough that the carriers can traverse through it without avalanching.

The Read diode is the basic type in the IMPATT diode family. The others are the one-sided abrupt *p-n* junction, the linearly graded *p-n* junction (or double-drift region), and the *p-i-n* diode, all of which are shown in Fig. 8-2-1.

The principle of operation of these devices, however, is essentially similar to the mechanism described for the Read diode.

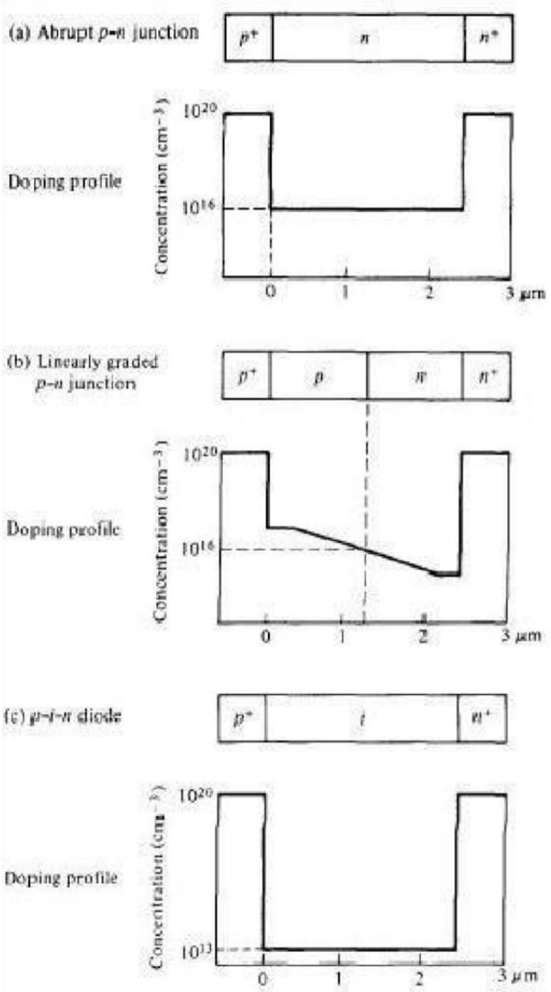
Negative Resistance

Small-signal analysis of a Read diode results in the following expression for the real part of the diode terminal impedance [5]:



$$R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta} \qquad (8\text{-}2\text{-}1)$$

where R_s = passive resistance of the inactive region
v_d = carrier drift velocity
L = length of the drift space-charge region
A = diode cross section
ϵ_s = semiconductor dielectric permittivity



Moreover, *()* is the transit angle, given by

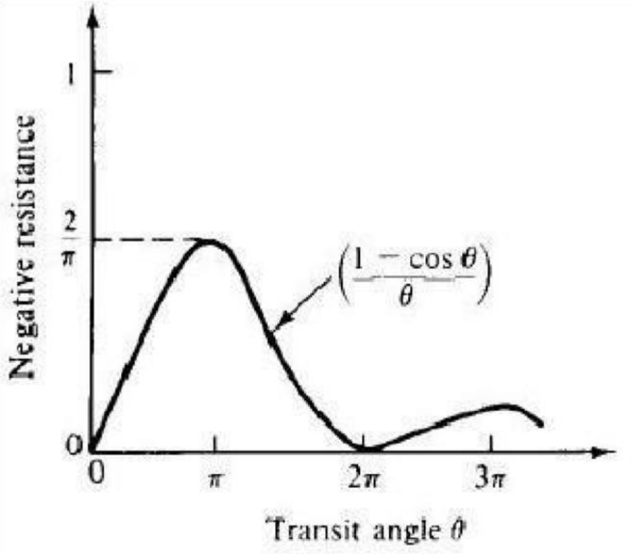
$$\theta = \omega\tau = \omega\frac{L}{v_d} \qquad (8\text{-}2\text{-}2)$$

and *w*, is the avalanche resonant frequency, defined by

$$\omega_r \equiv \left(\frac{2\alpha' v_d I_0}{\epsilon_s A}\right)^{1/2} \qquad (8\text{-}2\text{-}3)$$

The variation of the negative resistance with the transit angle when *w* > *Wr* is plotted in Fig. 8-2-2. The peak value of the negative resistance occurs near *()* = 7T. For transit angles larger than 7T and approaching 37T /2, the negative resistance of the diode decreases rapidly. For practical purposes, the Read-type IMPATT diodes work well only in a frequency range around the 7T transit angle. That is,

$$f = \frac{1}{2\tau} = \frac{v_d}{2L} \qquad (8\text{-}2\text{-}4)$$



Power Output and Efficiency

For a uniform avalanche, the maximum voltage that can be applied across the diode is given by

$$V_m = E_m L \qquad (8\text{-}2\text{-}5)$$

where

Lis the depletion length

Em is the maximum electric field.

This maximum applied voltage is limited by the breakdown voltage. Furthermore, the maximum current that can be carried by the diode is also limited by the avalanche breakdown process, for the current in the space-charge region causes an increase in the electric field. The maximum current is given by

$$I_m = J_m A = \sigma E_m A = \frac{\epsilon_s}{\tau} E_m A = \frac{v_d \epsilon_s E_m A}{L} \qquad (8\text{-}2\text{-}6)$$

Therefore the upper limit of the power input is given by

$$P_m = I_m V_m = E_m^2 \epsilon_s v_d A \qquad (8\text{-}2\text{-}7)$$

The capacitance across the space-charge region is defined as

$$C = \frac{\epsilon_s A}{L} \qquad (8\text{-}2\text{-}8)$$

Substitution of Eq. (8-2-8) in Eq. (8-2-7) and application of *2TTfT* = 1 yield

$$P_m f^2 = \frac{E_m^2 v_d^2}{4\pi^2 X_c} \qquad (8\text{-}2\text{-}9)$$

It is interesting to note that this equation is identical to Eq. (5-1-60) of the powerfrequency limitation for the microwave power transistor. The maximum power that can be given to the mobile carriers decreases as 1/ *f*. For silicon, this electronic limit is dominant at frequencies as

high as 100 GHz. The efficiency of the IMPATT diodes is given by

$$\eta = \frac{P_{\mathrm{ac}}}{P_{\mathrm{dc}}} = \left(\frac{V_a}{V_d}\right)\left(\frac{I_a}{I_d}\right) \qquad (8\text{-}2\text{-}10)$$