# UNIT-IV

# M-Type Tubes

## *MAGNETRON OSCILLATORS*

Hull invented the magnetron in 1921 , 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 inFig. 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

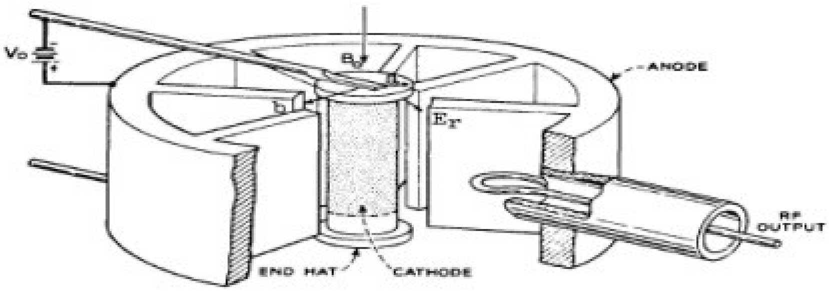


**Figure 10-1-1** Schematic diagram of a cylindrical magnetron.

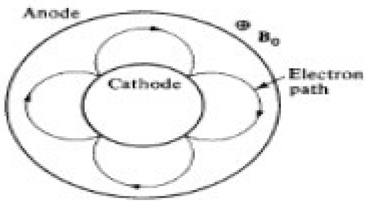


**Figure 10-1-2** Electron path in a cylindrical magnetron.

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

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

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 $\phi$ 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

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

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

$$\frac{m\mathcal{V}^2}{R} = e\mathcal{V}B \tag{10-1-13}$$

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

$$\omega_c = \frac{\mathcal{V}}{R} = \frac{eB}{m} \tag{10-1-14}$$

The period of one complete revolution can be expressed as

$$T = \frac{2\pi}{\omega} = \frac{2\pi m}{eB} \tag{10-1-15}$$

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

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

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

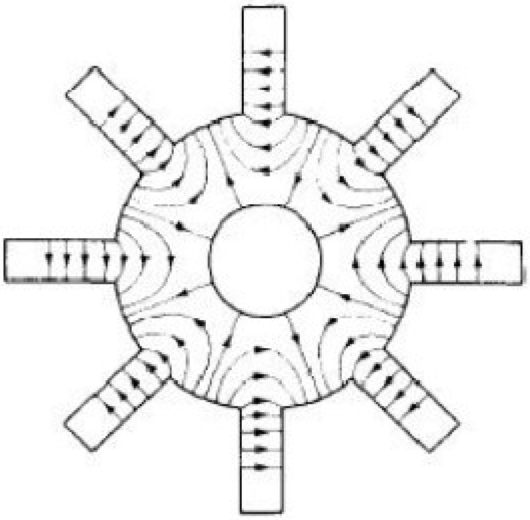


**Figure 10-1-3** Lines of force in $\pi$ mode of eight-cavity magnetron.

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

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

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,

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

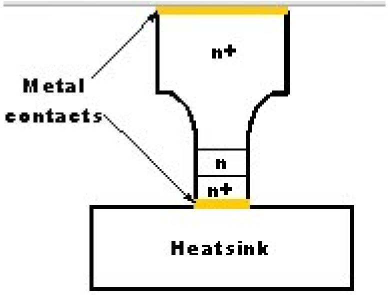
## GUNN DIODE

A diode is a two-terminal semiconductor electronic component that exhibits nonlinear current-voltage characteristics. It allows current in one direction at which its resistance is very low (almost zero resistance) during forward bias. Similarly, in the other direction, it doesn’t allow the flow of current – as it offers a very-high resistance (infinite resistance acts as open circuit) during reverse bias.

The diodes are classified into different types based on their working principles and characteristics. These include Generic diode, Schotty diode, Shockley diode, Constant-current diode, Zener diode, Light emitting diode, Photodiode, Tunnel diode, Varactor, Vacuum tube, Laser diode, PIN diode, Peltier diode, Gunn diode, and so on. On a special case, this article discuss about Gunn diode’s working, characteristics and applications.

# What is a Gunn Diode?

A Gunn Diode is considered as a type of diode even though it does not contain any typical PN diode junction like the other diodes, but it consists of two electrodes. This diode is also called as a Transferred Electronic Device. This diode is a negative differential resistance device, which is frequently used as a low-power oscillator to generate microwaves. It consists of only N-type semiconductor in which electrons are the majority charge carriers. To generate short radio waves such as microwaves, it utilizes the Gunn Effect.



Gunn Diode Structure

The central region shown in the figure is an active region, which is properly doped N-type GaAs and epitaxial layer with a thickness of around 8 to 10 micrometers. The active region is sandwiched between the two regions having the Ohmic contacts. A heat sink is provided to avoid overheating and premature failure of the diode and to maintain thermal limits.

For the construction of these diodes, only N-type material is used, which is due to the transferred electron effect applicable only to N-type materials and is not applicable to the P-type materials. The frequency can be varied by varying the thickness of the active layer while doping.

# Gunn Effect

It was invented by John Battiscombe Gunn in 1960s; after his experiments on GaAs (Gallium Arsenide), he observed a noise in his experiments' results and owed this to the generation of electrical oscillations at microwave frequencies by a steady electric field with a magnitude greater than the threshold value. It was named as Gunn Effect after this had been discovered by John Battiscombe Gunn.

The Gunn Effect can be defined as generation of microwave power (power with microwave frequencies of around a few GHz) whenever the voltage applied to a semiconductor device exceeds the critical voltage value or threshold voltage value.

### Gunn Diode Oscillator

Gunn Diode Oscillator

Gunn diodes are used to build oscillators for generating microwaves with frequencies ranging from 10 GHz to THz. It is a Negative Differential Resistance device – also called as transferred electron device oscillator – which is a tuned circuit consisting of Gunn diode with DC bias voltage applied to it. And, this is termed as biasing the diode into negative resistance region.

Due to this, the total differential resistance of the circuit becomes zero as the negative resistance of the diode cancels with the positive resistance of the circuit resulting in the generation of oscillations.

## Gunn Diode's Working

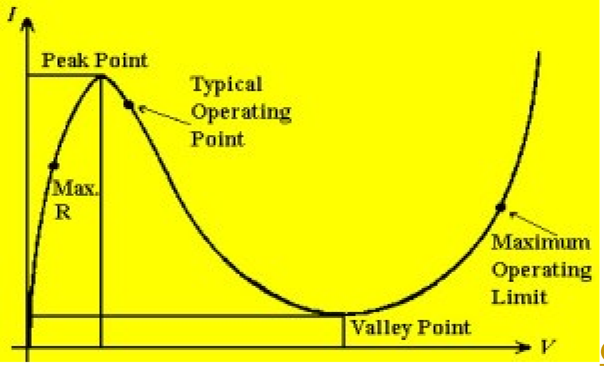
This diode is made of a single piece of N-type semiconductor such as Gallium Arsenide and InP (Indium Phosphide). GaAs and some other semiconductor materials have one extra-energy band in their electronic band structure instead of having only two energy bands, viz. valence band and conduction band like normal semiconductor materials. These GaAs and some other semiconductor materials consist of three energy bands, and this extra third band is empty at initial stage.

If a voltage is applied to this device, then most of the applied voltage appears across the active region. The electrons from the conduction band having negligible electrical resistivity are transferred into the third band because these electrons are scattered by the applied voltage. The third band of GaAs has mobility which is less than that of the conduction band.

Because of this, an increase in the forward voltage increases the field strength (for field strengths where applied voltage is greater than the threshold voltage value), then the number of electrons reaching the state at which the effective mass increases by decreasing their velocity, and thus, the current will decrease.

Thus, if the field strength is increased, then the drift velocity will decrease; this creates a negative incremental resistance region in V-I relationship. Thus, increase in the voltage will increase the resistance by creating a slice at the cathode and reaches the anode. But, to maintain a constant voltage, a new slice is created at the cathode. Similarly, if the voltage decreases, then the resistance will decrease by extinguishing any existing slice.

## Gunn Diode’s Characteristics



Gunn Diode Characterstics

The current-voltage relationship characteristics of a Gunn diode are shown in the above graph with its negative resistance region. These characteristics are similar to the characteristics of the tunnel diode.

As shown in the above graph, initially the current starts increasing in this diode, but after reaching a certain voltage level (at a specified voltage value called as threshold voltage value), the current decreases before increasing again. The region where the current falls is termed as a negative resistance region, and due to this it oscillates. In this negative resistance region, this diode acts as both oscillator and amplifier, as in this region, the diode is enabled to amplify signals.

Gunn Diode’s Applications


Gunn Diode Applications

Used as Gunn oscillators to generate frequencies ranging from 100mW 5GHz to 1W 35GHz outputs. These Gunn oscillators are used for radio communications, military and commercial radar sources.

- Used as sensors for detecting trespassers, to avoid derailment of trains.
- Used as efficient microwave generators with a frequency range of up to hundreds of GHz.
- Used for remote vibration detectors and rotational speed measuring tachometers.
- Used as a microwave current generator (Pulsed Gunn diode generator).
- Used in microwave transmitters to generate microwave radio waves at very low powers.
- Used as fast controlling components in microelectronics such as for the modulation of semiconductor injection lasers.
- Used as sub-millimeter wave applications by multiplying Gunn oscillator frequency with diode frequency.
- Some other applications include door opening sensors, process control devices, barrier operation, perimeter protection, pedestrian safety systems, linear distance indicators, level sensors, moisture content measurement and intruder alarms.

## Avalanche transit time devices:

The process of having a delay between voltage and current, in avalanche together with transit time, through the material is said to be Negative resistance. The devices that helps to make a diode exhibit this property are called as **Avalanche transit time devices**.

The examples of the devices that come under this category are IMPATT, TRAPATT and BARITT diodes. Let us take a look at each of them, in detail.

## IMPATT Diode

This is a high-power semiconductor diode, used in high frequency microwave applications. The full form IMPATT is **IMPact ionization Avalanche Transit Time diode**.

A voltage gradient when applied to the IMPATT diode, results in a high current. A normal diode will eventually breakdown by this. However, IMPATT diode is developed to withstand all this. A high potential gradient is applied to back bias the diode and hence minority carriers flow across the junction.

Application of a RF AC voltage if superimposed on a high DC voltage, the increased velocity of holes and electrons results in additional holes and electrons by thrashing them out of the crystal structure by Impact ionization. If the original DC field applied was at the threshold of developing this situation, then it leads to the avalanche current multiplication and this process continues. This can be understood by the following figure.

Due to this effect, the current pulse takes a phase shift of 90°. However, instead of being there, it moves towards cathode due to the reverse bias applied. The time taken for the pulse to reach cathode depends upon the thickness of **n+** layer, which is adjusted to make it 90° phase shift. Now, a dynamic RF negative resistance is proved to exist. Hence, IMPATT diode acts both as an oscillator and an amplifier.

The following figure shows the constructional details of an IMPATT diode.

The efficiency of IMPATT diode is represented as

$$\eta=[P_{ac}P_{dc}]=V_aV_d[I_aI_d]$$

Where,

- $P_{ac}$

☐ = AC power

☐ $P_{dc}$

☐ = DC power

☐ $V_a \& I_a$

☐ = AC voltage & current

☐ $V_d \& I_d$

- = DC voltage & current

### Disadvantages

Following are the disadvantages of IMPATT diode.

- It is noisy as avalanche is a noisy process
- Tuning range is not as good as in Gunn diodes

### Applications

Following are the applications of IMPATT diode.

- Microwave oscillator
- Microwave generators
- Modulated output oscillator
- Receiver local oscillator
- Negative resistance amplifications
- Intrusion alarm networks (high Q IMPATT)
- Police radar (high Q IMPATT)
- Low power microwave transmitter (high Q IMPATT)
- FM telecom transmitter (low Q IMPATT)
- CW Doppler radar transmitter (low Q IMPATT)

## TRAPATT Diode

The full form of TRAPATT diode is **TRApped Plasma Avalanche Triggered Transit diode**. A microwave generator which operates between hundreds of MHz to GHz. These are high peak power diodes usually **n+- p-p+** or **p+-n-n+** structures with n-type depletion region, width varying from 2.5 to 1.25 Âµm. The following figure depicts this.

The electrons and holes trapped in low field region behind the zone, are made to fill the depletion region in the diode. This is done by a high field avalanche region which propagates through the diode.

The following figure shows a graph in which AB shows charging, BC shows plasma formation, DE shows plasma extraction, EF shows residual extraction, and FG shows charging.

Let us see what happens at each of the points.

**A:** The voltage at point A is not sufficient for the avalanche breakdown to occur. At A, charge carriers due to thermal generation results in charging of the diode like a linear capacitance.

**A-B:** At this point, the magnitude of the electric field increases. When a sufficient number of carriers are generated, the electric field is depressed throughout the depletion region causing the voltage to decrease from B to C.

**C:** This charge helps the avalanche to continue and a dense plasma of electrons and holes is created. The field is further depressed so as not to let the electrons or holes out of the depletion layer, and traps the remaining plasma.

**D:** The voltage decreases at point D. A long time is required to clear the plasma as the total plasma charge is large compared to the charge per unit time in the external current.

**E:** At point E, the plasma is removed. Residual charges of holes and electrons remain each at one end of the deflection layer.

**E to F:** The voltage increases as the residual charge is removed.

**F:** At point F, all the charge generated internally is removed.

**F to G:** The diode charges like a capacitor.

**G:** At point G, the diode current comes to zero for half a period. The voltage remains constant as shown in the graph above. This state continues until the current comes back on and the cycle repeats.

The avalanche zone velocity $V_s$

is represented as

$$V_s = dxdt = JqN_A$$

Where

- $J$

- = Current density

- $q$

- = Electron charge 1.6 x $10^{-19}$

- $N_A$

- = Doping concentration

The avalanche zone will quickly sweep across most of the diode and the transit time of the carriers is represented as

$$\tau_s = L V_s$$

Where

- $V_s$

- = Saturated carrier drift velocity

- $L$

- = Length of the specimen

The transit time calculated here is the time between the injection and the collection. The repeated action increases the output to make it an amplifier, whereas a microwave low pass filter connected in shunt with the circuit can make it work as an oscillator.

## Applications

There are many applications of this diode.

- Low power Doppler radars
- Local oscillator for radars
- Microwave beacon landing system
- Radio altimeter
- Phased array radar, etc.

# BARITT Diode

The full form of **BARITT Diode is BARrier Injection Transit Time diode**. These are the latest invention in this family. Though these diodes have long drift regions like IMPATT diodes, the carrier injection in BARITT diodes is caused by forward biased junctions, but not from the plasma of an avalanche region as in them.

In IMPATT diodes, the carrier injection is quite noisy due to the impact ionization. In BARITT diodes, to avoid the noise, carrier injection is provided by punch through of the depletion region. The negative resistance in a BARITT diode is obtained on account of the drift of the injected holes to the collector end of the diode, made of p-type material.

The following figure shows the constructional details of a BARITT diode.

For a **m-n-m** BARITT diode, **Ps-Si** Schottky barrier contacts metals with **n-type Si wafer** in between. A rapid increase in current with applied voltage (above 30v) is due to the thermionic hole injection into the semiconductor.

The critical voltage $(Vc)$

depends on the doping constant $(N)$, length of the semiconductor $(L)$ and the semiconductor dielectric permittivity $(\epsilon S)$

represented as

$$V_c=qNL_2 2\epsilon S$$

# Monolithic Microwave Integrated Circuit (MMIC)

Microwave ICs are the best alternative to conventional waveguide or coaxial circuits, as they are low in weight, small in size, highly reliable and reproducible. The basic materials used for monolithic microwave integrated circuits are −

- Substrate material
- Conductor material
- Dielectric films
- Resistive films

These are so chosen to have ideal characteristics and high efficiency. The substrate on which circuit elements are fabricated is important as the dielectric constant of the material should be high with low dissipation factor, along with other ideal characteristics. The substrate materials used are GaAs, Ferrite/garnet, Aluminum, beryllium, glass and rutile.

The conductor material is so chosen to have high conductivity, low temperature coefficient of resistance, good adhesion to substrate and etching, etc. Aluminum, copper, gold, and silver are mainly used as conductor materials. The dielectric materials and resistive materials are so chosen to have low loss and good stability.

## Fabrication Technology

In hybrid integrated circuits, the semiconductor devices and passive circuit elements are formed on a dielectric substrate. The passive circuits are either distributed or lumped elements, or a combination of both.

Hybrid integrated circuits are of two types.

- Hybrid IC
- Miniature Hybrid IC

In both the above processes, Hybrid IC uses the distributed circuit elements that are fabricated on IC using a single layer metallization technique, whereas Miniature hybrid IC uses multi-level elements.

Most analog circuits use meso-isolation technology to isolate active n-type areas used for FETs and diodes. Planar circuits are fabricated by implanting ions into semi-insulating substrate, and to provide isolation the areas are masked off.

"**Via hole**" technology is used to connect the source with source electrodes connected to the ground, in a GaAs FET, which is shown in the following figure.

There are many applications of MMICs.

- Military communication
- Radar
- ECM
- Phased array antenna systems

- Spread spectrum and TDMA systems