

UNIT II

M-TYPE TUBES

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UNIT-II

M-Type Tubes

M-Type Tubes:

Introduction, Cross-field Effects, Magnetrons – Different Types, Cylindrical Traveling Wave Magnetron – Hull Cut-off and Hartree Conditions, Modes of Resonance and PI-Mode Operation, Separation of PI- Mode, o/p characteristics,

Microwave Solid State Devices: Introduction, Classification, Applications. TEDs – Introduction, Gunn

Diodes – Principle, RWH Theory, Characteristics, Modes of Operation - Gunn Oscillation Modes,

Principle of operation of IMPATT and TRAPATT Devices.

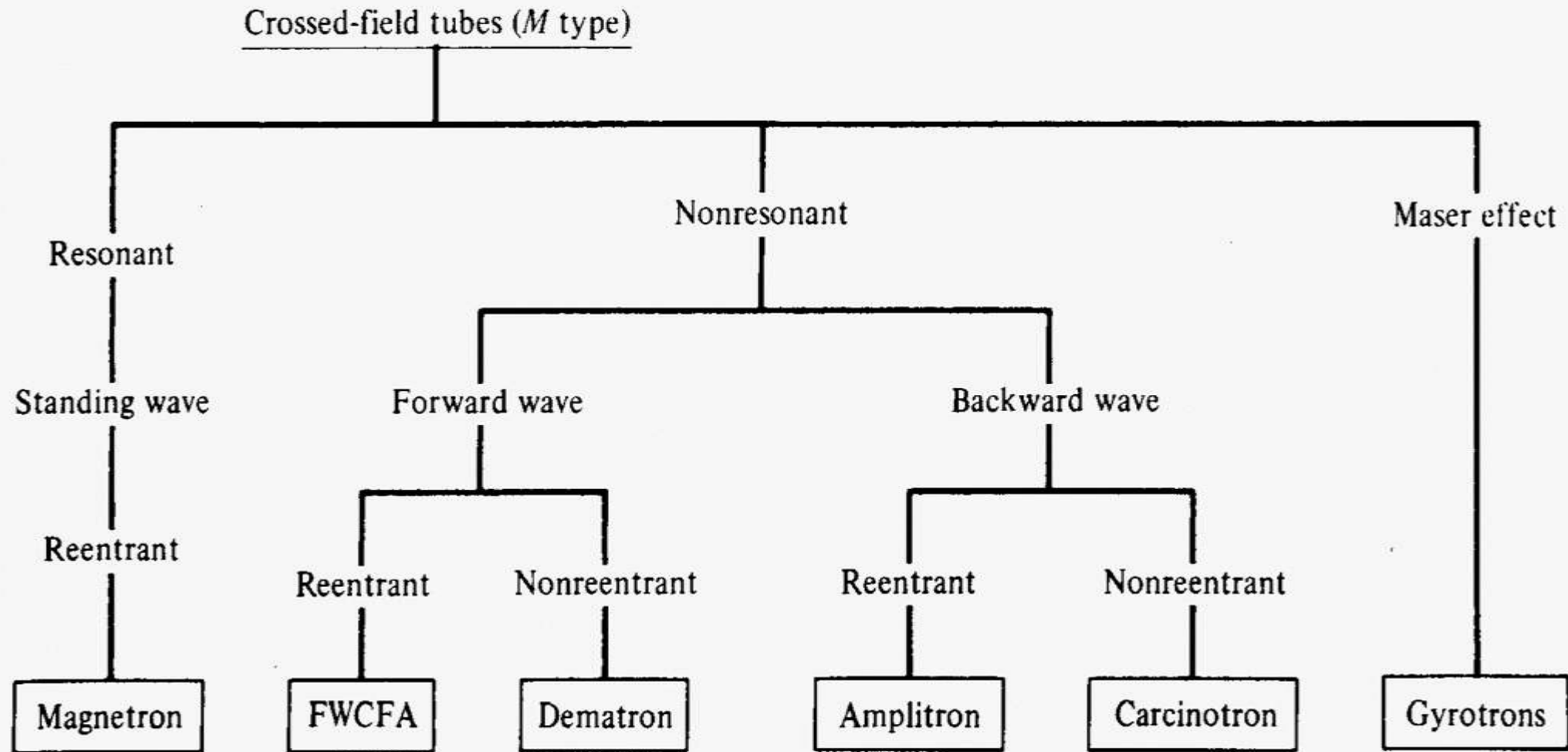
Cross Field/M Type Tubes

- M type tubes or crossed field tubes in which the dc magnetic field and dc electric field are perpendicular to each other.
- In crossed field tubes, the electrons emitted by the cathode are accelerated by the electric field and gain velocity, but the greater their velocity, the more their path is bent by the magnetic field.

Cross Field Effect

- If an RF field is applied to the circuit, the electrons entering the circuit during retarding field are decelerated and give up some of their kinetic energy to the RF field. Consequently, their velocity is decreased and these slower electrons will then travel the dc electric field far enough to regain essentially the same velocity as before.
- Because of crossed-field interactions, only those electrons that have given up sufficient energy to the RF field can travel all the way to the anode. This phenomenon would make the *M*-type devices relatively efficient.
- Those electrons entering the circuit during the accelerating field are accelerated by means of receiving enough energy from the RF field and are returned back towards the cathode. This back bombardment of the cathode produces heat in the cathode and decreases the operational efficiency.

Classification Cross Field Tubes



Magnetrons

- Magnetron was invented by Hull in 1921.
- An improved high power magnetron was developed by Randall and boot around 1939.
- Magnetrons provide microwave oscillations of very high frequency
- Because of cross field between cathode & anode , the electrons emitted from cathode are influenced by the cross field to move in a curved path.
- If the dc magnetic field is strong enough the electrons will not arrive at in the anode but return to the cathode, consequently anode current is cutoff.

Types of Magnetrons

1. Negative resistance Magnetron or Split anode magnetron

- These are useful at the frequency less than 500 MHz.
- These type of magnetrons uses the negative resistance between two anode segments.
- The negative resistance magnetrons are capable of generating high power output.
- The length of the tube plate is limited to few centimeters.
- The small diameter tube is required to make the magnetron operate efficiently at microwave frequencies.

Types of Magnetrons

2. Cyclotron Frequency Magnetron

- These are useful only for the frequencies greater than 100 MHz.
- Operates under the influence of synchronism between an alternating component of electric field and periodic oscillation of electrons in a direction parallel to this field.

3. Travelling Wave or Cavity Magnetron

- Provides the oscillations of very high power and hence these are used in radar applications.
- The working of these magnetrons depend upon the interaction of electrons with a travelling electromagnetic field of constant angular velocity.

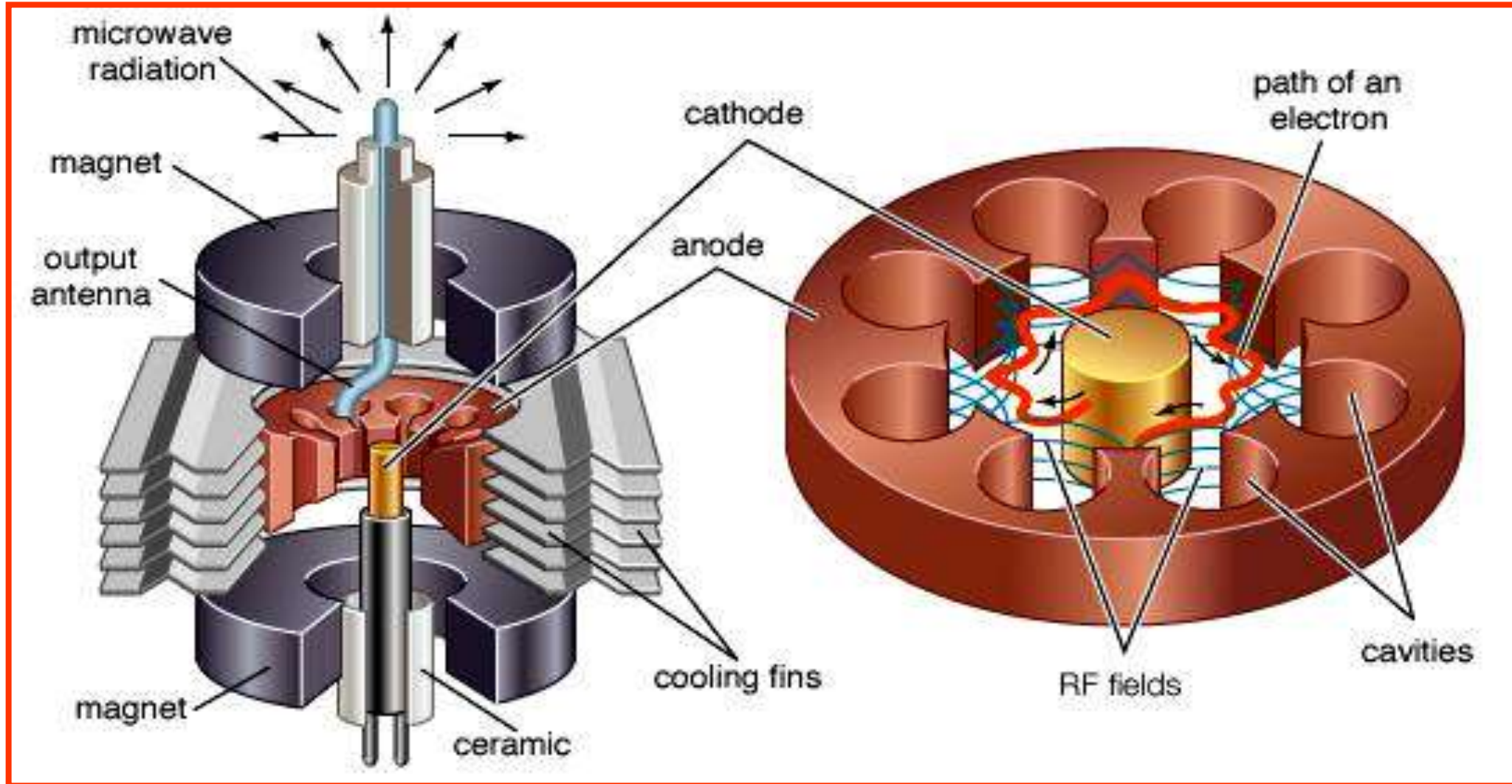
Cavity Magnetron or Cylindrical Magnetron

- Cylindrical magnetron Oscillator is also called as conventional Magnetron.
- In a cylindrical magnetron , several reentrant cavities are connected to the gaps and hence some times called as Cavity Magnetron.

Modes of Operation

- The cavity magnetron has 8 cavities and are tightly coupled to each other.
- A N-cavity tightly coupled system will have N –modes of operation.
- Each mode is characterizes by a combination of frequency and phase of oscillation relative to the adjacent cavity.
- The total phase shift around the ring of cavity resonators is $2n\pi$ where n is an integer.
- For the 8-cavity magnetron, minimum phase shift should be 45° ($8 * 45^\circ = 360^\circ$)

Cavity Magnetron or Cylindrical Magnetron



Cavity Magnetron or Cylindrical Magnetron

- The relative phase change of ac electric field across adjacent cavities is given by

$$Q_v = \frac{2\pi n}{N}$$

Where $n = 0, \pm 1, \pm 2, \pm \frac{N}{2} - 1, \pm \frac{N}{2}$ mode of resonance can exist if N is even number

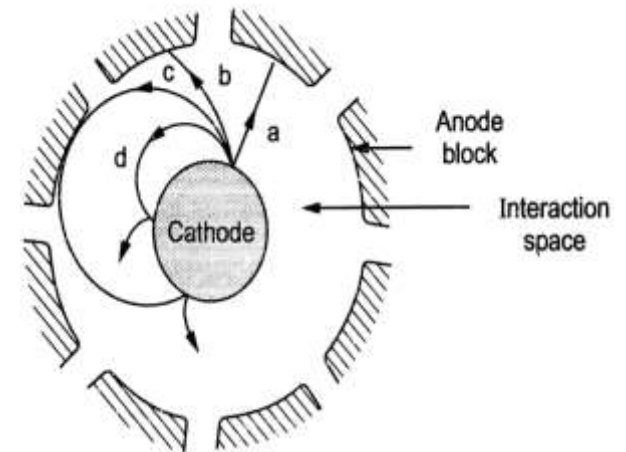
- If $n = \frac{N}{2}$, then $Q_v = \pi$ then the mode of operation is called π -mode.
- If $n = 0$, then $Q_v = 0$ then the mode of operation is called zero-mode.
- Zero-mode is not used in magnetron operation because there will be no RF electric field between anode and cathode (fringing field).

Cavity Magnetron or Cylindrical Magnetron

Working of magnetron

When there is no RF field in cavity magnetron (Zero mode)

- In the absence of magnetic field ($B = 0$), the electron travels straight from the cathode to the anode due to the radial electric field force acting on it (indicated by the trajectory 'a' in Fig).
- If the magnetic field strength is increased slightly (i.e., for moderate value of B) it will exert a lateral force bending the path of the electron as shown by path 'b' in Fig. The radius of the path is given by $R = mV/eB$, that varies directly with electron velocity and inversely as the magnetic field strength.



Cavity Magnetron or Cylindrical Magnetron

- If the strength' of the magnetic field is made sufficiently high so as to prevent the electrons from reaching the anode (as shown by path 'c' and those inside in Fig.) the anode current becomes zero.
- The magnetic field required to return electrons back to cathode just grazing the surface of the anode is called the critical magnetic field (B_c), the cut-off magnetic field.
- If the magnetic field is made larger than the critical field ($B > B_c$), the electron experiences a greater rotational force and may return back to cathode quite faster. All such electrons may cause back heating of the cathode.
- This can be avoided by switching off the heater supply after commencement of oscillations.

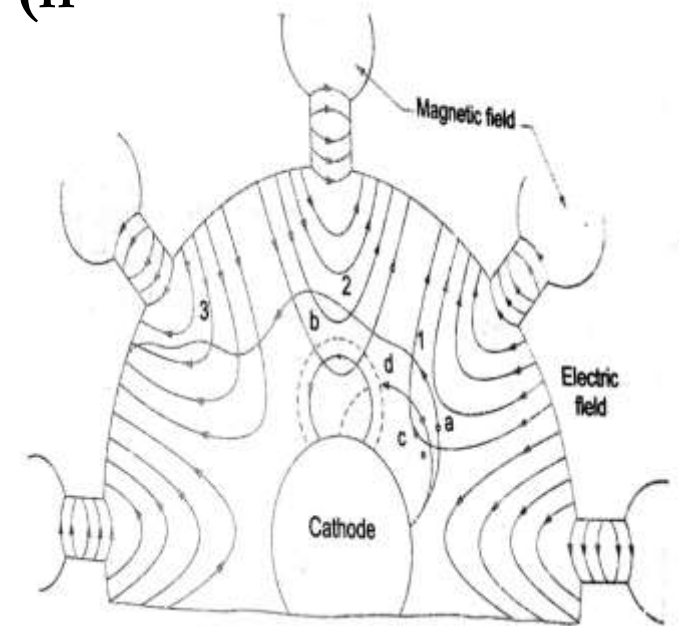
Cavity Magnetron or Cylindrical Magnetron

Magnetic Field	Path
$B=0$	a
Small B	b
Critical Magnetic Field ($B=B_c$)	c
$B>B_c$	d

Cavity Magnetron or Cylindrical Magnetron

When the RF oscillations Present in the cavity magnetron (π -mode)

- Assume that RF oscillations are initiated due to some noise transient within the magnetron and oscillations are sustained by the device operations.
- For best result $n=4$ is used in practice.
- The electron 'a' is seen to be slowed down in presence of oscillations thus transferring energy to the oscillations, during its longer journey from cathode to anode.



Cavity Magnetron or Cylindrical Magnetron

- Such electrons that transfer their energy to the oscillations are called as **avored electrons**. These electrons are responsible for **bunching effect**.
- The electron 'b' is accelerated by the RF field and it takes energy from oscillations resulting in increased velocity. Hence bends more sharply, spends very little time in the interaction space and is returned back to the cathode.
- Such electrons are called unfavored electrons which do not participate in the bunching process and cause back heating.
- Similarly an electron 'c' which is emitted a little later to be in correct position moves faster and tries to catch up with electron 'a' and an electron emitted at d will be slowed down to fall back in step with electron 'a' .
- As a result, the favored electrons a, c and d form electron bunches or electron clouds. The processes is called as "**Phase focusing effect**".
- The phase focusing effect of these favored electrons imparts enough energy to the RF oscillations so that they are sustained.

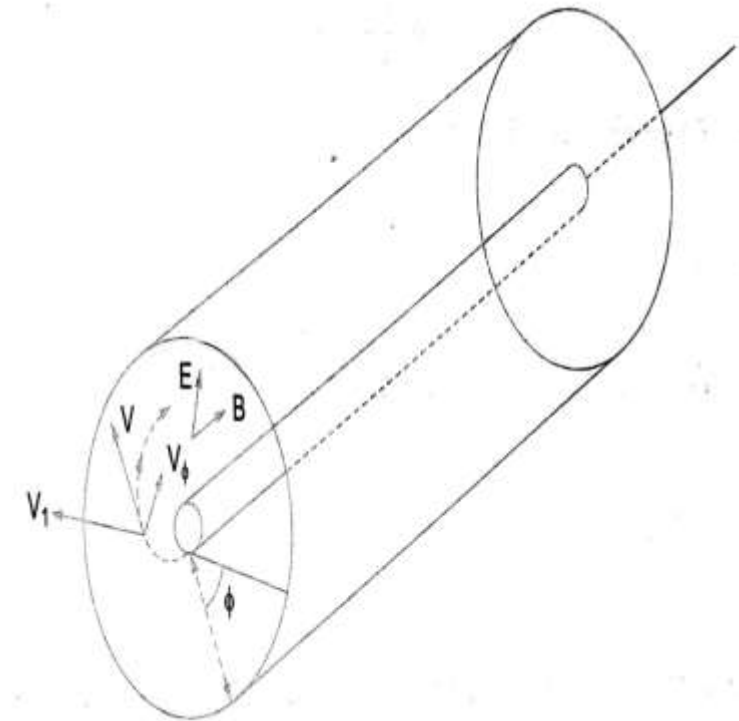
Cavity Magnetron or Cylindrical Magnetron

Mathematical Analysis

Let the cathode and anode radius be 'a' and 'b' respectively

ϕ is the angular displacement of the electron bends.

Being a cross field device electric and magnetic fields are perpendicular to each other and the path of the electrons in the presence of this cross field is naturally parabolic.



Hull Cut-off Voltage equation

Force acting on the electron is $F = Bev$

In the direction of φ , the force component F_φ is given by $F_\varphi = eBv_\rho$

Torque in φ direction is $T_\varphi = \rho F_\varphi = e\rho v_\rho B \longrightarrow \textcircled{1}$

Where $v_\rho =$ velocity in the direction of the radial distance ρ from the center of the cathode

Angular momentum = angular velocity x moment of inertia

$$= \frac{d\phi}{dt} \times m\rho^2$$

Time rate of angular momentum = $\frac{d}{dt} \left(\frac{d\phi}{dt} \times m\rho^2 \right) \longrightarrow \textcircled{2}$

which gives the Torque in φ direction

Hull Cut-off Voltage equation

- Equating 1 and 2

$$\frac{d}{dt} \left[\left(\frac{d\phi}{dt} \right) m\rho^2 \right] = e \cdot \rho \cdot v_{\rho} \cdot B$$

$$2 m\rho \frac{d\phi}{dt} + m\rho^2 \frac{d^2\phi}{dt^2} = e \cdot \rho \cdot v_{\rho} \cdot B$$

$$v_{\rho} = \frac{d\rho}{dt}$$

$$\rho v_{\rho} = \rho \cdot \frac{d\rho}{dt}$$

$$\int \rho \cdot \frac{d\rho}{dt} = \frac{\rho^2}{2}$$

Hull Cut-off Voltage equation

Integrating eq 3 with respect to 't' $2 m\rho \cdot \phi + m\rho^2 \cdot \frac{d\phi}{dt} = eB \cdot \frac{\rho^2}{2} \longrightarrow \textcircled{3}$

For particular direction φ , $m\rho\varphi$ can be thought of as a constant

$$m\rho^2 \frac{d\phi}{dt} + C = eB \cdot \frac{\rho^2}{2} \longrightarrow \textcircled{4}$$

Hull Cut-off Voltage equation

- Now applying boundary conditions

- i.e., at surface of the cathode $\rho=a$ and

$$\frac{d\phi}{dt} = 0$$

Sub C in

$$0 + C = \frac{e \cdot B \cdot a^2}{2} \text{ or } C = \frac{eBa^2}{2}$$

$$m\rho^2 \frac{d\phi}{dt} = \frac{eB}{2} (\rho^2 - a^2)$$

$$\frac{d\phi}{dt} = \frac{eB}{2m} \left(1 - \frac{a^2}{\rho^2} \right)$$

when $\rho \gg a$, $\frac{d\phi}{dt}$ approaches $(\omega)_{\max}$ (Maximum angular velocity).

$$\left(\frac{d\phi}{dt} \right)_{\max} = (\omega)_{\max} = \frac{eB}{2m} = \frac{eB_c}{2m}$$

Hull Cut-off Voltage equation

Potential energy of electron = Kinetic energy of electron

i.e.,

$$eV_0 = \frac{1}{2}mv^2$$

$$eV_0 = \frac{m}{2}(v_\rho^2 + v_\phi^2)$$

where v_ρ and v_ϕ are components in ρ and ϕ directions in cylindrical co-ordinates.

$$v_\rho = \frac{d\rho}{dt} \quad \text{and} \quad v_\phi = \rho \cdot \frac{d\phi}{dt}$$

$$eV_0 = \frac{m}{2} \left[\left(\frac{d\rho}{dt} \right)^2 + \rho^2 \left(\frac{d\phi}{dt} \right)^2 \right]$$

Hull Cut-off Voltage equation

- From eq

$$\left(\frac{d\phi}{dt}\right) = (\omega)_{\max} \left(1 - \frac{a^2}{\rho^2}\right)$$
$$eV_0 = \frac{m}{2} \left[\left(\frac{d\rho}{dt}\right)^2 + \rho^2 (\omega)_{\max}^2 \left(1 - \frac{a^2}{\rho^2}\right)^2 \right]$$

Hull Cut-off Voltage equation

At anode $\rho=b$ and $\frac{d\rho}{dt} = 0$ Substituting these boundary conditions in Eq (6)

$$\frac{m}{2} \left[b^2 \cdot (\omega)_{\max}^2 \left(1 - \frac{a^2}{b^2} \right) \right] = eV_0$$

$$B_c = \frac{1}{b} \sqrt{\frac{8 m V_0}{e}}$$

$$\frac{m}{2} b^2 \left(\frac{e B_c}{2m} \right)^2 \times \left(1 - \frac{a^2}{b^2} \right) = eV_0$$

This means that if $B_0 > B_{oc}$ for a given V_0 , the electrons will not reach the anode.

And this equation is called the Hull's cut-off magnetic equation

$$\frac{e^2 B_c^2 b^2}{8m} \left(1 - \frac{a^2}{b^2} \right) = eV_0$$

$$B_c = \frac{(8V_0 m/e)^{1/2}}{b \left(1 - \frac{a^2}{b^2} \right)}$$

Hull Cut-off Voltage equation

For a given magnetic field B_0 the cut-off voltage is given by

$$V_{oc} = \frac{e}{8m} B_0^2 b^2 \left(1 - \frac{a^2}{b^2} \right)^2$$

- Equation is called as Hull cut-off voltage equation
- This means that if $V_0 < V_{oc}$ for a given B_0 , the electrons will not reach the anode.

Hartree Condition

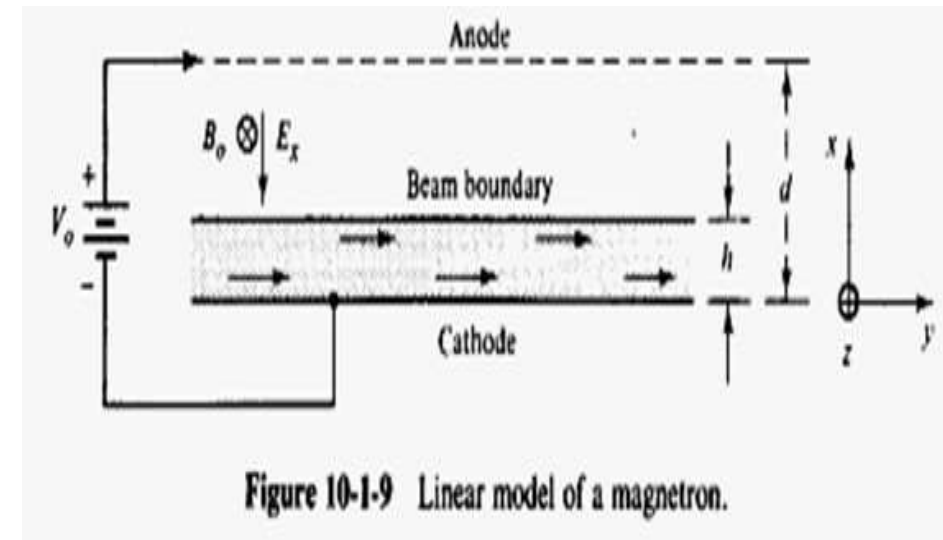
Hartree Condition

The Hull cutoff condition determines the anode voltage or magnetic field necessary to obtain nonzero anode current as a function of the magnetic field or anode voltage in the absence of an electromagnetic field.

The Hartree condition can be derived as follows

- The electron beam lies within a region extending a distance h from the cathode, where h is known as hub thickness.
- The spacing between the cathode and anode is d
- The electron motion is assumed to be in the positive y direction with a velocity

$$v_y = -\frac{E_x}{B_0} = \frac{1}{B_0} \frac{dV}{dx}$$



Hartree Condition

From the principle of conservation

$$\frac{1}{2} m v^2 = eV$$

Therefore

$$\left(\frac{dV}{dx}\right)^2 = \frac{2eV}{m} B_0^2$$

This differential equation may be rearranged as

$$\left(\frac{m}{2eB_0}\right)^{1/2} \frac{dV}{\sqrt{V}} = dx$$

Integration of above equation yields the potential within the electron beam as

$$V = \frac{eB_0^2}{2m} x^2$$

$$E_x = -\frac{dV}{dx} = -\frac{e}{m} B_0^2 x$$

Where the constant of integration has been eliminated for $V=0$ at $x=0$. The potential and electric field at the hub surface are given by

$$V(h) = \frac{e}{2m} B_0^2 h^2$$

Hartree Condition

- The potential at anode is

$$\begin{aligned}
 V_0 &= - \int_0^d E_x dx = - \int_0^h E_x dx - \int_h^d E_x dx \\
 &= V(h) + \frac{e}{m} B_0^2 h (d - h) \\
 &= \frac{e}{m} B_0^2 h (d - h/2)
 \end{aligned}$$

The electron velocity at the hub surface is $V_y(h) = \frac{e}{m} B_0 h$ obtained by

- For synchronism, this electron velocity is equal to the phase velocity of the slow wave structure

$$\frac{\omega}{\beta} = \frac{e}{m} B_0 h$$

- For the π -mode operation, the anode potential is finally given by

$$V_{0\pi} = \frac{\omega B_0 d}{\beta} - \frac{m}{2e} \frac{\omega^2}{\beta^2}$$

Hartree Condition

This is the Hartree anode voltage equation that is a function of magnetic flux density and the spacing between the cathode and anode.

Application of Magnetron

1. Magnetrons are widely used in radars with high output power.
2. In satellite and missiles for telemetry
3. Industrial heating
4. Microwave ovens
5. In oscillators with great power and pulsed operation at 100 GHz and greater

Advantages and Disadvantages of Magnetron

Advantages

- Magnetrons are a highly efficient device used for generation of the high power microwave signal.
- The use of magnetrons in radar can produce radar system of better quality for tracking purpose.
- It is usually small in size thus less bulky.

Disadvantages

- It is quite expensive.
- Despite producing a wide range of frequency, there exists a drawback in controllability of the generated frequency.
- It offers average power of around 1 to 2 kilowatts.
- Magnetrons are quite noisy.

Microwave Semiconductor/Solid State Devices

- In recent years there has been taken place a tremendous research activity for development of better, low noise, high frequency, greater bandwidth, lesser switching time, and other improvements in the performance characteristics of microwave devices.
- In this endeavor, several semiconductor microwave devices has been developed.
- Which includes three terminal devices such as bipolar and field effect transistors and two terminal devices such as transferred electron devices (Gunn diodes, LSA diodes), avalanche transit time devices (IMPATT, TRAPATT, BARITT parametric devices), tunnel diodes, varactors, quantum electronic devices such as MASERS semiconductor lasers and infrared devices.

Classification

Microwave Solid state devices are divided into four groups

1. Microwave Transistor

1. Microwave Bipolar Junction Transistor (BJT)
2. Hetero junction Bipolar Transistor (HBT)
3. Tunnel diode

2. Field Effect Transistors

1. Junction Field Effect transistors (JFETs)
2. Metal Semiconductor Field Effect Transistors (MESFETs)
3. High Electron Mobility Transistor (HEMTs)
4. Metal Oxide Semiconductor Field Effect transistors (MOSFETs)
5. N-type Metal Oxide Semiconductor transistors (NMOSs)
6. P-type Metal Oxide Semiconductor transistors (PMOSs)
7. Complementary Metal Oxide Semiconductor transistors (NMOSs)
8. Memory devices
9. Charged Coupled devices (CCDs)

Classification

3. Transferred Electron Devices (TEDs)
 1. Gunn diode
 2. Limited Space Charge Accumulation diode (LSA diode)
 3. Indium Phosphide diode (Inp diode)
 4. cadmium telluride diode
4. Avalanche Transit Time devices
 1. Read diode
 2. Impact Ionization Avalanche Transit Time diodes (IMPATT diode)
 3. Trapped Plasma Avalanche Transit Time diodes (TRAPATT diode)
 4. Barrier injected Transit Time diodes (BARITT diode)

Applications

1. Transistors

Applications

1. L-Band transmitters for telemetry systems and phased array radar systems
2. L-Band and S-band transmitters for communication systems

Advantages

1. Low cost
2. Low Power supply
3. Reliable
4. High CW power output
5. Light weight

Applications

2. TED

Applications

1. C-Band, X-band, ku-band, ECM amplifiers for wide band system
2. X-Band and ku-band transmitters for radar systems such as traffic control

Advantages

1. Low cost
2. Low Power supply
3. Reliable
4. Light weight
5. Low noise
6. High gain

Applications

3. IMPATT

Applications

1. Transmitters for multimeter wave communication systems

Advantages

1. Low cost
2. Low Power supply
3. Reliable
4. Light weight
5. High CW power out

Applications

4. TRAPATT

Applications

1. S-Band pulsed transmitter for phased array radar systems

Advantages

1. Low cost
2. Low Power supply
3. Reliable
4. High peak and average power

Transferred Electron Devices

- In electron devices at microwave frequencies negative conductance effect was discovered by Gunn as bulk effect.
- This bulk effect property of material may be obtained by reduction of electron drift velocity with increasing electric field above a threshold value.
- The electrons shift from high mobility to low mobility state under the influence of strong electric field. Such phenomena is called **transferred-electron** mechanism and device that exhibit this feature is called as **transferred-electron device**.

Difference between Transistors and TEDs

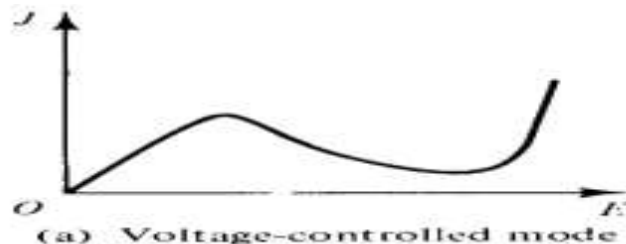
Transistors	TEDS
Operates with either junctions or gates	They are bulk devices having no junction and gates
They are fabricated from elemental semiconductors such as Ge and Si	TED's are fabricated from compound semiconductors such as GaAs, InP (Indium Phosphate) or CdTe (Cadmium telluride)
They operate with “warm” electrons whose energy is not much greater than their thermal energy (0.026 eV at room temperature)	TED's operate with hot electrons whose energy is very much greater than their thermal energy.

Ridley Watkins-Hilsum (RWH) theory

- Many explanations have been offered for the Gunn effect. In 1964 Kroemer suggested that Gunn's observations were in complete agreement with the Ridley Watkins-Hilsum (RWH) theory

1. Differential Negative Resistance

- The fundamental concept of the Ridley-Watkins-Hilsum (RWH) theory is the differential negative resistance
- There are two modes of negative-resistance devices: **voltage-controlled** and **current controlled** modes

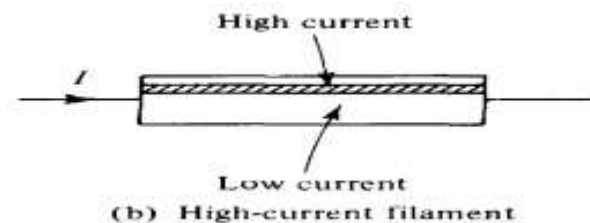
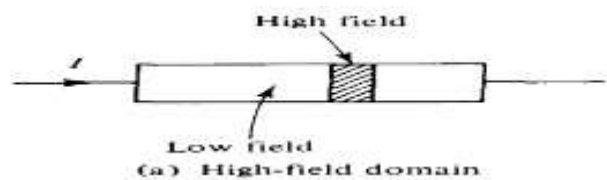


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Ridley Watkins-Hilsum (RWH) theory

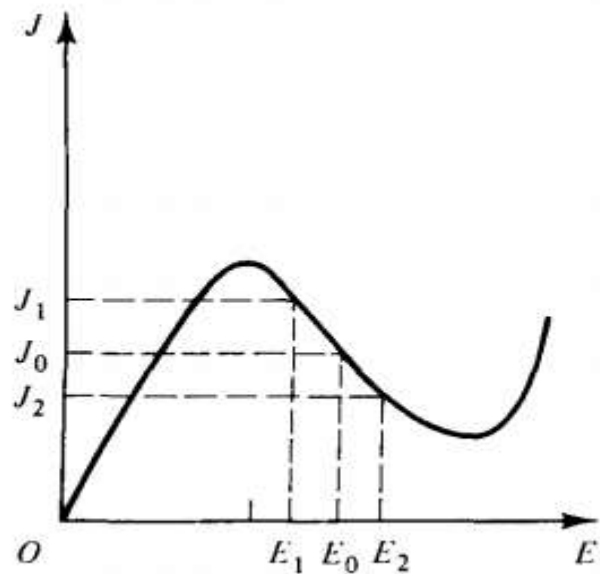
- In the voltage-controlled mode the current density can be multivalued, whereas in the current-controlled mode the voltage can be multivalued.
- In the voltage-controlled negative-resistance mode high-field domains are formed, separating two low-field regions. The interfaces separating low and high-field domains lie along equipotential; thus they are in planes perpendicular to the current direction.
- In the current-controlled negative-resistance mode splitting the sample results in high-current filaments running along the field direction



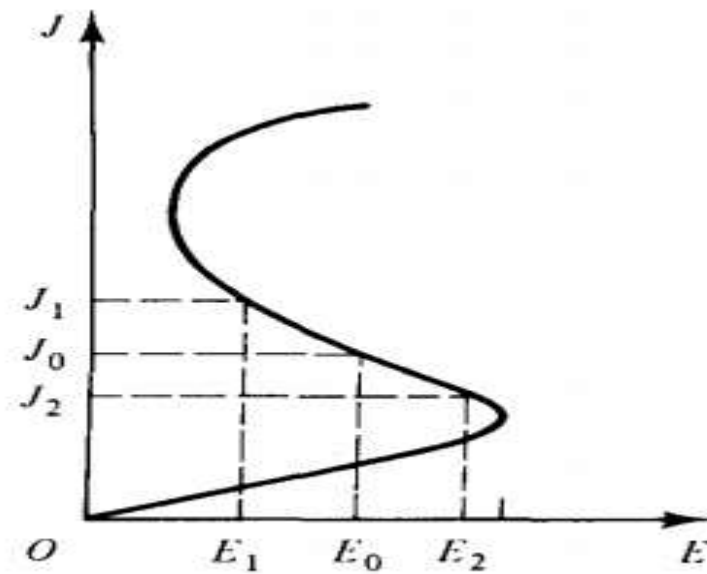
Ridley Watkins-Hilsum (RWH) theory

- Expressed mathematically, the negative resistance of the sample at a particular region is
 - $\frac{dI}{dV} = \frac{dJ}{dE} = \textit{negative resistance}$
 - If an electric field E_0 (or voltage V_0) is applied to the sample, for example, the current density J_0 is generated.
 - As the applied field (or voltage) is increased to E_2 (or V_2), the current density is decreased to J_2 .
 - When the field (or voltage) is decreased to E_1 (or V_1), the current density is increased to J_1 .
 - These phenomena of the voltage controlled negative resistance are shown in Fig (a). Similarly, for the current controlled mode, the negative-resistance profile is as shown in Fig (b).

Ridley Watkins-Hilsum (RWH) theory



(a) Voltage-controlled mode



(b) Current-controlled mode

Ridley Watkins-Hilsum (RWH) theory

Two-Valley Model Theory

- Gunn effect can be explained on the basis of two valley theory of Ridley Watkins-Hilsum (RWH) theory or the transferred electron mechanism.
- Basic mechanism involved in the operation of bulk n-type GaAs devices is the transfer of electrons from lower conduction valley (L-valley) to upper subsidiary valley the U-valley.

DATA FOR TWO VALLEYS IN GaAs

Valley	Effective Mass M_e	Mobility μ	Separation ΔE
Lower	$M_{eL} = 0.068$	$\mu_L = 8000 \text{ cm}^2/\text{V-sec}$	$\Delta E = 0.36 \text{ eV}$
Upper	$M_{eU} = 1.2$	$\mu_U = 180 \text{ cm}^2/\text{V-sec}$	$\Delta E = 0.36 \text{ eV}$

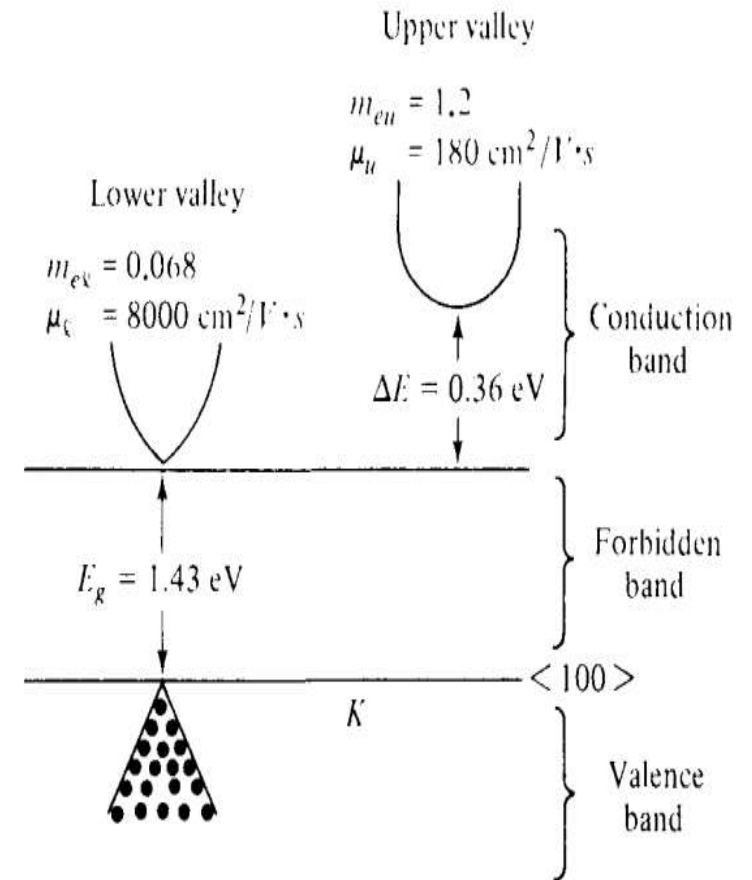
Ridley Watkins-Hilsum (RWH) theory

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.

Electron densities in the lower and upper valleys remain the same under an equilibrium condition.

Case 1:

When the applied electric field is lower than the electric field of the lower valley ($E < E_l$), no electrons will transfer to the upper valley



Ridley Watkins-Hilsum (RWH) theory

Case 2:

- When the applied electric field is higher than that of the lower valley and lower than that of the upper valley ($E_l < E < E_u$), electrons will begin to transfer to the upper valley.

Case 3:

- when the applied electric field is higher than that of the upper valley ($E_u < E$), all electrons will transfer to the upper valley.

If electron densities in the lower and upper valleys are n_l and n_u , the conductivity of the n-type GaAs is

$$\sigma = e(\mu_l n_l + \mu_u n_u)$$

where e = the electron charge

μ = the electron mobility

$n = n_l + n_u$ is the electron density

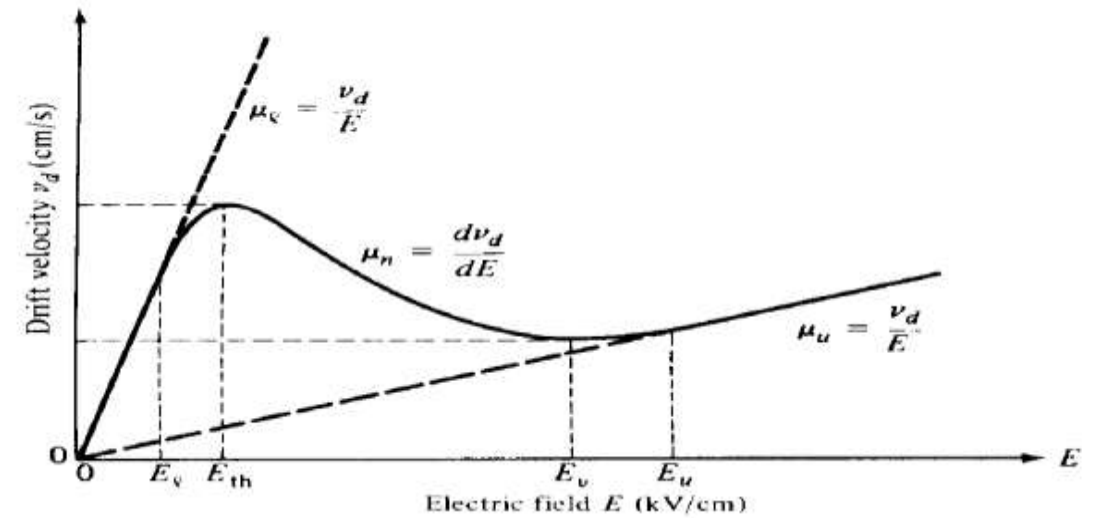
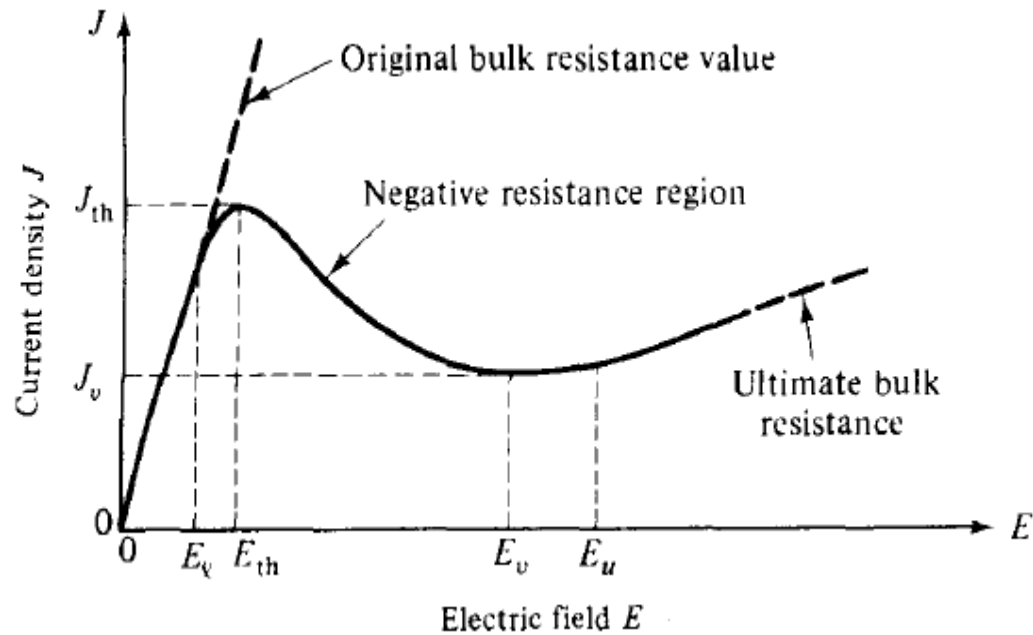
Ridley Watkins-Hilsum (RWH) theory

On the basis of the Ridley-Watkins-Hilsum, the band structure of a semiconductor must satisfy three criteria in order to exhibit negative resistance

1. The separation energy between the bottom of the lower valley and the bottom of the upper valley must be several times larger than the thermal energy. $\Delta E > 0.026$ eV.
2. The separation energy between the valleys must be smaller than the gap energy between the conduction and valence bands. This means that $\Delta E < E_g$.
3. Electrons in the lower valley must have high mobility, small effective mass, and a low density of state, whereas those in the upper valley must have low mobility, large effective mass, and a high density of state.

The two most useful semiconductors-silicon and germanium-do not meet all these criteria. Some compound semiconductors, such as gallium arsenide (GaAs), indium phosphide (InP), and cadmium telluride (CdTe) do satisfy these criteria.

Ridley Watkins-Hilsum (RWH) theory



Gunn Oscillation Modes

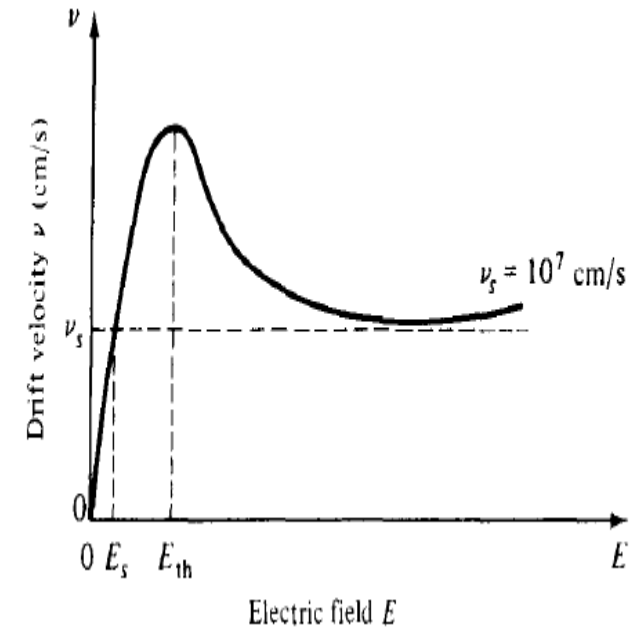
Depending upon the material parameters and operating conditions, gunn effect oscillator can be made to oscillate in any of the below frequency modes

1. Domain mode (Transit time mode or travelling domain mode)
2. Delay or Inhibited domain mode
3. Quenched domain mode
4. Limited space charge Accumulator mode (LSA)

Gunn Oscillation Modes

1. Domain mode (Transit time mode or travelling domain mode)

- This is also called as gunn mode.
- When the electron drift velocity v_d is equal to the sustaining velocity v_s , the high field domain is stable.
- In other words the electron drift velocity is given by $v_d = v_s = fL = 10^7 \text{ cm/s}$
- Efficiency is below 10% because the current is collected only when the domain arrives at the anode.
- In this mode oscillation period is equal to the transit time $\tau_0 = \tau_t$



Gunn Oscillation Modes

2. Delayed Domain mode ($10^6 \text{ cm/s} < fL < 10^7 \text{ cm/s}$)

- When the transit time is chosen so that the domain is collected while $E < E_{th}$, the new domain cannot form until the field rises above threshold again.
- Here oscillation period is greater than transit time $\tau_0 > \tau_t$.
- This delay mode is called inhibited mode and the efficiency of this mode is about 20%.

3. Quenched Domain mode ($fL > 2 \times 10^7 \text{ cm/s}$)

- If the bias field drops below sustaining field E_s during the negative half cycle, the domain collapses before it reaches the anode.
- When the bias field swings back above threshold, a new domain is nucleated and the process repeats.

Gunn Oscillation Modes

- Therefore the oscillations occurs at the frequency of the resonant circuit rather than at the transit time frequency.
- Theoretically the efficiency of quenched domain oscillators can reach 13%.

4. Limited space charge Accumulation mode ($fL > 10^7$ cm/s)

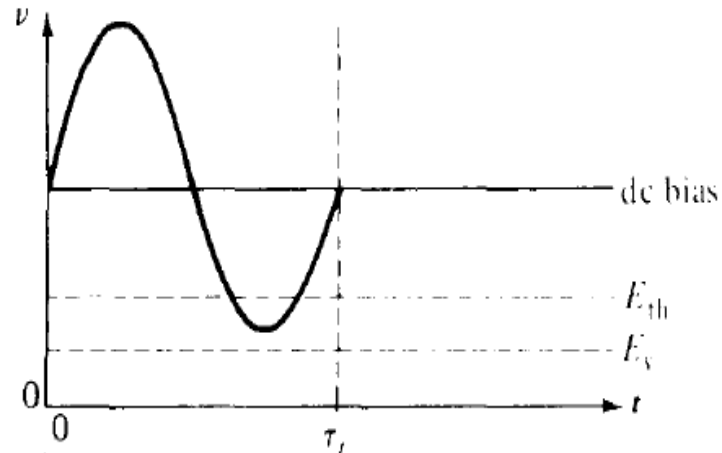
- When the frequency is very high, the domains do not have sufficient time to form while the field is above threshold. As a result, most of the domains are maintained in the negative conductance state during a large fraction of the voltage cycle.
- Any accumulation of electrons near the cathode has time to collapse while the signal is below threshold.
- Thus the LSA mode is the simplest mode of operation, and it consists of a uniformly doped semiconductor without any internal space charges.

Gunn Oscillation Modes

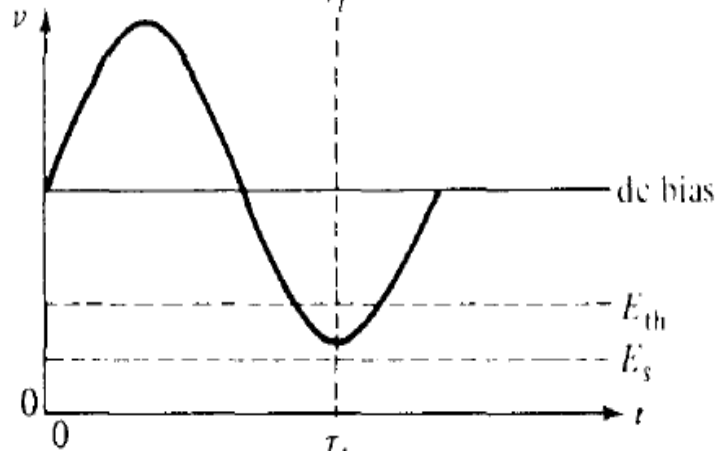
- In this instance, the internal electric field would be uniform and proportional to the applied voltage.
- The current in the device is then proportional to the drift velocity at this field level.
- The efficiency of the LSA mode can reach 20%.
- The oscillation period τ_0 should be no more than several times larger than the magnitude of the dielectric relaxation time in the negative conductance region τ_d .

Gunn Oscillation Modes

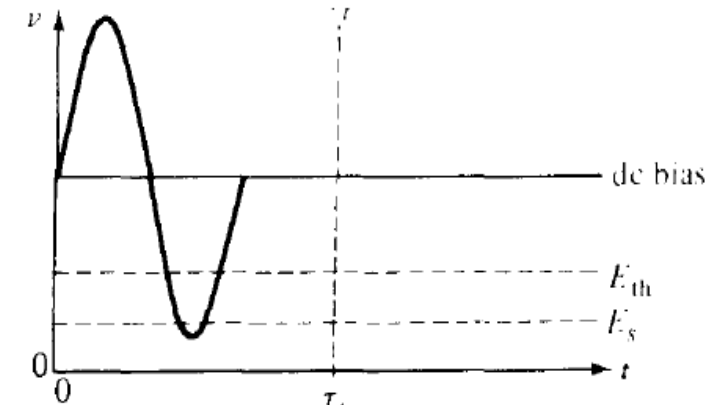
(a) Transit-time mode
 $\tau_0 = \tau_f$



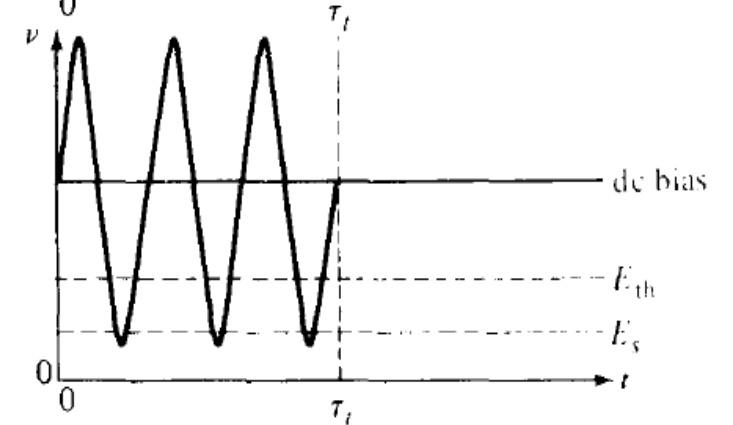
(b) Delayed mode
 $\tau_0 > \tau_f$



(c) Quenched mode
 $\tau_0 < \tau_f$



(d) LSA mode
 $\tau_0 < \tau_f$
 $\tau_0 = 3\tau_d$



Applications of Gunn Diode

1. In radar transmitters (Police radar, CW Doppler radar)
2. Pulsed Gunn diode oscillators used in transponders for air traffic control (ATC) and in industry telemetry systems.
3. Broad band linear amplifiers (replacing TWTs)
4. Fast combinational and sequential logic circuits.
5. Low and medium power oscillator in microwave receivers.
6. As pump sources in parametric amplifiers.

AVALANCHE TRANSIT TIME DEVICES(ATD)

- When a p-n junction diode is reverse biased, no current flows. But when reverse voltage exceeds the junction breakdown and current flows with only slight increase in voltage.
- This breakdown is caused by avalanche multiplication of electrons and holes in the space charge region of the junction.
- The p-n junction exhibits negative resistance characteristics in the avalanche breakdown conditions.
- This negative resistance region is used to generate microwave power and to amplify microwave signals. Such devices are called as **avalanche transit time devices**
- E.g IMPATT, TRAPATT, BARITT diodes

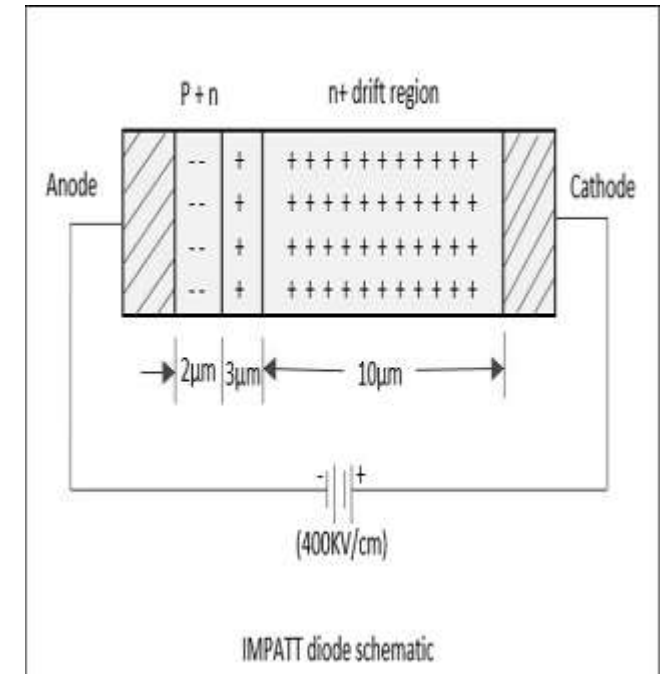
IMPATT

- Any device which exhibit negative resistance for dc will also exhibit it for ac i.e., if an ac voltage is applied current will rise when voltage falls at an ac rate.
- Hence negative resistance can also be defined as that property of a device which causes the current through it to be 180° out of phase with the voltage across it.
- This is the kind of negative resistance exhibited by IMPATT (IMPact Ionization Avalanche Transit Time diode).
- A voltage gradient applied to the IMPATT diode, results in high current. A normal diode will eventually breakdown by this. However this IMPATT diode is developed to withstand all this.
- Application of RF ac voltage is 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

IMPATT

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.

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.



IMPATT

- 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 voltage and current are 180° out of phase and a dynamic RF negative resistance has proved to exist. Hence, IMPATT diode acts both as an oscillator and an amplifier.

IMPATT

Output Power

The maximum output power is given by

$$p_m = I_m V_m$$
$$p_m = E_m^2 \epsilon_s v_d A$$

Where v_d = Drift velocity

E_m = Maximum Electric field

ϵ_s = Semiconductor Permittivity

A = Cross section area

IMPATT

Efficiency

The efficiency η of IMPATT diode is given by

$$\eta = \left(\frac{P_{ac}}{P_{dc}} \right) = \frac{V_a I_a}{V_d I_d}$$

Where P_{ac} = ac power

P_{dc} = dc power

V_a and I_a = ac voltage and current

V_d and I_d = dc voltage and current

IMPATT

Performance Characteristics

- Theoretical efficiency $\eta = 30\%$ and 15% for Si and 23% for Ga As
- Frequency = 1 to 300 GHz
- Maximum output power (for single diode) : 5W at X band to 0.5W at 30 GHz
- Maximum output power (for several diodes combined) : 40W at X band
- Pulsed power = 4 kW.

IMPATT

Disadvantages

- Very noise (Because avalanche is a noisy process)
- Noise figure is 30 dB, which is not as good as klystron/Gunn/TWT.
- Tuning range is not as good as Gunn diodes

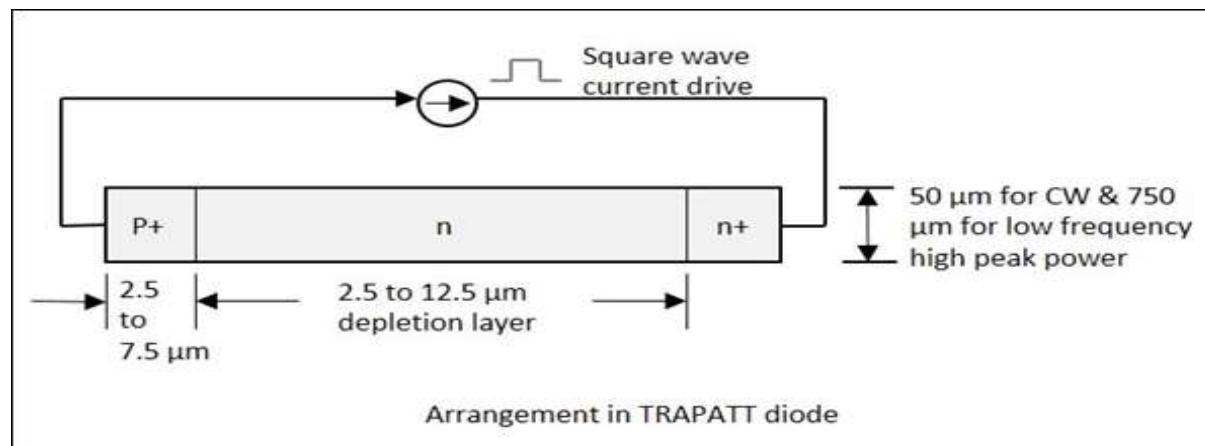
IMPATT

Applications

- IMPATT diodes are used as microwave oscillators such as
 - Microwave generators
 - Modulated output oscillators
 - Receiver local Oscillators
 - Parametric amplifier pumps
- High Q IMPATTs are used in Intrusion alarms, police radar and low power microwave transmitter whereas low Q IMPATTs are used in FM telecommunication transmitters and CW doppler radar transmitter.

TRAPATT

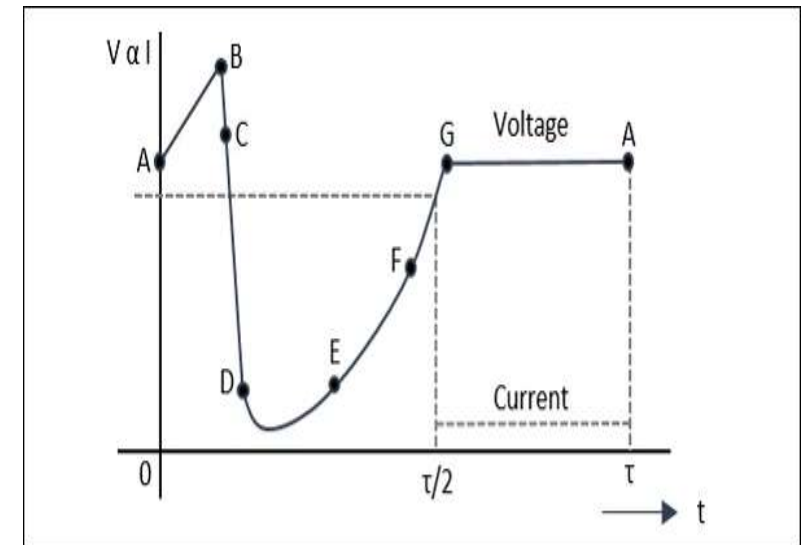
- TRAPATT (TRApped Plasma Avalanche Triggered Transit diode) is derived from the IMPATT diode.
- It is a high frequency microwave generator capable of operating from several hundred MHz to several GHz.
- It is typically p^+-n-n^+ Si or GaAs structure



TRAPATT

Operation

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.



TRAPATT

- The 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.

TRAPATT

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.

TRAPATT

- **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.

TRAPATT

Performance Characteristics

1. CW Power : 1-3 W between 8 GHz to 0.5 GHz
2. Pulse Power : 1.2 kW at 1.1 GHz
3. Operating Voltage : 60-150V
4. Efficiency : 15 to 40%
5. Noise figure : >30dB
6. Frequency : 3 to 50 GHz

TRAPATT

Disadvantages

- Very noisy

Applications

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