UNIT 2

M-TYPE TUBES AND MICROWAVE SOLID STATE DEVICES

Syllabus

M-Type Tubes: Introduction, Cross-field Effects, Magnetrons – Different Types, Cylindrical Traveling Wave Magnetron – Hull Cut-off and Hartree Conditions, Modes of Resonance and π-Mode Operation, Separation of π-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.

LEARNING OBJECTIVES

- Concept of M-type tubes
- Basic idea and types of magnetrons used.
- Construction, working, mathematical analysis, operating modes and O/P characteristics of cylindrical traveling wave magnetron.
- Concept of microwave solid state devices
- Basic idea and types of microwave solid state devices.
- Construction, working, mathematical analysis, operating modes and characteristics of TED such as GUNN diode.
- Construction and working of IMPATT device.
- Construction and working of TRAPATT device.

INTRODUCTION

In the previous unit, several commonly used linear-beam tubes such as two cavity, reflex klystron tubes and helix travelling wave tubes were described in detail. In these tubes, the dc magnetic field that is in parallel with the dc electric field is used merely to focus the electron beam. In this unit, we are going to discuss about crossed-field devices such magnetrons, where the dc magnetic field and the dc electric field are perpendicular to each other. In all

Crossed-field tubes, the dc magnetic field plays a direct role in the RF interaction process. Crossed-field tubes derive their name from the fact that the dc electric field and the dc magnetic field are perpendicular to each other. They are also called M-type tubes.

In this unit, we will also discuss about microwave solid state devices such as Transferred Electron Devices (TEDs), IMPATT and TRAPATT. These are bulk devices having no junctions or gates. The devices are fabricated from compound semiconductors, such as gallium arsenide (GaAs), indium phosphide (InP), or cadmium telluride (CdTe). These devices operate with "hot" electrons whose energy is very much greater than the thermal energy. Because of these characteristics, the theory and technology of transistors cannot be applied to microwave solid state devices.

PART-A SHORT QUESTIONS WITH SOLUTIONS

Q1. Write down the different types of magnetron.

Nov./Dec.-18, (R13), Q1(g)

(or)

Write about the classification of magnetrons.

Ans:

Magnetron is a type of microwae generator in which the electric and magnetic fields are perpendicular to each other. Hence, these tubes are also known as cross field tubes (or) M-type tubes there are theree types of magnetrons,

1. Negative resistance type
2. Cyclotron frequency type
3. Travelling wave (or) cavity type.

Q2. How cross-field concept is used to produce oscillations in magnetron?

Ans: (Model Paper, Q1(g) | May/June-19, (R15), Q1(h))

Magnetron is a self excited high power microwave oscillator. In these devices, electric field between anode and cathode is radial. Since magnetic field is perpendicular to plane of radial electric field, magnetron is also referred as cross field device.

If the orientation of electric and magnetic fields are perpendicular to each other, then the motion of electrons depend on electric or magnetic fields respectively. Hence, the magnetic field exerts no force on electrons when the direction of electric and magnetic fields are same or opposite. The interaction between the magnetic and electric fields of cavity is responsible for producing oscillations.

Q3. How to separate a π mode in magnetron?

Dec.-19, (R16), Q1(g)

(or)

What is strapping in magnetron.

Ans: May/June-19, (R15), Q1(g)

Strapping is a method to separate π-mode from other modes. In this strapping technique for π-mode, each strap is at same potential and no π-mode current flows in strap. The straps offer capacitance ϕ causes the frequency separation between π-mode and the other modes.

Q4. What are the advantages of magnetrons over TWT?

Ans:

The advantages of magnetrons over TWTs are as follows,

1. The initial and operational costs of magnetrons is low compared to TWTs.
2. Magnetrons have many manufactures wherein, TWTs have limited manufactures.
3. Magnetrons occupy large frequency range than TWTs.
4. Magnetron tube is cheaper than TWT tube.

Q5. Write the applications of magnetron.

Ans:

Magnetrons find applications in,

1. Radar communication
2. Microwave ovens
3. Microwave excited lighting systems.

Q6. What is mode jumping in cavity magnetron? How this can be avoided?

Ans: April/May-18, (R13), Q1(g)

The change in operating conditions of magnetron causes modes to jump from one to other, which results sudden changes in power output and oscillation frequency. This condition is called "Mode jumping".

Mode jumping in magnetrons can be overcome by using a common technique called strapping.

In strapping, alternate anode poles made of heavy guage wire are connected with a phase difference of 2π radians. Since the phase change is multiple of 2π, mode jumping can be avoided.

Q7. What are the Hull Cut-off and Hartree conditions?

Ans: (Model Paper, Q1(b) | Nov./Dec.-18, (R13), Q1(h))

Hull-cut off Condition

Hull cut-off condition specifies the maximum distance required for an electron to move in a direction normal to the cathode.

Hartree Condition

Hartree condition specifies an anode voltage that is required to synchronize the electron velocity with RF phase velocity.

Q8. What is the principle of working of backward wave oscillator?

Ans: Nov./Dec.-16, (R13), Q1(f)

Backward Wave Oscillator (BWO) is a self oscillating continuous wave oscillator. It delivers microwave power over a wide frequency range. The main operation involved in this device is the backward movement of travelling RF wave from the collector towards the electron gun to extract energy from the electron beam.

The slow wave structure in BWO is a folded transmission line similar to helix in TWT. When the electron beam focussed by the axial magnetic field, it is made to travel along the helix, so that the accelerating and retarding electric fields are generated. This results in interchange of energy between the electron beam and RF wave causing electron bunching.

Thus, the reflection produced in this process leads to oscillations as the reflections are in opposite or backward direction.

Q9. What are the disadvantages of strapping?

Nov./Dec.-16, (R13), Q1(g)

Ans: The disadvantages of strapping are,

1. Strapping causes power loss in the conducting rings.
2. With strapped resonators at higher frequencies, it is difficult to maintain the RF field within the interaction space.
3. It produces stray effects.
4. As the number of cavities increase (16 or 32), strapping has no effect on mode jumping (fails to prevent mode separation).

Q10. Compare the performance characteristics of magnetron and Klystron oscillator.

Ans: The performance characteristics of magnetron and klystron oscillator are given in table,

	Magnetron		Klystron
1.	Operating frequency range of magnetron is upto 10 GHz.	1.	Operating frequency range of klystron is 4 GHz to 200 GHz.
2.	Power output for magnetron is 800 kW.	2.	Power output for klystron is 10 mW to 2.5 W.
3.	Efficiency of magnetron is 40 to 70%.	3.	Efficiency of klystron is 20%.

Table

Q11. Compare the performance characteristics of TWT amplifier and magnetron.

Ans:

The comparison between the performance characteristics of TWT and magnetron is shown in table,

	Travelling Wave Tube (TWT)		Magnetron
1.	In TWT, the electrons interact with a travelling wave.	1.	In magnetron, the electron carrying energy are made to interact with RF field for a long duration.
2.	Efficiency of TWT is in the range of 5 to 20%.	2.	Efficiency provided by magnetron is in the range of 40 to 70%.
3.	Operating frequency of TWT is greater than 3 GHz.	3.	Operating frequency of magnetron is upto 10 GHz.
4.	Average power output of TWT is 10 kW.	4.	Power output of magnetron is 800 kW (Pulsed).

Table

Q12. What are microwave solid state devices? Give its applications.

Ans:

Microwave Solid State Devices: Microwave solid state devices are those which are used for low power microwave applications. These are of small size, light weight with high reliability.

Microwave solid state devices are classified into two types. They are,

1. Transferred-electron devices
2. Avalanche transit-time devices.

Applications

1. They are used in radio transmitters, such as CW doppler radar.
2. They are used in broadband linear amplifiers.
3. They are used as pump sources in parametric amplifiers.
4. They find application in transponders.
5. They are used in both the combinational and sequential logic circuits.
6. They are used in microwave receivers.

Q13. Mention the application of TEDs.

Nov./Dec.-17, (R13), Q1(h)

Ans: Transferred Electron Devices (TEDs) offer variety of applications. Some of them are,

1. TEDs act as microwave oscillators.
2. They serve as pump source for parametric amplifiers.
3. They can be used with fast combinational and sequential logic circuits.
4. They are used in various types of radar transmitters.

Q14. What is Gunn effect?

Ans:

When the voltage applied to a semiconductor device exceeds the critical voltage value (or) threshold voltage value in the frequencies of around a few GHz) is referred as Gunn effect. The unusual behaviour of semiconductor diode is due to the negative resistance effect.

Q15. What are the applications of Gunn diode?

(Dec.-19, (R16), Q1(h) | May/June-19, (R15), Q9(b))

(or)

List the applications of Gunn diode.

Ans:

The applications of Gunn diode are,

1. In microwave receivers, Gunn diodes are used as low and medium power oscillators.
2. They are used in radars and broadband microwave amplifiers.
3. Gunn diodes are used as pump source in parametric amplifiers.
4. They are used as motion detectors for door openers and security alarms.
5. These are used as transmitters for millimeter-wave communication.

Q16. Draw the diagram of IMPATT diode and carrier concentration.

Answer : April/May-18, (R13), Q1(b)

The schematic of IMPATT diode with carrier concentration is as shown in figure.

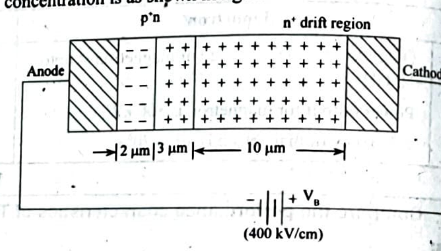


Figure: Schematic of IMPATT

Q17. Compare IMPATT and TRAPATT diodes.

Ans: The comparison between IMPATT and TRAPATT diodes is mentioned in table.

	IMPATT Diode		TRAPATT Diode
1.	IMPATT stands for Impact Avalanche and Transit Time.	1.	TRAPATT stands for Trapped Plasma Avalanche Triggered Transit.
2.	They exhibit negative resistance.	2.	They are derived from IMPATT diode in order to overcome the limitation of the same.
3.	Efficiency of IMPATT didoe is 30%.	3.	Efficiency of TRAPATT diode is between 15% to 40%.
4.	It's pulsed power is 4 kW.	4.	It's pulsed power is 1.2 kW at 1.1 GHz.
5.	It's operating frequency range is 1 to 300 GHz.	5.	It's operating frequency range from 3 to 50 GHz.
6.	It finds applications in microwave oscillators.	6.	They are used in low power Doppler radars, phased array radars, radio altimeter, etc.

Table

Q18. An IMPATT diode has drift length of 2 μm. Determine,

(i) Drift time of the carriers (ii) Operating frequency of IMPATT diode.

Ans:

Given that,

For an IMPATT diode,

Drift length, $L = 2$ μm

(i) Drift time of carriers, $\tau = ?$

(ii) Operating frequency, $f = ?$

(i) The expression for drift time of carrier is given by,

$$\tau = \frac{L}{v_d} = \frac{2\times10^{-6}}{10^5} \quad [\text{Let, } v_d = 10^5 \text{ cm/sec}]$$

$$= 2 \times 10^{-11}$$

$$\boxed{\therefore \tau = 2 \times 10^{-11} \text{ sec}}$$

(ii) The expression for operating frequency of IMPATT diode is given by,

$$f = \frac{1}{2\tau} = \frac{1}{2\times2\times10^{-11}}$$

$$\Rightarrow \quad f = 0.25 \times 10^{11} \text{ Hz}$$

$$\boxed{\therefore f = 25 \text{ GHz}}$$

PART-B ESSAY QUESTIONS WITH SOLUTIONS

2.1 M-TYPE TUBES

2.1.1 Introduction, Cross-field Effects, Magnetrons – Different Types, Cylindrical Traveling Wave Magnetron – Hull Cut-off and Hartee Conditions

Q19. List and explain different types of magnetrons.

Ans: (Model Paper, Q4(a) | Nov./Dec.-17, (R13), Q8)

Magnetron is a type of microwave generator in which the electric and magnetic fields are perpendicular to each other. Hence, these tubes are also known as cross field tubes (or) M-type tubes. Magnetrons are classified into three types:

1. **Negative Resistance Type Magnetron,** which uses a static negative resistance between two anode segments.
2. **Cyclotron Frequency Type Magnetron,** which functions on the principle 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 Type Magnetron,** which rely on the interaction of electrons with a traveling electromagnetic field of linear velocity. These are commonly referred as magnetrons.

From the above types, negative resistance and cyclotron frequency type magnetrons are not preferred due to their operating frequencies, small power output (about 1 W at 3 GHz), and very low efficiency (about 10%). Thus, traveling wave magnetrons such as the cylindrical magnetron, linear (or planar) magnetron, coaxial magnetron, voltage-tunable magnetron, inverted coaxial magnetron, and the frequency-agile magnetron are commonly used magnetrons in the microwave frequency range.

Cylindrical Magnetron

Magnetron is a self excited high power microwave oscillator which is used to combine magnetic and electric fields of a cavity to provide oscillations.

M-types or cross field devices are those devices whose electric field between anode and cathode is radial. Since magnetic field is perpendicular to plane of radial electric field, magnetron is also referred as cross field device.

Construction

The construction and cross sectional view of a magnetron is as shown in figure (1).

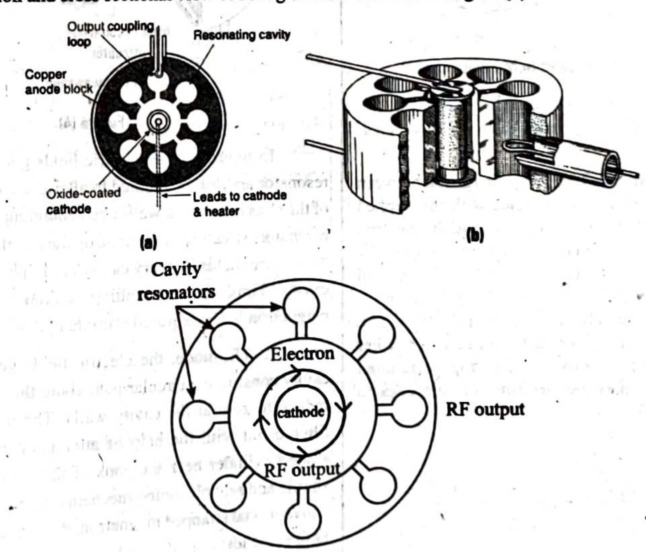


Figure (1): Cross-Sectional View of Cylindrical Magnetron

It consists of a c-shaped permanent magnet containing cylindrical anode block of equally spaced resonant cavities. The cavities control the output frequency as their diameter is adjusted only one half of the wavelength of required frequency.

A copper anode block contains an oxide coated cathode at the centre (interaction chamber) and a filament. Filament leads supports cathode and heater.

The permanent magnet provides magnetic field parallel to the cathode axis where as interaction chamber provides interaction between electric and magnetic fields for exerting force on electrons.

One of the anode of magnetron cavity is coupled to coaxial cable or waveguide provides the required outputs.

Working: The principle of operation of magnetron depends on electron motion based on electric and magnetic fields.

In interaction chamber, when a magnetic field is applied, the motion of electrons become curved and starts flowing into circular path. The magnetic field and anode voltage are responsible for the movement of electrons in circular loop. This circular movement of electrons causes cavities to excite and convert them into oscillation. The electron movement with and without applied magnetic field is as shown in figure (2) respectively.

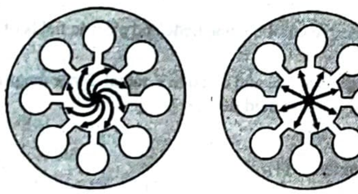


Figure (2): Electron Movement in Magnetron

Linear Magnetron

Figure (3) shows the schematic diagram of a linear magnetron.

In a linear magnetron, the electron propagation between the cathode and anode varies in accordance with the applied magnetic field strength 'B'. At zero magnetic field the electron from cathode reaches the anode in a straight path(indicated by a). The curved trajectory 'b' indicates that the electron field strength required to stop the electron in reaching the anode is known as critical magnetic field B_c. The electron along the path c just touches the anode cavity and returns to cathode. Further increase in field strength($B>B_c$) experiences high rotational force on electron which makes the electron to return back to cathode at a faster rate.

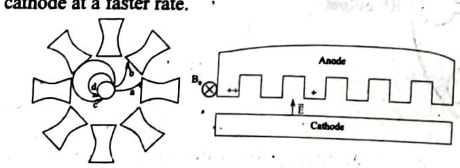


Figure (3): Linear Magnetron

Coaxial Magnetron

Figure (4) shows the schematic diagram of coaxial magnetron, which consists of an anode resonator structure covered by an inner-single, high-Q cavity to operate in TE01 mode.

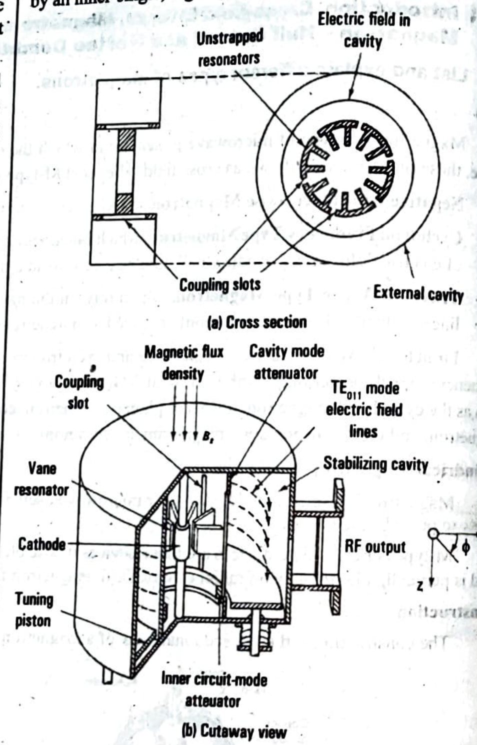


Figure (4)

In figure (4), the electric fields generated in the anode resonator are tightly coupled to alternate cavities with the help of the slots in the back walls of surrounding cavities of the these resonators structure. In π-mode operation of coaxial magnetron, the electric fields in every cavity are in phase with every other cavity. Thus, the surrounding coaxial cavity stabilizes the magnetron in the required π-mode operation.

In TE_{01}mode, the electric fields generated within the cavity constitute a circular path about the axis of the tube and reduce to zero at the cavity walls. The undesired modes are filtered out with the help of attenuator present in the inner slotted cylinder near the ends of the coupling slots. Here, a simple and reliable tuning mechanism is used. In contrast to the conventional strapped magnetron, the coaxial magnetron uses a larger and less complex anode resonator due to the absence of straps. Thus, the cathode loading is lower which in turn reduces voltage gradients.

Voltage Tunable Magnetron

The broadband microwave tube in which the operating frequency is set by tuning the voltage applied between anode and sole is known as voltage tunable magnetron. The cross sectional view of a voltage tunable magnetron is as shown in figure (5).

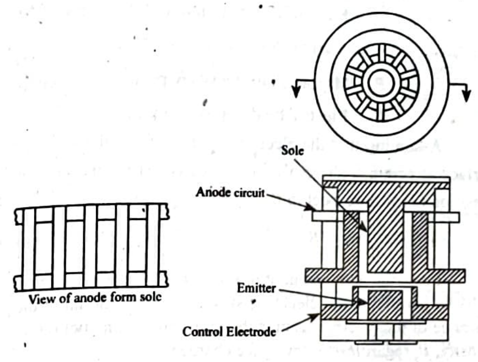


Figure (5): Voltage Tunable Magnetron

From one end of the tube the electrons ejected into the tube from short cylindrical cathode. At the cathode due to the electric and magnetic field electrons formed into a hollow beam. This electron beam radially comes out from the cathode and entered into the space between sole and anode based on applied magnetic field and the dc voltage between the anode and sole the elecrons rotates around the sole.

At low power levels the resonator of low Q-factor and bandwidth of greater than 50% is used in the voltage tunable magnetron. In π-mode of operation, the electron velocity causes the changes in frequency of oscillations i.e., the voltage applied between anode and sole effects the frequency of oscillations. The hollow beam forms the electron bunches in the resonator. The output power of magnetron can be varied by using a control electrode in the electron gun. The bandwidth of the tube changes in accordance with the power levels and frequency of oscillations. The magnetron is with a limited bandwidth at high frequency and high power level and it is about 70% at low frequency and low power level.

Inverted Coaxial Magnetron

A magnetron that builds by inverting the anode and cathode i.e., with the cathode surrounding the anode is referred as inverted coaxial magnetron. In this magnetron, the cavity is placed inside a slotted cylinder, and a resonator vane array is located on the outside. The cathode is arranged in the form of a ring around the anode. Figure (6) shows the schematic diagram of an inverted coaxial magnetron.

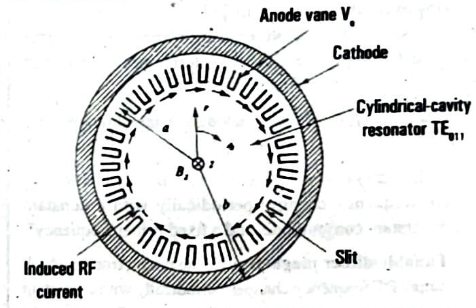


Figure (6)

Advantages of Inverted Coaxial Magnetron

1. Cathode current density can be reduced to one-tenth of that used in coaxial magnetrons.
2. Output waveguide can be in the circular electric mode that has extremely low transmission loss.

Figure (7) shows the comparison between the inverted coaxial magnetron and conventional magnetron designed for the same frequency with different cathode sizes.

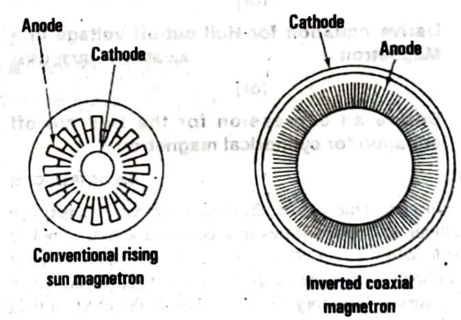


Figure (7)

Frequency-Agile Magnetron

The ability of a coaxial magnetron to tune the output frequency of the radar with sufficient high speed to generate a pulse-to-pulse frequency change higher than the amount required effectively to produce de-correlation of adjacent radar echoes is refereed as its Frequency Agility (FA) factor. Thus, a frequency-agile coaxial magnetron differs from a standard tunable magnetron. The frequency-agile magnetron along with necessary receiver integration circuits will,

1. Minimize target scintillation
2. Maximize the detectability of target in a clutter environment
3. Improve resistance to electronic countermeasures (ECM).
4. Improve the radar system performance for increase in pulse to pulse frequency separation.

However, the increase in pulse-to-pulse frequency separation results difficulties in centering a jamming transmitter on the radar frequency for effective interference with system operation.

The three types of frequency-agile coaxial magnetrons are,

(i) **Dither magnetrons:** The magnetrons in which output RF frequency changes periodically with a constant excursion, constant rate, and a fixed center frequency.

(ii) **Tunable/dither magnetrons:** The magnetron in which output RF frequency changes periodically with a constant excursion and constant rate, but the center frequency can be tuned either manually by hand or mechanically by a servomotor.

(iii) **Accutune magnetrons:** The magnetron in which output RF frequency variations are evaluated by the waveforms of an externally produced, low-level voltage signal.

Q20. How cross-field is used generate oscillations in magnetron and derive the Hull cut-off condition?

Dec.-19, (R16), Q8

(or)

Derive equation for Hull cut-off voltage in a Magnetron.

April/May-18, (R13), Q8(a)

(or)

Derive an expression for the Hull cut-off equation for cylindrical magnetron.

Nov.-15, (R09), Q6(b)

Ans:

In a linear magnetron, the electron propagation between the cathode and anode varies in accordance with the applied magnetic field strength 'B'. At zero magnetic field, the electron from cathode reaches the anode in a straight path(indicated by a). The curved trajectory 'b' indicates that the electron field strength required to stop the electron in reaching the anode is known as critical magnetic field B_c. The electron along the path c just touches the anode cavity and returns to cathode. Further increase in field strength($B > B_c$) experiences high rotational force on electron which makes the electron to return back to cathode at a faster rate.

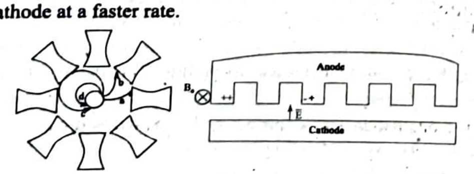


Figure (1)

Figure (1) shows the schematic diagram of a linear magnetron. In the crossed electric and magnetic fields, the differential equations for motion of electrons can be written as,

$$\frac{d^2x}{dt^2} = \frac{e}{m}\left[E_x - B_z\frac{dy}{dt}\right] \quad \dots (1)$$

$$\frac{d^2y}{dt^2} = \frac{e}{m}B_z\frac{dx}{dt} \quad \dots (2)$$

$$\frac{d^2z}{dt^2} = 0 \quad \dots (3)$$

Where,

$\frac{e}{m}$ – Ratio of charge to mass of electron (1.759×10^{11} C/kg)

B_z – Magnetic flux density in positive z-direction

E_x – Electric field in positive x-direction.

Assuming that the electrons emitted from the cathode surface at origin with zero initial velocity. Then, integrating equation (2) with respect to t,

$$\frac{dy}{dt} = \frac{e}{m}B_z x \quad \dots (4)$$

From the above equation, it is evident that the electron velocity parallel to the electrode surface is proportional to the distance of the electron from cathode, x and the magnetic flux density, B_z regardless of the space charges.

The differential electric field for negligible space charge and zero cathode voltage is given by,

$$\frac{dV}{dx} = E_x = \frac{V_0}{d} \quad \dots (5)$$

Where,

V_0 – Anode potential

d – Distance between cathode and anode.

Substituting equation (5) in equation (1),

$$\frac{d^2x}{dt^2} = \frac{e}{m}\left[\frac{V_0}{d} - B_z\frac{dy}{dt}\right] \quad \dots (6)$$

Substituting equation (4) in equation (6),

$$\frac{d^2x}{dt^2} = \frac{e}{m}\left[\frac{V_0}{d} - B_z\left[\frac{e}{m}B_z x\right]\right]$$

$$\Rightarrow \frac{d^2x}{dt^2} + \left(\frac{e}{m}B_z\right)^2 x - \frac{e}{m}\frac{V_0}{d} = 0 \quad \dots (7)$$

The solution for above second order differential equation is obtained as,

$$x = \frac{V_0}{B_z\omega_c d}\left[1 - \cos(\omega_c t)\right] \quad \dots (8)$$

Substituting x value in equation (4),

$$\frac{dy}{dt} = \frac{e}{m}B_z\left[\frac{V_0}{B_z\omega_c d}[1 - \cos(\omega_c t)]\right]$$

Integrating above equation with respect to 't' we get,

$$y = \frac{V_0}{B_z d}\int(1 - \cos\omega_c t)dt$$

Here,

ω_c – Cyclotron angular frequency $= \frac{e}{m}B_z$

$$\Rightarrow y = \frac{V_0}{B_z d}\left[t - \frac{\sin\omega_c t}{\omega_c}\right]$$

$$y = \frac{V_0}{B_z\omega_c d}\left[\omega_c t - \sin(\omega_c t)\right] \quad \dots (9)$$

$$z = 0 \quad \dots (10)$$

The equations (8), (9) and (10) are the equations of cycloid, which is obtained by rolling the point on the circle of $\frac{V_0}{B_z\omega_c d}$ on the plane of cathode. anode surface, when the anode and cathode distance separation d is just equal to the maximum distance to which the electron moves in a direction normal to the cathode. Thus, the cut-off condition is given by,

$$d = \frac{2V_0 m}{B_z^2 ed} \quad \dots (11)$$

$$\Rightarrow \frac{d^2B_z^2}{V_0} = 2\frac{m}{e} = 1.14 \times 10^{-11}$$

If the value of $\frac{d^2B_z^2}{V_0}$ is less than 1.14×10^{-11} then the electron just touches the anode, if it is greater electron returns back to cathode.

The path of electron in a linear magnetron is shown in figure (2).

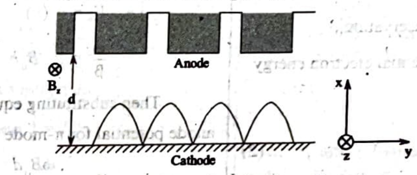


Figure (2): Electron Path in Linear Magnetron

Then, the Hull cut-off voltage of a linear magnetron is obtained from equation (11) as,

$$V_{0c} = \frac{1}{2}\frac{e}{m}B_0^2 d^2 \quad \dots (12)$$

Where,

$B_0 = B_z$ – Cut-off magnetic flux density in positive z-direction.

Thus, if $V_0 < V_{0c}$ the electrons prevent from reaching the anode.

In the same way, the expression for Hull cut-off magnetic flux density in a linear magnetron is obtained as,

$$\boxed{B_{0c} = \frac{1}{d}\sqrt{\frac{2m}{e}V_0}} \quad \dots (13)$$

Q21. Derive the Hartree anode voltage equation for linear magnetron.

Nov./Dec.-16, (R13), Q8(a)

(or)

Derive the Hartree anode voltage equation for magnetron.

Ans:

In a linear magnetron, the anode voltage or magnetic field strength required to get a non-zero anode current in the absence of electromagnetic field is determined by using Hull cut-off or Hartree condition.

A linear magnetron with a hub of thickness h is placed in the cathode-anode interaction space d as shown in figure.

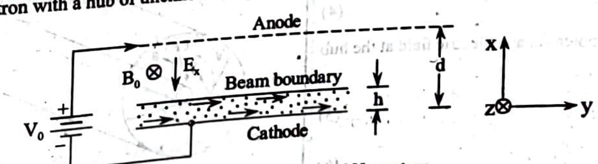


Figure: Linear Model of Magnetron

Hartree Resonance Condition

In π mode of operation, Hartree condition specifies an anode voltage that is required to synchronize the electron velocity with RF wave phase velocity. It is defined as,

$$V_{oh} = \frac{\omega}{\beta}\left(B_o d - \frac{m}{2e}\frac{\omega}{\beta}\right)$$

Assuming that the electron is moving in the positive y-direction, then the velocity of electron is given by,

$$v_y = -\frac{E_x}{B_0} = \frac{1}{B_0}\frac{dV}{dx} \quad \text{... (1)}$$

Where,

E_x – Electric field intensity in X-direction $\left(\frac{-dV}{dx}\right)$

$B_0 = B_z$ – The magnetic flux density in the positive z-direction

V – Potential applied

From the principle of energy conservation,

Kinetic energy of electron = Potential electron energy

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

$$v_y^2 = \frac{2eV}{m} \quad \text{... (2)}$$

From equation (1) and (2),

$$\left(\frac{dV}{dx}\right)^2 = \frac{2eV}{m} B_0^2 \quad \text{... (3)}$$

The above equation can be rearranged as,

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

Integrating on both sides,

$$\left[\frac{m}{2eB_0^2}\right]^{1/2} \int \frac{dV}{\sqrt{V}} = \int dx$$

$$\Rightarrow \left[\frac{m}{2eB_0^2}\right]^{1/2} \times 2\sqrt{V} = x + C \text{ (Constant)}$$

$$\left[\because \int x^n dx = \frac{x^{n+1}}{n+1} + c\right]$$

Since, the constant of integration is eliminated for $V = 0$ at $x = 0$. Then, the potential within the electron beam is given by,

$$V = \frac{eB_0^2}{2m} x^2 \quad \text{... (4)}$$

The expression for potential and electric field at the hub surface are given by,

$$V(h) = \frac{e}{2m} B_0^2 h^2 \quad \text{... (5)}$$

$$E_x = -\frac{dV}{dx} = \frac{-e}{m} B_0^2 h \quad \text{... (6)}$$

Then, the anode potential is given by,

$$V_0 = -\int_0^d E_x dx = -\int_0^h E_x dx - \int_h^d E_x dx$$

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

Substituting equation (5) in above equation,

$$V_0 = \frac{e}{2m} B_0^2 h^2 + \frac{e}{m} B_0^2 h (d-h)$$

$$\therefore V_0 = \frac{e}{m} B_0^2 h \left[d - \frac{h}{2}\right] \quad \text{... (7)}$$

The velocity of electron at the hub surface is obtained from equations (1) and (6) as,

$$v_y(h) = \frac{e}{m} B_0 h \quad \text{... (8)}$$

The phase velocity of the slow wave structure is equal to the velocity of electron,

i.e., $V_p = v_y(h)$

$$\frac{\omega}{\beta} = \frac{e}{m} B_0 h \quad \text{... (9)}$$

Then substituting equation (9) in equation (7), the final anode potential for π-mode is given by,

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

$$\boxed{V_{0h} = \frac{\omega}{\beta}\left(B_0 d - \frac{m}{2e}\frac{\omega}{\beta}\right)} \quad \text{... (10)}$$

The above equation is called "Hartree response condition" or "Hartree anode voltage equation", which is the function of the magnetic flux density, B_0 and the spacing between the cathode and anode, d.

Q22. Briefly explain the mathematical analysis of cylindrical magnetron.

Ans:

Cylindrical magnetrons are widely used microwave devices. Consider acylindrical magnetron with a and b as radius of cathode and anode respectively and the angular displacement of the bends equal to ϕ as shown in figure.

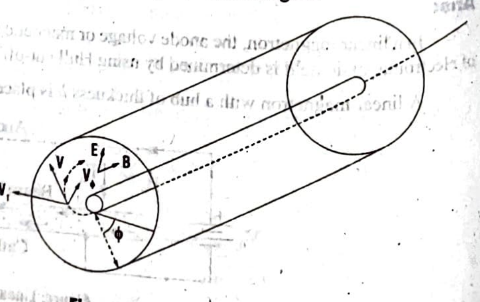


Figure: Geometry of Cylindrical Magnetron

Then, the force acting on moving electron due to the magnetic field becomes as,

$$F = Bev$$

Force acting on electron in the angular direction is given as,

$$F_\phi = eBv_\rho$$

Where,

v_ρ – Velocity in the direction of ρ

B – Magnetic flux density

e – Charge of electron (i.e., 1.6×10^{-19}C)

The torque along the angular direction is defined as,

$$T_\phi = \rho F_\phi = e\rho v_\rho B \quad \text{... (1)}$$

The Angular momentum is given by the product of angular velocity and moment of inertia.

i.e., Angular momentum $= \frac{d\phi}{dt} \times m\rho^2$

Rate of Change in angular momentum

$$= \frac{d}{dt}\left(\frac{d\phi}{dt} \times m\rho^2\right) = T_\phi \quad \text{... (2)}$$

From equations (1) and (2),

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

$$m\rho^2 \frac{d^2\phi}{dt^2} + 2m\rho \frac{d\phi}{dt} = e\rho v_\rho B \quad \text{... (3)}$$

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

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

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

$$= \frac{\rho^2}{2}$$

Integrating equation (3) with respect to 't', we get,

$$m\rho^2 \frac{d\phi}{dt} + 2m\rho.\phi = eB\left(\int \rho v_\rho dt\right)$$

$$= eB\frac{\rho^2}{2}$$

Here, $m\rho\phi$ is considered as a constant for a particular direction.

Hence,

$$m\rho^2 \frac{d\phi}{dt} + C = eB.\frac{\rho^2}{2}$$

For radial distance $\rho = a$, $\frac{d\phi}{dt} = 0$ (boundary condition), above equation becomes,

$$0 + C = \frac{eBa^2}{2}$$

$$C = \frac{eBa^2}{2}$$

Hence,

$$m\rho^2 \frac{d\phi}{dt} + \frac{eBa^2}{2} = eB\frac{\rho^2}{2}$$

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

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

$$\frac{d\phi}{dt} = \frac{eB}{2m}\left(1 - \frac{a^2}{\rho^2}\right) \quad \text{... (4)}$$

The maximum angular velocity(ω_{max}) is obtained as $1 >> \frac{a^2}{\rho^2}$ (i.e., $\rho >> a$)

$$\left(\frac{d\phi}{dt}\right)_{max} = \omega_{max} = \frac{eB_c}{2m} \quad \text{... (5)}$$

Where,

B_c - Cut-off magnetic flux density.

Under equilibrium condition,

Potential energy of electron = Kinetic energy of electron.

i.e., $eV_0 = \frac{1}{2} mv^2$

Here, $v^2 = v_\rho^2 + v_\phi^2$

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

Since, $V_\rho = \frac{d\rho}{dt}$ and $V_\phi = e.\frac{d\phi}{dt}$

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

From equations (4) and (5),

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

Hence,

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

For $\rho = b$ and $\frac{d\rho}{dt} = 0$,

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

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

($\because$ From equation (5))

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

$$\boxed{V_{0c} = \frac{eB_c^2 b^2}{8m}\left(1-\frac{a^2}{b^2}\right)^2}$$

Here,

V_{0c} - Hull's cut-off voltage.

Thus, the above equation is called Hull's cut-off voltage equation.

$$B_c^2 = \frac{8mV_{0c}}{eb^2} \times \frac{1}{\left(1-\frac{a^2}{b^2}\right)^2}$$

$$B_c = \frac{\sqrt{\frac{8mV_{0c}}{e}}}{b\left(1-\frac{a^2}{b^2}\right)}$$

If $b >> a$, equation B_c implies that,

$$\boxed{B_c = \frac{1}{b}\sqrt{\frac{8mV_{0c}}{e}}}$$

Q23. Compare magnetron and reflex klystron.

Ans:

The comparison between magnetron and reflex klystron is mentioned in table.

	Magnetron		Reflex Klystron
1.	Magnetrons are cross field tubes as they have the electric and magnetic fields perpendicular to each other.	1.	Reflex Klystron is a linear microwave beam tube.
2.	These are also referred to as M-type tubes.	2.	These are also referred to as O tubes or original tubes.
3.	The energy containing electrons interact with RF field for a long duration.	3.	The energy carrying electrons interacts the RF field for a short duration.
4.	The efficiency of magnetron is in the range of 40 to 70%.	4.	The efficiency provided by reflex Klystron is in the range of 10 to 20%.
5.	The operating frequency range for magnetron is 500 MHz to 12 GHz.	5.	The operating frequency range of reflex Klystron is 4 to 200 GHz.
6.	It has a cathode and an anode. The anode is divided into several slots and act as cavities. The RF out is taken out from one of the anode cavity.	6.	It has an electron gun (nothing but a filament surrounded by cathode) that generates electron beam. It has only two anode cavities, and the RF out is taken out from one of the anode cavity.
7.	In this, a permanent magnet is used such that it generates the magnetic field perpendicular to electric field.	7.	In reflex Klystron, a repeller electrode is used at the end in order to bounce back the electron beam.
8.	The magnetrons are also used as oscillators, but fixed frequency, Continuous Wave (CW) magnetrons are used for industrial heating and microwave ovens.	8.	The main application of a reflex Klystron is as a signal generator (source) or as an oscillator in microwave radars or receivers.
9.	The output power of magnetron is in the range of 2 mW to 250 kW.	9.	The output power of Reflex Klystron is in the range of 1 mW to 2.5 W.

Table

2.1.2 Modes of Resonance and π-model Operation, Separation of π-mode, O/P Characteristics

Q24. What is mode jumping in magnetrons and explain remedial measures to overcome it.

Ans:

In magnetron cavities, the alternating RF magnetic flux lines are parallel to the cathode axis, whereas alternating RF electric fields are across the slot and excited into the space between anode and cathode in transverse direction. There will be N resonant frequencies or modes for N number of resonant coupled cavities of the anode.

The resonant circuit is as shown in figure (1).

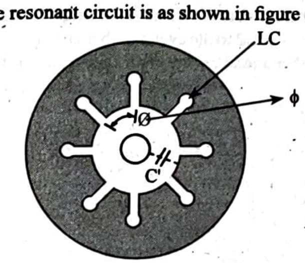


Figure (1): Resonant Circuit

For a closed slow wave structure, the oscillations are possible only if total phase shift is integral multiple of 2π radians.

The phase difference between two adjacent cavities is given by,

$$\phi_n = \frac{2\pi n}{N},\ n = 0, \pm 1, \pm 2, \pm 3 \ldots$$

For $n = 0$, there is no interaction between RF fields. The energy transfer i.e., continuous interaction between charge carriers and RF fields takes place when the anode dc voltage adjusted to match phase velocity of fields in interaction space with average rotational velocity of electrons.

For opposite phase in successive cavities, i.e. $\phi = \pi$ $\left(n = \frac{N}{2}\right)$ excitation is maximum in the cavities.

The change in the operating conditions of magnetron causes modes to jump from one to other, which results sudden changes in power output and oscillation frequency. This condition is called "Mode jumping".

Figure (2) shows a transmission line filter having various modes with small frequency difference between each other.

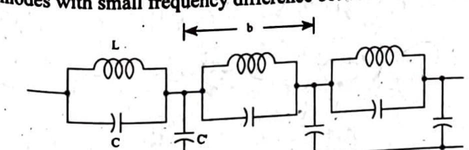


Figure (2): Band Pass Equivalent Circuit

Mode jumping in magnetrons can be overcome by using a common technique called strapping.

In strapping, alternate anode poles made of heavy guage wire are connected with a phase difference of 2π radians. Since the phase change is multiple of 2π, mode jumping can be avoided.

Q25. What is Hartee condition? Explain working of cylindrical travelling wave magnetron and its operation in π mode. March-21, (R16), Q6(a)

(or)

Explain the electron bunching process in cylindrical magnetron with neat diagrams and derive the Hartee condition. May/June-19, (R15), Q8

(or)

Explain the principle of operation of cavity magnetron and discuss phase focusing effect?

(Refer Only Bunching in Cavity Magnetron)

April/May-18, (R13), Q8(b)

(or)

Explain the pi-mode operation of magnetron. Nov./Dec.-18, (R13), Q8(a)

(Refer Only Bunching in Cavity Magnetron)

(or)

How is bunching achieved in a cavity magnetron? Explain.

(Refer Only Bunching in Cavity Magnetron)

Ans: Nov./Dec.-17, (R13), Q9(b)

Bunching in Cavity Magnetron

Bunching is caused due to the sustained interaction between the RF wave and the electron beam travelling with equal velocities.

Noise transients present in the magnetron introduces a continuous oscillations in the magnetron. The oscillations produced are stable only if the adjacent anode poles have a phase-shift of $\frac{n\pi}{4}$. ('n' represents an integer value).

Taking $n = 4$, $\frac{n\pi}{4} = \frac{4\pi}{4} = \pi$-mode of operation is as shown in figure (1).

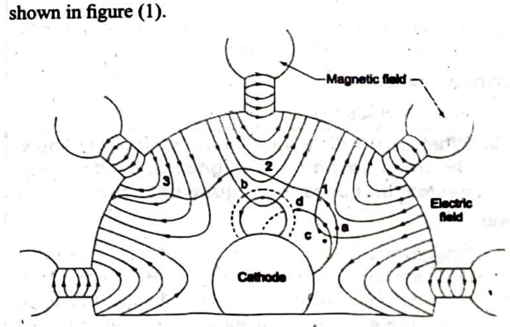


Figure (1): π-Mode of Magnetron

It can be seen that anodes are seperated by a phase-shift of π radians. The dotted lines indicate electron paths at zero RF field and the solid path lines indicate electron trajectories in presence of RF field.

Following points can be observed from the figure(1).

1. The electron 'a' travels a long distance from cathode to anode with its speed being slowed down by transmitting energy to the oscillations (RF field). These electrons to the RF field are known as favoured electrons and are causes bunching Effect.
2. The electron 'b', takes energy from the oscillations, and travels with increased velocity. Because of its high speed, electron 'b' reaches to the cathode quickly and is not responsible for bunching. Hence it is known as unfavoured electron. This inturn affects the system adversely by heating it.
3. The electron 'c', is released after a bit delay to get an appropriate position. It travels with a speed similar to that of electron 'a'. This also a favoured electron
4. The electron 'd' is also slowed down to catch the electron 'a'. So this electron is also responsible for Bunching.

Hence, the electrons that are responsible for bunching are restricted to the electron clouds only. It is known as phase focussing effect which is related to a bunch of electrons (a, c and d with 'a' as reference electron), as shown in figure(2).

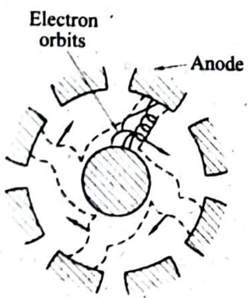


Figure (2): Phase Focusing Effect

This phase focussing effect provides sufficient amount of energy to get constant RF oscillations.

Hartree Condition

For answer refer Unit-2, Q21.

Q26. What are the disadvantages of strapping? Show the cross-section of a magnetron anode cavity system that does not require strapping.

Ans:

Strapping is a method to separate π-mode from other modes. In this strapping technique for π-mode, each strap is at same potential and no π-mode current flows in strap. The straps offer capacitance ϕ causes the frequency separation between π-mode and the other modes as shown in figure (1).

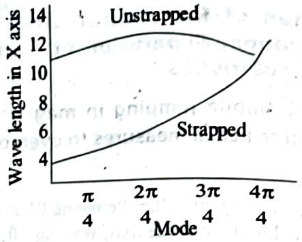


Figure (1): Mode Jumping in Magnetron

Strapping increases the frequency separation between the cavities and also avoids mode jumping.

Strapping consists of two metallic rings of heavy gauge with one ring connected to the even number anode and the other to the odd number anode cavities poles as shown in figure (2).

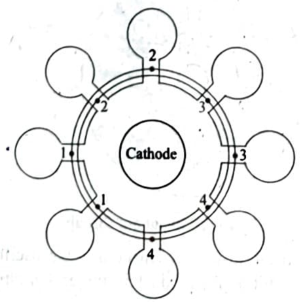


Figure (2): Strapping for TL Mode of Magnetron

The disadvantages of strapping are as follows,

(i) Strapping causes power loss in the conducting rings.

(ii) A strapped resonator is very much difficult.

(iii) With strapped resonator at higher frequencies it will be difficult to maintain the RF field within the interaction space.

(iv) It produces stray effects.

(v) As the number of cavities increase (16 or 32), strapping has no effect on mode jumping (fails to prevent mode separation).

Rising sun magnetron does not require strapping. It gets even anode cavities which give a wide separation of resonant frequency and hence provide high efficiency with low copper losses as shown in figure (3).

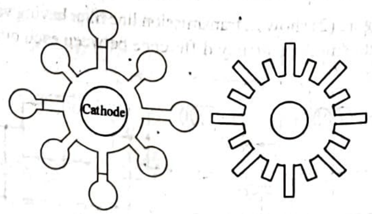


Figure (3): Rising Sun Magnetron

Q27. Interview about π-mode operation and separation and write its characteristics.

Ans: Oct./Nov.-20, (R16), Q7(a)

π-mode Operation

For answer refer Unit-2, Q25.

Separation of π-mode

For answer refer Unit-2, Q26.

Characteristics of Magnetron

The basic output characteristics of magnetrons include,

Thermal Drift

In resonant cavity magnetron, the operating frequency is widely proportional to the cavity size. The amount of power entering into the magnetron is varied either by swi̇tch-on or by a change in operating conditions. This will vary the amount of power dissipated in the anode (and cathode) with the corresponding changes in temperature. However, the power dissipated will affect the physical size of the cavity, which in turn alters the frequency of the magnetron. This phenomenon is referred as thermal drift, which occurs within a few seconds of the change.

Thermal drift is usually specified for each magnetron in kHz/Â°C. This value is almost invariably negative for magnetrons i.e., frequency decreases with increase in temperature.

Frequency Pushing

The change in frequency of the magnetron due to the changes in anode voltage is referred as frequency pushing. In the same way, the variation in oscillator frequency produced by varying the mode current for a constant load is known as pushing figure. A graph between frequency and current is called pushing characteristic and the slope of corresponding curve specifies the pushing figure. In order to avoid frequency pushing, a stabilized anode voltage power supply must be used.

Frequency Pulling

The change in frequency of the magnetron due to the changes in load impedance is referred as frequency pulling. In the same way, the variation in oscillator frequency produced by varying the load impedance for a constant mode current is known as pulling figure. A graph between frequency and the load is called pulling characteristic and the slope of corresponding curve specifies the pulling figure. In order to avoid frequency pulling, a stabilized load should be used.

Time Jitter

The random variation in time delay between the leading edge of the applied voltage pulse and the leading edge of the detected RF output pulse is referred as time jitter (or starting jitter). In general, time jitter results as a function of the interface between the particular modulator and magnetron. One of the important magnetron specifications responsible for stable operation is RRV (Rate of Rise of Voltage). RRV specifies the steepest slope of the leading edge of the applied high voltage pulse, measurable above 80% amplitude. It is usually expressed in kV/Âμs (kilovolts per microsecond).

Q28. A magnetron has a cathode radius of 2.5 mm and an anode radius of 5 mm. What is the cut-off potential if a 0.27-Wb/m² magnetic field is applied?

Ans: (Model Paper, Q4(b) | Nov./Dec.-16, (R13), 1(h))

Given that,

For a magnetron,

Cathode radius, $a = 2.5$ mm

Anode radius, $b = 5$ mm

Magnetic field density, $B = 0.27$ Wb/m²

Hull cut-off poetntial, $V_0 = ?$

The expression for Hull cut-off potential is given by,

$$V_0 = \frac{eB^2 b^2}{8m}\left[1 - \frac{a^2}{b^2}\right]^2 \quad \ldots (1)$$

Where,

Charge of electron, $e = 1.6 \times 10^{-19}$ coulombs

Mass, $m = 9.11 \times 10^{-31}$ kg

On substituting the corresponding values in equation (1),

$$V_0 = \frac{(1.6\times10^{-19})(0.005)^2(0.27)^2}{(8)(9.11\times10^{-31})} \times \left[1 - \frac{(0.0025)^2}{(0.005)^2}\right]^2$$

$$= \frac{2.916\times10^{-25}}{72.88\times10^{-31}} \times [1-0.25]^2$$

$$= \frac{2.916\times10^{-25}}{7.28\times10^{-30}} \times (0.75)^2$$

$= 0.400 \times 10^5 \times (0.75)^2$

$= 22506$ V

$= 22.506 \times 10^3$ V

$= 22.5$ kV

$\boxed{\therefore V_0 = 22.506 \text{ kV}}$

Q29. A pulsed cylindrical magnetron is operated with following parameters:

Anode voltage = 25 kV

Beam current = 25 A

Magnetic density = 0.34 Wb/m²

Radius of cathode cylinder = 5 cm

Radius of anode cylinder =10 cm

Find,

(i) Angular frequency

(ii) cut-off Voltage

(iii) cut-off magnetic flux density.

Ans:

Given that,

For a pulsed cylindrical magnetron,

Anode voltage, $V_o = 25$ kV,

Beam current, $I_o = 25$ A

Magnetic density, 'B_o' = 0.34 Wb/m^2

Cathode radius, 'a' = 5 cm

Anode radius, 'b' = 10 cm

(i) Angular frequency, $\omega_c = ?$

(ii) Cut-off voltage, $V_{oc} = ?$

(iii) Cut-off magnetic flux density, $B_c = ?$

(i) The expression for angular frequency is given by,

$$\omega_c = \frac{e}{m} B_o$$

$e = 1.6 \times 10^{-19}$ coulombs

$m = 9.11 \times 10^{-31}$ kilograms.

$$\therefore \text{Angular frequency, } \omega_c = \left[\frac{1.6\times10^{-19}}{9.11\times10^{-31}}\right] 0.34$$

$$= 0.5917 \times 10^{11} \text{ radians}$$

$$\boxed{\therefore \omega_c = 0.597\times10^{11} \text{ radians}}$$

(ii) The expression for cut off voltage is given by,

$$V_{oc} = \frac{eb^2B_o^2}{8m}\left[1-\frac{a^2}{b^2}\right]^2$$

$$= \frac{1.6\times10^{-19}\times(0.10)^2\times(0.34)^2}{8\times9.11\times10^{-31}} \times \left[1-\frac{(0.05)^2}{(0.10)^2}\right]^2$$

$$= 142.75 \text{ kV}$$

$$\boxed{\therefore V_{oc} = 142.75 \text{ kV}}$$

(iii) The expression for cut-off magnetic flux density is given by,

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

$$= \left(\frac{8\times25\times10^3\times1}{1.759\times10^{11}}\right)^{\frac{1}{2}} \frac{1}{0.10\left(1-\frac{(0.05)^2}{(0.1)^2}\right)}$$

$\Rightarrow \therefore B_c = 14.228$ mWb/m^2

$$\boxed{\therefore B_c = 14.228 \text{ mWb/m}^2}$$

Q30. A normal circular magnetron has the following parameters. Inner radius 0.15 m, outer radius 0.45 m, magnetic flux density 1.6 milli weber/m².

(i) Determine hull cut-off voltage

(ii) Determine the hull cut-off magnetic flux density if the beam voltage is 4000 V.

Nov./Dec.-16, (R13), Q8(b)

Ans:

Given that,

For a circular magnetron,

Inner radius, $a = 0.15$ m

Outer radius, $b = 0.45$ m

Magnetic flux density, $B_0 = 1.6$ milli weber/m^2

Beam voltage, $V_o = 4000$ V

(i) Hull cut-off voltage, $V_{oc} = ?$

(ii) Hull cut-off magnetic flux density, $B_c = ?$

(i) The expression for Hull cut-off voltage is given by,

$$V_{oc} = \frac{eB_0^2 b^2}{8\,m}\left(1-\frac{a^2}{b^2}\right)^2 \quad \text{... (1)}$$

$\because e = 1.6 \times 10^{-19}$ coulombs

$m = 9.11\times10^{-31}$ kg,

On substituting the corresponding values in equation (1), we get,

$$V_{oc} = \frac{1.759\times10^{11}\times(1.6\times10^{-3})^2\,(0.45)^2}{8}\left[1-\frac{(0.15)^2}{(0.45)^2}\right]^2$$

$$\left[\because \frac{e}{m} = 1.759\times10^{11} \text{ C/kg}\right]$$

$$= 9006.08 \text{ V}$$

$$= 9.006 \text{ kV}$$

$$\boxed{\therefore V_{oc} = 9.006 \text{ kV}}$$

(ii) The expression for Hull cut-off voltage is given by,

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

$$= \frac{\left(8\times4000\times\frac{1}{1.75\times10^{11}}\right)^{\frac{1}{2}}}{0.45\left(1-\frac{(0.15)^2}{(0.45)^2}\right)}$$

$$= 1.069 \times 10^{-3}$$

$$= 1.069 \text{ m Wb/m}^2$$

$$\boxed{\therefore B_{oc} = 1.069 \text{ mWb/m}^2}$$

Q31. A linear magnetron has the following parameters:

anode voltage V_o = 15 kV, cathode current, I_o = 1.2 A, operating frequency f = 8 GHz, magnetic flux density B = 0.015 Wb/m², hub thickness h = 2.77 cm distance between anode and cathode, d = 5cm.

Calculate

(i) The electron velocity at the hub surface

(ii) The phase velocity for synchronism

(iii) The Hartee anode voltage.

March-21, (R16), Q6(b)

(or)

A linear magnetron has following operating parameters,

V_o = 15 kV, I_o = 1.2 A, f = 8 GHz, B_o = 0.015 Wb/m², d = 5 cm, h = 2.77 cm. Calculate,

(i) Electron velocity at hub surface

(ii) Phase velocity for synchronism

(iii) Hartree anode voltage.

Ans:

Given that,

For a linear magnetron,

Anode voltage, $V_0 = 15$ kV

Beam current, $I_0 = 1.2$ A

Operating frequency, $f = 8$ GHz

Magnetic flux density, $B_0 = 0.015$ Wb/m^2

Distance, $d = 5$ cm

Height, $h = 2.77$ cm.

(i) Electron velocity at hub surface, $v_e = ?$

(ii) Phase velocity for synchronous, $v_{ph} = ?$

(iii) Hartree anode voltage, $V_{oh} = ?$

(i) The expression for electron velocity at hub surface in a linear magnetron is given by,

$$v_e = \left(\frac{e}{m}\right)B_0 h$$

$$= 1.759 \times 10^{11} \times 0.015 \times 2.77 \times 10^{-2}$$

$$= 73.086 \times 10^6 \text{ m/sec}$$

$$\boxed{\therefore v_e = 73.086\times10^6 \text{ m/sec}}$$

(ii) For synchronous in a linear magnetron, the phase velocity must be equal to electron velocity i.e.,

$$v_{ph} = \frac{\omega}{\beta} = \left(\frac{e}{m}\right)B_0 h$$

$$= 73.086 \times 10^6 \text{ m/sec}$$

$$\boxed{\therefore v_{ph} = 73.086\times10^6 \text{ m/sec}}$$

(iii) For synchronous in a linear magnetron, the phase velocity must be equal to electron velocity i.e.,

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

$$= 73.08 \times 10^6 \times 0.015 \times 5 \times 10^{-2} - \frac{1}{2\times7.759\times10^{11}} \times (73.086\times10^6)^2$$

$$= 39.63 \text{ kV}$$

$$\boxed{\therefore V_{oh} = 39.63 \text{ kV}}$$

Q32. A magnetron operates with following parameters: V_o = 25 kV, I_o = 1.25 A, B_o = 0.4 wb/m² diameter of the cathode = 8 cm, Radius of vane edge to center = 8 cm. Find the cyclotron frequency and cutoff voltage

Nov./Dec-18, (R13), Q8(b)

Ans:

Given that,

For an a magnetron,

Anode voltage, $V_0 = 25$ kV

Beam current, $I_0 = 1.25$ A

Magnetic flux density, $B_0 = 0.4$ Wb/sq.m

Diameter of cathode cylinder, $2a = 8$ cm

Radius of vane edge to centre, $b = 8$ cm

Cyclotron angular frequency, $\omega_c = ?$

Cut-off voltage, $V_{oc} = ?$

Then, the expression for cyclotron angular frequency is given by,

$$\omega_c = \frac{e}{m}B_0 = \frac{1.6\times10^{-19}}{9.11\times10^{-31}} \times 0.4$$

$$= 7.025 \times 10^{10} \text{ rad/sec}$$

$$\boxed{\therefore \omega_c = 7.025\times10^{10} \text{ rad/sec}}$$

and the expression for cut-off voltage for a fixed B_0 is given by,

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

$$= \frac{1.6\times10^{-19}}{8\times9.11\times10^{-31}} \times (0.4)^2 \times (8\times10^{-2})^2 \times \left[1-\frac{(4\times10^{-2})^2}{(8\times10^{-2})^2}\right]^2$$

$$= 1.264544 \times 10^7$$

$$\boxed{\therefore V_{oc} = 12645.44 \text{ kV}}$$

2.2 MICROWAVE SOLID STATE DEVICES

2.2.1 Introduction, Classification and Application

Q33. Give the classification of solid state microwave devices. Nov./Dec.-16, (R13), Q9(b)

(or)

Give the classification of solid state microwave devices along with examples. List its applications.

Ans:

Microwave Solid State Devices

Microwave solid state devices are those which are used for low power microwave applications. These are of small size, light weight with high reliability.

Microwave solid state devices are classified into two types. They are,

1. Transferred-electron devices
2. Avalanche transit-time devices.

1. Transferred Electron Devices

In electron devices, when the electron drift velocity decreases with increasing electric field above threshold value bulk effect is observed. This effect is due to negative resistance phenomeon at microwave frequencies. This negative resistance effect occurs by the swept of electrons from high mobility region to low mobility region. This phenomeon is called transferred-electron mechanism and the device exhibiting such phenomeon is referred as transferred electron device.

Example: Gunn diode.

2. Avalanche Transit-time Devices

In a p-n junction diode when a reverse biased voltage increases beyond the junction voltage, breakdown occurs and current flows even for slight increase in voltage. This breakdown is due to avalanche multiplication of holes and electrons at the junction in the space charge region. Hence p-n diode exhibits negative resistance characteristics in avalanche condition. The devices which exhibit such phenomeon to generate microwave power by amplifying the microwave signals are referred as avalanche transit-time devices.

In a simple way the junction devices which give the negative resistance by suitable combination of impact avalanche breakdown and charge carrier transit time effects are referred as 'Avalanche transit time devices'.

Example: IMPATT, TRAPATT and BARITT diodes.

Applications

1. They are used in radio transmitters, such as CW doppler radar.
2. They are used in broadband linear amplifiers.
3. They are used as pump sources in parametric amplifiers.
4. They find application in transponders.
5. They are used in both the combinational and sequential logic circuits.
6. They are used in microwave receivers.

2.2.2 TEDs – Introduction, Gunn Diodes – Principle, RWH Theory, Characteristics, Modes of Operation – Gunn Oscillation Modes

Q34. Discuss about the principle and operation of TEDs and write its applications. Oct./Nov.-20, (R16), Q7(b)

(or)

What is meant by transferred electron devices? Explain its principle of operation and draw its characteristics. Dec.-19, (R16), Q9 M[10]

Ans:

Transferred Electron Devices

For answer refer Unit-2, Q33, Topic: Transferred Electron Devices.

The commonly used transformed electron device is Gunn diode. Gunn diode is an n-type semiconductor slab of the compounds, namely GaAs (as shown in figure (1)), InP, InAs, INSb and CdTd. This diode exhibits dynamic negative resistances when it is biased to a potential gradient more than a certain value known as threshold field due to the increase of the carrier drift velocity from zero to maximum when the elecric field is changed from zero to threshold value known as gunn effect.

Construction of GUNN Diode

GUNN diodes can be constructed by using single piece of *n*-type silicon as shown in figure (1).

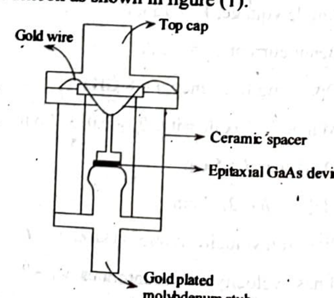


Figure (1): Construction of Gunn Diode

From figure (1), it can be observed that the top and bottom areas of the GUNN diode are doped heavily to produce n^+ material. This material forms a high conductivity for making connections to the device. The device is placed on conducting base (i.e., at top area) and a wire connection is made in order to operate as a heat sink for generated heat. The gold wire deposited on the top surface of the device is used to make the connections with the other terminal. The gold wire is necessarily used in the gunn diode construction as it provides high conductivity and relative stability.

The middle area of the device called "active region" (around 10 microns thickness) is also doped heavily in order to represent all voltages deposited across this device.

Gunn diode is made up of n-type material and it does not have any junction.

Characteristics

The *V-I* characteristics of Gunn diode depicts the negative resistance property of Gunn diode is as shown in figure (2).

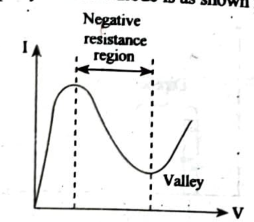


Figure (2): V-I Characteristics of Gunn Diode

Initially as the electric field is applied to GaAs, the current increases with voltage. When the voltage exceeds its peak value, the current reaches maximum and then starts decreasing till it reaches valley point. If the electrons transfer from lower to higher valley is high, then the current decreases simultaneously with increase in voltage. This region implies the negative resistance region of Gunn diode.

Applications

For answer refer Unit-2, Q33, Topic: Applications.

Q35. What is negative resistance phenomenon? Explain the operation and characteristics of Gun diode. March-21, (R16), Q7(a)

(or)

Draw the characteristics of Gunn diode and explain how negative resistance region is obtained? May/June-19, (R15), Q9(a)

Ans:

Negative Resistance Phenomenon

The region in which the current flow in a semiconductor device increases with the decrease in voltage i.e., the inverse of the normal effect in any other positive resistance element is referred as negative resistance region and the process of occurrence this region is called as negative resistance phenomenon. One of the best examples for observing negative resistance region is GUNN diode.

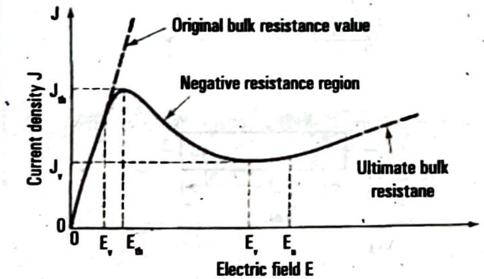
Operation of Gunn Diode

When the field generated for an applied voltage is less than a specific value, called threshold value Eth, the increase in field intensity E results an increased value of vd, which yields in positive mobility μ. Thus, an increase in E produces an increased value of I to yield positive resistance.

When the field generated for an applied voltage in between threshold value Eth and valley value Ev, the increase in the field intensity E results a decreased value of vd, which yields in negative mobility μ due to the onset of Transferred Electron Effect (TEE). Thus, an increase in E produces a decreased value of J to yield negative resistance.

When the field generated for an applied voltage is more than Ev the increase in the field intensity E results a increased value of vd, which yields in positive mobility μ due to the disappearance of the TEE. Thus, an increase in E produces an increased value of I to yield positive resistance.

The characteristics of GUNN diode are shown in figure.



Figure

Q36. Explain domain formation using relevant diagrams in Gunn diode.

Ans:

In the n-type GaAs diode, electrons are the majority carriers. When voltage is applied to the diode, electrons start conducting and electric field is produced. When the applied voltage is low GaAs is ohmic, as the drift velocity of the electrons is directly proportional to the electric field. The conduction current density in the diode is given as,

$$J = \sigma E_x = \frac{\sigma V}{L} U_x = \sigma v_x U_x$$

Where,

J – Conduction current density

σ – Conductivity

E_x – Electric field in the x-direction

L – Length of the diode

V – Applied voltage

ρ – Charge density

v – Driff velocity

U – Unit vector.

In the diode, current is carried by free electrons which are drifted by an fixed positive charge. When the applied voltage is greater than the threshold value, a high-field domain is formed near the cathode. As a result electric field in the rest of the material get reduces and current drops to two-third of its maximum value. The voltage at which this condition occurs is given as,

$$V = -\int_0^L E_x d_x$$

The formation of an electron accumulation layer in GaAs is as shown in figure (1).

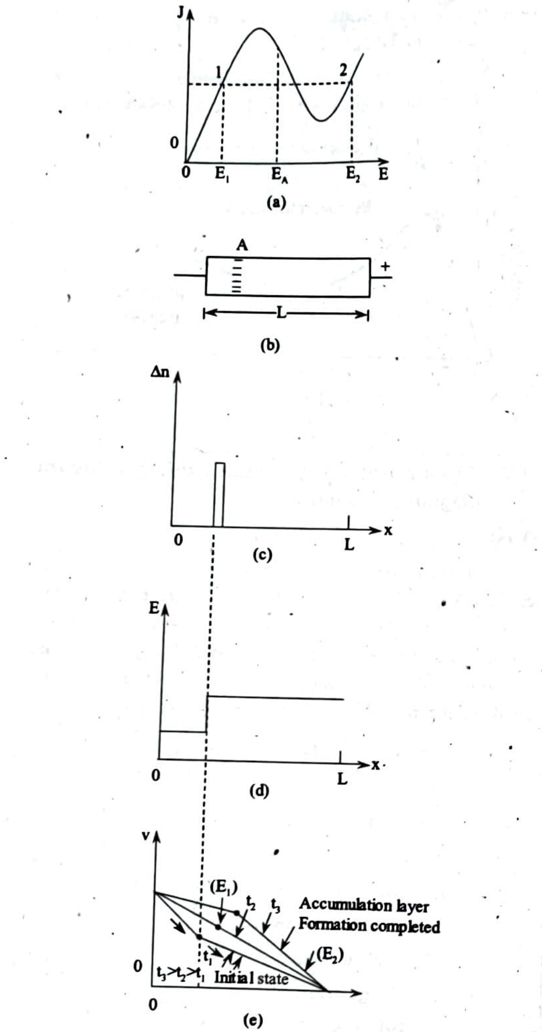


Figure (1): Formation of an Electron Accumulation Layer in GaAS

Consider that at points A in the J-E plot in figure 1(b) there is an accumulation of negative charges due to the random noise fluctuation (or) nonuniformity in doping in the n-type GaAs diode. Due to this accumulated charges an electric field is created as shown in figure 1 (d), the field at the left side of point A is less when compared to the right side. When the diode is biased at point E_A then, the current flowing into point A is greater than the current flowing out of point A. As a result, space charge accumulation increases. This process is repeated until low and high field values, satisfy the equilibrium condition outside the differential negative resistance region and settle at point 1 and 2 as shown in figure (1).

The formation of an electron dipole layer in GaAs is as shown in figure (2).

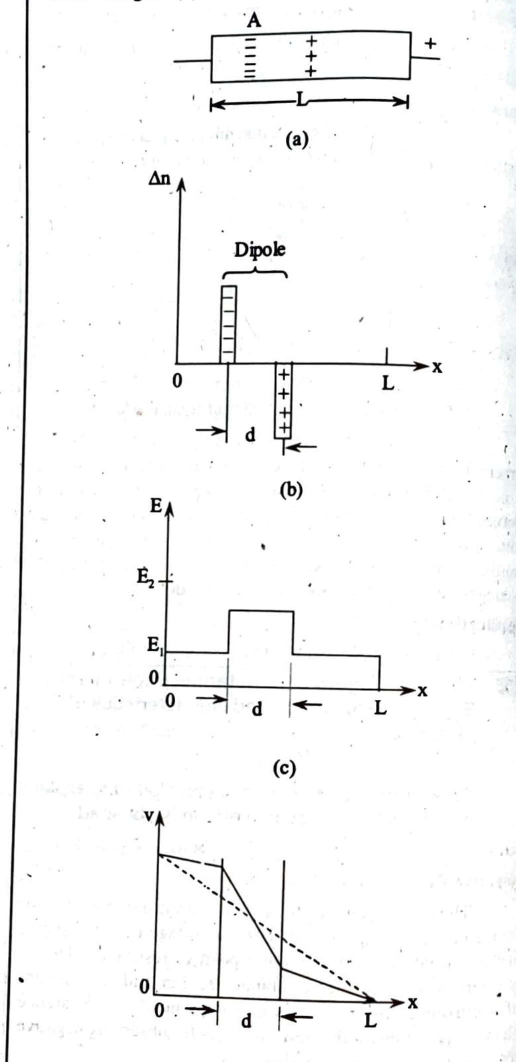


Figure (2): Formation of an Electron Dipole Layer in GaAs

Figure 2(c) illustrate that the field inside the dipole domain is greater than the fields on both side of the dipole. Due to the negative differential resistance, the current in low field region is greater than high field region. The two field values satisfy the equilibrium condition outside the differential negative-resistance region. Thus dipole field achieve a stable condition and moves towards the anode by passing through the specimen. At the anode, if high field domain disappears then, dipole field is formed again at the cathode and process is repeated in the same manner.

Q37. Explain Gunn effect using two-valley theory? Also explain several modes of operation and applications of Gunn diodes.

Nov./Dec.-16, (R13), Q9(a)

(or)

Discuss in detail the principle of operation of GUNN diode considering the two valley model theory and sketch its volt-ampere characteristics.

(Refer Only Two Valley Model Theory and Mathematical Analysis)

April/May-18, (R13), Q9(a)

Ans:

Two Valley Model Theory

The principle of operation of Gunn diode depends on the properties of negative resistance of bulk semiconductor materials. The energy band diagram of GaAs as shown in figure.

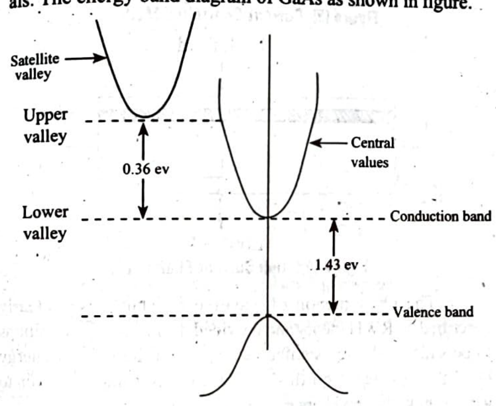


Figure: Two-Valley Model

Initially, the electrons are near to the conduction band in a valley called central valley under stable conditions. This value is at lowest energy level. When an electric field increases above the threshold value, the electrons crosses upper valley i.e., higher energy level. The electrons remain in lower valley until the field is greater than critical value. The energy of satellite valley is 0.36 ev higher than that of the central valley.

Such transfer of electrons from one valley to other is referred as transferred electron mechanism. Since, when the field increases above critical value, the current decreases. This represents the negative resistance characteristic of Gunn diode.

Mathematical Analysis

When voltage is less than critical value, the current increases with increase in voltage to critical value (transferred electron mechanism). The threshold of current decreases with further increase in voltage.

As the applied field increases the electrons from L - valley moves to U-valley with reduced electron velocity and increased mass, which inturn decreases current density, J.

Consider electron densities in lower and upper valleys as n_l and n_u. Then, the conductivity of n-type GaAs is given by,

$$\sigma = e(\mu_l n_l + \mu_u n_u) \quad \text{... (1)}$$

Where,

e – Electron charge

μ – Electron mobility

n – Electron density.

Differentiating equation (1) with respect to E, we get,

$$\frac{d\sigma}{dE} = e\left[\mu_l \frac{dn_l}{dE} + \mu_u \frac{dn_u}{dE}\right] + e\left[n_l \frac{d\mu_l}{dE} + n_u \frac{d\mu_u}{dE}\right] \quad \text{... (2)}$$

Since, $n = n_l + n_u$ and assuming that μ_l and μ_u are proportional to E^p (where p is a constant).

$$\text{Then, } \frac{dn}{dE} = \frac{d(n_l + n_u)}{dE} = 0 \quad \text{... (3)}$$

$$\Rightarrow \frac{dn_l}{dE} = -\frac{dn_u}{dE} \text{ and} \quad \text{... (4)}$$

$$\frac{d\mu}{dE} = \frac{dE^p}{dE} = pE^{p-1} = p\frac{\mu}{E} \quad \text{... (5)}$$

On substituting equations (4) and (5) in equation (2),

$$\frac{d\sigma}{dE} = e(\mu_l - \mu_u)\frac{dn_l}{dE} + e(n_l\mu_l + n_u\mu_u)\frac{p}{E} \quad \text{... (6)}$$

From Ohm's law, current density is given by,

$$J = \sigma E$$

On differentiating above equation with respect to 'E',

$$\frac{dJ}{dE} = \sigma + \frac{d\sigma}{dE}E$$

$$\Rightarrow \frac{1}{\sigma}\frac{dJ}{dE} = 1 + \frac{d\sigma/dE}{\sigma/E}$$

For negative resistance, J decreases with increase in field E. Then the condition for negative resistance is given by,

$$\frac{dJ}{dE} < 0$$

$$\Rightarrow 1 + \frac{d\sigma/dE}{\sigma/E} < 0 \Rightarrow \frac{-d\sigma/dE}{\sigma/E} > 1$$

On substituting $f = \frac{n_u}{n_l}$ in equations (1) and (6),

$$-\left[\frac{e(\mu_l - \mu_u)\frac{dn_l}{dE} + en_l(\mu_l + f\mu_u)\frac{p}{E}}{en_l(\mu_l + f\mu_u)/E}\right] > 1$$

$$\Rightarrow \left[\left(\frac{\mu_l - \mu_u}{\mu_l + f\mu_u}\right)\left(\frac{-E}{n_l}\frac{dn_l}{dE}\right) - p\right] > 1 \quad \text{... (7)}$$

The first term $\left(\frac{\mu_l - \mu_u}{\mu_l + \mu_u f}\right)$ must be positive to satisfy the inequality. For this, $\mu_l > \mu_u$. The maximum value of this term is unity. The factor $\frac{dn_l}{dE}$ represents the rate of carrier density with field at which electrons transfer to upper valley. It must be always negative and is influenced by electron temperature, gap energies in the two valleys and differences between electron density.

Applications

For answer refer Unit-2, Q15.

Modes of Operation

For answer refer Unit-2, Q39.

Q38. Explain the construction of GUNN diode using RWH theory.

(Model Paper, Q5(a) | Nov./Dec.-18, (R13), Q9(a)

(or)

Explain RWH theory. Nov./Dec.-17, (R13), Q1(g)

(or)

Explain the construction of the GUNN diode using RWH theory. Nov.-13, (R09), Q7(a)

(or)

Explain RWH theory with relevant diagrams.

Ans:

RWH Theory

The theory that explains the phenomeon of Negative Differential Resistance (NDR) in particular bulk materials is named as RWH theory. Bulk NDR devices are classified into two types. They are,

(i) Voltage controlled NDRs

(ii) Current controlled NDRs.

(i) Voltage Controlled NDRs

The negative resistance characteristics of voltage controlled NDRS is shown in figure (1).

In voltage controlled NDRs, the current density is multivalued. In this, the high field domains are formed normal to field direction, which separates two low field regions as shown in figure (2).

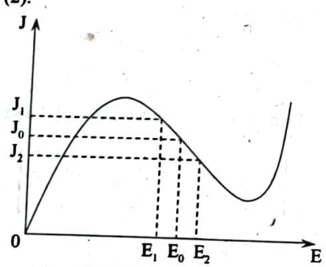


Figure (1): Voltage Controlled Mode

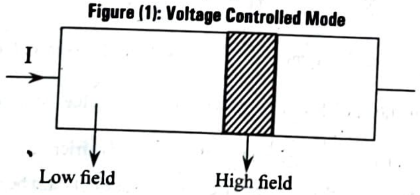


Figure (2): High Field Domain

(ii) Current Controlled NDRs

In current controlled NDRs, the voltage is multivalued. In this, the sample splits and forms the high current filament that runs along the field direction.

The negative resistance characteristics of current controlled NDRs and high current filament are as shown in figure (3) and figure (4) respectively.

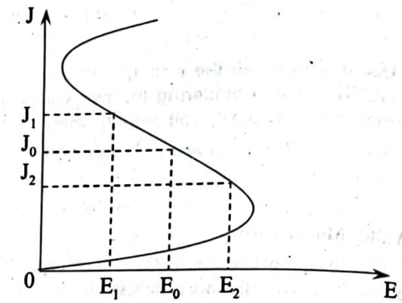


Figure (3): Current Controlled Mode

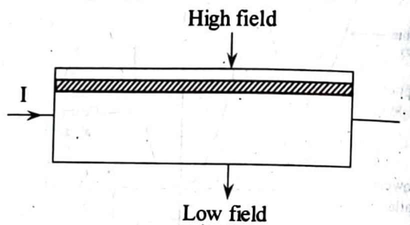


Figure (4): High Current Filament

The phenomenon of negative resistance was clearly described by RWH theory and provided the necessary conditions to be satisfied by the semiconductors with the help of energy band theory. Based on this theory, for any semiconductor to exhibit negative resistance;

(i) The conduction electrons must present in semiconductors at various energy levels or valleys.

(ii) The separation energy between the lower valley and the upper valley must be several times larger than the thermal energy (about 0.026 eV) of the electrons at room temperatures.

(iii) The separation energy between the valleys must be smaller than forbidden energy gap between the conduction band and valence band.

(iv) Electrons in the lower valley must have high mobility, small effective mass and low density of state whereas those in the upper valley must have low mobility, large effective mass and high density of state.

Q39. Explain about several modes of operation of GUNN diode.

Nov.-15, (R09), Q7(b)

Ans:

Modes of Operation

There are four different modes of operation that contribute to the microwave oscillations in a Gunn diode. They are,

1. Gunn Oscillation Mode or Transit-time Mode

When a voltage is applied to a Gunn diode i.e., GaAs crystal is above the threshold level, the electrons present in low energy level (high mobility conduction band) are transferred to high energy level (low mobility sub conduction band). At cathode, these electrons of high energy level accumulate to form an electric field dipole domain. For a constant applied voltage, electric field across domain increases above the average field. The resultant electric field stays below threshold level and avoids the formation of further domains. In presence of domain, the low mobility electrons drift with reduced velocity and conduction band electrons with constant velocity and results decrease in current.

In this mode, the Gunn diode acts as low impedance circuit as shown in figure (1).

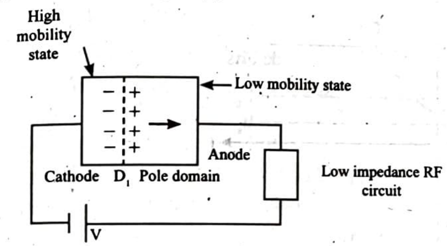


Figure (1): Gunn Diode as Low Impedance Circuit

The fluctuations in the output current of low impedance RF circuit can be observed in the duration of transit time. The transit time decreases, since the domain quenched before reaching anode. The movement of high field domain is as shown in figure (2).

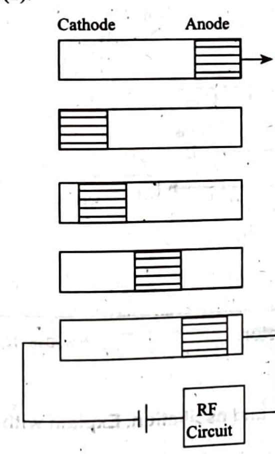


Figure (2): Movement of High Field Domain

This mode is defined in the region where the frequently-length product is about 10^7 cm/s and doping-length product is greater than 10^{12}/cm². In this region, the device is unstable.

Each domain produces a current pulse which result in a signal at low impedance RF circuit for microwave frequencies. As the high field domain is quenched before reaching the anode, the transit time gets decreased with increased frequency.

Transit-time mode has low power efficiency less than 10% and difficulty in handling the frequency using external circuit.

2. LSA Mode

LSA stands for "Limited Space Charge Accumulation". In this mode, the Gunn diode operates as a part of resonant circuit as shown in figure (3).

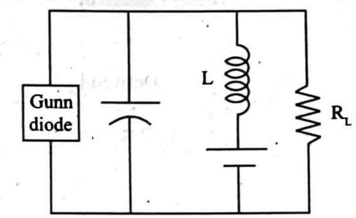


Figure (3): Gunn Diode as Resonant Circuit

This is defined in the region where frequency-length product is more than 10^7 cms^{-1} and doping quotient divided by frequency is between 2×10^4 and 2×10^5.

The circuit is tuned to a frequency that is greater than that in transit time mode of operation to operate as a negative resistance oscillator and to avoid dipole domain formation. In order to operate diode in negative resistance region the dc voltage must be maintained above threshold voltage and also within the region. R_L adjusted to 20% higher than maximum resistance value to develop oscillations. These oscillations become constant when the average negative resistance of diode equals load resistance R_L.

3. Quenched Domain Mode

In this mode, the dipole domain gets destroyed before it reaches the anode by negative swing of oscillation. Though the Gunn diode appears like operating in Gunn mode, this mode can be achieved when the resonant circuit is tuned above the transit time mode.

4. Delayed Mode

It is also known as inhibited mode. In this mode, the new dipole domains get delayed until oscillation voltage exceeds the threshold value. Here, the resonator circuit is tuned below the gunn mode such that the dipole domains reach the anode in time. The transit time is less than the oscillation period. This mode has efficiency of about 20%.

In transit-time domain mode when the electron drift velocity, v_d is equal to sustaining velocity, v_s the high-field domain is stable i.e., $v_d = v_s = f < \approx 10^7$ cm/s. Then oscillation period of transit time, $\tau_0 = \tau_t$. In delayed time mode, oscillation period is more than transit time, $\tau_0 = \tau_t$. For LSA mode, oscillation period, τ_0 is thrice the dielectric relaxation time, τ_d in negative conductance region. Thus, the characteristics of Gunn diode in different modes are shown in figure (4).

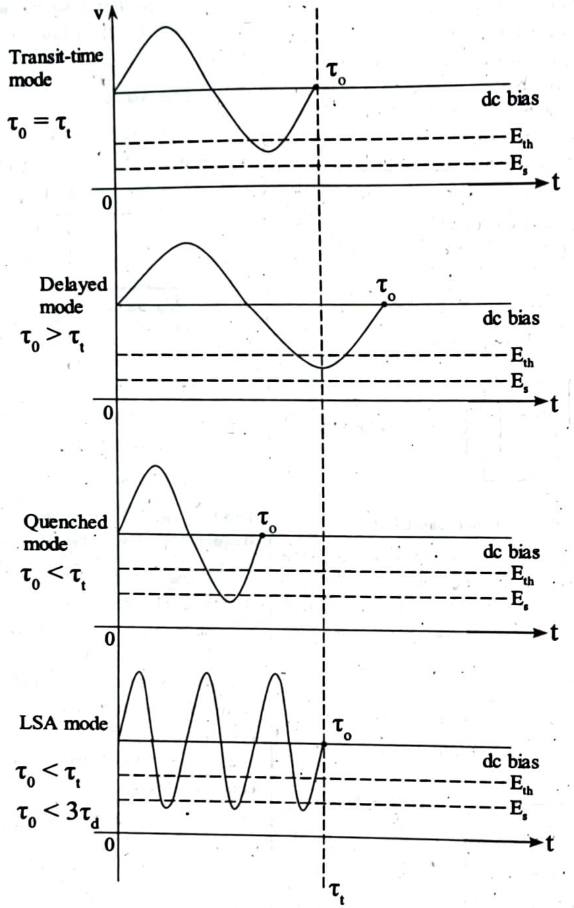


Figure (4)

Q40. Explain the principle of operation of the Gunn diode as an oscillator. Nov./Dec.-12, (R09), Q7(a)

(or)

Negative resistance devices can be used to produce amplification and oscillation. Explain with suitable examples.

Ans:

The negative resistance devices can be used to produce amplification and oscillation. Gunn diode is a negative resistance device, it is also used as an oscillator. The Gunn diode oscillator circuit is shown in figure.

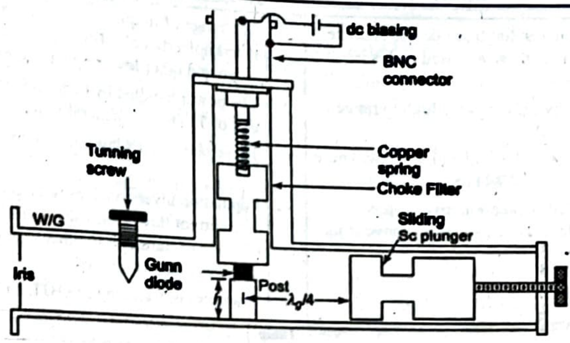


Figure: Gunn Diode Oscillator

Gunn diode oscillator is constructed by inserting a Gunn diode perpendicular to the centre of broad wall of a waveguide operating in TE_{10} mode. The waveguide is short circuited at one end and terminated by an iris at other end.

The intrinsic frequency of oscillation depends on electron drift velocity effective length and is given by,

$$f_0 = \frac{v_d}{l}$$

Where,

f_0 - Intrinsic frequency

v_d - Elect ron drift velocity

l - Effective length.

The position of sliding choke plunger is adjusted to tune the cavity to resonate at f_0. Tuning of frequency can also be achieved using tuning screw which is placed perpendicular to the broad wall.

The resultant resistance of oscillator is negative, only if the total resistive loading from cavity and external load maintained 20% higher than Gunn device resistance.

i.e., $\frac{-R_L R_j}{R_L - R_j} < 0$

The Gunn diode is placed on a metal post and a DC bias voltage is applied to it through BNC fitting. The inductive iris dimension determines degree of coupling to the external waveguide.

For continuous wave (CW) operation the output power of Gunn oscillator is in the range of few watts and is of 100-200 W for pulsed wave (PW) operation.

Q41. Differentiate between TEDs and transistors. Nov./Dec.-18, (R13), Q9(b)

Ans:

The differences between TEDs and transistors are mentioned in table.

	Transferred Electron Devices (TEDs)		Microwave Transistors
1.	TEDs are bulky devices. They don't have any junctions (or) gates as in case of the conventional transistors.	1.	The conventional transistors are simple in construction. They are with junctions like PN junction.
2.	These are manufactured from compound semi-conductor materials like GaAs, InP, cdTd.	2.	These are manufactured from elemental (basic) semi-conductors like Silicon (Si) and Germanium (Ge).
3.	TEDs operate with hot electrons. The energy of these electrons is very high compared to thermal energy.	3.	The transistors operate with warm electrons. The energy of these electrons is not greater than thermal energy.

4.	The range of frequencies that these devices handle is in GigaHertz. Hence, these are used and is in micro-wave devices.	4.	The range of frequencies that these transistors operate is in kiloHertz only. Thus, they are used in audio, and video and other low frequency circuits.
5.	The power handled by these is very high in range of Watts and kiloWatts (kW).	5.	The power handled by these is very low compared to that of TEDs. It is generally in range of milliwatts (mW).
6.	These do not obey linear laws like ohm's law. These only obey principles like RWH theory.	6.	These obey ohm's law for certain period of time.
7.	A phenomenon called population inversion is observed in these devices i.e., electrons move from L-valley to U-valley.	7.	Population inversion does not occurs in these devices. The current flow is only due to motion of electron from one side of transistor to other side which depends on the power supply applied.
8.	Example of a TED device is GUNN diode.	8.	Examples of transistor are BJT, FET, MOSFET etc.

Table

Q42. An n-type GaAs GUNN diode has the following specifications:

Threshold field	**3 kV/cm**
Applied field	**3.5 kV/cm**
Device length	**10 micrometers**
Doping constant	**10^{14} electron/cm^3**
Operating frequency	**10 GHz**

Calculate the current density (–ve) and electron mobility in the device.

Ans: April/May-18, (R13), Q7(a)

Given that,

For an n-type GaAs GUNN diode,

Threshold field, $E_T = 3$ kV/cm

Applied field, $E_v = 3.5$ kV/cm

Device length, $L = 10$ micrometers

Doping constant = 10^{14} electron/cm^3

Operating frequency, $f = 10$ GHz $= 10 \times 10^9$ Hz

Current density (– ve), $J = ?$

Electron mobility, $\mu_n = ?$

Then, the expession for electron mobility is given by,

$$\text{Electron mobility, } \mu_n = \frac{-v_d}{E_v} \quad [\because \text{ negative}]$$

Where,

$$v_d = f \times L$$

$$= 10^9 \times 10^{-2} = 10^7 \text{ cm/sec}$$

$$\Rightarrow \mu_n = \frac{10^7}{3500} = -2857.143$$

$$\therefore \boxed{\mu_n = -2857.143 \text{ cm}^2/\text{V.sec}}$$

and the current density (– ve) is expressed as,

$$J = qnv$$

Where,

q – Charge of electron = 1.6×10^{-19} C

n – Electron density = $f \times$ Doping constant

n – Average electron velocity

$$\Rightarrow J = 1.6 \times 10^{-19} \times 10^{20} \times 10 \times 10^9 \times 10^{-5} = 1.6 \times 10^6 \text{ A/m}^{-2}$$

$$\therefore \boxed{J = 1.6 \times 10^6 \text{ A/cm}^2}$$

Q43. An n-type GaAs Gunn diode has following parameters,

Electron drift velocity, $V_d = 2.5 \times 10^5$ m/s

Negative Electron mobility, $|\mu_n| = 0.015$ m^2/Vs

Relative dielectric constant, $\varepsilon_r = 13.1$

Determine the criterion for classifying the modes of operation.

Ans: Model Paper, Q5(b)

Given that,

For n-type GaAs diode,

Electron drift velocity, $V_d = 2.5 \times 10^5$ m/s

Negative electron mobility, $|\mu_n| = 0.015$ m^2/Vs

Relative dielectric constant $\varepsilon_r = 13.1$

Then, the expression for the criterion for classifying the modes of operation is given by,

$$n_0L > \frac{\epsilon V_d}{e|\mu_n|}$$

$$\Rightarrow n_0L > \frac{\epsilon_0 \epsilon_r V_d}{e|\mu_n|} \quad (\because \epsilon = \epsilon_0 \epsilon_r)$$

$$> \frac{8.85 \times 10^{-12} \times 13.1 \times 2.5 \times 10^5}{1.6 \times 10^{-19} \times 0.015}$$

$$> \frac{2.9 \times 10^{-5}}{2.4 \times 10^{-21}}$$

$$n_0L > 1.2 \times 10^{16}$$

Therefore, the product of the doping concentration and the device length must be greater than 1.2×10^{16}/m^2.

Q44. Determine the conductivity of n-type GaAs Gunn diode if

Electron density n = 10^{18} cm^{-3}, electron density at lower valley $n_l = 10^{10}$ cm^{-3}

Electron density at upper valley $n_u = 10^8$ cm^{-3}, temperature T = 300K.

March-21, (R16), Q7(b)

(or)

Determine the conductivity of n-type GaAs Gunn diode if,

Electron density n = 10^{18} cm^{-3}

Electron density at lower valley $n_l = 10^{10}$ cm^{-3}

Electron density at upper valley $n_u = 10^8$ cm^{-3}

Temperature T = 300 K.

Ans:

Given that,

For an n-type GaAs Gunn diode,

Electron density, $n = 10^{18}$ cm^{-3}

Electron density at lower valley, $n_l = 10^{10}$ cm^{-3}

Electron density at upper valley, $n_u = 10^8$ cm^{-3}

Temperature, $T = 300$ K

Then, the expression for conductivity of an n-type GaAs diode is given by,

$$\sigma = e(n_l \mu_l + n_u \mu_u) \quad \ldots (1)$$

Since, $\mu_l = 8000$ cm^2/V.sec $= 8000 \times 10^{-4}$ m/V.s

$\mu_u = 180$ cm^2/V.sec $= 180 \times 10^{-4}$ m/V.s

On substituting corresponding values in equation (1), we get,

$$\sigma = 1.6 \times 10^{-19} (8000 \times 10^{-4} \times 10^{16} + 180 \times 10 \times 10^{14})$$

$$= 1.28 \times 10^{-3}$$

$$\therefore \sigma = 1.28 \text{ m℧}$$

2.2.3 Principle of Operation of IMPATT and TRAPATT Devices

Q45. What are the characteristic features of avalanche transit time devices? Compare them with those of transferred electron devices.

Ans:

Characteristic Features of Avalanche Transit Time Devices

The junction devices which gives the negative resistance by suitable combination of impact avalanche breakdown and charge carrier transit time effects is referred as "Avalanche diodes". In semiconductors, avalanche breakdown occurs when there is a sufficient electric field is provided for the charge carriers to gain adequate amount of energy from the field to form a electron-hole pairs through impact ionization.

Avalanche transit-time devices are basically p-n junction diodes reverse-biased into the avalanche region i.e., they contain heavily doped p and n regions.

The electron-hole pairs can be generated from avalanche action. In which, the level of D.C bias is set nearly equal to the avalanche threshold level and then it is superimposed with an alternating voltage. As a result diode starts swinging into avalanche condition during alternate half - cycles, (as it is superimposed with alternating voltage). Thus, it leads to a formation of hole-electron pairs which generates the current due to the movements of holes in p-region and electrons in n-region.

There are two distinct types of avalanche transit devices. They are,

1. IMPATT diode
2. TRAPATT diode.

The comparison of characteristics of avalanche diodes and transferred electron devices is shown in table.

	Avalanche Transit Time Devices	Transferred Electron Devices
Operating frequency	1-100 GHz	0.5-100 GHz
Bandwidth	2% of centre frequency	1% of centre frequency
Construction	$n^+ n n^+$ GaAs	$n^+ p p^+$ reverse bias p-n
Noise figure	-	High
Application	Only oscillator	Oscillator and amplifier
Size	Small	Small
Basic semiconductor	GaAs, Inp	Si, Ge, G. As, Inp
Ruggedness	Yes	Yes

Table

Q46. Describe the physical Structure of an IMPATT diode, identifying its doping profile characteristics.

(or)

Explain the operation of IMPATT diode with neat diagram.

Ans:

IMPATT Diode

IMPATT stands for impact ionization avalanche transit-time. The IMPATT diode is fabricated from silicon carbide material due to its high breakdown fields it operates in the frequency range of 3 GHz to 100 GHz. As, this diode contains high power, it is employed in high frequency electronic and microwave devices.

The family of IMPATT diode involves several distinct junctions and metal semiconductor devices. A normal p-n junction diode can operate only for small voltages, whereas IMPATT diode conducts efficiently at highly doped breakdown region. It exhibits negative resistance characteristics due to impact ionization avalanche effect and transit-time effect.

Operation

The schematic of IMPATT diode is as shown in figure (1).

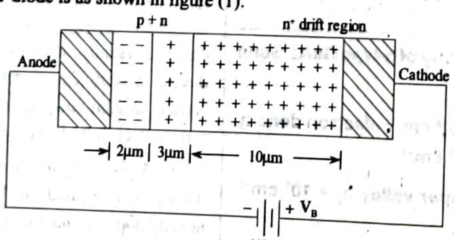


Figure (1): Schematic of IMPATT Diode

When the DC bias voltage, V_B is applied to the diode, the holes in the n^+ drift region moves into high resistive region called drift zone and from there electrons generated in avalanche region move towards the anode results in large current flow.

When high DC voltages are given as input to diode results in flow of minority carriers across the depletion region. Assuming an application in which an AC voltage is superimposed on a high input DC voltage. In this case, the avalanche breakdown occurs due to the additional charge carriers knocked out of the crystal structure. The applied DC voltage increases beyond threshold value during positive cycle of RF voltage which inturn causes avalanche current multiplication. The current pulse reaches maximum value at an instant where RF voltage is zero and negative going as shown in figure(2). This process results a phase change of 90° between applied voltage and carrier current.

The voltage and current characteristics with respect to 't' is as shown in figure (2).

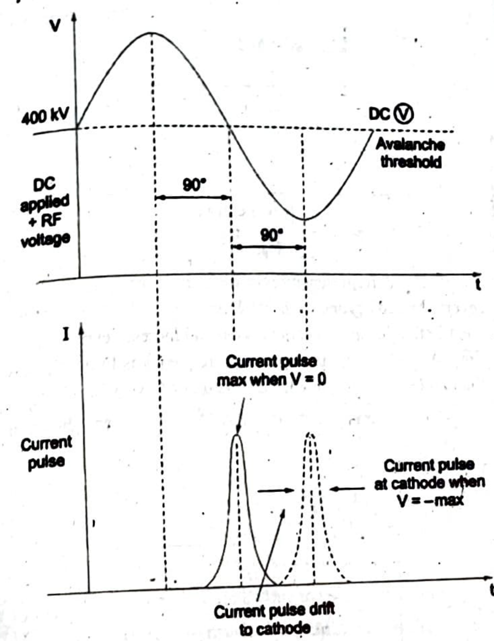


Figure (2): V and I vs t Characteristics

During negative half cycle i.e., reverse bias condition the concentration of charge carriers decreases which further reduces the flow of current in diode. The current pulse drift to cathode with an exact phase change of another 90°. The factors velocity of charge carriers and thickness of n^{+x} region effects the time required for current pulse to reach cathode. Thus, the total phase shift of 180° arises between voltage and current which proves that IMPATT diode is a negative resistance device. It can be used as both amplifier and oscillator. Hence, the expression for resonant frequency is given by,

$$f = \frac{v_d}{2L}$$

Where,

v_d - Drift velocity

L - Length of drift space region.

Advantages of IMPATT Diode

1. It has high power capability
2. They are highly compact.
3. It is inexpensive.

Disadvantages of IMPATT Diode

1. It generates high level of noise due to the statistical nature of the avalanche process.
2. It has a poor noise figure of 30 dB
3. The efficiency of the diode is low due to induced current.

Applications of IMPATT Diode

1. As microwave generators
2. Modulated output oscillators
3. Receiver local oscillators
4. It is suitable for negative resistance amplification.

Q47. Derive the equation for power output and efficiency of IMPATT diode.

Ans:

The maximum voltage applied across the IMPATT diode is given by,

$$V_m = E_m L \quad \dots (1)$$

Where,

E_m – Maximum electric field

L – Depletion length.

The breakdown voltage limits the applied voltage V_m. As a result the maximum current is also limited, i.e., the maximum current is given by,

$$I_m = J_m A$$

$$\Rightarrow \quad I_m = \sigma E_m A \qquad (\because J_m = \sigma E_m)$$

$$= \frac{\epsilon_s}{\tau} E_m A \qquad \left(\because \sigma = \frac{\epsilon_s}{\tau}\right)$$

$$= \frac{v_d \epsilon_s E_m A}{L} \qquad \left(\because \tau = \frac{L}{V_d}\right)$$

$$\therefore \quad I_m = J_m A = \frac{v_d \epsilon_s E_m A}{L} \quad \dots (2)$$

Upper limit of the input power is obtained as,

$$P_m = V_m I_m$$

On substituting equations (1) and (2) in above equation,

$$P_m = (E_m L) \times \frac{v_d \epsilon_s E_m A}{L}$$

$$\therefore \quad P_m = v_d \epsilon_s E_m^2 A \quad \dots (3)$$

$$\text{But,} \quad C = \frac{\epsilon_s A}{L} \quad \dots (4)$$

$$\Rightarrow \quad A = \frac{CL}{E_s}$$

Substituting equation (4) in equation (3),

$$P_m = v_d E_m^2 CL$$

Multiplying and dividing the R.H.S with $2\pi f$,

$$P_m = \frac{v_d E_m^2 CL.2\pi f}{2\pi f}$$

$$\Rightarrow \quad P_m = \frac{E_m^2 v_d L}{2\pi f X_C} \qquad \left[\because X_C = \frac{1}{2\pi f C}\right] \quad \dots (5)$$

Using $2\pi f \tau = 1$,

$$f = \frac{1}{2\pi\tau} = \frac{v_d}{2\pi L} \qquad \left[\because \tau = \frac{L}{v_d}\right]$$

$$\therefore L = \frac{v_d}{2\pi f} \quad \dots (6)$$

Substituting equation (6) in equation (5),

$$\Rightarrow \quad P_m = \frac{E_m^2 V_a V_a}{2\pi f X_C \cdot 2\pi f}$$

$$P_m = \frac{E_m^2 v_d^2}{4\pi^2 f^2 X_C}$$

$$\therefore \quad P_m f^2 = \frac{E_m^2 v_d^2}{4\pi^2 X_C}$$

$$\text{Efficiency, } \eta = \frac{P_{ac}}{P_{dc}} = \left[\frac{v_a \times I_a}{v_d \times I_d}\right]$$

For practical IMPATT diodes, the efficiency is less than 30%.

Q48. A Ku-band IMPATT diode has a pulse operating voltage of 100 V and a pulse operating current of 0.9 A. The efficiency is about 10%. Calculate,

(i) The output power

(ii) The duty cycle if the pulse width is 0.01 ns and frequency is 16 GHz.

Ans:

Given that,

For a ku-band IMPATT didoe,

Pulse operating voltage, $V_o = 100$ V

Pulse operating current, $I_o = 0.9$ A.

Efficiency, $\eta = 10\%$

(i) Output power, $P_{out} = ?$

(ii) For a pulse width of 0.01 ns and frequency 16 GHz, duty cycle, $D = ?$

(i) The expression for efficiency of IMPATT diode is given by,

$$\eta = \frac{P_{out}}{P_{dc}}$$

$$\Rightarrow \quad P_{out} = \eta P_{dc}$$

$$= \eta . V_o . I_o \qquad (\because P_{dc} = V_o I_o)$$

$$= \frac{10}{100} \times 100 \times 0.9 = 9 \text{ W}$$

$$\boxed{\therefore P_{out} = 9 \text{ W}}$$

(ii) Pulse width = 0.01 ns = 0.01×10^{-9} s

Frequency = 16 GHz = 16×10^9 Hz

Then, time, $T = \frac{1}{f} = \frac{1}{16 \times 10^9} = 6.25 \times 10^{-11}$

The expression for duty cycle is given by,

$$\text{Duty cycle} = \frac{\text{Pulse width}}{\text{Total time}} = \frac{0.01 \times 10^{-9}}{6.25 \times 10^{-11}} = 0.16$$

$$\boxed{\therefore \text{Duty cycle, } D = 0.16}$$

Q49. What is TRAPATT diode and explain the principle of operation.

Nov.-13, (R09), Q7(b)

Ans:

TRAPATT is a silicon diode and have p⁺nn⁺ as shown in figure (1).

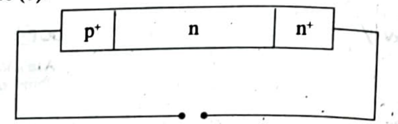


Figure (1)

The current density will be high as the p-n junction is reverse biased beyond the breakdown region, this decreases the electric field in space charge region and increses carrier transit time. At this instant, the operating frequency is limited to less than 10 GHz. The efficiency of this diode is very high.

The characteristics of TRAPATT diode are shown in figure (2).

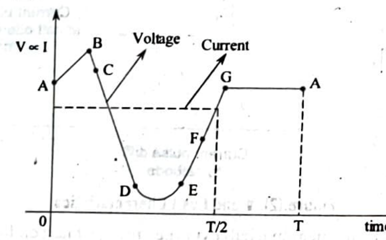


Figure (2)

The electric field is uniform at the point '*A*' and its magnitude is large. The diode charges at point '*A*' because of charge carriers, when a certain field is reached the electric field decreases throughout the depletion region, voltage drop results i.e., from point '*B*' to '*C*'. Due to the drift out of electrons and holes, the electric field is further decreased to point *D*. Now, by removing the plasma and residual charge, the electric field is increased to point *F*.

Now from point *F* the electric field again increases to point *G* due to the charging of capacitor. At point *G* the voltage remains constant as the diode current drops to zero. The drift through this diode is much slower than through a comparable IMPATT diode because the electrons and holes drift at velocities determined by the low field mobilities, and the transit of the carriers becomes much longer. The normal operating frequency of a TRAPATT diode is 3-50 GHz.

Because of slow drift time, the carrier transit time is increased. This causes the operating frequency of this diode to be limited to below 10 GHz.

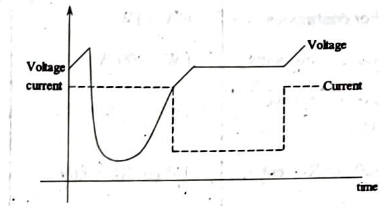
The typical efficiency of TRAPATT diode is in the range of 20 to 60% and output power is of the order 1.2 kW in 1 to 2 GHz range.

Q50. Explain how TRAPATT diode is better than IMPATT diode?

Ans:

A Trapped Plasma Avalanche Triggered Transit Time (TRAPATT) diode is basically a modified IMPATT diode in which the holes and electrons created by impact avalanche ionization multiplication do not completely exit from the transit domain of the diode during the negative half-cycle of the microwave signal. These holes and electrons form a plasma which is trapped in the diode and participates in producing a large microwave current during the positive half cycle.

The output waveform of TRAPATT diode is shown in below figure.



Figure

The main advantage of TRAPATT diode over IMPATT diode is its efficiency.

As the transit time is longer due to low voltage, the operating frequency is limited to below 10 GHz, and the current pulse is associated with low voltage, hence the power dissipation is low, thus resulting high efficiency.

However, the drawbacks of TRAPATT diode are,

(i) High noise figure

(ii) Strong harmonics due to short current pulse.

Q51. Compare the merits and demerits of TEDs and Avalanche Transit time Devices.

Ans:

The comparison of merits and demerits of TEDs and avalanche transit time devices is mentioned in table.

	Transfer Electron Devices (TEDS)		Avalanche Transit Time Device (ATTD)
1.	Though TEDs are diodes, but they do not use pn-junction. Instead, they use a bulk semiconductor.	1.	Avalanche transit time device uses reverse-bias pn-junction to generate microwave power.
2.	It inheritantly exhibits negative resistance characteristics.	2.	It shows negative resistance characteristics only when it is coupled with a high Q-resonator and biased at an appropriate operating point.
3.	Efficiency of converting DC bias to RF power is very low.	3.	Efficiency of converting DC bias to RF power is very high.
4.	TEDs have very low noise.	4.	ATTDs have very high noise.
5.	The characteristics of TEDs change with temperature.	5.	The characteristics of ATTDs are not temperature sensitive and thus remain stable even when temperature changes.
6.	TEDs have very low power.	6.	ATTDs have very high power.
7.	Frequency range of TEDs is 2 to 100 GHz.	7.	Frequency range of ATTDs is from few hundred MHz to several GHz.
8.	Oscillation cycles in TEDs can be timed accurately.	8.	Oscillation cycles in ATTDs can not be timed accurately due to their high phase noise.
9.	TEDs start to oscillate automatically without any modifications.	9.	ATTDs oscillate only when their bias voltage is increased beyond a certain point.

Table

Q52. Give the comparison between Gunn, IMPATT and TRAPATT diodes.

Ans:

The comparison between Gunn, IMPATT and TRAPATT diodes on the basis of various parameters is shown in table.

Parameters	Gunn diode	IMPATT diode	TRAPATT diode
Operating frequency	1–100 GHz	0.5–100 GHz	1–10 GHz
Output power	For continuous wave – few watts For pulse wave 100 – 200 watts	CW – 1W PW – 400 W	PW – high power (several 100 W)
Bandwidth	0.02 of RF center frequency	10% of RF center frequency	–
Noise figure	–	High (30 dB)	High (60 dB) IMPATT diode
Efficiency	–	CW – 3%, PW - 60%	PW – 20 to 60%
Construction	n^+nn^+ GaAs single crystal	n^+pp^+ reverse bias p-n junction	p^+nn^+ or n^+pp^+ reverse bias pn junction p-n junction
Basic semiconductors	GaAs, InP	Si, Ge, GaAs, InP	Si
Size		small	small small
Harmonics	–	Less	Strong
Ruggedness	Yes	Yes	Yes
Application	Oscillator	Amplifier, Oscillator	Oscillator

Table

Frequently Asked & Important Questions

Q1. How to separate a π mode in magnetron? REPEATED 2 TIMES

(Dec.-19, (R16), Q1(g) | May/June-19, (R15), Q1(g))

Ans: Refer Q3.

Q2. What are the applications of Gunn diode? REPEATED 2 TIMES

(Dec.-19, (R16), Q1(h) | May/June-19, (R15), Q9(b))

Ans: Refer Q15.

Q3. How cross-field is used generate oscillations in magnetron and derive the Hull cut-off condition? REPEATED 3 TIMES

(Dec.-19, (R16), Q8 | April/May-18, (R13), Q8(a) | Nov.-15, (R09), Q6(b))

Ans: Refer Q20.

Q4. What is Hartee condition? Explain working of cylindrical travelling wave magnetron and its operation in π mode. REPEATED 5 TIMES

(March-21, (R16), Q6(a) | May/June-19, (R15), Q8 | April/May-18, (R13), Q8(b) | Nov./Dec.-18, (R13), Q8(a) | Nov./Dec.-17, (R13), Q9(b))

Ans: Refer Q25.

Q5. Discuss about the principle and operation of TEDs and write its applications. REPEATED 2 TIMES

(Oct./Nov.-20, (R16), Q7(b) | Dec.-19, (R16), Q9 M[10])

Ans: Refer Q34.

Q6. What is negative resistance phenomenon? Explain the operation and characteristics of Gun diode. REPEATED 2 TIMES

(March-21, (R16), Q7(a) | May/June-19, (R15), Q9(a))

Ans: Refer Q35.

Q7. Explain Gunn effect using two-valley theory? Also explain several modes of operation and applications of Gunn diodes. REPEATED 2 TIMES

(Nov./Dec.-16, (R13), Q9(a) | April/May-18, (R13), Q9(a))

Ans: Refer Q37.

Q8. Explain RWH theory with relevant diagrams. REPEATED 3 TIMES

(Nov.-13, (R09), Q7(a) | Nov./Dec.-17, (R13), Q1(g) | Nov./Dec.-18, (R13), Q9(a))

Ans: Refer Q38.

Q9. List and explain different types of magnetrons. Important Question

Ans: Refer Q19.

Q10. Derive the Hartree anode voltage equation for linear magnetron. Important Question

Ans: Refer Q21.

Q11. What is mode jumping in magnetrons and explain remedial measures to overcome it. Important Question

Ans: Refer Q24.

Q12. Interview about π-mode operation and separation and write its characteristics. Important Question

Ans: Refer Q27.

Q13. A linear magnetron has the following parameters: anode voltage V_0 = 15 kV, cathode current, I_0 = 1.2 A, operating frequency f = 8 GHz, magnetic flux density B = 0.015 Wb/m², hub thickness h = 2.77 cm distance between anode and cathode, d = 5cm.

Calculate

(i) The electron velocity at the hub surface

(ii) The phase velocity for synchronism

(iii) The Hartee anode voltage.

Ans: Refer Q31.

Important Question

Q14. Give the classification of solid state microwave devices.

Ans: Refer Q33.

Important Question

Q15. Explain domain formation using relevant diagrams in Gunn diode.

Ans: Refer Q36.

Important Question

Q16. Explain about several modes of operation of GUNN diode.

Ans: Refer Q39.

Important Question

Q17. Explain the principle of operation of the Gunn diode as an oscillator.

Ans: Refer Q40.

Important Question

Q18. Differentiate between TEDs and transistors.

Ans: Refer Q41.

Important Question

Q19. Describe the physical Structure of an IMPATT diode, identifying its doping profile characteristics.

Ans: Refer Q46.

Important Question

Q20. Derive the equation for power output and efficiency of IMPATT diode.

Ans: Refer Q47.

Important Question

Q21. Explain how TRAPATT diode is better than IMPATT diode?

Ans: Refer Q50.

Important Question

Exercise Questions

1. **A normal cylindrical magnetron has the following parameters,**

   Inner radius – 0.15 m

   Outer radius – 0.45 m

   B_o – 1.2 milli Webers /m²

   Findout (a) Hull cutoff Voltage (b) Cutoff magnetic field for V_o – 6 kV.

   [Ans: (a) 5.04 kV, (b)1.3 mWeber/m2]

2. **A Magnetron operates with following parameters,**

   V_o–25 kV, I_o–25 A, B_o–0.34 T, Diameter of cathode –8 cm, Radius of vane edge to centre – 8 cm. Find the cyclotron frequency and cut off voltage. Consider a – 4 cm, b – 8 cm, 1 Tesla – 1 Web/m².

   [Ans: 5.9808×10^{10} Rad /s, 9150 kV]

3. **In a GaAs Gunn diode, working at a frequency of 8 GHz, the threshold field is 3 kV/m, applied field is 3.5 kV/m, device length is 10 × 10^{-8} m and the doping constant is 10^{16} electrons/cm³ . Calculate the current density and negative electron mobility in the device, explaining the relations used.**

   [Ans: 12.8×10^7 A /m², –22.8 m²/Vs]

4. **An IMPATT diode has the following parameters: carrier drift velocity v_d – 3 × 10^7 cm/s, drift region length L – 1 x 10^{-6} m, maximum operating voltage $V_{o.max}$ – 150 V, maximum operating current $I_{o.max}$ – 200 mA, an efficiency of η – 20%. Find the maximum CW output power in watts and resonant frequency.**

   [Ans: 6 W, 21.4 GHz]

5. **Calculate the avalanche zone velocity of a TRAPATT diode with doping concentration NA – 2 × 10^{15} cm^{-3} and current density J – 20 kA/cm².**

   [Ans: 6.25×10^7 c /m²]