Module- 4 Microwave Sources

Microwave frequencies and applications, Microwave Tubes: TWT, Klystron amplifier, Reflex Klystron & Magnetron. Semiconductor Devices: Gunn diode, Tunnel diode, IMPATT – TRAPATT - BARITT diodes, PIN Diode

GENERATION OF MICROWAVE SIGNAL

- Microwave Tubes – klystron, reflex klystron, magnetron and TWT.

- Diode semiconductor – Tunnel, Gunn, Impatt, Varactor diodes, PIN, LSA, Schottky barrier diode.

MICROWAVE TUBES

- Used for high power/high frequency combination.
- Tubes generate and amplify high levels of microwave power more cheaply than solid state devices.
- Conventional tubes can be modified for low capacitance but specialized microwave tubes are also used.

MICROWAVE TUBES

- **CROSSED-FIELD AND LINEAR-BEAM TUBES**
- Klystrons and Traveling-Wave tubes are examples of linear-beam tubes
  - These have a focused electron beam (as in a CRT)
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- Magnetron is one of a number of crossed-field tubes
  - Magnetic and electric fields are at right angles

MICROWAVE SOLID-STATE DEVICES (SEMICONDUCTOR)

- Quantum Mechanic Tunneling – Tunnel diode
- Transferred Electron Devices – Gunn, LSA, *InP and CdTe*
- Avalanche Transit Time – IMPATT, *Read*, *Baritt & TRAPATT*
- Parametric Devices – Varactor diode
- Step Recovery Diode – PIN,
- Schottky Barrier Diode.
- Designed to minimize capacitances and transit time.
- NPN bipolar and N channel FETs preferred because free electrons move faster than holes
- Gallium Arsenide has greater electron mobility than silicon.

MICROWAVE SOLID-STATE DEVICES

- Semiconductors are a group of substances having electrical conductivities that are intermediate between metals and insulators.
- Since the conductivity of the semiconductors can be varied over wide ranges by changes in their temperature, optical excitation, and impurity content, they are the natural choices for electronic devices.
- The energy bands of a semiconductor play a major role in their electrical behavior.
- For any semiconductor, there is a forbidden energy region in which no allowable states can exist.

https://www.thehindubusinessline.com/business-tech/iisc-develops-super-flexible-composite-semiconductors-for-next-gen-tech/article67067860.ece

Applications of Semiconductor Devices

Devices	Applications	Advantages
Transistor	L-band transmitters for telemetry systems and phased array radar systems L- and S-band transmitters for communications systems	Low cost, low power supply, reliable, high CW power output, light weight
TED	C-, X-, and Ku-band ECM amplifiers for wideband systems X- and Ku-band transmitters for radar systems, such as traffic control	Low power supply (12 V), low cost, light weight, reliable, low noise, high gain
IMPATT	Transmitters for millimeter-wave communications systems	Low power supply, low cost, reliable, high CW power output, light weight
TRAPATT	S-band pulsed transmitters for phased array radar systems	High peak and average power, reliable, low power supply, low cost
BARITT	Local oscillators in communications and radar receivers	Low cost, low power supply, reliable, low noise

Over View of Gunn

What is it?

The Gunn diode is used as local oscillator covering the microwave frequency range of 1 to 100GHz

How it works?

By means of the transferred electron mechanism, it has the negative resistance characteristic

What's the applications?

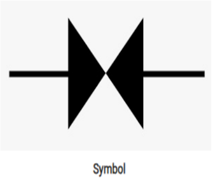
Local Oscillator and Avoid Collision Radar instead of Klystron etc..

What's the advantages?

Low noise, High frequency operation and Medium RF Power

GUNN DIODE

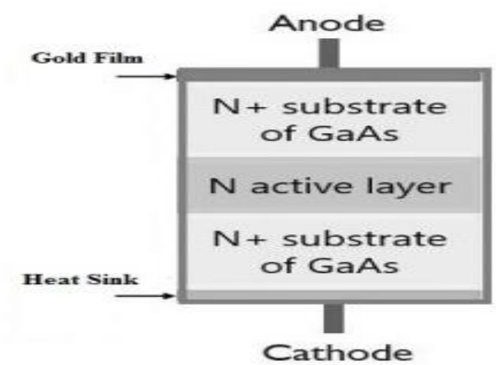
- Gunn diode is made with N-type semiconductor because it comprises majority charge carriers like electrons.
- This diode uses the negative resistance property to produce current at high frequencies.
- This diode is mainly used to produce microwave signals around 1 GHz & RF frequencies around 100 GHz.
- Gunn diodes are also known as TED (transferred electron devices).



- Even though it is a diode, the devices do not have a PN-junction but include an effect called the Gunn Effect.

Gunn Diode Construction

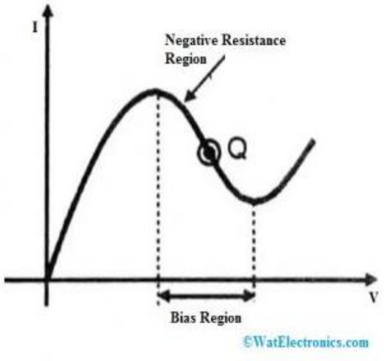
- The fabrication of the Gunn diode can be done with an N-type semiconductor.
- The materials which are used most frequently are GaAs (gallium Arsenide) & InP (Indium Phosphide) and other materials have been utilized like Ge, ZnSe, InAs, CdTe, InSb.
- It is essential to utilize n-type material because the effect of the transferred electron is simply appropriate to electrons & not holes found in a p-type material. In this device, there are 3 main regions which are called top, bottom & middle areas.



Construction

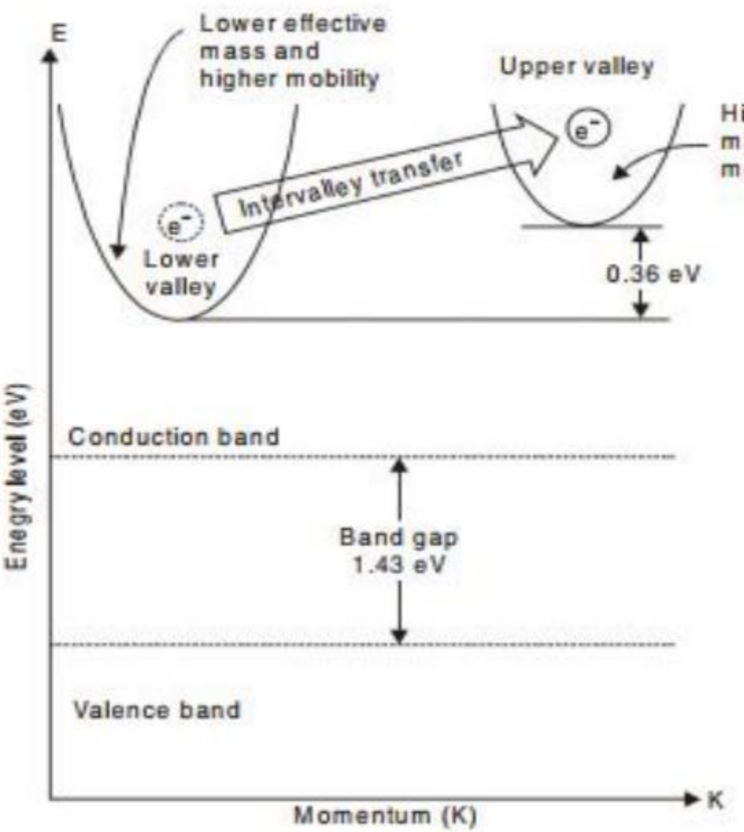
Gunn Diode Characteristics

- The Gunn diode characteristics show a negative resistance area on its VI characteristic.
- Here, the negative resistance area in the Gunn diode is nothing but once the flow of current increases then the voltage drops. This phase reverse allows the diode to work like an oscillator & an amplifier.
- The flow of current in this diode increases through the DC voltage.
- At a specific end, the flow of current will start decreasing, so this is called a peak point or threshold point.
- Once the threshold point is crossed then the flow of current will start reducing to create a negative resistance region within the diode.

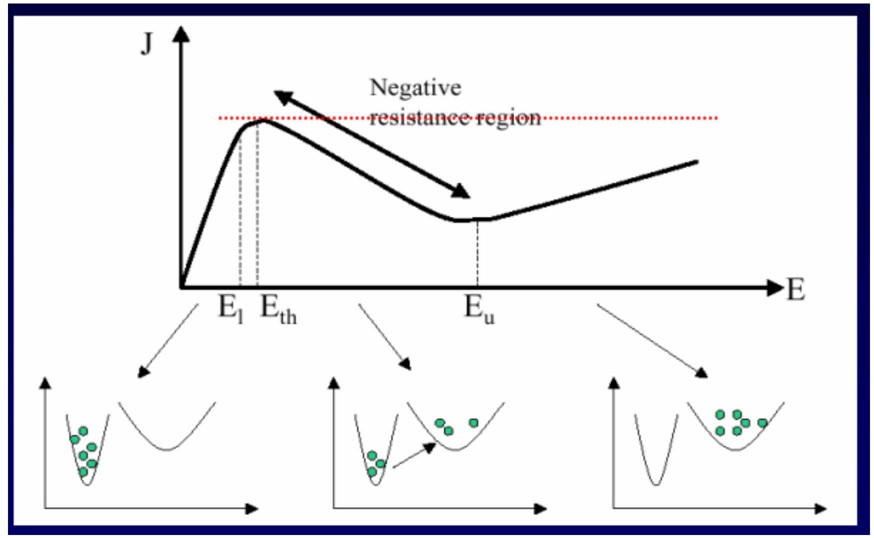


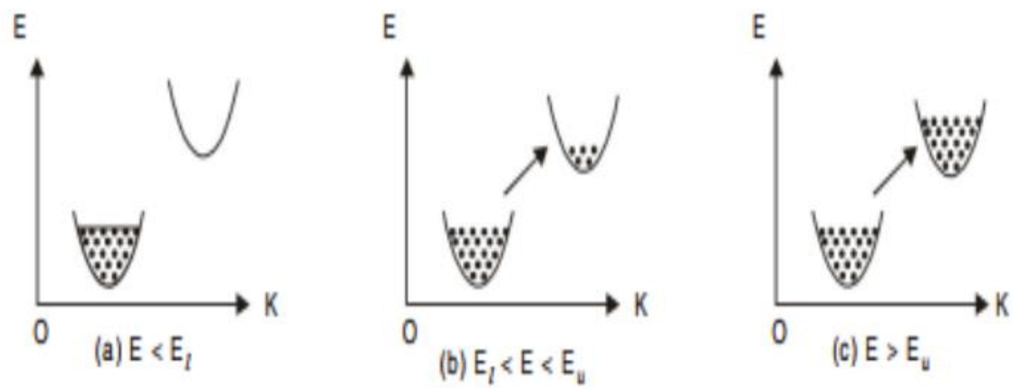
Characteristics of Gunn Diode

Gunn Diode (Two Valley Model)



Two Valley model





Transfer of Electron Densities

Gunn Diode - Two Valley Model

When E < El

When the applied electric field is lower than the electric field of the lower valley (E < E*l*), then electrons will occupy states in the lower valley Thus the material is in the highest average velocity state (electron in lower valley has high mobility) and drift velocity increases linearly with increasing potential. Thus increasing the current density J and hence positive differential resistance (ohmic region).

RWH theory is based on population inversion principle.

When El < E < Eu

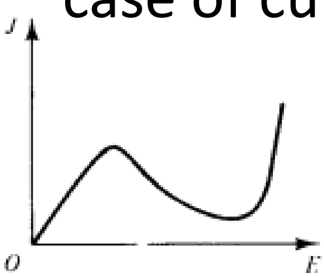
As the applied field is increased (2–4 kV/cm) higher than that of the lower valley and lower than that of the upper valley (E*l* < E < E*u*), electrons will gain energy from it and move upward to upper valley As the electrons transfer to the upper valley, their mobility decreases and the effective mass is increased thus decreasing the current density J and hence negative differential resistivity.

When E>Eu

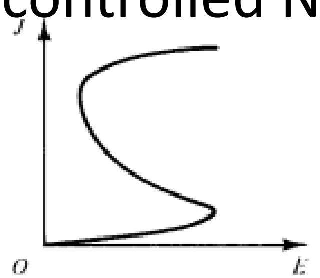
when the applied field is higher than that of the upper valley $E>E_U$ all electrons will transfer to the upper valley

Ridley, Watkins and Hilsum (RWH) Theory

- Ridley, Watkins and Hilsum (RWH) proposed a theory to explain the phenomenon of Negative Differential Resistance (NDR) in certain bulk materials.
- Its salient features are as follows: Bulk NDR devices are classified into two groups.
- One voltage controlled NDRs and second current controlled NDRs.
- The characteristic relation between electric field E and the current density J of voltage controlled NDRs is N shaped and that of the current controlled NDRs is S shaped
- The electric field is multi-valued in the case of voltage controlled NDRs and it is electric current that is multi-valued in case of current controlled NDRs.



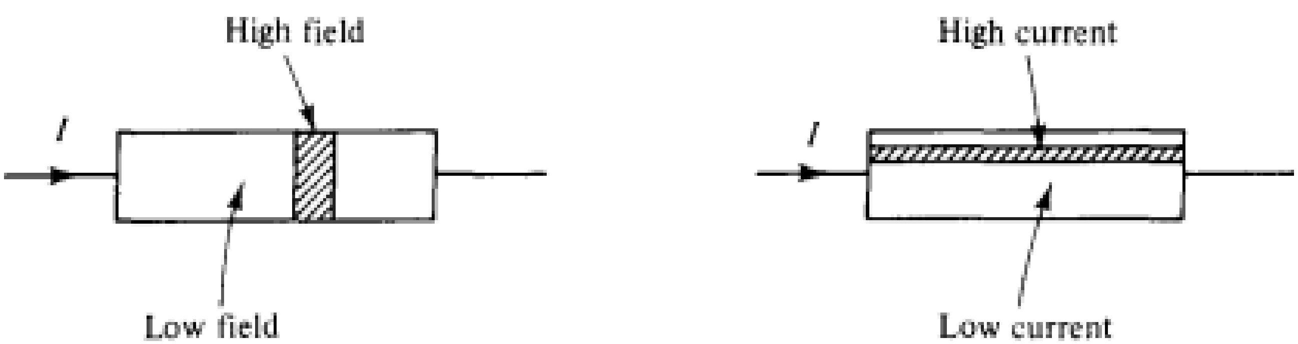
(a) Voltage-controlled mode



(b) Current-controlled mode

Ridley, Watkins and Hilsum (RWH) Theory

- Because of NDR, the initially homogeneous semiconductor becomes heterogeneous to achieve stability.
- It results in 'High field domains' in voltage controlled NDRs and 'High current filaments' in current controlled NDRs.
- The high field domain starts forming at a region, where the field intensity is higher extending further perpendicular to the direction of current flow separating two low field regions
- The high current filament starts forming at a region where the field intensity is higher extending further along the direction of the current flow separating two low current regions.



(a) High-field domain (b) High-current filament

Modes of Operation of Gunn Diode

Major factors that determine the modes of operation are:

- Concentration and uniformity of the doping
- Length of the active region
- Operating bias voltage
- Cathode contact property
- Type of the external circuit used

Gunn diode operates in four modes:

- Gunn Oscillation Mode
- Stable Amplification Mode
- LSA Oscillation Mode
- Bias Circuit Oscillation Mode

Gunn Oscillation Mode

- Gunn oscillation mode can be defined in the area wherever the sum of frequency can be multiplied by 10^7 cm/s lengths.
- The sum of doping can be multiplied through the length is higher than $10^{12}/cm^2$.
- In this region, the diode is not stable due to the formation of cyclic either the high field domain & the accumulation layer.

Modes of Operation of Gunn Diode

Stable Amplification Mode

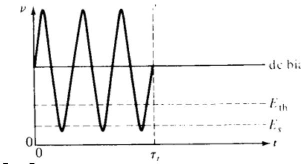
- This kind of mode can be defined in the area wherever the sum of frequency times length is 10^7cm/sec & the doping product length for time ranges from 10^{11} & $10^{12}/cm^2$

Bias Circuit Oscillation Mode

- This kind of mode happens simply once there is either LSA or Gunn oscillation takes place.
- Generally, it is the area wherever the time's length product of frequency is very small to appear within the figure.
- Once the biasing of a bulk diode is done to the threshold then the average current drops suddenly when the oscillation of Gunn starts.

Modes of Operation of Gunn Diode

Limited Space charge Accumulation LSA) mode $\left(\frac{nL \cong 10^{12} cm^{-2}}{fL > 2\times 10^{7} cm/s}\right)$



- The coefficient of doping divided by frequency (n l f) should be in between 2 x 10^4 and 2 x 10^5 .
- This is the simplest mode of operation and it consists of uniformly doped semiconductor without any internal space charge.
- As the frequency is high the domains do not get sufficient time to form
- Most of the domains find themselves in the negative conduction state during a large fraction of voltage cycle.

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- This mode is suitable to generate short pulses of high peak power. LSA mode of operation can produced several watts of power with minimum efficiencies of 20%.
- The power output decreases with frequency, viz 1 W at 10 GHz and several mW at 100 GHz.
- Its maximum operating frequency is much lower than that of the TT devices.
- Its limitations are sensitivity to load conditions, temperature and doping fluctuations

AVALANCHE TRANSIT TIME DEVICES

- Avalanche transit time devices are p-n junction diodes with the highly doped p and n regions.
- They could produced a negative resistance at microwave frequencies by using a carrier impact ionization avalanche breakdown and carriers drift in the high filed intensity region under reverse biased conditions.
- There are three types of these devices
  - Impact Ionization Avalanche Transit Time effect (IMPATT)
  - Trapped Plasma Avalanche Triggered Transit effect (TRAPATT)
  - Barrier Injected transit Time effect (BARITT)

Impact Ionization Avalanche Transit Time effect (IMPATT) Diode

- The IMPATT diode is now one of the most powerful solid state sources for the generation of microwaves, generate higher CW power outputs in millimetre wave frequencies, i.e. above 30 GHz of all solid state devices.
- These are compact, inexpensive, moderately efficient and with improved device fabrication technology these diodes also have become reliable under high temperature operation.

The salient features of this diode are as follows:

• IMPATT stands for IMPact ionization Avalanche Transit Time'.

• IMPATT diodes employ 'Impact ionization' and 'Transit time' properties of semi-conductor structures to get negative resistance at microwave frequencies.

• Impact ionization or Avalanche multiplication:

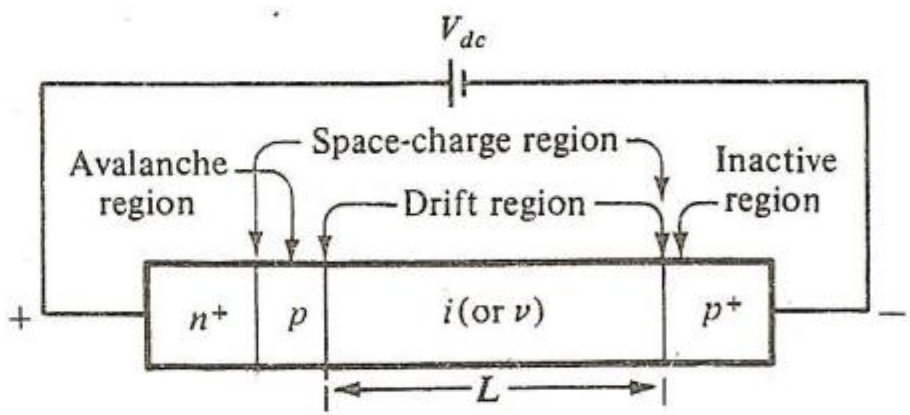
generation and multiplication of hole electron pair takes place due to knocking off the valence electrons into conduction band by the highly energetic carriers when the electric field is increased above certain value'.

Transit time delay by the finite time for the carriers to cross the drift region

Impact Ionization Avalanche Transit Time effect (IMPATT) Diode

- Unlike, the Gunn diode, the IMPATT diode has a p-n junction.

It is a four-layer device



- IMPATT diode is an n + -p-i-p + structure, where the subscript plus sign denotes very high doping and i or v refers to intrinsic material.
- The device operates in the reverse breakdown (avalanche) region.

Avalanche region: In this region avalanche multiplication takes, doping concentration and field intensity are high. The avalanche or injection region creates the carriers which may be either holes of electrons

Impact Ionization Avalanche Transit Time effect (IMPATT) Diode

Drift region: In this region avalanche multiplication does not take place, doping concentration and field levels are low. Carriers move across the diode taking a certain amount of time dependent upon its thickness

Depletion region is Avalanche Region plus Drift Region.

Impact Ionization Avalanche Transit Time effect (IMPATT) Diode

- Once the carriers have been generated the device relies on negative resistance to generate and sustain an oscillation.
- The total field across the diode is the sum of the dc and ac fields
- This field causes breakdown in the positive half cycle, the avalanche current multiplication will taking place during this entire time.
- This process generates a current pulse at the junction and moves towards the cathode.
- The instant at which the current pulse arrives at the cathode terminal, the ac voltage there is at its negative peak.
- The current peaks are found to be 180° out of phase with the voltage.

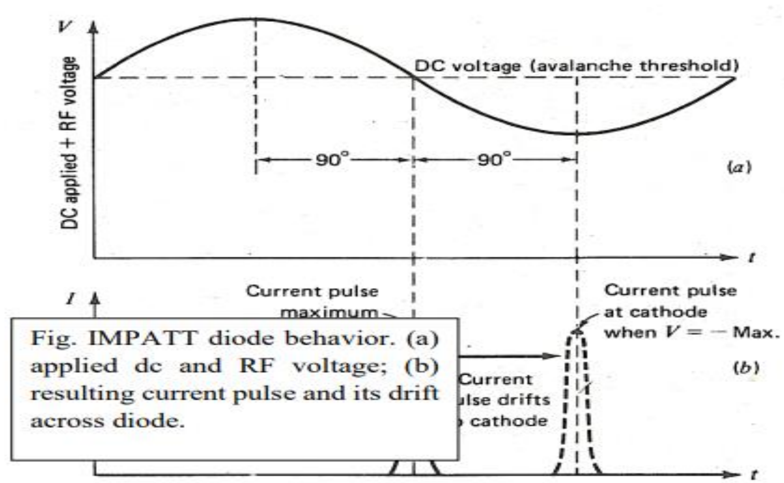


Fig. IMPATT diode behavior. (a) applied dc and RF voltage; (b) resulting current pulse and its drift across diode.

Impact Ionization Avalanche Transit Time effect (IMPATT) Diode

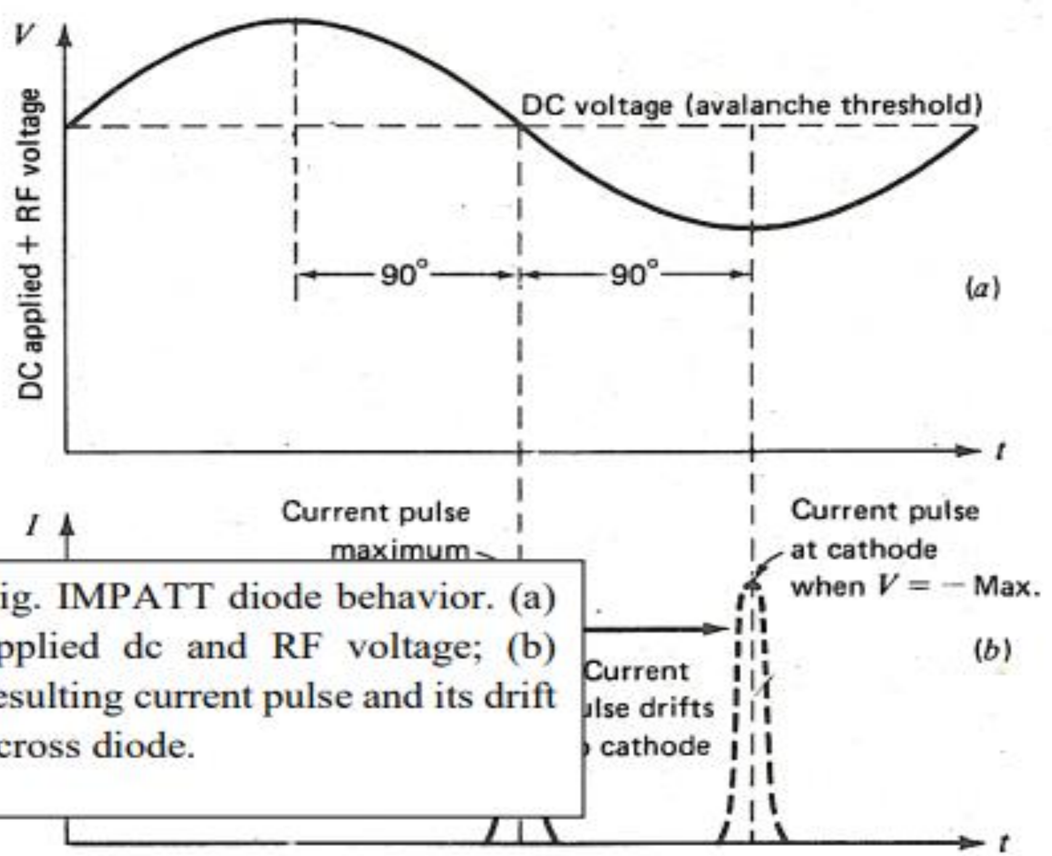
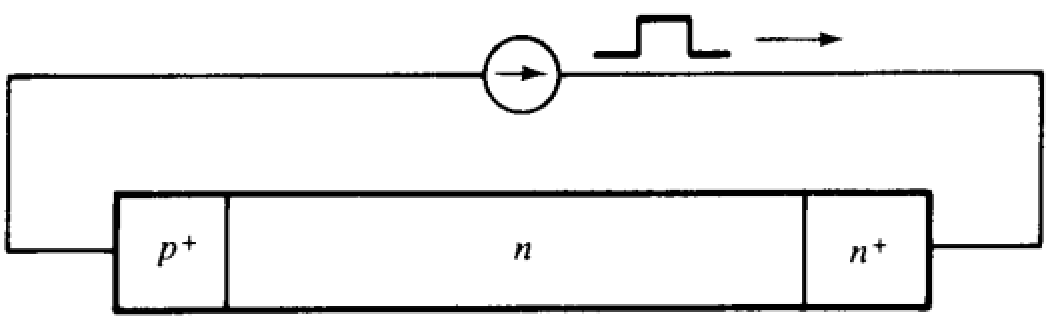


Fig. IMPATT diode behavior. (a) applied dc and RF voltage; (b) resulting current pulse and its drift across diode.

TRApped Plasma Avalanche Triggered (TRAPATT) Diode

- It is a high power and high efficiency microwave generator capable of operating up to several GHz.
- It is a semiconductor p-n junction diode reverse biased to current densities well in excess of those encountered in normal avalanche operation.
- The doping of the depletion region is generally such that the diodes are well punched though at breakdown.
- The device's p+ region is kept as thin as possible at 2.5 to 7.5 μ m.
- The TRAPATT diode's diameter ranges from as small as 50 μ m for CW operation to 750 μ m at lower frequency for high peak-power devices.



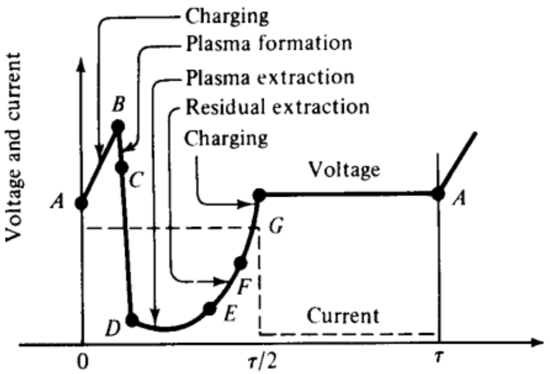
TRAPATT

At point A: The diode current is turned on. the only charge carriers present are by the thermal generation, the diode initially charges up like a linear capacitor, driving the magnitude of electric field above the breakdown voltage.

B to C: When sufficient number of carriers is generated, the particle current exceeds the external current and the electric field is depressed throughout the depletion region causing the voltage to decrease.

C to D: electric field is sufficiently large for the avalanche to continue, and a dense plasma of electrons and holes is created.

As some of the electrons and holes drift out of the ends of the depletion layer, the field is further depressed and traps the remaining plasma. The voltage decreases to point D



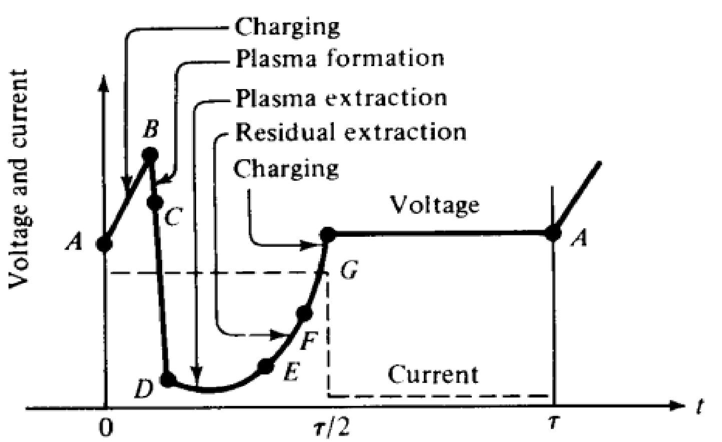
TRAPATT

D to E: A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time.

At point E plasma is removed, but a residual charge of holes in the other end.

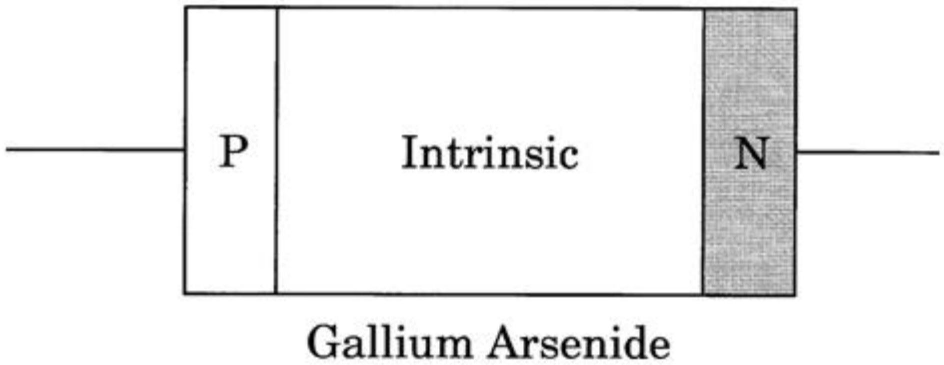
E to F: As the residual charge is removed, the voltage increases from point E to F. At point F all the charge that was generated internally has been removed. This charge must be greater than at point A.

F to G: The diode charge up again like a fixed capacitor. At point G the diode current goes to zero for half a period and the voltage remain constant at VA until the current comes back on and the cycle repeats.



PIN DIODE

- P-type --- Intrinsic --- N-type
- Used as switch and attenuator
- Reverse biased - off
- Forward biased - partly on to on depending on the bias

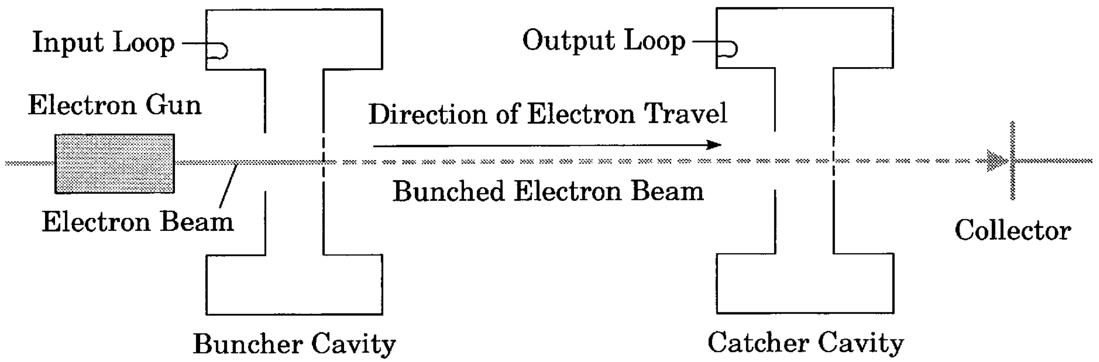


PIN DIODE

KLYSTRON

- Used in high-power amplifiers
- Electron beam moves down tube past several cavities.
- Input cavity is the *buncher*, output cavity is the *catcher.*
- *Buncher* modulates the velocity of the electron beam

KLYSTRON CROSS SECTION



KLYSTRON

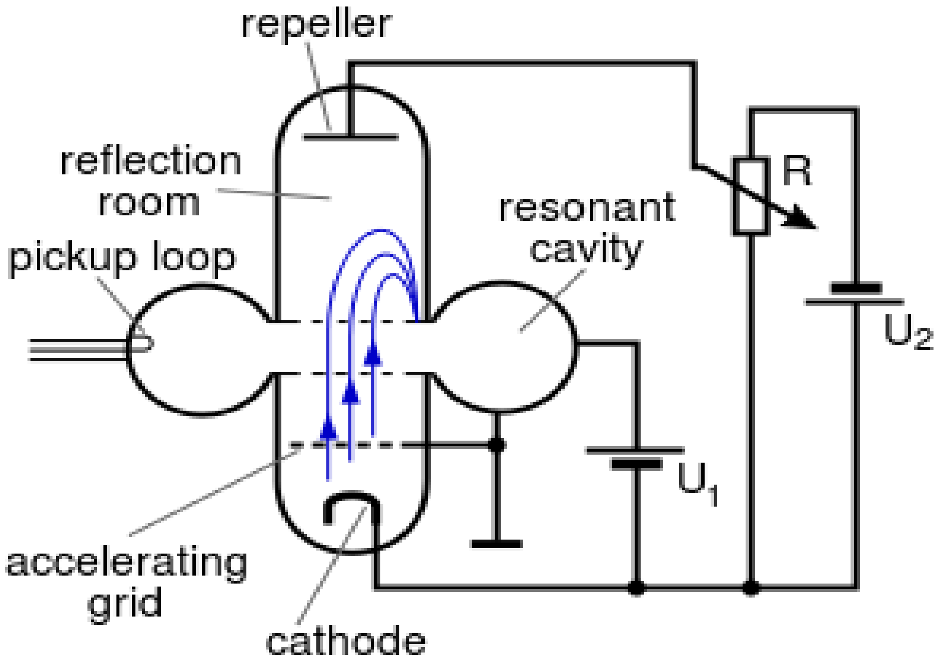
The major element are;

- An electron gun to form and accelerate a beam of electrons
- A focusing magnet to focus the beam of electrons through the cavities
- Microwave cavities where the electron beam power is converted to microwave power
- A collector to collect the electron beam after the microwave power has been generated
- A microwave input where the microwave signal to be amplified is introduced into the klystron
- A microwave output where the amplified microwave power is taken out

VELOCITY MODULATION

- Electric field from microwaves at buncher alternately speeds and slows electron beam
- This causes electrons to bunch up
- Electron bunches at catcher induce microwaves with more energy
- The cavities form a slow-wave structure

REFLEX KLYSTRON



REFLEX KLYSTRON

- The electron beam passes through a single resonant cavity.
- The electrons are fired into one end of the tube by an electron gun.
- After passing through the resonant cavity they are reflected by a negatively charged reflector electrode for another pass through the cavity, where they are then collected.
- The electron beam is velocity modulated when it first passes through the cavity.

REFLEX KLYSTRON

- The formation of electron bunches takes place in the drift space between the reflector and the cavity.
- The voltage on the reflector must be adjusted so that the bunching is at a maximum as the electron beam re-enters the resonant cavity, thus ensuring a maximum of energy is transferred from the electron beam to the RF oscillations in the cavity.
- The voltage should always be switched on before providing the input to the reflex klystron as the whole function of the reflex klystron would be destroyed if the supply is provided after the input.

REFLEX KLYSTRON

- The reflector voltage may be varied slightly from the optimum value, which results in some loss of output power, but also in a variation in frequency.
- At regions far from the optimum voltage, no oscillations are obtained at all.
- This tube is called a reflex klystron because it repels the input supply or performs the opposite function of a klystron.

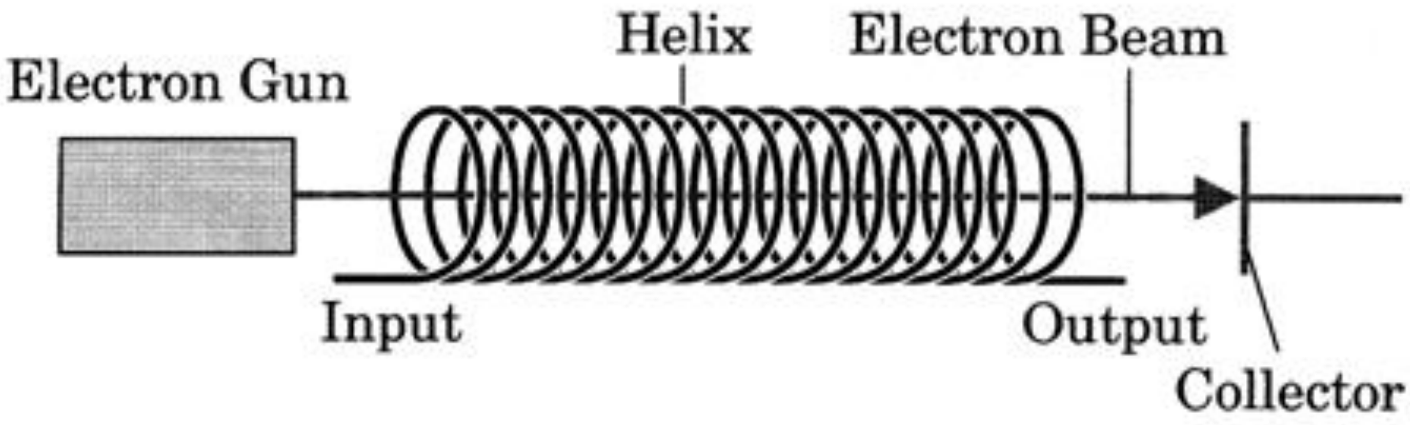
REFLEX KLYSTRON

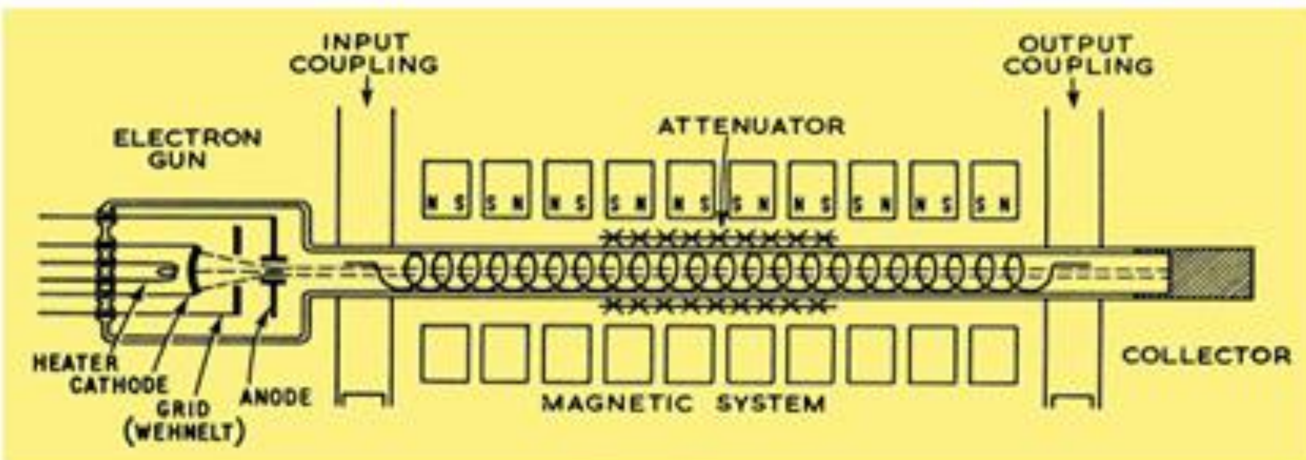
- There are often several regions of reflector voltage where the reflex klystron will oscillate; these are referred to as modes.
- The frequency of oscillation is dependent on the reflector voltage, and varying this provides a crude method of frequency modulating the oscillation frequency, albeit with accompanying amplitude modulation as well.

TRAVELING-WAVE TUBE (TWT)

- Uses a helix as a slow-wave structure
- Microwaves input at cathode end of helix, output at anode end
- Energy is transferred from electron beam to microwaves

TRAVELING-WAVE TUBE (TWT





TRAVELING-WAVE TUBE (TWT

The major elements include;

- An electron beam to form and accelerate a beam of electrons
- A focusing magnet/magnetic system to focus the beam of electrons through the interaction structure
- A collector to collect the electron beam after the microwave power has been generate

TRAVELING-WAVE TUBE (TWT

- An input window where the small microwave signal to be amplified is introduced to the interaction structure
- An helix as interaction structure, where the electron beam interacts with the microwave signal to be amplified
- A microwave output window, where the microwave power is taken out of the tube
- An internal attenuator, to absorb the power reflected back into the tube from mismatches in the output transmission line

TRAVELING-WAVE TUBE (TWT

Operation

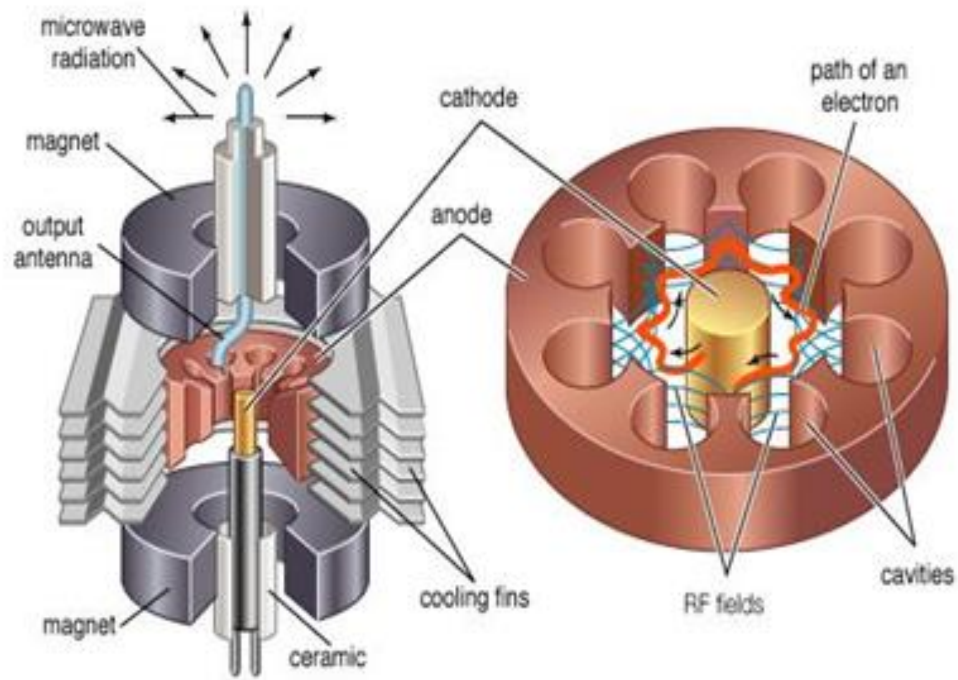
- The helix acts as a delay line, in which the RF signal travels at near the same speed along the tube as the electron beam.
- The electromagnetic field due to the RF signal in the helix interacts with the electron beam, causing bunching of the electrons (an effect called velocity modulation), and the electromagnetic field due to the beam current then induces more current back into the helix (i.e. the current builds up and thus is amplified as it passes down).
- A second directional coupler, positioned near the collector, receives an amplified version of the input signal from the far end of the helix.
- An attenuator placed on the helix, usually between the input and output helices, prevents reflected wave from traveling back to the cathode.

MAGNETRON

- The magnetron is a high-powered vacuum tube that generates microwaves using the interaction of a stream of electrons with a magnetic field.

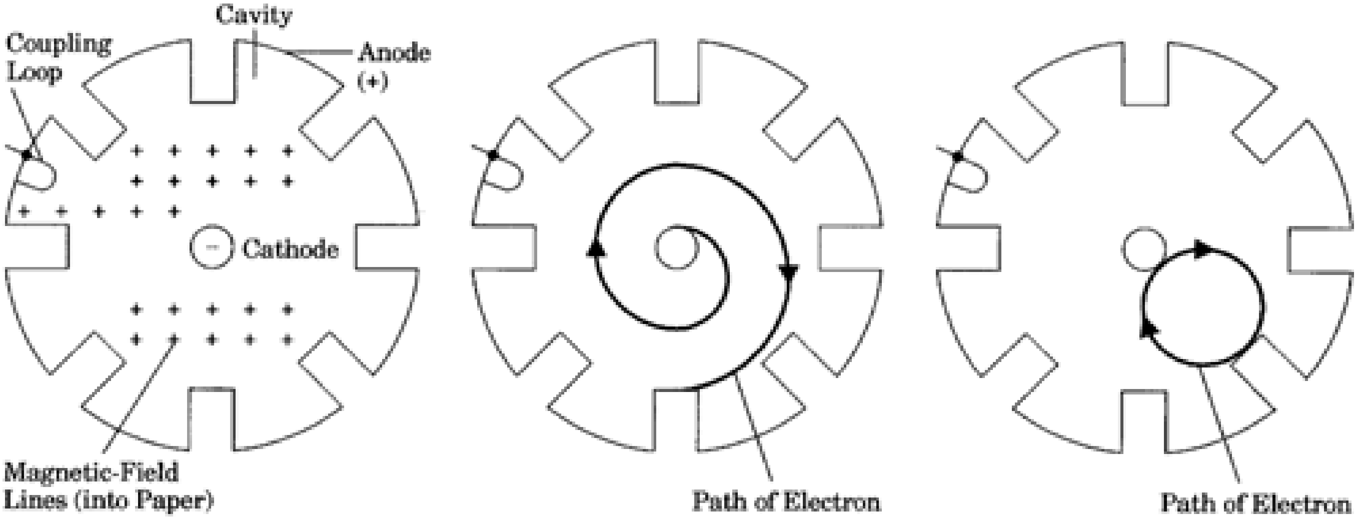
- High-power oscillator
- Common in radar and microwave ovens
- Cathode in center, anode around outside
- Strong dc magnetic field around tube causes electrons from cathode to spiral as they move toward anode
- Current of electrons generates microwaves in cavities around outside

MAGNETRON



microwave radiation
magnet
output antenna
cathode
anode
path of an electron
cooling fins
magnet
ceramic
RF fields
cavities

MAGNETRON



(a) Cross Section

(b) Electron Paths in Normal Operation

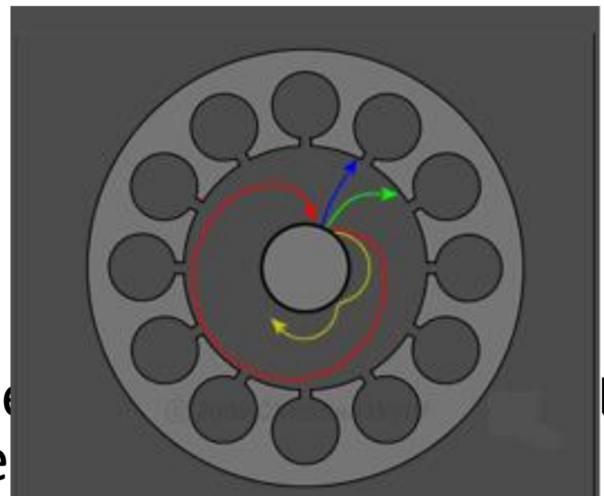
(c) Electron Paths at Cutoff

MAGNETRON-operation

- In a magnetron, the source of electrons is a heated cathode located on the axis of an anode structure containing a number of microwave resonators.
- Electrons leave the cathode and are accelerated toward the anode, due to the dc field established by the voltage source E.
- The presence of a strong magnetic field B in the region between cathode and anode produces a force on each electron which is mutually perpendicular to the dc field and the electron velocity vectors, thereby causing the electrons to spiral away from the cathode in paths of varying curvature, depending upon the initial electron velocity at the time it leaves the cathode.

MAGNETRON

The electron path under the influence of different strength of the magnetic field

- 

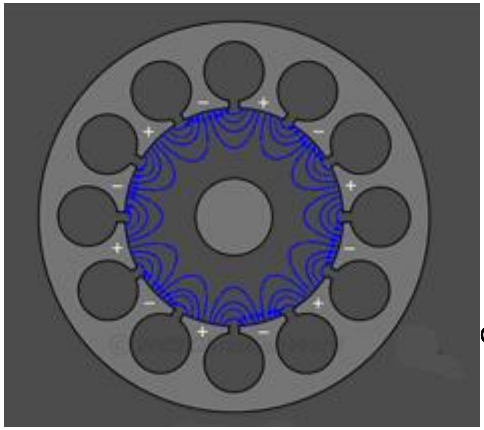
- As this cloud of e … the anode, it falls under the influe … the vane tips, and electrons will either be retarded in velocity, if they happen to face an opposing RF field, or accelerated if they are in the vicinity of an aiding RF field.

MAGNETRON

- Since the force on an electron due to the magnetic field B is proportional to the electron velocity through the field, the retarded velocity electrons will experience less "curling force" and will therefore drift toward the anode, while the accelerated velocity electrons will curl back away from the anode.
-
- The result is an automatic collection of electron "spokes" as the cloud nears the anode with each spoke located at a resonator having an opposing RF field.

MAGNETRON

- On the next half cycle of RF oscillation, the RF field pattern will have reversed polarity and the spoke pattern will rotate to maintain its presence in an opposing field.



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