UNIT - VII

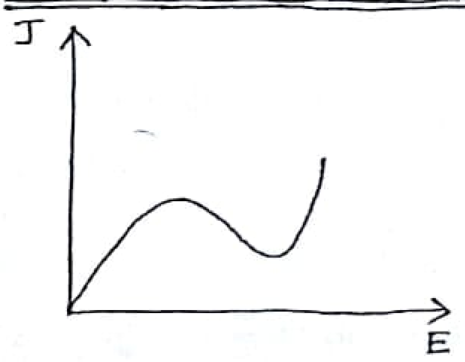
GUNN EFFECT DIODES

- GaAs Diode
- J. B. Gunn - 1963
- Gunn Effect - A periodic fluctuations of current passing through n type GaAs specimen when the applied voltage exceeded a certain critical value.

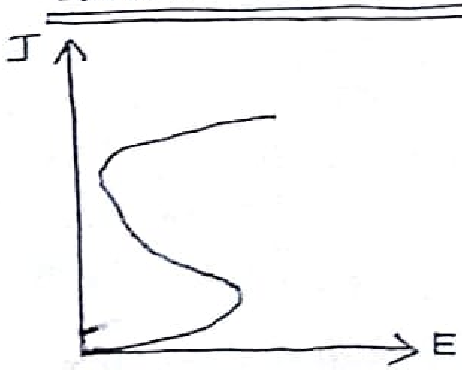
RIDLEY - WATKINS - HILSUM (RWH) THEORY:

- Two valley Model Theory
- The fundamental concept of RWH Theory is Differential Negative Resistance when either a voltage (or electric field) or current is applied to the terminals of the sample.
- There are two modes of Negative Resistance Devices
  - (i) voltage controlled Mode.
  - (ii) current controlled Mode.

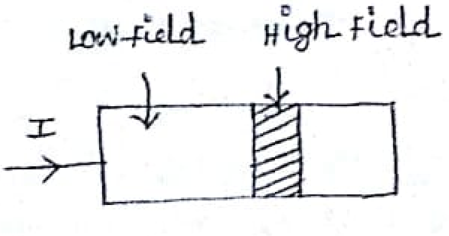
Voltage-controlled Mode



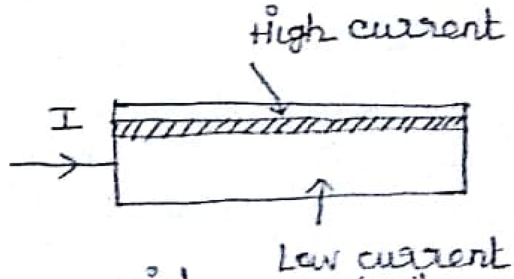
Current-controlled Mode



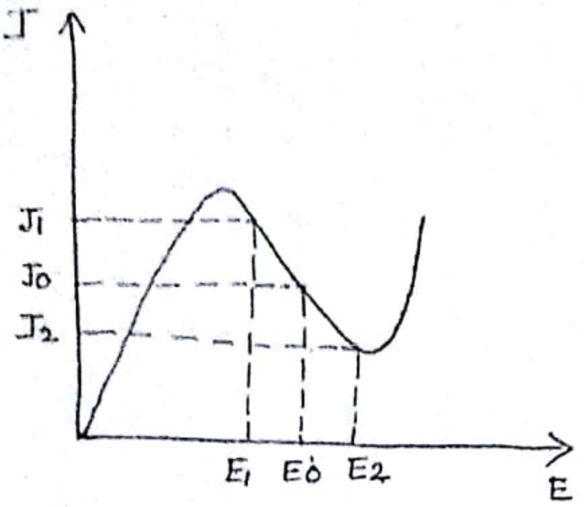
* In vt controlled Mode, current Density can be Multivalued.
* In ct controlled Mode, voltage can be Multivalued.



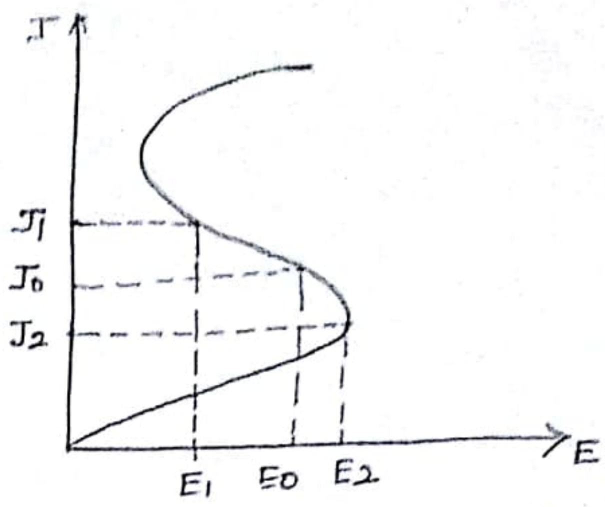
High Field Domain



High current Filament



Voltage-controlled Mode



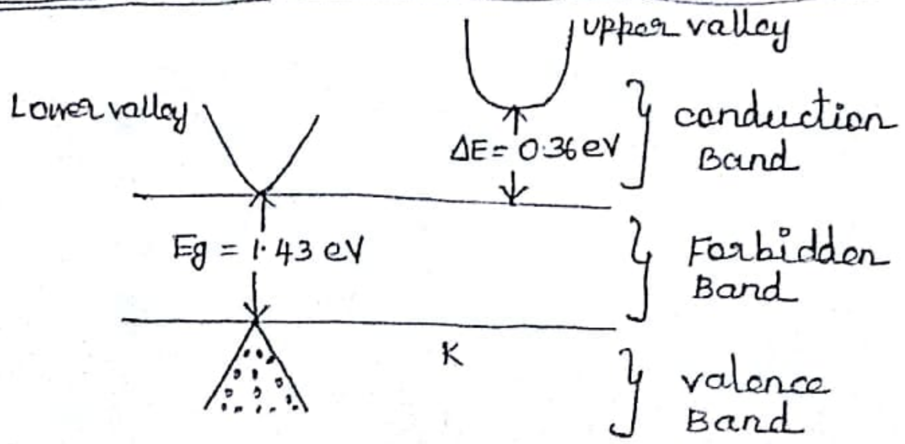
current controlled Mode

* In voltage controlled mode, high field domains are formed, seperating two low field regions. The interfaces seperating low and high field domains lie along equipotentials, thus they are in planes $\perp^r$ to current direction.
* In current controlled mode, splitting the sample results in high-current filaments running along the field direction.
* The negative resistance of a sample at a particular region is

$$\frac{dI}{dV} = \frac{dJ}{dE} = \text{Negative Resistance}$$

* Vt E_0 applied, ct density J_0 is generated.
* $\uparrow$ Vt to E_2, ct density reduced to J_2.
* $\downarrow$ Vt to E_1, ct density $\uparrow$ to J_1.

Two valley Model of Electron Energy versus wave no for n type GaAs



μ_l – mobility of electron in lower valley

n_l – Density of electron in lower valley

μ_u – mobility of electron in upper valley

n_u – Density of electron in upper valley

MODES OF OPERATION:

1. GUNN OSCILLATION MODE:

- operating frequency (f) × Length (L) ≈ 10^7 cm/sec.
- Doping (n_0) × Length (L) > 10^{12}/cm²
- In this mode the device is unstable.

2. STABLE AMPLIFICATION MODE:

- operating frequency (f) × Length (L) ≈ 10^7 cm/sec
- Doping (n_0) × Length (L) = 10^{11} to 10^{12} / cm²

3. LIMITED SPACE CHARGE ACCUMULATION (LSA) MODE:

- operating frequency (f) × Length (L) > 2×10^7 cm/sec
- In LSA mode, the Gunn Diode is placed in a resonator which is tuned to an oscillation frequency of f_0.

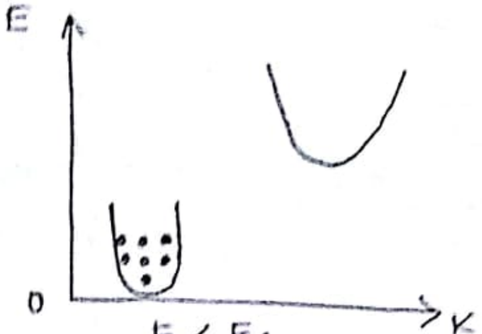
$$f_0 = \frac{1}{T_0} = \frac{1}{\text{oscillation period}}$$

- In this mode, the device can be biased to several times the threshold voltage.

4. BIAS CIRCUIT OSCILLATION MODE:

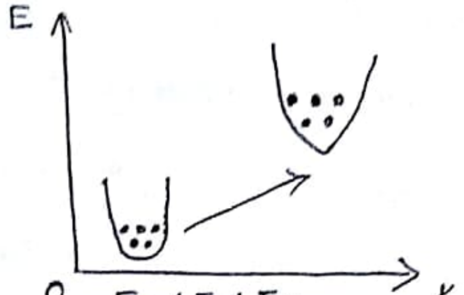
- operating frequency (f) × Length (L) ≈ very small.
- The device is biased at the Threshold.
- The oscillation frequency can be obtained in the range of 1KHZ to 100 MHZ.

* Electron Densities in the lower and upper valleys are the same under an equilibrium condition.
* when the applied electric field is lower than the electric field of the lower valley ($E < E_l$), no electrons will transfer to upper valley.



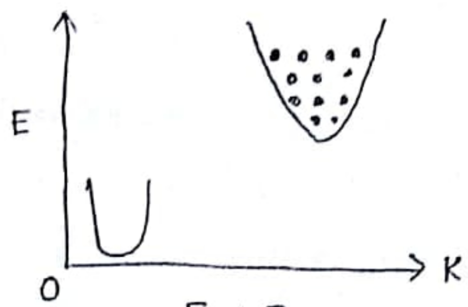
$\underline{E < E_l}$

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



$\underline{E_l < E < E_u}$

* when the applied electric field is higher than that of upper valley ($E_U < E$), all electrons will travel to upper valley



$\underline{E_U < E}$

The conductivity of n type GaAs is given as

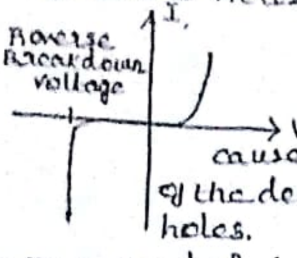
$$\sigma = e(\mu_l n_l + \mu_u n_u)$$

where e - charge of e^- ($1.6 \times 10^{-19} C$)

PERATION:

* p^+ region - heavily doped.
* n region - normally doped.
* i - undoped.

* The p^+n junction will breakdown when the applied reverse bias Vt exceeds a Threshold value.



* The rapid increase in current at the Breakdown voltage is caused by the Avalanche Multn of the density of electrons and holes.

* If a Read Diode is placed in a cavity and a reverse bias somewhat smaller than Breakdown Vt is applied, along with a small RF voltage, then breakdown will occur when the RF voltage becomes +ve.

* when the Breakdown is initiated, a large no of holes and e^- are created at p^+n junction.

The e^- are swept across the n region to drift region.

After a Transit Time delay, the electrons are collected at the n^+ terminal.

The current pulse moves through the diode from right to left.

When the time for Avalanche charge ~~for~~ build up plus that for charge through the drift region exceeds one half period, the current will lag the RF Vt by more than 90°.

With these condns, the diode will exhibit a -ve resistance for RF currents.

APPLICATIONS:-

(i) Microwave Receivers.

(ii) Parametric amplifiers.

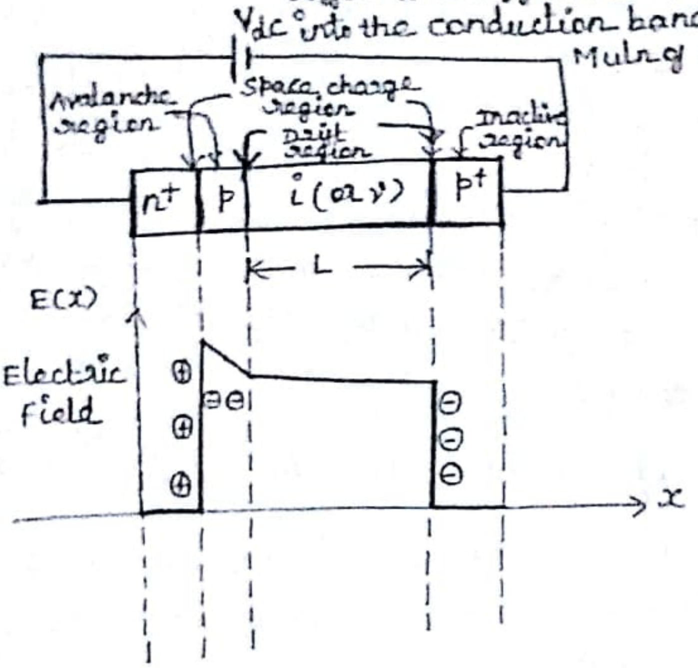
(iii) Radars.

(v) Broad Band Microwave Amplifiers.

READ DIODE:

Physical Description:

* under reverse biased condn. the characteristics of different regions of the Diode is as shown.
* when the reverse bias vt exceeds Breakdown vt V_B, a max elec field of very high value appears at n^+p jn.
* the holes moving in the high field region acquire sufficient energy to excite valence electrons of the atom into the conduction band resulting in Avalanche Mul^n of electron-hole pairs.



Silicon Structure

Field Distribution

* Read Diode is a $n^+-p-i\ p^+$ structure, where the subscript + indicates very high doping.
* i or ν refers to Intrinsic material.
* The Device consists of Two regions.
  - → one is the thin p region at which Avalanche Multiplication occurs. This region is called High Field or Avalanche region
  - → The other region is i or ν region through which generated holes must drift in moving to p^+ contact. This region is called Intrinsic region or Drift region
* The p region is very thin.
* The space between n^+-p junction and $i-p^+$ junction is called space charge region

AVALANCHE MULTIPLICATION:

* when the reverse-biased voltage is well above the Breakdown voltage, the space-charge region always extends from n^+-p junction through the p and i regions to the $i-p^+$ junction.
* A positive charge gives a rising field in moving from Left to Right.
* The maximum field which occurs at the n^+-p junction, is about several hundred kilovolts per centimeter.
* carriers (holes) moving in the high field near the n^+-p junction acquire energy to knock valence electrons into the conduction band, thus producing hole-electron pairs.
* By proper doping, the field can be given a relatively sharp peak so that avalanche multiplication is confined to a very narrow region at the n^+-p junction.
* The electrons move into the n^+ region and the holes drift through the space-charge region to the p^+ region with a constant velocity v_d of about 10^7 cm/s for silicon.

The Transit time of a hole across the drift i-region L is given by

$$\tau = \frac{L}{v_d}$$

The Avalanche Multiplication factor is given by

$$\boxed{M = \frac{1}{1-(V/V_b)^n}}$$

where

V = applied voltage

V_b = Avalanche Breakdown voltage

n = 3-6 for silicon

The o/p power is gn by $P = 0.707\, V_a I_d$ W/unit area

V_a - amplitude of ac voltage

I_d - Direct current

Quality factor (Q) of a circuit is defined as

$$Q = \omega \frac{\text{maximum stored energy}}{\text{Average Dissipated power}}$$

AVALANCHE TRASIT TIME DEVICES:

* these devices employ Avalanche and Transit time properties of semiconductor structure to produce negative resistance at μwave frequencies.
* this negative resistance is employed in μwave amplifiers and oscillators.

IMPACT AVALANCHE AND TRANSIT TIME DIODES (IMPATT)

* IMPATT Diodes have many forms

  (i) $n^+ - p - i - p^+$

  (ii) $p^+ - n - i - n^+$

* It's basic mechanism is interaction of Impact Ionization Avalanche and the Transit Time of charge carriers. Hence Read Type Diodes are called IMPATT Diodes.
* These Diodes exhibit Differential Negative Resistance as follows

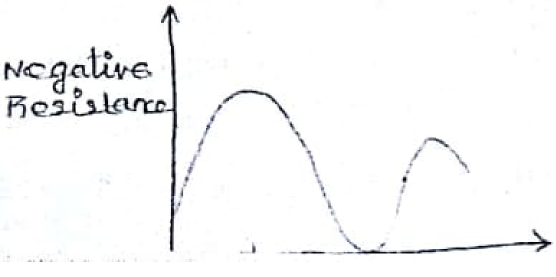
⇒ when a p-n junction is reverse biased, in the depletion layer, Avalanche Breakdown takes place.

⇒ Avalanche current lags the applied field by $\pi/2$ radians.

⇒ The carriers constituting avalanche current will drift to the respective electrodes (ie) holes to negative electrode and electrons to positive electrode.

⇒ The distance travelled by various carriers are not equal but the additional phase shift caused by the drift of carriers makes the carriers to create a negative resistance.

The variation of Negative Resistance w.r.to Transit angle is as shown below



* The graph shows that maximum resistance is offere at $\theta = \pi$. Above π, the resistance decreases rapidly.

* The operating frequency around the π Transist angle.

$$f = \frac{1}{2\tau}$$

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

τ - Transit Time

v_d - Drift velocity (m/s)

L - Drift length (m)

* θ is the Transit angle and is given by

$$\theta = \omega\tau$$

$$\boxed{\theta = \omega \frac{L}{v_d}}$$

* At a gn freq, the max o/p power of a single Diode is limited by semiconductor materials.

For a uniform Avalanche, maximum voltage that can be applied across the Diode is given by

$$\boxed{V_m = E_m L}$$

where L - Depletion Length

E_m - Maximum Electric Field

* The Maximum current is given by

$$\boxed{I_m = J_m A}$$

$$I_m = \sigma E_m A$$

$$I_m = \frac{\epsilon_s}{\tau} E_m A$$

$$\boxed{I_m = \frac{v_d \epsilon_s E_m A}{L}}$$

* $\therefore$ The upper limit of the power input is given by

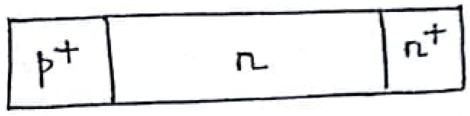
$$P_m = V_m I_m$$

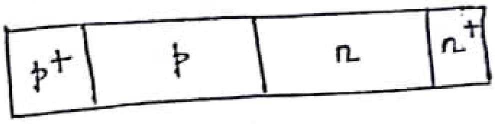
$$\boxed{P_m = E_m^2 \epsilon_s v_d A}$$

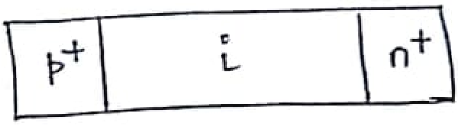
Efficiency (η) = $\frac{P_{ac}}{P_{dc}}$

$$\boxed{\eta = \frac{V_a I_a}{V_d I_d}}$$

p-n junction

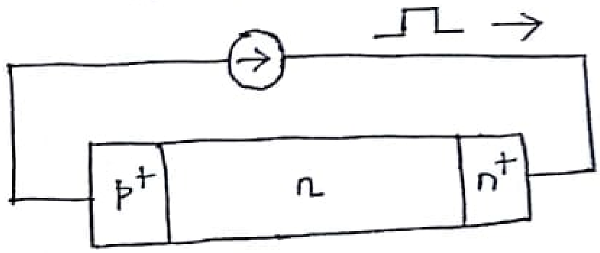






TRAPATT DIODES:

* TRAPATT - Trapped plasma Avalanche Triggered Transit diode

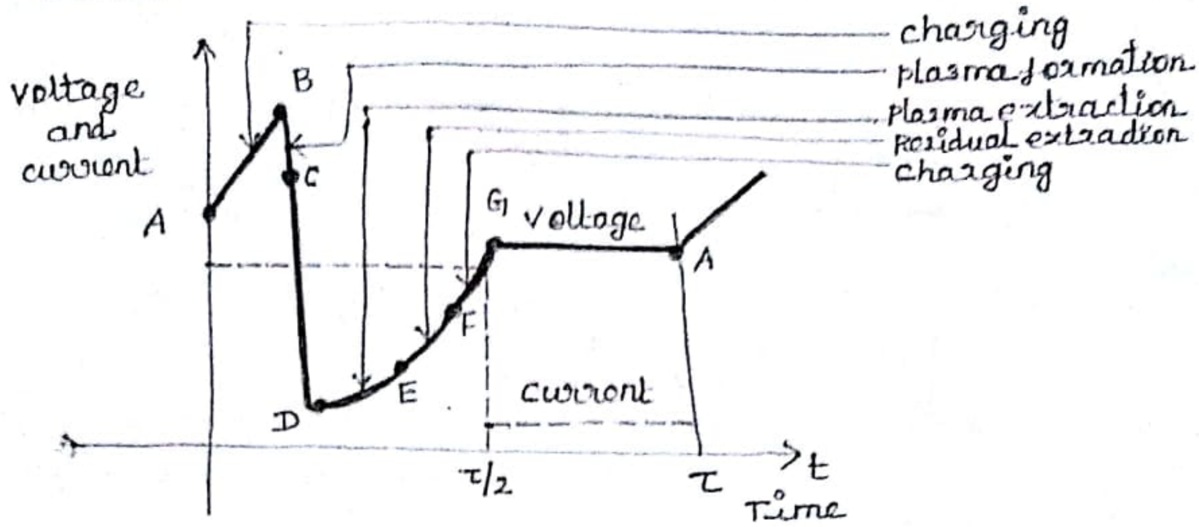


* A squared pulse is used to excite TRAPATT Diode.
* As soon as the Diode is excited, the charge is accumulated in the Depletion region at the junction and electric field across the junction varies linearly.
* when sufficient carriers are generated, it then depress throughout the depletion region, causing voltage to fall down. formation of plasma takes place.
* During this interval, formation of plasma takes place.
* voltage and current continue to decrease to residual value

and the plasma is extracted from the region.

* As the residual charge is removed, the voltage increases further and Diode charges again.
* At some point the Diode is charged fully and maintains a constant voltage across it while current drops down.

Voltage and current waveforms of TRAPATT Diode



Thus TRAPATT Diode can operate at comparitively Low freq.

TYPICAL PARAMETERS:

→ Power – 1·2 KW at 1·1 GHZ.

→ Efficiency – 75% at 0·6 GHZ.

→ Freq range – 0·5 GHZ to 50 GHZ.