# TUNNEL DIODE

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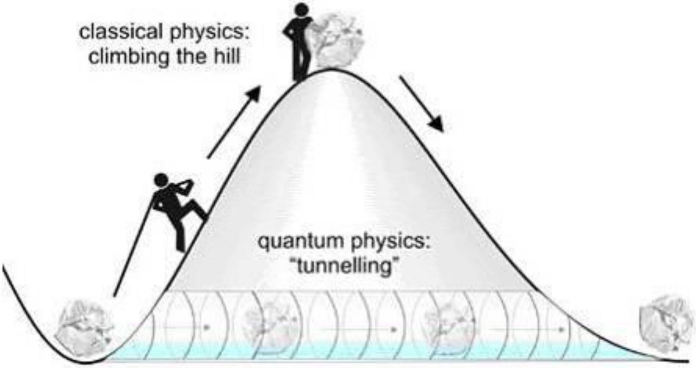
# Tunnel diode

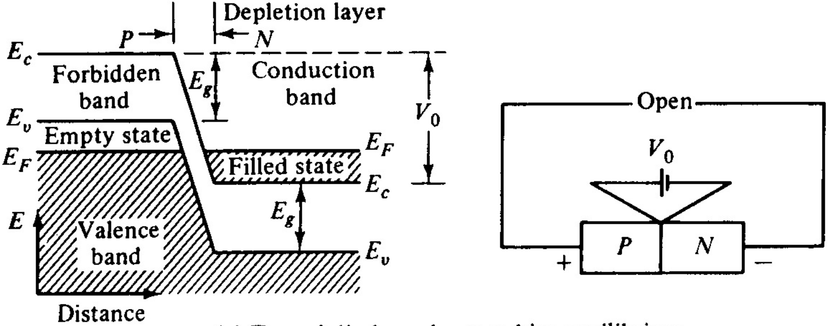
- The depletion width is very narrow in case of a tunnel diode.
- Due to the very narrow depletion region width the charge carriers instead of climbing up the potential barrier like they do in case of a conventional PN junction diode, may pierce through the junction with little or no bias applied.
- This phenomenon, called tunneling or quantum tunneling , is responsible for its behavior as a very good conductor both in forward as well as reverse direction for a very small applied bias of the order of 0.1 volt.
- Fig. shows the energy-band diagram & I-V characteristics of a tunnel diode. From its characteristics, it is clear that both in the forward as well as reverse directions, the diode responds with a huge current for a very small applied voltage.

# Quantum Tunneling

- There are two paths of getting to the other side of a mountain. In classical physics, one must climb the mountain to get to the other side. In quantum physics, objects can cross the mountain by tunnelling horizontally through it.

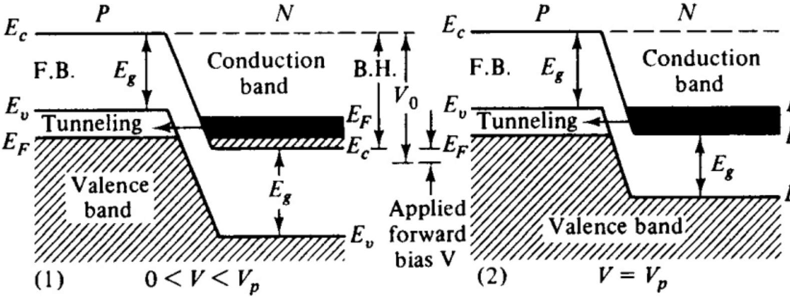


# Tunnel diode

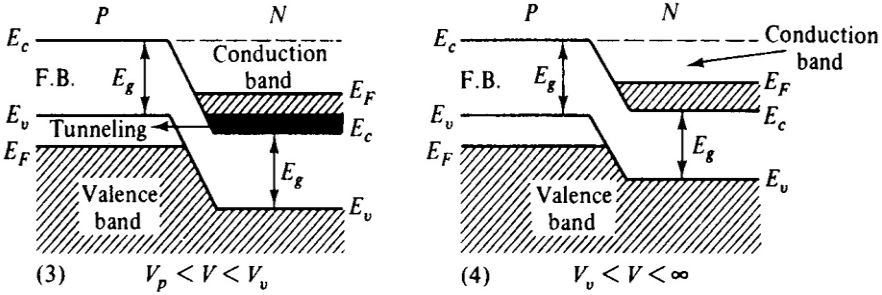



(a) Tunnel diode under zero-bias equilibrium

# Tunnel diode



# Tunnel diode




(b) Tunnel diode with applied forward bias

# Transferred Electron Devices

- Three types of diodes other than the tunnel diode that can oscillate due to negative resistance characteristics are
  1. Gunn diode
  2. IMPATT diode
  3. TRAPATT diode

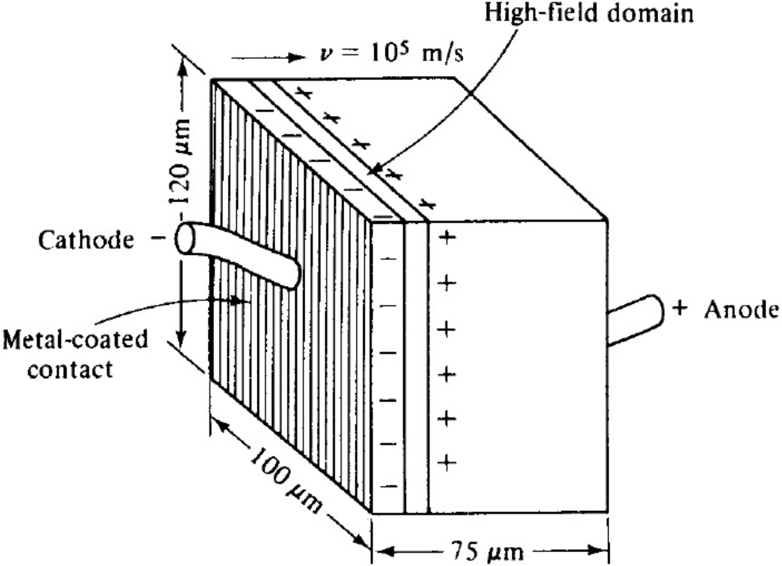
# Gunn diode

- Gunn diodes, also called transferred-electron devices (TEDs), are not diodes in the usual sense because they do not have junctions.
- A Gunn diode is a thin piece of N-type gallium arsenide (GaAs) or indium phosphide (InP) semiconductor which forms a special resistor when voltage is applied to it theoretically described by B. K. Ridley and T.B. Watkins in 1961 [RW61].
- In 1962, Hilsum predicted the possibility of transfer-electron amplifiers and oscillators
- In spite of Ridley-Watkins-Hilsum work, the transferred electron effect was named after an IBM researcher interested in the response of III-V semiconductors on pulsed voltages, J. B. Gunn.
- The Gunn diode exhibits a negative-resistance characteristic.
- Gunn diodes oscillate at frequencies up to 200GHz

# Gunn diode

- Slab of N-type GaAs (gallium arsenide) sandwitched between thin slides of highly doped N region.
- Has a negative-resistance region where drift velocity decreases with increased voltage
- This causes a concentration of free electrons called a domain
- The Gunn diode has an I-V characteristic that exhibits a negative differential resistance (negative slope) that can be used to generate
- RF power from DC.
- In 1962, independently Gunn observed a "noisy" resistance, measured as a function of the voltage, applying 704 V on a GaAs sample.

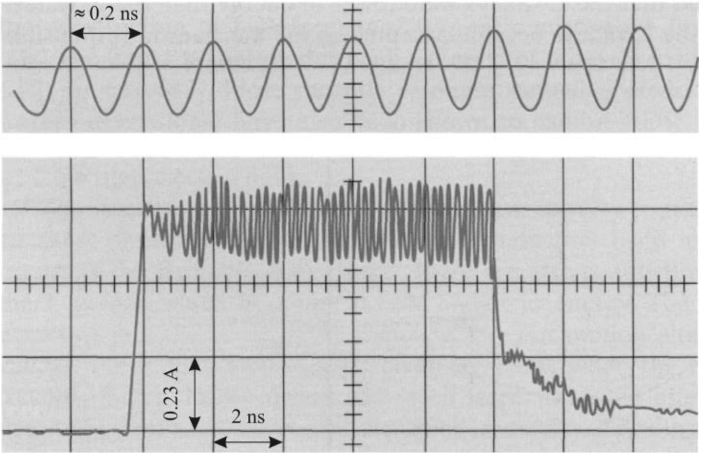
# Gunn diode



High-field domain
ν = 10^5 m/s
120 μm
Cathode −
Metal-coated contact
+ Anode
100 μm
75 μm

# Gunn diode

- In 1962, independently Gunn observed a "noisy" resistance, measured as a function of the voltage, applying 704 V on a GaAs sample.



# Transferred electron effect/Gunn effect

- According to transferred electron effect (or Gunn effect), the electrons in a high mobility lower energy level in the conduction band that is partially or fully filled get transferred to another low mobility, high energy level that is empty when the applied electric field or the applied voltage for a given semiconductor slice thickness exceeds a certain threshold value
- This electric field is 3.3KV/cm for **Gallium arsenide**
- Other semiconductor materials which exhibit this effect and which have been exploited for fabrication of practical Gunn devices include,

**Indium Phosphide (InP), Cadmium Telluride (CdTe), Gallium Arsenide,**

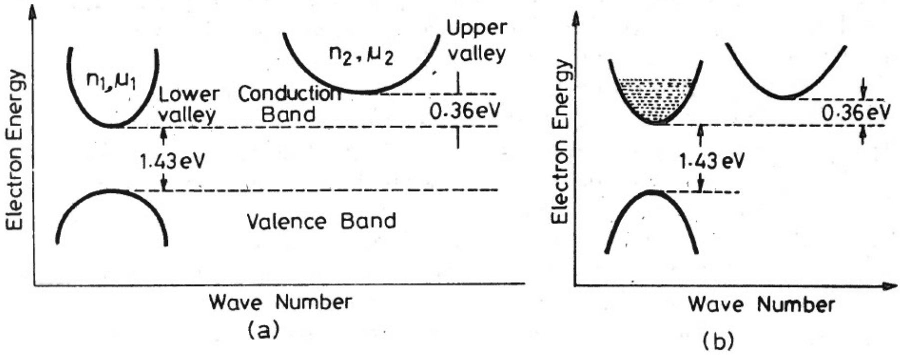
**Phosphide (GaAsP), Indium Arsenide (InAs) etc.**

# Transferred electron effect/Gunn effect

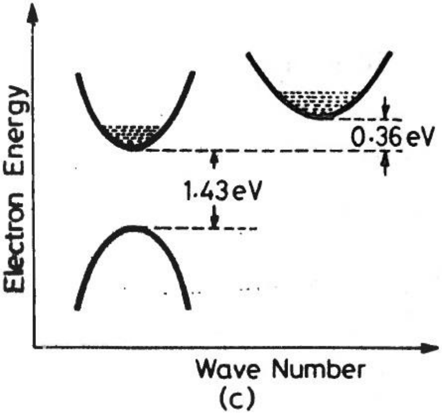
- Condition for Gunn effect to happen

1. Firstly, the semiconductor should have two energy sub-levels in the conduction band, one partially or fully filled and the other empty.
2. Secondly, the lower and upper energy levels involved in the transfer process should have a forbidden gap that is much smaller than the energy band gap of the semiconductor. Otherwise, the complete crystal structure of the device would probably get destroyed before any transfer of electrons could take place.
3. This gap is typically 0.36 eV in GaAs while its semiconductor band gap is 1.43 eV.
4. Thirdly, the electron mobility in the lower level should be much higher than the electron mobility in the upper level.

# Transferred electron effect/Gunn effect/Ridley-Watkins-Hilsum(RWH) theory

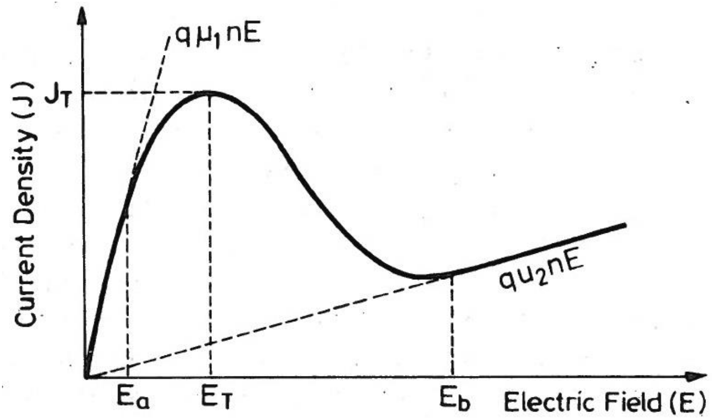


# Transferred electron effect/Gunn effect



# Transferred electron effect/Gunn effect

- The transferred electron effect leads to what is known as Negative Differential Mobility which further causes the current density to decrease for increasing electric field after it exceeds the threshold



# Transferred electron effect/Gunn effect

- When applied electric field E is less than the required threshold electric field ET , the electrons in the lower level move towards the positive end and contribute to current.
- Increasing field yields increasing current. This is the case of a normal positive resistance as shown in fig (b)
- When the field equals ET , the electron transport mechanism comes into play. The electrons move to a higher level having a much lower mobility with the result that current decreases as shown in fig(c)
- Further increase in electric field leads to further reduction in current as more and more electrons are transferred to the upper level
- Finally, the applied electric field reaches a value where all electrons are transported to upper level. Eventually, applied electric field is strong

# Gunn diode modes of operation

- The two main operational modes of Gunn diodes include

1. Gunn mode
2. Limited space charge accumulation mode

# Modes of operation-Gunn mode

- An excess charge distribution in a material exhibiting a positive resistance or conductance characteristics will always disperse due to mutual repulsion forces.
- This decay of excess charge is known as dielectric relaxation effect
- For the case where conductivity is negative, the dielectric relaxation phenomenon becomes a dielectric growth phenomenon i.e. any small perturbation in charge density grows instead of decaying
- Gunn diode when biased in the negative differential conductivity region.
- A space charge domain nucleated at the cathode travels towards the anode under the influence of the electric field.

# Modes of operation-Gunn mode

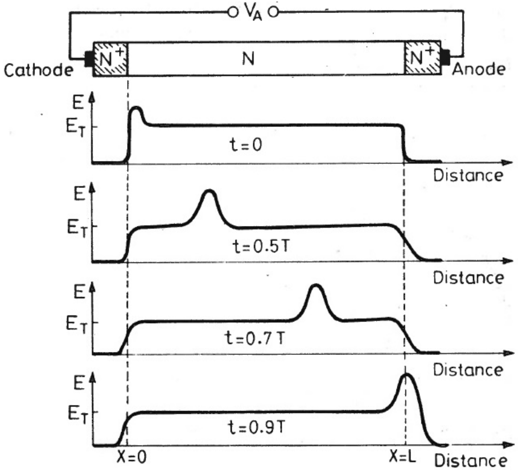
- As it travels, it grows up exponentially due to the device being biased in the negative differential conductivity region.
- As a result, the electric field in the region outside the domain falls below the threshold.
- Formation of domain near the cathode can be explained as follows. The doping concentration in the semiconductor is never absolutely uniform. It is quite probable that some part near the cathode has less concentration.
- This region would therefore have less free electrons and hence less conductivity or higher resistance.
- This means that for a given applied voltage, this part has a higher mobility and therefore a higher probability of being the first to attain negative differential mobility.

# Modes of operation-Gunn mode

- Negative differential mobility leads to bunching of electrons as those which are behind catch up with the slower ones in the domain and the those which are ahead move faster and go further away
- This leads to formation of a domain.
- The domain grows up more and more as it moves towards the anode, this grown up more mature domain finally disappears at the anode.
- At this moment, when the domain is disappearing, the electric field again rises above the threshold and another domain is nucleated at the cathode.

# Modes of operation-Gunn mode

- Each time the domain disappears at the anode, it gives rise to a current pulse in the external circuit

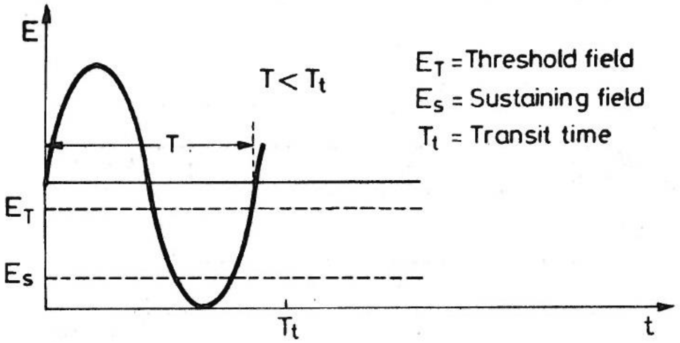


# Modes of operation-Gunn mode

- The frequency of oscillations in this mode is given by 'Vs/L' where Vs
- is the saturated drift velocity and L is the device length to be traversed by the domain.
- Two variations of the Gunn mode are the Quenched Gunn Mode and Delayed Gunn Mode
- These are obtained by enclosing the Gunn diode in a resonant cavity

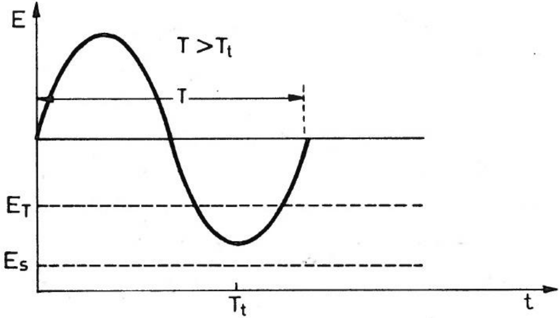
# Modes of operation-Gunn mode

- In the Quenched Gunn Mode, the RF voltage swing is large enough to extinguish a domain in transit itself at the voltage minimum of the RF cycle as shown in Fig
- In this mode, the domain never transits fully across the device length with the result that the operational frequency is higher than the frequency in the Gunn mode.



# Modes of operation-Gunn mode

- In the Delayed Mode, RF swing is large enough to keep the field below the threshold during the negative swing after a domain is exited
- Formation of a new domain is delayed with the result that operational frequency in this mode is lower than the Gunn mode frequency
- In both these modes, the operational frequency is decided by the resonant cavity and not the transit time.



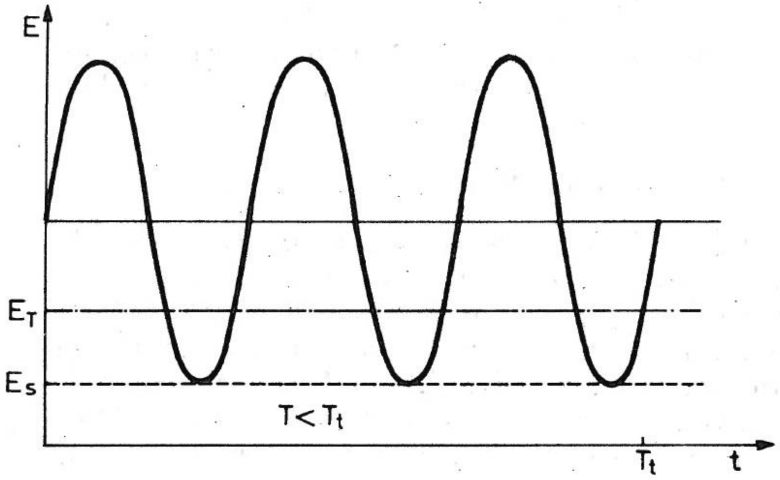
# Modes of operation-LSA mode

- The DC to RF conversion efficiency in Gunn modes is in the range of
- 1% to 5 %.
- One of the reasons for this low efficiency is that in the domain mode, when the domain is propagating, most of the device is below the threshold field
- The major part of the device thus, acts like a parasitic lossy resistance
- If the domain formation could somehow be prevented, the entire region could be made to participate in generation of power and as a result, efficiency would improve.
- In the LSA mode, RF has a large swing and a time period that is small as compared to dielectric growth time.

# Modes of operation-LSA mode/LSA diodes

- The peak to peak amplitude of RF is such that for most of the time it is in negative conductivity region and it swings below the threshold field for small part of the RF cycle
- The amount of space charge that can accumulate during the time the device is in negative conductivity region is limited.
- While the field is below the threshold, the limited space charge gets dispersed due to relaxation effect
- Since LSA mode does not depend for its operation on the transit time effects, the device can have a long active region with the result that very large pulse powers of the order of hundreds of watts can be achieved from a single large chip

# Modes of operation-LSA mode/LSA diodes



# Introduction ATT

- The family of transit time microwave devices depend for their operation on two mechanisms namely the generation of charge carriers and the movement of these charge carriers through a drift space within the semiconductor.
- Different devices belonging to this family can be distinguished from one another on the basis of the mechanism used for generation of charge carriers.
- The prominent members of this family include the IMPATT and TRAPATT diodes, BARRITT diode, TUNNET diode and so on.
- The IMPATT (Impact Ionization Avalanche Transit time) diode, as the name suggests, utilizes impact ionization for carrier generation.

# Introduction ATT

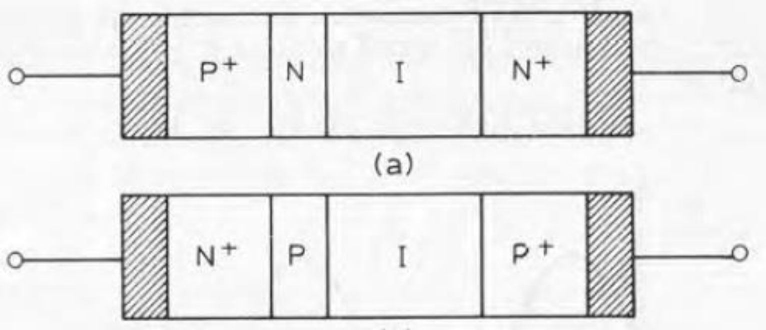
- TRAPATT (Trapped Plasma Avalanche Triggered Transit time) diode is derived from the Impatt with some modifications in the doping profiles so as to achieve higher pulsed microwave powers at better efficiency values.
- Impatts and Trapatts are relatively noisier but are capable of high CW and pulsed powers at reasonably good efficiencies with Trapatt having an edge in terms of pulse operational efficiency.

# IMPATT

- The IMPATT diode depends for its operation on the generation of charge carrier by impact ionization in a certain small region around a reverse biased PN junction in a semiconductor material and the subsequent transit of these carrier through a drift region within the semiconductor.
- Silicon and Gallium Arsenide are the semiconductor materials favored for microwave IMPATT diodes.
- The device exhibits a dynamic negative resistance across its terminals which is exploited for its use in amplifiers and oscillators in the microwave and millimetre wave region.
- The IMPATT diode utilises the delay inherent to the phenomenon of carrier generation by impact ionisation leading to an avalanche and also the transit time delay to achieve the phase difference of 180 degree between the input RF excitation voltage and the terminal current pulse.

# IMPATT

- Fig. shows two possible device structures originally proposed by Read for fabricating an IMPATT diode, in both types, there is a PN junction and the avalanche action takes place in a very small region around the reverse biased junction.
- Also, there is a single drift space through which, the avalanche multiplied charge carriers have to drift to reach the device cathode.



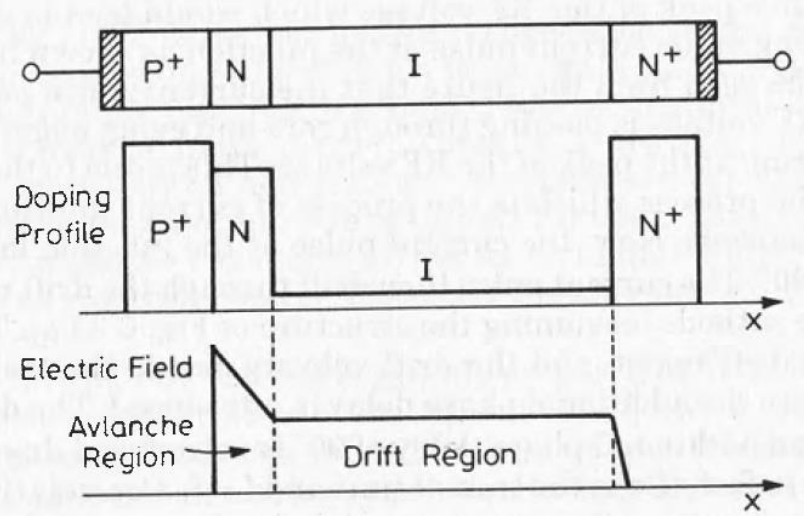
# IMPATT

- When the device is sufficiently back biased so as to produce a reverse electric field of hundreds of kilovolts per cm (typically 400 KV/cm), the minority carriers crossing the junction acquire so much energy that they are able to knock out more electrons and holes from the crystal structure, the process being called Impact ionisation.
- The process of impact ionisation leads to multiplication of charge carriers in what is known as an avalanche condition.
- The IMPATT diode is so fabricated as to be able to withstand such a high voltage gradient across the junction.
- In the actual operation, the device is back biased so as to be at the threshold of an avalanche to develop.

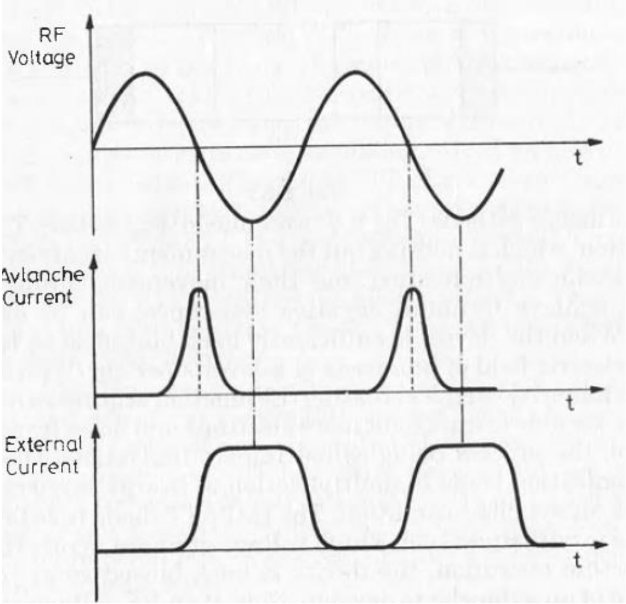
# IMPATT

- Now, if an RF voltage exists across the junction, then the avalanche would set in at the positive peak of this RF voltage which would lead to generation of a high peak value current pulse at the junction.
- The current pulse peak occurs when the RF voltage is passing through zero and going negative rather than occurring at the peak of the RF voltage. This is due to the fact that the avalanche process which is the process of current multiplication is not instantaneous.
- Now, the current pulse at the junction lags the RF voltage by 90degree.
- The current pulse then drift through the drift region and reaches the cathode
- The thickness of the drift region and the drift velocity decide the transit time. And therefore the additional phase delay is introduced. The device is so made that an additional phase delay of 90 degree is introduced due to transit time effect.

# IMPATT


P+
N
I
N+
Doping
Profile
P+
N
N+
I
x
Electric Field
Avlanche
Region
Drift Region
x

# IMPATT

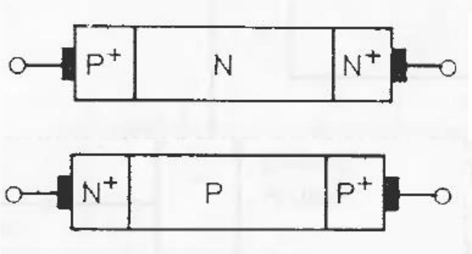


# IMPATT-Applications

1. IMPATT diodes are used as microwave oscillators and amplifiers over a frequency range extending well into millimetre wave range.
2. For single drift versions, CW output powers may vary from 20W at a few GHz to about 50mW at 200 GHz.
3. Efficiency varies from 10% to 20% up to a few tens of GHz reducing to 1% at 200 GHz
4. Pulsed output powers are still higher
5. Double drift versions produce greater powers at higher efficiencies.

# TRAPATT

- TRAPATT (Trapped Plasma Avalanche Triggered Transit Time) diode is similar to IMPATT diode in structure and is usually of P+NN+ or N+PP+ type.
- The device is back biased into avalanche like the IMPATT.




- The difference between the two lies in the mechanisms of avalanche initiation and carrier drift.
- A TRAPATT in operation is placed in a high resonant cavity and back biased to avalanche threshold.

# TRAPATT-Operation

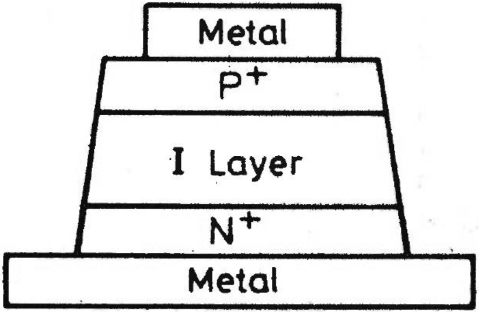
- When the RF oscillations begin, they build up extremely rapidly due to the resonant structure thus taking the voltage across the diode to a value much above the avalanche threshold
- The result is generation of a conducting plasma of holes and electrons which rapidly fills the entire drift zone
- As a consequence of this, the voltage across the diode falls which does not allow the carriers in the plasma to escape as quickly as they would have in case of IMPATT operation where there is a high electric field in the drift region.
- The charge carriers are said to be trapped and hence the name trapped plasma.
- The carriers are now able to drift with a relatively much lower velocity due to the residual electric field.
- As they reach the device electrode, they constitute a large current.

# TRAPATT-Operation

- When the entire plasma is extracted, the voltage again rises above the avalanche threshold and another cycle is initiated.
- TRAPATT diode is essentially a pulsed device capable of operating at much larger pulse powers as compared to IMPATTs
- The operating frequencies are however much lower Also, they are noisier than IMPATTs.
- Pulse powers of kilowatt level have been achieved at frequencies around 10 GHz with effciency approaching 25%.

# PIN diode

- A PIN diode consists of a heavily doped P-type semiconductor material (P+) and a heavily doped N-type semiconductor material (N+) separated by a layer of extremely high resistivity intrinsic semiconductor material
- Fig. shows the cross sectional view of a typical PIN diode.

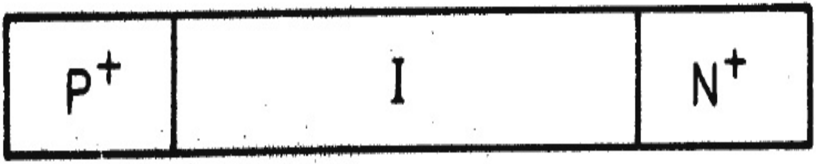


# PIN diode

- A more practical definition of a PIN diode calls it a semiconductor diode which consists of two heavily doped P and N regions separated by substantially higher resistivity P or N region.
- This leads to two types of PIN diode structures.
- The first is the one of heavily doped P and N regions separated by an unusually lightly doped P-type intrinsic layer (also referred to as π-type) and the other is heavily doped P and N regions and a layer of lightly doped N-type intrinsic material (also referred to as v-type) sandwiched between the two.
- Except that in case of the former the semiconductor junction occurs at the N+ interface and in case of the latter, it occurs at P+ interface, there are no other major performance differences.

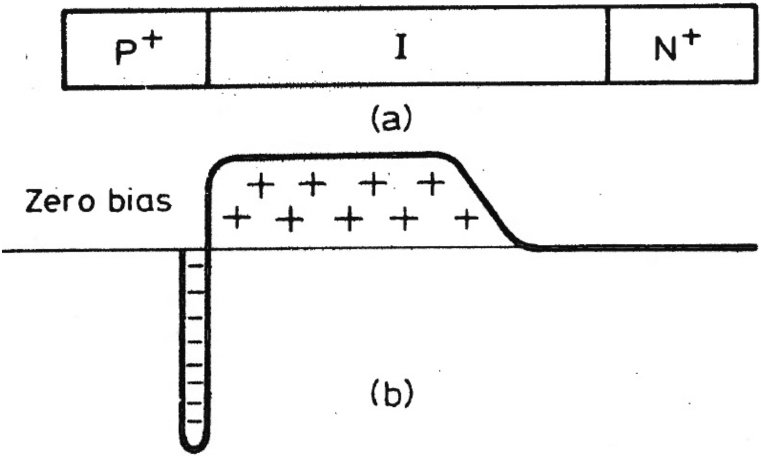
# PIN diode - Operation

- When a practical PIN diode is unbiased (zero bias), a small region around the junction will be depleted of charge carriers and since l-layer is very-lightly doped, a major portion of I-layer will be depleted and the depletion zone extends very little into the heavily doped semiconductor region.
- Fig. shows the phenomenon in case of a PIN diode using a v-type I-layer.



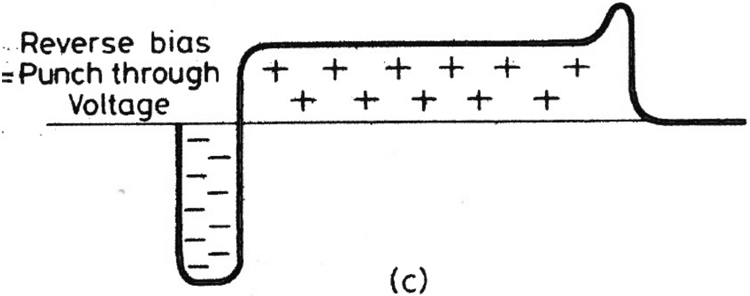
# PIN diode - Operation

- Fig.(b) shows the ionised impurity profile for a zero bias.



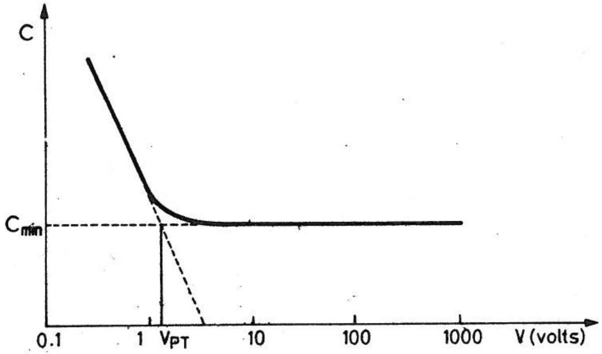
# PIN diode - Operation

- As the reverse bias voltage is increased, the depletion zone extends rapidly into the I-layer due to its light doing level and very slowly into the P+ region.
- At a sufficient reverse bias level equal to Punch Through Voltage, I-layer is completely depleted of charge carriers as shown in Fig. c producing a nearly open circuit across the device terminals.



# PIN diode - Operation

- The other relevant parameter with the PIN diode under reverse bias is the junction capacitance.
- The junction capacitance decreases as the reverse bias increases due to widening of the depletion zone.
- It reaches its minimum value at the punch through voltage beyond which it remains constant.



# PIN diode - Operation

- As is clear from the curve, the characteristics have a soft knee. The punch through voltage, by convention, is the voltage corresponding to two straight line projected slopes as shown.
- It may be mentioned here that such a Capacitance versus Voltage characteristics would be obtained if the measurements are done at a relatively low frequency, typically 1 MHz.
- At microwave frequencies, the junction capacitance would be constant and equal to Cmin irrespective of the applied reverse bias voltage.
- This is due to the reason that silicon has a high dielectric constant and its dielectric susceptibility at microwave frequencies is much larger than the conductivity of either ν-type or π-type intrinsic material

# PIN diode - Operation

- The frequency at which the two equal is called dielectric relaxation frequency of the material.
- At an operating frequency equal to or more than three times this frequency, the junction capacitance is constant at Cmin to irrespective of reverse bias voltage.
- The junction capacitance offered by a PIN diode at microwave frequencies is particularly important when it is to be used for microwave switching applications
- The PIN diode capacitance measured at a low frequency such as 1 MHz to a good approximation represents the effective capacitance at microwave frequencies provided that while making low frequency test, it should be ensured that the supplied reverse bias fully depletes the I-layer

# PIN diode - Operation

- Under forward bias, the PIN diode principally behaves as an electrically variable resistor.
- When increasing forward bias is applied, more and more charge carriers (Holes from P+ and Electrons from N+ regions) are injected into the I-layer thus decreasing its resistivity.
- This conductivity modulation by a varying forward bias is made use of in its application as a variable attenuator.