19ECCN1701 – RF and Microwave Engineering

Unit III – Microwave Solid State Devices

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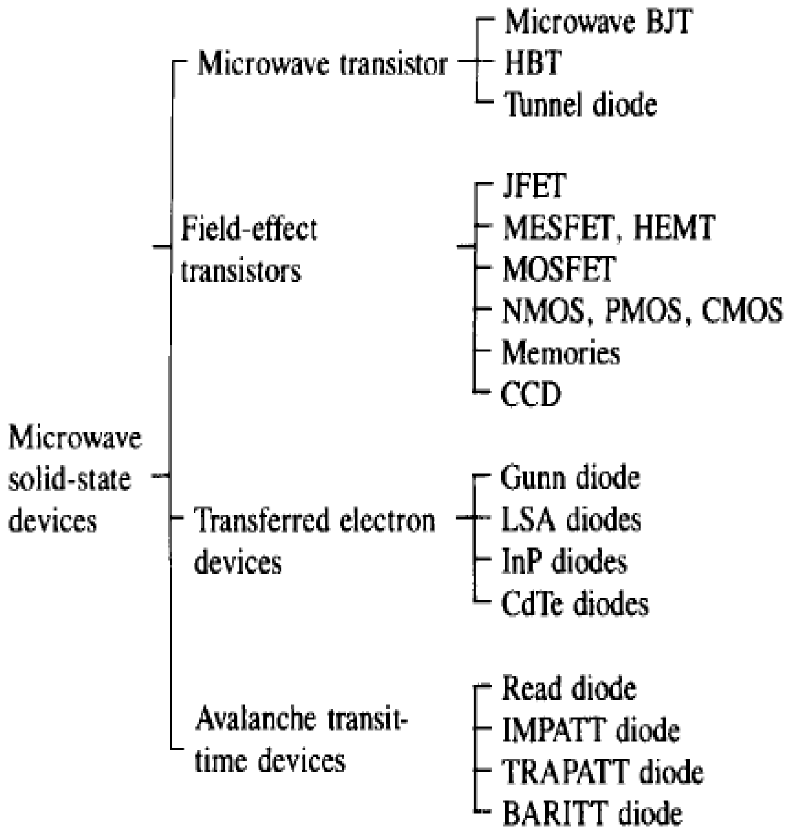
Microwave Solid State Devices

- Microwave solid-state devices are becoming increasingly important at microwave frequencies.
- These devices can be broken down into four groups.



Applications of Microwave Solid state 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

Microwave Bipolar Transistors

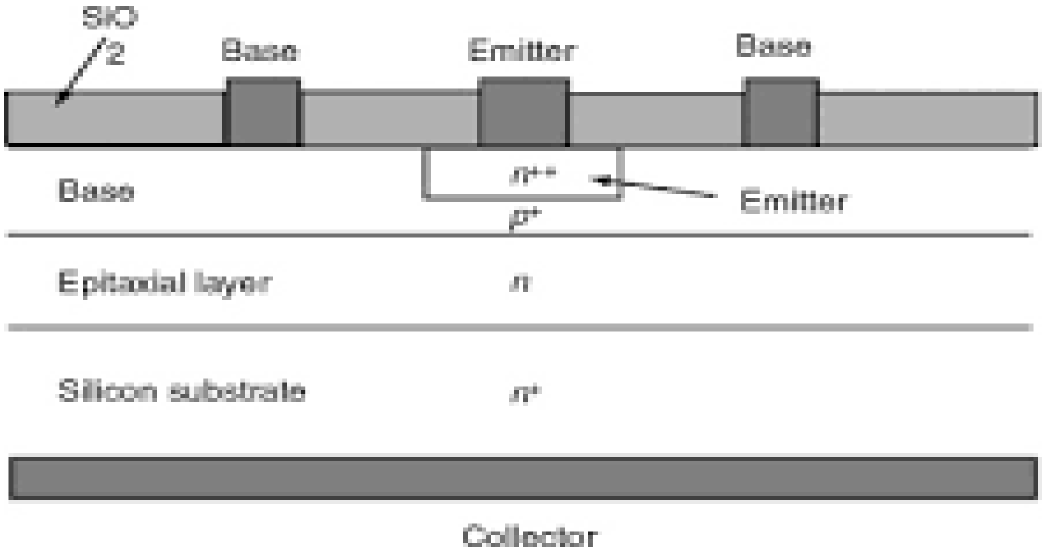
- The Microwave transistor is a non linear device and its principle of operation is similar to that of the low frequency device, but requirements for dimensions, process control, heat sinking and packaging are much severe.
- For microwave applications, the silicon bipolar transistors dominate for frequency range from UHF to about S band (about 3 GHz).
- All the present time devices are capable of producing useful power up to 22 GHz.

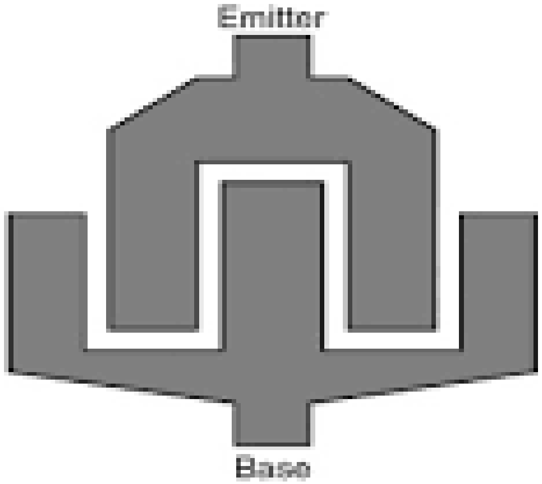
Microwave Bipolar Transistors

- The Si bipolar transistor is inexpensive, durable, integrative and offers gain much higher than available with competing field effect devices.
- It has moderate noise figure in RF amplifiers and 1/f noise characteristics that are about 10-20 dB superior to GaAs MESFETs.
- For these reasons, the Si bipolar transistors dominate in amplifier applications for the low microwave frequencies and are often the devices of choice for local oscillations.

Construction of Microwave Bipolar Transistors

- A typical bipolar construction is shown below, in which the Epitaxial n layer is formed by condensing a single crystal film semiconductor material upon a low resistivity Si wafer of substrate n^+
- Above this, a p type diffused base and n^+ type diffused emitter are formed.





Microwave Bipolar Transistors

- Typically the emitter width is 1 micron, base thickness is 2 microns and emitter length is 35 microns.
- In general, the transit time can be reduced by using narrow p and n regions, especially the base.

Microwave Bipolar Transistors

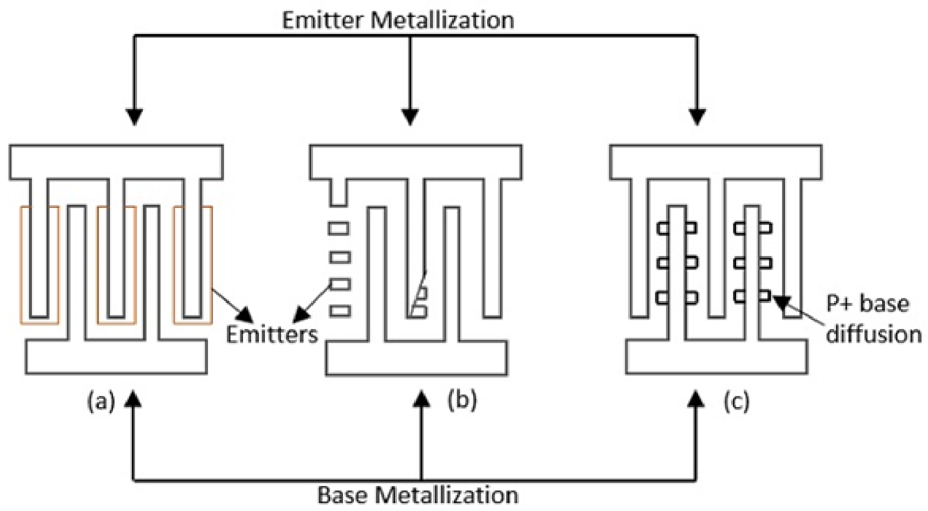
- The transit time can also be reduced by reducing the depletion layer width at the reverse-biased collector base junction.

- The cut of frequency of the device is given by,

$$f_T = \frac{1}{2\pi T} \; at\, which\, current\, gain = 1$$

Physical Structures

- All microwave transistors are now planar in form and almost all are of the silicon n-p-n type. The geometry can be characterized as follows,
  a. Interdigitated
  b. Overlay and
  c. Matrix (mesh or emitter grid)

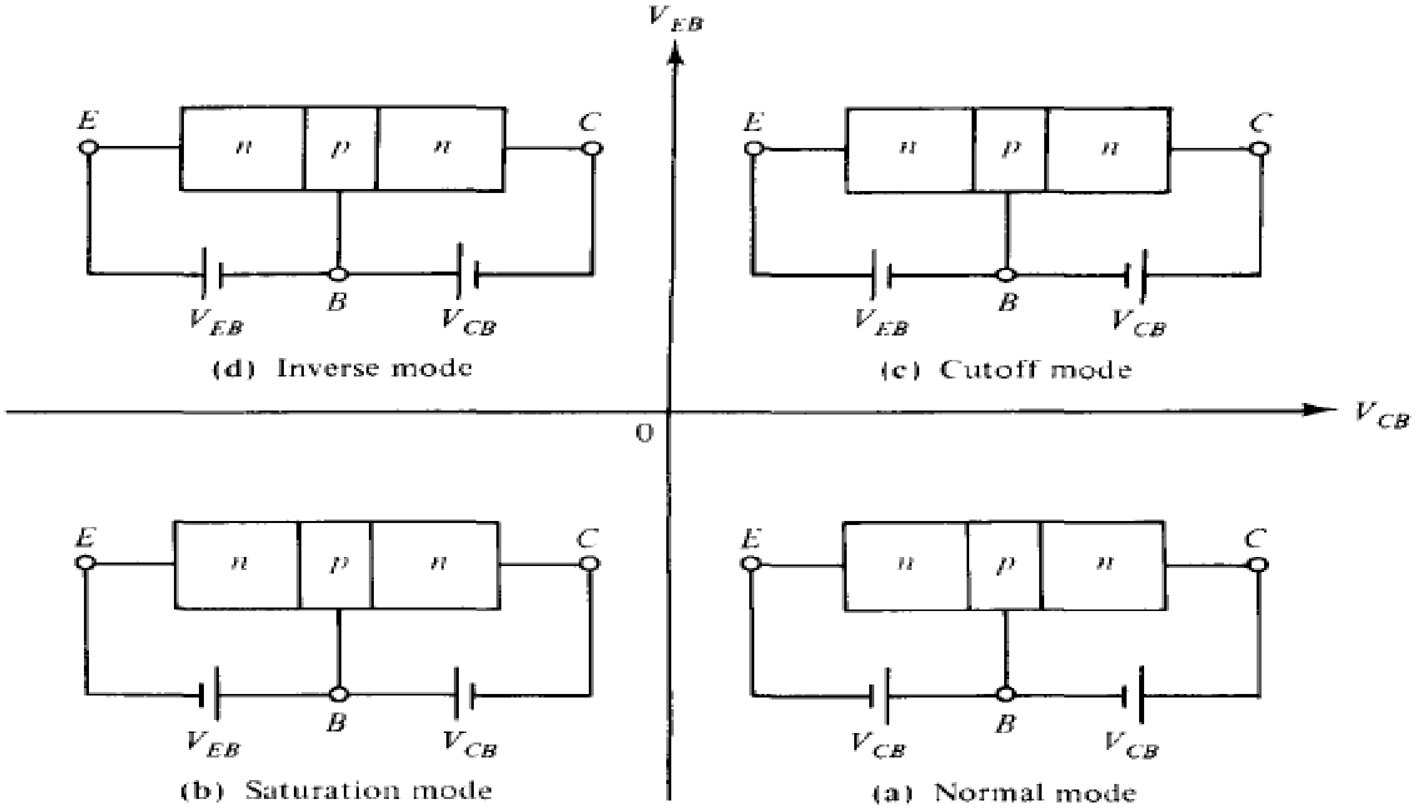


Surface geometry of n-p-n microwave transistor
(a) Inter-digitated (b) Overlay (c) Matrix

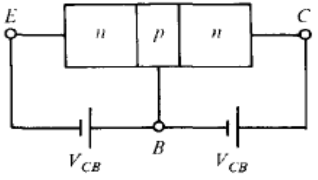
Principles of Operation

- The bipolar junction transistor (BJT) is an active three-terminal device which is commonly used as an amplifier or switch.
- A bipolar transistor can operate in four different modes depending on the voltage polarities across the two junctions:
    1) Normal (active) mode
    2) Saturation mode
    3) Cutoff mode
    4) Inverse (or inverted) mode

Principle of Operation



Principle of Operation: (1) Normal Mode

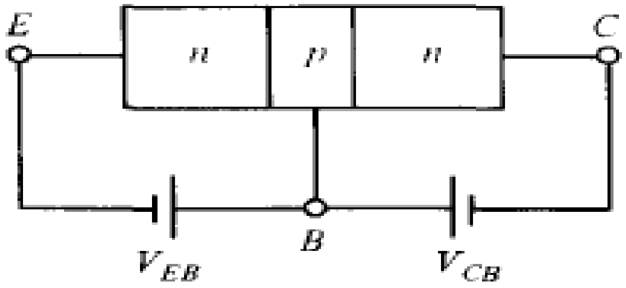


(a) Normal mode

- If the emitter junction of an n-p-n transistor is forward-biased and the collector is reverse-biased.
- The term forward bias means that the positive polarity of the bias voltage is connected to the p side and the negative polarity to the n side for a p-n junction; the opposite obtains for reverse bias.
- Most transistor amplifiers are operated in normal mode, and its common-base current gain alpha is known as the normal alpha α_N

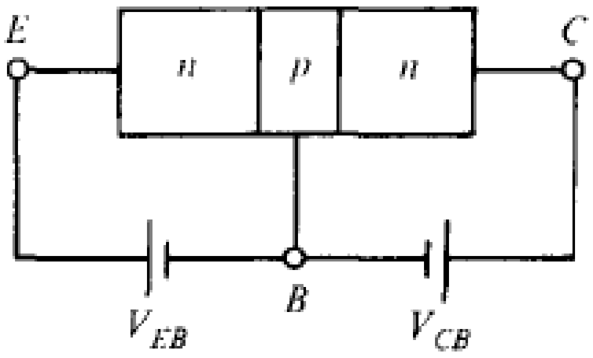
Principle of Operation: (2) Saturation Mode

- When both transistor junctions are forward-biased, the transistor is in its saturation mode with very low resistance, and acts like a short circuit



(b) Saturation mode

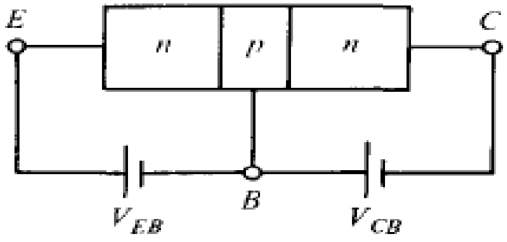
Principle of Operation: (3) Cutoff Mode



(c) Cutoff mode

- If both transistor junctions are reverse-biased the transistor is operated in its cutoff mode.
- As the current is cut off, the transistor acts like an open circuit.
- Both the cutoff and saturation modes of a transistor are used as switching devices for the OFF and ON states

Principle of Operation: (4) Inverse Mode



(d) Inverse mode

- When the emitter is reverse-biased and the collector is forward-biased, the transistor is operated in the inverse (or inverted) mode, and its current gain is designated as the inverse alpha α_I .
- If the transistor is symmetric, the *normal alpha* α_N is nearly equal to the inverse alpha α_I. The two current gains, however, are not actually equal because of their unequal dopings.
- In practice, the inverse mode is not commonly used except as a multimeter transistor in TTL (transistor-transistor logic) logic gate.

Heterojunction Bipolar Transistor (HBT)

- The Heterojunction Bipolar Transistor (HBT) is a type of bipolar junction transistor (BJT) that uses a different type of semiconductor material for the emitter and base regions, creating a heterojunction.

There are two versions of HBT,

- Single Heterojunction Bipolar Transistor (SHBT)
- Double Heterojunction Bipolar Transistor (DHBT)

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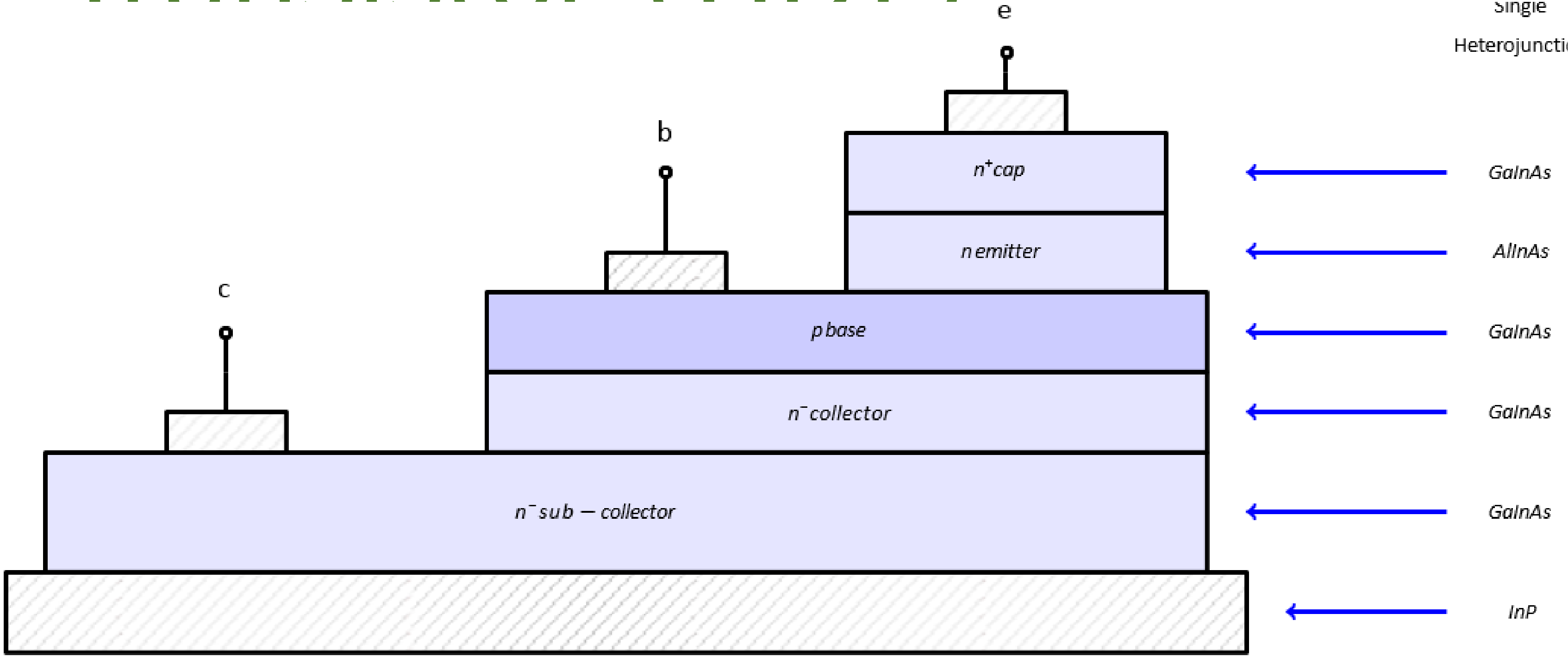
Heterojunction Bipolar Transistor (HBT)

Single

Heterojunction



Metal-Semiconductor Field Effect transistor (MESFET)

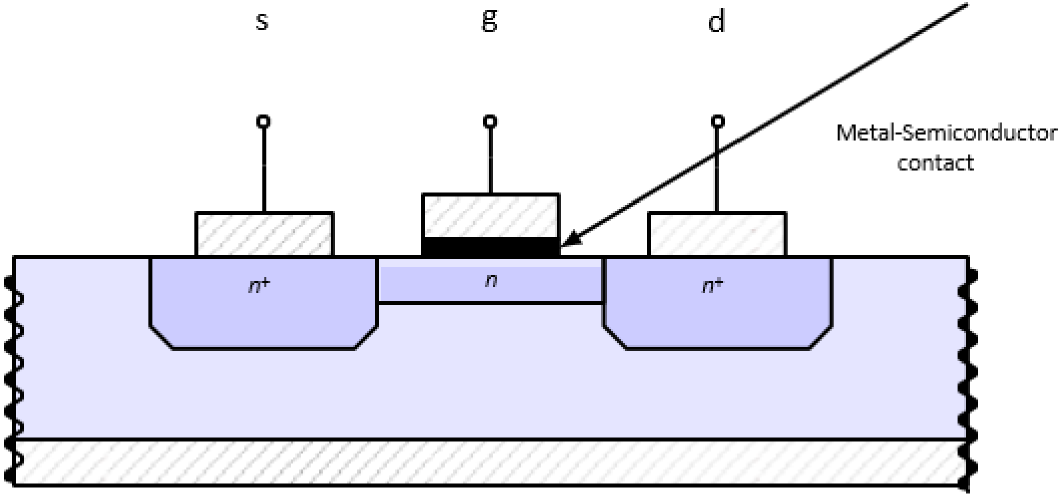


Figure : Conceptual MESFET cross-section

The device consists of a channel of semiconducting material positioned between source and drain regions. The carrier flow from source to drain is controlled by the voltage applied to the gate electrode.

Metal-Semiconductor Field Effect transistor (MESFET)

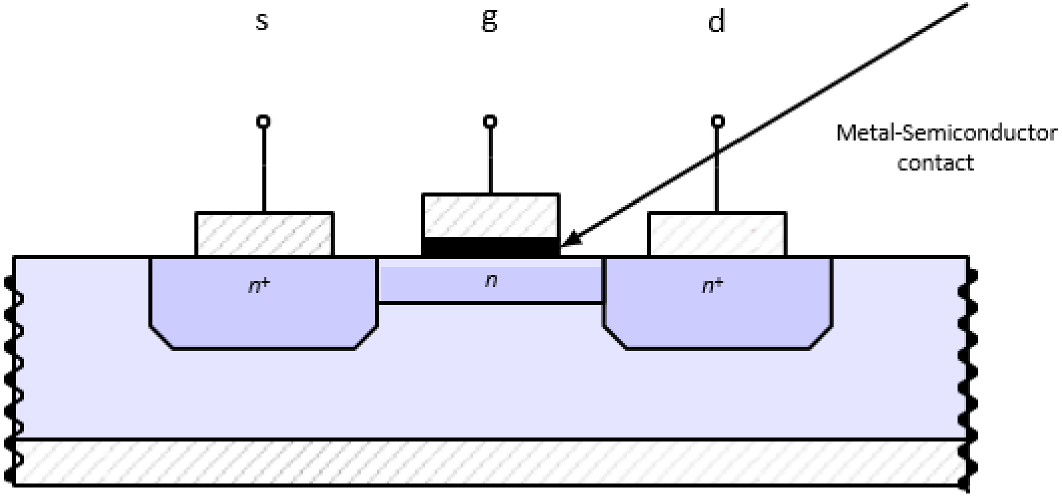


Figure : Conceptual MESFET cross-section

The controlled current flows only through the thin n-type channel between the two highly doped n+ regions, meaning that MESFETs are unipolar devices.

Metal-Semiconductor Field Effect transistor (MESFET)

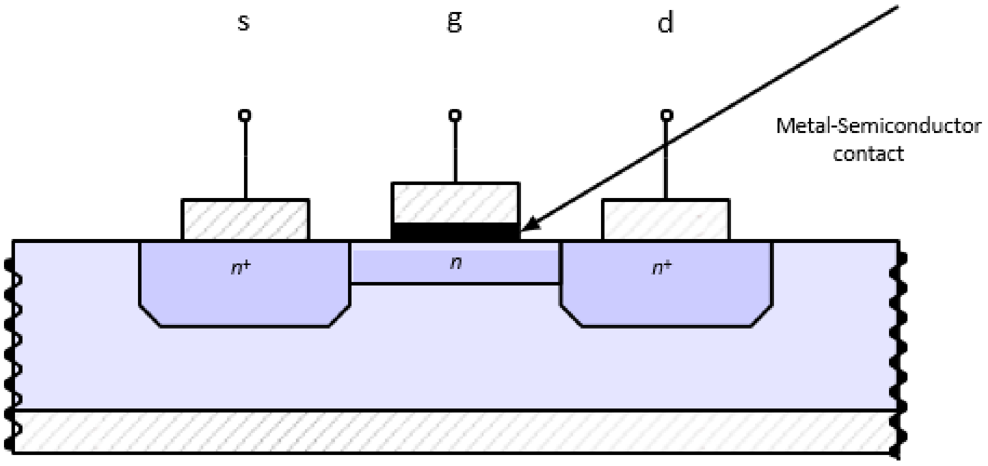


Figure : Conceptual MESFET cross-section

The main advantage of a unipolar device is that the the charge storage phenomenon seen in the base region of a conventional BJT is eliminated.

Metal-Semiconductor Field Effect transistor (MESFET)

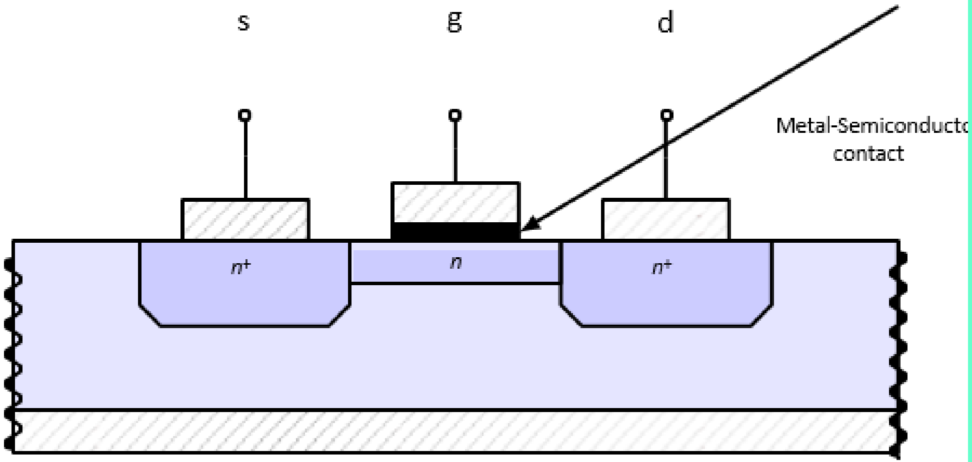


Figure : Conceptual MESFET cross-section

It is this charge storage which primarily limits the high frequency performance of bipolar devices. The control of the channel is effected by varying the depletion layer width underneath the metal contact which modulates the thickness of the conducting channel and thereby the current between source and drain.

High Electron Mobility Transistors (HEMT))

The High Electron Mobility Transistors (HEMT) is basically the heterojunction approach applied to the MESFET topology

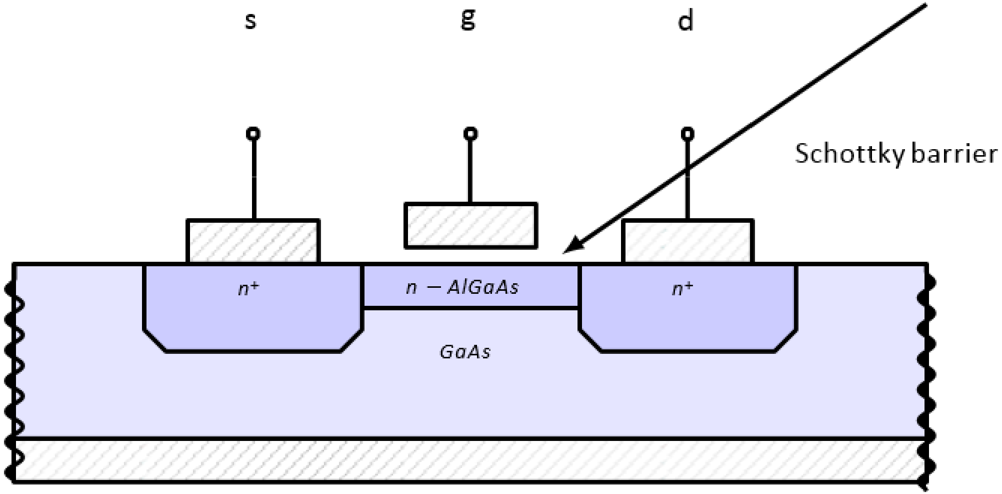


Figure :Conceptual HEMT cross-section

High Electron Mobility Transistors (HEMT))

This means that the channel region of the FET is constructed of two materials with different band gaps instead of a doped region of single material in the case for the simple MESFET, an approach known as *modulation do*

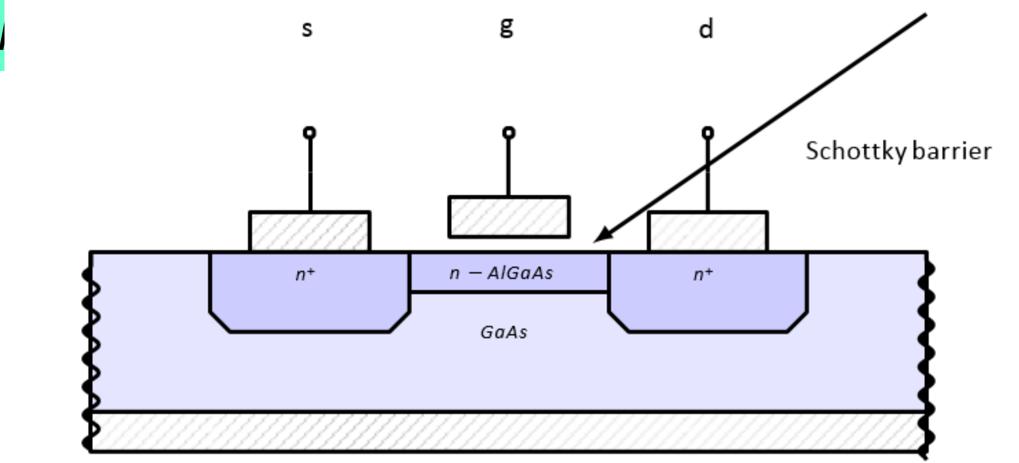


Figure :Conceptual HEMT cross-section

High Electron Mobility Transistors (HEMT))

The heterojunction approach results in higher electron mobility in the channel, allowing the device to respond to rapid changes in the gate voltage.

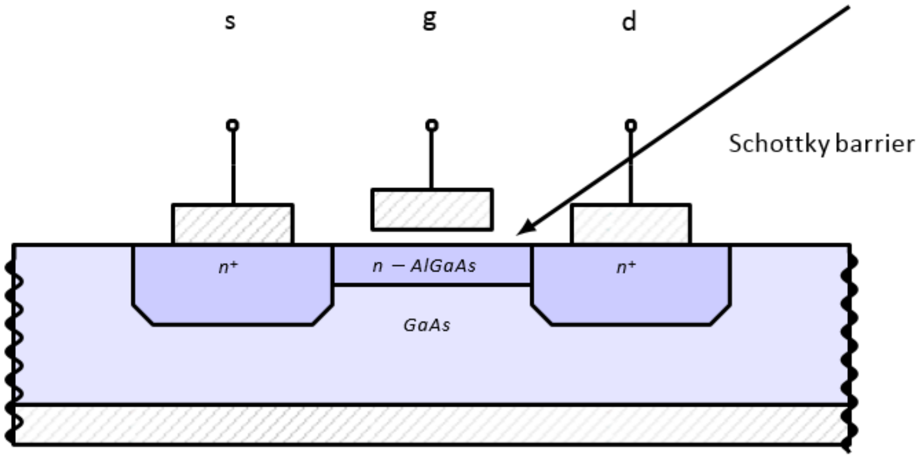


Figure :Conceptual HEMT cross-section

HEMT

- High Electron Mobility Transistor - Similar to GaAsFET construction
- Difference is that motion of charge carriers is confined to a thin sheet within a GaAs buffer layer - GaAs/AlGaAs heterostructure epitaxy.
- The thickness of the channel remains constant while the number of carriers is modulated by the gate bias as opposed to a MESFET that modulates the channel thickness.
- PHEMT- Pseudomorphic HEMT used above 20 GHz (mm wave)

Transferred Electron Devices

Microwave transistor

- Operate with either junction or gates
- Elemental semiconductor are Silicon and germanium
- Transistor

Transferred electron devices

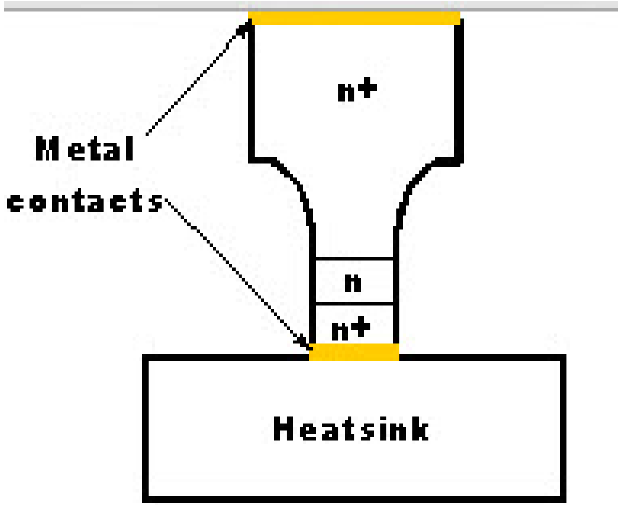
- Bulk devices with no junction or gates
- GaAs, InP, Cd Te.GaN
- Transistor

Gunn Diode

- Negative Resistance Device
- by J.B.Gunn in 1963,discovered
  - A periodic fluctuations of current passing through the n type gallium arsenide specimen when applied voltage exceeds a certain critical value
- Low power oscillators in micr
- Local oscillators in microwav
  front end
- Source of microwave signal
  in laboratory

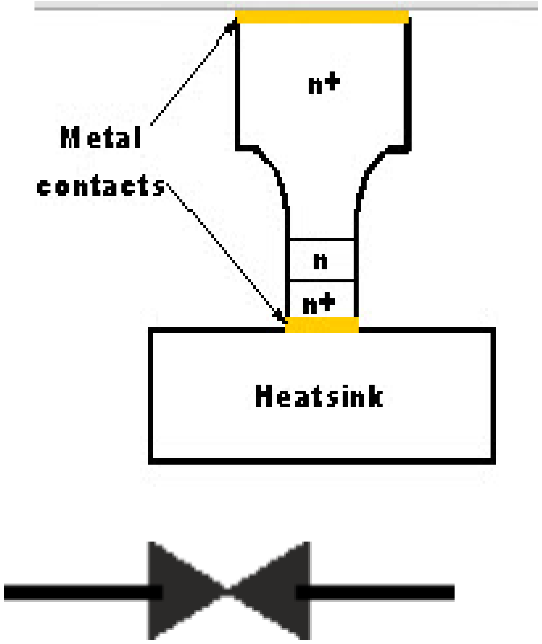
Difference b/w Gunn and Tunnel Diodes

- Bulk devices in sense that microwave amplifications and oscillations are derived from the bulk negative resistance property of uniform semiconductors rather than from the junction negative resistance property between two different semiconductors, as in tunnel diode



Difference b/w Gunn and Tunnel Diodes

- Gunn Diode is also known as Transfer Electron Device.
- Even though it is called as a diode it does not contain PN junction.
- Gunn diodes are fabricated from a single piece of n-type semiconductor



Gunn Diode

only applicable to electrons and not to holes

- The most common method of manufacturing a Gunn diode is to grow and epitaxial layer on a degenerate n+ substrate. The active region is very thin and its thickness is between a few microns and a few hundred

How to achieve negative mobility ?

- In bulk semi conductors by transferring electrons from high mobility energy band to low mobility energy bands –[Ridley and Watkinson]

- The careful calculation of transferred electron effect in several III-V compounds; TEOs & TEAs- [Hilsum]

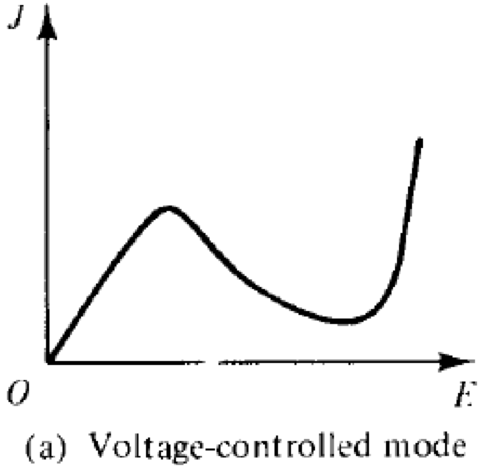
- Gunn effect from thin disks of n type GaAs and n type InP specimens [J.B.Gunn]

How to achieve negative mobility ?

- The field domain is continuously moving through the crystal, disappearing at the anode and then reappearing at a favored nucleating centre, and starting the whole cycle one more [Ridley]

- Kromer stated that the origin of negtaive differential mobiltiy is Ridley-watkinson-Hilsum's mechanism of electron transfer into the satellite valleys that occur in the conduction bands of both the n type GaAs and the n type Inp.

RWH Theory



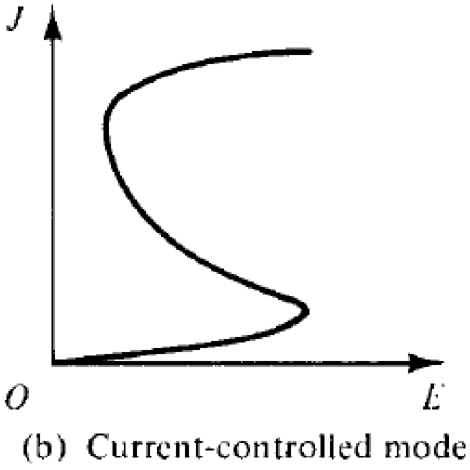
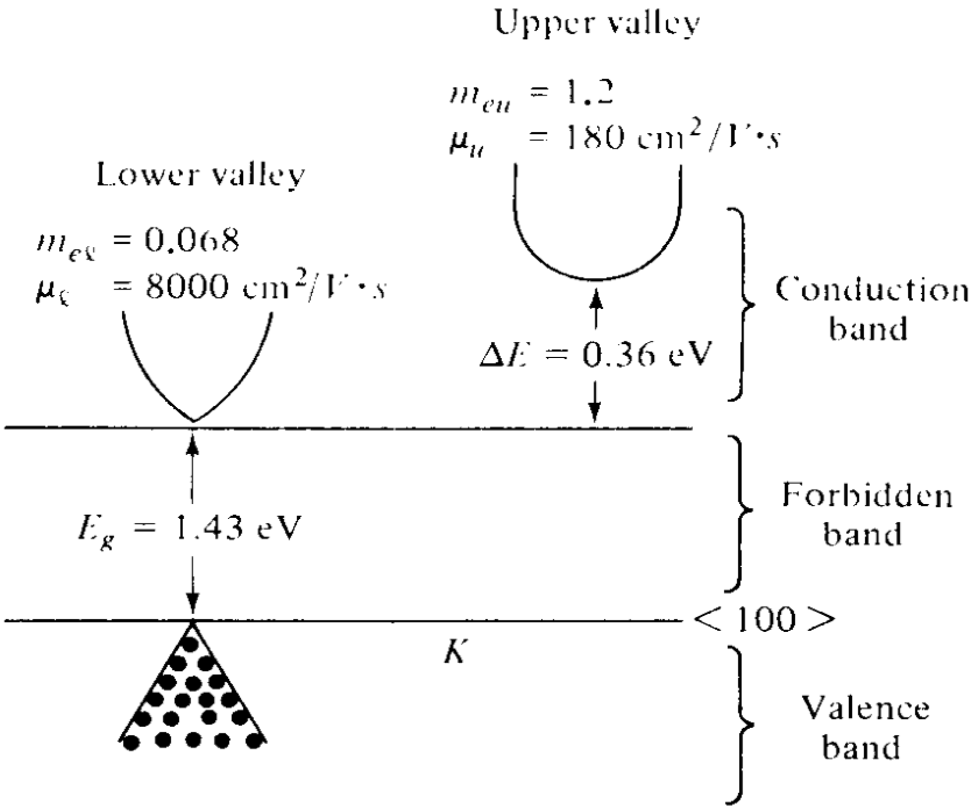
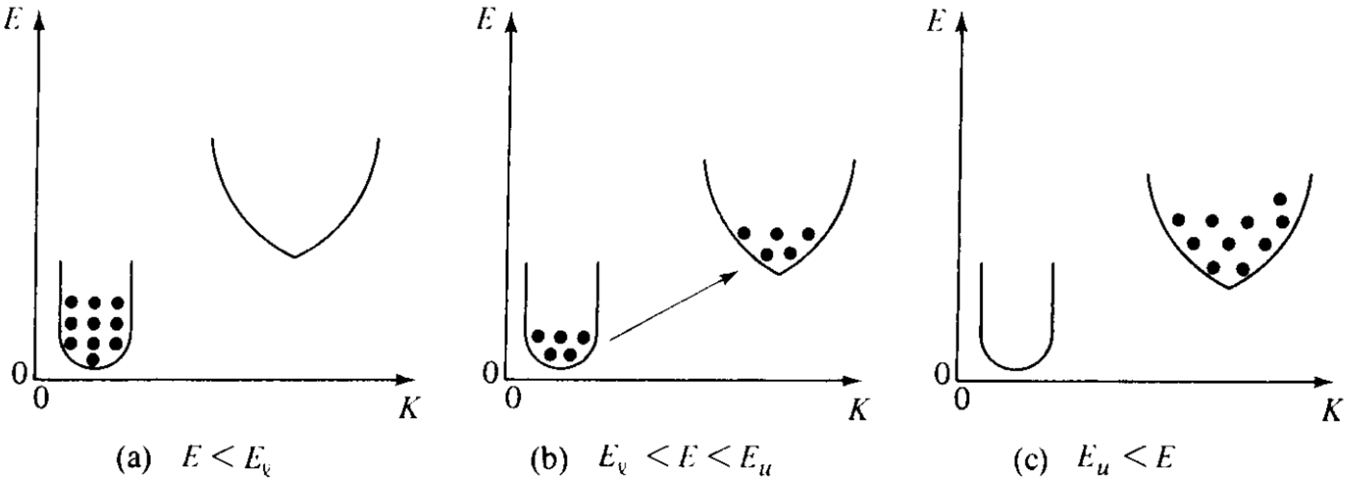


Diagram of negative resistance.

Two Valley Model Theo

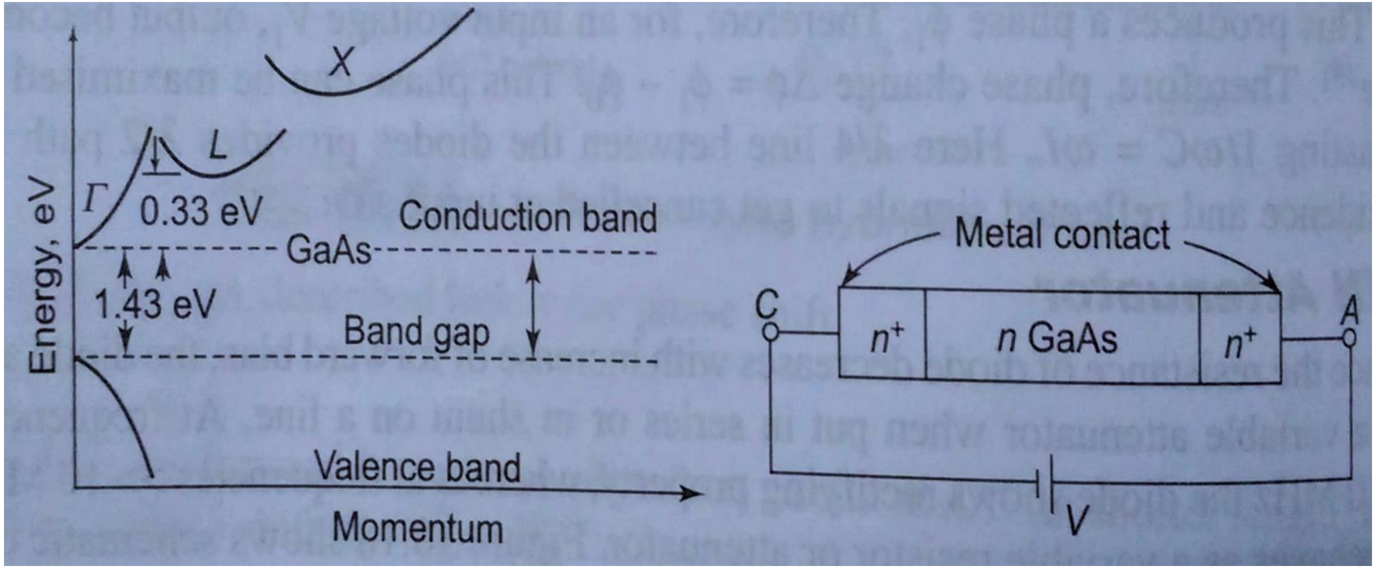


Two Valley Model Theory



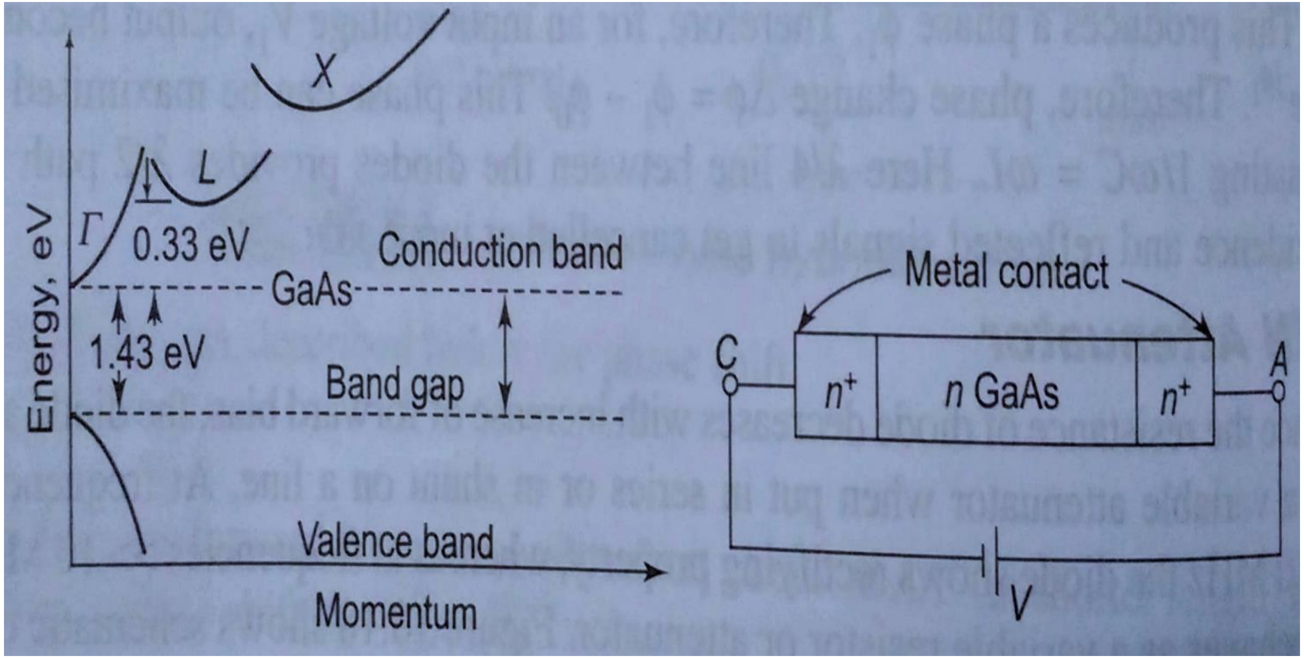
Multiple energy Valley

- Some semiconductors have closely spaced multiple energy valleys in the conduction band
- GaAS, CdTe and InP



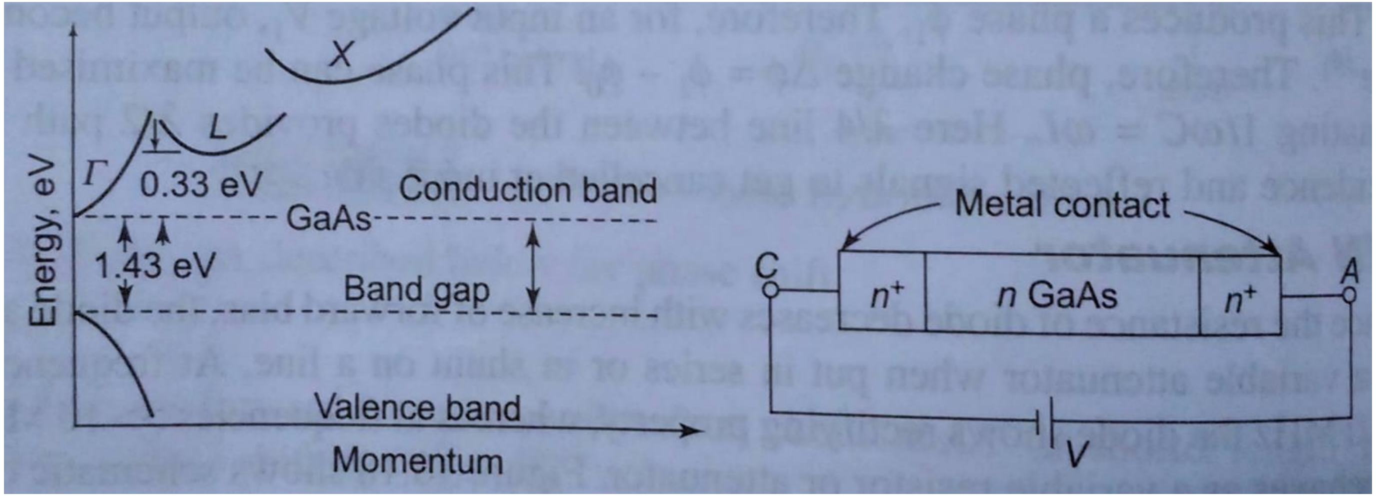
Multiple energy Valley

- When dc bias applied across the material, an electric field established across it.



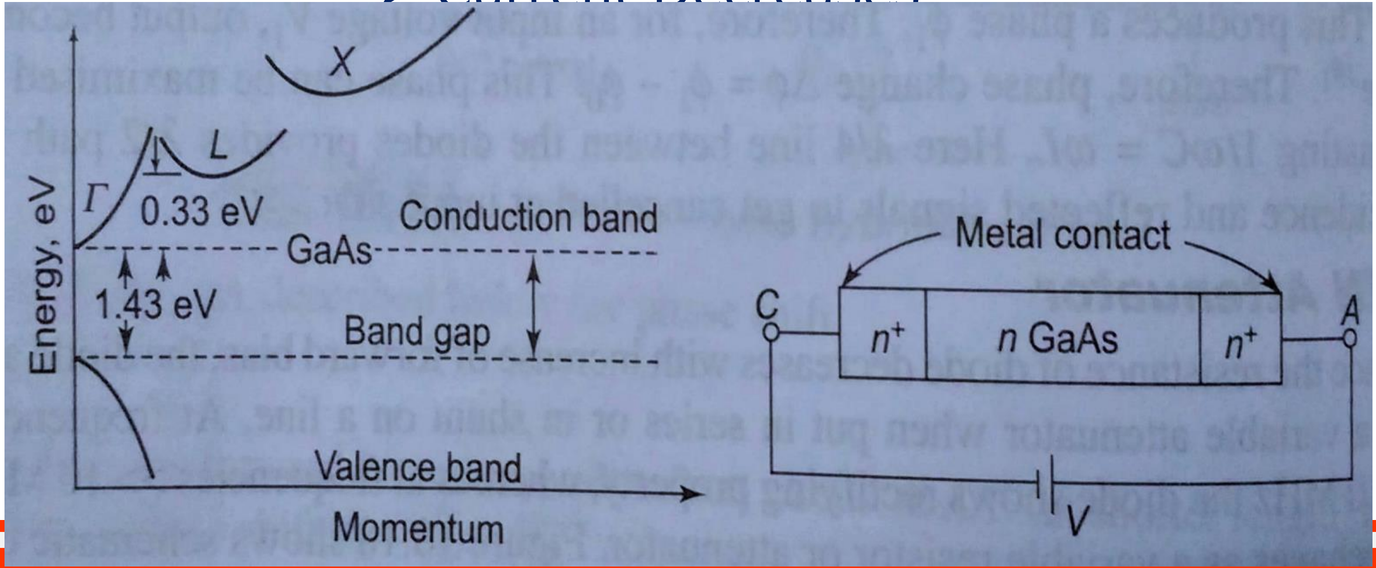
Multiple energy Valley

- At low E filed electrons remains in the lower energy center valley Γ
- At higher E field most of the electrons will be transferred to the higher energy satellite L and X valleys



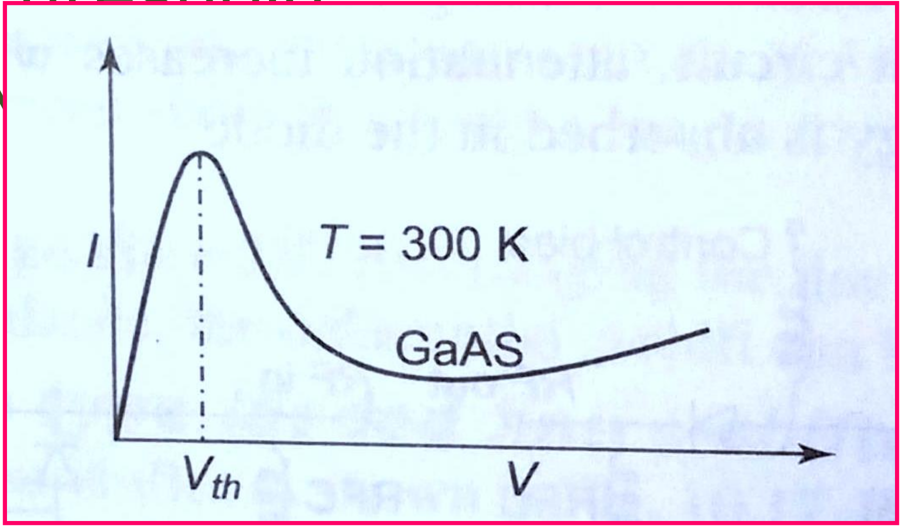
Multiple energy Valley

- In higher valleys Effective electron mass is larger. So that the electron mobility is lower.
- Conductivity α Mobility
  - ➢ Current Decreases



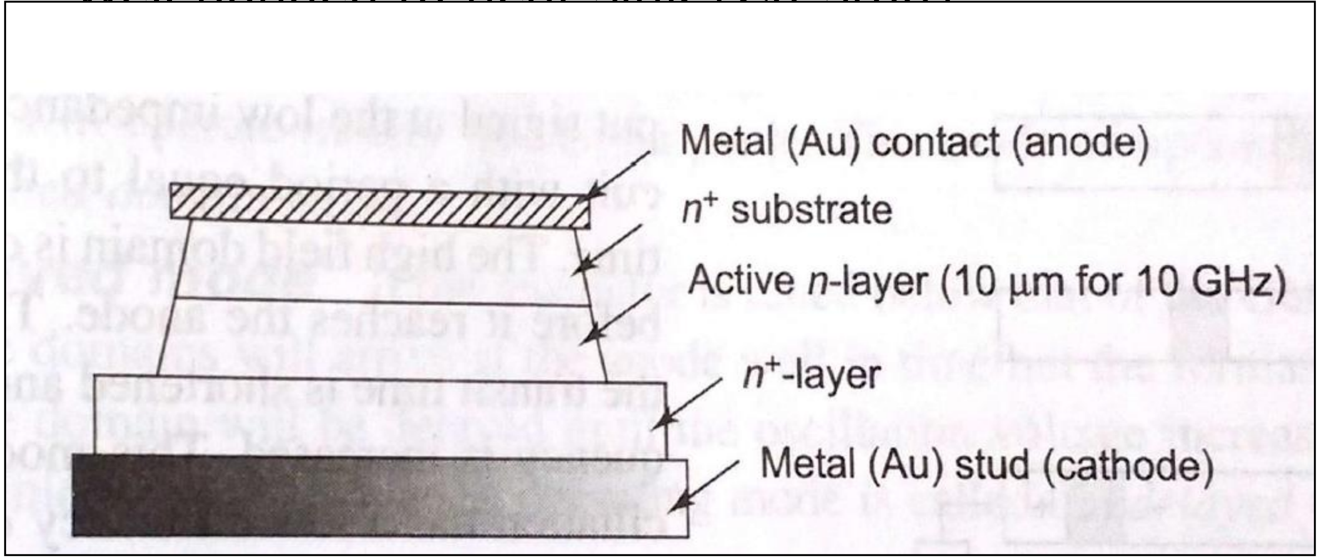
IV Characteristics of Gunn Diode

- Transferred Electron effect-TED
- Threshold
- N



Construction of Gunn Diode

- No junction, but cathode and Anode –hence Diode
- At threshold Voltage is E field is 3.2KV/cm for GaAS
- Well bonded to heat sink (Cu-stud)

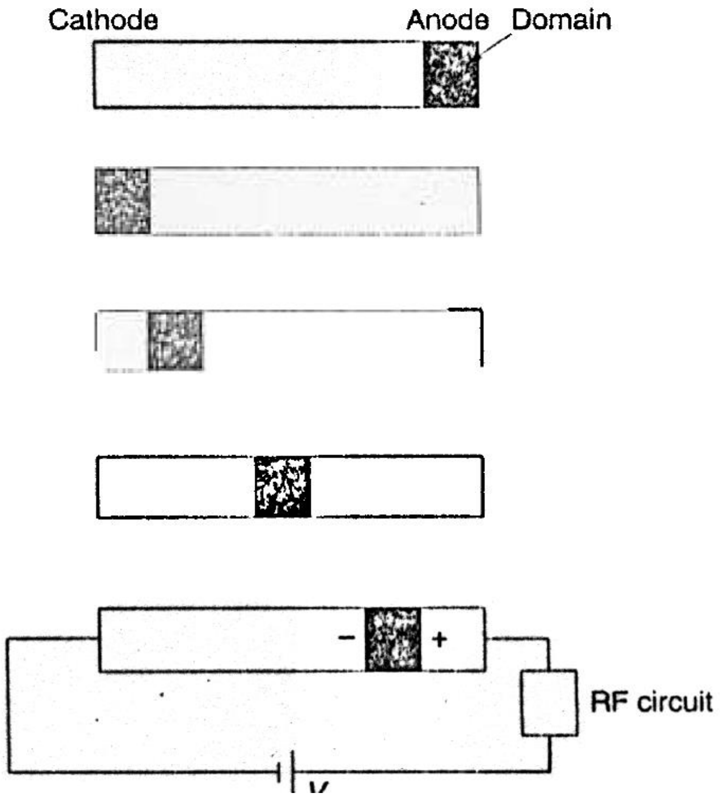


Modes of Operation

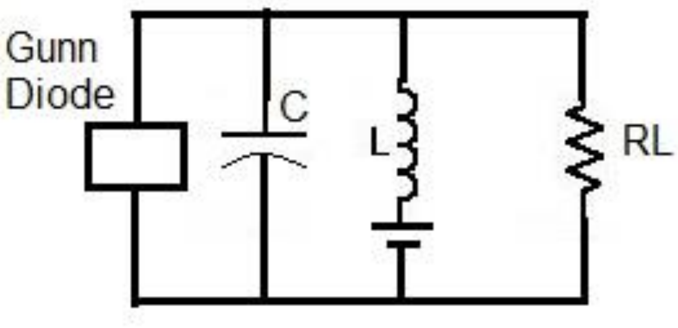
- Two principal modes are of microwave oscillation
    - Transit Time mode
    - Limited Space Charge mode

- Two special modes are,
    - Quenched domain mode
    - Delayed mode

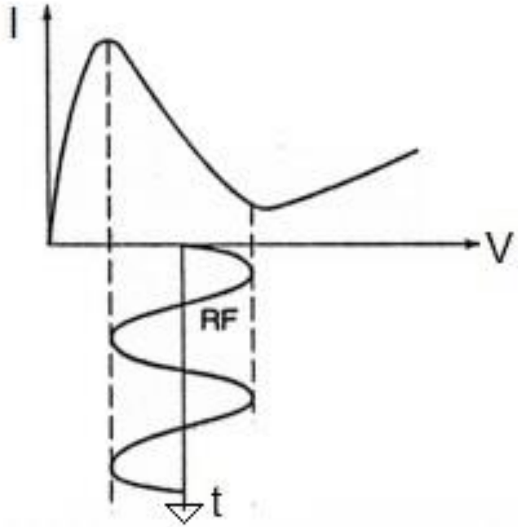
Transit Time Mode (TT)



Limited Space Charge mode(LSA)



Gunn Diode in LSA mode

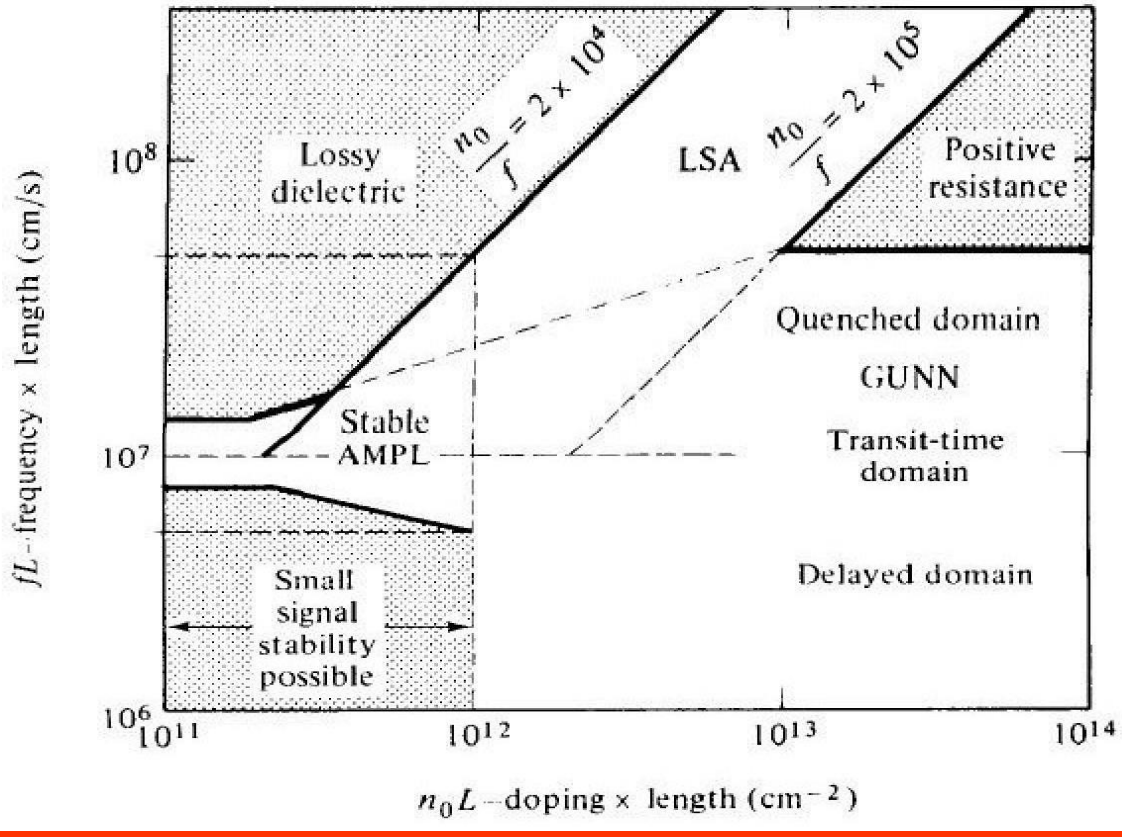


MODES OF OPERATION OF GUNN DIODE

A gunn diode can operate in four modes:

1. Gunn oscillation mode
2. Stable amplification mode
3. LSA oscillation mode
4. Bias circuit oscillation mode(It occurs either in Gunn oscillation or LSA Oscillation mode)

MODES OF OPERATION OF GUNN DIODE



1. Gunn oscillation mode

- This mode is defined in the region where the product of frequency multiplied by length is about 107 cm/s and the product of doping multiplied by length is greater than 1012/cm2.
- In this region the device is unstable because of the cyclic formation of either the accumulation layer or the high field domain.
- When the device is operated is a relatively high Q cavity and coupled properly to the load, the domain I quenched or delayed before nucleating.

2. Stable amplification mode

- This mode is defined in the region where the product of frequency times length is about 107 *cmls and the product of doping* times length is between 10^{11} and $10^{12}/cm^2$

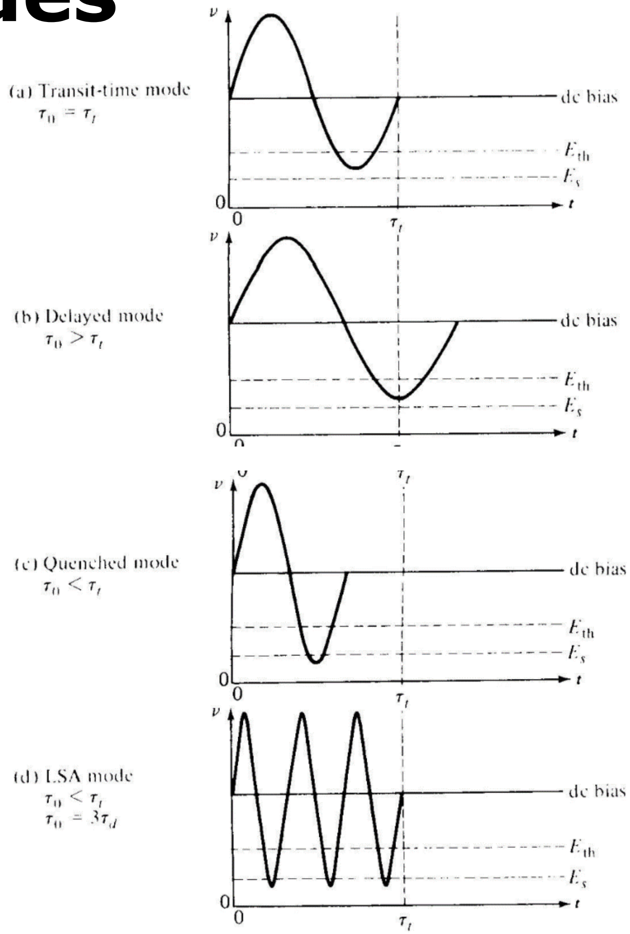
3. LSA oscillation mode

- This mode is defined in the region where the product of frequency times length is above 10^7 *cmls and the quotient of doping divided by* frequency is between 2 x 10^4 and 2 x 10^5

4. **Bias-circuit oscillation mode**

- This mode occurs only when there is either Gunn or LSA oscillation. and it is usually at the region where the product of frequency times length is too small to appear in the figure. When a bulk diode is biased to threshold. the average current suddenly drops as Gunn oscillation begins

1. Various Gunn oscillation modes



Delayed domain mode (106 cm/s < fL < 107 cm/s).

- When the transit time is Chosen so that the domain is collected while E < Eth as shown in Fig. 7-3-4(b), a new domain cannot form until the field rises above threshold again. In this case, the oscillation period is greater than the transit time-that is, To > T,. This delayed mode is also called inhibited mode. The efficiency of this mode is about 20%.

Quenched domain mode (fL > 2 X 107 cm/s).

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

Quenched domain mode (fL > 2 X 107 cm/s).

Therefore the oscillations occur at the frequency of the resonant circuit rather than at the transit-time frequency, It has been found that the resonant frequency of the circuit is several times the transit-time frequency, since one dipole does not have enough time to readjust and absorb the voltage of the other dipoles . Theoretically, the efficiency of quenched domain oscillators can reach 13%

Applications

Gunn diode can be used as an amplifier and as an oscillator. The applications of Gunn diode are

- In broadband linear amplifier
- In radar transmitters.
- Used in transponders for air traffic control.
- In fast combinational and sequential logic circuit.
- In low and medium power oscillators in microwave receivers

Avalanche Transit Time Devices

- IMPATTT Diode
- TRAPATT Diode
- BARITT Diode

Introduction

- Rely on the effect of voltage breakdown across a reverse biased p-n junction.
- The avalanche diode oscillator uses carrier impact ionization and drift in the high field region of a semiconductor junction to produce a negative resistance at microwave frequencies.

Negative Resistance Effect

1. The impact ionization avalanche effect, which causes the carrier current $I_0(t)$ and the ac voltage to be out of phase by 90°
2. The transit-time effect, which further delays the external current $I_e(t)$ relative to the ac voltage by 90°

Introduction

Two distinct modes of avalanche oscillator is observed

1) IMPATT (IMPact ionization Avalanche Transit Time operation)

   - DC-to-RF c.e. is 5 to 10%

2) TRAPPAT (Trapped Plasma Avalanche Triggered Transit operation)

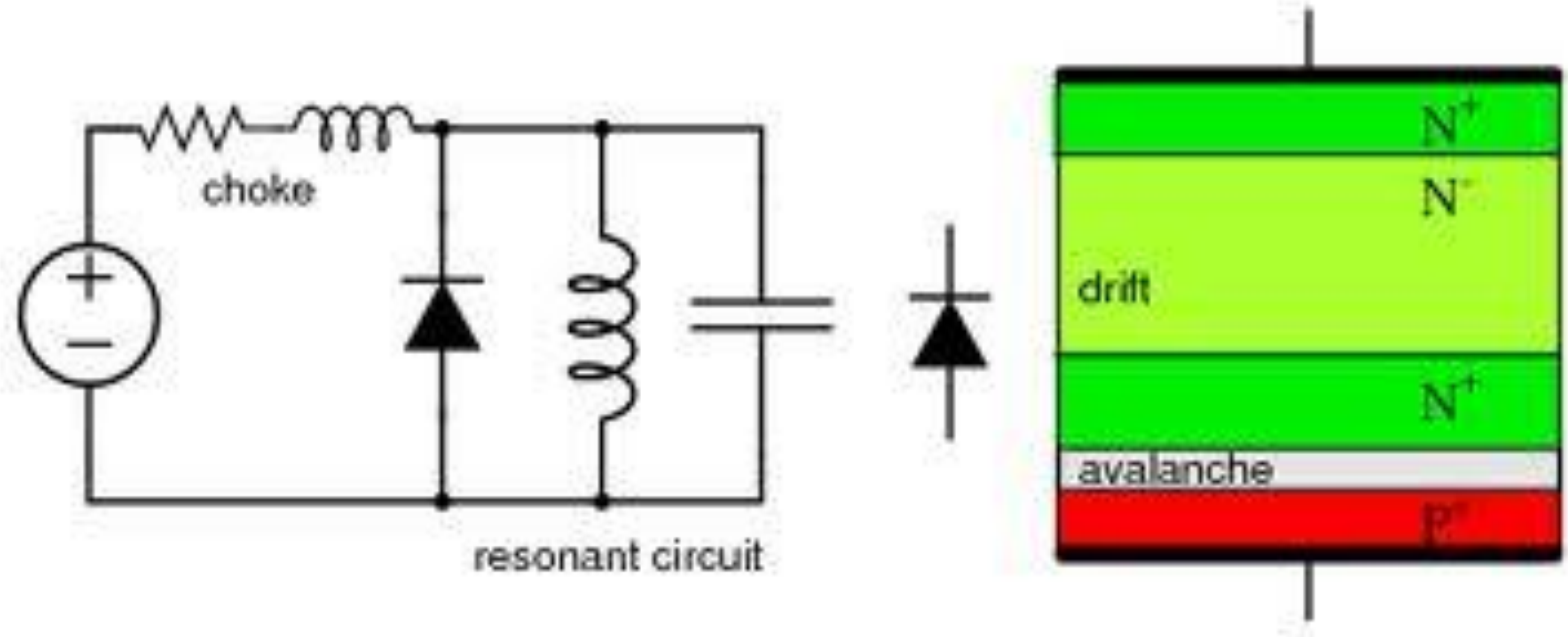
   - 20 to 60%

- Another type of active microwave device is BARITT (Barrier Injected Transit Time Diode)

Introduction

- Form of high power diode used in high frequency electronics and microwave devices
- Typically made from silicon carbides due to their high breakdown fields.
- Frequency - 3 to 100 GHz
- High power capability
- From low power radar systems to alarms
- Generate high level of phase noise – avalanche process

IMPATT Diode as oscillator



IMPATT Diode

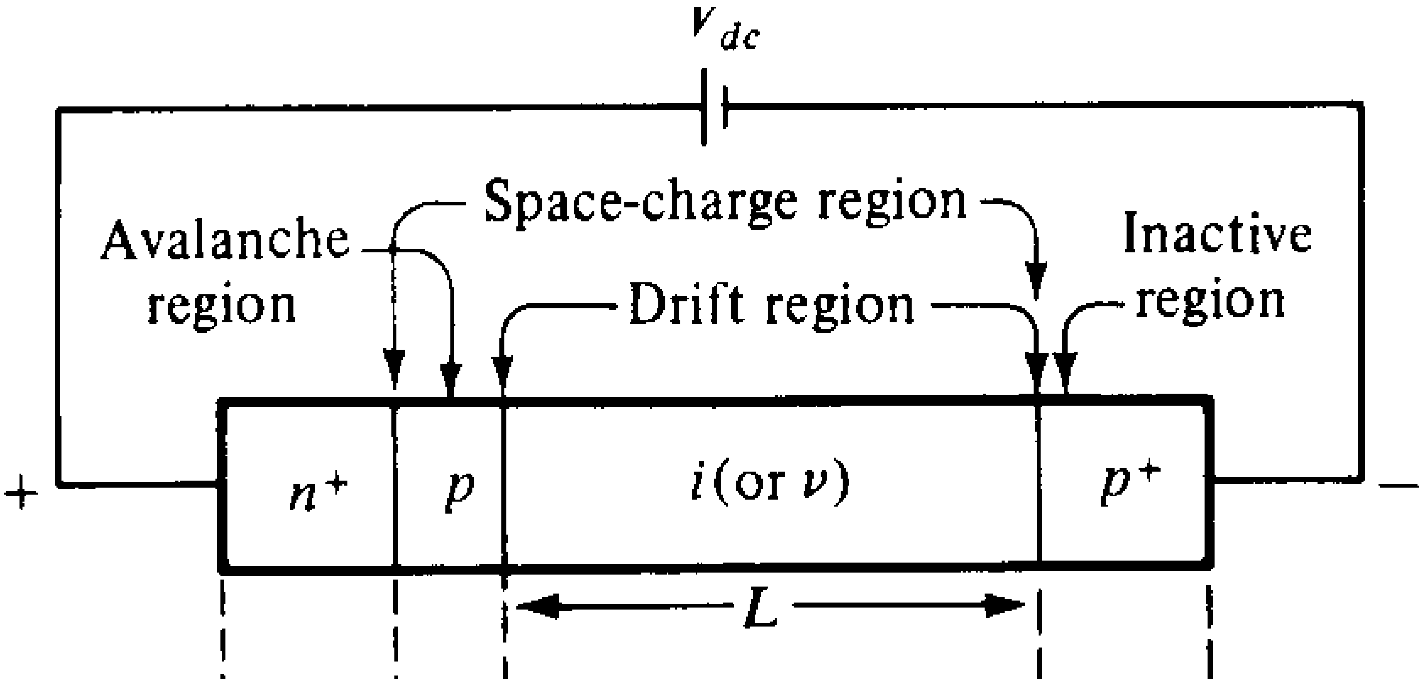
- The IMPATT diode family includes many different junctions and metal semiconductor devices.
- The first IMPATT oscillation was obtained from a simple silicon p-n junction diode biased into a reverse avalanche break down and mounted in a microwave cavity.

Avalanche Effect and Transit Time Effect

- Electron–hole pairs are generated in the high field region. The generated electron immediately moves into the N region, while the generated holes drift across the P region.

- The time required for the hole to reach the contact constitutes the transit time delay.

Physical Description – Read Diode



Physical Description – Read Diode

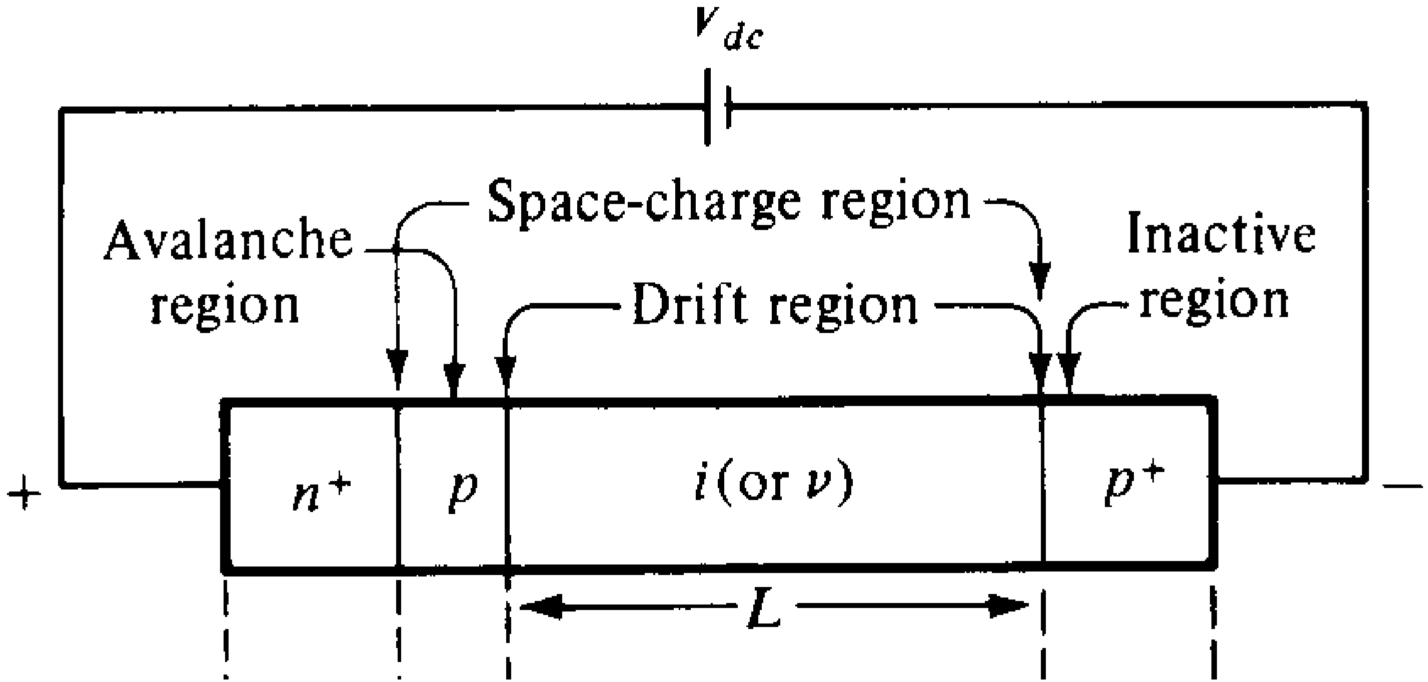
- The original proposal for a microwave device of the IMPATT type was made by **Read.** Read diode is the basic type in the IMPATT diode family

The Read diode consists of two regions:

1) The Avalanche region (a region with relatively high doping and high field) in which avalanche multiplication occurs and

2) the drift region (a region with essentially intrinsic doping and constant field) in which the generated holes drift towards the contact.

Physical Description – Read Diode



Physical Description

$$n^{+}\text{-}p\text{-}i\text{-}p^{+}$$

- + very high doping
- i or v intrinsic material
- Two regions:
  1) Thin p region (High field/Avalanche region) – avalanche multiplication occurs
  2) Intrinsic region (Drift region) – generated holes must drift towards the p+ contact

Impact Ionization

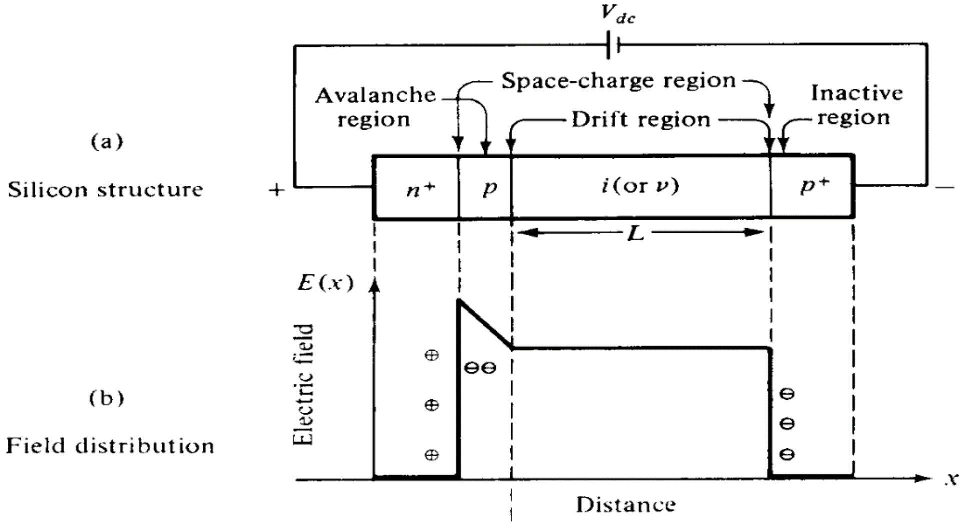
- If a free electron with sufficient energy strikes a silicon atom, it can break the covalent bond of silicon and liberate an electron from the covalent bond.
- If the electron liberated gains energy by being in an electric field and liberates other electrons from other covalent bonds then this process can cascade very quickly into a chain reaction producing a large number of electrons and a large current flow.
- This phenomenon is called impact avalanche.

Impact Ionization

- The space between n+ -p junction and the i –p+ junction is called the space charge region
- The diode is reverse biased and mounted in a microwave cavity. The impedance of the cavity is mainly inductive which is matched with the capacitive impedance of the diode to form a resonant circuit.
- Such device can produce a negative ac resistance that in turns delivers power from the dc bias to the oscillation

Avalanche Multiplication

- When the reverse bias voltage is above the breakdown voltage, the space charge region always extends from n+ -p junction to the i –p+ junction through the p and the i regions.



Avalanche Multiplication

- A positive charge moves from left to right and gives a rising field.
- The maximum field which is at the n+ -p junction is about several hundred kilovolt/cm
- Carriers (holes) in the high field region near the n+ -p junction acquire energy to knock down the valence electrons in the conduction band and hence electron hole pairs are generated.
- This is avalanche multiplication.

Avalanche Multiplication

- 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.
- The field throughout the space charge is about 5 kV/cm.

Avalanche Multiplication

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

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

And the avalanche multiplication factor is

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

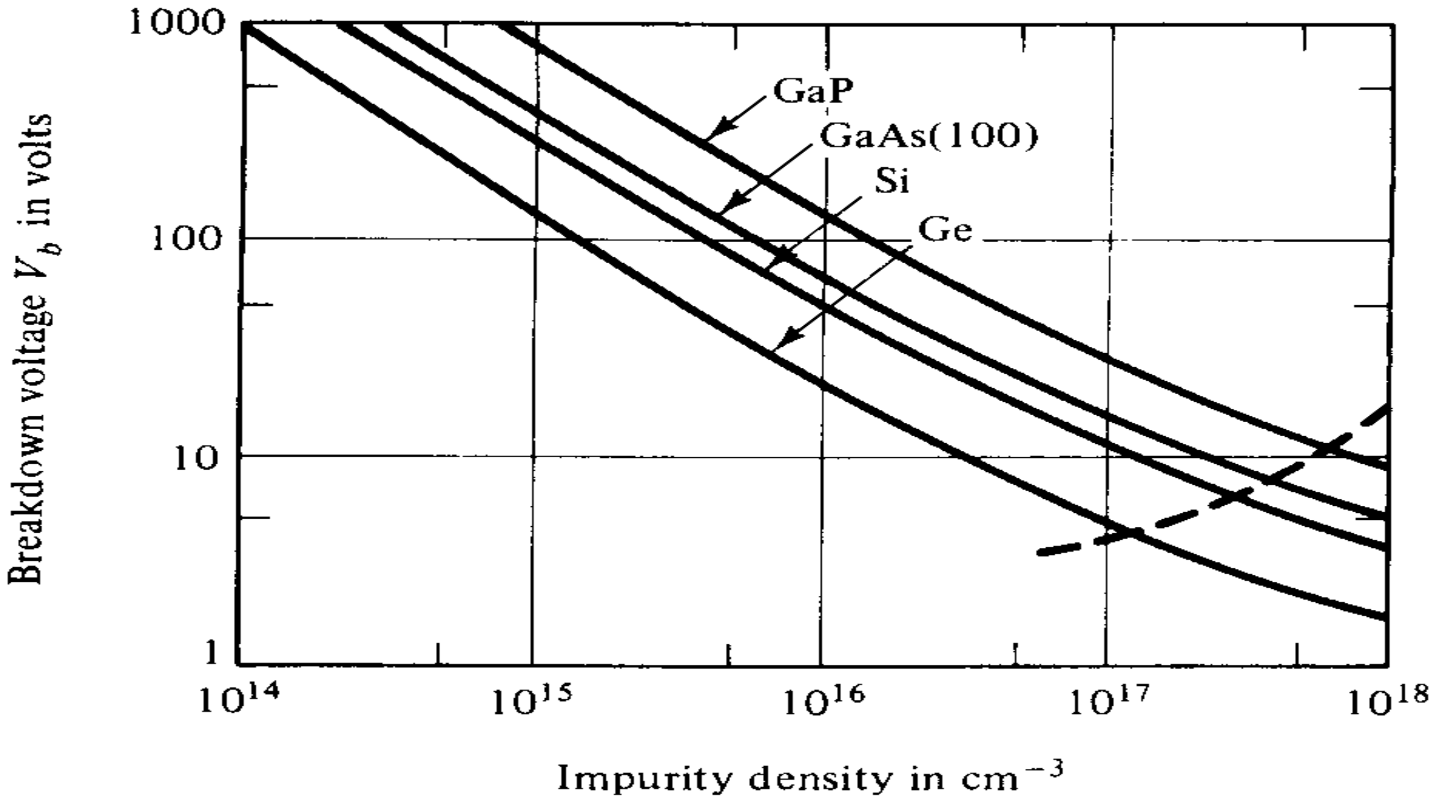
where V = applied voltage
V_b = avalanche breakdown voltage
n = 3–6 for silicon is a numerical factor depending on the doping of p^+-n or n^+-p junction

- The breakdown voltage for a silicon p+ -n junction can be expressed as

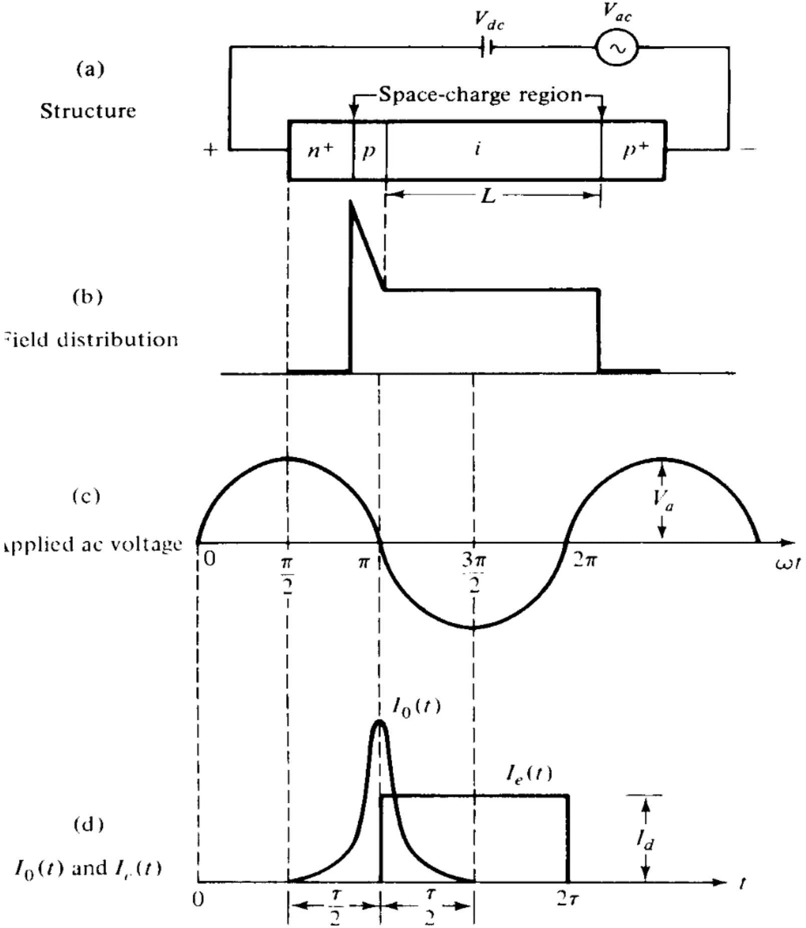
$$|V_b| = \frac{\rho_n \mu_n \epsilon_s |E_{\max}|_b^2}{2}$$

where ρ_n = resistivity
μ_n = electron mobility
ϵ_s = semiconductor permittivity
$E_{\max}$ = maximum breakdown of the electric field

Breakdown voltage Vs impurity doping



Carrier Current Io(t) and External Current Ie(t)



Carrier Current Io(t) and External Current Ie(t)

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- The diode can be mounted in a microwave resonant circuit
- An ac voltage can be maintained at a given frequency in the circuit, and the total field across the diode is the sum of ac and dc fields which causes breakdown at the n+ -p junction during the positive half cycle of the ac voltage cycle if the field is above the breakdown voltage.
- The carrier current (hole current in this case) Io(t) generated at the n+ -p junction by the avalanche multiplication grows exponentially with time while the field is above critical voltage.

Carrier Current Io(t) and External Current Ie(t)

- During the negative half cycle, when the field is below breakdown voltage, the carrier current decays exponentially.

- Io(t) is in the form a pulse of very short duration and it reaches its maximum in the middle of the ac voltage cycle or one quarter of the cycle later than the voltage.

Carrier Current Io(t) and External Current Ie(t)

- Under the influence of electric field the generated holes are injected into the space region towards the negative terminal.

- As the injected holes traverse the drift space,

  a. They induce a current Ie(t) in the external circuit.

  b. Cause a reduction of the field

Carrier Current Io(t) and External Current Ie(t)

- Since the velocity of the holes in the space charge is constant

$$I_e(t) = \frac{Q}{\tau} = \frac{v_d Q}{L}$$

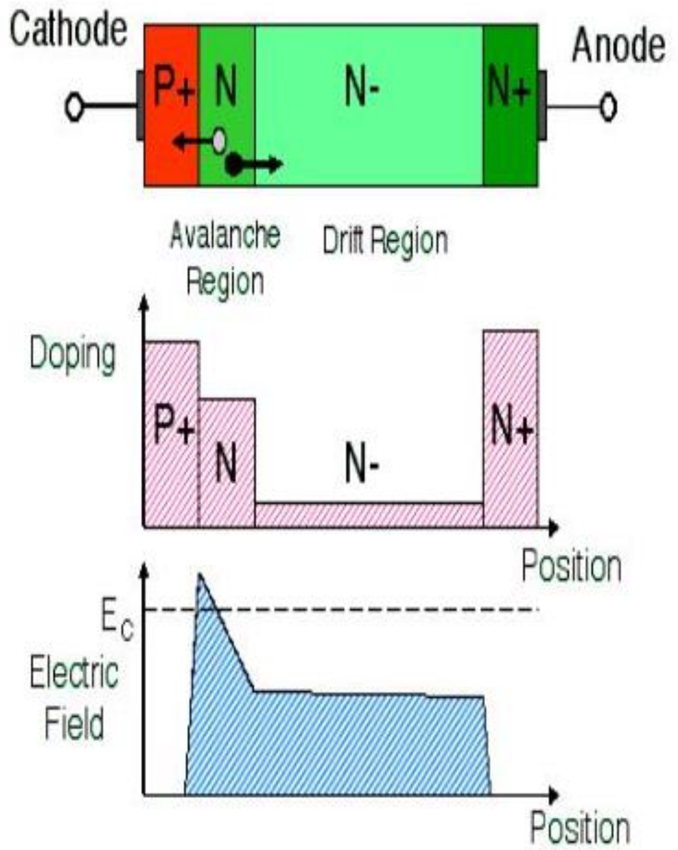
where Q = total charge of the moving holes
v_d = hole drift velocity
L = length of the drift i region

Carrier Current Io(t) and External Current Ie(t)

- The external current Ie(t) because of the moving holes is delayed by 90 degree relative to the pulsed Io(t).
- Since the carrier current Io(t) is delayed by one quarter cycle or 90 degree relative to the ac voltage, Ie(t) is then delayed by 180 degree relative to the voltage.
- Hence negative conductance occurs and the diode can be used for microwave oscillation and amplification.

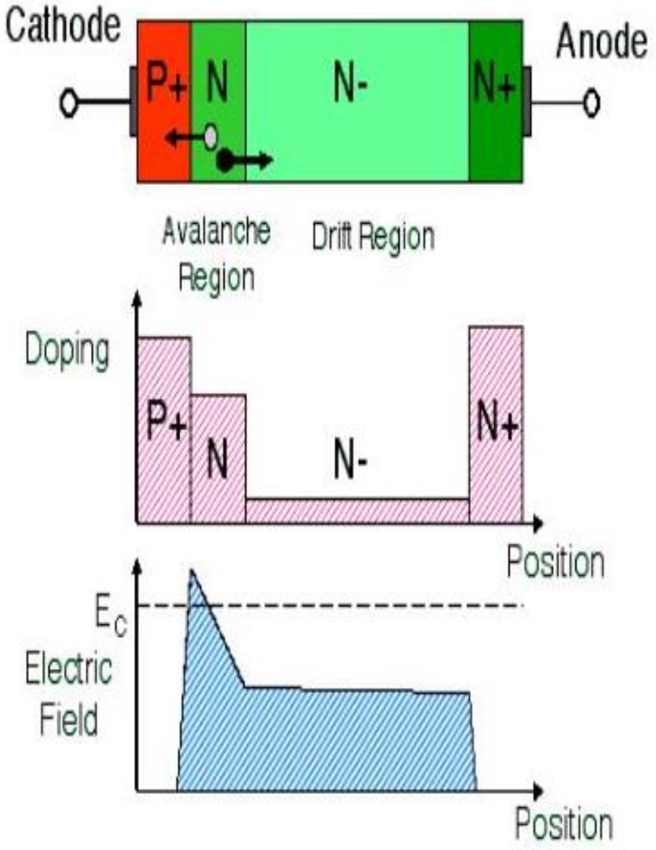
IMPATT Diode - Operation

- Diode is operated in reverse bias near breakdown, and both the N and N- regions are completely depleted
- Electric field is highly peaked in the avalanche region and nearly flat in drift region



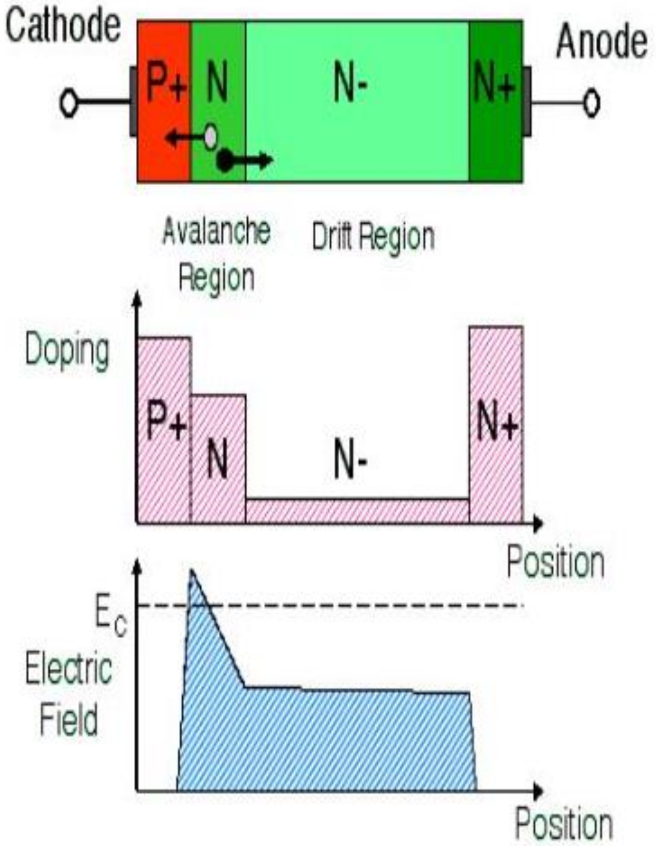
IMPATT Diode - Operation

- Avalanche breakdown occurs at the point of highest electric field, and this generates a large number of hole-electron pairs by impact ionization
- Holes swept into the cathode – electrons travel across drift region toward anode

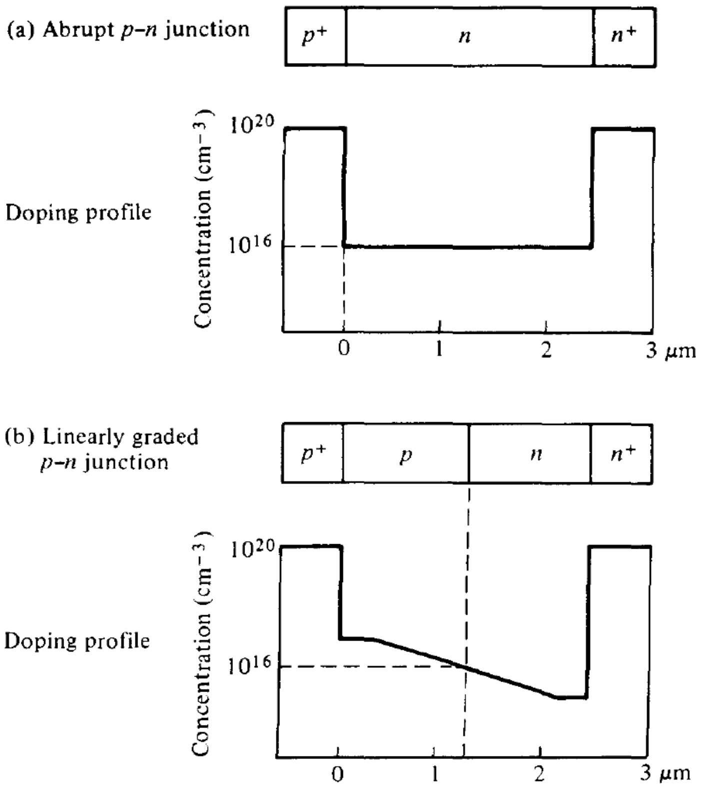


IMPATT Diode - Operation

- As they drift, they induce image charges on the anode, giving rise to a displacement current in the external circuit that is 180 degree out of phase with the nearly sinusoidal voltage waveform

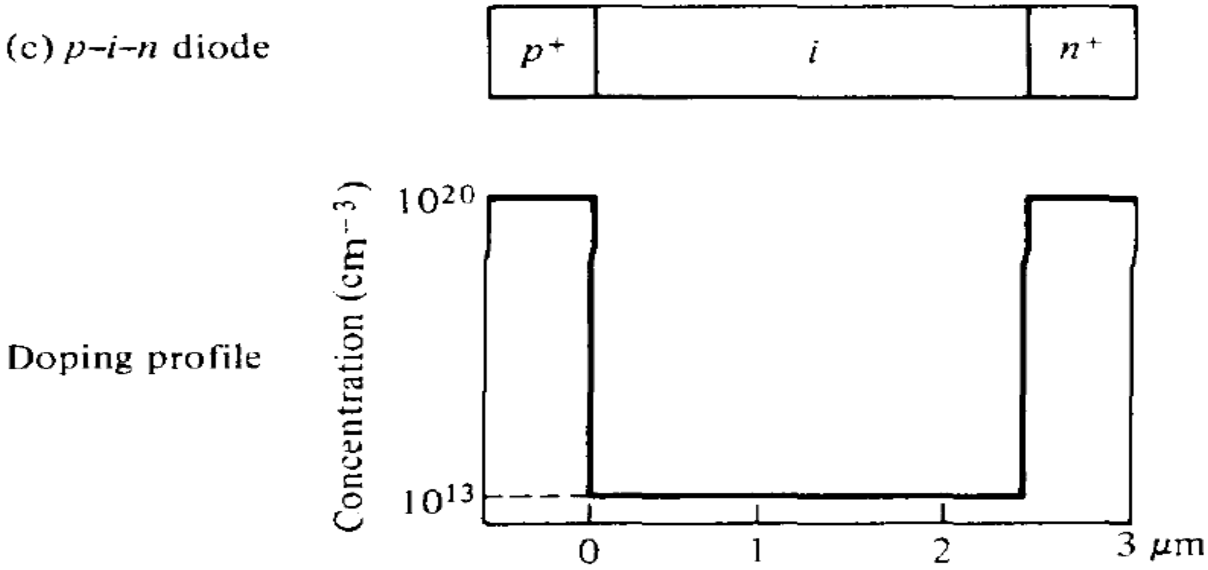


IMPATT Diode Physical Structure



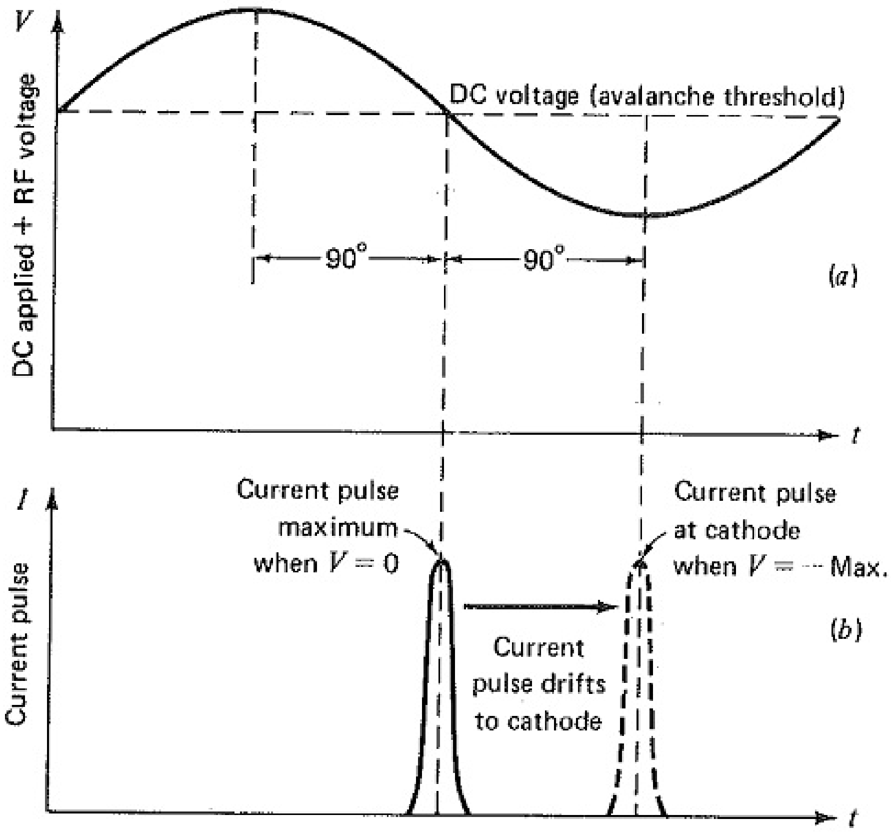
Three typical silicon IMPATT diodes

IMPATT Diode Physical Structure



Three typical silicon IMPATT diodes

IMPATT Diode



(a) Applied and RF voltage

(b) Resulting current pulse and its drift across diode

IMPATT Diode – Negative Resistance

$$R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta}$$

where R_s = passive resistance of the inactive region

v_d = carrier drift velocity

L = length of the drift space-charge region

A = diode cross section

e_s = semiconductor dielectric permittivity

Applications of IMPATT diode

- Used in a variety of applications from low power radar systems to alarms
- In view of its high levels of phase noise, it is used in transmitters more frequently than as a local oscillator in receivers where the phase noise performance is generally more important

Applications of IMPATT diode

The following products are available as examples of IMPATT diode application:

1. Cavity stabilized IMPATT diode oscillator CIDO series
2. Pulsed IMPATT power sources IPSP series
3. IMPATT active frequency multipliers IAFM series
4. Pulsed and CW IMPATT injection-locked amplifiers IILAP and IILA series
5. Voltage controlled IMPATT oscillators VCIO series

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Thank you