GUDLAVALLERU ENGINEERING COLLEGE

(An Autonomous Institute with Permanent Affiliation to JNTUK,Kakinada)

Seshadri Rao Knowledge Village, Gudlavalleru – 521 356.

Department of Computer Science Engineering

HANDOUT

on

ELEMENTS OF ELECTRONICS ENGINEERING

Vision

To be a Centre of Excellence in Computer Science and Engineering education and training to meet the challenging needs of the industry and society. Computer Science and Engineering 02

Mission

- To impart quality education through well-designed curriculum in tune with the growing software needs of the industry.
- To serve our students by inculcating in them problem solving, leadership, teamwork skills and the value of commitment to quality, ethical behavior &respect for others.
- To foster industry-academia relationship for mutual benefit and growth.

PROGRAM EDUCATIONAL OBJECTIVES (PEOs)

- Identify, analyze, formulate and solve Computer Science and Engineering

  problems both independently and in a team environment by using the appropriate modern tools.
- Manage software projects with significant technical, legal, ethical, social,

  environmental and economic considerations.
- Demonstrate commitment and progress in lifelong learning, professional

  development, leadership and communicate effectively with professional clients and the public.

HANDOUT ON ELEMENTS OF ELECTRONICS ENGINEERING

Class& Sem. :I B.Tech – II Semester Year :2019-20
Branch : CSE Credits : 3

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1. Brief History and Scope of the Subject

Basic electronics exploit the electronic properties of semiconductor materials, principally silicon, germanium, and gallium arsenide. Semiconductor devices have replaced thermionic devices (vacuum tubes) in most applications. They use electronic conduction in the solid state as opposed to the gaseous state or thermionic emission in a high vacuum.

Semiconductor materials are useful because their behavior can be easily manipulated by the addition of impurities, known as doping. Semiconductor conductivity can be controlled by the introduction of an electric or magnetic field, by exposure to light or heat, or by the mechanical deformation of a doped monocrystalline grid; thus, semiconductors can make excellent sensors. Current conduction in a semiconductor occurs via mobile or "free" electrons and holes, collectively known as charge carriers.

Advanced topics in Semiconductor devices include manufacturing semiconductor devices both as single discrete devices and as integrated circuits (ICs), which consist of a number—from a few (as low as two) to billions of devices manufactured and interconnected on a single semiconductor substrate or wafer.

2. Pre-Requisites

Semiconductor physics

3. Course Objectives:

- To familiarize the construction, characteristics and applications of various semiconductor devices.
- To introduce various electronic circuits and their operation.

4. Learning Outcomes:

Upon successful completion of the course, the students will be able to

CO1: Distinguish the behavior of PN junction diode under forward bias and reverse bias conditions.
CO2: Select appropriate semiconductor devices for different electronic circuits.
CO3: Analyze the rectifier circuits with and without filters.
CO4: Characterize the performance of BJT, FET & MOSFETs.

5. Program Outcomes:

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments,

analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
12. **Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

Mapping of Course Outcomes with Program Outcomes:

	a	b	c	d	e	f	g	h	i	j	k
CO1											
CO2											
CO3											
CO4											

6. Prescribed Text Books:

a. Jacob Millman and Christos C Halkias, Electronic Devices and Circuits, 2nd Edition, TMH, 2002.(UNITS I – IV& UNIT VI)
b. Robert L Boylested and Louis Nashelsky, Electronic Devices and Circuit Theory, 8th Edition, PHI, 2003 (UNIT V)

7. Reference Text Books:

a. K.Rajarajeswari, B.Visvesvararao, K.Bhaskara Rama Murthy and P.Chalamrajupantulu- Electronic Devices and Circuits, 2nd Edition, Pearson Education
b. David A Bell, Electronic Devices and Circuits, 4th Edition, PHI, 2003
c. Floyd, Thomas, Electronic devices, Pearson Education, 5th Edition.
d. S. C. Sarkar, Electronic Devices and Circuits-1, The Millennium Edition, 2001.

8. URLs and Other E-Learning Resources

a. Basic Electronics -- Prof.R.V.Raja Kumar -- 38 Units.
b. Introduction to Electronic Circuits -- Prof.S.C.Dutta Roy --39 Units.
c. Solid state devices -- Dr.S.Karmalkar -- 42 Units.
d. Analog Electronic Circuits -- Prof. S.C.Dutta Roy -- 51 Units.

9. Digital Learning Materials:

Video courses:

a. Basic Electronics by Prof. Chitralekha Mahanta (IITG)
b. Semiconductor Devices by Dr. G.S. Visweswaran (IITD)

c. Electronics for Analog Signal Processing–I by Prof. K.RadhakrishnaRao

d. Electronics for Analog Signal Processing – II by Prof. K. RadhakrishnaRao

e. Analog Circuits by Prof. A.N. Chandorkar (IITB)

URLs:

- http://newton.ex.ac.uk/teaching/CDHW/Electronics2/Electronics Resources.html
- www.Williamson-labs.com/480_xtor.htm
- www.discovercircuits.com/resources/tutorials.html
- www.discovercircuits.com/circuit-solutions/circuit-solu4.html
- www.discovercircuits.com/other-links.html
- http://users.pandora.be/educypedia/electronics/components.html

10. Lecture Schedule / Lesson Plan

UNIT	TOPIC	PERIODS
I	**Introduction**	**11**
	Resistors, Capacitors and Inductors	3
	Material Classification	2
	Mobility and Conductivity	1
	Intrinsic and Extrinsic Semiconductor	1
	Mass Action Law and Hall Effect	2
	Drift and Diffusion Currents	1
	Tutorial	1
II	**Semiconductor Diode Characteristics**	**13**

	Open circuited p-n junction	2
	Current components in a p-n diode,	2
	Diode forward and reverse currents	2
	The volt-ampere characteristics	2
	Temperature dependence of V-I characteristics	
	Resistance, Transition capacitance	2
	Diffusion capacitance	1
	Tutorial	2
III	**Special Semiconductor Devices**	**10**
	Breakdown diodes	1
	Tunnel diode	2
	Varactor diode	1
	Photo diode	1
	LED	1
	UJT	1
	SCR	1
	Tutorial	2
IV	**Rectifiers and Filters**	**12**
	Diode as a rectifier, half wave rectifier	2
	Full wave bridge rectifiers and comparison	2

	With inductor filter, capacitor filter	2
	L section filter, π-section filter, comparison	2
	Zener diode voltage regulator	2
	Tutorial	2
V	**Bipolar Junction Transistor**	**09**
	Construction of a transistor, transistor current components	1
	Transistor configurations – CB, CE and CC	2
	Early effect, comparison of CB, CE and CC	1
	Transistor operating regions, typical transistor junction voltage values, Maximum voltage rating	2
	Operating point	1
	Tutorial	2
VI	**Field Effect Transistor**	**10**
	Classification of FETs, Construction of JFET, Characteristics of FET,	2
	FET as a voltage variable resistor (VVR)	1
	Transfer Characteristics, comparison with BJT,	1
	Depletion type MOSFET	2
	Enhancement type MOSFET	2
	Tutorial	2
	TOTAL NO. OF CLASSES	**65**

UNIT I
INTRODUCTION

OBJECTIVES:

- To describe the passive & active elements and their principles.
- To describe the types of materials, electrical properties and Hall Effect.

SYLLABUS:

Passive circuit components: Resistors, capacitors, inductors, Material classification, Mobility and conductivity, Intrinsic and extrinsic semiconductor, mass-action law, Hall effect, drift and Diffusion currents.

OUTCOMES:

Student will be able to

- Differentiate the passive and active components.
- Classify the materials and describe their electrical properties.
- Calculate the charge concentration using mass-action law in a given semiconductor.

- **Passive** component: one which consumes power (and can’t generate it).

RESISTOR:

- A **resistor** is a passive two-terminal electrical component that implements electrical resistance as a circuit element.
- Their purpose is to create specified values of current (i.e., to control the flow of current to other components) and voltage in a circuit.

  Example: If too much current flows through an LED it is destroyed. So a **resistor** is used to limit the current.

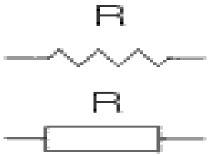


Figure 1.1: Symbols for resistor

- **Resistance** is the opposition that a substance offers to the flow of electric current.
- The unit for measuring resistance is the **OHM** (Ω).
- Higher resistance values are represented by "k" (kilo-ohms) and M (mega-ohms).

Types of Resistors:

- Resistors come in a variety of shapes and sizes. They might be through-hole or surface-mount. They might be a standard, static resistor, a pack of resistors, or a special variable resistor.
- **Through-hole** resistors come with long, pliable leads which can be stuck into a breadboard or hand-soldered into a prototyping board or printed circuit board (PCB).

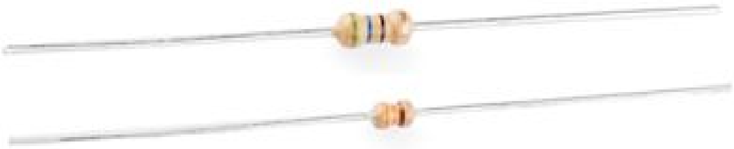


Figure 1.2: *A half-watt (½W) resistor (above) sized up to a quarter-watt (¼W)*

- The most common through-hole resistors come in an axial package. The size of an axial resistor is relative to its power rating.
- **Surface-mount** resistors are usually tiny black rectangles, terminated on either side with even smaller, shiny, silver, conductive edges.

Resistor composition:

- Resistors can be constructed out of a variety of materials. Most common, modern resistors are made out of either a **carbon, metal, or metal-oxide film**.
- In these resistors, a thin film of conductive (though still resistive) material is wrapped in a helix around and covered by an insulating material.
- Most of the standard, no-frills, through-hole resistors will come in a carbon-film or metal-film composition.

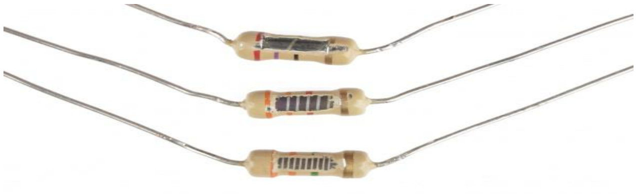


Figure 1.3: *Peek inside the guts of a few carbon-film resistors. Inside the resistor, a carbon film is wrapped around an insulator. More wraps means a higher resistance. Pretty neat!*

Special resistor packages:

- There is a variety of other, special-purpose resistors out there. Resistors may come in pre-wired packs of five-or-so resistor arrays. Resistors in these arrays may share a common pin, or be set up as voltage dividers.

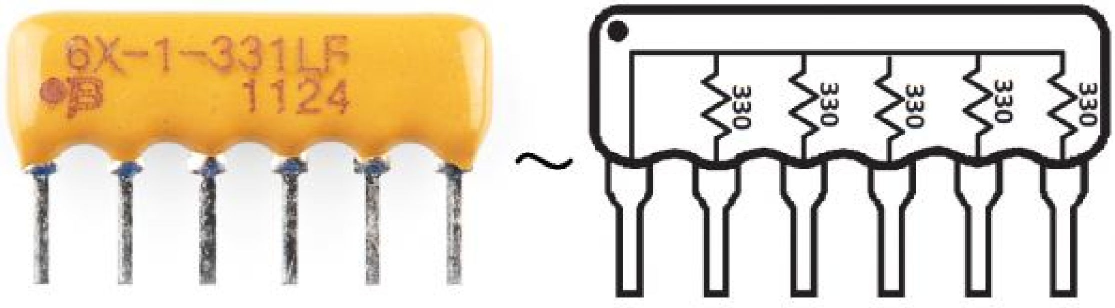


Figure 1.4: *An array of five 330Ω resistors, all tied together at one end.*

- Resistors don't have to be static either. Variable resistors, known as **rheostats**, are resistors which can be adjusted between a specific range of values.
- Similar to the rheostat is the **potentiometer**. Pots connect two resistors internally, in series, and adjust a center tap between them creating an adjustable voltage divider. These variable resistors are often used for inputs, like volume knobs, which need to be adjustable.

Decoding the colour bands:

Color	Digit value	Multiplier	Multiplied Out	Tolerance
Black	0	10^0	1	
Brown	1	10^1	10	

Red	2	10^2	100	
Orange	3	10^3	1,000	
Yellow	4	10^4	10000	
Green	5	10^5	100,000	
Blue	6	10^6	1,000,000	
Violet	7	10^7	10,000,000	
Gray	8	10^8	100,000,000	
White	9	10^9	1,000,000,000	
Gold				±5%
Silver				±10%

Here's an example of a 4.7kΩ resistor with four colour bands:

Power Rating:

- Power is the rate at which energy is transformed into something else.
- It's calculated by multiplying the voltage difference across two points by the current running between them, and is measured in units of a watt (W).
- Every resistor has a specific maximum power rating. In order to keep the resistor from heating up too much, it's important to make sure the power across a resistor is kept under it's maximum rating.

$$P=I^2R \text{ (or) } P=V^2/R$$

Series resistors:

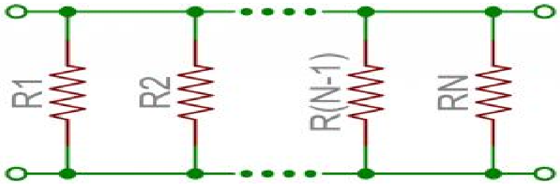
When connected in series resistor values simply add up.

$$R_{tot} = R_1 + R_2 + \ldots + R_{N-1} + R_N$$

Figure 1.5: *N resistors in series. The total resistance is the sum of all series resistors.*

Parallel resistors:

The total resistance of *N* resistors in parallel is the inverse of the sum of all inverse resistances.



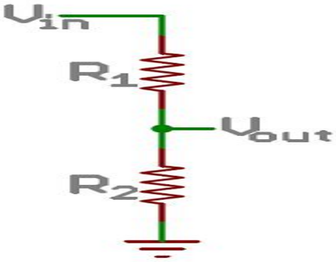
$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_{N-1}} + \frac{1}{R_N}$$

Figure 1.6: *N resistors in parallel. To find the total resistance, invert each resistance value, add them up, and then invert that.*

Voltage Dividers:

A voltage divider is a resistor circuit which turns a large voltage into a smaller one. Using just two resistors in series, an output voltage can be created that's a fraction of the input voltage.

Here's the voltage divider circuit:



Two resistors, R_1 and R_2, are connected in series and a voltage source (V_{in}) is connected across them. The voltage from V_{out} to GND can be calculated as:

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

CAPACITOR

- Just like the Resistor, the **Capacitor**, sometimes referred to as a **Condenser**, is a simple passive device that is used to "store electrical energy". The capacitor is a component which has the ability or "capacity" to store energy in the form of an electrical charge producing a potential difference (*Static Voltage*) across its plates, much like a small rechargeable battery.
- ***Application:*** There are many different kinds of capacitors available from very small capacitor beads used in resonance circuits to large

power factor correction capacitors, but they all do the same thing, they store charge.

- In its basic form, a capacitor consists of two or more parallel conductive (metal) plates which are not connected or touching each other, but is electrically separated either by air or by some form of a good insulating material such as waxed paper, mica, ceramic, plastic or some form of a liquid gel as used in electrolytic capacitors. The insulating layer between capacitors plates is commonly called the **Dielectric**.
- Due to this insulating layer, DC current cannot flow through the capacitor as it blocks it allowing instead a voltage to be present across the plates in the form of an electrical charge.
- The flow of electrons onto the plates is known as the capacitors **Charging Current** which continues to flow until the voltage across both plates (and hence the capacitor) is equal to the applied voltage V_c. At this point the capacitor is said to be "fully charged" with electrons.
- The amount of potential difference present across the capacitor depends upon how much charge was deposited onto the plates by the work being done by the source voltage and also by how much capacitance the capacitor has.

Capacitor Construction

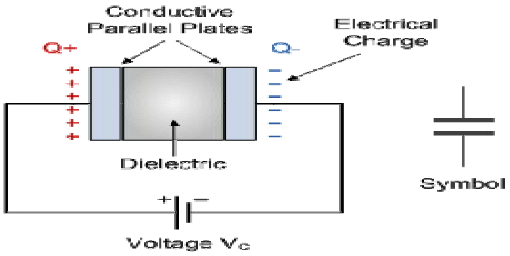


Figure 1.7: Capacitor construction and Symbol

- Capacitance is the electrical property of a capacitor and is the measure of a capacitors ability to store an electrical charge onto its two plates with the unit of capacitance being the **Farad**
- Capacitance is defined as being that a capacitor has the capacitance of **One Farad** when a charge of **One Coulomb** is stored on the plates by a voltage of **One volt**.
- By applying a voltage to a capacitor and measuring the charge on the plates, the ratio of the charge Q to the voltage V will give the capacitance value of the capacitor and is therefore given as: C = Q/V
- The capacitance of a parallel plate capacitor is proportional to the area, A in metres^2 of the smallest of the two plates and inversely proportional to the distance or separation, d (i.e. the dielectric thickness) given in metres between these two conductive plates.

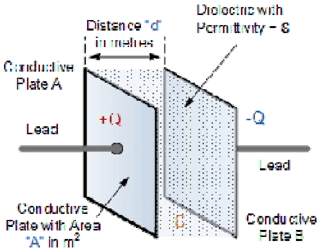


Figure1.8: Capacitor construction

Problem: A capacitor is constructed from two conductive metal plates 30cm x 50cm which are spaced 6mm apart from each other, and uses dry air as its only dielectric material. Calculate the capacitance of the capacitor.

$$\text{Using: } C = \varepsilon_0 \frac{A}{d}$$

$$\text{where: } \varepsilon_0 = 8.84 \times 10^{-12}$$

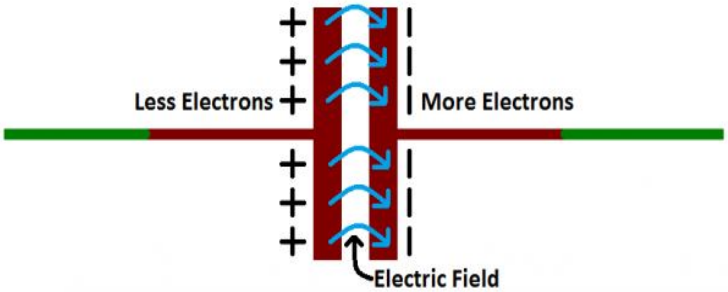
$$A = 0.3 \times 0.5\, m^2 \quad \text{and} \quad d = 6 \times 10^{-3}\, m$$

$$C = \frac{8.84 \times 10^{-12} \times (0.3 \times 0.5)}{6 \times 10^{-3}} = 0.221 nF$$

Then the value of the capacitor consisting of two plates separated by air is calculated as 221pF or 0.221nF

How a Capacitor Works

- When current flows into a capacitor, the charges get "stuck" on the plates because they can't get past the insulating dielectric.
- Electrons – negatively charged particles – are sucked into one of the plates, and it becomes overall negatively charged.
- The large mass of negative charges on one plate pushes away like charges on the other plate, making it positively charged.



- The charges will forever be stuck on the plate (until they have somewhere else to go).
- The stationary charges on these plates create an electric field, which influence electric potential energy and voltage. When charges group together on a capacitor like this, the capacitor is storing electric energy just as a battery might store chemical energy.
- When positive and negative charges coalesce on the capacitor plates, the capacitor becomes **charged**.
- If a path in the circuit is created, which allows the charges to find another path to each other, they'll leave the capacitor, and it will **discharge**.
- The gist of a capacitor's relationship to voltage and current is this: the amount of **current through a capacitor** depends on both the capacitance and how quickly the **voltage is rising or falling**.
- If the voltage across a capacitor swiftly rises, a large positive current will be induced through the capacitor.

- A slower rise in voltage across a capacitor equates to a smaller current through it.
- If the voltage across a capacitor is steady and unchanging, no current will go through it.

$$i = C\frac{dv}{dt}$$

Types of Capacitors

1. Ceramic Capacitors

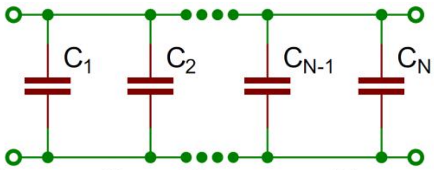
- The most commonly used and produced capacitor out there is the ceramic capacitor. The name comes from the material from which their dielectric is made.

2. Aluminium and Tantalum Electrolytic

- Electrolytic are great because they can pack *a lot* of capacitance into a relatively small volume. If you need a capacitor in the range of 1µF-1mF, you're most likely to find it in an electrolytic form. They're especially well suited to high-voltage applications because of their relatively high maximum voltage ratings.
- Electrolytic caps are usually **polarized**. They have a positive pin – the anode – and a negative pin called the cathode.
- Another common capacitor type is the **film capacitor**, which features very low parasitic losses (ESR), making those great for dealing with very high currents.
- **Variable capacitors** can produce a range of capacitances, which makes them a good alternative to variable resistors in tuning circuits.

Capacitors in Parallel

- When capacitors are placed in parallel with one another the total capacitance is simply the **sum of all capacitances**. This is analogous to the way resistors add when in series.



$$C_{Tot} = C_1 + C_2 + \ldots + C_{N-1} + C_N$$

Figure 1.9: Capacitors in Parallel

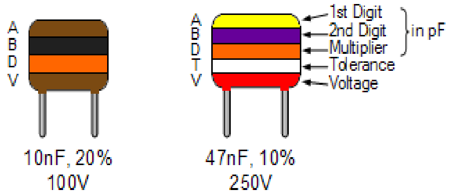
Capacitors in Series

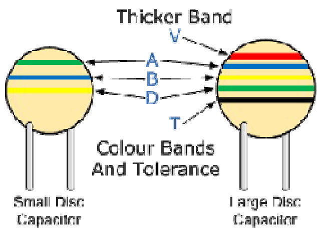
- Much like resistors are a pain to add in parallel, capacitors get funky when placed in *series*. The total capacitance of *N* capacitors in series is the inverse of the sum of all inverse capacitances.

$$\frac{1}{C_{Tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_{N-1}} + \frac{1}{C_N}$$

Figure 1.10: Capacitors in series

Capacitor Colour Codes





INDUCTOR

Fleming's Right Hand Rule: when an electrical current flows through a wire conductor, a magnetic flux is developed around the conductor producing a relationship between the direction of this magnetic flux which is circulating around the conductor and the direction of the current flowing through the same conductor.

- There is also another important property relating to a wound coil that also exists, which is that a secondary voltage is induced into the same coil by the movement of the magnetic flux as it opposes or resists any changes in the electrical current flowing it.
- **Inductor** is nothing more than a coil of wire wound around a central core.

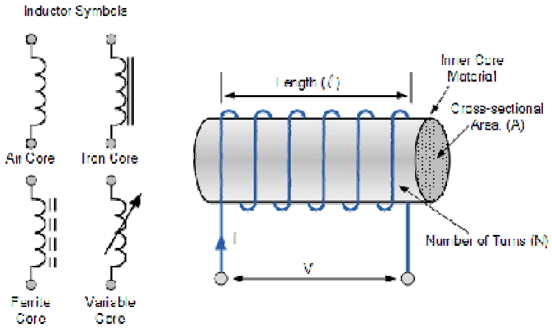


Figure 1.11: Inductor construction

- The current, i that flows through an inductor produces a magnetic flux that is proportional to it. But unlike a capacitor which opposes a change of voltage across their plates, an inductor opposes the rate of change of current flowing through it due to the build up of self-induced energy within its magnetic field.

$$V_L = N\frac{d\Phi}{dt} = \frac{\mu N^2 A}{\ell}\frac{di}{dt}$$

Where: N is the number of turns A is the cross-sectional Area in m2; Φ is the amount of flux in Webers

μ is the Permeability of the core material;

l is the Length of the coil in meters

di/dt is the Currents rate of change in amps/second;

Current and Voltage in an Inductor

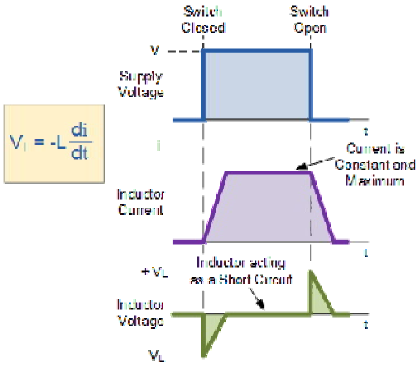


Figure 1.12: Voltage and Current in an inductor

- How much induced voltage will be produced by the inductor depends upon the rate of current change.

  Problem: A steady state direct current of 4 ampere passes through a solenoid coil of 0.5H. What would be the back emf voltage induced in the coil if the switch in the above circuit was opened for 10mS and the current flowing through the coil dropped to zero ampere.

$$V_L = L\frac{di}{dt} = 0.5\frac{4}{0.01} = 200\,\text{volts}$$

- **Inductance** is the name given to the property of a component that opposes the change of current flowing through it and even a straight piece of wire will have some inductance.
- Inductors do this by generating a self-induced emf within itself as a result of their changing magnetic field.
- In an electrical circuit, when the emf is induced in the same circuit in which the current is changing this effect is called **Self-induction**
- When the emf is induced into an adjacent component situated within the same magnetic field, the emf is said to be induced by **Mutual-induction**

Units: **Henry or Weber per Ampere**

Definition: a coil will have an inductance value of one Henry when an emf of one volt is induced in the coil was the current flowing through the said coil changes at a rate of one ampere/second

MATERIAL CLASSIFICATION

- Solid-state materials can be classified into three groups: insulators, semiconductors and conductors.
- Insulators are materials having an electrical conductivity $\sigma < 10^{-8} S/cm$ (like diamond:10-14S/cm);
- semiconductors have a conductivity $10^{-8} S/cm < \sigma < 10^{3} S/cm$ (for silicon it can range from 10-5S/cm to 103S/cm);
- Conductors are materials with high conductivity: $10^{3} S/cm < \sigma$ (like silver: 106S/cm.)
- The electrical properties of a given material depend on the electronic populations of the different allowed bands.

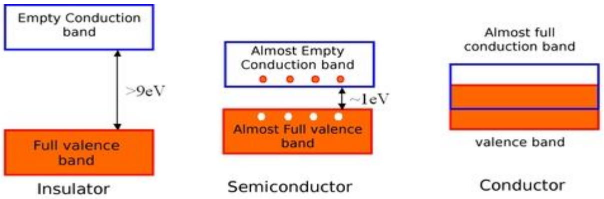


Figure1.13: Representation of Energy bands

A) INSULATOR:

- A material with fully occupied or empty energy bands is then an **insulator**. This is the case when the gap energy exceeds ~9eV, because for such gaps, the thermal energy at 300K (~25 meV) is clearly insufficient to allow electrons from the valence band to be promoted to the conduction band. In this case the valence band (and all bands of lower energy) is fully occupied, and the conduction band is empty.

B) CONDUCTOR:

- For a **conductor**, conduction bands and valence bands are not separated and there is therefore no energy gap. The conduction band is then partially occupied (even at low temperatures), resulting in a "high" electrical conductivity.

Information: An important parameter in the band theory is the Fermi level, the top of the available electron energy levels at low temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties.

C) SEMICONDUCTOR:

A **semiconductor** is primarily an insulator at 0K. However, since the energy gap is lower compared to insulators (~1eV), the valence band is slightly thermally populated at room temperature, whereas the conduction band is slightly depopulated. Since electrical conduction is directly connected to the number of electrons in the “almost empty” conduction band and to the number of holes in the “almost fully occupied” valence band, it can be expected that the electrical conductivity of such an intrinsic semiconductor will be very small.

i) Intrinsic Semiconductor:

- Those semi conductors in which impurities are missing are known as intrinsic semiconductors.
- The electrical conductivity of the semiconductor depends upon the total no of electrons shifted to the conduction band from the valence band. This phenomenon is called as intrinsic conductivity.

  Eg: Silicon: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$, Germanium: $1s^2 2s^2 2p^6 3s^2 3p^6\ 3d^{10} 4s^2 4p^2$
- In the electronic configuration of both the semiconductor crystals there are four valence electrons. These four electrons will form covalent bonds, with the neighbouring electrons of the germanium atoms. Each covalent bond is formed by sharing each electron from the each atom. After bond formation, no free electron will remain in the outermost shell of the germanium semi conductor.

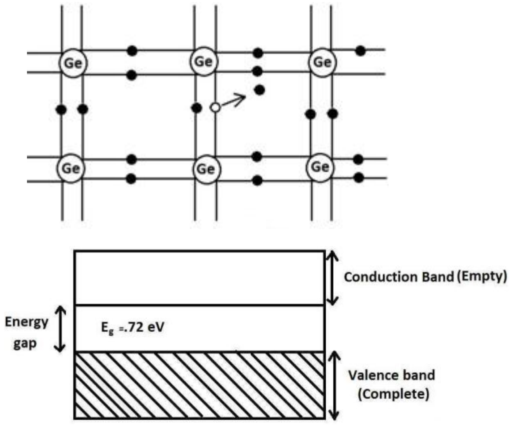


Figure 1.14: Schematic structure and band structure of an intrinsic semiconductor

- If the temperature will be maintained at zero Kelvin, then the valence band will be full of electrons. Energy gap is nearly 0.72 eV for germanium. So, at such a low temperature range it is impossible to cross the energy barrier. It will act as an insulator at zero Kelvin.
- Electrical conduction starts only if there is breakage in the covalent bonds and some of the electrons become free to jump from valence band to the conduction band.
- As the temperature increases, the shifting of the electrons from the valence band to the conduction band will also increase.
- Equation between the density of free electrons, density of holes and the density of the semiconductor is

$$\mathbf{n_e = n_h = n_i}$$

- Formula which can be used to calculate the no of holes and the electrons in the semi conductor is given by:

$$\mathbf{n_e = n_h = AT^{3/2}e^{-Eg\,/\,2kT}}$$

ii) Doped (extrinsic) semiconductors

An extrinsic semiconductor is a semiconductor doped by a specific impurity which is able to deeply modify its electrical properties, making it suitable for electronic applications (diodes, transistors, etc.) or optoelectronic applications (light emitters and detectors).

P-type semiconductors

A **P-type semiconductor** is an intrinsic semiconductor (like Si) in which an impurity acting as an *acceptor* (like e.g. boron B in Si) has been intentionally added. These impurities are called acceptors since once they are inserted in the crystalline lattice; they lack one or several electrons to realize a full bonding with the rest of the crystal.

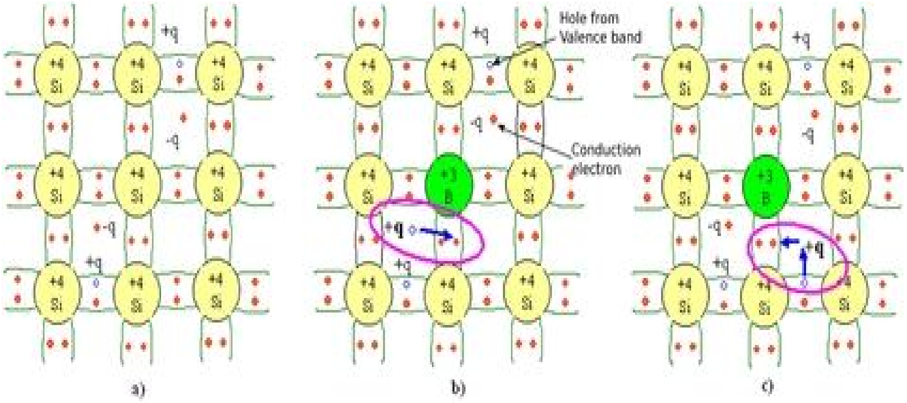


Figure 1.15: *schematic representation of a Si crystal doped with boron (B)*

From figure, we see that a p-type semiconductor has a lower electron density n and a higher hole density p than the same intrinsic semiconductor. Electrons are said to be the **minority carriers** whereas holes are the **majority carriers**.

For extrinsic semiconductors, the dopant density is always far higher than the intrinsic carrier density: $N_A >> n_i$. In the case of a p-type material, the hole density is then close to the dopant density N_A. Since the law of mass action is always true, we obtain the following expressions for the carrier densities

$$n = n_i^2/N_A; \; p = N_A$$

The **Fermi level for a p-type semiconductor** or chemical potential is then:

$$E_{FP} = E_V + kT \ln(N_V/N_A)$$

When the acceptor density is increased, the Fermi level moves closer to the edge of the valence band. If $N_A = N_V$ the Fermi level enters the valence band, the semiconductor is then said to be degenerate.

The important points regarding p-type semiconductors are summarized graphically in figure.

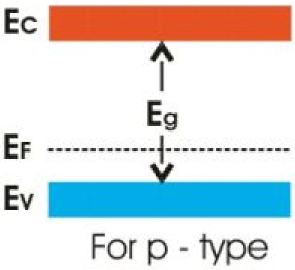


Figure 1.16: *P-type semiconductor*

N-type semiconductors

A **N-type semiconductor** is an intrinsic semiconductor (e.g. silicon **Si**) in which a donor impurity (e.g. arsenic **As** in Si, or Si in GaAs) has been intentionally introduced. The impurities are called donor impurities since they have to give an extra electron to the conduction band in order to make all the bonds with neighbouring atoms (As is pentavalent while Si is tetravalent).

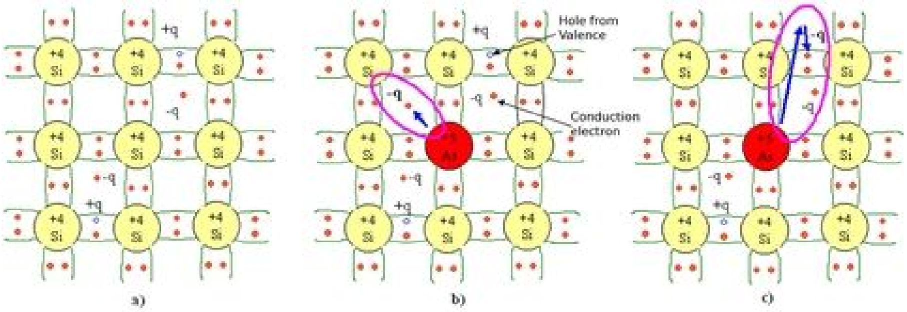


Figure 1.17: *Schematic representation of electronic bonds in a Silicon crystal doped with Arsenic As (n doping)*

From figure, we see that a n-type semiconductor has a higher electron density n and a lower hole density p than the same intrinsic semiconductor. Holes are said to be the **minority carriers** whereas electrons are the **majority carriers**.

Like in p-type semiconductors, we can write the following relationships, where N_D is the donor density:

$$p = n_i^2/N_D;\ n = N_D$$

The **Fermi level for a n-type semiconductor** is then:

$$E_{FP} = E_C - kT\ln(N_C/N_D)$$

When the donor density is increased, the Fermi level moves closer to the edge of the conduction band. If $N_D = N_C$ the Fermi level enters the conduction band, the semiconductor is then said to be degenerate.

The important points regarding n-type semiconductors are summarized graphically in figure.

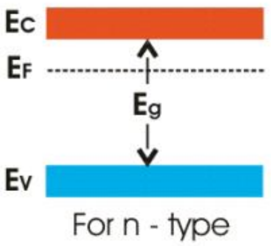


Figure 1.18: *N-type semiconductor*

LAW OF MASS ACTION

- The law of mass action states that the product of number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of amount of donor and acceptor impurity added.

Mathematically it is represented as

$$\mathbf{np = n_i^2 = constant}$$

Where n_i is the intrinsic carrier concentration

n is number of electrons in conduction band p is number of holes in valence band

Law of mass action for n-type semiconductor

- The law of mass action for n-type semiconductor is mathematically written as

$$n_n \, p_n = n_i^2 = \text{constant}$$

Where n_n = number of electrons in n-type semiconductor
p_n = number of holes in n-type semiconductor

- The electrons are the majority carriers and holes are the minority carriers in n-type semiconductor.

Law of mass action for p-type semiconductor

- The law of mass action for p-type semiconductor is mathematically written as

$$p_p \, n_p = n_i^2 = \text{constant}$$

Where p_p = number of holes in p-type semiconductor
n_p = number of electrons in p-type semiconductor

MOBILITY AND CONDUCTIVITY:

If a constant electric field E is applied to the metal, the electrons would be accelerated and the velocity would increase indefinitely with time, at each inelastic collision with an ion, an electron loses energy, and steady state condition is reached where a finite value of drift speed □ is attained.

The resultant drift velocity is in the direction opposite to that of the electric field, and its magnitude is proportional to E

$$\square = \mu E$$

where μ is called the mobility of the electrons

When a steady-state drift speed has been superimposed upon the random thermal motion of the electrons, a directed flow of electrons constitutes a current.

If the concentration of free electrons is n, the current density J is

$$J = ne\square = ne\mu E = \sigma E \qquad \text{(Ohm's law)}$$

Where conductivity of the metal in (ohm meter)$^{-1}$ is $\sigma = ne\mu$

DRIFT CURRENT

- The flow of charge carriers, which is due to the applied voltage or electric field is called drift current.
- The electrons (negatively charged particle) are attracted towards the positive terminal of a battery and holes (positively charged particle) are attracted towards the negative terminal.

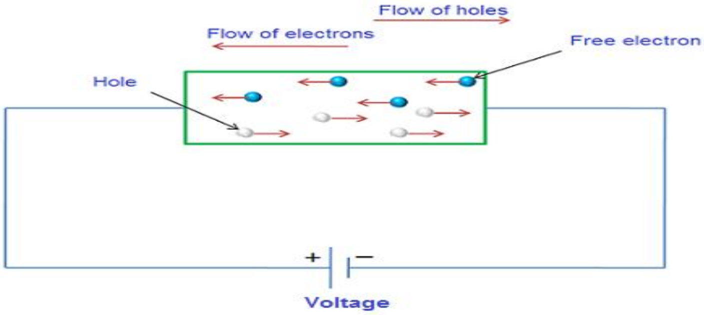


Figure 1.19: Flow of charge particles

- In a semiconductor, the electrons always try to move in a straight line towards the positive terminal of the battery.
- But, due to continuous collision with the atoms they change the direction of flow. Each time the electron strikes an atom it bounces back in a random direction.
- The applied voltage does not stop the collision and random motion of electrons, but it causes the electrons to drift towards the positive terminal.
- The average velocity that an electron or hole achieved due to the applied voltage or electric field is called drift velocity.
- The drift velocity of electrons is given by

$$V_n = \mu_n E$$

- The drift velocity of holes is given by

$$V_p = \mu_p E$$

Where V_n = drift velocity of electrons V_p = drift velocity of holes

μ_n = mobility of electrons μ_p = mobility of holes E = applied electric field

- The drift current density due to free electrons is given by

$$J_n = e n \mu_n E$$

- The drift current density due to holes is given by

$$J_p = e p \mu_p E$$

Where J_n = drift current density due to electrons

J_p = drift current density due to holes

e = charge of an electron = 1.602×10^{-19} Coulombs (C).

n = number of electrons

p = number of holes

Then the total drift current density is

$$J = J_n + J_p = e n \mu_n E + e p \mu_p E$$

$$J = e\,(n\mu_n + p\mu_p)\,E$$

DIFFUSION CURRENT

- The process by which, charge carriers (electrons or holes) in a semiconductor moves from a region of higher concentration to a region of lower concentration is called diffusion.

- Current produced due to motion of charge carriers from a region of higher concentration to a region of lower concentration is called diffusion current. Diffusion process occurs in a semiconductor that is non-uniformly doped.

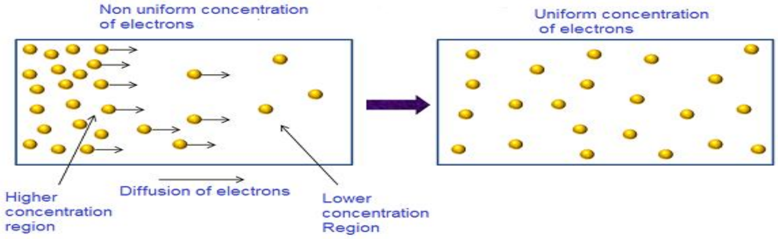


Figure 1.20: Illustration of diffusion current

- Electrons that move from left side to right side will constitute current. This current is called diffusion current. In p-type semiconductor, the diffusion process occurs in the similar manner.

- Both drift and diffusion current occurs in semiconductor devices. Diffusion current occurs without an external voltage or electric field applied. Diffusion current does not occur in a conductor. The direction of diffusion current is same or opposite to that of the drift current.

Concentration gradient

- The diffusion current density is directly proportional to the concentration gradient. Concentration gradient is the difference in concentration of electrons or holes in a given area. If the concentration gradient is high, then the diffusion current density is also high. Similarly, if the concentration gradient is low, then the diffusion current density is also low.

- The concentration gradient for n-type semiconductor is given by

$$J_n \propto \frac{dn}{dx}$$

- The concentration gradient for p-type semiconductor is given by

$$J_p \propto \frac{dp}{dx}$$

Where J_n = diffusion current density due to electrons

J_p = diffusion current density due to holes

- The diffusion current density due to electrons is given by

$J_n = +e\, D_n \frac{dn}{dx}$ Where D_n is the diffusion coefficient of electrons

- The diffusion current density due to holes is given by

$J_p = -e\, D_p \frac{dp}{dx}$ Where D_p is the diffusion coefficient of holes

- The total current density due to electrons is the sum of drift and diffusion currents.

$$J_n = \text{Drift current} + \text{Diffusion current}$$

$$J_n = en\mu_n E + e\, D_n \frac{dn}{dx}$$

- The total current density due to holes is the sum of drift and diffusion currents.

$$J_p = \text{Drift current} + \text{Diffusion current}$$

$$J_p = ep\mu_p E - e\, D_p \frac{dp}{dx}$$

- The total current density due to electrons and holes is given by

$$J = J_n + J_p$$

HALL EFFECT:

- If a specimen carrying a current **I** is placed in a transverse magnetic field **B**, an electric filed E is induced in the direction perpendicular to both **I** and **B**. This phenomenon, known as the Hall Effect.
- I is in the positive X direction and B is in the positive Z direction, a force will be exerted in the negative Y direction on the current carriers.

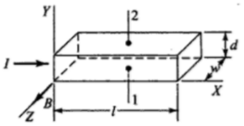


Figure 1.21: *Pertaining to the Hall Effect. The carriers are subjected to a source in the negative Y direction*

- If the semiconductor is n-type, so that the current is carried by electrons, these electrons will be forced downward toward side 1 and side 1 becomes negatively charged with respect to side 2.

- Hence a potential V_H, called the Hall voltage, appears between the surfaces 1 and 2.
- In the equilibrium state the electric field intensity E due to the Hall effect must exert a force on the carrier which just balances the magnetic force

$$eE=Be\square$$

e : Magnitude of the charge on the carrier

$\square$: Drift speed

$E = V_H/d$, D is the distance between surfaces 1 and 2.

- Current density $J = \rho\square = I/wd$, ρ is the charge density, and w is the width of the specimen in the direction of the magnetic field.
- Combining the above relations, we get

$$V_H = Ed = B\square d = BJd/\rho = BI/\rho w$$

- If polarity of V_H is positive at terminal 2, then the carriers must be electrons, and $\rho=ne$, where n is the electro concentration. If , on the other hand, terminal 1 becomes charged positively with respect to terminal 2, the semiconductor must be p-type and $\rho=pe$, where p is the hole concentration.
- Hall coefficient R_H is defined as,

$$R_H = 1/\rho$$

$$\text{Hence } R_H = V_H w/BI$$

- If conduction is due primarily to charges of one sign, the conductivity σ is related to the mobility μ by $\sigma = \rho\mu$
- If the conductivity is measured together with the Hall coefficient, the mobility can be determined from $\mu = \sigma R_H$

- If the thermal distribution of current carriers is taken into account R_H is defined by $3\Pi/8\rho$. Also, $\mu = (8\sigma/3\Pi)R_H$

Applications:

- Used to determine whether a semiconductor is n- or p-type and
- To find the carrier concentration. Also, by simultaneously measuring the conductivity σ, the mobility μ can be calculated.

Assignment-Cum-Tutorial Questions

UNIT-I

SECTION – A

Objective Questions

1. The factors governing the resistance of a conductor at a given temperature are [ ]
   a) resistivity, length, cross sectional area c) length, width & height
   b) resistivity, width & cross sectional area d)length,resistivity & height
2. Resistance, voltage and current are connected in an electrical circuit by (give the relation)______________.
3. Resistance is measured in ___________.
4. Mention the different types of resistors______________ &__________________.
5. Write the equation for the capacitance in terms of its physical parameters_____________.
6. What do variable capacitors use for dielectric? [ ]

   a) ceramic, electrolytic, mica or paper c) ceramic, paper, plastic or mica
   b)air, ceramic, mica or plastic d) mica, ceramic, plastic or electrolytic
7. Draw the symbols for resistor, capacitor and inductor ________________.
8. In insulators, the energy gap between valence and conduction bands is
   a) very large b) zero c) very small d) infinite [ ]
9. The concentration of minority carriers in an extrinsic semiconductor under equilibrium is [ ]
   (a) Directly proportional to the doping concentration.
   (b) Inversely proportional to the doping concentration.
   (c) Directly proportional to the intrinsic concentration.
   (d) Inversely proportional to the intrinsic concentration.
10. Drift current in semiconductors depends upon [ ]
    (a) Only the electric field
    (b) Only the carrier concentration gradient

(c) Both the electric field and the carrier concentration

(d) Neither the electric field nor the carrier concentration gradient

11. A thin P – type silicon sample is uniformly illuminated with light which generates excess carriers. The recombination rate is directly proportional to

(a) The minority carrier mobility [ ]

(b) The minority carrier recombination lifetime

(c) The majority carrier concentration

(d) The excess minority carrier concentration

12. Define mass action law

13. A P-type silicon sample has higher conductivity compared to an n-type silicon sample having the same dopant concentration. **[TRUE/FALSE]**

14. Mention the applications of Hall Effect

15. In a semiconductor, the energy gap between valence and conduction bands is about [ ]

a) 15eV b) 100eV c) 50eV d) 1eV

16. Measurement of Hall coefficient enables the determination of [ ]

a) mobility of charge carriers

b) type of conductivity and concentration of charge carriers

c) temperature coefficient and thermal conductivity

d) resistivity of the material

17. Addition of pentavalent impurity to a semiconductor creates many[ ]

a) free electrons b) holes c) valence electrons d) bound electrons

18. The conductivity of an intrinsic semiconductor is given by [ ]

a) $\sigma_i = en_i^2 (\mu_n - \mu_p)$ **b)** $\sigma_i = en_i (\mu_n - \mu_p)$ **c)** $\sigma_i = en_i (\mu_n + \mu_p)$ **d)** $\sigma_i = en_i (\mu_n + \mu_p)$

2

19. The Hall Effect voltage in intrinsic silicon is [ ]

a) positive b) zero c) negative d) fraction

20.The electron and hole concentration in an intrinsic semiconductor are n_i/ cm^3 at 300k. Now, if acceptor impurities are concentration of N_a cm^{-3} (where $N_a >> n_i$), the electron concentration cm^{-3} at 300k will be [ ]

(a) n_i (b) $n_i + N_a$ (c) $N_a - n_i$ (d) n_i^2 / N_a

21. The Probability that an electron in a metal occupies the Fermi level, at any temperature. (> 0K) [ ]

(a) 0 (b)1 (c) 0.5 (d)1.0

22. In a P-type Si sample the hole concentration is$2.25 \times 10^{15}/cm^3$. The intrinsic carrier Concentration is $1.5 \times 10^{10}/cm3$ the electron concentration is [ ]

(a) Zero (b)$10^{10}/cm3$ (c) $10^5\ /cm3$ (d)$1.5 \times 10^{25}/cm3$

23. A small concentration of minority carries is injected into a homogeneous semiconductor crystal at one point. An electric field of 10V/cm is applied across the crystal and this moves the minority carries a distance of 1 cm in 20 μ sec. The mobility (in cm^2 /v-sec) will be [ ]

(a) 1,000 (b)2,000 (c) 5,000 (d)500,000

24.Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the [ ]

(a) Diffusion current (b) Drift current
(c) Recombination current (d) Induced current

SECTION-B

Descriptive Questions

1. What do you understand by intrinsic and extrinsic semiconductors?
2. What do you understand by a semiconductor? Discuss the types.
3. Define and explain Hall Effect.
4. Derive the drift and diffusion currents.
5. Define hall Resistivity.

TUTORIAL TASK

1. Find the resistance of a 100-m long tungsten ($\rho = 5.6 \times 10^{-8}$ Ωm) wire that has a circular cross section with a diameter of 0.1mm.
2. The voltage across an inductance is 250V when its current changes at the rate of 10mA/μs. What is L?
3. In a P-type silicon sample, the hole concentration is 2.25×10^{15} /cm^3. If the intrinsic carrier concentration is 1.5×10^{10} /cm^3, find out the electron concentration.
4. Determine the conductivity of Germanium
   a) In intrinsic condition at 300K
   b) with donor impurity of 1 in 10^7
   c) With acceptor impurity of 1 in 10^8
   d) with both impurities simultaneously
   Given that for Germanium at room temperature n_i=2.5X10^{13}/cm^3, μ_n=3800cm^2/V-S, μ_p=1800cm^2/V-S and a number of Germanium atoms/cm^3=4.4x10^{22}/cm^3.
5. Find the conductivity of silicon when the donor impurity of 1 in 10^8 is applied. The intrinsic value of silicon atom is 1.5x10^{10} cm^{-3} at 300^0K. The mobility of electrons and holes are 1300cm^2/V-sec and 500 cm^2/V-sec respectively. The number of silicon atoms is 5x10^{25} cm$^{-3.}$
6. The intrinsic carrier concentration of silicon sample at 3000 K is $1.5 \times 10^{16}/m^3$. If after doping, the number of majority carriers is $5 \times 10^{20}/m^3$, the minority carrier density is?
7. A silicon bar is doped with donor impurities $N_D = 2.25 \times 10^{15}\ atoms/\ cm^3$. Given the intrinsic carrier concentration of silicon at T = 300 K is $ni = 1.5 \times 10^{10}\ cm^{-3}$. Assuming complete impurity ionization, the equilibrium electron and hole concentrations are?
8. Find the magnitude of the Hall voltage in an N-type silicon bar, which has a majority carrier concentration $N_D = 10^{13}$ /cm^3. Assume B_z= 0.2Wb/m^2, d= 5mm, and E_x=5V/cm.

9. Find the magnitude of the Hall voltage in an P-type silicon bar, which has a majority carrier concentration $N_A = 10^{12}/cm^3$. Assume $B_z= 0.2Wb/m^2$, d= 5mm, and $E_x=5V/cm$.
10. Hall coefficient of a specimen depends on Si, found to be 3.66×10^{-4} m^3/C. The resistivity of the specimen is 8.93×10^{-3} m. Find the mobility and density of the charge carriers.
11. The Hall coefficient of certain Si specimen was found to be 7.35×10^{-5} m^3/C from 100 to 400K. If the conductivity was found to be 200 $1/\Omega m$. Calculate the density and mobility of the charge carrier.

SECTION - C

GATE QUESTIONS

1. Consider two energy levels: E1, E eV above teh Fermi level and E2, E eV below the Fermi level. P1 and P2 are the probablilities of E1 and E2 being occupied by the electron respectively. Then [GATE-87]

a) P1>P2 b) P1 = P2 [ ]

c) P1 < P2 d) P1 and P2 depend on number of free electrons.

2. In an intrinsic semiconductor, the free electron concentration depends on [GATE-87]

a) Effective mass of electrons only [ ]

b) Effective mass of holes only

c) Temperature of the semiconductor

d) Width of the forbidden energy band of the semiconductor

3. According to the Einstein relation, for any semiconductor, the ratio of diffusion constant to mobility of carriers [GATE-87]

a) Depends upon the temperature of the semiconductor [ ]

b) Depends upon the type of the semiconductor

c) Varies with life time of the semiconductor

d) Is a universal constant.

4. Direct band gap semiconductors [GATE-87]

a) Exhibit short carrier lifetime and they are used for fabricating BJTs

b) Exhibit long carrier lifetime and they are used for fabricating BJTs

c) Exhibit short carrier lifetime and they are used for fabricating LASERs

d) Exhibit long carrier lifetime and they are used for fabricating LASERs

5. Due to illumination by light, the electron and hole concentrations in a heavily dope N-type semiconductor increases by Δn and Δp respectively, if n_i is the intrinsic carrier concentration then [GATE-89]

   a) $\Delta n < \Delta p$ b) $\Delta n > \Delta p$ c) $\Delta n = \Delta p$ d) $\Delta n \times \Delta p = n_i^2$ [ ]

6. The concentration of ionized acceptors and donors in a semiconductor are N_A, N_D respectively. If $N_A > N_D$ and n_i is the intrinsic concentration, then the position of the Fermi level with respect to the intrinsic level depends on [GATE-89]

   a) $N_A - N_D$ b) $N_A + N_D$ c) $(N_A \times N_D)/ n_i^2$ d) n_i [ ]

7. A silicon sample is uniformly doped with 10^{16} phosphorous atoms/cm^3 and 2×10^{16} boron atoms/cm^3. If all the dopants are fully ionized, the material is ____________________. [GATE-91]

8. An n type Si sample, having electron mobility μ_n twice the hole mobility μ_p, is subjected to a steady illumination such that the electron concentration doubles from its thermal equilibrium value, as a result, the conductivity of the sample increases by a factor of ____________. [G-91]

9. A p-type Si sample has a higher conductivity compared to an n-type sample having the same dopant concentration. (TRUE/FALSE). [G-94]

10. The drift velocity of electrons, in Si [GATE-95]

    a) is proportional to the electric field for all values of electric field.

    b) is independent of the electric field

    c) increases at low values of electric field and decreases at high values of electric field exhibiting negative differential resistance

    d) Increases linearly with electric field at low values of electric field and gradually saturates at higher values of electric field.

11. The probability that an electron in a metal occupies the Fermi level at any temperature T is ($T > 0^0K$)_______. [GATE-95]

12. A long specimen of p-type semiconductor is [GATE-98]

a) is positively charged b) is electrically neutral

c) has an electric field directed along its length d) acts as a dipole

13. The units of (q/KT) are ______________. [GATE-98]

14. N-type silicon is obtained by doping silicon with [GATE-03]

a) Germanium b) Aluminium c) Boron d) Phosphorous

15. The band gap of Si at 300^0K is [GATE-03]

a) 1.36eV b) 1.10eV c) 0.80eV d) 0.67Ev [ ]

16. The primary reason for the widespread use of silicon in semiconductor device technology is [GATE-05]

a) Abundance of Si on the surface of the earth

b) Larger band gap of Si in comparison to Ge

c) Favorable properties of SiO_2

d) Lower melting point

17. The concentration of minority carriers in an extrinsic semiconductor under equilibrium is [GATE-06]

a) Directly proportional to the doping concentration [ ]

b) Inversely proportional to the doping concentration

c) Directly proportional to the intrinsic concentration

d) Inversely proportional to the intrinsic concentration

18. Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the [GATE-06]

a) Diffusion current b) Drift current

c) Recombination current d) Induced current

19. The ratio of the mobility to the diffusion coefficient in a semiconductor has the units _________________. [GATE-09]

20. Drift current in semiconductors depends upon [GATE-11]

a) Only the electric field

b) Only the carrier concentration gradient

c) Both the electric field and the carrier concentration

d) Both the electric field and the carrier concentration gradient.

21. An N-type semiconductor having uniform doping is biased as shown in the figure. [GATE-14]

UNIT-2

SEMICONDUCTOR DIODE CHARACTERISTICS

Objectives

- Understand the operation and characteristics of P-N junction.
- Analyze the concept of junction voltages and current components.
- Define diode resistances and capacitances under different biasing regions.

Syllabus:

Open circuited p-n junction, Current components in a p-n diode, Diode forward and reverse currents, The volt-ampere characteristics, Temperature dependence of V-I characteristics, Resistance, Transition capacitance, Diffusion capacitance.

Outcomes

After completion of this unit, student will be able to

- Analyze the working principle of a p-n junction diode under different biasing regions.
- Understand the current components involved in the working of a p-n diode.
- Analyze the V-I characteristics and temperature affect on them.
- Define the various resistances under different biasing regions.
- Understand the transition and diffusion capacitance.

1. OPEN CIRCUITED P-N JUNCTION

- ➢ N-type semiconductor has an excess of free electrons compared to the P-type region, and P-type has an excess of holes compared to the N-type region. Therefore when N-doped and P-doped pieces of semiconductor are placed together to form a junction, electrons migrate into the P-side and holes migrate into the N-side(much as ink diffuses into water until it is uniformly distributed).

- Departure of an electron from the N-side to the P-side leaves a positive donor ion behind on the N-side, and likewise the hole leaves a negative acceptor ion on theP-side.
- The diffused electrons come into contact with holes on the P- side and are eliminated by recombination. Likewise for the diffused holes on the N-side. The net result is the diffused electrons and holes are gone, leaving behind the charged ions adjacent to the interface in a region with no mobile carriers (called the depletion region). The uncompensated ions are positive on the N side and negative on the Pside.

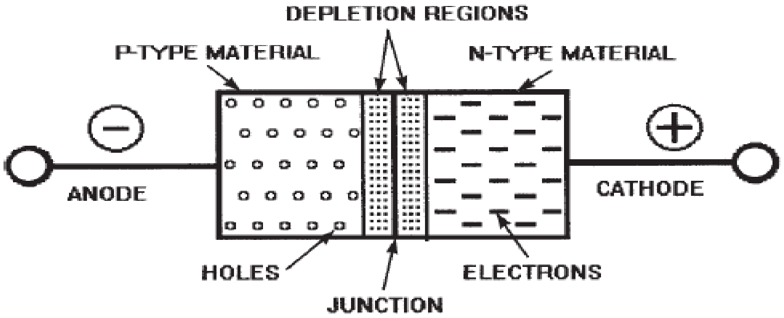


Fig. 2.1:Formation of P-N junction

- This creates an electric field that provides a force opposing the continued exchange of charge carriers. When the electric field is sufficient to arrest further transfer of holes and electrons, the depletion region has reached its equilibrium dimensions.
- Barrier Potential: Near the junction one side there are many positive charges and other side there is many negative charges. According to coulomb's law, there exists a force between the charges. The direction of an electric field is from positive charge toward negative charge. The opposite charges existing near the junction creates a potential difference across the junction. This potential difference is called the built-in voltage also called the junction voltage or barrier voltage or contact potential.

Energy Band Diagram of Open Circuited PN Junction (or) Derivation for Barrier Potential

- The energy band diagram of p and n regions undergo relative shift to equalize the Fermi level. The Fermi level should be constant throughout the specimen at equilibrium.
- Fermi level E_F is closer to the conduction band edge E_{Cn}in the n-type material and closer to the valence band edge E_{Vp} in the p side.
- The conduction band edge E_{Cp}in the p material cannot be at the same level as E_{Cn}, nor can the valence band edge E_{Vn} in the n side line up with E_{Vp}.
- Hence the energy-band diagram for a p-n junction appears as shown in figure 1.4, where a shift in energy levels is E_0.

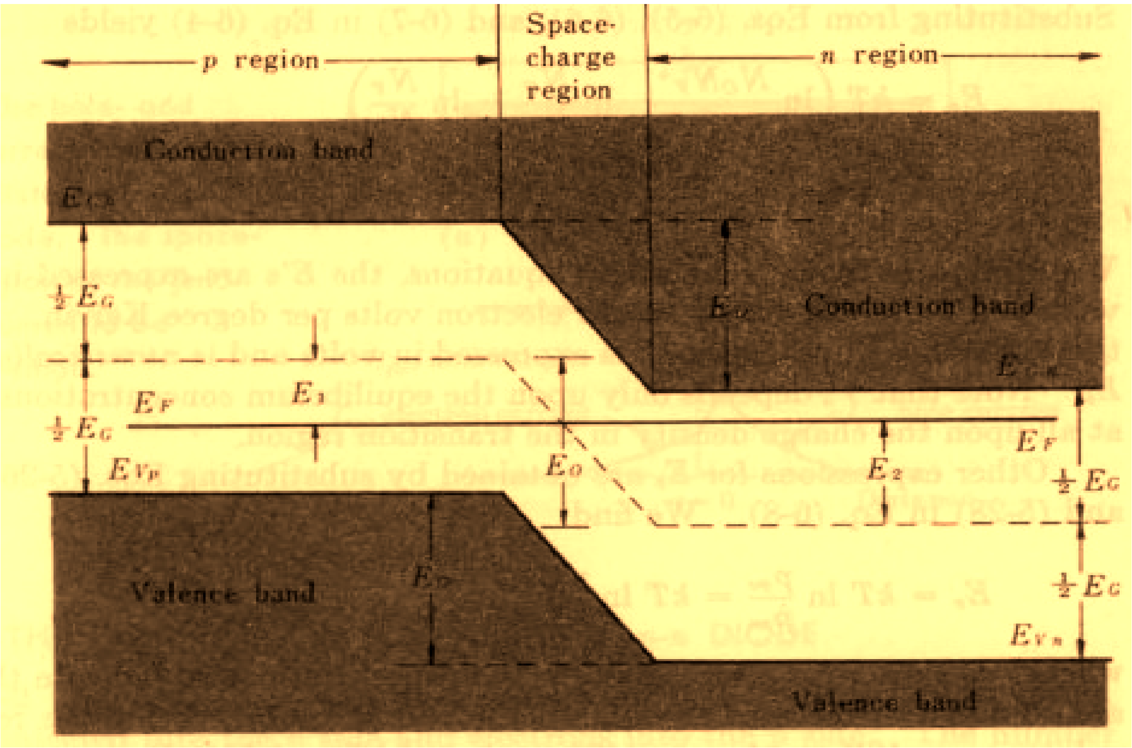


Fig.2.2: Band diagram for a p-n junction under open-circuit conditions.

From the above figure,

$$E_o = E_{Cp} - E_{Cn} = E_{Vp} - E_{Vn} = E_1 + E_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

This energy E_0 represents the potential energy of the electrons at the junction.

$$E_F - E_{V_p} = \tfrac{1}{2}E_G - E_1 \quad \text{----------------------} \quad (2.2)$$

$$E_{Cn} - E_F = \tfrac{1}{2}E_G - E_2 \quad \text{---------------------} \quad (2.3)$$

By adding above two equations

$$E_o = E_1 + E_2 = E_G - (E_{Cn} - E_F) - (E_F - E_{V_p}) \quad \text{-------------------} \quad (2.4)$$

From the equations

$$E_G = kT \ln \frac{N_C N_V}{n_i^2} \quad \text{--------------------} \quad (2.5)$$

for n type

$$E_{Cn} - E_F = kT \ln \frac{N_C}{N_D} \quad \text{--------------------} \quad (2.6)$$

for p type

$$E_F - E_{V_p} = kT \ln \frac{N_V}{N_A} \quad \text{--------------------} \quad (2.7)$$

Substituting equations (2.5), (2.6) and (2.7) into equation (2.4), we obtain

$$\begin{aligned} E_o &= kT \left(\ln \frac{N_C N_V}{n_i^2} - \ln \frac{N_C}{N_D} - \ln \frac{N_V}{N_A} \right) \\ &= kT \ln \left(\frac{N_C N_V}{n_i^2} \frac{N_D}{N_C} \frac{N_A}{N_V} \right) = kT \ln \frac{N_D N_A}{n_i^2} \end{aligned} \quad \text{-------------------} \quad (2.8)$$

The contact difference in potential V_0 is expressed in volts and is numerically equal to E_0. Note that V_o depends only upon the equilibrium concentrations.

By using the relations

$N_n = N_D$; $p_n = n_i^2/N_D$; $n_p.p_p = n_i^2$; $p_p = N_A$; $np = n_i^2/N_A$

We can write equation (2.8) as

$$E_o = kT \ln \frac{p_{po}}{p_{no}} = kT \ln \frac{n_{no}}{n_{po}} \quad \text{-------------------} \quad (2.9)$$

Where the subscripts 0 are added to the concentrations to indicate that these are obtained under thermal equilibrium conditions.

2.THE CURRENT COMPONENTS IN A P-N JUNCTION DIODE

- The current carried by electrons which is diffusion current due to minority carriers, decreases exponentially with respect to distance measured from the junction. This current due to electrons, on p-side which are minority carriers is denoted as I_{np}.

- Similarly holes from p-side diffuse into n-side carry current which decreases exponentially with respect to distance measured from the junction. This current due to holes on n-side, which are minority carriers is denoted as I_{pn}.
- If distance is denoted by x then,

  $I_{np}(x)$ = Current due to electrons in p-side as a function of x

  $I_{pn}(x)$ = Current due to holes in n-side as a function of x
- At the junction i.e. at $x = 0$, electrons crossing from n-side to p-side constitute a current, $I_{np}(0)$ in the same direction as holes crossing the junction from p-side to n-side constitute a current, $I_{pn}(0)$.
- Hence the current at the junction is the total conventional current I flowing through the circuit.

$$I = I_{pn}(0) + I_{np}(0)$$

- As the entire circuit is a series circuit, the total current must be maintained at, independent of x. This indicates that on p-side there exists one more current component which is due to holes on p-side which are the majority carriers. It is denoted by I_{pp} (x) and the addition of the two currents on p-side is total current I.

I_{pp} (x) = Current due to holes in p-side.$I_{nn}(x)$ = Current due to electrons in n-side.

- **On p-side**, $I = I_{pp}(x) + I_{np}(x)$; **On n-side**, $I = I_{nn}(x) + I_{pn}(x)$

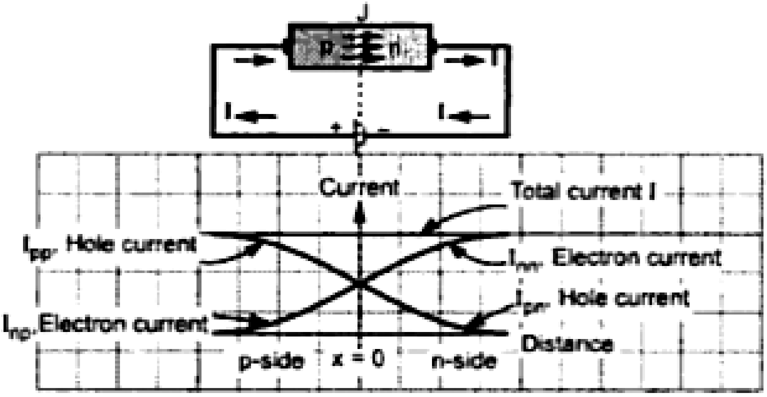


Fig.2.3:Carrier distribution in P-N junction

Therefore current I at x=0 is

$$I = I_{pn}(0) + I_{np}(0) \quad \text{-----------------------} \quad (2.10)$$

If a forward bias is applied to the diode, holes are injected from the p side into the n material. The concentration P_n of holes in the n side is increased above its thermal-equilibrium value P_{no}

$$p_n(x) = p_{no} + P_n(0)\epsilon^{-x/L_p} \quad \text{-----------------------} (2.11)$$

where the parameter L_p is called the diffusion length for holes in the n material, and the injected, or excess, concentration at x = 0 is

$$P_n(0) = p_n(0) - p_{no} \quad \text{----------------------} (2.12)$$

These several hole-concentration components are indicated in figure 2.4.

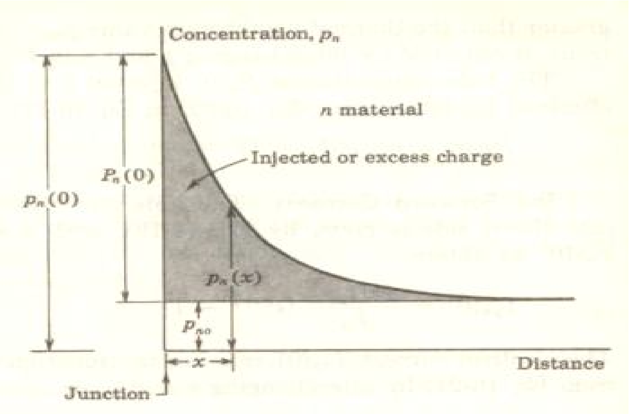


Fig.2.4: Defining the several components of hole concentration in the n side of a forward-biased diode.

$$I_{pn} = -AeD_p \frac{dp_n}{dx} \text{ ------------------------(2.13)}$$

Taking derivative of above equation

$$I_{pn}(x) = \frac{AeD_p P_n(0)}{L_p} \epsilon^{-x/L_p} \text{ ------------------------(2.14)}$$

$$I_{pn}(0) = \frac{AeD_p P_n(0)}{L_p} \text{ ------------------------ (2.15)}$$

It is clear that the hole current decreases exponentially with distance. The dependence of I_{pn}upon applied voltage is contained implicitly in the factor $P_n(0)$ because the injected concentration is a function of the applied voltage.

For an open circuited p-n junction, $P_p = P_{p0}$,$P_n = P_{no}$ and $V_B=V_0$, then

$$P_{po} = P_{no}.\ \exp(V_B/V_T)\text{------------------------(2.16)}$$

If the p-n junction is forward biased, then $V_B = V_0 - V$, then at x=0, $P_n = P_n(0)$ then

$$P_{po} = P_n(0)\ \exp[(Vo-V)/\ V_T]\text{-------------------(2.17)}$$

Comparing above two equations, results in

$$P_{no}\exp(Vo/V_T) = P_n(0)\ .\ \exp[(Vo-V)/\ V_T]$$

$$P_n(0) = P_{no}\ .[\ \exp(Vo/V_T)\ /\ \exp((Vo-V)/\ V_T)]\text{---------------(2.18)}$$

It is clear that the hole current decreases exponentially with distance. The dependence of Ip_nupon applied voltage is contained implicitly in the factor $P_n(0)$ because the injected concentration is a function of voltage.

For an open circuited p-n junction, $p_p = p_{po}$,$p_n = p_{no}$ and $V_B=V_o$, then

$$p_{po} = p_{no}.\ \exp(V_B/V_T)\text{----------------------------(2.19)}$$

If the p-n junction is forward biased, then $V_B = V_0 - V$, then at x=0, $p_n = p_n(0)$. then

$$p_{po} = p_n(0)\ \exp[(Vo-V)/\ V_T]\text{-------------------(2.20)}$$

Comparing above two equations, results in

$p_{n0}.\ \exp(Vo/V_T) = p_n(0)\ .\ \exp((Vo-V)/\ V_T)$

$p_n(0) = p_{no}\ .\{\exp(Vo/V_T)\ /\ \exp((Vo-V)/\ V_T)\}$

$\mathbf{p_n(0) = p_{no}.\ exp\ (V/V_T)}$------------------------(2.21)

The equation (2.21) is called as the **law of junction**.

As we know,

$$P_n(0) = p_n(0) - p_{no} \text{ ----------------------(2.22)}$$

By substituting $p_n(0)$ in equation (2.22),

$$P_n(0) = p_{no}\ .\ [\exp(V/V_T) - 1] \text{--------------------(2.23)}$$

Where $P_n(0)$ is the concentration of holes injected into n –side at the junction.

$$I_{pn}(0) = \frac{AeD_pP_n(0)}{L_p} \Rightarrow I_{pn}(0) = \frac{AeD_pp_{no}}{L_p}(\epsilon^{V/V_T} - 1) \text{ ----------------(2.24)}$$

Similarly

$$I_{np}(0) = \frac{AeD_nn_{po}}{L_n}(\epsilon^{V/V_T} - 1) \text{ --------------------(2.25)}$$

1.3 DIODE FORWARD CURRENT

The total diode current I is given by sum of $I_{pn}(0)$ and $I_{np}(0)$. i.e., $\mathbf{I = I_{pn}(0) + I_{np}(0)}$

$$I = I_o(\epsilon^{V/V_T} - 1) \text{ ------------ (2.26)}$$

Equation (1.29) is called **diode forward current equation (or) diode equation.**

$$I_o \equiv \frac{AeD_pp_{no}}{L_p} + \frac{AeD_nn_{po}}{L_n} \text{ ----------------- (2.27)}$$

where I_o is called as reverse saturation current.

DIODE REVERSE CURRENT

I_0=$[AeD_p\ /L_p\ )\ P_{no} + AeD_n\ /Ln)\ n_{po}\ ]$

According to mass action law $n.p = n_i^2$,

P-type: $n_p p_p = n_i^2$

$n_p = n_i^2/\ p_p$

$n_p = n_i^2/\ N_A$

N-type: $n_n p_n = n_i^2$

$p_n = n_i^2/\ n_n$

$p_n = n_i^2/\ N_D$

So, the reverse saturation current is given by $I_0=[AeD_p\ n_i^2/L_p\ N_D)\ + AeD_n n_i^2\ /Ln\ N_A)]$

$$I_o = Ae\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right) n_i^2 \quad \text{--------------------}(2.28)$$

Wheren_i^2 is given by

$$n_i^2 = A_o T^3 \epsilon^{-E_{G0}/kT} = A_o T^3 \epsilon^{-V_{G0}/V_T} \quad \text{-------------------------}(2.29)$$

Where V_{G0} is a voltage which is numerically equal to the forbidden-gap energy E_{G0} in eV.

V_T is the volt equivalent of temperature.

The temperature dependence of I_0 is $I_0= k_1\ T^2 \epsilon^{-V_{G0}/V_T}$ where k_1 is a constant independent of temperature.

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$ (For ideal diode)

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$ (For non ideal diode)

Where

I = the net current flowing through the diode;

I_0 = "dark saturation current", the diode leakage current density in the absence of light;

V = applied voltage across the terminals of the diode;

q = absolute value of electron charge ($1.602 * 10^{-19}$ C)

k = Boltzmann's constant ($1.38 * 10^{-23}$ J/K)

T = absolute temperature (K).

η = ideality factor, a number between 1 and 2 which typically increases as the current decreases.

- The "dark saturation current" (I_0) is an extremely important parameter which differentiates one diode from another. I_0 is a measure of the recombination in a device. A diode with a larger recombination will have a larger I_0.

3. DIODE FORWARD AND REVERSE CURRENTS

Forward Bias:

- In forward bias, the p-type is connected with the positive terminal and the n-type is connected with the negative terminal. with a battery connected this way, the holes in the P-type region and the electrons in the N-type region are pushed toward the junction. This reduces the width of the depletion zone.

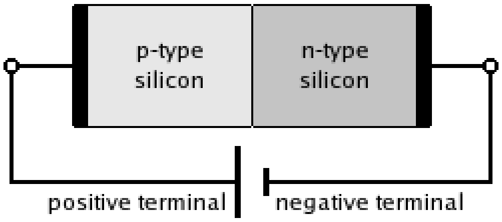


Fig.2.5: Forward Biased P-N Junction diode

- The positive potential applied to the P-type material repels the holes, while the negative potential applied to the N-type material repels the electrons. As electrons and holes are pushed toward junction, the distance between them decreases.

- This lowers the barrier in potential. With increasing forward-bias voltage, the depletion zone eventually becomes thin enough that the zone's electric field cannot counteract charge carrier motion across the p–n junction, as a consequence reducing electrical resistance.
- The electrons that cross the p–n junction into the P-type material (or holes that cross into the N-type material) will diffuse in the near-neutral region. Therefore, the amount of minority diffusion in the near-neutral zones determines the amount of current that may flow through the diode.

Reverse Bias:

- Connecting the *P-type* region to the *negative* terminal of the battery and the *N-type* region to the *positive* terminal corresponds to reverse bias. If a diode is reverse-biased, the voltage at the cathode is comparatively higher than the anode. Therefore, no current will flow until the diode breaks down. The connections are illustrated in the diagram to the right.

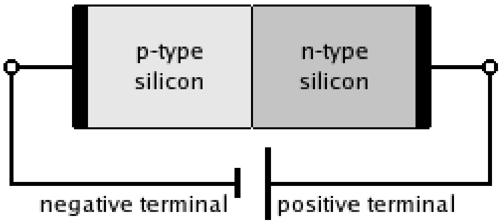


Fig. 2.6: Reverse Biased P-N Junction diode

- Because the p-type material is now connected to the negative terminal of the power supply, the 'holes' in the P-type material are pulled away from the junction, causing the width of the depletion zoneto increase.

- Likewise, because the N-type region is connected to the positive terminal, the electrons will also be pulled away from the junction. Therefore, the depletion region widens, and does so increasingly with increasing reverse-bias voltage.

- This increases the voltage barrier causing a high resistance to the flow of charge carriers, thus allowing minimal electric current to cross the p–n junction. The increase in resistance of the p–n junction results in the junction behaving as an insulator.

4. JUNCTION DIODE STATIC I-V CHARACTERISTICS

- The operation of diodes (as with other semiconductor devices) is often described by a special graph called a "characteristic curve". These graphs show the relationship between the currents and voltages associated with the different terminals of the device.
- In forward conduction of the diode initially no current flows until the applied voltage is at about the forward junction potential, after which current rises steeply showing that the forward resistance (I/V) of the diode is very low; a small increase in voltage giving a large increase in current.
- Here we see that although the reverse voltage increases hardly any current flows. This small current is called the leakage current of the diode and is typically only a few micro-amps with germanium diodes and even less in silicon.
- If a high enough reverse voltage is applied however there is a point (called the reverse breakdown voltage) where the insulation of the depletion layer breaks down and a very high current suddenly flows. In most diodes this breakdown is permanent and a diode subjected to this high reverse voltage will be destroyed.

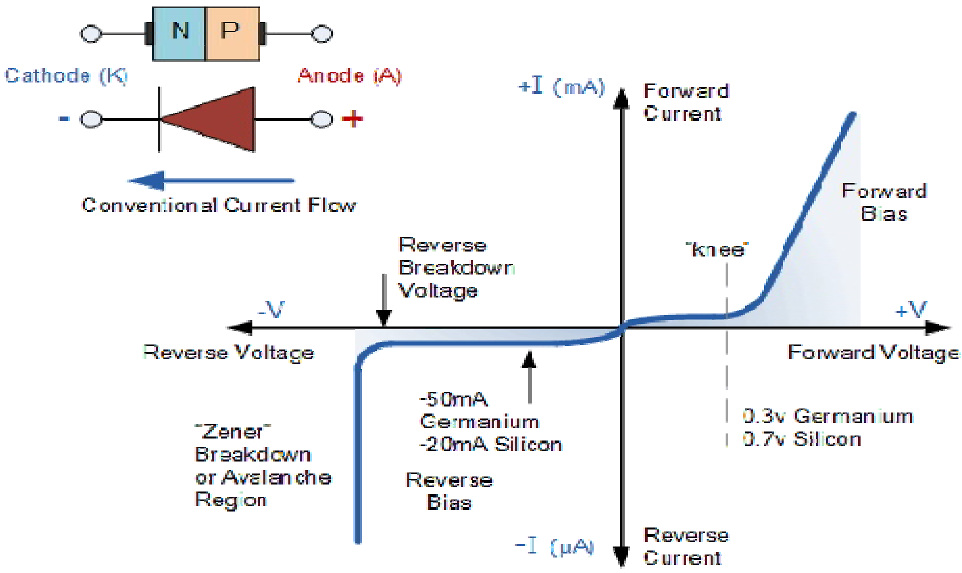


Fig. 2.7: Diode symbol and V-I characteristics

- The junction (depletion) region has a physical thickness that varies with the applied voltage.
- When a diode is **Zero Biased** no external energy source is applied and a natural **Potential Barrier** is developed across a depletion layer which is approximately 0.5V to 0.7V for silicon diodes and approximately 0.3 volt for germanium diodes.
- When a junction diode is **Forward Biased** the thickness of the depletion region reduces and the diode acts like a short circuit allowing full current to flow.
- When a junction diode is **Reverse Biased** the thickness of the depletion region increases and the diode acts like an open circuit blocking any current flow, (only a very small leakage current).

5. TEMPERATURE DEPENDENCE ON V-I CHARACTERISTICS OF A P-N JUNCTION DIODE

The temperature has following effects on the diode parameters,

1. The cut-in voltage decreases as the temperature increases. The diode conducts at smaller voltage at large temperature.

2. The reverse saturation current increases as temperature increases.

   This increases in reverse current I_o is such that it doubles at every 10 °C rise in temperature. Mathematically,

$$I_{02} = I_{01} * 2^{(\Delta T/10)}$$

Where I_{o2} = Reverse current at T_2 °C
I_{o1} = Reverse current at T_1 °C
$\Delta T = (T_2 - T_1)$

3. The voltage equivalent of temperature V_T also increases as temperature increases.
4. The reverse breakdown voltage increases as temperature increases.

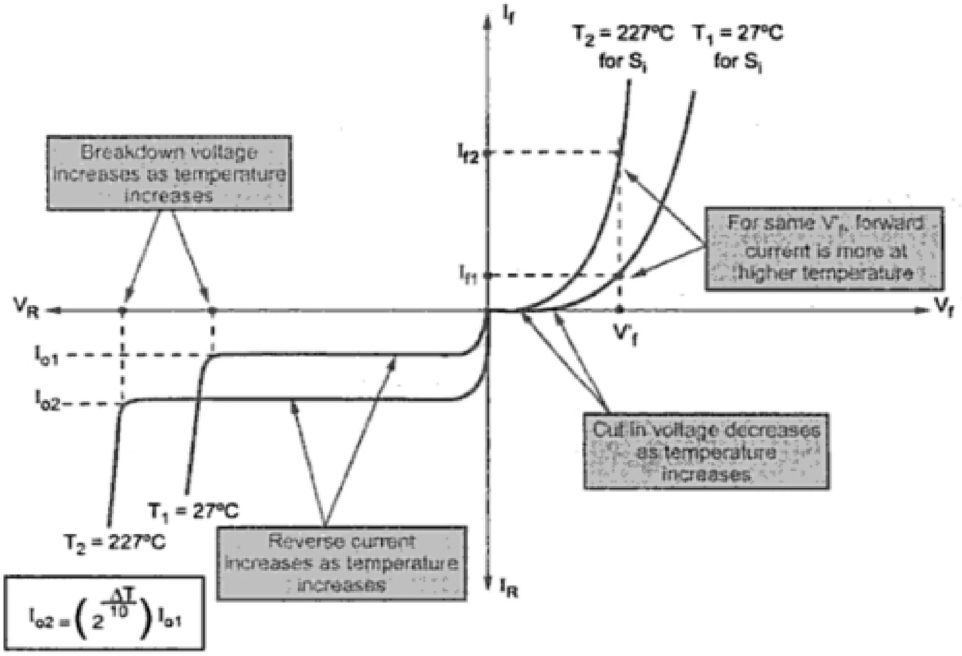


Fig.2.8: V-I Characteristics of P-N junction diode

6. DC (or) STATIC RESISTANCE

- Static resistance or DC resistance of a P-N junction diode defines the diode's resistive nature when a DC source is connected to it.
- If an external DC voltage is given to the circuit in which the semiconductor diode is a part of it, results in a Q-point or operating

point on the P-N junction diode characteristic curve that does not alter with time.

- The static resistance at the knee of the curve and below of it will be much greater than the resistance values of the vertical rise section of the characteristic curve.
- Minimum is the current passing through a diode maximum is the level of DC resistance.

$$R_{DC} = V_{DC} / I_{DC}$$

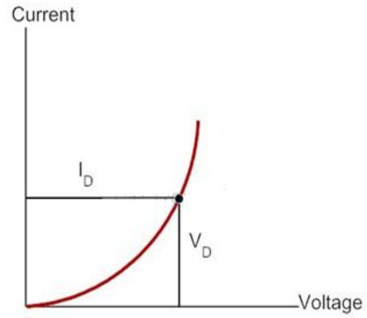


Fig.2.9:Static resistance calculation from V-I characteristics

AC (or) DYNAMIC RESISTANCE

- Dynamic resistance is derived from Shockley's Diode Equation. It defines the diode resistive nature when an AC source which depends on the DC polarization of the PN junction diode is connected to it.
- If an external sinusoidal signal is given to the circuit consisting of a diode, the altering input will shift the instantaneous Q – point slightly from the current position in the characteristics and therefore it defines a definite change in voltage and current.
- When no external alternating signal is applied, the operating point will be the Q – point (or quiescent point) which is determined by the applied DC signal levels.

- The AC resistance of the diode is increased by lowering the Q-point of operation. In short, it is equivalent to slope of voltage – current of the P-N diode.

$$r_d = \Delta V_d \,/\, \Delta I_d$$

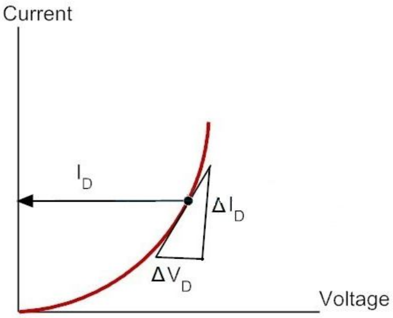


Fig.2.10: Dynamic resistance calculation

- We have seen that the dynamic resistance is the reciprocal of the slope of the V-I characteristics of a diode. For the incremental change in voltage and current we have write,

$$r = \frac{1}{\text{Slope of graph}} = \frac{1}{\left[\frac{dI}{dV}\right]} \quad \dots (1)$$

Now current equation of a diode is given by

$$I = I_0\left(e^{V/\eta V_T} - 1\right)$$

$$\therefore \quad \frac{dI}{dV} = I_0\left[\frac{1}{\eta V_T} \cdot e^{V/\eta V_T}\right]$$

$$\therefore \quad \frac{dI}{dV} = \frac{I_0\, e^{V/\eta V_T}}{\eta V_T} \quad \dots (2)$$

$$\therefore \quad \boxed{r = \frac{1}{\left[\frac{dI}{dV}\right]} = \frac{\eta V_T}{I_0\, e^{V/\eta V_T}}} \quad \dots (3)$$

But from the current equation we can write

$$I = I_0\, e^{V/\eta V_T} - I_0$$

$$\therefore \quad I_0\, e^{V/\eta V_T} = I + I_0 \quad \dots (4)$$

Substituting in equation (3) we get

$$r = \frac{\eta V_T}{I + I_0} = \text{Dynamic resistance} \quad \text{... (5)}$$

While determining the value of dynamic resistance under forward biased and reverse biased conditions, the general expression, equation (3) is used.

Note : For forward biased condition treat V positive while for reverse biased condition treat V as negative, while using the expression.

AVERAGE AC RESISTANCE:

- If the input signal is sufficient enough to produce a large swing, then the resistance related to the diode for this region is called as AC average resistance. It is determined by the straight line that is drawn linking the intersection of the minimum and maximum values of external input voltage.

$$R_{avg} = (\Delta V_d / \Delta I_d)_{\text{pt to pt}}$$

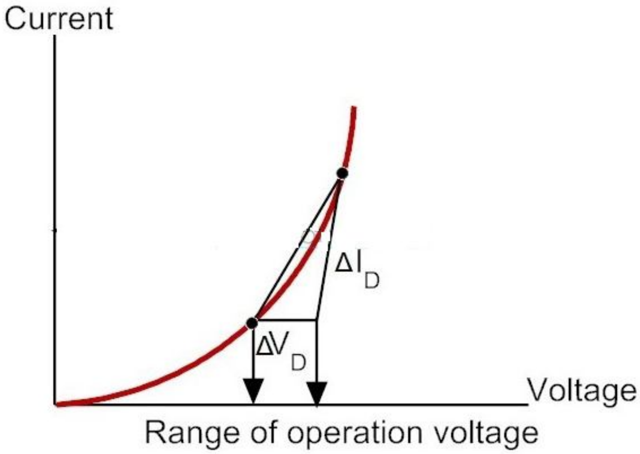


Fig.2.11:Average AC resistance

JUNCTION CAPACITANCE

Basically, there are two types of capacitance associated with a p-n junction

1. The first is junction capacitance:
    a. Due to the dipole in the transition region.

   b. Also called **transition region capacitance** or depletion layer capacitance.
   c. Dominates under reverse bias conditions.

2. The second is the charge storage capacitance:

   a. Arises from the voltage lagging behind the current due to charge storage effects.
   b. Also referred to as **diffusion capacitance**.
   c. Dominant when the junction is forward biased.

- Junction capacitance is easy to visualize from the charge distribution

   i. Uncompensated acceptor atoms on the p-side provide the negative charge.
   ii. Uncompensated donor atoms on the n-side provide the positive charge.

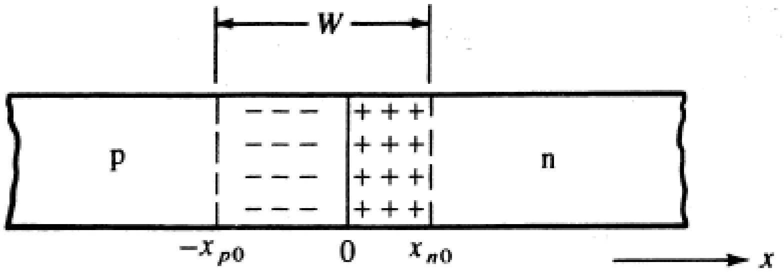


Fig.2.12: p-n junction under reverse bias

7. TRANSITION CAPACITANCE

- The general definition for the capacitance of a structure

$$C = \left|\frac{dQ}{dV}\right|$$

Since we know the charge varies non-linearly with the applied voltage.

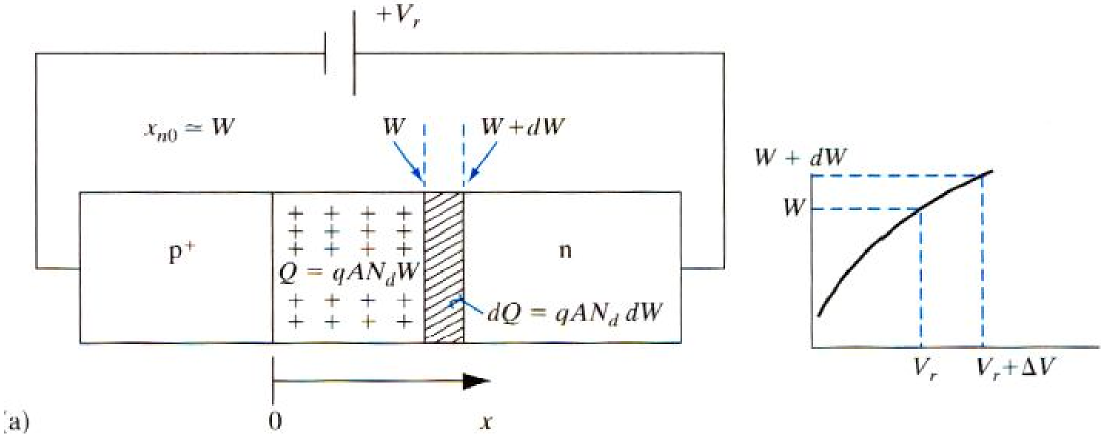


Fig.2.13:Charge storage phenomenon in p-n junction

We know the equations for the variation of the depletion width

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2} \quad (equilibrium)$$

$$W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2}$$ (Under applied voltage)

The transition capacitance is given by

$$\mathbf{C_T = \epsilon A/W}$$

8. DIFFUSION CAPACITANCE

For a forward bias a capacitance which is much larger than the transition capacitance C_T comes into play. The origin of the large capacitance lies in the injected charge stored near the junction outside the transition region. It is convenient to introduce an incremental capacitance, defined as the rate of change of injected charge with voltage, called diffusion or storage capacitance C_D.

$$C_D = dQ/dV$$

We have $I = Q/\tau_p \Rightarrow Q = \tau_p * I$; Where τ_p is mean life time of holes (or electrons)

Therefore, $C_D = \tau_p dI/dV = \tau_p g = \tau_p/r$, g is the diode incremental conductance

$$\mathbf{C_D = \tau_p I/\eta V_T}$$

Assignment-Cum-Tutorial Questions

UNIT-II

SECTION – A

Objective Questions

1.What is p-n junction?

2. Define barrier potential?

3. What is an ideal diode?

4. Define dynamic resistance of the diode under forward bias?

5. What is static resistance of the diode?

6. Define reverse saturation current?

7. Give the expression for dynamic resistance?

8. The arrow direction in the diode symbol indicates --- [ ]

a. Direction of electron flow b. Direction of hole flow

c. Opposite to the direction of hole flow d. None of the above

9. The knee voltage of Si diode is ---- [ ]

a. 0.2 V b. 0.7 V c. 0.8V d. 1.0V

10.When the diode is forward biased, it is equivalent to [ ]

a. An off switch b. An on switch c. high resistance device d. None

11.When a reverse bias is applied to a diode, it will [ ]

a. Raise the potential barrier b. Lower the potential barrier

c. Increases the majority-carrier a current greatly d. None of the above.

12. Which capacitance dominates in the reverse-bias region? [ ]

a. Depletion b. Conversion c. Diffusion d. None of the above

13. Reverse saturation current in a Silicon PN junction diode nearly doubles for every----- [ ]

a.2^0 rise in temp. b.5^0rise in temp. c.6^0 rise in temp. d.10^0rise in temp.

14. A forward potential of 10V is applied to a Si diode. A resistance of 1 KΩ is also in series with the diode. The current is............... [ ]

a. 0mA b. 9.3mA c. 0.7mA d. 0

15. In the diode equation, the voltage equivalent of temperature is [ ]

a. 11600/T b.T/11600 c.T x11600 d.$11600/T^2$

16. Barrier potential at the room tem. (25^0 C) is 0.7V, its value at 125^0 C is.... [ ]

a. 0.5 V b. 0.3 V c.0.9V d.0.7 V

17. What is the resistor value of an ideal diode in the region of conduction?

a.0Ω b.5KΩ c.Infinity d.Undefined

18. Calculate static resistance R_D of a diode having I_D = 30 mA and V_D = 0.75 V...... [ ]

a.25Ω b.40KΩ c.0.04Ω d.0.025Ω

SECTION – B

Descriptive Questions

1. Explain the formation of depletion region in an open – circuited p–n junction with neat sketches.(or) Explain how a barrier potential is developed at the junction?
2. Explain the operation of a PN junction diode under forward bias and reverse bias?
3. Explain the current components of diode.
4. Explain the V – I characteristics of p – n junction diode also explain the effect of temperature on V-I characteristics of the diode.
5. Explain the term transition capacitance C_T of a p-n junction diode
6. Explain the term diffusion capacitance C_D of a p-n junction diode.
7. Derive diode current equation.

TUTORIAL TASK

1. Determine the forward resistance of a p – n junction diode, when the forward current is 5mA at T = 300^0K. Assume silicon diode.
2. The diode current of 0.6mA when applied voltage is 0.4V and 20mA when the applied voltage is 0.5 V. Determine □ and reverse saturation current of the diode.

3. The reverse saturation current of a silicon p-n junction diode is 10μA. Calculate the diode current for the forward bias voltage of 0.6V at 25^0C.
4. Determine the diode current at 20°C for a silicon diode with I_S=50 nA and an applied forward bias of 0.6 V.
5. In the reverse-bias region the saturation current of a silicon diode is about 0.1 A (T= 20°C). Determine its approximate value if the temperature is increased 40°C.
6. A PN junction diode has a reverse saturation current of 30μA at temperature of 125^o C. At the same temperature find the dynamic resistance for 0.2V bias in forward and reverse directions.

SECTION - C

GATE QUESTIONS

1. In a junction diode [ ]

(a) the depletion capacitance increases with increase in the reverse bias

(b)the depletion capacitance decreases with increase in the reverse bias

(c) the depletion capacitance increases with increase in the forward bias

(d)the depletion capacitance is much higher than the depletion capacitance when it is forward biased [GATE 1990: 1 Mark]

2. The diffusion potential across a p n-junction [ ]

(a)decreases with increasing doping concentration

(b)increases with decreasing band gap

(c) does not depend on doping concentrations

(d)increases with increases in doping concentration [GATE 1995: 1 Mark]

3.The depletion capacitance, Cj of an abrupt p – n junction with constant doping on either side varies with Reverse Bias VR as ….[GATE 1995: 1 Mark]

(a) $C_J \propto V_R$

(b) $C_J \propto V_R^{-1}$

(c) $C_J \propto V_R^{-1/2}$

(d) $C_J \propto V_R^{-1/3}$

4. For small signal ac operation, a practical forward biased diode can be modelled as [ ]

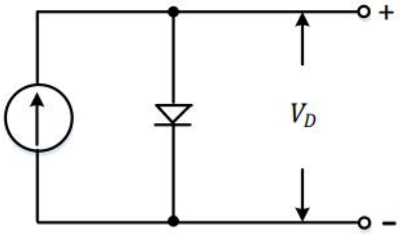
(a) a resistance and a capacitance (b) an ideal diode and resistance in parallel

(c) a resistance and an ideal diode in series (d) a resistance [GATE-98: 1M]

5. The static characteristic of an adequately forward biases p-n junction is a straight line, if the plot of [ ]

(a) log I vs log V (b)log I vs V (c) I vs log V (d)I vs V [GATE 1998: 1 Mark]

6. In the figure, silicon diode is carrying a constant current of 1 mA. When the temperature of the diode is 20℃, V_D is found to be 700 mV. If the temperature rises to 40℃, V_D becomes approximately equal to---- [ ]



(a) 740 mV (b)660 mV (c) 680 mV (d)700 mV [GATE 2002: 1 Mark]

7. A Silicon PN junction at temperature of 20℃ has a reverse saturation current of 10 pico-Amperes (pA). The reverse saturation current at 40℃ for the same bias is approximately [ ]

(a) 30 pA (b)40 pA (c) 50 pA (d)60 pA [GATE 2005: 1 Mark]

8. In a p+n junction diode under reverse bias, the magnitude of electric field is maximum at [ ]

(a) the edge of the depletion region on the p-side

(b)the edge of the depletion region on the n-side (c) the p+n junction

(d)the centre of the depletion region on the n-side [GATE 2007: 1 Mark]

9. Which of the following is NOT associated with a p-n junction? [ ]

(a)Junction Capacitance (b)Charge Storage Capacitance

(c) Depletion Capacitance (d)Channel Length Modulation [GATE -08: 1M]

10. A Silicon PN junction is forward biased with a constant current at room temperature. When the temperature is increased by 10℃, the forward bias voltage across the PN junction ……… [ ]

(a) increases by 60 mV (b)decreases by 60 mV (c) increases by 25 mV

(d)decreases by 25 mV [GATE 2011: 1 Mark]

11. In a forward biased p - n junction, the sequence of events that best describes the mechanism of current flow is [ ]

(a) injection, and subsequent diffusion and recombination of minority carriers
(b)injection, and subsequent drift and generation of minority carriers
(c) extraction of subsequent diffusion and generation of minority carriers
(d) extraction, and subsequent drift and recombination of minority carriers

[GATE 2013: 1 Mark]

UNIT III

SPECIAL SEMICONDUCTOR DEVICES

Course objectives

- To familiarize the construction, characteristics and applications of various semiconductor diodes.

Syllabus

Special Semiconductor Devices: Breakdown diodes, Tunnel Diode, Varactor Diode, Photo Diode, LED, UJT and SCR (characteristics only).

Learning outcomes

Students will be able to

- distinguish the behavior of Zener diode under forward and reverse bias conditions.
- differentiate the photo diode and light emitting diode.
- analyze the operation of tunnel diode.
- characterize the performance of UJT and SCR.

3.1 Breakdown Mechanism

- Under normal reverse voltages only very small reverse current due to minority carriers exists.
- As the reverse bias voltage is further increased it reaches a point where the reverse current suddenly shoots up. This occurs due to junction "breakdown".
- The junction breakdown is of two types
  a) Avalanche breakdown
  b) Zener breakdown

a) Avalanche breakdown

  - This occurs in lightly doped diodes where the depletion layer is very wide.
  - The reverse voltage applied imparts high energy to the minority carriers.
  - The minority carriers with sufficient kinetic energy disrupt (break) covalent bonds in the crystal thus releasing the valence electron. This process is called "impact ionization".
  - The newly released valence electrons gain enough energy to disrupt the covalent bonds.
- The process is like a uncontrolled chain reaction and is cumulative process and is known as "avalanche multiplication".

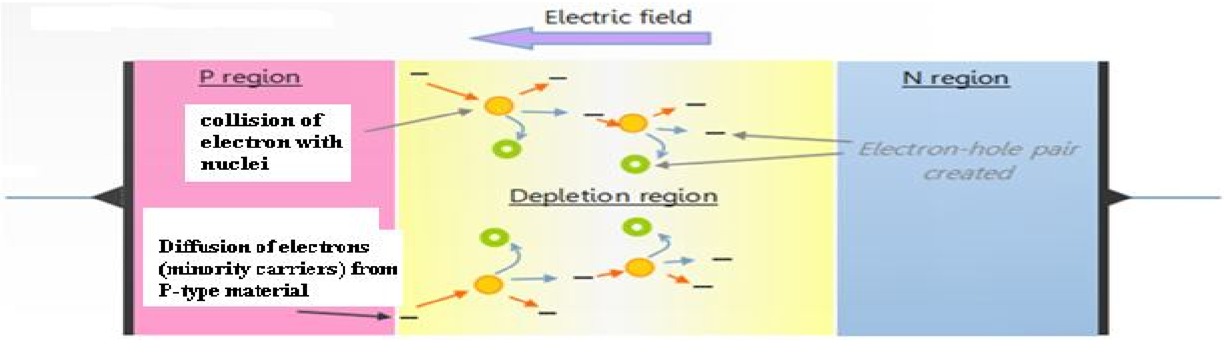


Fig.3.1: Avalanche breakdown Mechanism

b) Zener breakdown

- This occurs in heavily doped diodes because of heavily doping. The depletion region is very small.
- When reverse biasing a diode a very strong electric field exists across the Depletion region.

  Eg: for an applied reverse bias voltage of 6V or less, the electric field is nearly $2*10^7$ V/m.
- This very high electric field breaks covalent bonds and creates new electron hole-Pairs, which increase the reverse current, thus a large reverse current flows.

Comparision in between zener breakdown mechanism and avalanche breakdown mechanism

Sl.No	Zener breakdown	Avalanche breakdown
1.	It occurs in heavily doped diodes Eg: Zener Diode	It occurs in lightly doped diodes Eg: PN Junction Diode
2.	It occurs with reverse bias voltage is less than 6V	It occurs in PN Junction diode with reverse bias voltage greater than 6V.
3.	The reverse bias V-I characteristics is very sharp in breakdown region.	The V-I characteristics in reverse bias is not sharp.
4.	It occurs by breaking covalent bonds due to very high electric field established by the reverse bias (due to direct rupture of covalent bonds)	It occurs by breaking covalent bonds due to collision of accelerated electrons as a chain of reaction.

5.	The breakdown voltage decreases if the junction temperature increases	The breakdown voltage increases if the junction temperature increases.
6.	Temperature coefficient is Negative	Temperature coefficient is positive

3.2 ZENER DIODE (1 Part in 10^5 atoms)

- Zener diode is heavily doped diode than the ordinary diode.
- Its doping is nearly 100 times greater than the ordinary PN Junction diode.

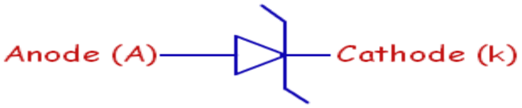


Fig.3.2:Symbol for zener diode

Zener diode under forward bias

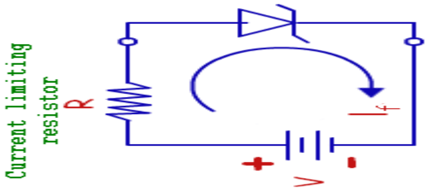


Fig.3.3: Zener diode under forward bias condition

- The operation of zener diode is same as that of the ordinary diode under forward bias condition.
- Upto the cut-in voltage the diode conducts zero current after that cut-in voltage, current increases.

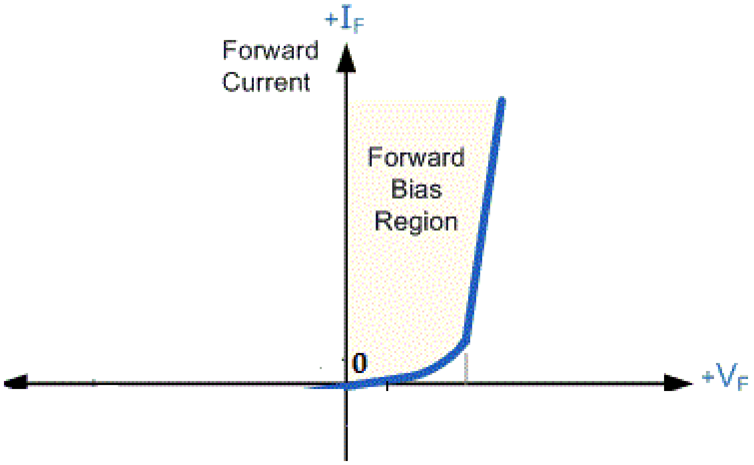


Fig.3.4: Zener diode forward bias characteristics

Zener diode under reverse bias

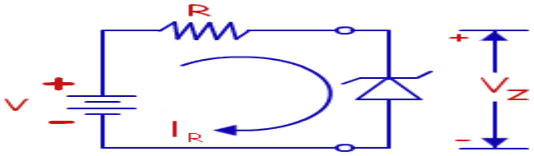


Fig.3.5: Zener diode under reverse bias condition

- When the reverse bias voltage reaches breakdown voltage in normal PN diode, the current through the junction and power dissipated at the junction will be high. Such an operation is destructive and diode is damaged.
- Whereas zener diode is designed to handle high currents even in breakdown region. The breakdown voltage depends upon the amount of doping.

Depletion width α$(1/amont\ of\ doping)$

  - If the diode is heavily doped, the depletion width is very small and hence the breakdown occurs at low reverse voltage. Whereas lightly doped diodes has high breakdown voltage.

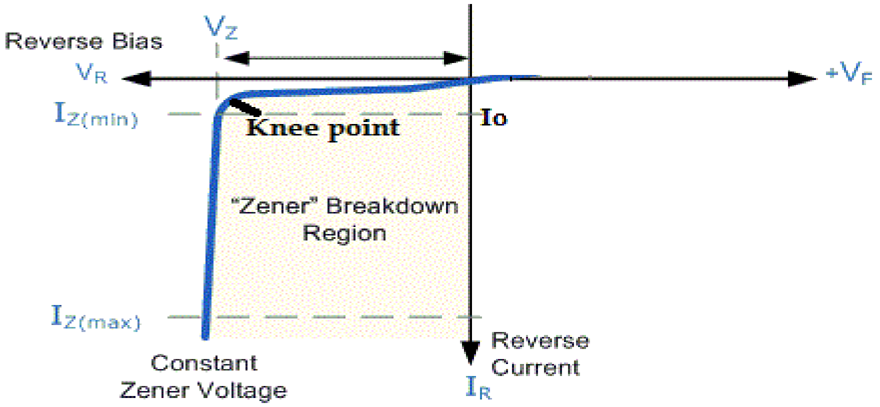


Fig.3.6: Zener diode reverses bias characteristics

Application: voltage Regulator.

3.3 VARACTOR DIODE

- Varactor diode is basically a reverse biased PN junction, which utilizes the capacitance of depletion layer.
- It is also known as varicap, voltcap or tuning diode. It is used as voltage variable capacitor.
- When the reverse bias voltage increases, the depletion region widens. This increases the dielectric thickness, which in turn reduces the capacitance.
- $CT = A\varepsilon/w$ =>$CT\ \alpha\ 1/w$ => as 'w' increases, cT decreases.
- When the reverse bias voltage decreases, the depletion layer narrows down. This decreases the dielectric thickness, which in turn increases the capacitance. The depletion layer acts as insulator preventing conduction between the N and P regions of the diode, Just like a dielectric, which separates the two plates of the capacitor.

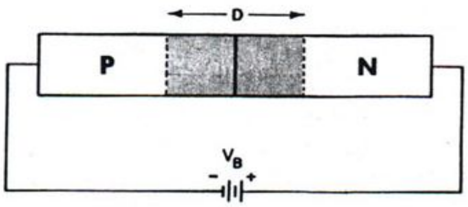


Fig.3.7: Varactor diode construction and its symbol

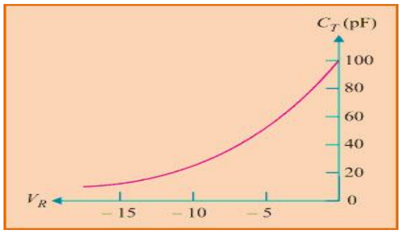


Fig.3.8: Varactor diode characteristics

Applications: a) used in FM radio receivers

b) used in TV Receivers.

3.4 PHOTO DIODE

- Photo diode is a light sensitive device, also called photo detector, which converts light signals into electrical signals.

Fig.3.9: Circuit symbol for photodiode

- The diode is made of a semiconductor PN junction kept in a sealed plastic or glass casing.
- The cover is so designed that the light rays are fall on one surface across the junction.
- When light falls on reverse biased PN photodiode junction, hole-electron pairs are created.

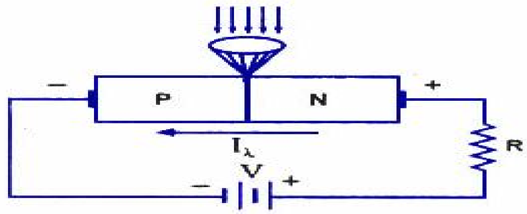


Fig.3.10: Basic biasing arrangement and construction of photodiode

- The movement of these hole-electron pairs in a properly connected circuit results in current flow.
- The magnitude of photocurrent depends on the number of charge carriers generated. This current is also affected by the frequency of the light falling on the junction of photodiode.
- The magnitude of the current under large reverse bias is given by $I = I_o[\exp(V/\eta V_T) - 1]$, **where I_o is reverse saturation current or dark current**

η =1 for Ge and 2 for Si.

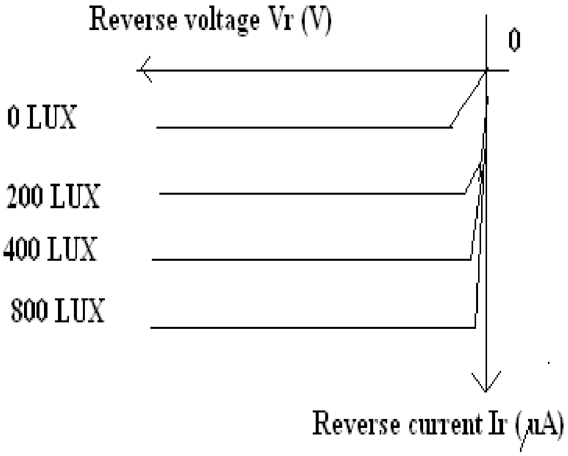


Fig.3.11: Photo Diode characteristics

Applications:

- Light detectors
- Demodulators and encoders
- Optical communication system
- High speed counting and switching circuits

3.5 LIGHT EMITTING DIODE (LED)

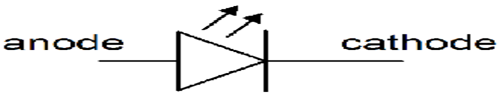


Fig.3.12: Circuit symbol for Light Emitting Diode

- APN junction diode, which emits light when forward biased, is known as Light emitting diode (LED).
- The amount of light output is directly proportional to the forward current
- A P-type layer is grown on the N-type layer. When an external positive voltage is applied to the P- type region with respect to N- type, both the depletion region width resulting potential barrier are reduced and the diode is said to be forward biased.

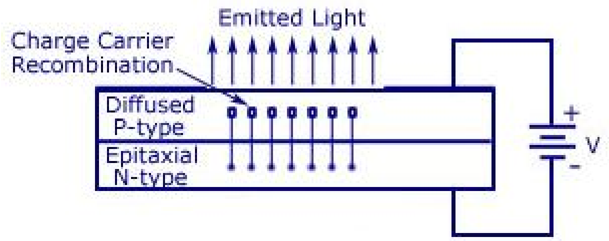


Fig.3.13: Constructional diagram of LED

- When LED ids forward biased, the electrons and holes moves towards the junction and

  Recombination takes place.
- After recombination, the electrons lying in the conduction band of N-region, holes lying in the valence band of P-region.
- The difference of energy between the conduction band and valence band is radiated in the form of light energy.
- E_g=hf =hc/λ => λ=1.24/E_g

  Where λ= wave length of light

  h=flanks constant =6.626*10^{-34}Jsec

  c= velocity of light=3*10^8 m/sec
- Materials used: GaAs (Infrared light(invisible)), GaAsP (red or yellow visible light), GaP (red or green visible light)

Applications: a) visual displays b) in optical communications as source c) As on-off indicator d) used in remote controls.

3.6 TUNNEL DIODE or ESAKI DIODE (1 Part in 10^3 atoms)

- Tunnel diode is a heavily doped diode; its doping is nearly 1000 times greater than the ordinary PN junction diode.
- It is a thin junction diode which exhibits negative resistance under forward bias conditions. Because of heavy doping the depletion layer width reduces.
- For such a thin potential energy barriers the electrons will penetrate through the junction rather than surmounting them. This phenomenon is called "Tunneling" and hence the diode is called as "Tunnel Diode" or "Esaki Diode".
- Materials used for tunnel diode: Ge

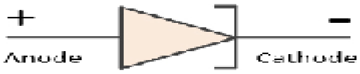


Fig.3.14: Circuit symbol for Tunnel Diode

Conditions for tunneling:

1) Width of depletion region should be very narrow.
2) At one side of diode filled states should exists at other side at the same energy level empty states should exists.

If the above two conditions are satisfied, then the electron tunnels from filled states to empty states.

Under Open Circuit condition

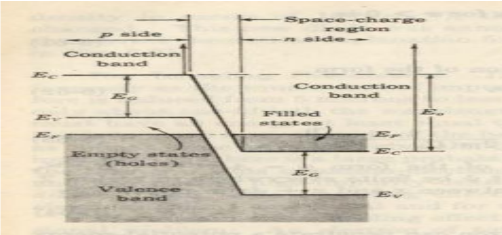


Fig.3.15 Energy band diagram of tunnel diode under open circuited condition

It can be observed that the second condition of tunneling is not satisfied hence tunneling is not possible hence current is zero then V and I are zero.

Under Reverse bias conditions:

- Under reverse bias condition the height of the potential barrier 'Eo' is given by Eo=VB * q
- VB= Vo – (-V) = Vo +V.
- From the above equation,VB increases, hence 'Eo', the potential barrier height increases.
- Eo =ECp –ECnis increasing hence N-side levels shift down.
- Hence top filled states of valence band of P become parallel to the bottom empty states of conduction band of N type.
- Hence the second condition of tunneling is satisfied, and then electrons tunnel from filled states to empty states (P to N) and produces current from N to P. so, V and I are Negative.
- As reverse bias further increases, N-side levels further move down causing the reverse current to increase i.e. in reverse bias excellent conduction is possible.

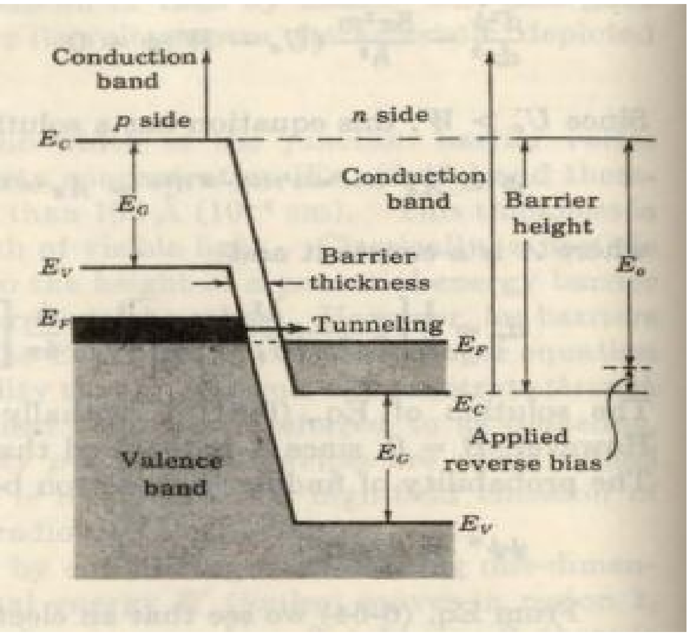


Fig.3.16 Energy band diagram of tunnel diode under Reverse bias

Under Forward bias conditions

- Under forward bias condition, the height of the potential barrier 'Eo' is given by Eo=V_B * q
- And V_B= V_o – (+V) = V_o -V. From the above equation, as applied bias increases then valence band decreases. Hence the potential height 'Eo' decreases.
- Eo =E_Cp –$E_C$nis decreasing hence N- side levels moves up. Top filled states of conduction band of N become parallel to the bottom empty states of valence band of P.
- Hence electrons will move from filled states to empty states (i.e. N to P) and produces current from P to N. the applied voltage and current (V& I) are positive

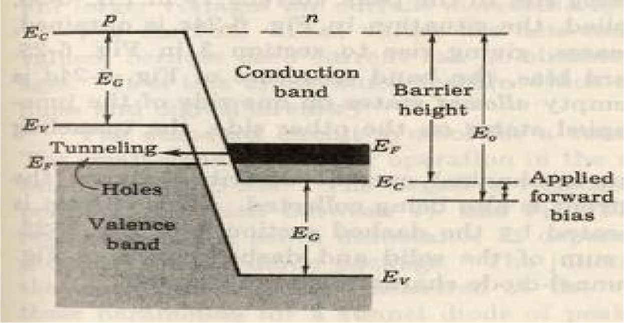


Fig.3.17: Energy band diagram of tunnel diode under low forward bias

As forward bias voltage increases, forward current starts from zero to reaches a maximum. Later on decreases.

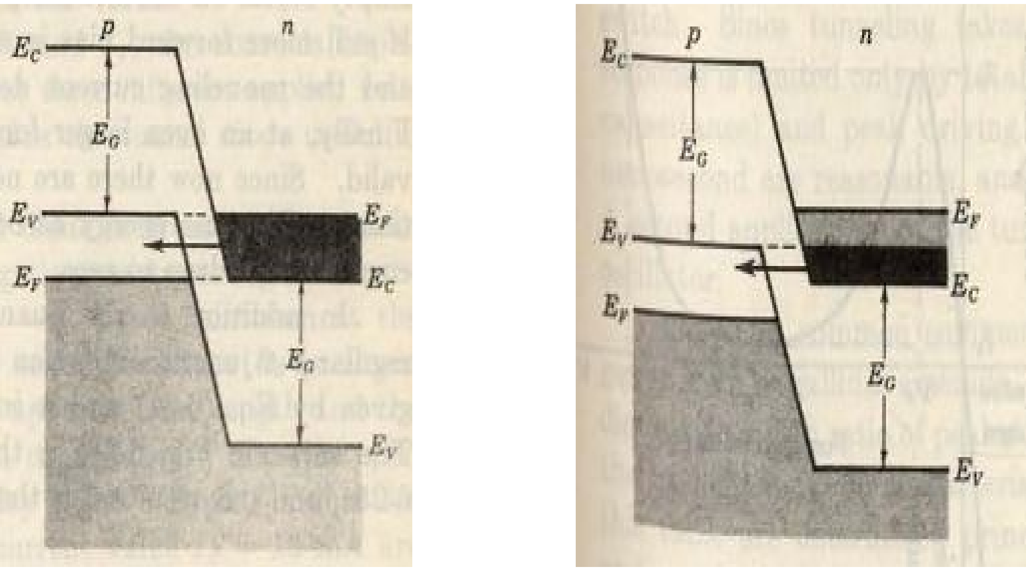


Fig.3.18: Energy band diagram of tunnel diode under medium forward bias

Due to large forward bias, E_o decreases and $E_G>E_0$ occurs which is valid only for PN diode and hence after reaching valley point, the curve is similar to the PN junction diode forward bias characteristics.

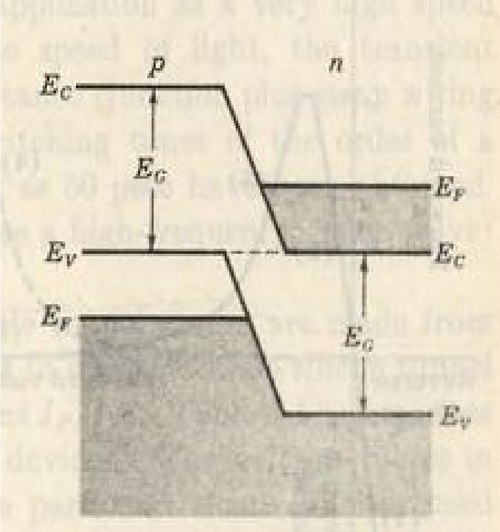


Fig.3.19: Energy band diagram of tunnel diode under large forward bias

Tunnel diode V-I characteristics

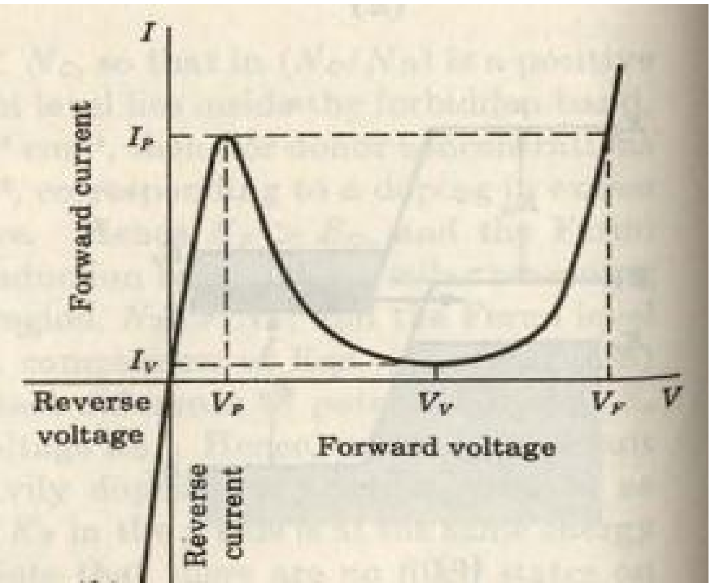


Fig.3.20: Tunnel diode V-I characteristics

Reverse bias:

If the tunnel diode is reverse biased, it acts like an excellent conductor.i.e. the reverse current increases with the increase in reverse voltage.

Forward bias

- The applied forward voltage increased from zero, the current increases very rapidly, till it reaches its maximum value known as peak current (I_P).
- If the forward voltage is further increased (beyond V_P), the current decreases, till it reaches its minimum value is known as valley current (I_V). As the voltage further increased the current increases in a usual manner like a PN junction diode.

Tunnel Diode Equivalent circuit:

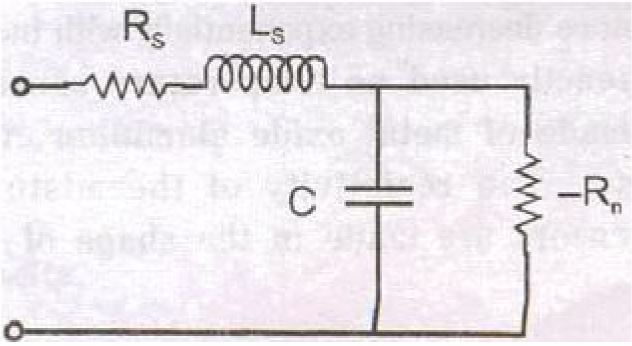


Fig.3.21 Equivalent circuit of a tunnel diode.

R_S : series Resistance: It is the resistance due to leads, contacts and semiconductor material. Its typical value is 1-5Ω.

L_S :series Inductance: due to load lengths. Its typical value is 0.1 to 4 nH.

C: the junction capacitance is due to diffusion capacitance and applied voltage.

Its typical value is 0.35 to 100 pf.

Applications:

- High speed switching device.
- High frequency oscillator (Microwave range: 10^9 Hz).
- Used in digital circuits.
- As logic memory storage device.

3.7 UNI JUNCTION TRANSISTOR (UJT)

- The device has only one junction, so it is called the uni junction device.
- The device, because of one P-N junction, is quite similar to a diode but it differs from an ordinary diode as it has three terminals.
- The structure of a UJT is quite similar to that of an N-channel JFET. The main difference is that P-type (gate) material surrounds the N-type (channel) material in case of JFET and the gate surface of the JFET is much larger than emitter junction of UJT.

- The Emitter junction is positioned along the channel so that it is closer to terminal B2 than B1. An arrow is used in the UJT symbol which points towards the base indicating that the Emitter terminal is positive and the silicon bar is negative material.
- A bar of high resistivity n_typesi has two ohmic contacts attached to its ends. The bar is known as base (B) and the two leads as B1 and B2.An aluminum wire , called emitter E is alloyed to base
- The N-type silicon bar has a high resistance and the resistance between emitter and base-1 is larger than that between emitter and base-2. It is because emitter is closer to base-2 than base-1.
- UJT is operated with emitter junction forward- biased while the JFET is normally operated with the gate junction reverse-biased.
- UJT does not have ability to amplify but it has the ability to control a large ac power with a small signal. It exhibits a negative resistance characteristic and so it can be employed as an oscillator.

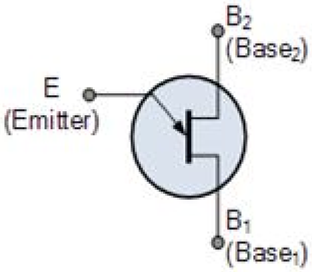


Fig.3.22: Circuit symbol of UJT

Consruction of UJT

A bar of high resistivity n_type si has two ohmic contacts attached to its ends. The bar is known as base (B) and the two leads as B1 and B2.An aluminum wire , called emitter E is alloyed to base.

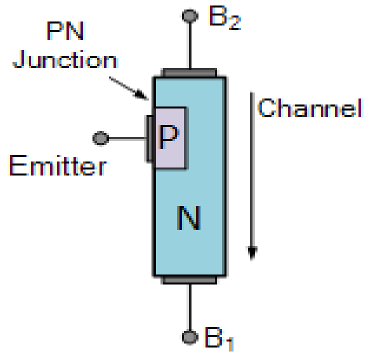


Fig.3.23: Construction of UJT

Equivalent circuit of UJT

In the equivalent circuit of UJT R_{B1} and R_{B2} represents resistances of silicon bar from the junction to base B_1 and base B_2 respectively. R_{B1} is shown as variable resistance, since its value depends on bias voltage V_D .The diode represents the p-n junction formed between the emitter and the base.

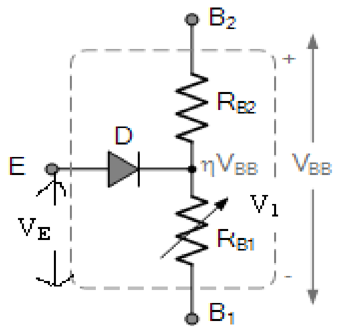


Fig.3.24: Equivalent circuit of UJT

Principle of operation

- If emitter E is open, then the voltage V_{BB} between B_1 and B_2 will get divided across R_{B1} and R_{B2} .The voltage V_1 across R_{B1} will be

$$V1 = \frac{RB1}{RB1+RB2} V_{BB}$$

$$= \eta V_{BB}$$

Where η= stand-off ratio = $\frac{RB1}{RB1+RB2}$

A typical value of η is between 0.5 to 0.8.

Let us V_{BB}= 12V and η=0.5 therefore V_1 =6V

Also let V_D= 0.6V.

Therefore, the diode will remain reverse biased for emitter voltages up to 6V +0.6V=6.6V

- When the emitter voltage V_E just exceeds (V_1+V_D) volts, the diode becomes forward biased as a result, holes will be injected will reduce. This reduction in resistance gives a **negative –resistance** effect. In to the silicon bar and the resistance between E and B_1.

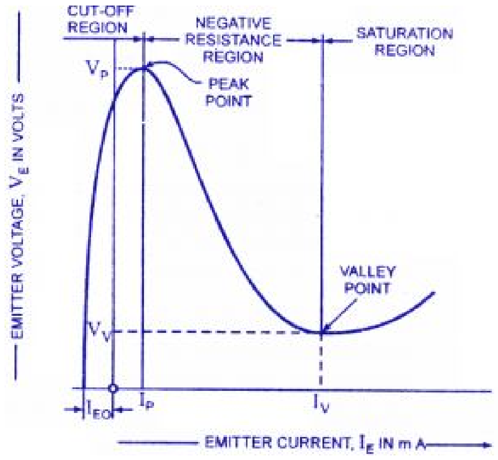


Fig.3.25: V-I characteristics of UJT

3.8 SILICON CONTROLLED RECTIFIER (SCR)

- The silicon controlled rectifier (SCR) is a three terminal semiconductor switching device which can be used as a controlled switch to perform various functions such as rectification, inversion and regulation of power flow.
- An SCR can handle currents up to several thousand amperes and voltages up to more than 1KV.
- SCR has different names such as thyristor, thyrode transistor.

- Like the diode, SCR is a unidirectional device,i.e. it will only conduct current in one direction only, but unlike a diode, the SCR can be made to operate as either an open-circuit switch or as a rectifying diode depending upon how its gate is triggered.
- In other words, SCR can operate only in the switching mode and cannot be used for amplification.
- Hence, it is extensively used in switching d.c. and a.c., rectifying a.c. to give controlled output, converting d.c. into a.c. etc.
- When a pn junction is added to a junction transistor, the resulting three pnjunctions device is called a silicon controlled rectifier. It is an ordinary rectifier (pn) and a junction transistor (NPN) combined in one unit to form pnpn device.

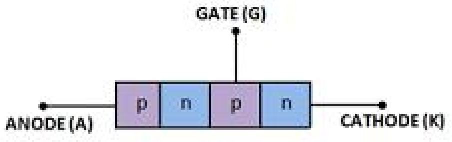


Fig.3.26: Constuction of SCR

- Three terminals are taken; one from the outer p-type material called anode A, second from the outer layer of n-type material called cathode K and the third from the base of transistor section and is called gate G.
- In the normal operating conditions of SCR, anode is held at high positive potential w.r.t. cathode and gate at small positive potential w.r.t. cathode.

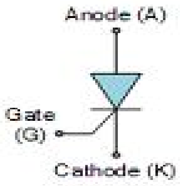


Fig.3.27: Circuit symbol of SCR.

Working of SCR

- In a silicon controlled rectifier, load is connected in series with anode.
- The anode is always kept at positive potential w.r.t. cathode.
- The working of SCR can be studied under the following two heads:

(i) When gate is open

SCR circuit with gate open i.e. no voltage applied to the gate.

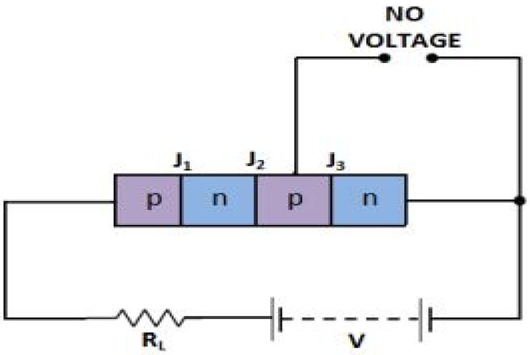


Fig.3.28:SCR with gate open

- Under this condition, junction J_2 is reverse biased while junction J_1 and J_3 are forward biased.
- Hence, the situation in the junctions J_1 and J_3 is just as in anpn transistor with base open.
- Consequently, no current flows through the load R_L and the SCR is cut off.
- However, if the applied voltage is gradually increased, a stage is reached when the reverse biased junction J_2 breaks down.
- The SCR now conducts heavily and is said to be in the ON state.
- The applied voltage at which SCR conducts heavily without gate voltage is called Break over voltage.

(ii) When gate is positive w.r.t. cathode

The SCR can be made to conduct heavily at smaller applied voltage by applying a small positive potential to the gate as shown in Fig 3.29.

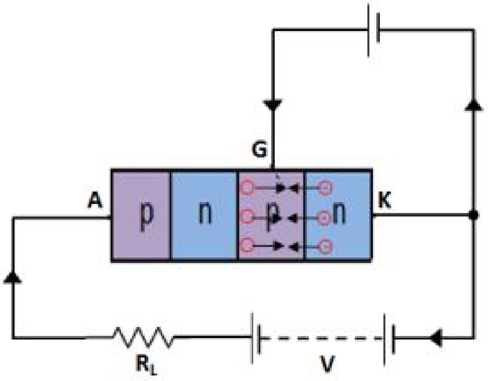


Fig.3.29: SCR gate is positive w.r.t. cathode

- Now junction J_3 is forward biased and junction J_2 is reverse biased.
- The electrons from n-type material start moving across junction J_3 towards left whereas holes from p-type towards the right.
- Consequently, the electrons from junction J_3 are attracted across the junction J_2 and gate current starts flowing.
- As soon as the gate current flows, anode current increases. The increased current in turn makes more electrons available at junction J_2.
- This process continues and in an extremely small time, junction J_2 breaks down and the SCR starts conducting heavily.
- Once SCR starts conducting, the gate loses all control. Even if gate voltage is removed, the anode current does not decrease at all.
- The only way to stop conduction i.e. to bring the SCR in off condition is to reduce the applied voltage to zero.

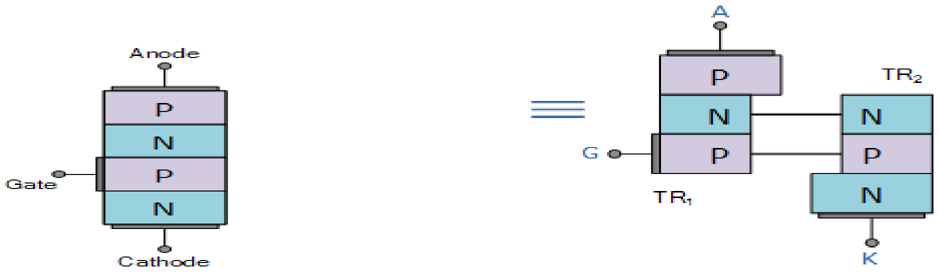


Fig.3.30: SCR separated as two transistors

Assignment-Cum-Tutorial Questions

UNIT-III

SECTION – A

Objective Questions

1. What is true about the breakdown voltage in a zener diode? [ ]
   a. It decreases when current increases. b. It destroys the diode.
   c. It equals the current times the resistance. d.It is approximately constant.
2. Which of these is the best description of a zener diode? [ ]
   a. It is a rectifier diode. b. It is a constant-voltage device.
   c. It is a constant-current device. d. It works in the forward region.
3. A zener diode [ ]
   a. Is a battery b. has a constant voltage in the breakdown region
   c. has a barrier potential of 1 V d. Is forward-biased
4. The voltage across the zener resistance is usually [ ]
   a. Small b. large
   c. Measured in volts d. Subtracted from the breakdown voltage
5. In the second approximation, the total voltage across the zener diode is the sum of-the breakdown voltage and the voltage across the [ ]
   a. Source b. Series resistor c. Zener resistance d. Zener diode
6. The load voltage is approximately constant when a zener diode is [ ]
   a. Forward-biased b. Reverse-biased
   c. operating in the breakdown region d. Unbiased
7. The capacitance of a varactor diode increases when the reverse voltage across it [ ]
   a. Decreases b. Increases c. breaks down d. Stores charges
8. Breakdown does not destroy a zener diode provided the zener current is less than the [ ]
   a. Breakdown voltage b. Zener test current
   c. Maximum zener current rating d. Barrier potential

9. To display the digit 8 in a seven-segment indicator, [ ]

a. C must be lighted b. G must be off

c. F must be on d. All segments must be on

10. A photodiode is normally [ ]

a. Forward-biased b. Reverse-biased

c. Neither forward- nor reverse biased d. Emitting light

11. When the light increases, the reverse minority carrier current in a photodiode [ ]

a. Decreases b. Increases c. Is unaffected d. Reverses direction

12. The device associated with voltage-controlled capacitance is a [ ]

a. Light-emitting diode b. Photodiode c. Varactor diode d.Zener diode

13. If the depletion layer gets wider, the capacitance [ ]

a. Decreases b. Stays the same c. Increases d. Is variable

14. When the reverse voltage increases, the capacitance [ ]

a. Decreases b. Stays the same c. Increases d. has more bandwidth

15. The varactor is usually [ ]

a. Forward-biased b. Reverse-biased

c. Unbiased d. Operated in the breakdown region

16. Which of the following has a negative-resistance region? [ ]

a. Tunnel diode b. Step-recovery diode c. Schottky diode d. Optocoupler

17. For typical operation, you need to use reverse bias with a [ ]

a. Zener diode b. Photodiode c. Varactor d. All of the above

18. Fabricated layers of SCR are [ ]

a. n-p-n-p b. p-n-p-n c. n-p-n d. either (a) or (b)

19. For normal SCRs switching turn on depends on [ ]

a. gate current b. anode current c. cathode current d. none of the above.

20. A forward voltage can be applied to an SCR after its [ ]

a. anode current reduces to zero. b. gate recovery time

c. reverse recovery time d. anode voltage reduced to zero.

21. A SCR is a ------------------- switch. [ ]

a. two directional b. one directional c. Three directional d. four directional

SECTION-B

Descriptive Questions

1.Distinguish between Avalanche and Zener Breakdown mechanisms?

2. Explain the working principle and operation of varactor diode?

3. Explain the working principle and operation of LED?

4. Explain the construction and working of a photodiode.

5. Draw the characteristics of tunnel diode.

6. Explain the V-I characteristics of Tunnel diode with the help of Energy band diagram?

7. Explain the working of Silicon controlled rectifier.

8. Explain the working of UJT.

9. Name the various applications of an SCR.

10. Draw the symbol of a SCR and explain its V-I characteristics.

11. Draw and explain the V-I characteristics of a UJT.

12. Show the symbol and V-I characteristics of an LED.