NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

COURSE MATERIALS

ECT201:SOLID STATE DEVICES

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2002
- Course offered : B.Tech in Electronics and Communication Engineering

  M.Tech in VLSI
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

Providing Universal Communicative Electronics Engineers with corporate and social relevance towards sustainable developments through quality education.

DEPARTMENT MISSION

1) Imparting Quality education by providing excellent teaching, learning environment.

2) Transforming and adopting students in this knowledgeable era, where the electronic gadgets (things) are getting obsolete in short span.

3) To initiate multi-disciplinary activities to students at earliest and apply in their respective fields of interest later.

4) Promoting leading edge Research & Development through collaboration with academia & industry.

PROGRAMME EDUCATIONAL OBJECTIVES

PEOI. To prepare students to excel in postgraduate programmes or to succeed in industry / technical profession through global, rigorous education and prepare the students to practice and innovate recent fields in the specified program/ industry environment.

PEO2. To provide students with a solid foundation in mathematical, Scientific and engineering fundamentals required to solve engineering problems and to have strong practical knowledge required to design and test the system.

PEO3. To train students with good scientific and engineering breadth so as to comprehend, analyze, design, and create novel products and solutions for the real life problems.

PEO4. To provide student with an academic environment aware of excellence, effective communication skills, leadership, multidisciplinary approach, written ethical codes and the life-long learning needed for a successful professional career.

PROGRAM OUTCOMES (POS)

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.

PROGRAM SPECIFIC OUTCOMES (PSO)

PSO1: Ability to Formulate and Simulate Innovative Ideas to provide software solutions for Real-time Problems and to investigate for its future scope.

PSO2: Ability to learn and apply various methodologies for facilitating development of high quality System Software Tools and Efficient Web Design Models with a focus on performance optimization.

PSO3: Ability to inculcate the Knowledge for developing Codes and integrating hardware/software products in the domains of Big Data Analytics, Web Applications and Mobile Apps to create innovative career path and for the socially relevant issues.

COURSE OUTCOMES

ECT 201

SUBJECT CODE: ECT 201	
COURSE OUTCOMES	
C201.1	Apply Fermi-Dirac Distribution function and Compute carrier concentration at equilibrium and the parameters associated with generation, recombination and transport mechanism
C201.2	Explain drift and diffusion currents in extrinsic semiconductors and Compute current density due to these effects.
C201.3	Define the current components and derive the current equation in a pn junction diode and bipolar junction transistor
C201.4	Explain the basic MOS physics and derive the expressions for drain current in linear and saturation regions.
C201.5	Discuss scaling of MOSFETs and short channel effects

MAPPING OF COURSE OUTCOMES WITH PROGRAM OUTCOMES

CO'S	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
C201.1	3	3										
C201.2	3	3										
C201.3	3	3										
C201.4	3	3										
C201.5	3											
C206	3	3										

CO'S	PSO1	PSO2	PSO3
C201.1	3	3	3
C201.2	3	3	3
C201.3	2	3	2
C201.4	2		2
C201.5			2
C206	3	3	2

SYLLABUS

ELECTRONICS AND COMMUNICATION ENGINEERING

ECT201	SOLID STATE DEVICES	CATEGORY	L	T	P	CREDIT
		PCC	3	1	0	4

Preamble: This course aims to understand the physics and working of solid state devices.

Prerequisite: EST130 Basics of Electrical and Electronics Engineering

Course Outcomes: After the completion of the course the student will be able to

CO 1	Apply Fermi-Dirac Distribution function and Compute carrier concentration at equilibrium and the parameters associated with generation, recombination and transport mechanism
CO 2	Explain drift and diffusion currents in extrinsic semiconductors and Compute current density due to these effects.
CO 3	Define the current components and derive the current equation in a pn junction diode and bipolar junction transistor.
CO 4	Explain the basic MOS physics and derive the expressions for drain current in linear and saturation regions.
CO 5	Discuss scaling of MOSFETs and short channel effects.

Mapping of course outcomes with program outcomes

	PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12
CO 1	3	3										
CO 2	3	3										
CO 3	3	3										
CO 4	3	3										
CO 5	3											

Assessment Pattern

Bloom's Category	Continuous Assessment Tests		End Semester Examination
	1	2	
Remember	10	10	20
Understand	25	25	50
Apply	15	15	30
Analyse			
Evaluate			
Create			

Mark distribution

Total Marks	CIE	ESE	ESE Duration
150	50	100	3 hours

Continuous Internal Evaluation Pattern:

Attendance : 10 marks
Continuous Assessment Test (2 numbers) : 25 marks
Assignment/Quiz/Course project : 15 marks

End Semester Examination Pattern: There will be two parts; Part A and Part B. Part A contain 10 questions with 2 questions from each module, having 3 marks for each question. Students should answer all questions. Part B contains 2 questions from each module of which student should answer any one. Each question can have maximum 2 sub-divisions and carry 14 marks.

Course Level Assessment Questions

Course Outcome 1 (CO1): Compute carrier concentration at equilibrium and the parameters associated with generation, recombination and transport mechanism

1. Derive the expression for equilibrium electron and hole concentration.
2. Explain the different recombination mechanisms
3. Solve numerical problems related to carrier concentrations at equilibrium, energy band diagrams and excess carrier concentrations in semiconductors.

Course Outcome 2 (CO2) : Compute current density in extrinsic semiconductors in specified electric field and due to concentration gradient.

1. Derive the expression for the current density in a semiconductor in response to the applied electric field.
2. Derive the expression for diffusion current in semiconductors.
3. Show that diffusion length is the average distance a carrier can diffuse before recombining.

Course Outcome 3 (CO3): Define the current components and derive the current equation in a pn junction diode and bipolar junction transistor.

1. Derive ideal diode equation.
2. Derive the expression for minority carrier distribution and terminal currents in a BJT.

3. Solve numerical problems related to PN junction diode and BJT.

Course Outcome 4 (CO4): Explain the basic MOS physics with specific reference on MOSFET characteristics and current derivation.

1. Illustrate the working of a MOS capacitor in the three different regions of operation.

2. Explain the working of MOSFET and derive the expression for drain current.

3. Solve numerical problems related to currents and parameters associated with MOSFETs.

Course Outcome 5 (CO5): Discuss the concepts of scaling and short channel effects of MOSFET.

1. Explain the different MOSFET scaling techniques.

2. Explain the short channel effects associated with reduction in size of MOSFET.

SYLLABUS

MODULE I

Elemental and compound semiconductors, Intrinsic and Extrinsic semiconductors, concept of effective mass, Fermions-Fermi Dirac distribution, Fermi level, Doping & Energy band diagram, Equilibrium and steady state conditions, Density of states & Effective density of states, Equilibrium concentration of electrons and holes.

Excess carriers in semiconductors: Generation and recombination mechanisms of excess carriers, quasi Fermi levels.

MODULE II

Carrier transport in semiconductors, drift, conductivity and mobility, variation of mobility with temperature and doping, Hall Effect.
Diffusion, Einstein relations, Poisson equations, Continuity equations, Current flow equations, Diffusion length, Gradient of quasi Fermi level

MODULE III

PN junctions : Contact potential, Electrical Field, Potential and Charge distribution at the junction, Biasing and Energy band diagrams, Ideal diode equation.
Metal Semiconductor contacts, Electron affinity and work function, Ohmic and Rectifying Contacts, current voltage characteristics.
Bipolar junction transistor, current components, Transistor action, Base width modulation.

MODULE IV

Ideal MOS capacitor, band diagrams at equilibrium, accumulation, depletion and inversion, threshold voltage, body effect, MOSFET-structure, types, Drain current equation (derive)-linear and saturation region, Drain characteristics, transfer characteristics.

MODULE V

MOSFET scaling – need for scaling, constant voltage scaling and constant field scaling.

Sub threshold conduction in MOS.
Short channel effects- Channel length modulation, Drain Induced Barrier Lowering, Veloci Saturation, Threshold Voltage Variations and Hot Carrier Effects.
Non-Planar MOSFETs: Fin FET –Structure, operation and advantages

Text Books

1. Ben G. Streetman and Sanjay Kumar Banerjee, Solid State Electronic Devices, Pearsc 6/e, 2010 (Modules I, II and III)

2. Sung Mo Kang, CMOS Digital Integrated Circuits: Analysis and Design, McGraw-Hill, Third Ed., 2002 (Modules IV and V)

Reference Books

1. Neamen, Semiconductor Physics and Devices, McGraw Hill, 4/e, 2012
2. Sze S.M., Semiconductor Devices: Physics and Technology, John Wiley, 3/e, 2005
3. Pierret, Semiconductor Devices Fundamentals, Pearson, 2006
4. Sze S.M., Physics of Semiconductor Devices, John Wiley, 3/e, 2005
5. Achuthan, K N Bhat, Fundamentals of Semiconductor Devices, 1e, McGraw Hill,2015
6. Yannis Tsividis, Operation and Modelling of the MOS Transistor, Oxford University Press.
7. Jan M.Rabaey, Anantha Chandrakasan, Borivoje Nikolic, Digital Integrated Circuits - A Design Perspective, PHI

No	Topic	No. of Lectures
1	**MODULE 1**	
1.1	Elemental and compound semiconductors, Intrinsic and Extrinsic semiconductors, Effective mass	2
1.2	Fermions-Fermi Dirac distribution, Fermi level, Doping & Energy band diagram,	2
1.3	Equilibrium and steady state conditions, Density of states & Effective density of states	1
1.4	Equilibrium concentration of electrons and holes.	1
1.5	Excess carriers in semiconductors: Generation and recombination mechanisms of excess carriers, quasi Fermi levels.	2
1.6	TUTORIAL	2
2	**MODULE 2**	
2.1	Carrier transport in semiconductors, drift, conductivity and mobility,	2

	variation of mobility with temperature and doping.	
2.2	Diffusion equation	1
2.3	Einstein relations, Poisson equations	1
2.4	Poisson equations, Continuity equations, Current flow equations	1
2.5	Diffusion length, Gradient of quasi Fermi level	1
2.6	TUTORIAL	2
3	**MODULE 3**	
3.1	PN junctions : Contact potential, Electrical Field, Potential and Charge distribution at the junction, Biasing and Energy band diagrams,	2
3.2	Ideal diode equation	1
3.3	Metal Semiconductor contacts, Electron affinity and work function, Ohmic and Rectifying Contacts, current voltage characteristics.	3
3.4	Bipolar junction transistor – working,, current components, Transistor action, Base width modulation.	2
3.5	Derivation of terminal currents in BJT	2
3.6	TUTORIAL	1
4	**MODULE 4**	
4.1	Ideal MOS capacitor, band diagrams at equilibrium, accumulation, depletion and inversion	2
4.2	Threshold voltage, body effect	1
4.3	MOSFET-structure, working, types,	2
4.4	Drain current equation (derive)- linear and saturation region, Drain characteristics, transfer characteristics.	2
4.5	TUTORIAL	1
5	**MODULE 5**	
5.1	MOSFET scaling – need for scaling, constant voltage scaling and constant field scaling.	2
5.2	Sub threshold conduction in MOS.	1
5.3	Short channel effects- Channel length modulation, Drain Induced Barrier Lowering, Velocity Saturation, Threshold Voltage Variations and Hot Carrier Effects.	3
5.4	Non-Planar MOSFETs: Fin FET –Structure, operation and advantages	1

QUESTION BANK

MODULE I				
NO	**QUESTIONS**	**CO**	**KL**	**PAGE NO:**
1	List out Different types of semiconductors.	CO1	K1	1
2	Explain effective mass	CO1	K2	8
3	Explain Elemental and compound semiconductors,	CO1	K2	9
4	Explain Intrinsic and Extrinsic semiconductors	CO1	K2	16
5	Explain Fermions-Fermi Dirac distribution.	CO1	K2	7
6	Differentiate elemental and compound semiconductors.	CO1	K4	20-21
7	Explain Fermi level.	CO1	K2	23
8	Explain Doping & Energy band diagram,	CO1	K2	24
9	Explain Equilibrium and steady state conditions	CO1	K2	25
10	Analyze Density of states & Effective density of states.	CO1	K4	27
MODULE2				
1	Explain Carrier transport in semiconductors.	CO2	K2	2
2	Explain drift movement of carriers.	CO2	K2	3
3	Write short notes onconductivity and mobility.	CO2	K2	6-7
4	Explain variation of mobility with temperature and doping	CO2	K2	12
5	Analyze continuity equation.	CO2	K4	14-15
6	Discuss current flow equation.	CO2	K2	17

MODULE III				
1	Discuss PN junctions..	CO3	K2	
2	Explain : Contact potential.	CO3	K2	
3	Discuss Electrical Field, Potential and Charge distribution at the junction	CO3	K2	
4	Discuss Biasing and Energy band diagrams of a pn junctions.	CO3	K2	
5	Analyze Ideal diode equation..	CO3	K4	
6	Differentiate ohmic and rectifying contacts.	CO3	K4	
7	Differentiate current voltage characteristics metal and rectifying contacts...	CO3	K4	
8	Explain BJT manufacturing.	CO3	K2	
9	Explain signed and unsigned instructions.	CO3	K2	
10	Discuss current components and Transistor action BJT .	CO3	K2	

MODULE IV				
1	State Ideal MOS capacitor.	CO4	K3	
2	Explain band diagrams of MOS at equilibrium, accumulation, depletion and inversion conditon.	CO4	K2	
3	Analyze threshold voltage equation.	CO4	K4	
4	Explain body effect in MOSFET.	CO4	K2	
5	Analyze drain current equation of MOSFET.	CO4	K4	
6	Explain structure, types of MOSFET..	CO4	K2	
7	Discuss linear and saturation region in Drain characteristics.	CO4	K2	
8	Illustrate drain and transfer characteristics of MOSFET.	CO4	K3	
MODULE V				
1	Explain MOSFET scaling .	CO5	K2	85
2	Explain need for scaling.	CO5	K2	86
3	Differentiate constant voltage scaling and constant field scaling.	CO5	K4	88
4	Explain Sub threshold conduction in MOS	CO5	K2	90
5	Explain Short channel effects.	CO5	K2	95
6	Discuss Channel length modulation.	CO5		
7	Explain Drain Induced Barrier Lowering.	CO5	K2	
8	Analyze Velocity Saturation,	CO5	K4	
9	Differentiate Threshold Voltage Variations and Hot Carrier Effects.	CO5	K4	
10	Discuss Fin FET –Structure, operation and advantages	CO5	K4	

APPENDIX 1		
CONTENT BEYOND THE SYLLABUS		
S:NO;	**TOPIC**	**PAGE NO:**
1	8085 INSTRUCTION SET	

Module 1

SOLID STATE DEVICES.

MODULE 1

As isolated atoms are brought together to form a solid, Various interactions occurs between neighbouring atoms. The forces of attraction and repulsion between atoms will find a balance at the proper inter-atomic spacing for the Crystal. In this process important changes Occurs in the electron energy level Configurations and these changes result in the Various electrical properties of Solids.

METALS, SEMICONDUCTORS AND INSULATORS.

Materials are classified into three :- metal, insulators and Semiconductors. Every Solid has its own characteristic energy band. The Variation in band structure is responsible for the wide range of electrical characteristics observed in Various materials

For an electron to experience accelaration in applied electrical field. they must be able to move into new energy states. ie, there must be empty energy States available to electrons.

Material in which the electrons are loosely bound to the Central nucleus is called Conductors.

Material in which the Outer electrons are tightly bound to the nucleus is called insulator.

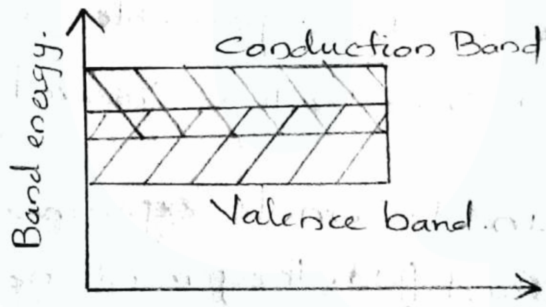
Semiconductors are those materials their

Conductivity lies in between the Conductivity of Conductors and insulators. are Called Semi-Conductors

ENERGY BAND DIAGRAMS:-

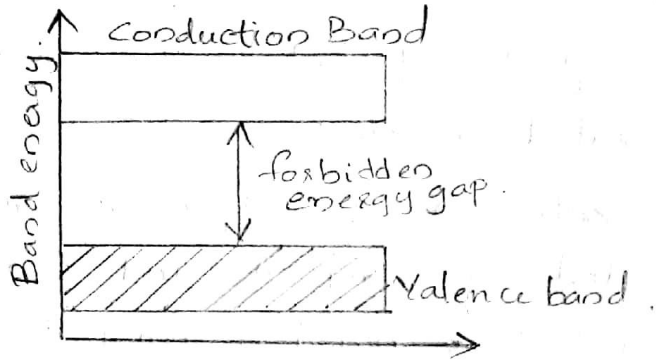
CONDUCTORS:-

In the energy band diagram of Conductors there is no forbidden energy gap between the Valance band and the Conduction band. The two bands actually Overlap as shown in fig. It indicates that, the Valance band energies are the Same as the Conduction band energies and it is Very easy for a Valance electron to become a Conduction electron. Therefore without Supplying additional energy these materials can have a large number of free electrons and act as good conductors.



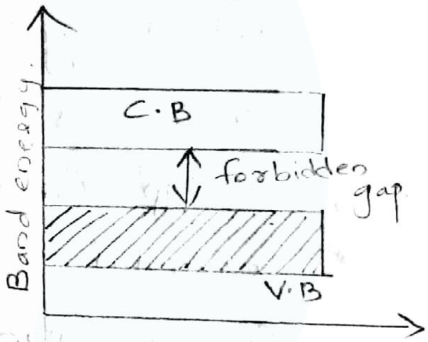
INSULATORS:-

Here the Valence band is full while the Conduction band is empty. More Over the energy gap between Valance band and Conduction band (15eV). Therefore a Very high electric field is required to lift the Valance electrons to the Conduction band. Due to this reason the electrical Conductivity of insulator is extremely small and can be regarded as zero under normal condition.



SEMICONDUCTOR.

In the case of semiconductors, the Valance band is almost filled and Conduction band is empty. But the forbidden energy gap is very small (1eV). Therefore comparatively a smaller electric field [smaller than required in the case of insulator but greater than conductor] is required to lift the Conduct Valence electron in CB. Thus the conductivity of semi conductor lies b/w a conductor and insulators.



SEMICONDUCTORS.

Semiconductors are two types:- Intrinsic semi-conductor and extrinsic semiconductor.

1. INTRINSIC SEMICONDUCTORS.

A semiconductor in its purest form is known as intrinsic semiconductor. In such materials there are no charge carriers at 0 K. Since Valance band is filled with electrons and conduction band is empty. At higher temperature, electron-hole pairs are generated. As Valance band electrons are excited thermally to Conduction band. The energy required to excite electrons to Conduction band is Called <u>band gap energy. (E_g)</u>. In this electrons and holes are Created in pairs.

Concentration of electrons in Conduction band is denoted by using 'n' and Concentration of holes in Valance band is denoted as P.

So for intrinsic Semiconductor, $n = P = n_i$

where n_i is the intrinsic Concentration.

2. EXTRINSIC SEMICONDUCTORS.

Generating Carriers in Semiconductors by introducing impurities into the Crystal is Called dopping. There are two types of dopped Semiconductors; n-type (mostly electrons) & P-type (mostly holes). When a Crystal is dopped, such that equilibrium Carrier Concentration n_0 and P_0 are different from the intrinsic Carrier Concentration n_i, the material is said to be extrinsic.

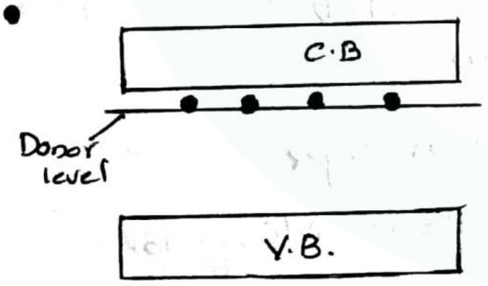
When impurities are introduced into a perfect Crystal additional levels are Created in the energy band structure within the band gap. A Pentavalent impurity introduced to Conduction band in Ge Or Si. This level is filled with electrons at 0 K. and Very little thermal energy is required to excite these electrons to Conduction band. ie, electrons at this impurity level donated to C.B at about 50-100K. So such an impurity level is Called <u>donor level</u> and such impurities are Called <u>donor impurity</u>.

Semiconductors dopped with a significant number of donor atoms will have $n_o >> (n_i, P_o)$ at room temperature. This is <u>n-type materials</u>

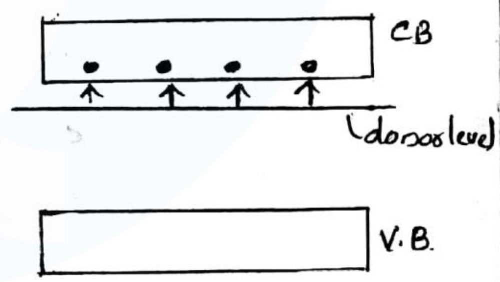
A trivalent impurity introduce impurity levels in Ge or Si near the Valance band. These levels are empty of electrons at 0 k. At low temperature, enough thermal energy is available to excite e^-s from Valance band into the impurity level, leaving behind holes in Valance band. Since this type of impurity level accepts electrons from the Valance band, it is called an <u>acceptor level</u> and these impurities are called <u>acceptor impurities.</u>

Doping with acceptor impurities can create a Semiconductor with a hole concentration P_o much greater than the conduction band electron concentration n_o. This type is <u>P-type material.</u>

ENERGY BAND DIAGRAM FOR N-type.

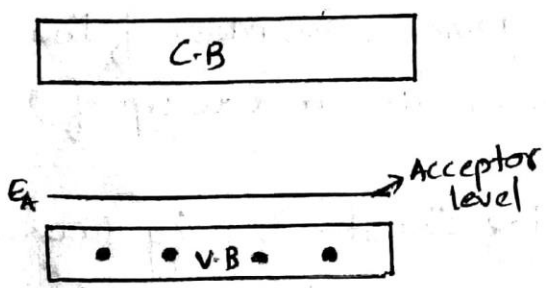
- 

T= 0k

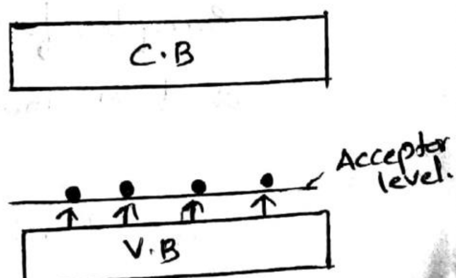


T= 50 k.

- P_type.



T= 0k



T=50k.

ELEMENTAL AND COMPOUND SEMICONDUCTORS

Semiconductors which are constituted by a single species of atoms are called Elemental Semi-conductors. In periodic table, IVth group elements are called elemental semiconductors (Si & Ge).

As a semiconductor material, silicon has several advantages.

1. Silicon is abundant in nature.
2. Silicon devices can be operated at higher temperature due to its wider bandgap.
3. A stable oxide (SiO_2) is available for silicon which can be used.
   a. as mask during fabrication process.
   b. for isolation.
   c. as passivation layer.
   d. as gate oxide in MOSFETs.

Because of these, the fabrication process is simpler for silicon devices. So, most of the IC's and electronic devices are made up of silicon.

A semiconductor constituted by two or more different species of atoms is called Compound Semiconductor.

These are the examples of compound Semiconductor.

- III-V Compounds :- Compounds formed by element from third and fifth group. [AlP, AlAs, AlSb, GaP, GaAs etc]

- II-VI Compounds :- Compounds formed by element from second and sixth group.
  [ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe].

* Binary Compounds :- A Compound Semi-Conductor consist of two elements.
  - 4th group elements are also called binary compound.

* Ternary Compounds :- A Compound Semi-Conductor consist of three elements.
  - eg :- GaAsP, AlGaAs.

* Quaternary Compounds :- A Compound Semi-Conductor consist of four elements.
  - eg :- AlGaAsP, InGaAsP.

FERMI-DIRAC DISTRIBUTION FUNCTION.

The distribution of electrons over a range of allowed energy level at thermal equilibrium.

$$f(E) = \frac{1}{1 + e^{(E-E_f)/kT}}$$

where, k is Boltzmann's Constant.
$(1.38 \times 10^{-23} J/k)$
$8.62 \times 10^{-5} eV/k$.
T is absolute temperature
E_f is fermi-level or fermi energy level.

The function $F(E)$ is called as Fermi-Dirac Distribution function.

The Occupation probability of E_f is.

$$F(E_f) = \frac{1}{1+e^{(E_f - E_f)/kT}}$$

$$= \frac{1}{1+e^0} \quad ; T>0$$

$$= \frac{1}{1+1} = \frac{1}{2}$$

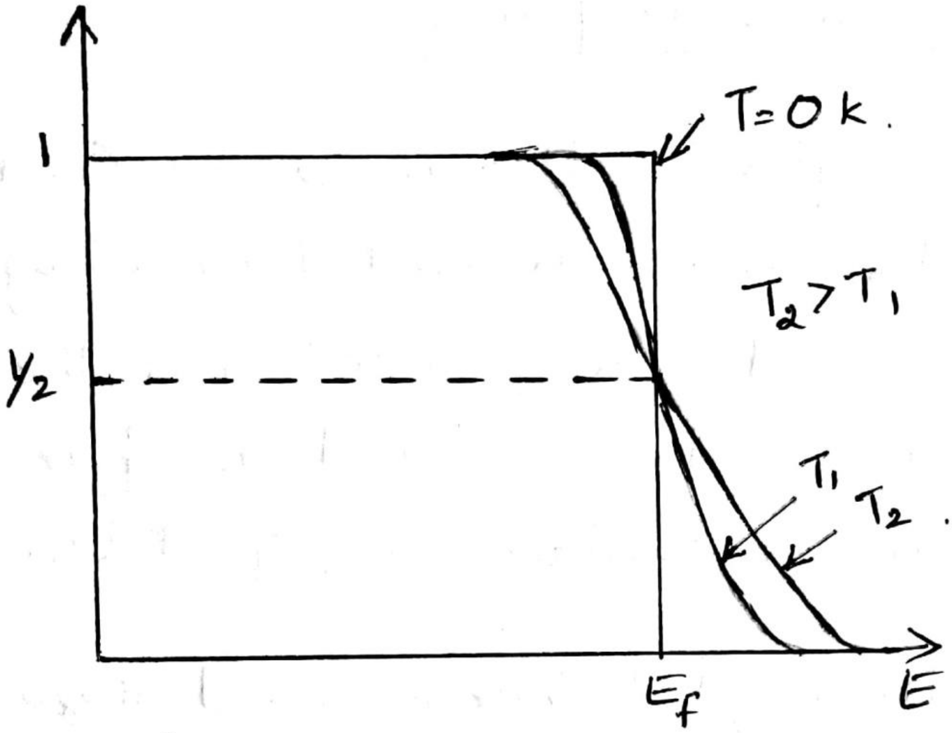
At 0k, $F(E)$ take a simple rectangular form

when $E < E_f$.

$$F(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$$

when $E > E_f$

$$F(E) = \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty} = 0$$

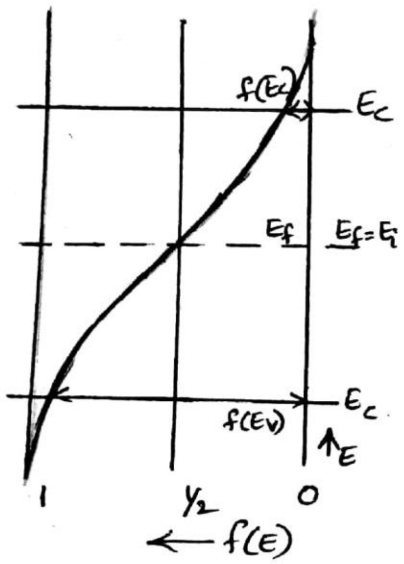


fermi-dirac distribution function.

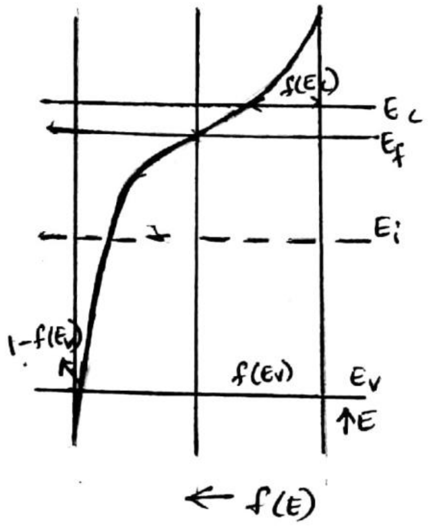
This implies that at 0 k, every energy state below E_f is filled with electrons and all state above E_f are empty.

At temperature higher than 0 k, Some probability exsist for states above the fermi levels are filled and there is a corresponding probability. 1 - F(E) that states below E_f are empty. Fermi function is symmetrical about E_f for all temperatu

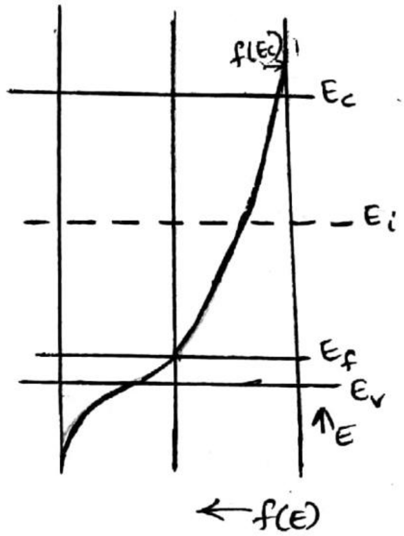
FERMI-DIRAC DISTRIBUTION FUNCTION APPLIED TO S.C.



Energy band of intrinsic S.C for f(E).



Energy band diagram along with f(E) for n-type.



Energy band diagram along with f(E) for P-type.

For Intrinsic Semiconductor, Probability of Occupany in C.B equals the Probability of Vacancy in V.B. ie, $1-F(E_v) = F(E_c)$, to satisfy the Condition E_f must be at the middle of the bandgap. (ie, $E_i = E_f$).

For n-type Semiconductor, Probability of Occupany in C.B is much greater than the Probability of Vacancy in V.B. ie, $f(E_c) >> 1-f(E_v)$ to satisfy the Condition E_f must be above the middle of the bandgap. As doping Increases E_f moves towards E_c.

For P-type Semiconductor, Probability of Occupany in C.B is much lesser than the Probability of Vacancy in V.B. ie, $f(E_c) << 1-f(E_v)$ to satisfy the Condition E_f must be below the middle of the bandgap. As doping increases E_f moves towards E_v.

CHARGE CARRIERS IN SEMICONDUCTORS.

As the temperature of semiconductors is raised from 0k, some electrons in the valence band receive enough thermal energy to be excited across the band gap to the conduction band. Thus an empty space is created in the valance band. This is called a hole.

If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called electron-hole pair.

After excitation to the conduction band an electron is surrounded by a large number of unoccupied energy states. Thus the few electrons in the conduction band are free to move about the many available empty states.

In a filled valence band, there is no movement of electrons. So there is no net current flow. But if we remove an electron from the valence band, there will be a net current flow. ie, an empty. Conduction band completely devoid of electrons or valence band completely full of electrons, cannot be give rise to net motion of electrons. and thus no current conduction.

ELECTRON & HOLE CONCENTRATION AT EQUILIBRIUM.

The fermi-distribution function can be used to calculate the concentration of electrons and holes in a semiconductors. If the density of available states in valence band and conduction band are known. The concentration of electrons in conduction band is,

$$n_0 = \int_{E_c}^{\infty} F(E)\, N(E)\, dE$$

where,

N(E) dE is the density of states in the energy range dE.

dE is the no. of electron per unit Volume in the energy range.

f(E) is the Probability of Occupancy.

As per the above equation, The total electron Concentration in the Conduction band is the integral of product of density of states and probability of occupancy over the entire Conduction band.

$$N(E) = \frac{\sqrt{2}}{\pi^2}\left(\frac{m^*}{h^2}\right)^{3/2} E^{1/2}$$

from eqn,

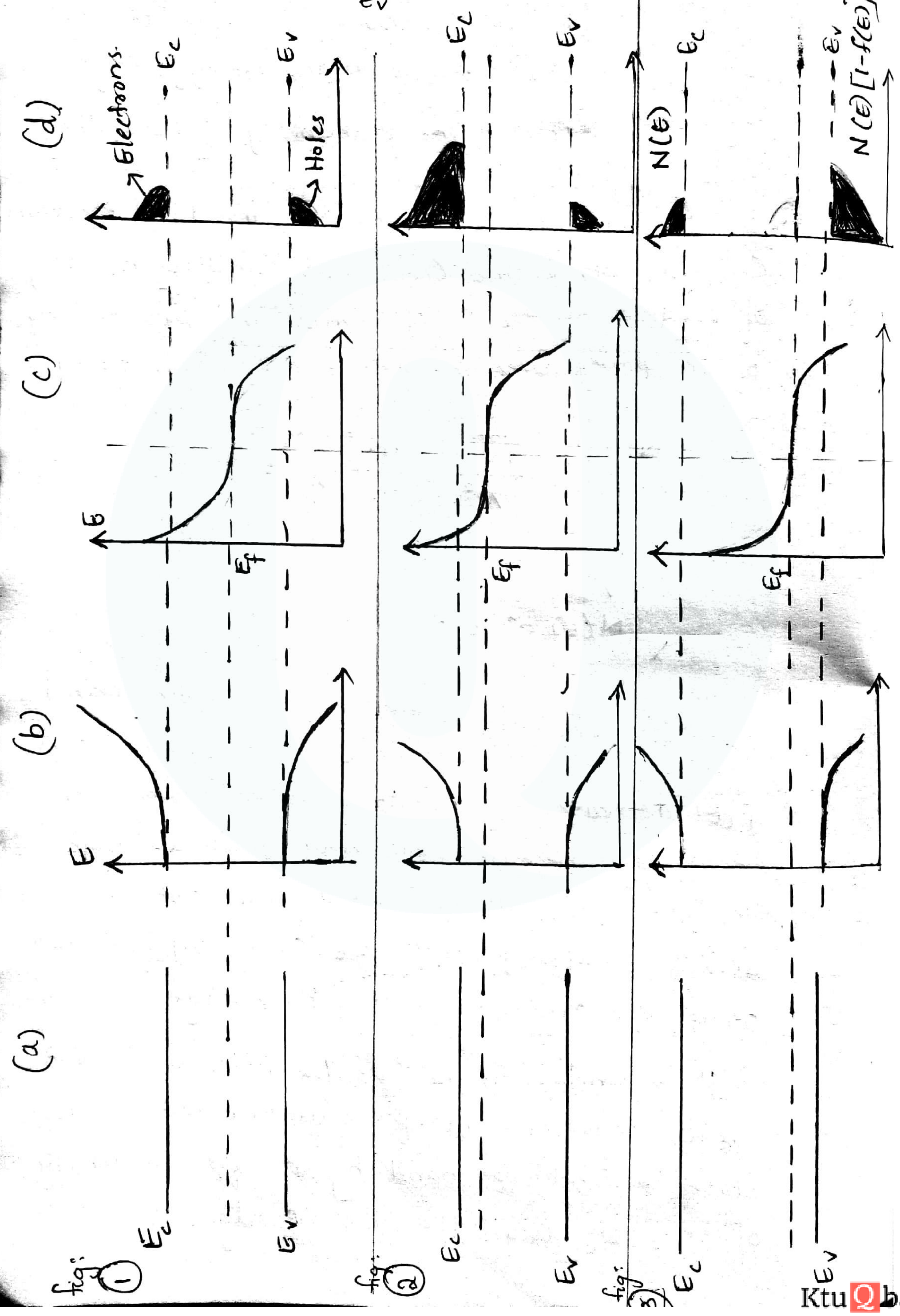
$$N(E) \propto E^{1/2}$$

ie, The density of states in Conduction band increases with increases in electron energy. But F(E) decreases exponentially with increase in energy and become extremely Small at large energies. The result is that product F(E) N(E) is decreases rapidly above E_c and Very few electron occupy far above Conduction band edge.

It is Similar in the Case for holes in the V.B. If we represent all of the distributed electron states in Conduction band by an effective density of state N_c located at the CB edge.

$1 - f(E_v)$ is the Probability of Vacancy at E_v

$$P_0 = \int_{E_v}^{\infty} [1 - F(E)]\, N(E)\, dE.$$



Schematic band diagram, density of states, fermi-dirac distribution and the carrier concentrations for (1) intrinsic (2) n-type (3) p-type semiconductors at thermal equilibrium.

∴ Area under $f(E)N(E)$ in the conduction band is a measure of electron concentration. Similarly area under $N(E)[1-f(E)]$ in the valence band is a measure of hole concentration in the valance band.

For intrinsic semiconductor, these quantities are equal as shown in fig(1).

For n-type semiconductor, $N(E)f(E)$ in the conduction band has a larger area than $N_v[1-f(E)]$ in the valence band. ie, $n_o >> p_o$ [fig 2]

For p-type semiconductor, $N(E)f(E)$ in the conduction band is much less than $N(E)[1-f(E)]$ in the valence band. ie, $p_o >> n_o$ [fig 3].

Derivation.

Effective density of state in the conduction band.

$$N_c = 2\left[\frac{2\pi m_n^* kT}{h^2}\right]^{3/2}$$

Effective density of state N_c, the electron concentration in the conduction band.

$$n_o = N_c f(E_c) \quad \text{——— (1)}$$

$$f(E_c) = \frac{1}{1+e^{(E_c-E_f)/kT}}$$

we assume that fermi level E_f lies by atleast several kT. below the Conduction band. Then the exponential terms is large compared to unity. So $f(E_c)$ can be simplified as.

$$f(E_c) = \frac{1}{e^{(E_c - E_f)/kT}}$$

$$= e^{-(E_c - E_f)/kT} \quad \text{———} (2)$$

Sub (2) in (1).

$$\therefore n_o = N_c \cdot e^{-(E_c - E_f)/kT}$$

Similarly, the concentration of holes in the Valance band. is,

$$P_o = N_v \left[1 - f(E_v)\right] \quad \text{———} (3)$$

where

$$N_v = 2\left[\frac{2\pi m_p^* kT}{h^2}\right]^{3/2}$$

(N_v is the effective density of state in the V.B)

$1 - f(E_v)$ is the probability of Vacancy in V.B

$$1 - f(E_v) = 1 - \frac{1}{1 + e^{(E_v - E_f)/kT}}$$

$$= \frac{e^{(E_v - E_f)/kT}}{1 + e^{(E_v - E_f)/kT}}$$

if $E_f - E_v >> kT$.

$$1 - f(E_v) = e^{(E_v - E_f)/kT}$$

$$= e^{-(E_f - E_v)/kT} \quad \text{——— (4)}$$

Sub (4) in (3)

$$\boxed{P_o = N_v \cdot e^{-(E_f - E_v)/kT}}$$

For intrinsic Semiconductor, E_f fermi level lies exactly at the middle of the bandgap and is denoted using E_i. So, the carrier Concentration of intrinsic Semicconductor is.

$$n_0 = N_c \cdot e^{-(E_c - E_i)/kT} \qquad \therefore n_o = n_i = P_o.$$

$$P_0 = N_v \cdot e^{-(E_i - E_v)/kT}$$

$$\underbrace{n_0 P_0 = n_i^2}_{\text{Mass Action Law}} = N_c \cdot N_v \left[e^{-E_c + E_i - E_i + E_v / kT} \right]$$

$$= N_c N_v \, e^{-(E_c - E_v)/kT}$$

where, $E_c - E_v = E_g$.

$$n_i^2 = N_c N_v e^{-E_g/kT}.$$

$$\boxed{n_i = \sqrt{N_c N_v e^{-E_g/kT}}}$$

Electron & hole Concentration in terms of intrinsic.

$$n_o = n_i e^{(E_f - E_i)/kT}$$

$$P_o = n_i e^{(E_i - E_f)/kT}.$$

TEMPERATURE DEPENDENCE OF CARRIER CONCENTRATION.

Intrinsic Carrier Concentration (n_i) is

$$n_i(T) = \sqrt{N_c N_v e^{-E_g/2kT}}$$

$$= \sqrt{2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \times 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \times e^{-E_g/2kT}}$$

$$n_i(T) = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$$

from this equation, we can see that as temperature increases carrier concentration increases.

$$n_i \propto T^{3/2}$$

The exponential temperature dependence dominates $n_i(T)$.

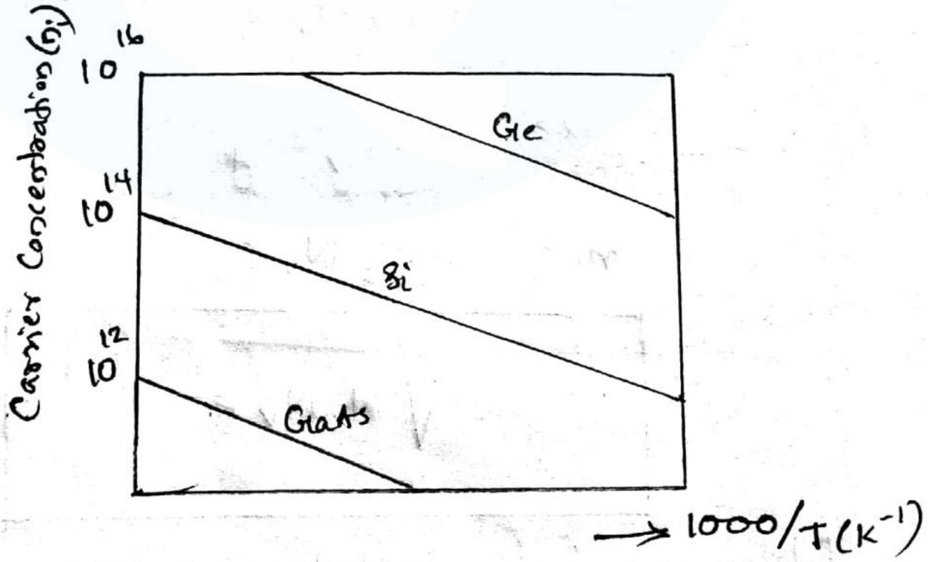
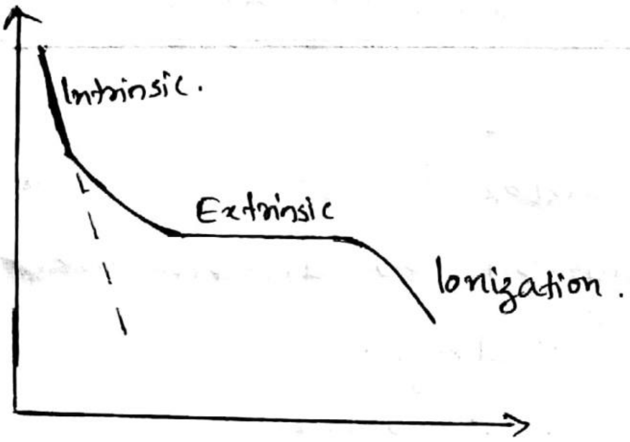


fig: Variation of intrinsic Carrier Concentration of Si, Ge & GaAs with inverse temperature.

Extrinsic S.C.



At low temperatures, negligible intrinsic holes-electron pairs exists and donor electrons are bound to donor atoms. As temperature is raised these electrons are donated to conduction band. And at about 100 k, all the donor atoms are ionised. ie, every available electrons is transfered to conduction band. Carrier concentration is virtually constant with temperature. finally at higher temperature more intrinsic carriers generated & intrinsic carrier concentration dominates the extrinsic concentration.

The temperature dependence of n_o carrier concentration is shown above fig. It consist three regions

1. Ionization region
2. Extrinsic region
3. Intrinsic region.

CARRIER TRANSPORT IN SEMICONDUCTORS. MOBILITY AND CONDUCTIVITY.

Carrier transport in Semi Conductor is mainly by two different mechanisms:

1. drift.
2. diffusion.

- Drift Current results from the movement of electrons or holes under an electric field similar to the current flow in a metal
- Diffusive motion is due to gradients in Carrier Concentrations.

The charge Carriers in a Solid are in Constant motion even at thermal equilibrium This motion is by random scattering from impurities, other electrons etc. So there is no net flow of electrons.

Suppose if an electric field $\mathcal{E}_x$ is applied in the x-direction, each electron experiences a net force $-q\mathcal{E}_x$ from the field. If P_x is the x Component of the total momentum of the group.

The force of the field on the n electrons

$$-nq\mathcal{E}_x = F.$$

$$-nq\mathcal{E}_x = \frac{dP_x}{dt} \quad \text{——— (1)}$$

$P = mV$

$\frac{dP}{dt} = m\frac{dV}{dt}$

$= ma$

$\frac{dP}{dt} = F$

If the Collisions are truely random there will be a Constant probability of collisions at any time for each electron.

Let us Consider a group of N_o electrons at time $t=0$ and define $N(t)$ as the number of electrons that have not undergone a Collision by time t.

The rate of decrease in $N(t)$ at any time t is proportional to no. of electrons left unscatted at t.

ie,

$$-\frac{dN(t)}{dt} \propto N(t)$$

$$-\frac{dN(t)}{dt} = \frac{1}{\bar{t}} \cdot N(t).$$

where, $\bar{t}$ is Called as mean free time.

[Mean free time – It is the mean time b/w successive Collision]

The probability that any electrons has a Collision in time interval dt is $dt/\bar{t}$

The differential change in momentum due to Collision is

$-P_x \cdot dt$

$$dP_x = -P_x \cdot \frac{dt}{\bar{t}}$$

Rate of change of momentum due to Collisions.

$$\frac{dP_x}{dt} = \frac{-P_x}{\bar{t}} \quad \text{——— (2)}$$

The sum of acceleration & deceleration on effects must be 0 at steady state

ie, acc decelrn

$$-nq\mathcal{E}_x - \frac{P_x}{\bar{t}} = 0 \quad \text{——— (3)}$$

$-nq\mathcal{E}_x - \frac{P_x}{\bar{t}} = 0$

from (3),

$-\frac{P_x}{\bar{t}} = nq\mathcal{E}_x$

$$P_x = -nq\mathcal{E}_x\bar{t}$$

$P_x = nq\mathcal{E}_x\bar{t}$

Average momentum for n electrons is

$$\langle P_x \rangle = -q\mathcal{E}_x\bar{t}$$

Average Velocity for n electrons is

$$\langle V_x \rangle = \frac{\langle P_x \rangle}{m_n^*}$$

$$= \frac{-q\mathcal{E}_x\bar{t}}{m_n^*} \quad \text{——— (4)}$$

The Current density

$$J_x = -qn\langle V_x \rangle$$

Sub (4) in J

$$= -qn \times \frac{-q\mathcal{E}_x\bar{t}}{m_n^*}$$

$$J_x = \frac{q^2 n \mathcal{E}_x \bar{t}}{m_n^*} \quad \text{——— (5)}$$

from ohm's law,

$$J = \sigma \mathcal{E}_x. \quad \text{——— (a)}$$

where $\sigma = \dfrac{q^2 n \bar{t}}{m_n^*}$ ——— (6)

∴ σ is Conductivity.

~~Hn~~ we can write Conductivity σ as

$$\sigma = q_1 n \mu_n \quad \text{——— (7)}$$

μ_n = mobility of electrons

Comparing (7) & (6)

$$\mu_n = \frac{q\bar{t}}{m_n^*}$$

Sub (7) in (a), Current density for electrons is,

$$\boxed{J_n = q_1 \mu_n n \mathcal{E}_x.}$$

Current density for holes is

$$\boxed{J_p = q p \mu_p \mathcal{E}_x.}$$

Mobility :- It describes the ease with which electrons drift in the materials.

conductivity of the material.

$$\therefore J_x = q(n\mu_n + p\mu_p)\mathcal{E}_x = \sigma \mathcal{E}_x$$

EFFECT OF TEMPERATURE AND DOPING ON MOBILITY.

Mobility with temperature:-

Mobility of charge carriers is decided by the scattering or collision mechanisms.

Two basic types of scattering mechanism that influence electron and hole mobility are lattice scattering and impurity scattering.

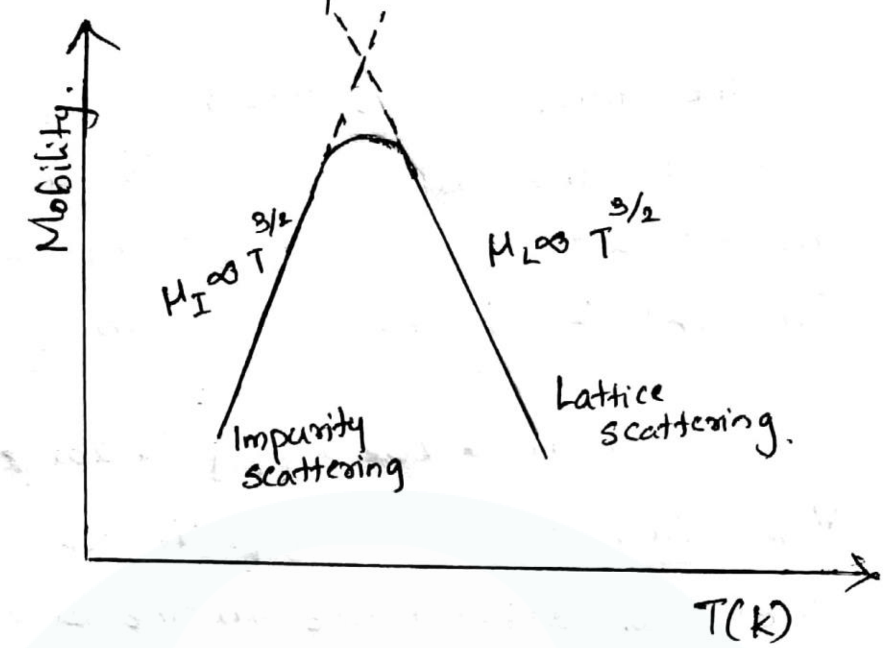
As the scattering increases, mobility decreases. Lattice scattering increases with increase in temperature as the thermal agitation of lattice increases. ∴ mobility due to lattice scattering decreases with increase in temperature ($\mu_L \propto T^{-3/2}$)

Lattice Scattering :- This scattering mechanism due to vibration of lattice.

Ionized impurity Scattering :- Ionized impurity scattering of charge carriers with ionized impurities.

At low temperature, the thermal motion of carrier is slower. Slowly moving carrier scattered more strongly by interaction with a charged ion. Therefore, mobility due to ~~lattice~~ &

ionized impurity scattering decreases with decreases in temperature.



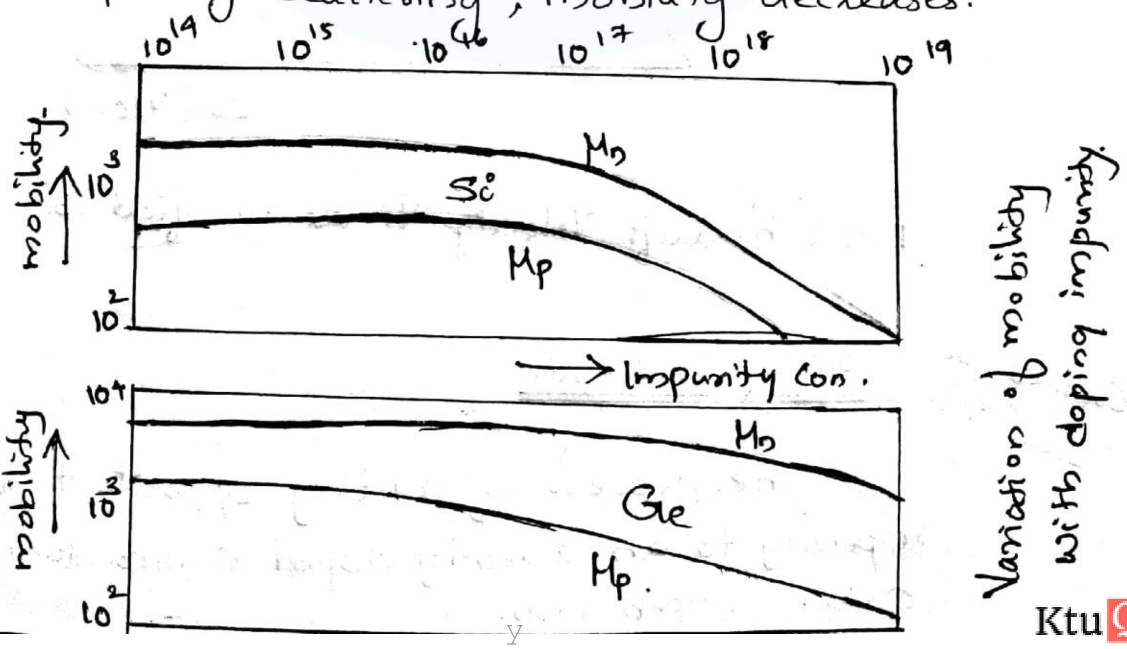
Variation of mobility with temperature.

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \cdots$$

where, μ is the effective mobility.

Mobility with doping:-

As the concentration of impurities increases (increase in doping), due to increased ionized impurity scattering, mobility decreases.



$$B_x = B_y = 0 \quad \text{and} \quad V_y = V_z = 0.$$

The net force experienced by a hole along the y direction is the sum of the forces due to the electric field and magnetic field along y-direction.

force due to electric field $= q\mathcal{E}_y$.

force due to magnetic field $= q$ x, y Component of $v \times B$

$$= q\left[-V_x B_z - B_z V_z\right]$$

$$= q\left(-V_x B_z\right)$$

since $V_z = 0$

In the y-direction, the net force is,

$$F_y = q\left(\mathcal{E}_y - V_x B_z\right) \quad \text{——— (2)}$$

The above equation shows that, unless an electric field is established along the y-direct the hole will experience a net force and acceleration in y-direction due to $V_x B_z$.

∴ To maintain a steady state flow of holes down the length of the bar, the electric field $\mathcal{E}_y$ must just balance the product $V_x B_z$

$$\mathcal{E}_y = V_x B_z.$$

The establishment of electric field $\mathcal{E}_y$ is known as Hall Effect and the resulting Voltage $V_{AB} = \mathcal{E}_y \cdot w$ is called Hall Voltage.

$(V = \mathcal{E} d)$

~~Hall effect~~

$$\therefore \mathcal{E}_y = \frac{J_x B_z}{q P_o} \quad \text{---} (3)$$

$$\mathcal{E}_y = R_H \cdot J_x B_z.$$

(Hall effect or field is proportional to the product of current density and magnetic flux density)

$$\frac{J_x B_z}{q P_o} = R_H J_x B_z.$$

$$R_H = \frac{1}{q P_o}.$$

The proportionality constant $\left[R_H = \frac{1}{q P_o} \right]$ is called Hall Coefficient.

from (3)

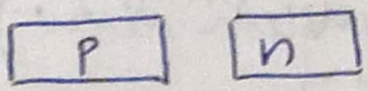
$$P_o = \frac{J_x B_z}{q \mathcal{E}_y}$$

$$= \frac{\left(I_x / wt\right) B_z}{q \left(\frac{V_{AB}}{w}\right)} = \frac{I_x B_z}{q t V_{AB}}.$$

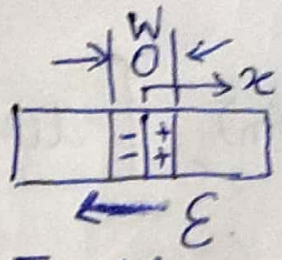
Since, all the quantities in the equation are measurable the majority carrier concentration can be measured using Hall effect.

16/10/2020

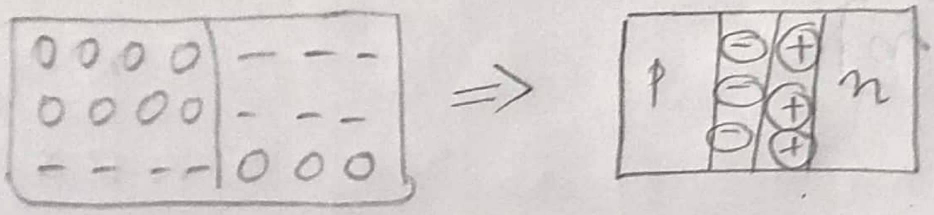
Module 3

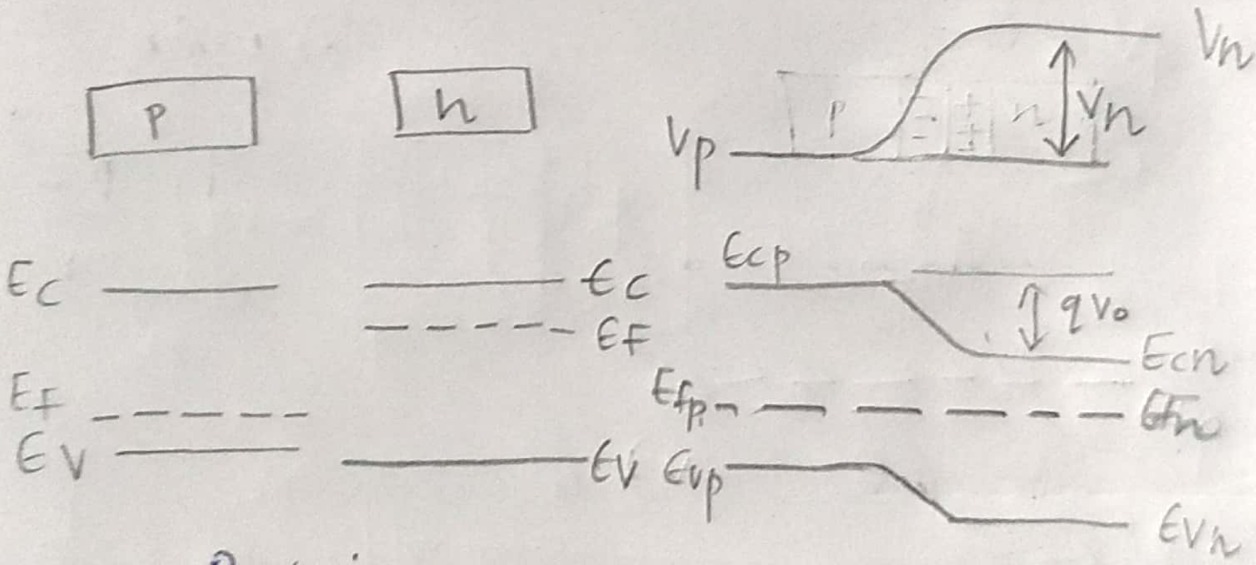


Individual p-type and n type material



Junction





Particle flow | **Current**

⟶ hole diffusion ⟶ | e⁻ current & diff still opposite but whole same

$f = q\varepsilon$ ⟵ hole drift ⟵

⟵ ē diff ⟶

$f = -q\varepsilon$ ⟶ e⁺ drift ⟵

These currents having same magnitude, so they get cancelled & the resultant current becomes 0. Under equilibrium, the net current will become 0. So,

Once barrier is developed $I = 0$. Because they can't cross the barrier.

equal line indicate same magnitude

$$J_p(\text{drift}) + J_p(\text{diff}) = 0$$

$$J_n(\text{drift}) + J_n(\text{diff}) = 0$$

$$\mathcal{E}_x = \frac{-d(V(x))}{dx}$$

=> W is transition region, Vo is contact potential.

$V_0 = V_n - V_p$ (from fig, V_n is ↑ than V_p).

Relationship between contact potential Vo & doping concentration

The drift & diffusion component of hole current just cancel at equilibrium.

$$J_p(x) = q\left[\mu_p p(x)\mathcal{E}(x) - D_p \frac{dp(x)}{dx}\right] = 0. \rightarrow (1)$$

$$\mu_p p(x)\mathcal{E}(x) = D_p \frac{dp(x)}{dx}$$

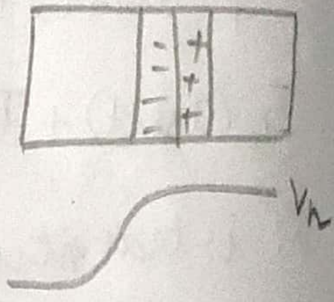
$$\frac{\mu_p}{D_p}\mathcal{E}(x) = \frac{1}{p(x)}\frac{dp(x)}{dx} \longrightarrow (2)$$

From Einstein Relation $\frac{D}{\mu} = \frac{kT}{q}$, so $\frac{\mu_p}{D_p} = \frac{q}{kT}$

So (2) becomes, $\frac{q}{kT} \mathcal{E}(x) = \frac{1}{p(x)} \frac{dp(x)}{dx}$

& $\mathcal{E}(x) = \frac{-d}{dx} V(x)$.

$\therefore \frac{-q}{kT} \frac{d}{dx} V(x) = \frac{1}{p(x)} \frac{dp(x)}{dx} \rightarrow (3)$.



Integrating (3)

$$-\frac{q}{kT} \int_{V_p}^{V_n} dV = \int_{P_p}^{P_n} \frac{1}{p}\, dp$$

→ So limits will be P → n looking from p side.

$$-\frac{q}{kT} \left[V \right]_{V_p}^{V_n} = \left[\ln p \right]_{P_p}^{P_n}$$

→ We are deriving conc of P_0 & V_0. So conc of holes on n side & p side is taken.

$$-\frac{q}{kT} \left[V_n - V_p \right] = \ln P_n - \ln P_p = \ln \frac{P_n}{P_p}$$

So $V_n - V_p = V_0$ (Contact potential).

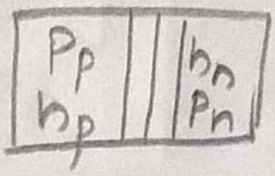
- holes on n side = P_n
- holes on p side = P_p

$$\frac{-q}{kT} (V_0) = \ln \frac{P_n}{P_p}$$

$$V_0 = \frac{-kT}{q} \ln \frac{P_n}{P_p} \quad \text{or} \quad \boxed{V_0 = \frac{kT}{q} \ln \frac{P_p}{P_n}} \longrightarrow (4)$$

Taking exponential on both sides.

$$\boxed{\frac{P_p}{P_n} = e^{qV_0/kT}}$$



P_p - holes on P

P_n - holes on n

n_p - e's on p

n_n - e's on n.

Subscript shows the material, main shows the conc.

Mass action on both p & n, $n_i^2 = P_p * n_p$

$$n_i^2 = n_n P_n$$

P_p - Majority hole conc on p type $= N_a$ (acceptor)

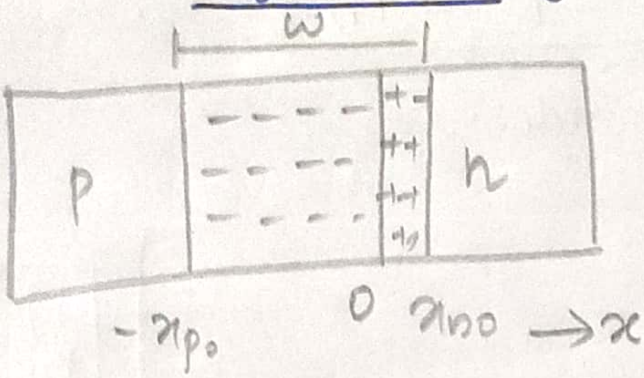
n_n = Majority conc on n type $= N_d$ (donor)

and $P_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_d}$.

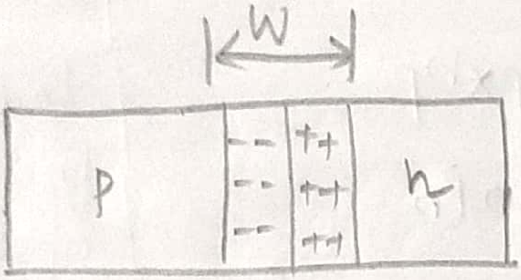
So (4) => $V_0 = \frac{kT}{q} \ln \frac{N_a}{n_i^2/N_d} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$

$$\boxed{\frac{P_p}{P_n} = \frac{n_n}{n_p} = e^{qV_0/kT}}$$

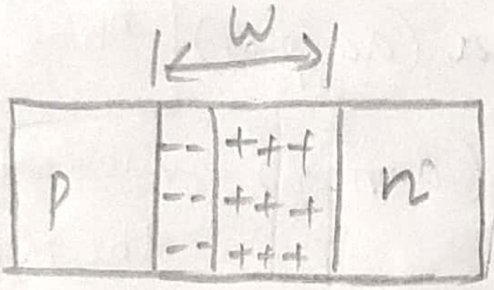
Space charge at a junction



$N_d > N_A$

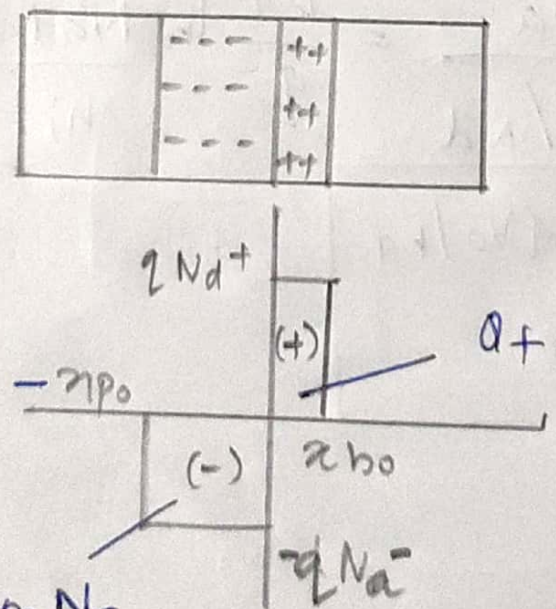


$N_d = N_a$. To maintain charge neutrality



$N_d > N_a$.

when doping greater, penetration will be less.



$Q_+ = qAx_{n0}N_d$

$Q_- = -qAx_{p0}N_a$

$Q_- = Q_+ \Rightarrow -qAx_{p0}N_a = qAx_{n0}N_d$ (1)

Since the dipole about the junction must have an equal no: of charges on either side, the transition region may extend into the p and n regions unequally, depending on relative doping. If p is more lightly doped than the n side ($N_a < N_d$), the space charge region must extend farther into p than n material. (eq ①)

x_{p0} = penetration of spacecharge region into p.

To calculate the electric field distribution within the transition region, we begin with Poisson's equation, which relates the gradient of the electric field to the local space charge at any point x:

mobile hole, immobile donor

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}\left(p - n + N_d^+ - N_a^-\right) \longrightarrow (1)$$

ϵ = epsilon.

immobile acceptor

mobile e^{-1}

We neglect the contribution of the carriers (p-n) to space charge. because space charge consist of only immobile ions.
(Electric field sweeps out mobile holes & electrons, i.e. p & n)

(1) becomes
$$\frac{d\mathcal{E}}{dx} = \frac{q}{\epsilon}\left(N_d^+ - N_a^-\right) \longrightarrow (2) \quad \text{(entire w)}$$

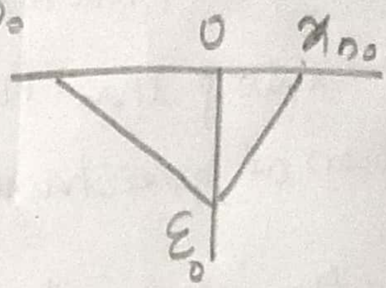
(2) for entire transition region 2.

Separating entire region to 2 parts, it becomes,

$$\frac{d\mathcal{E}}{dx} = \frac{q}{\epsilon} N_d \qquad 0 < x < x_{n0} \longrightarrow (3)$$

$$\frac{d\mathcal{E}}{dx} = \frac{-q}{\epsilon} N_a \, , \quad -x_{p0} < x < 0 \rightarrow (4)$$

$$(3) \Rightarrow d\mathcal{E} = \frac{q}{\epsilon} N_d \, dx \rightarrow (5)$$



$$(4) \Rightarrow d\mathcal{E} = \frac{-q}{\epsilon} N_a \, dx \rightarrow (6)$$

Integrating (5), (6).

$$\int_{\mathcal{E}_0}^{0} d\mathcal{E} = \frac{q}{\epsilon} N_d \int_0^{x_{n0}} dx \, , \quad 0 < x < x_{n0}$$

$$\int_0^{\mathcal{E}_0} d\mathcal{E} = \frac{-q}{\epsilon} \int_{-x_{p0}}^{0} dx \, , \quad -x_{p0} < x < 0 .$$

$$\text{So, } [\mathcal{E}]_{\mathcal{E}_0}^{0} = \frac{q}{\epsilon} N_d [x]_0^{x_{n0}}$$

$$\mathcal{E}_0 = \frac{-q}{\epsilon} N_d x_{n0} .$$

Similarly $\mathcal{E} = \frac{-q}{\epsilon} N_a x_{p0}$

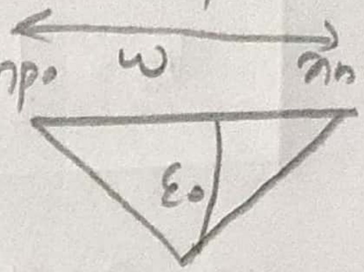
$$\mathcal{E} = -\frac{q}{\epsilon} N_d x_{n0} = \frac{-q}{\epsilon} N_a x_{p0} \rightarrow (7) .$$

$$\mathcal{E}(x) = \frac{-d}{dx} V(x) \quad \text{or} \quad -V_0 = \int_{-x_{p0}}^{x_{n0}} \mathcal{E}(x)\, dx$$

$$V(x) = -\int \mathcal{E}(x)\, dx$$

$$V_0 = -\int_{-x_{p0}}^{x_{n0}} \mathcal{E}(x)\, dx.$$

which is just the area of $\mathcal{E}(x)$ vs x Δ.



$$\text{area} = \frac{1}{2} \mathcal{E}_0 W \rightarrow (8)$$

Substitute (7) in (8).

$$\frac{1}{2} \mathcal{E}_0 W = \frac{1}{2} \frac{q}{\epsilon} N_d x_{n0} w \longrightarrow (9)$$

$a = \frac{1}{2} bh.$

b, base $= w$

h, height $\mathcal{E}_0$

Since the balance of charge requirement is,

$$Q^+ = Q^-$$

$$qAx_{p0}N_a = qAx_{n0}N_d$$

$$x_{p0}N_a = x_{n0}N_d.$$

and w is $x_{p0} + x_{n0}$, we can write,

$$x_{p0} = W - x_{n0}.$$

$$x_{n0}N_d = (w - x_{n0})N_a$$

$$x_{n0}N_d = wN_a - N_a x_{n0}$$

$$x_{n0}(N_a + N_d) = wN_a$$

$$x_{no} = \frac{W N_a}{N_a + N_d} \rightarrow 10$$

Substitute 10 in 9.

$$V_0 = \frac{1}{2} \frac{q}{\epsilon} \frac{N_a N_d}{N_a + N_d} W^2$$

$$W^2 = \frac{2 \epsilon V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right)$$

$$W = \sqrt{\frac{2 \epsilon V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right)}$$

Penetration of transition region to the n and p materials:

$$x_{po} = \frac{W N_d}{N_a + N_d} = \frac{W N_d}{N_d \left[1 + N_a / N_d\right]}$$

charge neutrality

$$x_{no} N_d = x_{po} N_a$$

$$x_{po} = \frac{x_{no} N_d}{N_a}$$

$$= \frac{W N_a N_d}{(N_a + N_d) N_a}$$

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

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

as $V_0 = \frac{kT}{q} \ln \frac{P_p}{P_n}$, $\Rightarrow V_0 = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$

$$W = \left[\frac{2\epsilon}{q^2} kT \ln \left[\frac{N_a N_d}{n_i^2}\right] \left[\frac{N_a + N_d}{N_a N_d}\right] \right]^{1/2}.$$

$x_{no} N_d = x_{po} N_a$

$$x_{po} = \frac{x_{no} N_d}{N_a}$$

$$= \frac{W N_a N_d}{(N_a + N_d) N_a} = \frac{W N_d}{N_a + N_d}.$$

$$= \sqrt{\frac{2\epsilon V_0}{q} \left[\frac{N_a + N_d}{N_a N_d}\right)} \frac{N_d}{N_a + N_d} = \sqrt{\frac{2\epsilon V_0}{q} \frac{N_d}{N_a (N_a + N_d)}}$$

~~$x_{no} = \frac{x_{po} N_a}{N_d}$~~ $\Rightarrow$ $x_{po} + x_{no} = W \Rightarrow x_{no} = W - x_{po}$.

$x_{no} N_d = x_{po} N_a \Rightarrow (W - x_{po}) = x_{po} N_a \Rightarrow x_{po} = \frac{W N_d}{N_a + N_d}$.

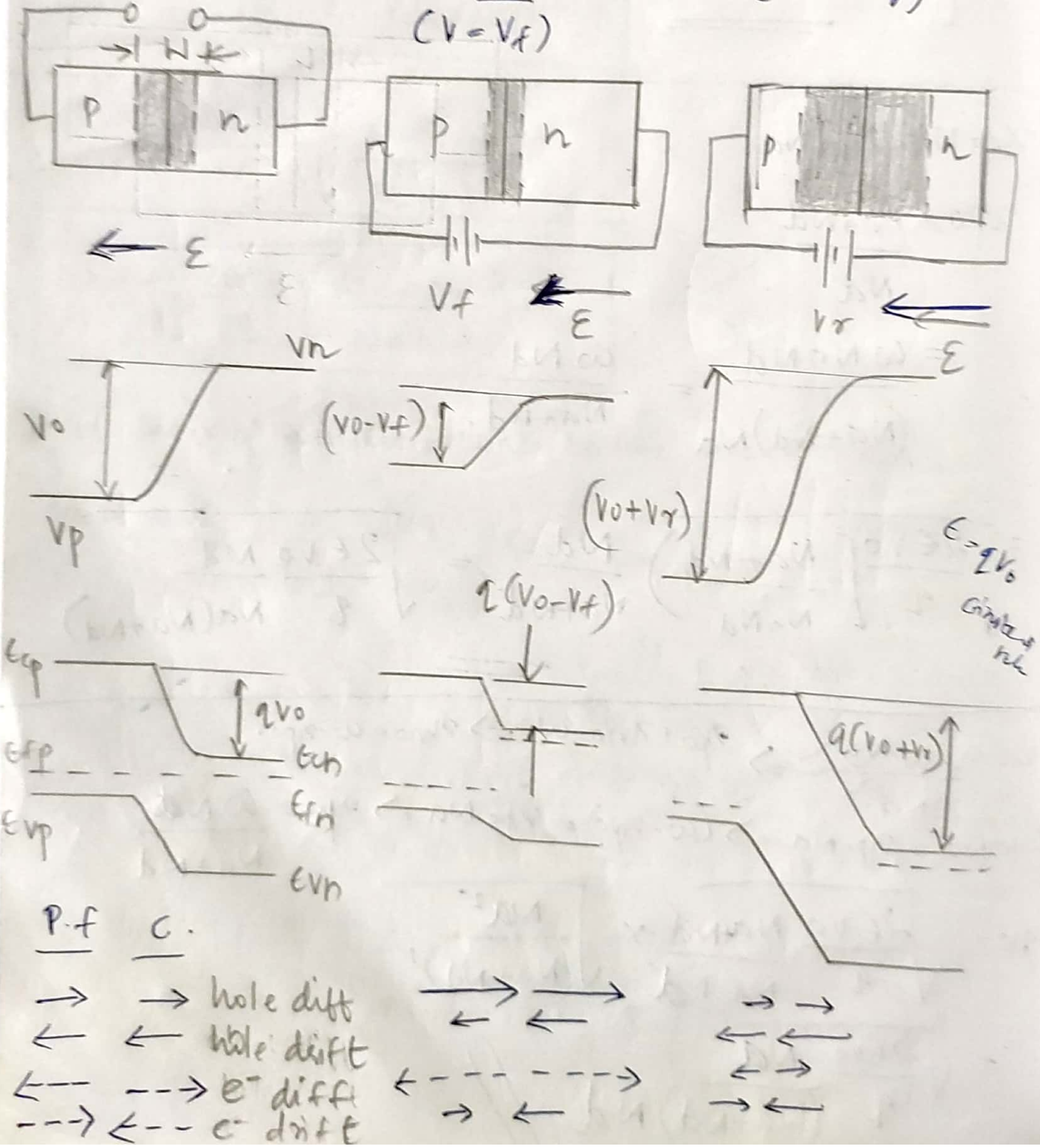
$$x_{po} = \sqrt{\frac{2\epsilon V_0}{q} \frac{N_a + N_d}{N_a N_d}} \times \sqrt{\frac{N_d^2}{(N_a + N_d)^2}}$$

$$= \sqrt{\frac{2\epsilon V_0}{q} \frac{N_d}{(N_a + N_d) N_d}} \quad //$$

(a) Equilibrium ($V=0$)

(b) forward bias ($V=V_f$)

(c) Reverse bias ($V=-V_r$)



⇒ Electrostatic potential

The electrostatic potential at junction is lowered. $(V_0 - V_f)$ in forward bias because, forward bias raises the electrostatic potential on the p side relative to n side.

The electrostatic potential at junction is increased $(V_0 + V_r]$ in reverse bias because, reverse bias decreases the Ep on p side relative to n side.

⇒ Electric field

With forward bias, electric field ↓ since the applied field opposes the built in field.

With reverse bias, electric field ↑, since the field at the junction is increased by the applied field (same dir^n)

⇒ Width of W.

Decreases in FB

increases in RB.

Scanned by CamScanner

Ideal diode current equation (211)

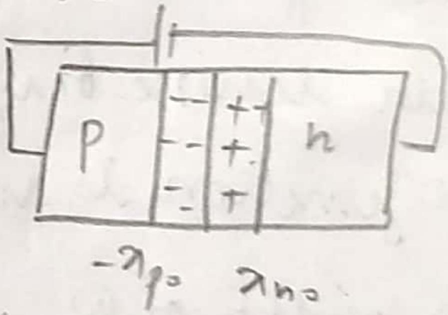
The minority carrier concentration on each side of a p-n junction to vary with the applied bias because of variations in the diffusion of carrier across the junction. The equilibrium ratio of hole concentrations on each side

$$\frac{P_p}{P_n} = e^{qV_0/kT} \longrightarrow (1) \quad \text{(equilibrium condition)}$$

eq ① becomes with bias → holes on p side $(-x_{p0})$

$$\frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V_0-V)/kT} \rightarrow ②$$

→ fB condition



This equation uses the altered barrier V_0-V to relate the steady state hole concentrations on the 2 sides of the transition region with either fB or RB

Taking $P(-x_{p0})$ as P_p itself ie the relative change in majority carrier concentration can be assumed to vary slightly with bias compared with equilibrium values.

$$\frac{p_p}{p(x_{no})} = e^{q(V_0 - V)/kT} \rightarrow (2a)$$

In (3) eqn if V=0

P(xno) = Pn itself

that is eqm condition

No external Voltage.

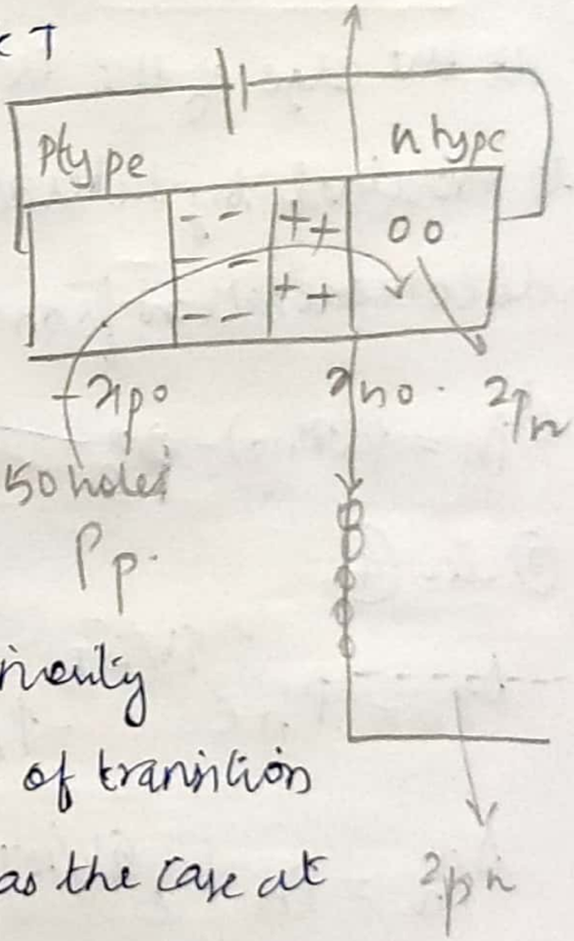
Ratio of (1) to (2a)

$$\frac{(1)}{(2a)} \Rightarrow \frac{p_p}{p_n} = e^{qV_0/kT}$$

$$\frac{p_p}{P(x_{no})} = e^{qV_0/kT} \cdot e^{-qV/kT}$$

$$\frac{P(x_{no})}{P_n} = e^{qV/kT} \longrightarrow (3)$$

$$P(x_{no}) = P_n e^{qV/kT}$$



eq (3) suggest a greatly increased minority carrier hole concentration at the edge of transition region on the n side P(xno) than was the case at eqm. The hole conc (Pxno) under reverse bias its reduced below the equilibrium value Pn.

eqm - Pn

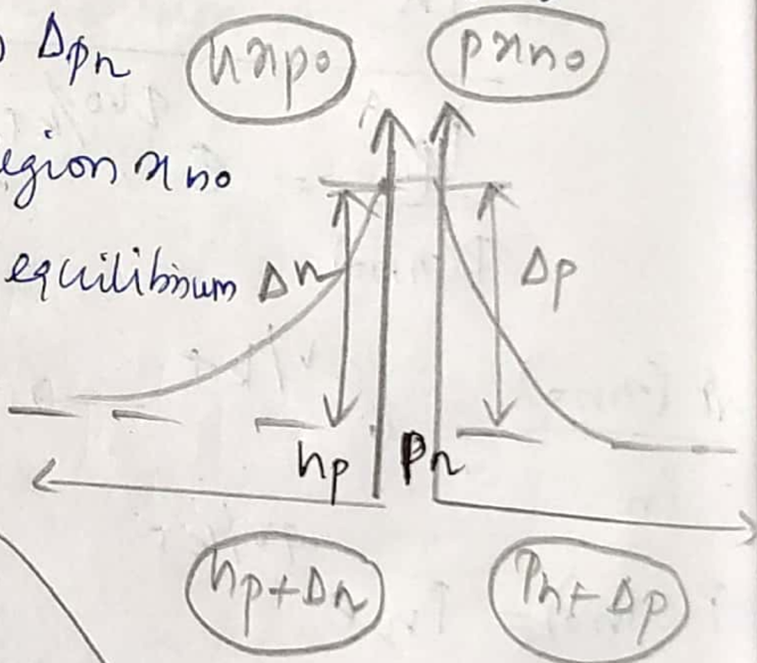
FB - Pn ↑

RB - Pn ↓

eqm minority holes reach at xno, so injecting holes at xno.

The ~~exponenti~~ exponential ~~of~~ increase of hole concentration at x_{n0} with forward bias is an example of minority carrier injection

Forward bias V results in a steady state injection of excess holes into n region and electrons in the p region. The excess hole concentration Δp_n at the edge of the transition region x_{n0} is obtained by subtracting the equilibrium hole concentration from eq ③



$$\Delta p_n = p(x_{n0}) - p_n \longrightarrow ④$$

$$p(x_{n0}) = p_n + \Delta p$$

$$\Delta p = p(x_{n0}) - p_n$$

③ in ④.

$$\Delta p_n = p_n e^{qV/kT} - p_n$$

$$\Delta p_n = p_n \left[e^{qV/kT} - 1 \right] \longrightarrow ⑤$$

and similarly for electrons

$$\Delta n_p = n(-x_{p0}) - n_p \Rightarrow \Delta n_p = n(x_{n0}) - \Delta n$$

$$\Delta n_p = n_p \left[e^{qV/kT} - 1 \right] \longrightarrow ⑥$$

As the holes diffuse deeper into the n region, they recombine with electrons in the n material and the resulting excess hole distribution is obtained as a solution of diffusion equation.

From the solution of diffusion equation,

$$\delta p(x_n) = \Delta P_n \, e^{-x_n/L_p} \longrightarrow (7)$$

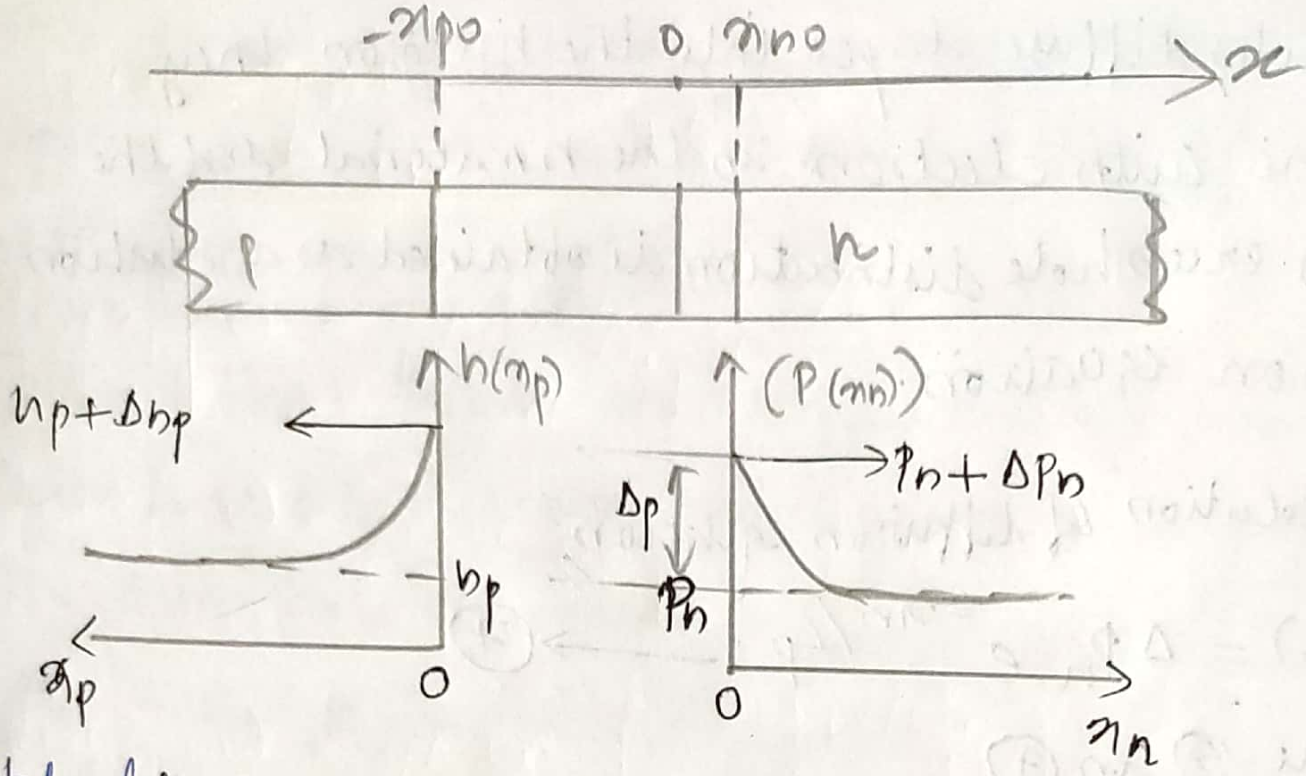
Substitute (5) in (7)

$$\delta p(x_n) = P_n \left[e^{qV/kT} - 1 \right] e^{-x_n/L_p}$$

Similarly on the p side same thing takes place, e's from n will reach to p.

$$\delta n(x_p) = \Delta n_p \, e^{-x_p/L_n} \longrightarrow (9) \quad (6) \text{ in } (9)$$

$$\delta n(x_p) = n_p \left[e^{qV/kT} - 1 \right] e^{-x_p/L_n} \longrightarrow (10)$$



Hole diffusion current at any point x_n in the n material is obtained by

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n} \rightarrow (11)$$

$J = \frac{I}{A}$

$I = JA$

Substitute (8) in (11)

$$I_p(x_n) = -qAD_p \frac{d}{dx_n} \Delta p\, e^{-x_n/L_p}$$

$$I_p(x_n) = -qAD_p \left[-\frac{1}{L_p}\right]\left[\Delta p_n e^{-x_n/L_p}\right]$$

$$I_p(x_n) = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n/L_p} \rightarrow (12)$$

$$\boxed{I_p(x_n) = qA\frac{D_p}{L_p}\delta p(x_n).}$$

where A is the cross sectional area of the junction.

The total hole current injected into n material at the junction can be obtained by,

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\Delta p_n e^{0/L_p}.$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\Delta p_n.$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\left[p_n e^{qV/kT} - 1\right] \rightarrow (13).$$

Similarly the injection of electrons into p material leads to an electron current at the junction

$$I_n(x_p) = J_n A.$$

$$I_n(x_p) = qAD_n\frac{d\,\delta n(x_p)}{dx_p}. \longrightarrow (14)$$

(10) in (14)

$$I_n(x_p) = qAD_n\frac{d}{dx_p}\left(\Delta n_p e^{-x_p/L_n}\right)$$

$$I_n(x_p) = qAD_n\left(\frac{-1}{L_n}\right)\left[\Delta n_p e^{-x_p/L_n}\right] \rightarrow (15)$$

$$I_n(x_p) = -q A \frac{D_n}{L_n} \delta n(x_p)$$ →

$$I_n(x_p = 0) = -q A \frac{D_n}{L_n} \Delta n_p e^{0/L_n}$$

$$I_n(x_p = 0) = -q A \frac{D_n}{L_n} \Delta n_p \quad \text{from } (6)$$

$$I_n(x_p = 0) = -q A \frac{D_n}{L_n} \left[n_p e^{qV/kT} - 1 \right] \longrightarrow 17.$$

The minus sign means that the election current is opposite to the x_p direction ie the -ve direction of x in $+x$ direction

The total diode current I at x_{no} can be calculated as the sum of I at x_{no} and $-I_n(x_p = 0)$. If we take the $+x$ direction as the reference direction for the current I (∵ x_p is defined in opp dirn to $+x$ dirn)

$$I = I_p(x_n = 0) + -I_n(x_p = 0)$$

Sub 13 & 15

$$I = qA\frac{D_p}{L_p}p_n\left(e^{qV/kT}-1\right) + qA\frac{D_n}{L_n}n_p\left[e^{qV/kT}-1\right]$$

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left[e^{qV/kT}-1\right]$$

$$\boxed{I = I_0\left(e^{qV/kT}-1\right)}$$

2/11/2020

normal p-n junction diode in ↑ f, creates noise and many more problems; collision. So for high frequency applica

Metal Semiconductor junction

In normal p-n junction diode 2 semiconductors are joined. But in metal semiconductor diode, a contact between metal & semiconductor is maintained. For high frequency applications, metal semiconductor diodes are used.

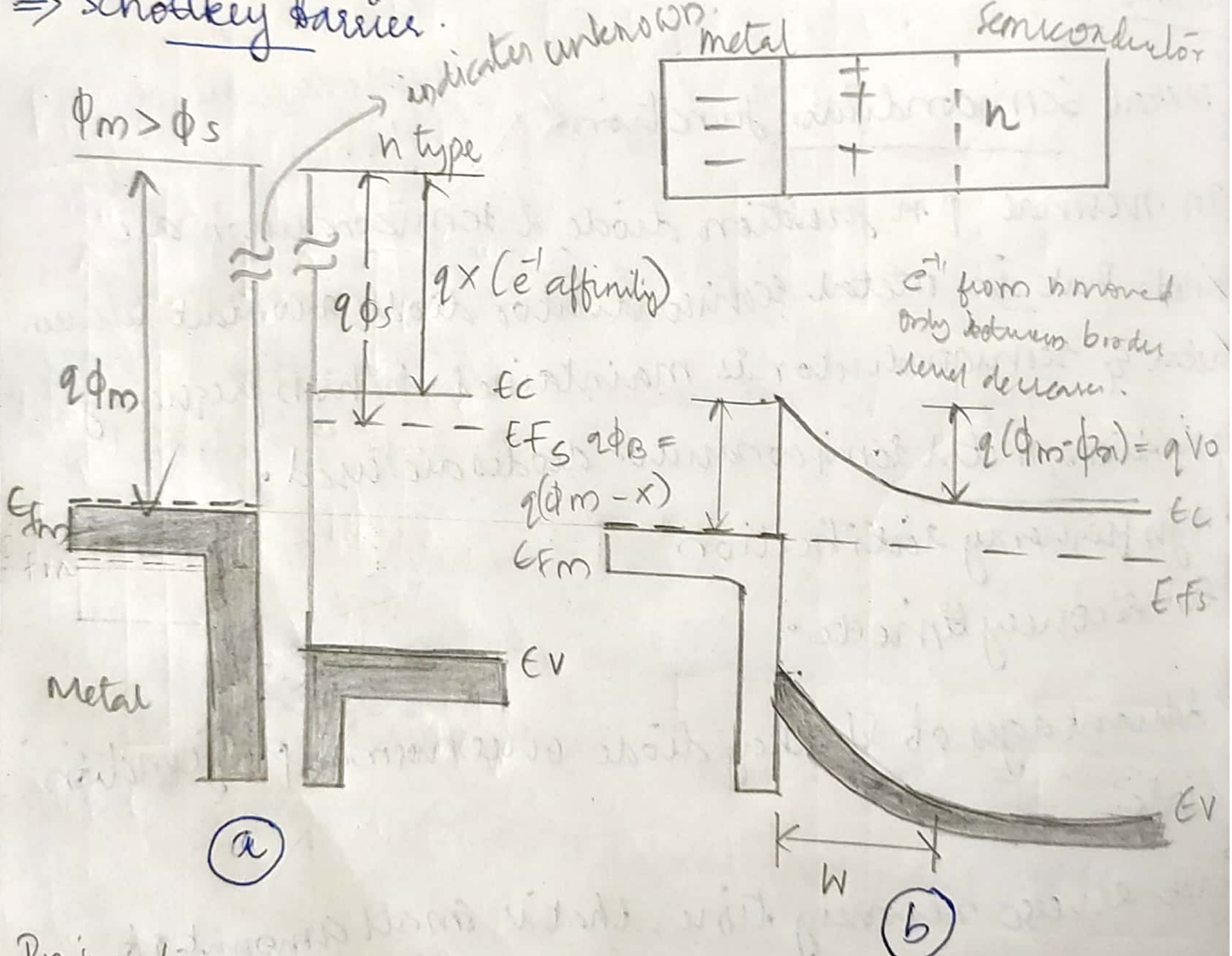
- High frequency rectification
- Fast recovery time etc.

⇒ Advantages of Schottkey diode over normal p-n junction diode.

- Fast reverse recovery time, that is small amount of charge stored with Schottkey diode makes it ideal for high speed switching applications

- Less noise
  Schottky diode produce less noise than normal
- Better performance and increased efficiency
- Schottky diodes are used as rectifiers in SMPS where high speed switching is required

⇒ Schottky barrier



Pn junction → one dirn (on) off in reverse dirn (switch)

2 contacts → ohmic contact → conducts in both dirn
rectifier contact → conducts in one dirn

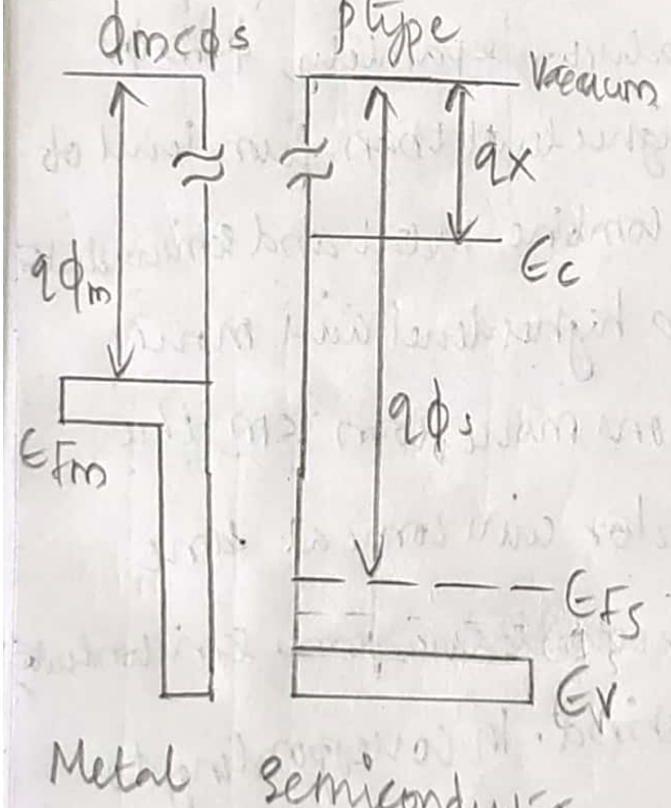
$q\phi_m$ is the work function ie energy required to remove an e^- at fermi level to the vaccum outside the metal.

Ohmic contact is a metal to semiconductor contact of very low resistance in both directions and is independent of the applied voltage, but rectifying contact is a metal semiconductor contact that allows high current to flow in one direction and a low current in the other direction, thus behaving like a conventional junction diode

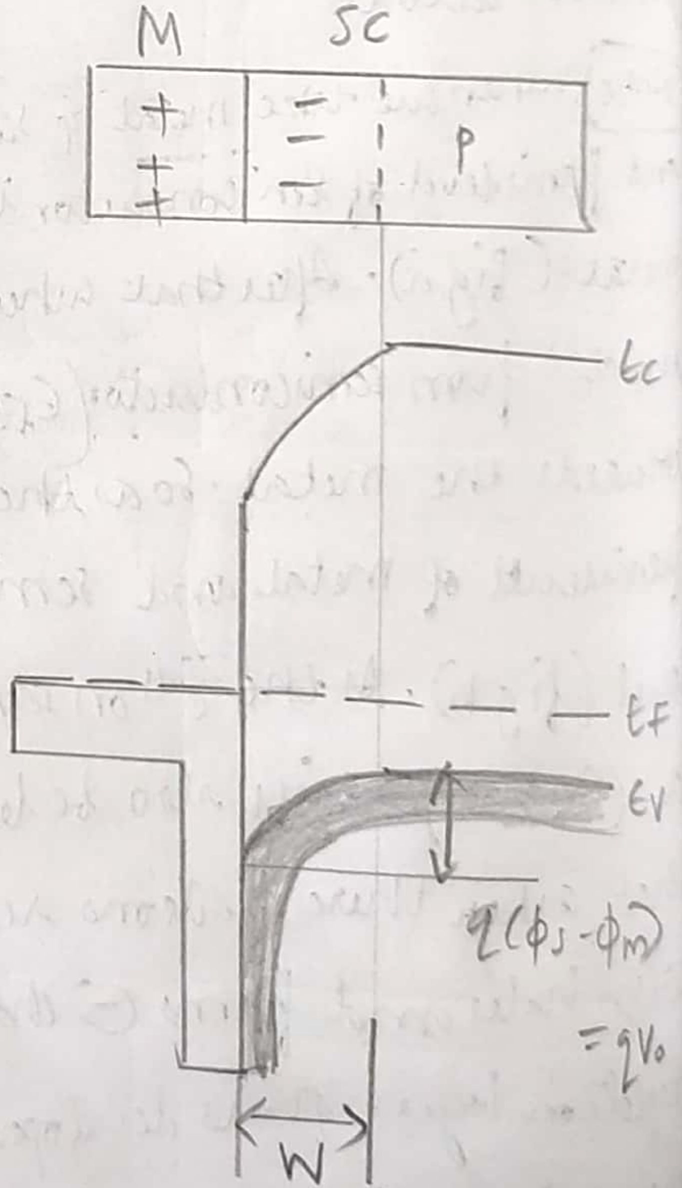
Note: when we take metal & semiconductor separately, $\phi_m > \phi_s$ and fermilevel of semiconductor is at higher level than fermilevel of metal. (fig a). After that when we combine metal and semiconductor the e^-s from semiconductor (E_{fs}) at a higher level will move towards the metal. So as the electrons move from SM, the fermilevel of metal and semiconductor will come at same level (fig b). As the e^-s on semiconductor leave from semiconductor a ⊕ charge will also be left behind. In corresponding to that, when these electrons reach at metal, they combine with holes and forms ⊖ charge. This leads to formation of depletion layer. qV_0 is developed contact potential. when this shift in fermilevel happens, the E_c also shifts.

As the e^{-1s} from the edge of move, Only at these position E_F shifts and correspondingly E_c and at the remaining positions that will be same as that of n-type semiconductor itself. In the (fig b) the e^{-s} in metal can't cross the higher energy level. Therefore current flow occurs only in one direction and thus Rectifying contact.

P type



Metal Semiconductor



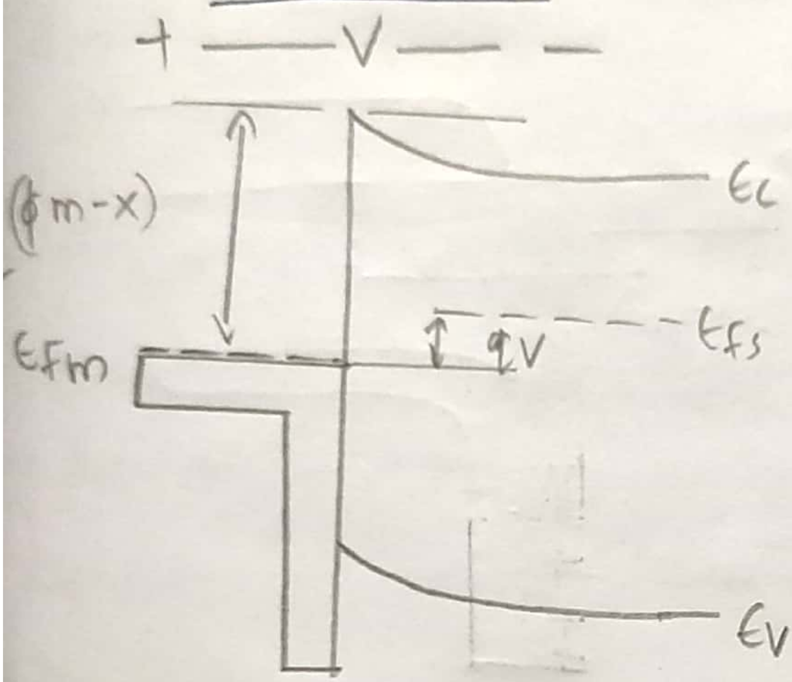
hole energy increases in downward dirn.

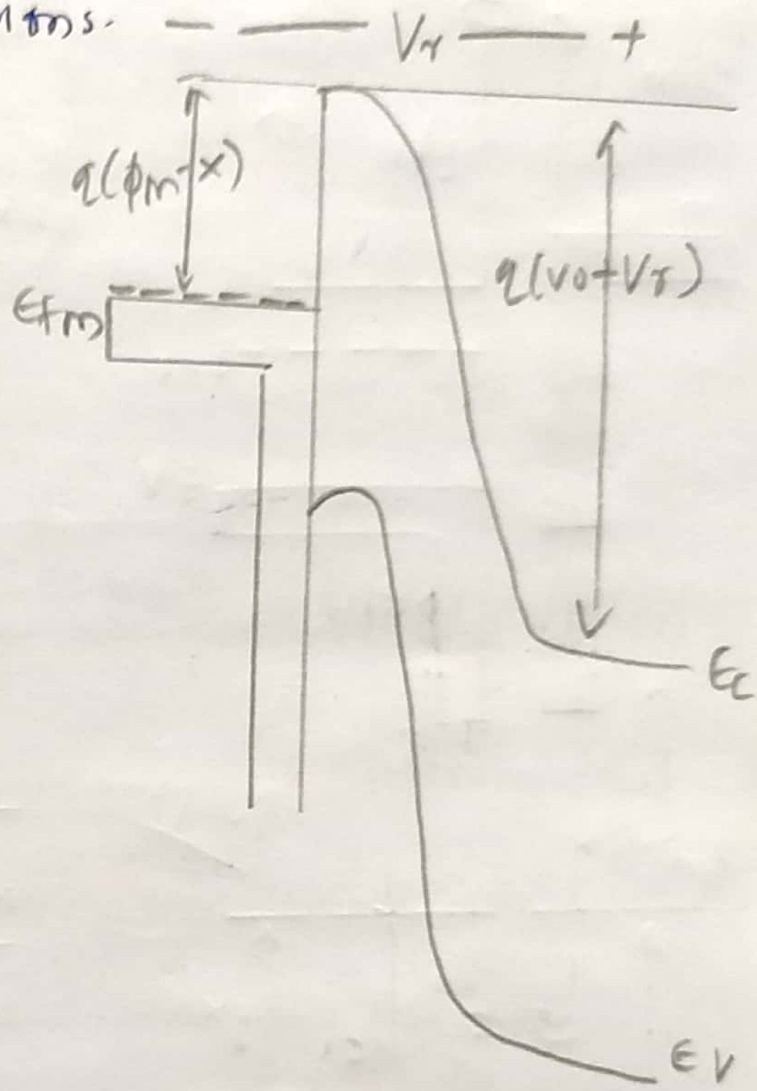
($E_{Fm} > E_{Fs}$ virtually only)

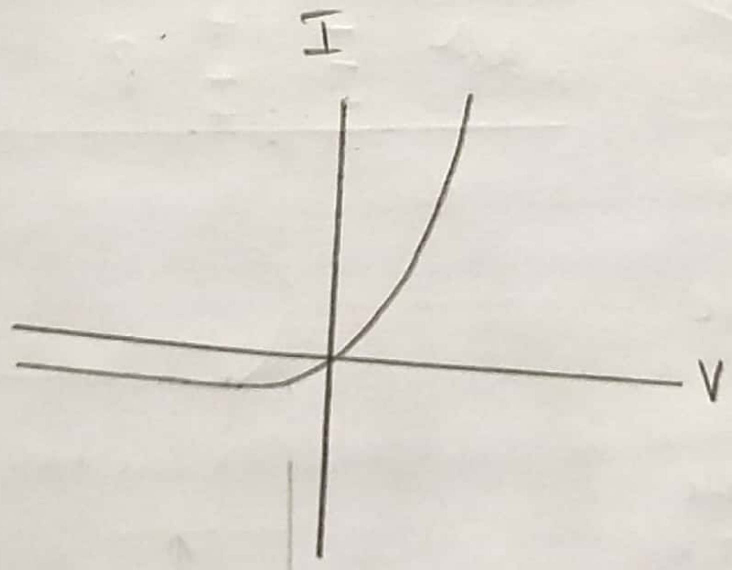
Wire variety at edge.

Here also metal to semiconductor flow not possible. S to M flow stops after the formation of barrier.

Forward and Reverse bias conditions.

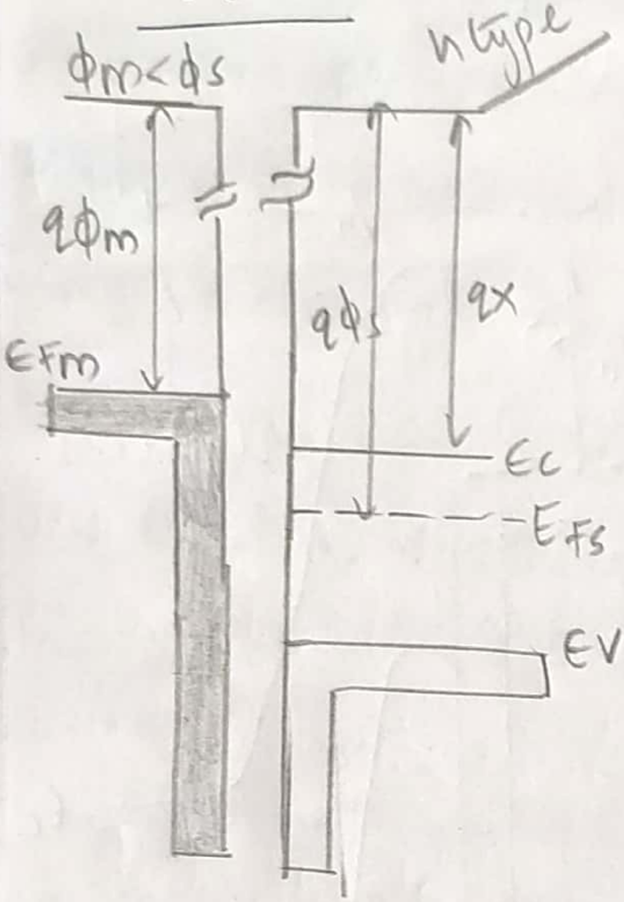


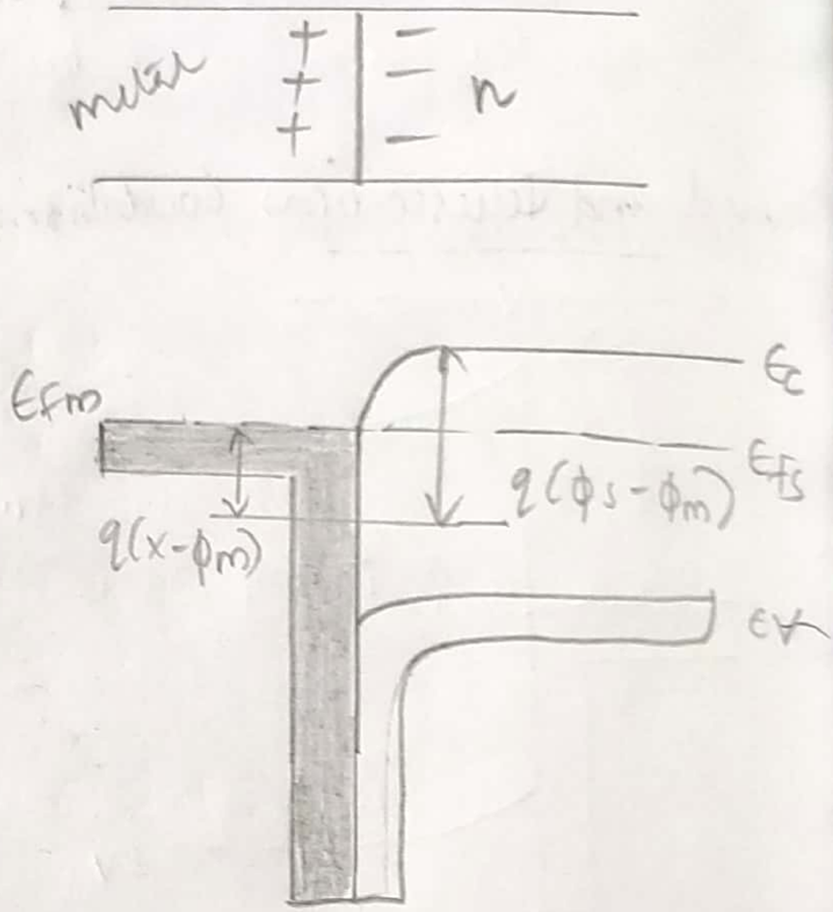




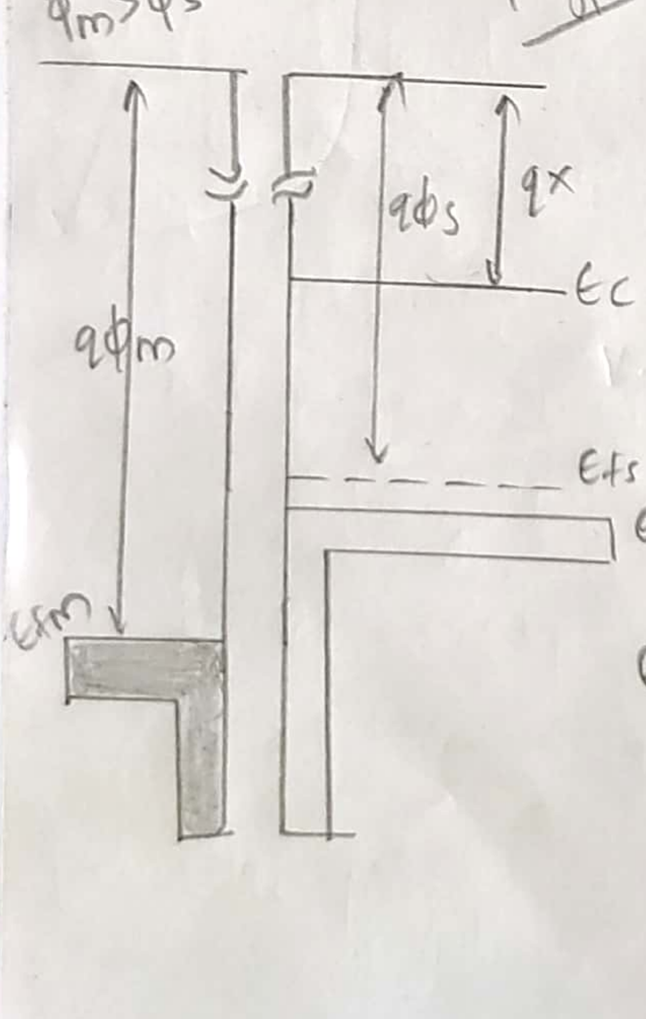
ohmic contact

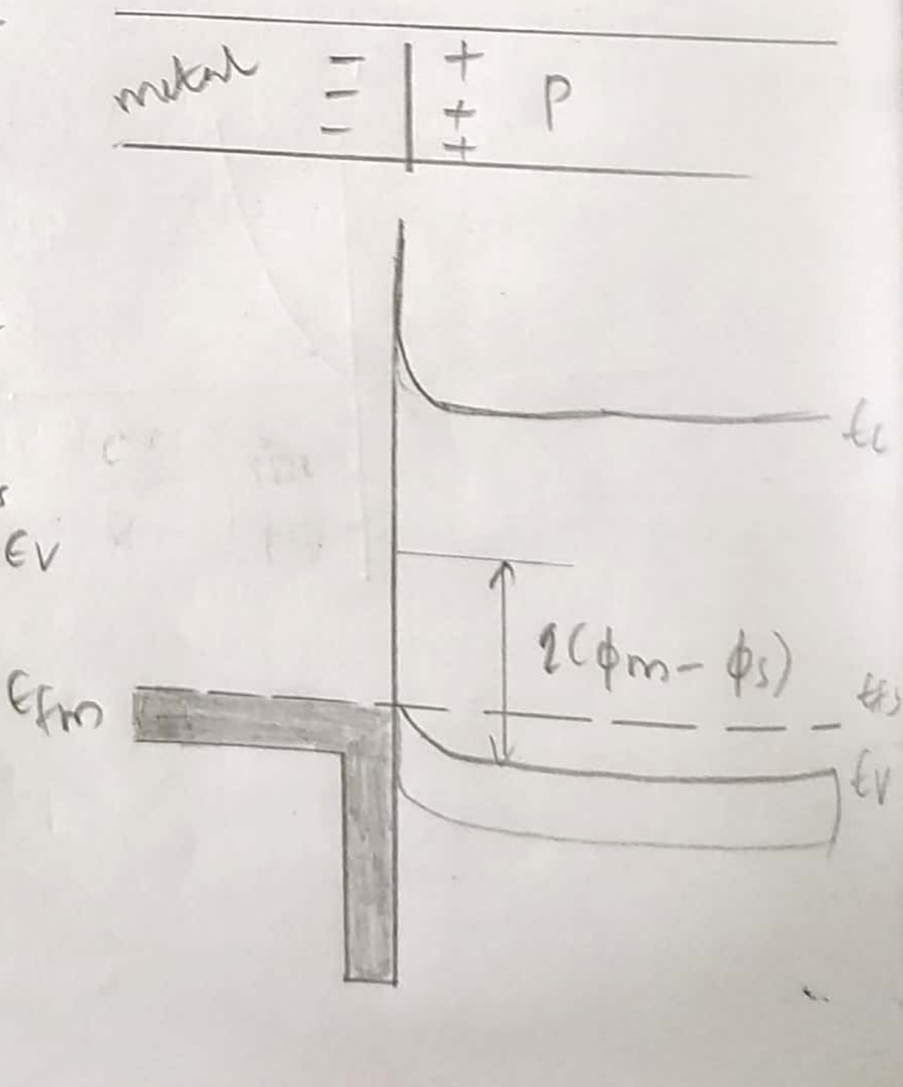
$\phi_m < \phi_s$





$\phi_m > \phi_s$





Scanned by CamScanner

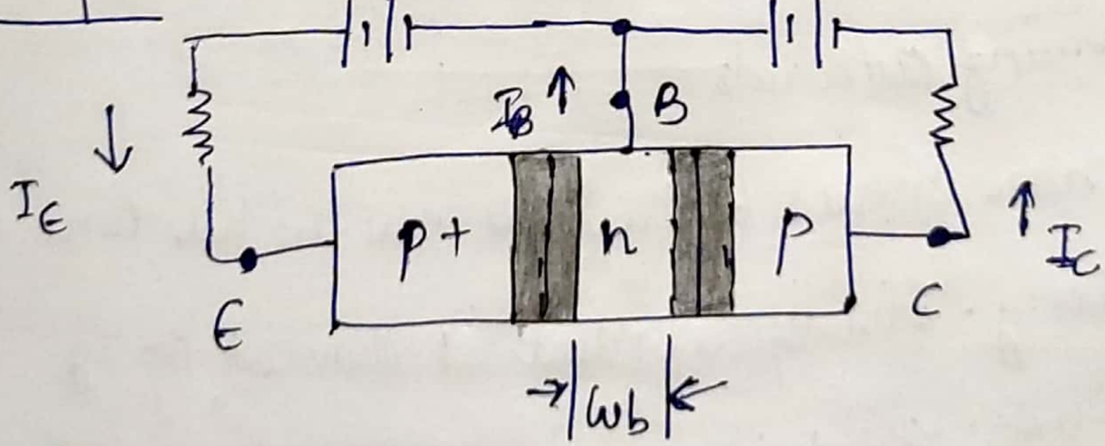
Rectifying	Metal n type	Metal p type
$\phi_m > \phi_s$	Rectifying	ohmic
$\phi_m < \phi_s$	ohmic	Rectifying

6/11/2020 Bipolar junction transistors

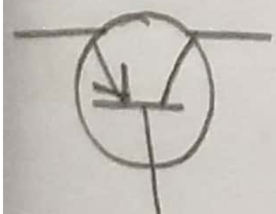
→ Combination of 2 p-n junction diode
→ Both charge carries contribute to current. So bipolar junction transistor.
→ Base, Emitter, collector.
→ npn and pnp transistors

Emitter - heavily doped
Collector - moderately
base - lightly

Pnp



p+ ↳ heavily doped



holes injected → holes collected →

Baseemitter - FB

base collector - RB

Performance determined by how many carriers are collector

Emitter current through E-B

Collector current through B-C

Pnp - majority charge carriers are holes so in forward biasing of emitter base, holes will flow to base, the I_E will be in same direction as that of holes.

$$I_E = I_B + I_C$$

E-B forward biased. base current due to $e^{-1}s$ and as the $e^{-1}s$ enter to emitter, base current will be opposite, that is why it is flowing outwards.

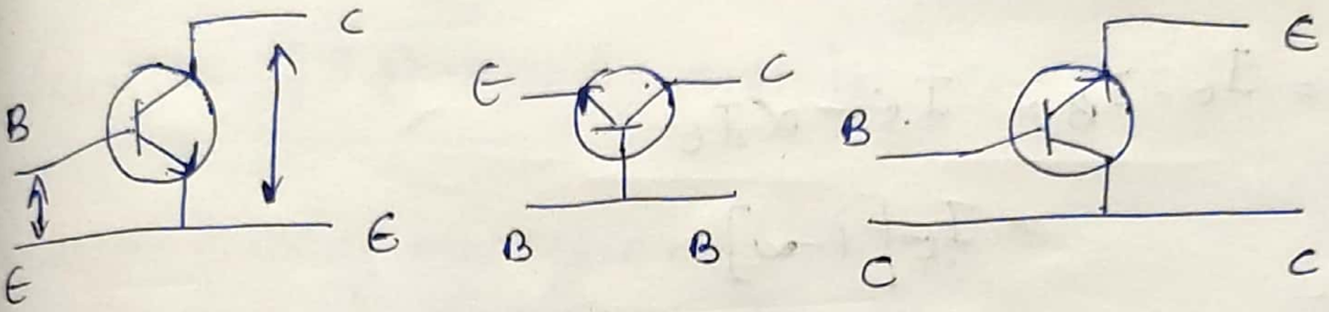
⇒ n type base should be narrow. and the hole time τ_p should be long. This requirement is summed up by specifying $W_b <<< L_p$. W_b = length of base

L_p = diffusion length.

for better performance.

Minority carrier distributions and terminal currents.

⇒ C.E CB C.C



$$\beta = \frac{I_C}{I_B} \qquad \alpha = \frac{I_C}{I_E} \qquad \gamma = \frac{I_E}{I_B}$$

⇒ $\alpha = \frac{I_C}{I_E} \rightarrow (1)$ $\beta = \frac{I_C}{I_B} \rightarrow (2)$

$$I_C = \beta I_B$$

We know, $I_E = I_B + I_C$

$$I_E = I_B + \beta I_B$$

$$I_E = I_B(\beta + 1)$$

Sub $\alpha = \frac{I_C}{I_E} = \frac{\beta I_B}{I_B(\beta+1)} = \frac{\beta}{1+\beta} = \alpha$

$$\alpha = \frac{I_C}{I_E} \Rightarrow I_C = \alpha I_E$$

$$I_E = I_B + I_C$$

$$I_C = I_E - I_B = I_E - \alpha I_E$$

$$= I_E[1-\alpha]$$

but $\beta = \frac{I_C}{I_B} = \frac{\alpha I_E}{I_E[1-\alpha]} = \frac{\alpha}{1-\alpha}$

$$\alpha = \frac{\beta}{1+\beta} \qquad \beta = \frac{\alpha}{1-\alpha}$$

Pg no: 379

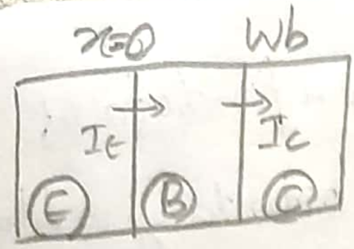
Minority carrier distributions and terminal currents

Pnp

Holes are injected into the base at the forward biased emitter and these holes diffuse to the collector junction

The 1st step is to solve for the excess hole con^c in the base (I_E)

The 2nd step is to evaluate gradient of the hole distribution on each side of the base. (I_C)



$I_E = I_{Ep} + I_{En}$ $I_B = I_E - I_C$

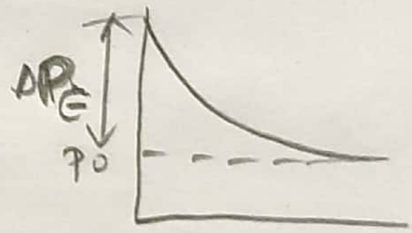
finding out this

Solution of diffusion equation in base region

current entering base region = I_E $(x=0)$
current leaving the base region = I_C. $(x=W_b)$

The excess hole conc at the edge of the emitter depletion region Δp_E and the corresponding concentration of the collector side of the base Δp_C are :-

$\Delta p_n = p_n\left(e^{qV/kT} - 1\right]$



$$\Delta p_E = p_n\left(e^{qV_{EB}/kT} - 1\right) \rightarrow (1)$$

$$\Delta p_C = p_n\left(e^{qV_{CB}/kT} - 1\right] \rightarrow (2)$$

If emitter base emitter is strongly fwd biased, $(V_{EB} >>> kT/q)$ and collector junction is strongly reverse biased, these excess concentration simplify to,

hole entering E, Δp_E

For specification doing modification and ceiling V_{EB}, V_{CB} etc.

$$\Delta p_E \cong p_n e^{qV_B/kT} \rightarrow (3)$$

$p_n(e^{-}$

$$\Delta p_C \cong -p_n \rightarrow (4)$$

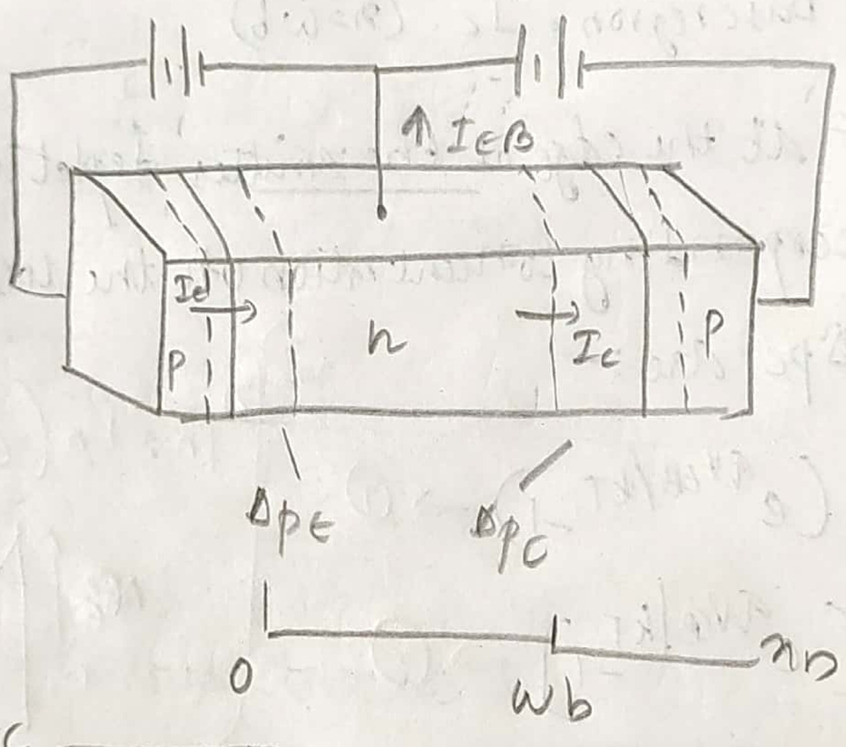
$e^{V_{EB}/kT/q} = (1)$

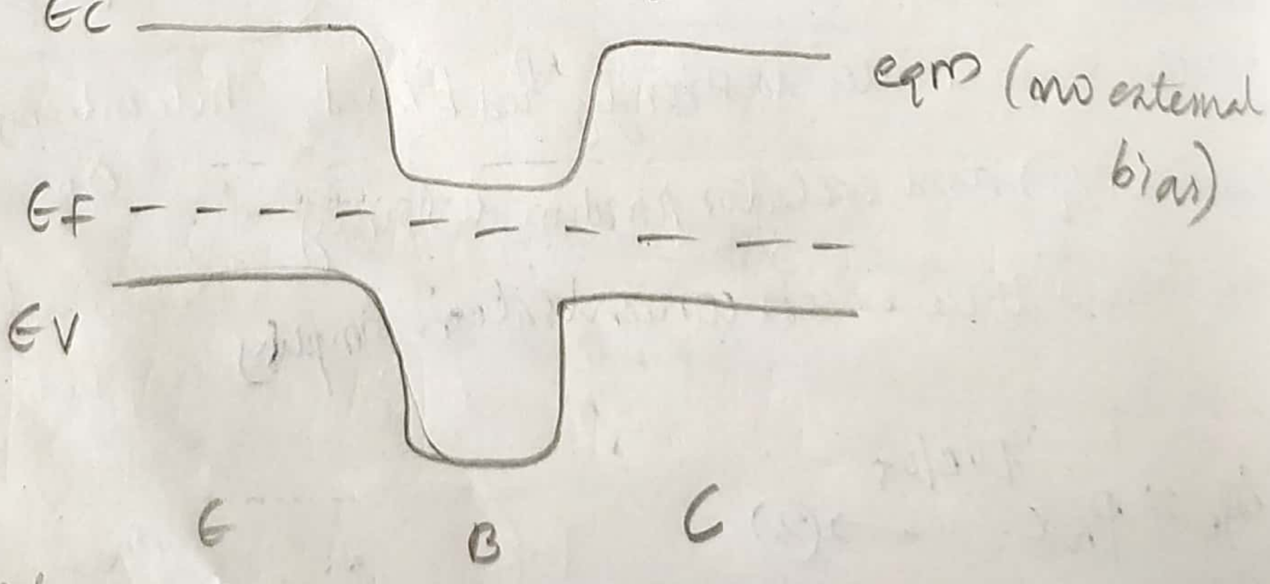
$\Delta p_C = p_n(0-1) = -p_n$

We can solve for the excess hole concentration, as a function of distance in the base $\delta p(x_n)$ using proper boundary conditions in the diffusion equation,

$$\frac{d^2\,\delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2} \rightarrow (5)$$

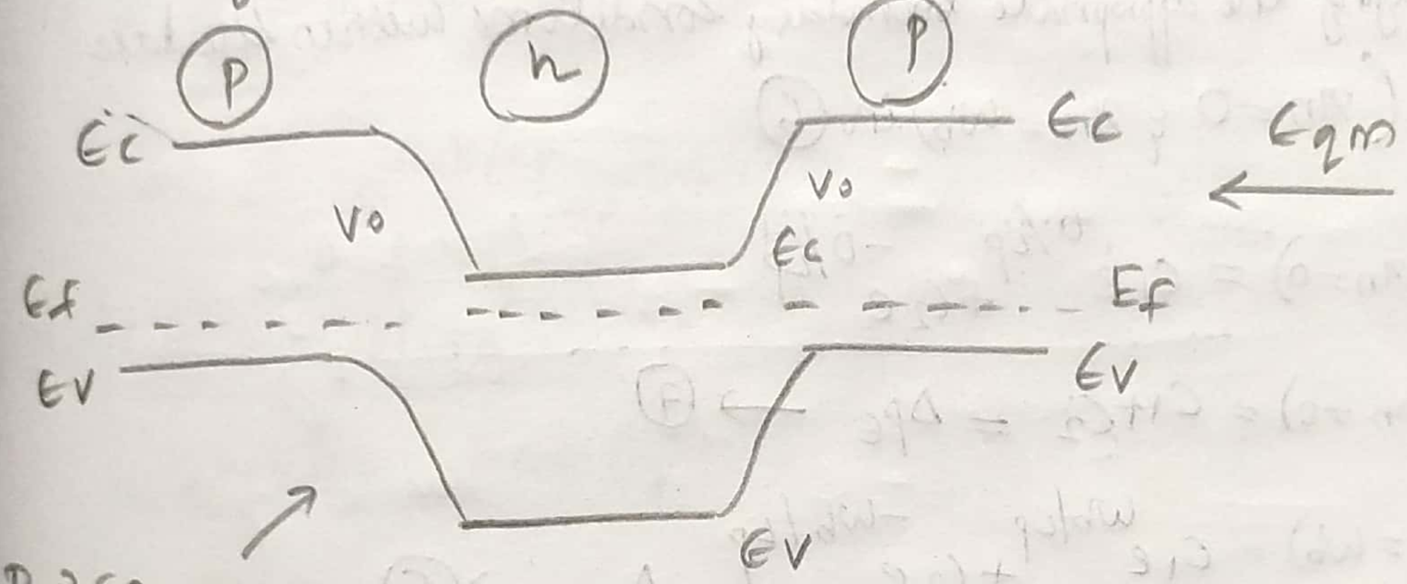
lightly doped
more penetration
fig in text.





Here as hole energy increases downwards, we have to apply fwd biase for holes to climb the hill and conducts current.

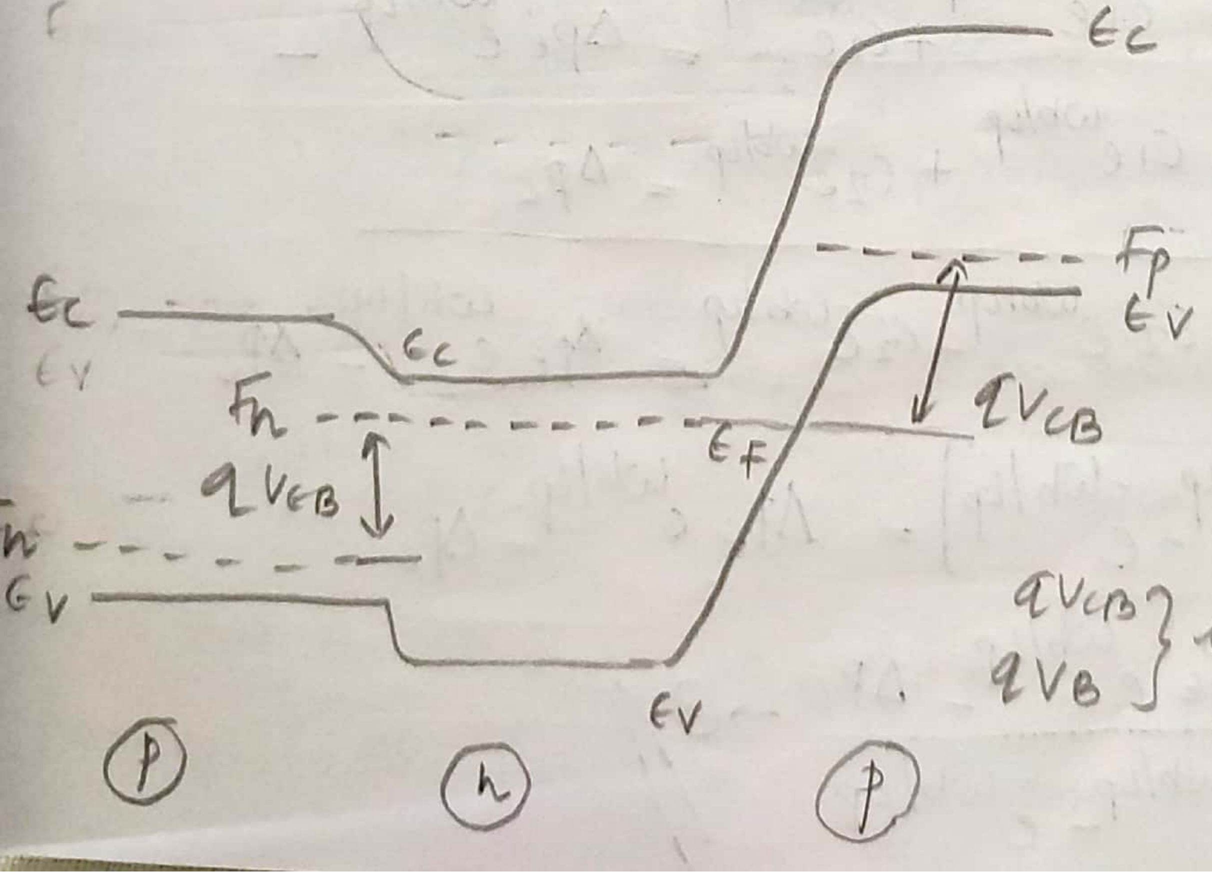
when fwd and rev biase is applied. as E.B junction is fwd biased, the barrier will reduce. and as B.C junction is reverse biased the barrier will be increased. If we change Ec and Ev, the changes will correspondly affect the fermi level also. pnp ⇒ 3 regions so 3 level energy diagrams.



p ⇒ Ef near Ev

n ⇒ Ef near Ec

under the application of fwd and rev biased



qVCB, qVB } indicates the shift

The solution of the eqn,

if npn: $\delta n(x_p) = C_1 e^{x_p/L_n} + C_2 e^{-x_p/L_n}$

$$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p} \rightarrow (6)$$

$L_p \Rightarrow$ Diffusion length of holes

By applying the appropriate boundary conditions within the base region ($x_n = 0$ & $x_n = W_b$) in (6)

$$\delta p(x_n = 0) = C_1 e^{0/L_p} + C_2 e^{-0/L_p}$$

Δp_E & Δp_C (from fig) carrier injection

$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E \rightarrow (7)$$

$$\delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C \rightarrow (8)$$

Solving 7 & 8.

$$(7) \times e^{W_b/L_p} = C_1 e^{W_b/L_p} + C_2 e^{W_b/L_p} = \Delta p_E e^{W_b/L_p}$$

$$C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

$$C_2 e^{W_b/L_p} - C_2 e^{-W_b/L_p} = \Delta p_E e^{W_b/L_p} - \Delta p_C$$

$$C_2 \left[e^{W_b/L_p} - e^{-W_b/L_p} \right] = \Delta p_E e^{W_b/L_p} - \Delta p_C$$

$$C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}} \rightarrow (9)$$

as $C_2 + C_1 = \Delta p_E$.

$$C_2 = \Delta P_E - \left[\frac{\Delta P_E e^{w_b/L_p} - \Delta P_C}{e^{w_b/L_p} - e^{-w_b/L_p}}\right]$$

$$C_1 = \frac{\Delta P_E e^{w_b/L_p} - \Delta P_E e^{-w_b/L_p} - \Delta P_E e^{w_b/L_p} + \Delta P_C}{e^{w_b/L_p} - e^{-w_b/L_p}}$$

$$C_1 = \frac{\Delta P_C - \Delta P_E e^{-w_b/L_p}}{e^{w_b/L_p} - e^{-w_b/L_p}} \rightarrow (10)$$

Substitute (9) & (10) in eq (6)

$$\delta p(x_n) = \left(\frac{\Delta P_C - \Delta P_E e^{-w_b/L_p}}{e^{w_b/L_p} - e^{-w_b/L_p}}\right) e^{x_n/L_p} + \left(\frac{\Delta P_E e^{w_b/L_p} - \Delta P_C}{e^{w_b/L_p} - e^{-w_b/L_p}}\right) e^{-x_n/L_p}$$

$$\delta p(x_n) = \frac{\Delta P_C e^{x_n/L_p} - \Delta P_E e^{-w_b/L_p} e^{x_n/L_p}}{e^{w_b/L_p} - e^{-w_b/L_p}} + \frac{\Delta P_E e^{w_b/L_p} e^{-x_n/L_p} - \Delta P_C e^{-x_n/L_p}}{e^{w_b/L_p} - e^{-w_b/L_p}}$$

Assume that the collector junction is strongly reverse biased from eq (4) $\Delta P_C = -P_n$ and eqm hole conc P_n is negligible compared with the injected hole conc P_E) $\Delta P_E = P_n e^{qV_B/kT}$

$(\Delta P_C \cong 0)$

So P_E increases exponentially but $\Delta P_C = -P_n$ this represents minority holes in

$$\delta p(x_n) = \frac{-\Delta P_E e^{-W_b/L_p} e^{x_n/L_p} + \Delta P_E e^{W_b/L_p} e^{-x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

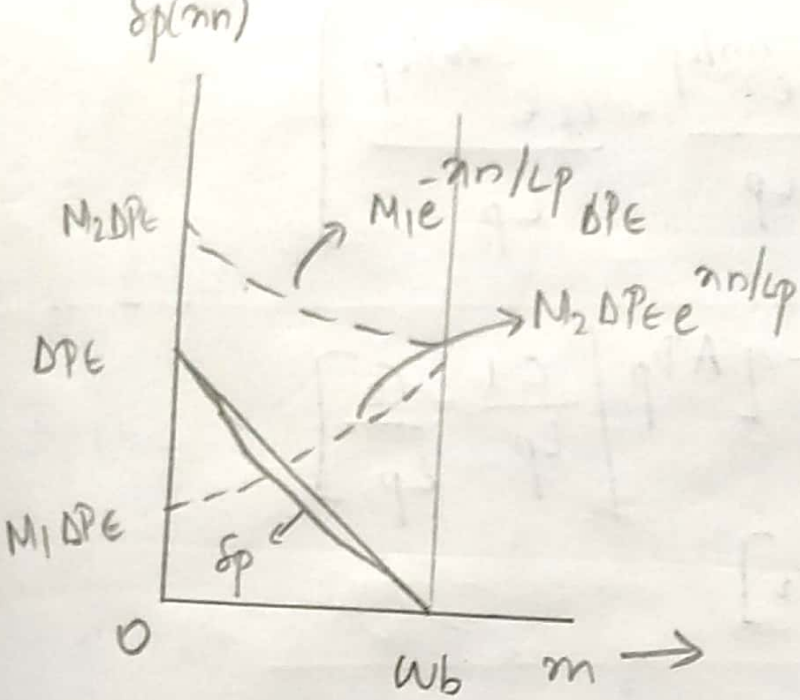
$$\delta p(x_n) = \frac{\Delta P_E \left[e^{W_b/L_p} e^{-x_n/L_p} - e^{-W_b/L_p} e^{x_n/L_p} \right]}{e^{W_b/L_p} - e^{-W_b/L_p}} \rightarrow (11)$$

Evaluation of the terminal currents

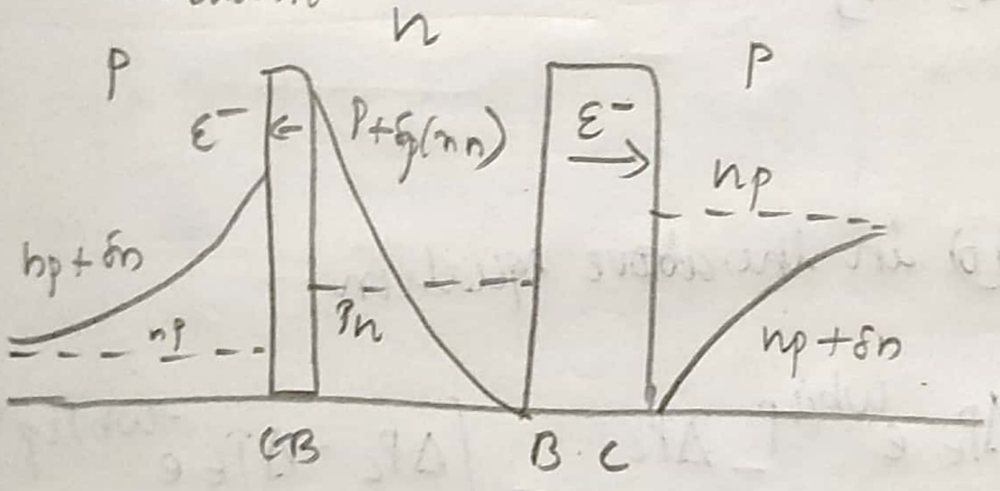
$$\delta p(x_n) = \frac{\Delta P_E e^{W_b/L_p} e^{-x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} - \frac{e^{-W_b/L_p} e^{x_n/L_p} \Delta P_E}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$\delta p(x_n) = M_1 \Delta P_E e^{-x_n/L_p} - M_2 e^{x_n/L_p} \Delta P_E$$

where, $M_1 = \dfrac{e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$ $\quad M_2 = \dfrac{e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$



electron distribution



Evaluation of Terminal currents

$$I_p(x_n) = -qAD_p \frac{d\,\delta p(x_n)}{dx_n} \rightarrow (12)$$

⑥ in ⑫

$$I_p(x_n) = -qAD_p \frac{d}{dx_n}\left[C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}\right]$$

$$I_p(x_n) = -qAD_p\left[\frac{C_1 e^{x_n/L_p}}{L_p} - \frac{C_2 e^{-x_n/L_p}}{L_p}\right]$$

$$I_{Ep} = I_p(x_n = 0) = -qAD_p\left[\frac{C_1}{L_p} - \frac{C_2}{L_p}\right]$$

$$I_{Ep} = -q\frac{AD_p}{L_p}\left[C_1 - C_2\right]$$

$$= q\frac{AD_p}{L_p}\left[C_2 - C_1\right]$$

substitute ⑨ & ⑩ in the above equation

$$I_{Ep} = q\frac{AD_p}{L_p}\left[\frac{\Delta P_E e^{W_b/L_p} - \Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}} - \left(\frac{\Delta P_C - \Delta P_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)\right]$$

$$I_{Ep} = q\frac{AD_p}{L_p}\left[\frac{\Delta P_E\left[e^{W_b/L_p} + e^{-W_b/L_p}\right] - 2\Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$I_{Ep} = q\frac{AD_p}{L_p}\left[\frac{\Delta P_E 2\cosh\left[\frac{W_b}{L_p}\right]}{2\sinh\left[W_b/L_p\right]} - \frac{2\Delta P_C}{2\sinh(W_b/L_p)}\right]$$

$$I_{Gp} = \frac{qAD_p}{L_p}\left[\Delta P_E \coth\left[\frac{W_b}{L_p}\right] - \Delta P_C \operatorname{cosech}\left[\frac{W_b}{L_p}\right]\right]$$

Similarly for I_C, $x = W_b$.

$$I_C = I_p(x = W_b) = -q\frac{AD_p}{}\frac{d}{dx_n}\left[\delta p(x_n)\right]$$

$$= -q\frac{AD_p}{}\frac{d}{dx_n}\left[C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}\right]$$

$$= -qA\frac{D_p}{}\left[\frac{C_1 e^{x_n/L_p}}{L_p} - \frac{C_2 e^{-x_n/L_p}}{L_p}\right]$$

$$I_C = I_p(x_n = W_b) = -q\frac{AD_p}{L_p}\left[C_1 e^{W_b/L_p} - C_2 e^{-W_b/L_p}\right]$$

9 & 10 in the above equation,

$$I_C = q\frac{AD_p}{L_p}\left[C_2 e^{-W_b/L_p} - C_1 e^{+W_b/L_p}\right]$$

$$= qA\frac{D_p}{L_p}\left[\left(\frac{\Delta P_E e^{W_b/L_p} - \Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)e^{-W_b/L_p} - \left[\frac{-\Delta P_E e^{-W_b/L_p} + \Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]e^{W_b/L_p}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E e^{wb/L_p} \cdot e^{-wb/L_p} - \Delta P_C e^{-wb/L_p} + \Delta P_E e^{-wb/L_p} e^{wb/L_p} - \Delta P_C e^{wb/L_p}}{e^{wb/L_p} - e^{-wb/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{-\Delta P_C\left[e^{-wb/L_p} + e^{wb/L_p}\right] + 2\Delta P_E}{e^{wb/L_p} - e^{-wb/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{Cosech}(wb/L_p) - \Delta P_C \left(\frac{\cosh(wb/L_p)}{\sinh(wb/L_p)}\right)\right]$$

$$I_C = \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{Cosech}(wb/L_p) - \Delta P_C \operatorname{Coth}\left(\frac{wb}{L_p}\right)\right]$$

Base current $I_B = I_E - I_C$.

$$= \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{Coth}\left(\frac{wb}{L_p}\right) - \Delta P_C \operatorname{Cosech}\left[\frac{wb}{L_p}\right]\right] -$$

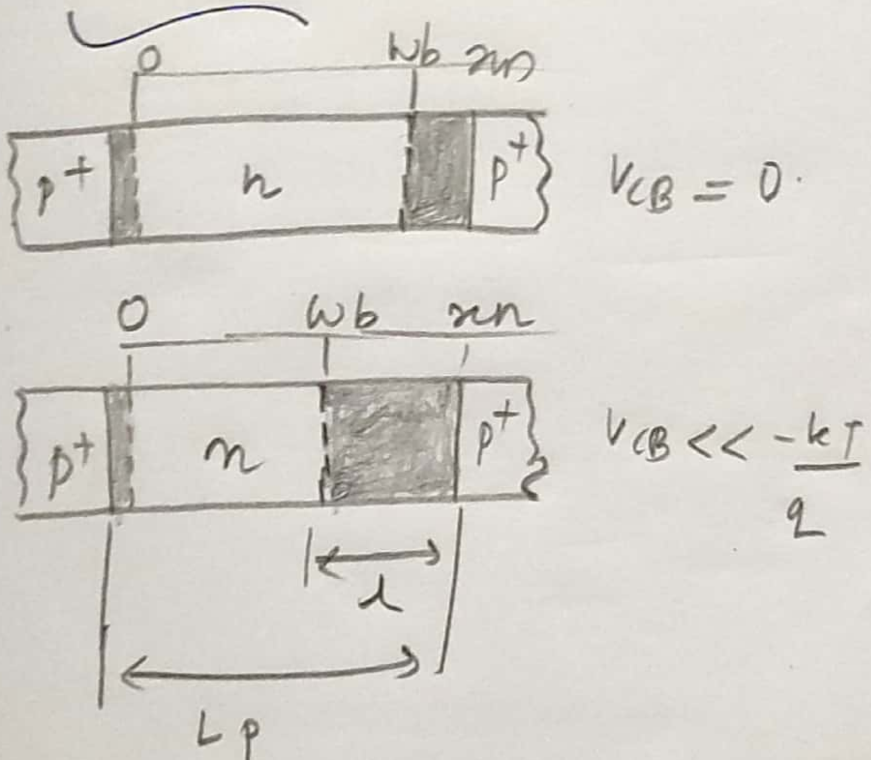
$$\left[\Delta P_E \operatorname{Cosech}\left(\frac{wb}{L_p}\right) - \Delta P_C \operatorname{Coth}\left(\frac{wb}{L_p}\right)\right]$$

$$I_B = \frac{qAD_p}{L_p}\left[(\Delta p_E + \Delta p_C)\left(\coth\frac{W_b}{L_p} - \operatorname{cosech}\frac{W_b}{L_p}\right)\right]$$

$$I_B = \frac{qAD_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\left(\frac{W_b}{2L_p}\right)\right]$$

$$\left(\coth x - \operatorname{cosech} x = \tanh(x/2)\right)$$

Base Width Modulation



If the reverse bias on the collector junction is increased far enough, it is possible to decrease W_b to the extent that the collector depletion region essentially fills the entire base. In this punch-through condition holes are swept directly from the emitter region to collector, & transistor action is lost

MODULE - IV

DIODE CAPACITANCE:-

Junction Capacitance when P-N junction diode forward and reverse biased

There are two types of Capacitance associated with a junction.

1. The junction Capacitance due to the dipole in the transition region.
2. The Charge storage Capacitance arising from the lagging behind of Voltage as current changes, due to charge storage effect.

Both of these capacitances are important and they must be considered in designing P-n junction devices for use with time-varying signals. The junction Capacitance is dominant under reverse bias conditions and charge storage capacitance is dominant when the junction is forward biased. The junction Capacitance of a diode is easy to visualize from the charge distribution in the transition region.

Instead of common expression, Capacitance.

$$C = Q/V \qquad V_0 - V$$

$$\therefore C = \left| dQ/dV \right|.$$

At equilibrium

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

With bias, V_0 is replaced by $V_0 - V$.

$$\therefore W = \left[\frac{2\varepsilon (V_0 - V)}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}.$$

Charge density,

$$|Q| = qAN_d x_{no} = qAN_a x_{po}.$$

The value of Q is written in terms of doping concentration and transition region width on each side.

$$x_{no} = \frac{N_a W}{N_a + N_d} \quad ; \quad x_{po} = \frac{N_d}{N_a + N_d} W.$$

$$|Q| = \frac{qAN_aN_d}{N_a+N_d}\, W$$

$$= \frac{qAN_aN_d}{N_a+N_d}\left[\frac{2\varepsilon(V_0-V)}{q}\cdot\frac{N_a+N_d}{N_aN_d}\right]^{1/2}$$

$$Q = A\left[2q\varepsilon(V_0-V)\left(\frac{N_aN_d}{N_a+N_d}\right)\right]^{1/2}$$

We can calculate junction capacitance C_j. Since voltage that varies the charge in the transition region is barrier height (V_0-V), we must take derivative w.r.t potential difference.

$$C_j = \left|\frac{dQ}{d(V_0-V)}\right|$$

$$= \frac{d}{d(V_0-V)}\left[A\left(2q\varepsilon(V_0-V)\frac{N_aN_d}{N_a+N_d}\right)\right]^{1/2}$$

$$= \left[2q\varepsilon\frac{N_aN_d}{N_a+N_d}\right]^{1/2}\cdot\frac{d(V_0-V)^{1/2}}{d(V_0-V)}$$

$$= A\left[2q\varepsilon\frac{N_aN_d}{N_a+N_d}\right]^{1/2}\cdot\frac{1}{2\sqrt{V_0-V}}$$

$$= \frac{A}{2}\left[\frac{2q\varepsilon N_aN_d}{(N_a+N_d)(V_0-V)}\right]^{1/2}.$$

Multiplying & dividing by ε.

$$\therefore\ C_j = \frac{\varepsilon A}{2\varepsilon}\left[\frac{2\varepsilon q N_aN_d}{(N_a+N_d)(V_0-V)}\right]^{1/2}.$$

$$= \varepsilon A\left[\frac{qN_aN_d}{2\varepsilon(N_a+N_d)(V_0-V)}\right]^{1/2}$$

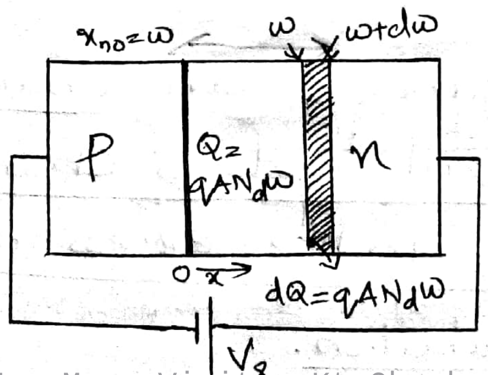
$$= \varepsilon A \times \frac{1}{W}.$$

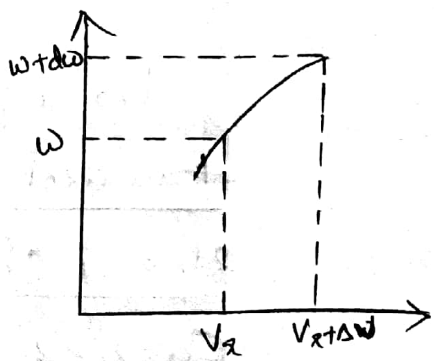
$$\therefore\ C_j = \frac{\varepsilon A}{W}.$$

$\frac{\varepsilon_0\varepsilon_r A}{W}$

For p-n junction, $N_a >> N_d$ and $x_{n0} \simeq W$, while x_{p0} is negligible.

$$\therefore\ C_j = \frac{A}{2}\left[\frac{2q\varepsilon}{V_0-V}N_d\right]^{1/2}$$





for long diode.

$$C = \frac{1}{3}\frac{q^2}{kT} A_c P_n e^{qV/kT}.$$

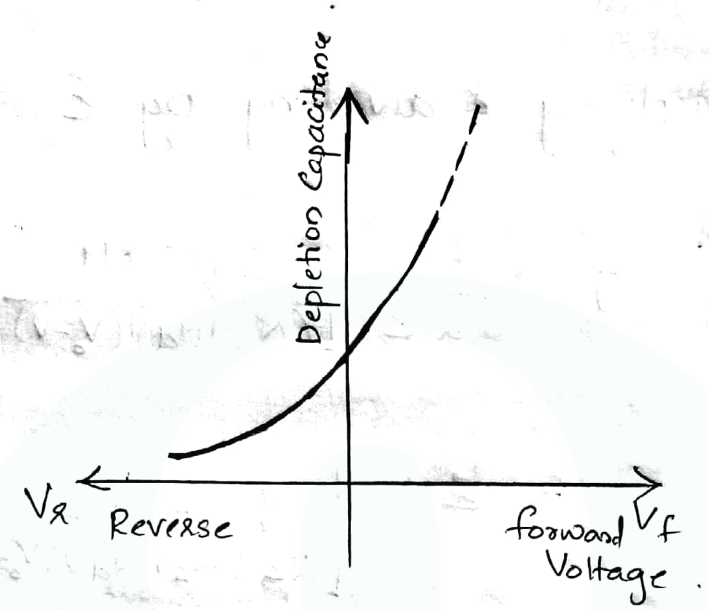


fig: Variation of depletion Capacitance with Reverse bias.

SWITCHING TRANSIENT.

Most of the Solid state devices are Used for Switching or for Processing ac Signals. The effect of excess Carriers on transient response is discussed below.

In a p-n junction any change in forward Current leads to Change in the Stored Charge in the excess minority Carrier distribution.

The time dependent Continuity equation is,

$$-\frac{\partial J_p(x,t)}{\partial x} = q\frac{\delta p(x,t)}{\tau_p} + q\frac{\partial p(x,t)}{\partial t}.$$

for getting the instantaneous Current density. we integrate both side at time t.

$$\int_0^x -\frac{\partial}{\partial x} J_p(x,t) = \int_0^x q\cdot\frac{\delta p(x,t)}{\tau_p} + \int_0^x q\cdot\frac{\partial p(x,t)}{\partial t}.$$

$$J_p(0) - J_p(x) = q\int_0^x \left[\frac{\delta p(x,t)}{\tau_p} + \frac{\partial p(x,t)}{\partial t}\right] dx.$$

Multiplying by A to get Current.

$$i(t) = A(J_p(0) - J_p(x)).$$

$$i(t) = i_p(x_{n=0,t}).$$

for p-n junction, $W_N >> L_p$, the current $x_n=0$ it can be considered due to holes only.

As $x_n \to \infty$

$$W_N = J_p(x) = 0.$$

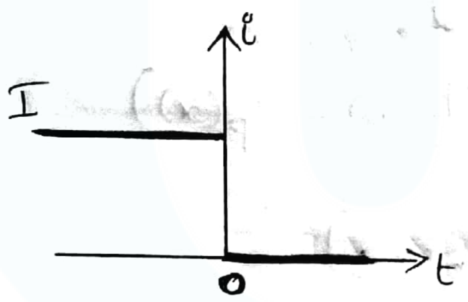
$$\therefore \quad i(t) = i_p(x_n=0,t).$$

$$= \frac{qA}{\tau_p}\int_0^\infty \delta_p(x,t)dx_n + qA\frac{\partial}{\partial t}\int_0^\infty \delta p(x_n,t)dx_n$$

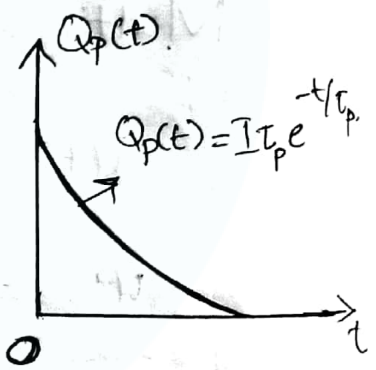
$$= \underbrace{\frac{Q_p(t)}{\tau_p}}_{\text{Recombination rate}} + \underbrace{\frac{dQ_p(t)}{dt}}_{\text{Charge buildup term}} \quad \text{——— (1).}$$

Charge buildup term, which shows that the distribution of excess carriers can be increasing or decreasing.

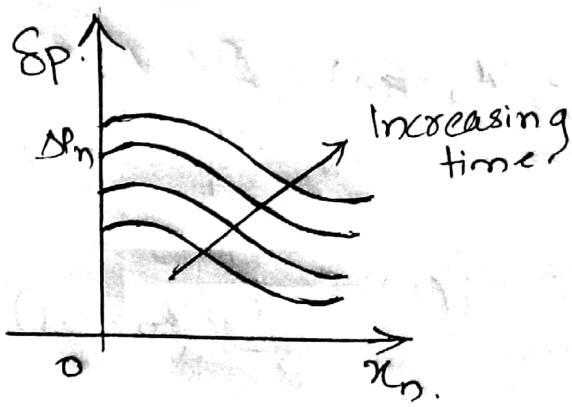
→ for example, a step turn-off transient in a p-n diode.



ⓐ Current through the diode



ⓑ decay of stored charge



ⓒ Excess holes distribution.

Taking the laplace transform of eq (1).

$$\therefore i(t) = \frac{Q_p(s)}{\tau_p} + s\,Q_p(s) - Q_p(0) \quad \text{---(2)}$$

where,

$$Q_p(0) = I\tau_p \quad \text{---(a)}$$

$$i(t>0) = 0$$

$$\therefore i(t) = 0 \quad \text{---(b)}$$

Sub (a) & (b) in (2)

$$\Rightarrow \frac{1}{\tau_p} Q_p(s) + s\,Q_p(s) - I\tau_p = 0$$

$$\frac{1}{\tau_p} Q_p(s) + s\,Q_p(s) = I\tau_p$$

$$Q_p(s)\left[\frac{1}{\tau_p} + s\right] = I\tau_p$$

$$Q_p(s) = \frac{I\tau_p}{\left[\frac{1}{\tau_p} + s\right]} \quad \text{---(3)}$$

Taking inverse laplace transform eq (3).

$$L^{-1}\left[Q_p(s)\right] = I\tau_p e^{-t/\tau_p}$$

$$\therefore \boxed{Q_p(t) = I\tau_p e^{-t/\tau_p}}$$

→ for Quasi-steady state approximation of P-n junction.

$$\Delta P_n(t) = P_n\left(e^{qV(t)/kT} - 1\right).$$

Gradient in charge is,

$$\delta p(x_n, t) = \Delta P_n(t)\, e^{-x_n/L_p}.$$

The stored charge at any instant of time, is,

$$Q_p(t) = qA \int_0^\infty \Delta P_n(t)\, e^{-x_n/L_p}\, dx_n.$$

$$= qA\, \Delta P_n(t) \int_0^\infty e^{-x_n/L_p}\, dx_n.$$

$$= qA\, \Delta P_n(t) \left[\frac{e^{-x_n/L_p}}{-1/L_p}\right]_0^\infty$$

$$= qA\, \Delta P_n(t)\, L_p.$$

$$\Delta P_n(t) = \frac{Q_p(t)}{qAL_p}.$$

$$P_n\left(e^{qV(t)/kT} - 1\right) = \frac{Q_p(t)}{qAL_p}.$$

$$\frac{Q_p(t)}{qAL_pP_n} = e^{qV/kT} - 1.$$

$$\frac{Q_p(t)}{qAL_pP_n} + 1 = e^{qV/kT}$$

$$\frac{qV(t)}{kT} = \ln\left[\frac{Q_p(t)}{qAL_pP_n} + 1\right]$$

$$qV(t) = kT\ln\left[\frac{Q_p(t)}{qAL_pP_n} + 1\right]$$

$$V(t) = \frac{kT}{q}\ln\left[\frac{Q_p(t)}{qAL_pP_n} + 1\right].$$

where, $Q_p(t) = I\tau_p e^{-t/\tau_p}$.

$$\therefore \boxed{V(t) = \frac{kT}{q}\ln\left[\frac{I\tau_p e^{-t/\tau_p}}{qAL_pP_n} + 1\right]}$$

BREAKDOWN MECHANISM.

There are two type of breakdown mechanisms in the p-n junction diodes.

1. Zener breakdown.
2. Avalanche breakdown.

ZENER BREAKDOWN.

When a heavily doped junction is reverse biased, the energy bands become crossed at relatively low voltage (n-side C.B appears opposite to P-side V.B). The crossing of band alligns the large no. of empty state in n-side C.B and opposite the many filled state of P-side V.B.

If the barrier separating these two bands is narrow, tunneling of electrons can occur. Tunneling of electrons from P side V.B to n-side C.B constitute a reverse current from n to p. this is called Zener effect.

The basic requirement of tunneling current are a large no. of electrons separated from a large no. of empty states by a narrow barrier of finite height. Tunneling distance (d) become smaller as reverse bias is increased, because the higher electric field result in steeper slopes for band edges. However, if Zener breakdown doesnot occur with reverse bias of few Volts, avalanche breakdown will be dominant.

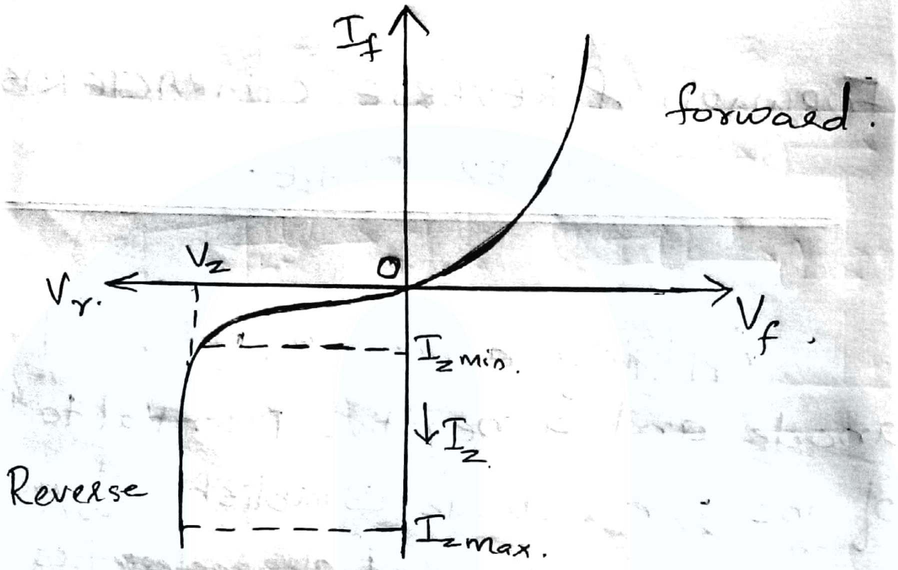
FORWARD & REVERSE CHARACTERISTICS OF ZENER DIODE.

Applying a positive potential to the anode and a negative potential to the cathode of the zener diode establish a forward bias Condition. The forward characteristics of the zener diode is same as that of a p-n junction diode (ie) as the applied potential increases.

The current increases exponentially. Applying a negative potential to the anode and positive potential to the cathode is reverse biases the Zener diode. As the reverse bias increases the current rapidly in a direction opposite to that of the positive Voltage region.

Thus under reverse bias Condition breakdown occurs. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and generate carriers. The breakdown

Voltage depends upon the amount of doping. for a heavily Voltage doped depletion layer will be thin and breakdown occurs at low reverse Voltage and the breakdown Voltage is Sharp.



AVALANCHE BREAKDOWN

for lightly doped junction, electron tunneling is negligible, and instead the breakdown mechanism involves the impact ionization of host atoms by energetic carriers. Normal lattice scattering event can results in creation of EHP's, if carriers being scattered has sufficient energy.

for eg: if electric field in the transition region is large, an electron entering from P-side may be accelerated to high enough kinetic energy to cause an ionization collision with lattice. A single such interaction result in carrier multiplication, the original electrons and generated electrons are both swept to n-side of the junction and generated holes to p-side.

The degree of multiplication can become very high, if carrier generated within transition region also have ionization collision with lattice.

for eg: an incoming electron may have a collision with lattice and create an EHP, each of these carrier has a chance of creating a new EHP and so forth. This is avalanche process, since each incomming carrier can initate the creation of large no. of new carriers.

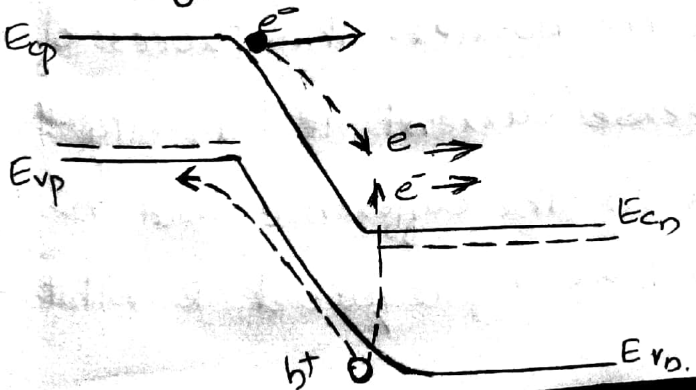
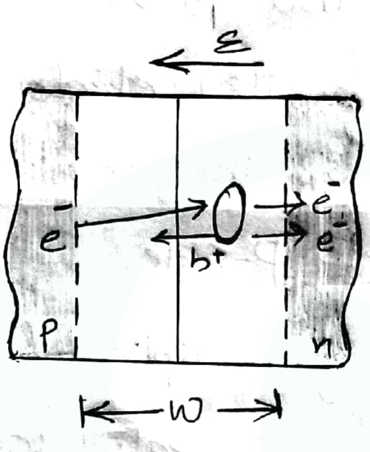
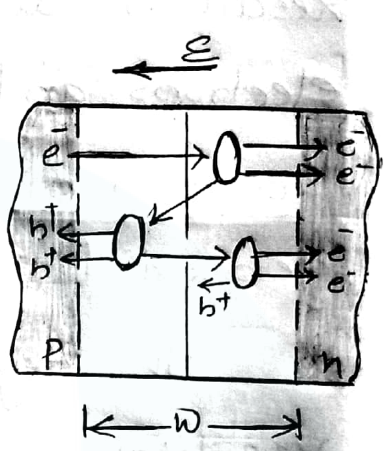


fig: (a) Band diagram of in Reverse bias of P-n junction.

The figure showing the band diagram of p-n junction in reverse bias, the electron gaining K.E in the field of the depletion region and creating a electron-hole pair by impact ionization.



(a) Single ionization Collision by incoming e^- in the depletion region.



(b) Primary, Secondary and tertiary Collision.

TUNNEL DIODE.

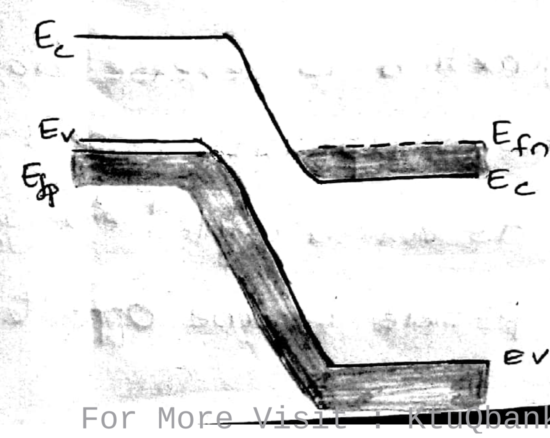
Tunnel diodes are p-n junction devices that operate on the basis of the quantum mechanical tunneling of electrons through the junction barrier. This process of tunneling for reverse Current is basically the zener effect with the difference that negligible reverse bias is required to initate tunneling

Tunnel diode is also called ESAKI diode and finds application in high speed switching circuit, amplification and oscillation.

Tunnel diode is basically a negative resistant device.

When a semiconductor material is highly doped, the interactions between the impurities cause the fermi level to shift from the band gap. The fermi level no longer remains in the band gap but shifts to the conduction or the valence band.

For eg. if the conduction band electron concentration exceeds the effective density of states, the fermi-level shifts to conduction band. In case of hole concentration exceeding the effective density of states the fermi level lies in the valence band. ie, the heavily doped semiconductor with fermi level lying inside the valence band or conduction band is called degenerate semiconductor.



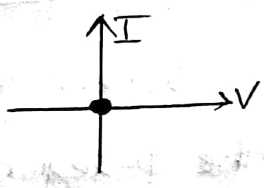
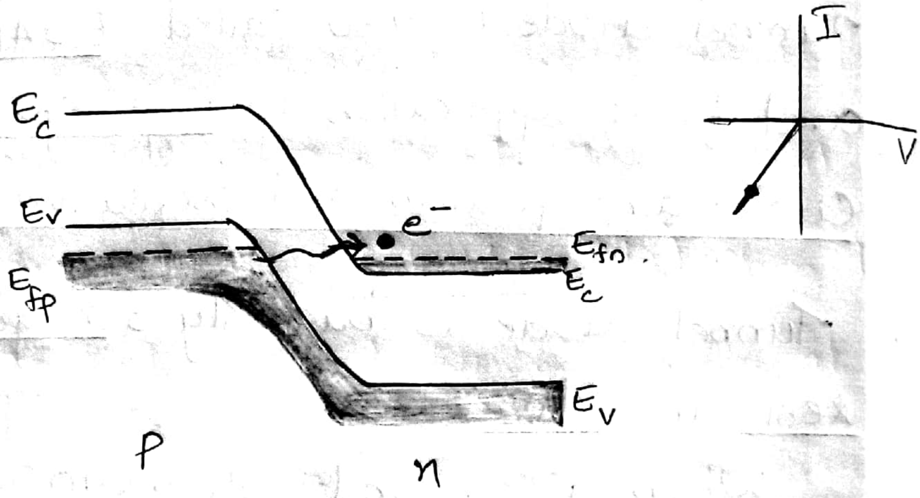
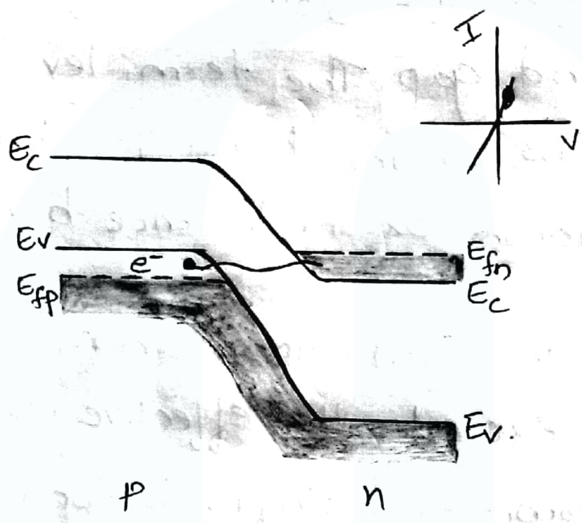
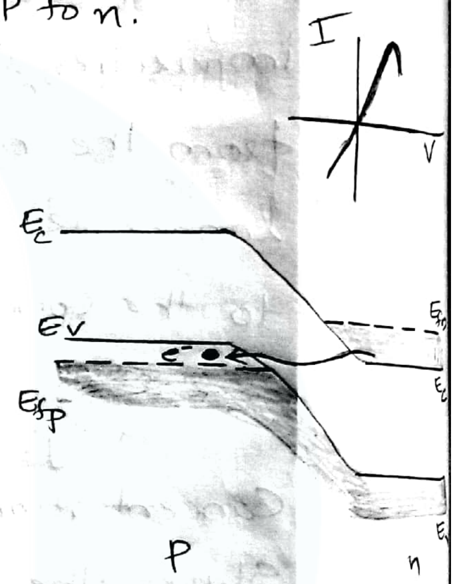


fig: Equilibrium Condition, no net tunneling.



(b) Small reverse bias, electron tunneling from p to n.





(c) Small forward bias, electron tunneling from n to p.

(d) Increased forward bias, electron tunneling from n to p decreases as band pass by each other.

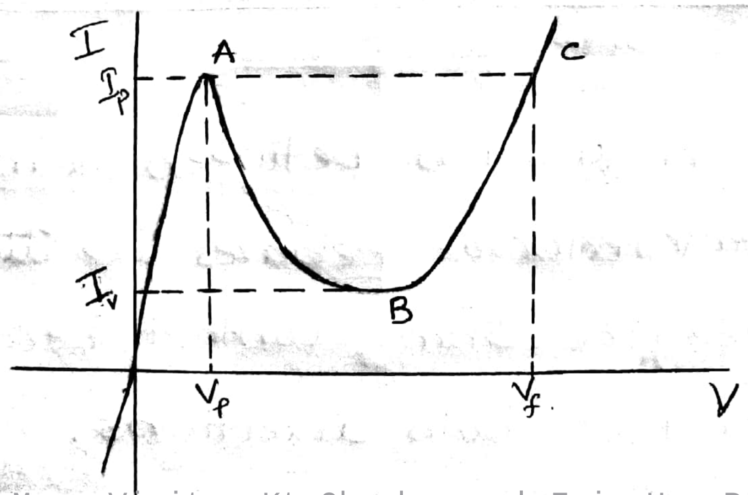
REVERSE BIASED.

When the junction is reverse biased, the p-region moves up with respect to the N-region. As a result, filled energy levels on the p-side become opposite empty energy levels on the N-side. At this stage electrons tunnel through the narrow space charge region (depletion region) from the higher energy levels on the P-side to the lower energy levels on the N-side despite the fact that the junction is reverse biased, significant current flows.

FORWARD BIASED.

When the tunnel diode is forward biased, its initial behaviour is similar to that when it is reverse biased. Now some of the filled energy levels on the N-side shift to high energy levels than empty level on the p-side. Now tunneling occurs from the N side to P side with the increase in forward bias more and more electrons tunnel from the N-side to the P-side.

V-I CHARACTERISTICS OF TUNNEL DIODE.



When forward bias is applied, Significant Current is Produced. The Current quickly rises to its peak Value (I_P) when the applied forward Voltage reaches at V_P (point A). When forward Voltage is increased further diode Current starts decreasing till it achieves its minimum Value called Valley Current (I_V) Corresponding to Valley Voltage V_V. Current starts increasing again as in any Ordinary Junction diode. Between the Peak point A and Valley Point B, current decreases with increases in the applied Voltage. In other words, tunnel diode Possesses negative resistance in this region.

METAL SEMICONDUCTOR CONTACTS.

A Junction between a metal and Semiconductor behaves like diode or it may be Ohmic Contact, because it Conduct both directions.

A rectifying metal semiconductor contact is called Schottky diode.

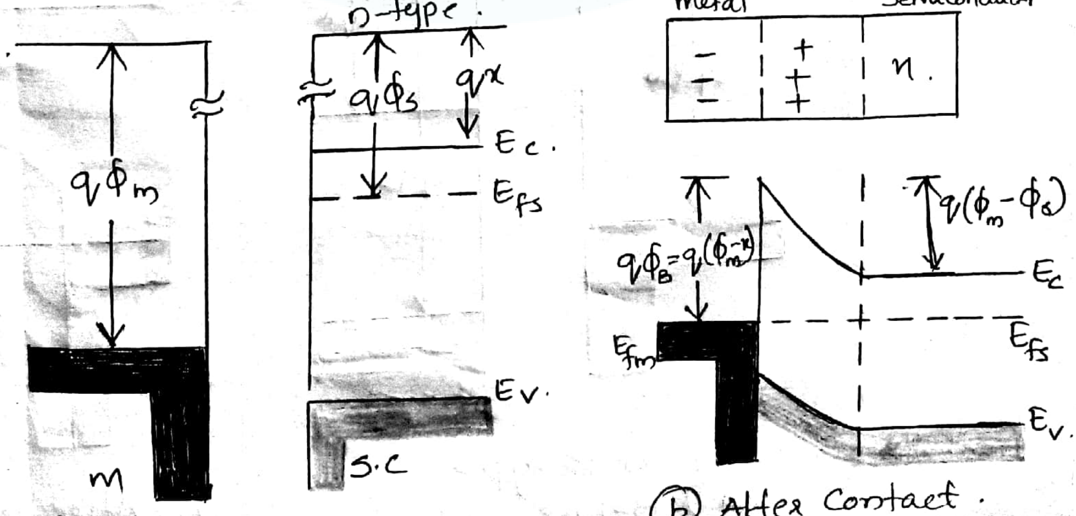
The behaviour of an ideal metal semiconductor contact depends on the relative values of workfunction of metal (ϕ_m) and work function of semiconductor (ϕ_s).

SCHOTTKY BARRIER.

When a metal with work function $q\phi_m$ is in contact with semiconductor having a work function $q\phi_s$, charge transfer occurs until the fermi levels align at equilibrium.

When $q\phi_m > q\phi_s$, the semiconductor fermi level is initally higher than that of the metal before contact is made. To allign the two fermi level, the electrostatic potential of the semiconductor must be raised. (ie, electron energies must be lowered).

$\phi_m > \phi_s$.



(a) Before joining
(b) After contact.

Barrier Potential at equilibrium.

$$qV_0 = q\phi_m - q\phi_s$$
$$= q(\phi_m - \phi_s).$$

Barrier height,

$$q\phi_B = q(\phi_m - \chi).$$

Where,

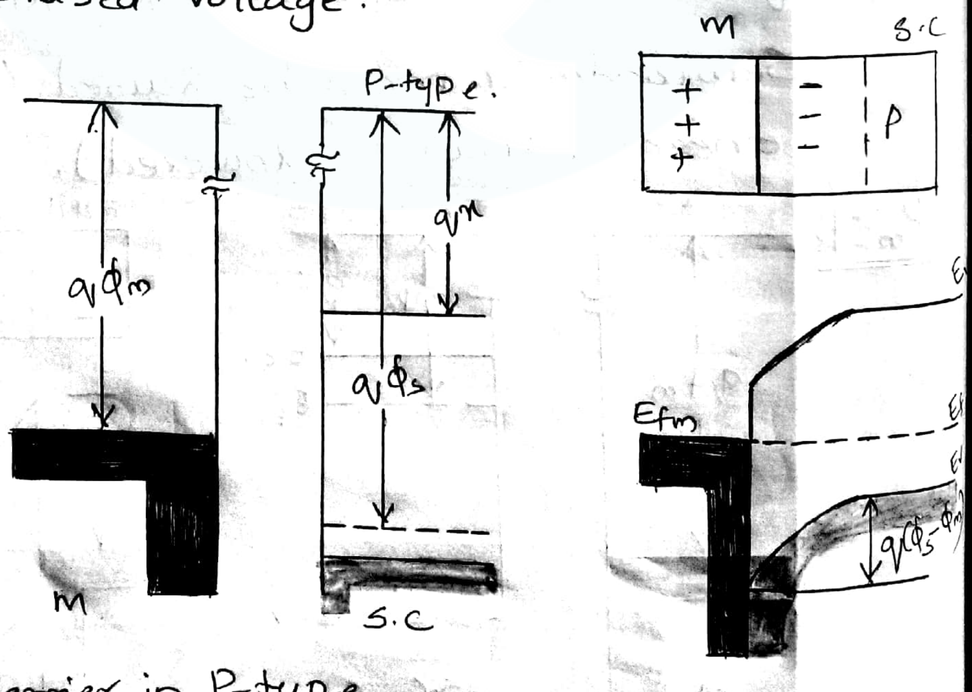
$q\phi_m$ is the metal work function.

$q\phi_s$ is the Semiconductor work function

$q\chi$ is the electron affinity

The equilibrium potential difference, V_0 can be decreased or increased by the application of either forward- or reverse biased Voltage.

$\phi_m < \phi_s$



Schottky barrier in P-type
(a) Before Contact (b) After joining.

When $q\phi_m < q\phi_s$, the semiconductor fermi level is initally lower than that of the metal before contact is made. To allign the two fermi level, the electrostatic potential of the semiconductor must be lowered.

Barrier potential at equilibrium

$$qV_0 = q\phi_s - q\phi_m$$
$$= q(\phi_s - \phi_m)$$

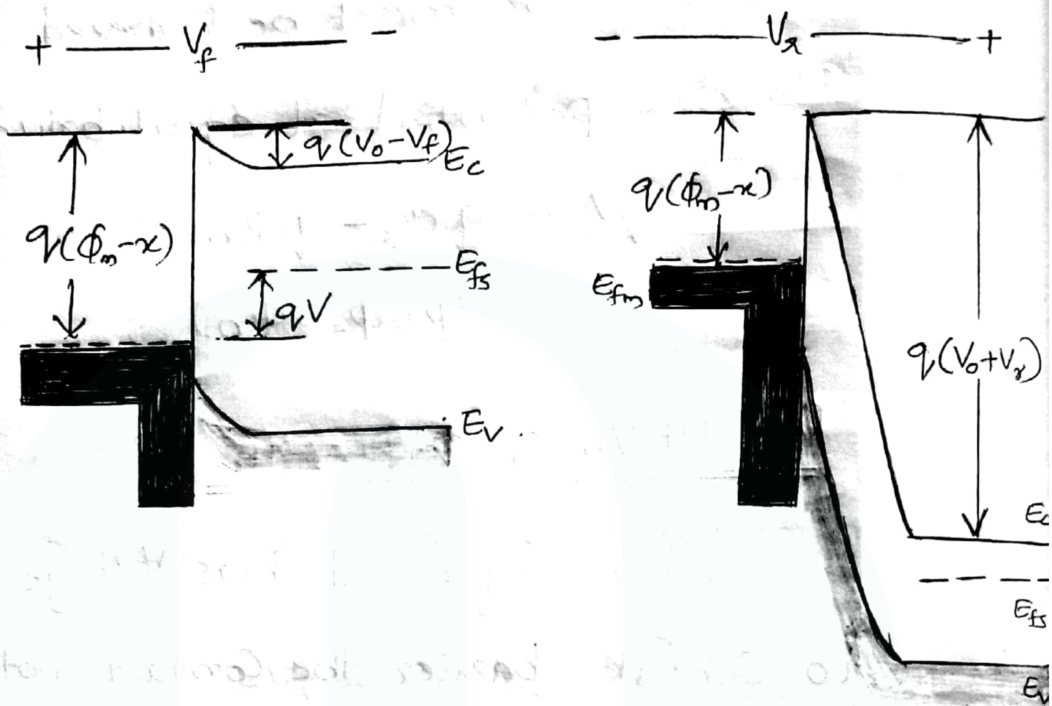
RECTIFYING CONTACTS.

When a forward bias voltage V is applied to Schottky barrier the contact potential is reduced from V_0 to $(V_0 - V)$. As a result electron in semiconductor C.B can diffuse across depletion region to metal. This gives rise to forward current (metal to S.C) through the junction. Conversely, reverse bias increase barrier to $V_0 + V$ and electron flow from SC to metal become negligible. In either case flow of electron from metal to S.C is retarded by barrier $(\phi_m - \chi)$. The resulting diode equation is similar in form to that of the p-n junction.

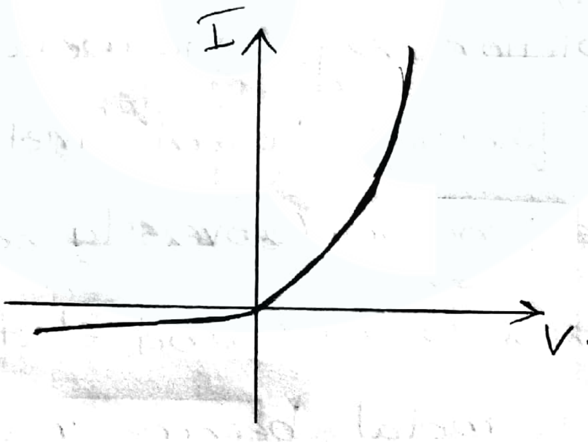
$$I = I_0 \left(e^{qV/kT} - 1\right).$$

where,

$$I_0 \propto e^{-q\phi_B/kT}$$



ⓐ forward biased ⓑ Reverse biased.



ⓒ typical Current-Voltage Characteristics.

OHMIC CONTACTS.

The ohmic metal-Semiconductor Contact having a linear V-I characteristics in both biasing direction. It is important that such contacts be ohmic with minimum resistance and no tendency to rectify signals.

In ideal metal - Semiconductor Contacts are ohmic, when charge induced in S.C in alligning fermi level is provided by majority carriers.

When $\phi_m < \phi_s$ [for n-type Semiconductor] the fermi level are aligned at equilibrium by transfering electron from metal to semiconductor. This raises the semiconductor electron energies (lowers the electrostatic potential) relative to metal at equilibrium.

Barrier potential at equilibrium

qV_0 = Work fn of Sc – Work fn in metal.

$= q\phi_s - q\phi_m$.

$= q(\phi_s - \phi_m)$.

Barrier height

$q\phi_v = q(\chi - \phi_m)$.

When $\phi_m > \phi_s$ [p-type Semiconductor]

The semiconductor fermi-level above the metal fermi level. To allign two fermi level the electron energy must be lowered. ie, the electrostatic potential of semiconductor must be raised relative to that of metal barrier potential at equilibrium.

Barrier potential at equilibrium.

$$qV_0 = q(\phi_m - \phi_s).$$

$\phi_m < \phi_s$

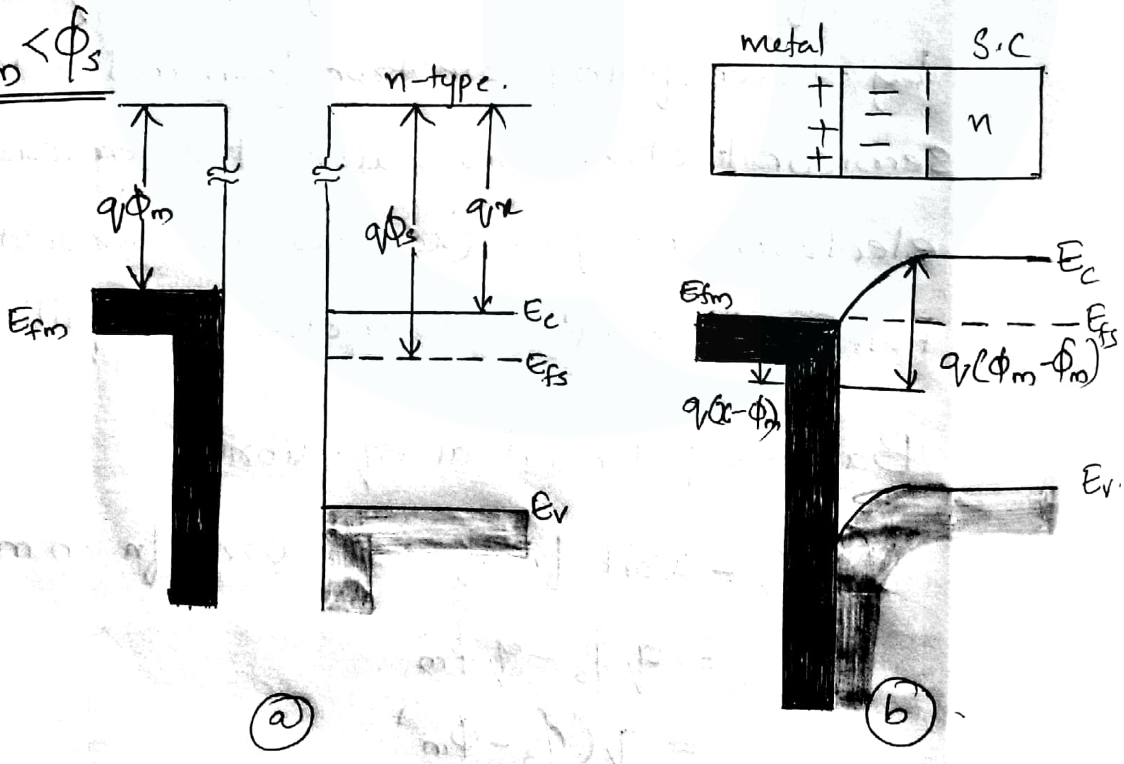
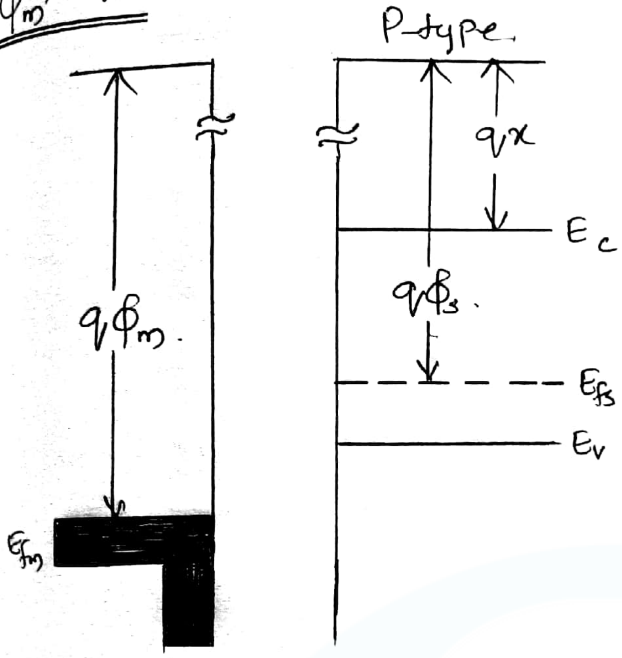
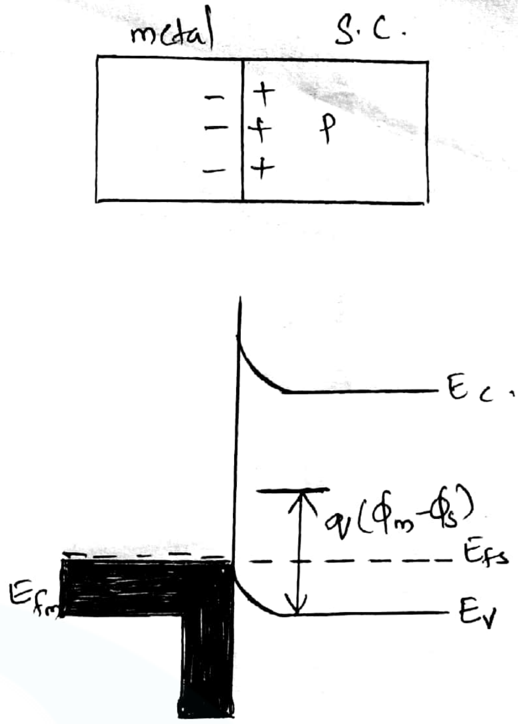


fig: (a) $\phi_m < \phi_s$ for an n-type Semiconductor
(b) the equilibrium for the Junction.

$\phi_m > \phi_s$.



(c) $\phi_m > \phi_s$ for P-type Semiconductor.



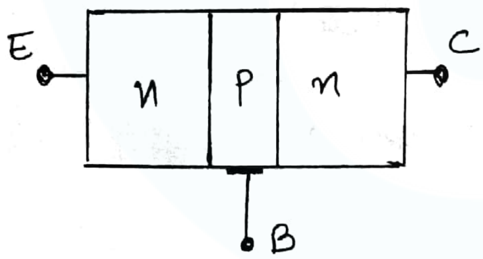
(d) The junction at equilibrium

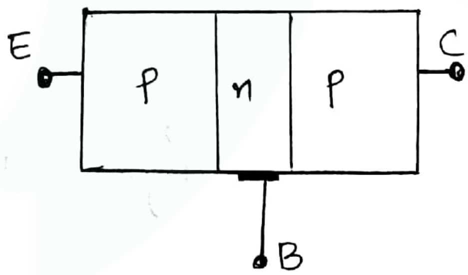
MODULE - 5.

Bipolar Junction Transistors. (BJT).

A Bipolar junction transistor (BJT) Consist of two p-regions Separated by an n-region or two n-regions separated by a p-region. This formers are Called P-n-P transistor and n-p-n transistors.

The middle region is designated as the base of the transistor and the regions at the ends as emitter and Collector. A BJT Consist of two P-n Junctions (emitter-base junction and Collector-base junction) and three terminals (emitter, base, Collector).





A Convenient hole injection device is a forward biased p-n junction. If we make the n-side of the forward-biased junction the Same as the n side of the reverse-biased junction, the p^+-n-p structure is Shown below. With this Configuration, injection of holes from p-n.

junction into the Center n region supplies the minority carrier holes ~~to~~ in the reverse current through the n-p junction.

The forward-biased junction which injects holes into the center n region is called the emitter junction and reverse biased junction which serves as the source of injected holes is called Collector junction.

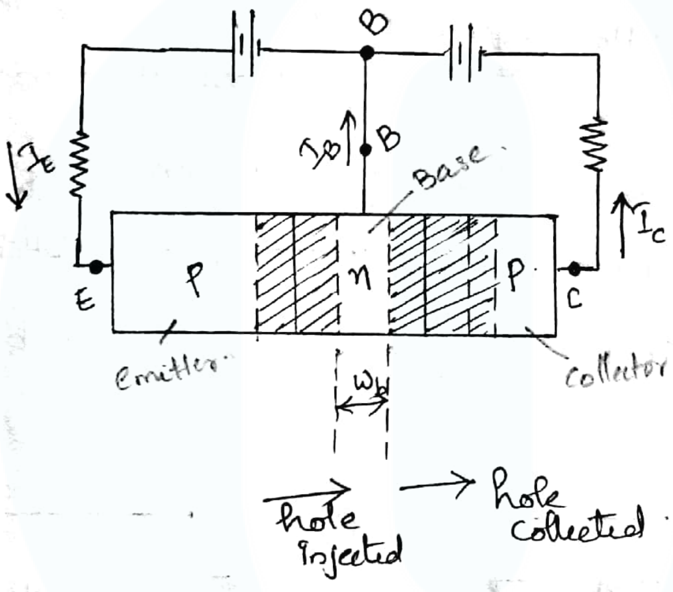


fig: A P-n-p transistor.

CURRENT COMPONENTS.

The below figure shows the different current components in a P-n-p BJT under forward (normal) active mode of operation.

In normal active mode of operation, emitter-base junction is forward biased and Collector-base junction is reverse-biased. Holes are injected from emitter to base and electrons from base to emitter. A portion of holes injected into the base recombine with electrons in the base region and the remaining portion reaches the collector. Minority carrier current I_{CBO} flows across the base collector junction.

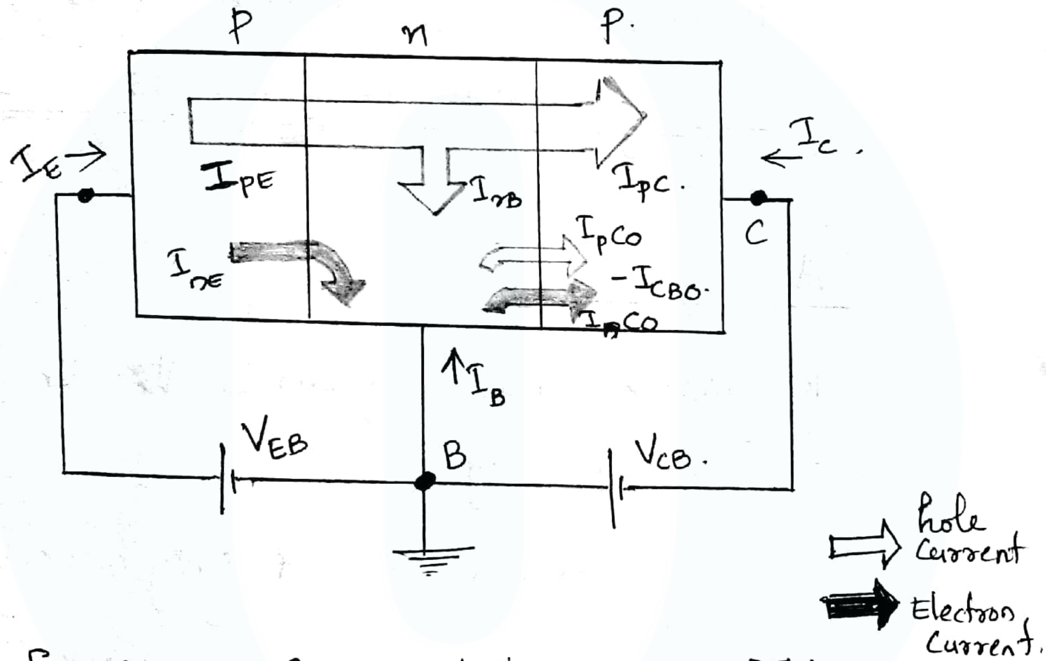


Fig: Current Components in a p-n-p BJT in forward active mode of operation.

I_{PE} – Emitter Current due to holes injected from emitter to base.

I_{nE} – Emitter Current due to electrons injected from base to emitter.

I_{rB} – Base Current due to recombination in the base region.

I_{pc} – Collector Current due to holes reaching the collector which are injected from the emitter.

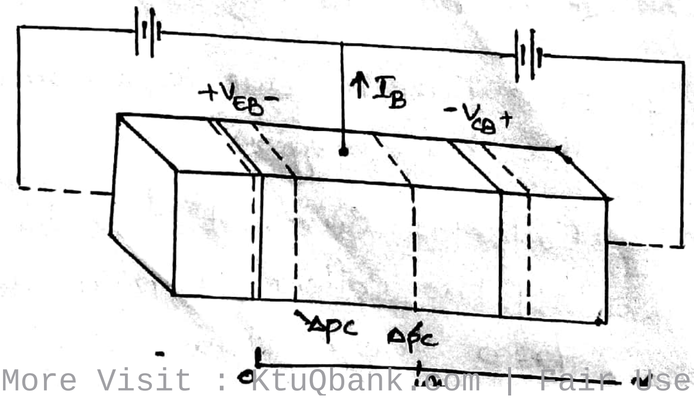
I_{CBO} – Reverse Saturation Current of Collector-base junction with emitter open.

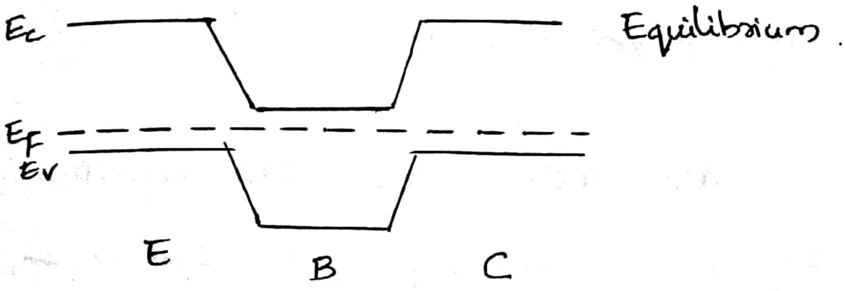
This Current is Constituted by the minority Carrier Crossing the junction. It is known as leakage current of collector-base junction.

MINORITY CARRIER DISTRIBUTIONS AND TERMINAL CURRENTS.

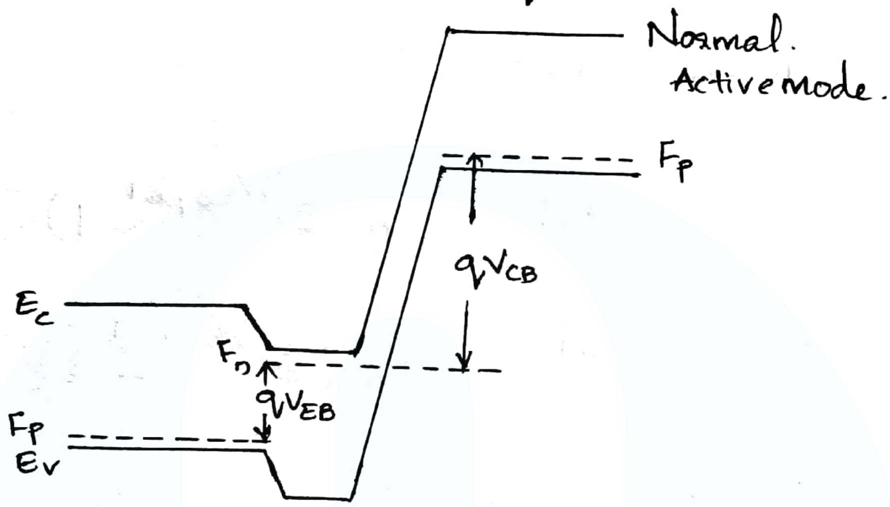
Assumptions:-

1. Charge Carriers from emitter should reach Collector only.
2. Emitter Current should only due to holes.
3. Reverse Saturation Current almost equal to zero.
4. Active part of base region should be same as junction.
5. All the Voltage and Current are in steady state.





(a) PnP transistor at equilibrium.



(b) With normal active bias, the quasi fermi levels are separated by the applied Voltage times q.

In the above figure, the base width is W_b between the two depletion regions and area is A. In equilibrium, the fermi level is flat, and the band diagram Corresponds to that for two back to back pn junctions. But for a forward-biased emitter and a reverse biased Collector (normal active mode), the fermi-level splits up into quasi-fermi levels.

The barrier at the emitter-base junction is reduced by the forward bias and the

Collector-base junction is increased by the reverse bias.

The excess hole concentration at the edge of the emitter depletion region Δp_E and the concentration on the collector side of the base is Δp_C.

$$\Delta p_E = p_n \left(e^{qV_{EB}/kT} - 1\right)$$

$$\Delta p_C = p_n \left(e^{qV_{CB}/kT} - 1\right)$$

If emitter junction is strongly forward biased ($V_{EB} \gg kT/q$) and the collector junction is strongly reverse biased ($V_{CB} \ll 0$).

So, the excess concentration is,

$$\Delta p_E \simeq p_n e^{qV_{EB}/kT}$$

$$\Delta p_C \simeq -p_n$$

The excess hole concentration as a function of distance in the base $\delta p(x_n)$ by using boundary conditions in the diffusion eq.

$$\frac{d^2 \delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2}$$

The solution of this equation.

$$\delta p(x_n) = c_1 e^{x_n/L_p} + c_2 e^{-x_n/L_p} \quad \text{—— (1)}$$

Applying boundary condition.

$$\delta p(x_n=0) = c_1 e^{0/L_p} + c_2 e^{0/L_p}$$

$$\Delta P_E = c_1 + c_2 \quad \text{—— (2)}$$

$$\delta p(x_n=W_b) = c_1 e^{W_b/L_p} + c_2 e^{-W_b/L_p}$$

$$\Delta P_c = c_1 e^{W_b/L_p} + c_2 e^{-W_b/L_p} \quad \text{—— (3)}$$

$$c_1 = \Delta P_E - c_2.$$

Then,

$$\Delta P_c = (\Delta P_E - c_2) e^{W_b/L_p} + c_2 e^{-W_b/L_p}$$

$$= \Delta P_E e^{W_b/L_p} - c_2 e^{W_b/L_p} + c_2 e^{-W_b/L_p}$$

$$\Delta P_c = \Delta P_E e^{W_b/L_p} - c_2 \left(e^{W_b/L_p} - e^{-W_b/L_p}\right)$$

$$c_2 \left(e^{W_b/L_p} - e^{-W_b/L_p}\right) = \Delta P_E e^{W_b/L_p} - \Delta P_c$$

$$\therefore c_2 = \frac{\Delta P_E e^{W_b/L_p} - \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$\Delta P_E = C_1 + \frac{\Delta P_E e^{W_b/L_p} - \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$\therefore C_1 = \frac{-\Delta P_E e^{-W_b/L_p} + \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

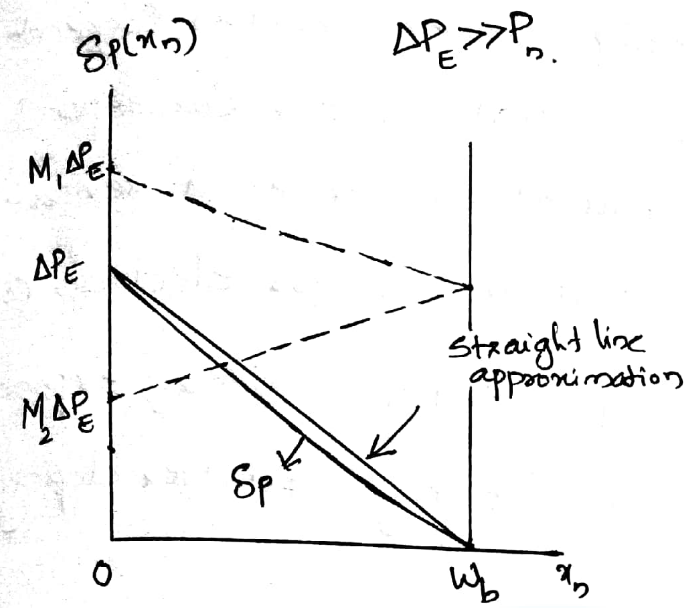
By taking $\Delta P_c = 0$, sub c_1 & c_2 in eq(1).

$$\delta p(x) = \frac{-\Delta P_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} e^{x_n/L_p} + \frac{\Delta P_E e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \cdot e^{-x_n/L_p}$$

$$= \frac{\Delta P_E}{e^{W_b/L_p} - e^{-W_b/L_p}} \left[e^{W_b/L_p} \cdot e^{-x_n/L_p} - e^{-W_b/L_p} \cdot e^{x_n/L_p} \right]$$

$$= \frac{\Delta P_E}{e^{W_b/L_p} - e^{-W_b/L_p}} \left[e^{W_b/L_p - x_n/L_p} - e^{-W_b/L_p + x_n/L_p} \right]$$

$$\boxed{\delta p(x_n) = \frac{\Delta P_E}{e^{W_b/L_p} - e^{-W_b/L_p}} \left[e^{\frac{W_b - x_n}{L_p}} - e^{-\frac{W_b + x_n}{L_p}} \right]}$$



$$\delta p(x_n) = M_1 \Delta P_E e^{-x_n/L_p} - M_2 \Delta P_E e^{x_n/L_p}$$

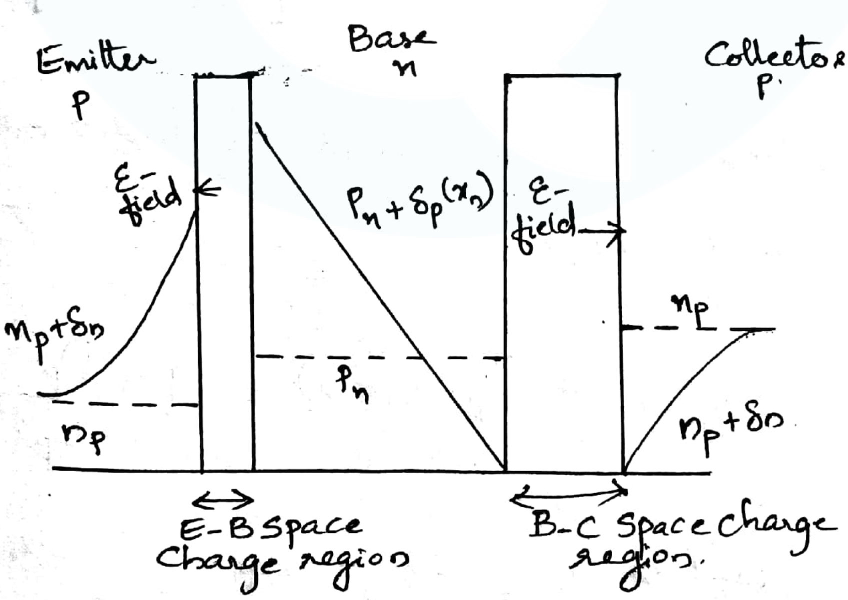
where,

$$M_1 = \frac{e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}},$$

$$M_2 = \frac{e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

(a) hole distribution in the base region.

The $\delta p(x)$ Varies almost linearly between the emitter and collector Junction depletion region. In the figure, Slight deviation from linearity of the distribution means, the small Value of I_B Caused by recombination in the base region.



(b) Electron distributions in the emitter and Collector.

The minority carrier electron concentrations in the emitter and collector corresponding to a forward-biased emitter and reverse-biased collector. In that, the excess electron concentration in the p emitter is decay exponentially to zero., because at high emitter doping levels.

TERMINAL CURRENTS.

The excess hole distribution in the base region is evaluated by the emitter and collector currents from the gradient of the hole current concentration at each depletion region edge.

$$I_p(x_n) = -qAD_p\left[\frac{d\,\delta p(x_n)}{dx}\right]$$

The hole component of the emitter current at $x_n = 0$,

$$I_{EP} = I_p(x_n = 0) = qA\frac{D_p}{L_p}(C_2 - C_1)$$

$$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}.$$

$$\frac{d\,\delta p[x_n]}{dx} = C_1 \frac{d}{dx}\left(e^{x_n/L_p}\right) + C_2 \frac{d}{dx}\left(e^{-x_n/L_p}\right)$$

$$= C_1 e^{x_n/L_p} \cdot \frac{1}{L_p} + C_2 e^{-x_n/L_p} \cdot \frac{-1}{L_p}$$

$$= \frac{C_1 e^{x_n/L_p}}{L_p} - \frac{C_2 e^{-x_n/L_p}}{L_p}$$

Then,

$$I_p(x_n) = -qAD_p \cdot \left[\frac{C_1 e^{x_n/L_p}}{L_p} - \frac{C_2 e^{-x_n/L_p}}{L_p}\right]$$

$$= -\frac{qAD_p}{L_p}\left[C_1 e^{x_n/L_p} - C_2 e^{-x_n/L_p}\right]$$

→ $I_p(x_n=0) = I_{EP}$. (emitter current due to holes)

$$= -\frac{qAD_p}{L_p}\left[C_1 - C_2\right]$$

$$\boxed{I_{EP} = \frac{qAD_p}{L_p}\left[C_2 - C_1\right]}$$

$I_p(x_n = W_b) = I_{CP}$ (collector current due to holes)

$$= -\frac{qAD_p}{L_p}\left[C_1 e^{W_b/L_p} - C_2 e^{-W_b/L_p}\right]$$

$$\therefore \boxed{I_c = \frac{qAD_p}{L_p}\left[C_2 e^{-W_b/L_p} - C_1 e^{W_b/L_p}\right]}$$

we know that,

$$C_1 = \frac{\Delta P_c - \Delta P_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$C_2 = \frac{\Delta P_E e^{W_b/L_p} - \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$I_{Ep} = \frac{qAD_p}{L_p}\left[C_2 - C_1\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{(\Delta P_E e^{W_b/L_p} - \Delta P_c)}{e^{W_b/L_p} - e^{-W_b/L_p}} - \frac{(\Delta P_c - \Delta P_E e^{-W_b/L_p})}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E e^{W_b/L_p} - \Delta P_c - \Delta P_c + \Delta P_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E (e^{W_b/L_p} + e^{-W_b/L_p}) - 2\Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$\frac{e^{\theta} + e^{-\theta}}{2} = \cosh(\theta)$

$$= \frac{qAD_p}{L_p}\left[\frac{\frac{\Delta P_E (e^{W_b/L_p} + e^{-W_b/L_p})}{2}}{\frac{(e^{W_b/L_p} - e^{-W_b/L_p})}{2}} - \frac{2\Delta P_c}{2\frac{(e^{W_b/L_p} - e^{-W_b/L_p})}{2}}\right]$$

$\frac{e^{\theta} - e^{-\theta}}{2} = \sinh(\theta)$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E \cosh(W_b/L_p)}{\sinh(W_b/L_p)} - \frac{\Delta P_c}{\sinh(W_b/L_p)}\right]$$

$$= \frac{qAD_p}{L_p}\left[\Delta P_E \coth(W_b/L_p) - \Delta P_c \frac{1}{\sinh(W_b/L_p)}\right]$$

$$I_E = I_{EP} = \frac{qAD_p}{L_p}\left[\Delta P_E \coth(W_b/L_p) - \Delta P_c \operatorname{cosech}\left(\frac{W_b}{L_p}\right)\right] \quad \text{--- (1)}$$

$$I_c = \frac{qAD_p}{L_p}\left[C_2 e^{-W_b/L_p} - C_1 e^{W_b/L_p}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E e^{W_b/L_p} - \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}} \times e^{-W_b/L_p} - \frac{\Delta P_c - (\Delta P_E e^{-W_b/L_p} \times e^{W_b/L_p})}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_E e^{W_b/L_p} \cdot e^{-W_b/L_p} - \Delta P_c \times e^{-W_b/L_p} - \Delta P_c e^{W_b/L_p} + \Delta P_E e^{-W_b/L_p} \cdot e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{2\Delta P_E e^{W_b/L_p} \times e^{-W_b/L_p} + \Delta P_c(e^{-W_b/L_p} - e^{W_b/L_p})}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{2\Delta P_E}{e^{W_b/L_p} - e^{-W_b/L_p}} + \frac{\Delta P_c(-e^{W_b/L_p} - e^{W_b/L_p})}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{2\Delta P_E}{2(e^{W_b/L_p} - e^{-W_b/L_p})/2} - \frac{\Delta P_c (e^{W_b/L_p} + e^{-W_b/L_p})/2}{(e^{W_b/L_p} - e^{-W_b/L_p})/2}\right]$$

$$= \frac{qAD_p}{L_p}\left[\Delta P_E \cdot \frac{1}{\sinh(W_b/L_p)} - \Delta P_c \cdot \frac{\cosh(W_b/L_p)}{\sinh(W_b/L_p)}\right]$$

$$\boxed{I_c = \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{cosech}(W_b/L_p) - \Delta P_c \coth(W_b/L_p)\right]}$$

$$I_E = I_B + I_c.$$

$$I_B = I_E - I_c.$$

$$I_B = \frac{qAD_p}{L_p}\left[\Delta P_E \coth(W_b/L_p) - \Delta P_c \operatorname{cosech}(W_b/L_p)\right] - \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{cosech}(W_b/L_p) - \Delta P_c \coth(W_b/L_p)\right]$$

$$= \frac{qAD_p}{L_p}\left[\coth(W_b/L_p)(\Delta P_E + \Delta P_c) - \operatorname{cosech}(W_b/L_p)(\Delta P_E + \Delta P_c)\right]$$

$$= \frac{qAD_p}{L_p}(\Delta P_E + \Delta P_c)\left[\coth(W_b/L_p) - \operatorname{cosech}(W_b/L_p)\right]$$

$$= \frac{qAD_p}{L_p}(\Delta P_E + \Delta P_c)\left[\frac{\cosh(W_b/L_p)}{\sinh(W_b/L_p)} - \frac{1}{\sinh(W_b/L_p)}\right]$$

$$= \frac{qAD_p}{L_p}(\Delta P_E + \Delta P_c)\left[\frac{\cosh(W_b/L_p) - 1}{\sinh(W_b/L_p)}\right]$$

where, $\tanh(x/2) = \frac{\cosh(x) - 1}{\sinh(x)}$

$$\therefore I_B = \frac{qAD_p}{L_p}(\Delta P_E + \Delta P_c)\tanh(W_b/2L_p)$$

TERMINAL CURRENT APPROXIMATIONS.

If the Collector is reverse biased, $\Delta P_c = -P_n$ Sub

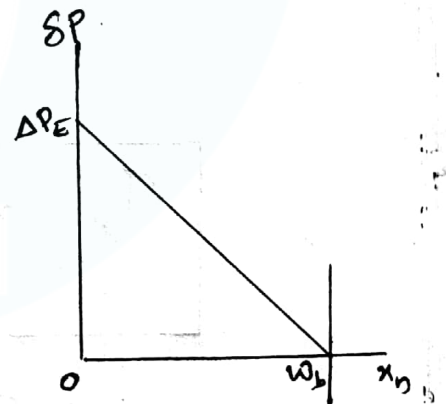


fig. excess hole distribution in the base.

$$I_E \simeq \frac{qAD_p}{L_p}\left[\Delta P_E \coth\left(\frac{W_b}{L_p}\right) - \Delta P_c \operatorname{cosech}(W_b/L_p)\right]$$

where $\Delta P_c \approx 0$

$$I_E = \frac{qAD_p}{L_p}\left[\Delta P_E \coth(W_b/L_p)\right]$$

$$I_C = \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{Cosec}(W_b/L_p)\right]$$

$$I_B = \frac{qAD_p}{L_p}\left[\Delta P_E \tanh(W_b/2L_p)\right]$$

hyperbolic function

$$\tanh y = y - \frac{y^3}{3} + \cdots$$

The first order approximation of base current.

$$I_B \approx \frac{qAD_p}{L_p}\left[\Delta P_E \cdot \frac{W_b}{2L_p}\right]$$

$$\approx \frac{qAD_p}{2L_p^2} \cdot \Delta P_E \cdot W_b$$

$$\boxed{I_B \approx \frac{qA\Delta P_E \cdot W_b}{2\tau_p}}$$

$$\frac{D_p}{L_p} = \frac{L_p}{\tau_p}$$

$$\frac{D_p}{L_p^2} = \frac{1}{\tau_p}$$

$$\operatorname{Coth} x = \frac{1}{x} + \frac{x}{3} - \frac{x^3}{45} + \cdots$$

$$\operatorname{Cosech} y = \frac{1}{y} - \frac{y}{6} + \frac{7y^3}{36} + \cdots$$

The same approximation for the base current is found from the difference in the first-order approximation to I_E and I_C.

$$I_E = \frac{qAD_p}{L_p}\left[\Delta P_E \cdot \frac{1}{\frac{W_b}{L_p}} + \frac{W_b}{\frac{L_p}{3}}\right]$$

$$I_C = \frac{qAD_p}{L_p}\Delta P_E\left[\frac{1}{W_b/L_p} - \frac{W_b}{L_p/6}\right]$$

$$I_B = I_E - I_C.$$

$$= \frac{qAD_p}{L_p}\Delta P_E\left[\frac{1}{W_b/L_p} + \frac{W_b}{L_p/3} - \frac{1}{W_b/L_p} - \frac{W_b}{L_p/6}\right]$$

$$= \frac{qAD_p}{L_p}\frac{W_b \Delta P_E}{2L_p}.$$

$$\boxed{I_B = \frac{qAW_b\Delta P_E}{2\tau_p}}$$

ie, $I_B = I_E - I_C$.

BASIC PARAMETERS.

The most important parameters of a transistor are its emitter injection efficiency (γ) and base transport factor (α_T). As a Circuit designer is concerned, short-circuit common-base current gain (α_0) and common-emitter current gain (β) are the basic parameters of a transistor. But these parameters are decided by the injection efficiency and transport factor.

(a) Base transport factor. (β)

$$i_C \propto i_{Ep} \qquad \beta = 1.$$

$$i_C = \beta i_{Ep}. \quad \therefore \beta = i_C / i_{Ep}.$$

The proportionality factor β, is the fraction of injected holes which make it across the base to collector.

(b) Emitter injection Efficiency. (γ)

The total emitter current (i_E) is made up of the hole component (i_{Ep}) and the electron component (i_{En})

$$i_{E} = i_{Ep} + i_{En}. \qquad \gamma = 1$$

$$\gamma = \frac{i_{Ep}}{i_E} = \frac{i_{Ep}}{i_{Ep} + i_{En}}$$

(c) Current transfer ratio (α)

The relation between the collector and emitter currents is,

$$\frac{i_c}{i_E} = \frac{\beta i_{Ep}}{i_{En} + i_{Ep}} = \beta\gamma = \alpha$$

Base to Collector Current amplification factor (β)

$$i_B = i_{En} + (1-\beta)\, i_{EP}$$

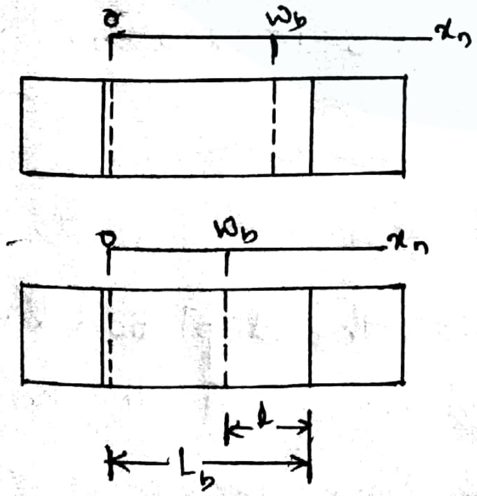
$$\frac{i_c}{i_B} = \frac{\beta i_{EP}}{i_{En} + i_{EP} - \beta i_{EP}}$$

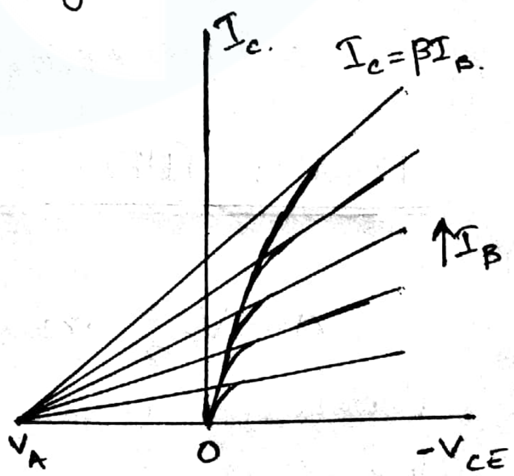
$$= \frac{\beta i_{EP}/(i_{En} + i_{EP})}{1 - \frac{\beta i_{EP}}{i_{En} + i_{EP}}}$$

$$= \frac{\alpha}{1-\alpha} = \beta$$

Base Width Modulation

The effective width of the base region is the difference between the total base width and the depletion layer width of the collector-base junction into the base region.





$W_b = L_b - l$. fig. Early Effect

$I \propto \sqrt{V_{BC}}$.

$$l = \left(\frac{2\varepsilon V_{BC}}{[illegible]}\right)^{1/2}$$

The effective width of the base region decreases with increase in reverse-bias on the collector-base junction. This is called <u>base width modulation or Early Effect.</u>

Due to base width modulation, as reverse-bias on the collector base junction increases I_c and I_E increases. Due to increase in V_{CB}, W_b decreases which increases the slope of minority carrier distribution. As the slope increases I_{EP} and I_c increases.

As the width of the base is reduced, the transport factor (α_T) increases. The recombination in the base region reduces, reducing I_B and increasing α of the transistor. As α increases, β also increases.

PUNCH THROUGH.

As V_{CB} increases, the depletion layer penetrates more and more into the base and the effective width of base decreases and become zero at a collector-base reverse voltage called punch through voltage.