EE204: Analog Electronics

COURSE AIMS

- To provide an understanding of basic transistor electronics.
- To be able to analyse and design basic FET transistor circuits
- To be able to construct a range of op-amp circuits.

LEARNING OUTCOMES

At the end of this module a student should be able to:

1. Explain the basic operating principles of a FET transistor (JFET and MOSFET)
2. Construct small signal equivalent circuits for FET transistor circuits.
3. Design a small signal low frequency amplifier using either FETs
4. Analyze and synthesize DC bias circuits for FET transistors
5. Construct and measure basic transistor circuits in a laboratory.
6. Design and build a selection of basic operational amplifier circuits (integrator, adder, amplifier, etc.)
7. Design a multi-stage filter using op-amps.

COURSE OUTLINES

- The operation of a diode, JEFT and MOSFET transistor
- Introduction to basic FET circuits
- Introduction to a small signal model for a basic FET amplifier
- Design of basic digital logic gates from transistors
- Introduction to op-amps, DC and small signal behavior
- Basic op-amp circuits, including amplifiers, adders, integrators and differentiators.
- More advanced op-amp circuits – including multi-stage filters
- Bode plots as used for op-amp circuits.

BOOKS

- Sedra & Smith, Microelectronic Circuits, 5th Edition. 2004. Oxford University Press. ISBN 0195142527 (Text Book)
- Ramakant A. Gayakwad, Op-Amps and Linear Integrated Circuits, Fourth Edition, 2000. Prentice Hall. ISBN 0132808684 (Reference Book)

- You are free to use any other book

ASSESSMENT

- Final Exam 70 %
- Laboratories 30 %

- Laboratories will start in Week3 and cannot be repeated. In truly exceptional cases, it may be possible to repeat a lab you missed in the last week of term.

- If you are ill and have submitted appropriate note to the EE admin office, that lab will be ignored when calculating your lab average.

- Late submissions are penalised at 10% per day late.

COURSE FLOW

- Introduction to Solid State
- BJTs
- FETs
- FET Amplifiers
- Small Signals v Large Signals
- Op Amps
- 6 x Labs

INTRODUCTION TO SOLID STATE BASICS

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

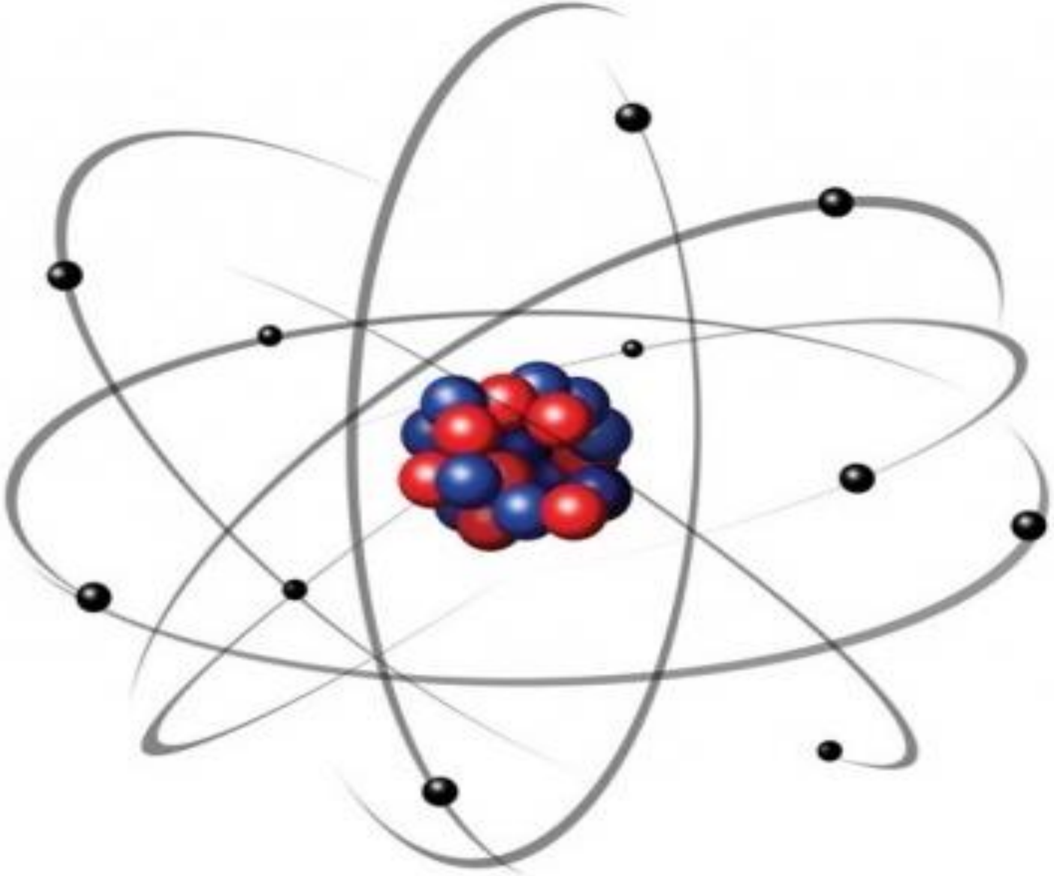
Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

BOHR MODEL

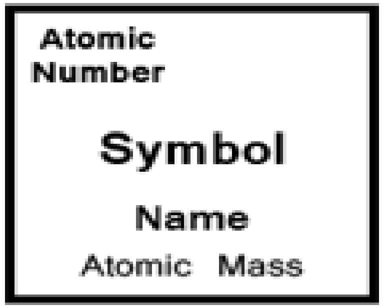
- **1913 Niels Bohr & Ernest Rutherford.**
- **Atoms made up of:**

Nucleus (+)

  - **Protons (+)**
  - **Neutrons (no charge)**
  - Electrons **(-)**



ATOMIC NUMBER



The atomic number:

= number of protons in the nucleus.

= number of electrons in an electrically balanced (Neutral) atom.

Hydrogen = 1

Silicon = 14

OTHER IMPORTANT TERMS

- **Masses** : Protons and neutrons have the same mass (1.67 x 10^{-27}kg); The mass of an electron is much smaller (9.11x10^{-31}kg), neglected in atomic mass calculation); the atomic mass is roughly equal to the mass of protons plus the mass of neutrons
- **Isotope number** = number of neutrons
- **AMU (Atomic Mass Units)** – defined as 1/12 of the most common isotope of a Carbon atom having 6 protons and 6 neutrons, i.e. ^{12}C atom is 12 AMU
- **Atomic weight** –mass per mole of an element; The number of atoms in a mole is called Avogadro number (6.023x10^{23}) E.G. Atomic weight of Si = 28.0855 amu/atom = 28.0855 g/mole

ELECTRONS AND SHELLS.

Electrons orbit the nucleus of the atom a certain distances from the nucleus.

This distance corresponds to a discrete energy level.

These are known as shells. 1,2,3…..

1 being closest to the nucleus.

To put it in perspective if the proton in a hydrogen atom was the size of a golf ball, the electron orbit would be approximately one mile away (1/1836 the size)

ELECTRONS AND SHELLS (CONTD)

Each shell can have a max number of electrons in each shell.

$$N_{\text{no of electrons}} = 2n^2$$

n = number of shell.

VALENCE SHELL

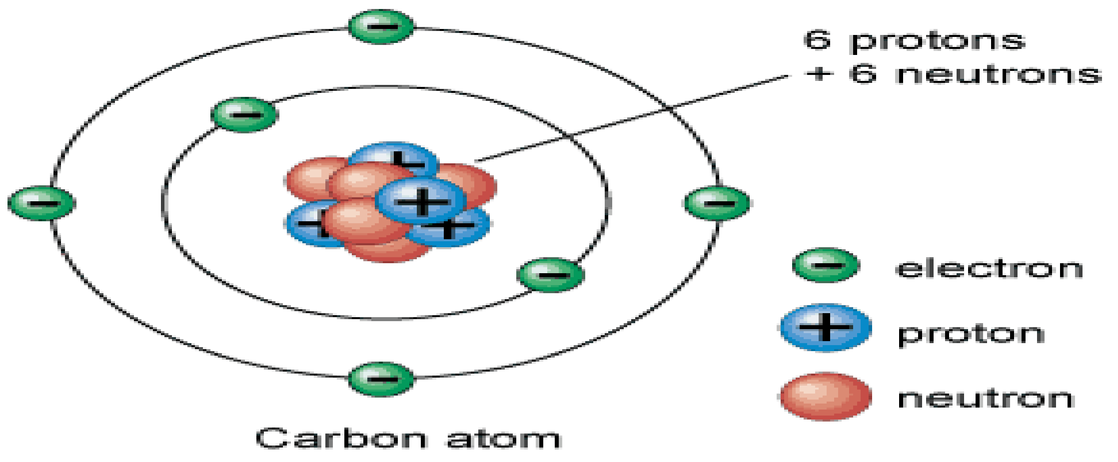
- Electrons that orbit in the outermost shells and furthest from the **nucleus** have the highest energy levels and are less tightly bound to the atom.
- Easier to displace these from the atom.
- Outermost shell is known as **the valence shell** and the electrons are **valence electrons.**
- The process of losing a valence electron is known as **ionization**.

IONISATION

When an atom absorbs energy (heat) , the electron energies are raised. The valence electrons possess more energy and are more loosely bound to the atom than the inner electrons so can actually escape from the outer shell and the atoms influence

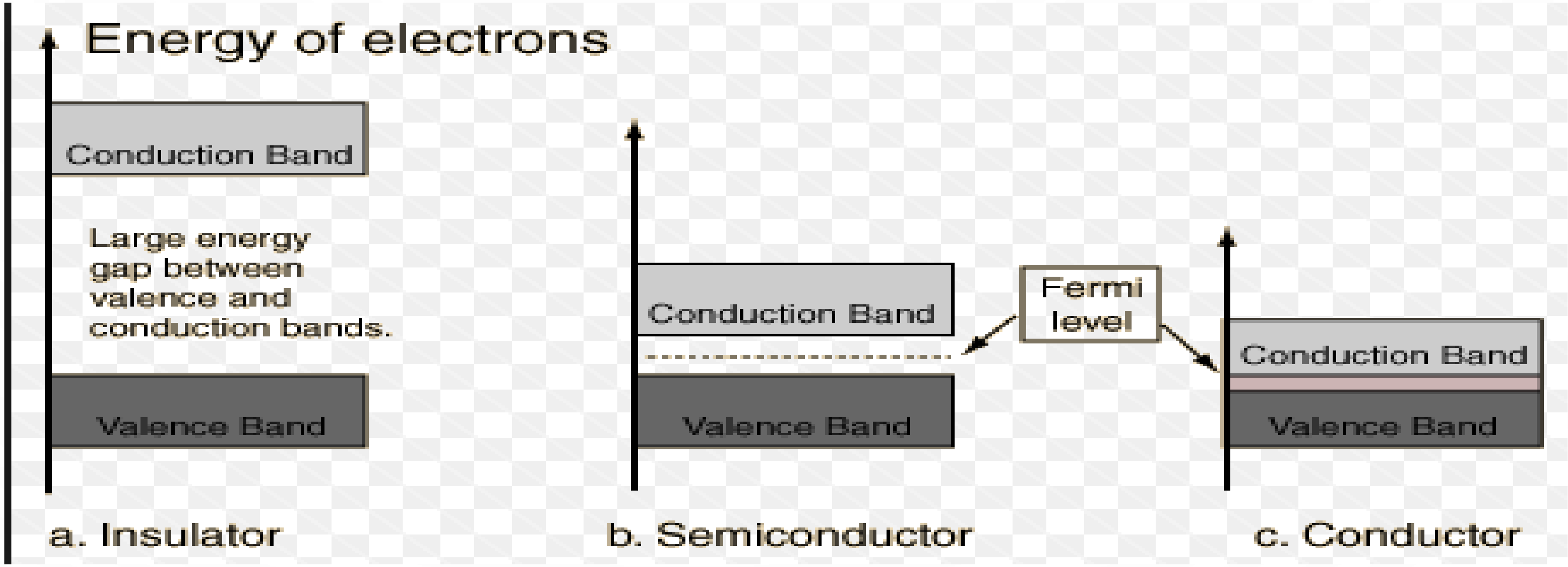
DEFINITIONS

For the purposes of discussing electrical properties, an atom can be represented by the valence shell and a core that consists of all the inner shells and the nucleus, example carbon atom below. The core has a net charge of +4 …..



BAND GAP

When an electron acquires enough additional energy, it can leave the valence band, become a free electron, and exist in what is known as the conduction band

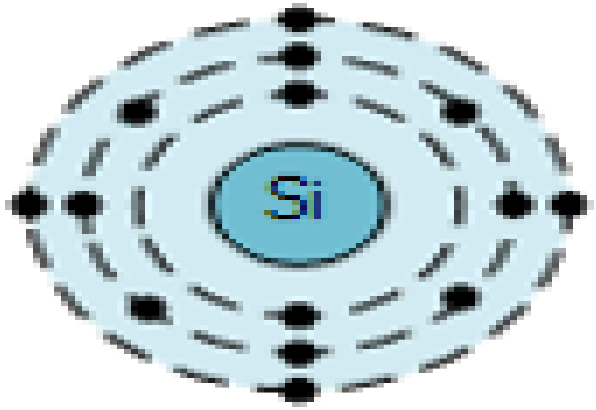


DEFINITIONS

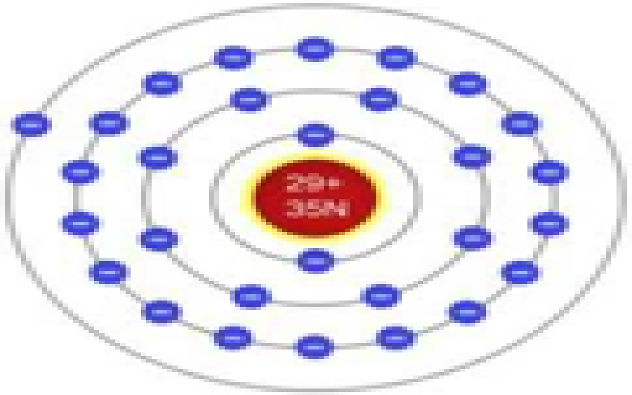
- An **Insulator** is a material that does not conduct electrical current under normal conditions.(Rubber, plastic, glass)
- A **Conductor** is a material that easily conducts electrical current.(Copper, silver, gold)
- A **Semiconductor** is a material that is somewhere between an insulator and a conductor (Silicon)

SEMICONDUCTOR ATOM VS CONDUCTOR ATOM

Silicon (Semiconductor)



Copper (Conductor)



Note that the silicon core has a net +4 charge while the copper core has a net +1 charge (means there is more force trying to hold a valence electron to the atom in silicon than copper)

CONDUCTOR

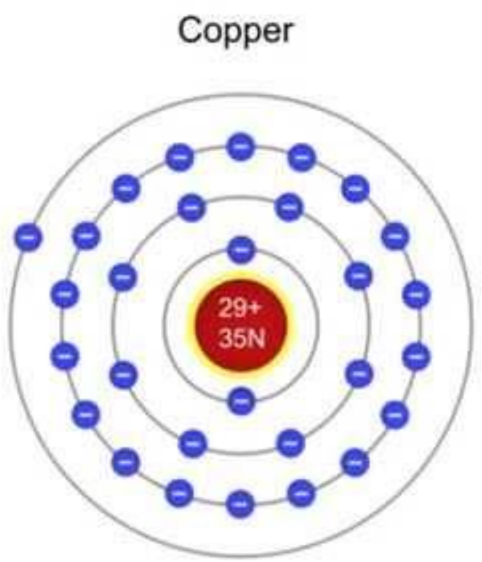
What makes copper a good conductor ?

Lets look at its atomic structure. (atomic no. 29)

Copper has one electron in its valence shell

Easy for it to shed it's outer electron so that the previous shell is complete.

This free electron is used to conduct electricity



IDEAL STATE

In an ideal state every atom will have a full outer (valence) shell

Atoms may give away a few electrons to expose an underlying complete shell.

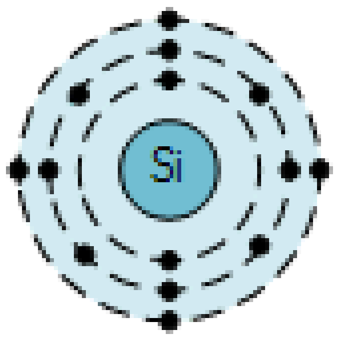
Atoms may accept a few electrons to complete the outer shell.

A simpler solution to this is to share electrons.

SILICON

2 electrons in the 1 – shell
8 electrons in the 2 – shell
4 electrons in the 3 – shell (valence)
14 = Atomic number.

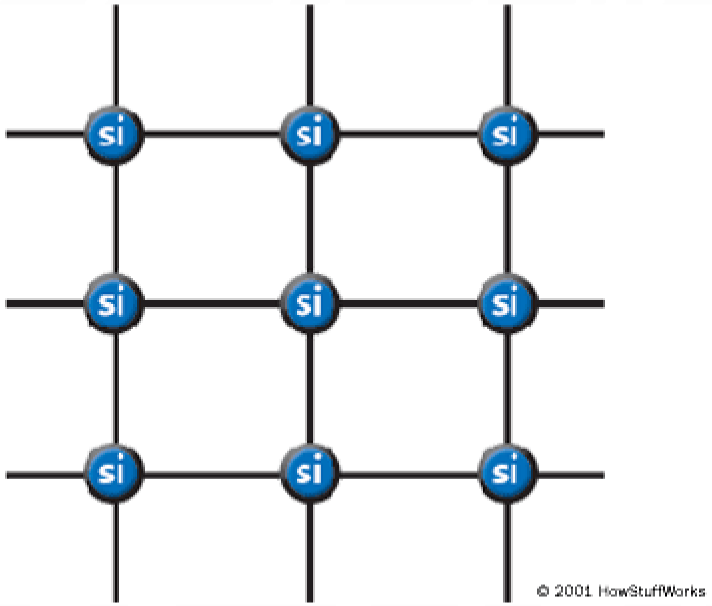
A Silicon Atom,
Atomic number = "14"

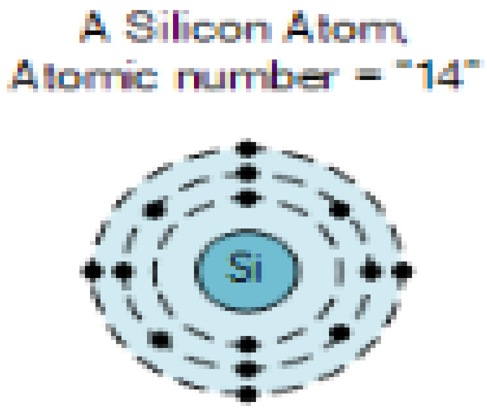


SILICON

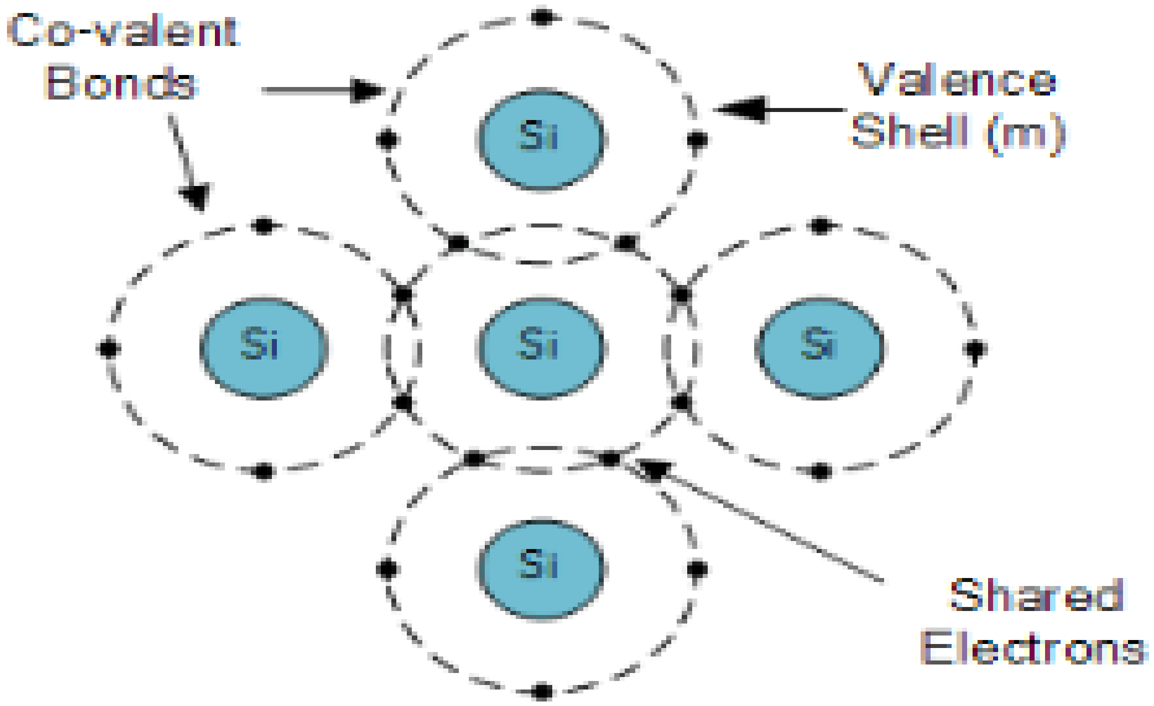
5 Silicon atoms come together to share the single electron in the valence.

Thus each atom now thinks that it has a complete valence shell with 8 electrons





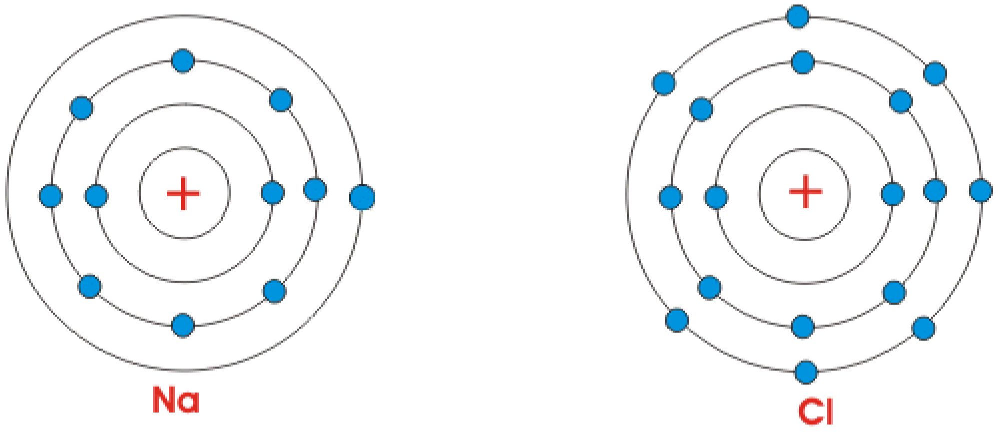
<u>Silicon atom showing 4 electrons in its outer valence shell (m)</u>



<u>Silicon Crystal Lattice</u>

ELECTRON SHARING

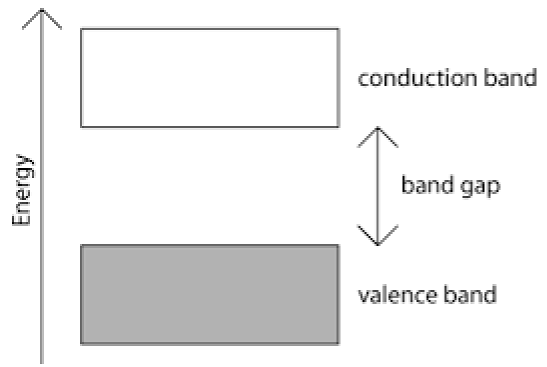
- Let’s have a look at electron sharing with 2 dissimilar elements
- Sodium (Na) is a group 1 element with one electron in its outer shell.
- Chlorine (Cl) is a group 7 element with 7 electrons in it outer shell.



Common Salt (NaCl)

CURRENT IN SEMICONDUCTORS

- In an unexcited (no external energy such as heat) atom, there are no electrons in the conduction band. This condition occurs only at absolute 0 Kelvin



- At room temperature (300k) some valence electrons bridge the gap into the conduction band and become conduction electrons. The vacancy left in the valence band is called a hole
- Recombination occurs when an electron loses energy and falls back into a hole in the valence band

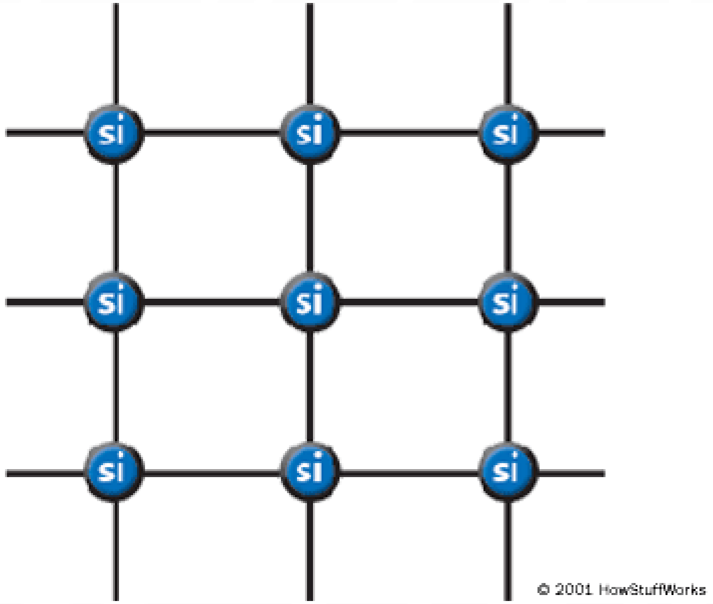
ELECTRON AND HOLE CURRENT

- When a voltage is applied across a piece of intrinsic silicon, the previously generated free electrons in the conduction band are attracted towards the positive end – electron current.

- Hole current moves towards the negative end

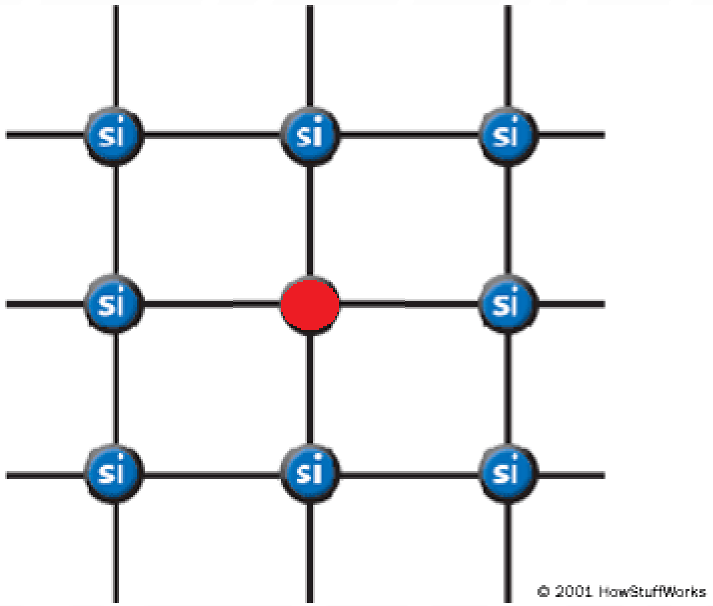
INTRINSIC SEMICONDUCTORS (PURE)

- Intrinsic Semiconductors are made up of all the same atoms i.e Silicon.
- The silicon atom has 4 electrons in the valence shell and it shares with 4 adjoining silicon atoms to fulfil it's outer shells.
- This is known as a **Covalent Bond** and is electrically neutral.



EXTRINSIC SEMICONDUCTORS (IMPURE)

- In order to drastically improve the conductivity of a semiconductor we add impurities to the intrinsic atoms.
- This is called “doping”
- This produces two types of material.
  - N-Type (Negatively charged)
  - P-Type (Positively charged)



N TYPE DOPING

Lets start with a pure Silicon (Si)

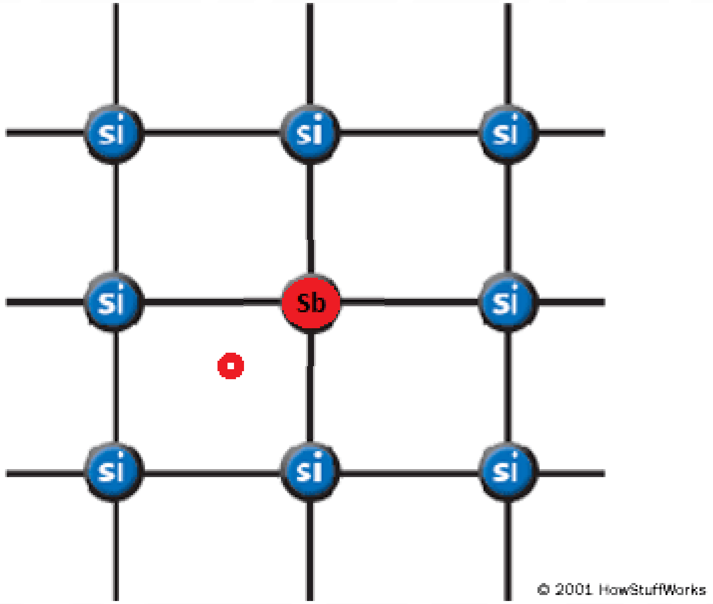
It has 4 electrons in it's Valence shell.

Introduce an Antimony (Sb)

This has 5 electrons in its valence shell.

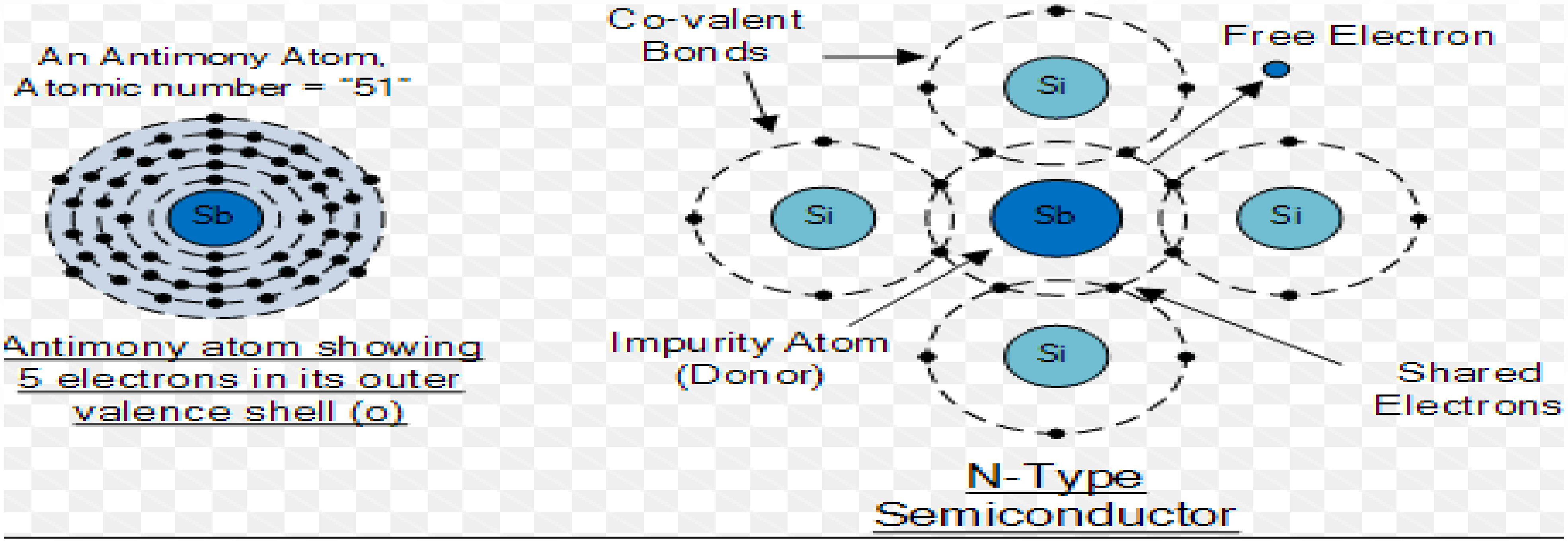
4+5 = 9 electrons in valence shell.

Too many => 1 free electron



N TYPE DOPING

- Antimony (Sb), Arsenic (As), Phosphorous (P) and Bismuth (Bi) are all known as pentavalent impurity atoms i.e. they have 5 valence electrons



P TYPE DOPING

Again let's start with a pure Silicon (Si)

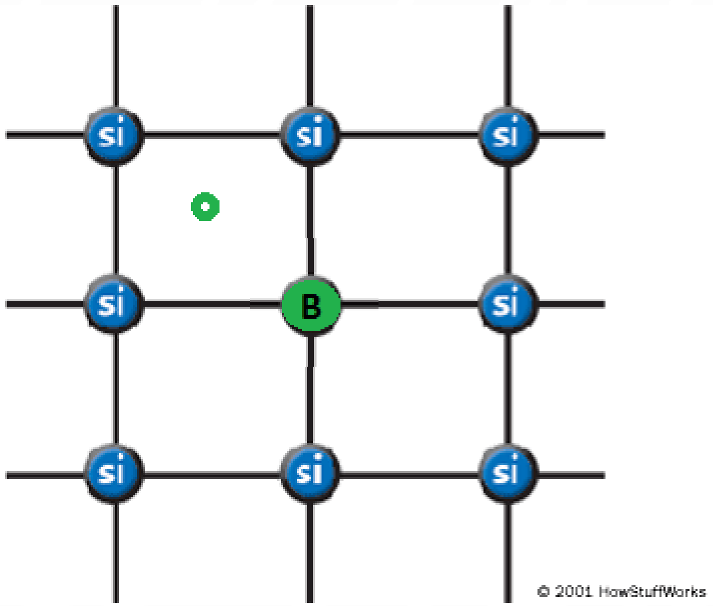
It has 4 electrons in it's valence shell.

Introduce a Boron (B)

This has 3 electrons in its valence shell.

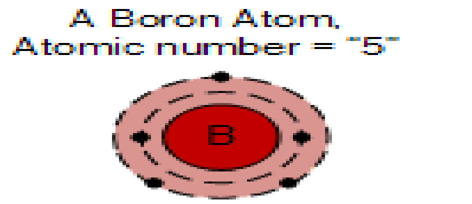
4+3 = 7 electrons in valence shell.

Too little=> 1 missing electron (Hole)

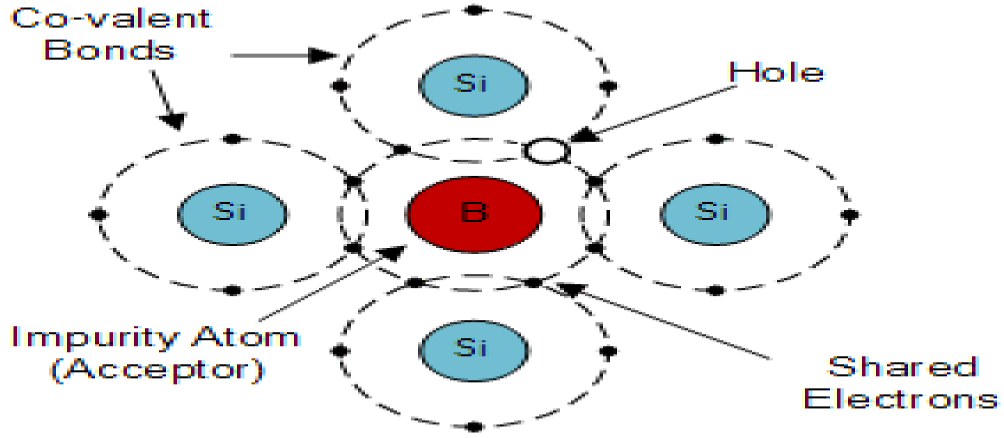


P TYPE DOPING

To increase the number of holes in intrinsic silicon, trivalent impurity atoms are added i.e. atoms with 3 valence electrons such as Boron (B), Indium (In) and Gallium (Ga)



Boron atom showing 3 electrons in its outer valence shell (L)



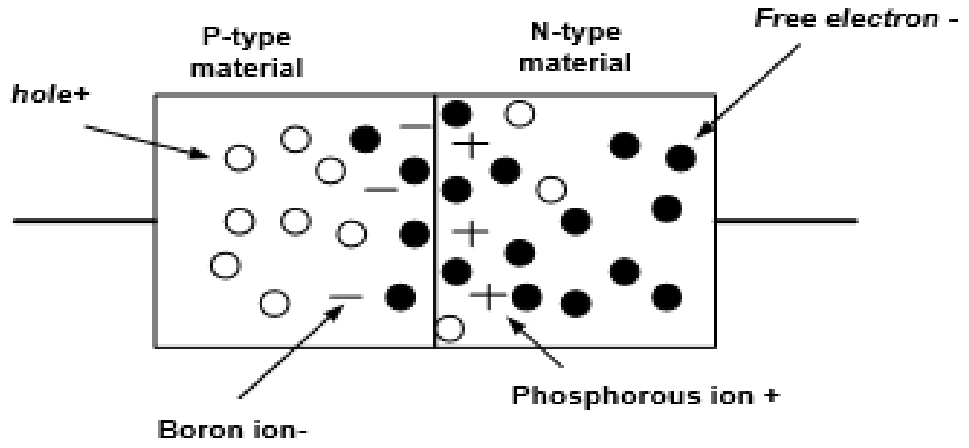
P-Type Semiconductor

PN JUNCTION

- If a piece of intrinsic silicon is doped so that part is n type and the other part is p type, a pn junction is formed at the boundary between the 2 regions and a diode is created.
- The p region has many holes (majority carriers) and only a few free electrons (minority carriers) while the n region has many free electrons (majority carriers) and only a few holes (minority carriers)

PN JUNCTION

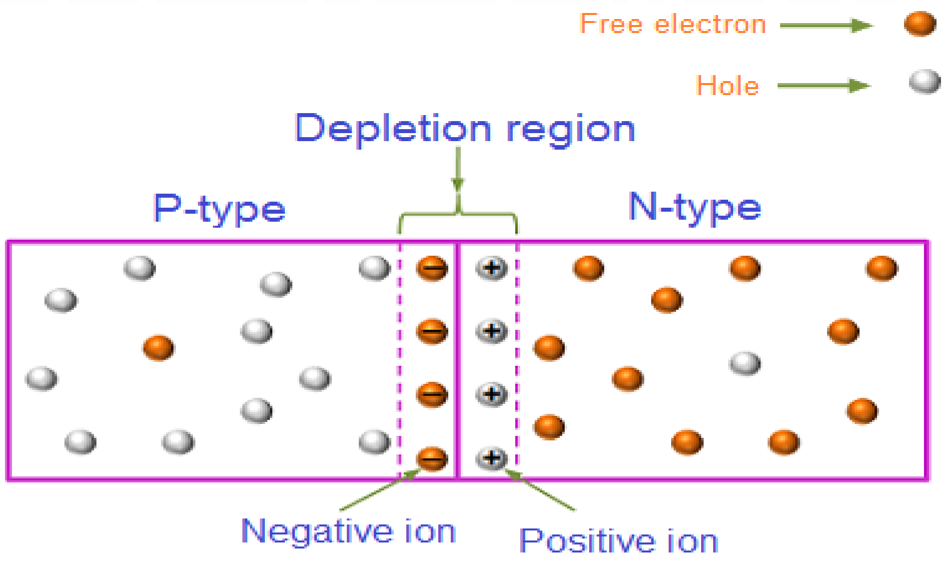
- The free electrons in the n region are randomly drifting in all directions. At the instance of pn junction formation, the electrons near the junction begin to diffuse across and combine with holes near the junctio
- Before the pn junction is formed both sides are neutral in terms of net charge
- The region in the n region which loses free electrons forms a layer of positive charges



- The region in the p region where the holes are recombining with the electrons forms a layer of negative charges
- These 2 layers of charges form the <u>depletion region</u>

PN JUNCTION

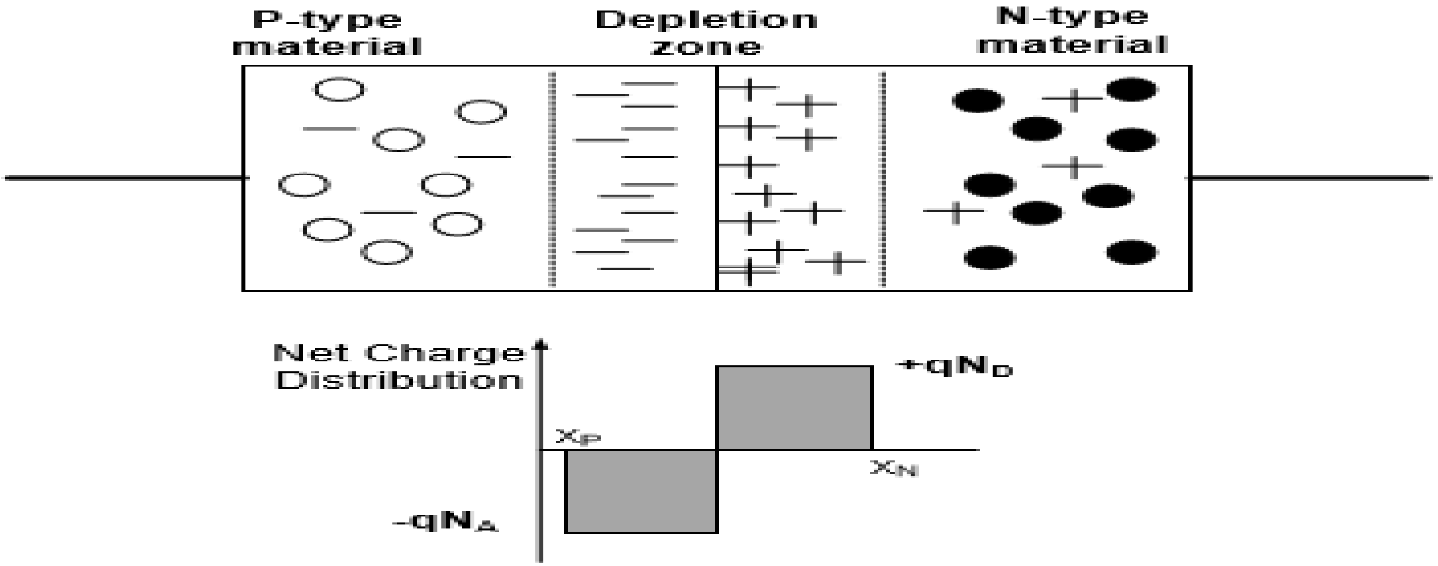
The depletion region is very thin compared to the n and p regions and acts as a barrier to the further movement of electrons



The barrier potential is the potential difference of the electric field across the depletion region and is expressed in volts. A certain amount of voltage equal to the barrier potential (and correct polarity) must be applied across a pn junction before electrons will begin to flow across the junction.

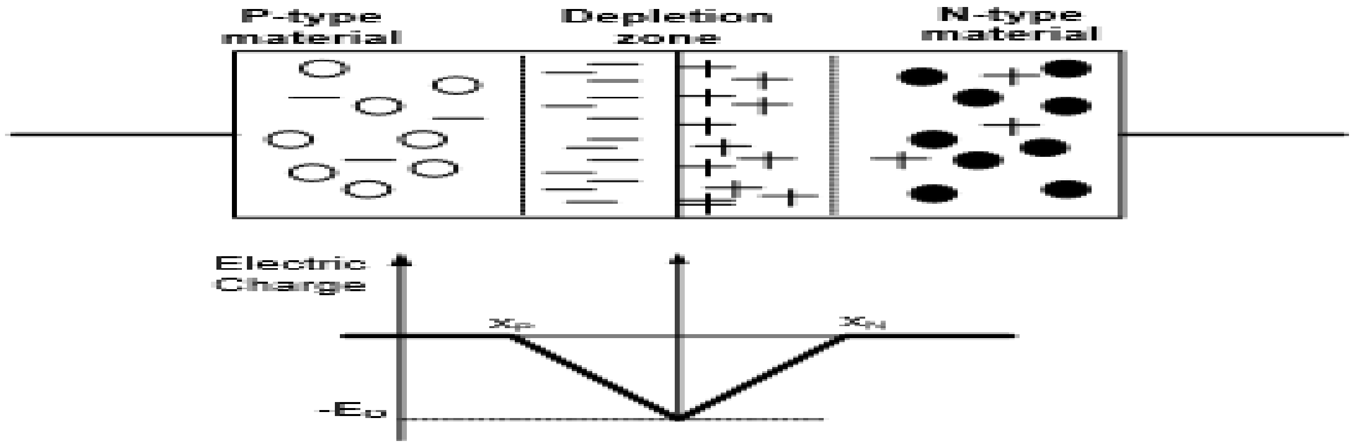
PN JUNCTION

As an electric field now exists across the junction and we can separate the positive and negative charge densities. Fig below shows the charge distribution in the pn junction assuming that the p-type material and the n-type material were doped to similar levels. Note if the doping is equivalent on both sides then $x_P = x_N$.



WIDTH OF THE DEPLETION ZONE

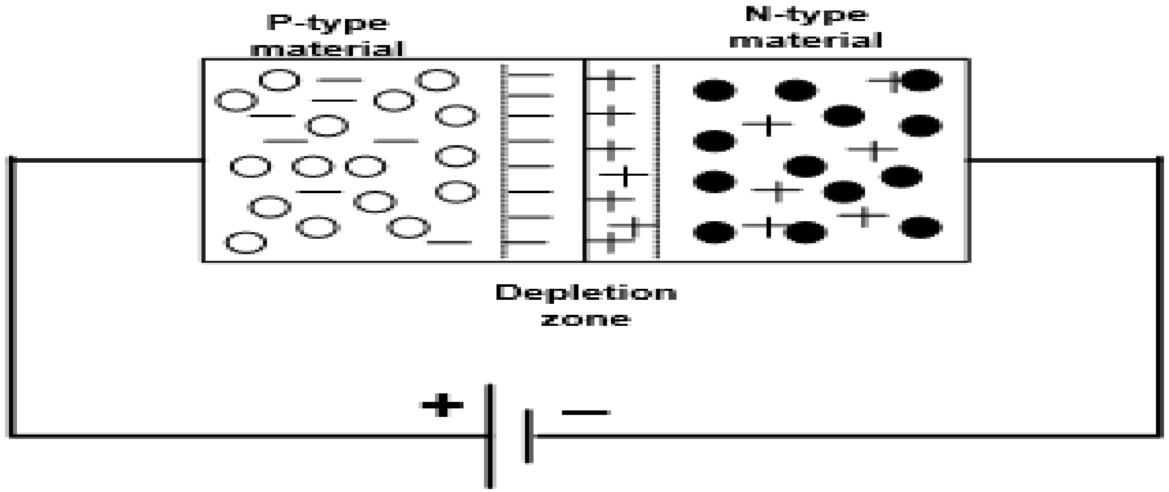
- We can see from the diagram below that the depletion zone extends into the p-type region to a point designated as x_P and extends into the n-type region to a point designated as x_N. Then the total width of the depletion zone is given by $W = x_N + x_P$



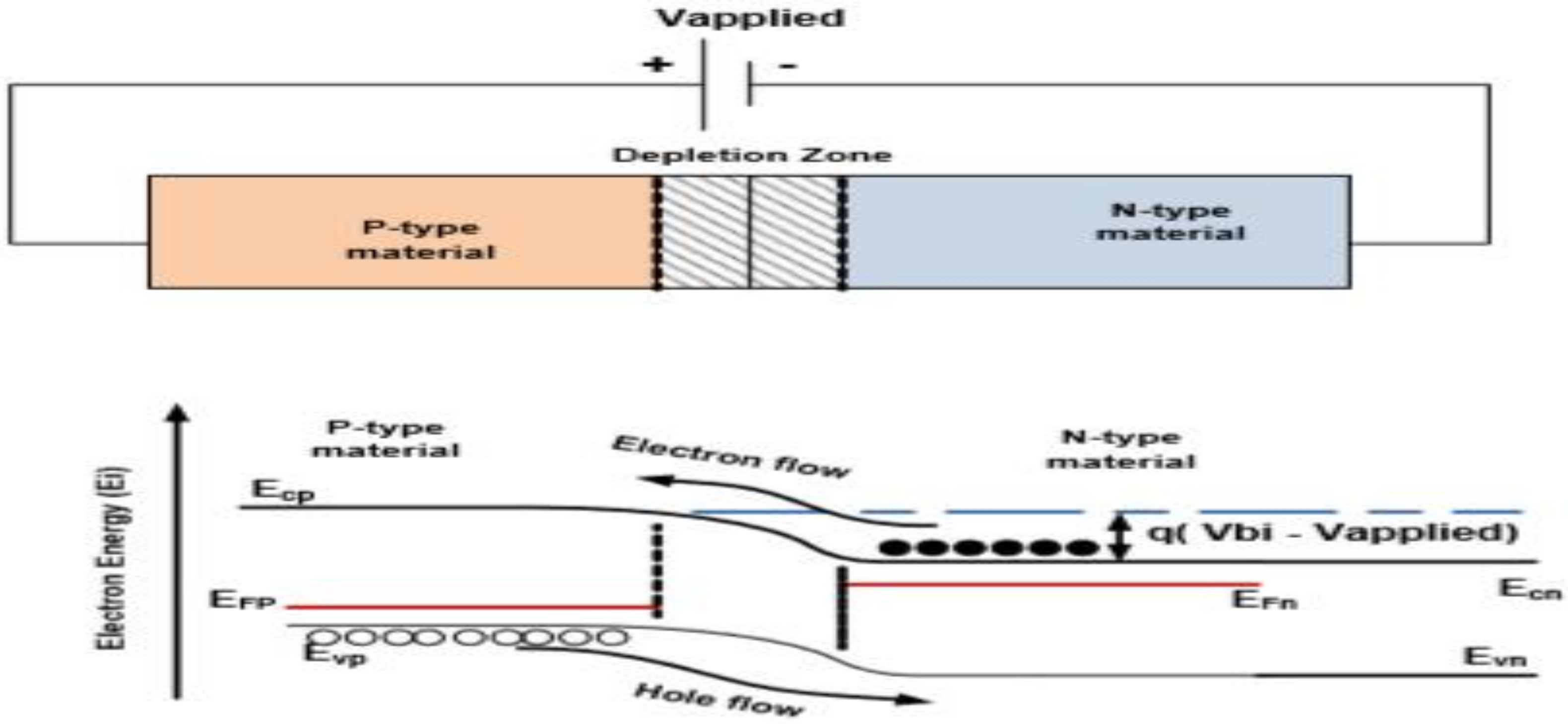
The overall charge in the p-type area of the depletion zone is equal to the number of ionised acceptor atoms (NA) per unit area by the p-type area involved while the charge in the n-type area of the depletion zone is equal to the number of ionised donor atoms (ND)per unit area by the n-type area involved.

FORWARD BIASING THE PN JUNCTION

When a forward bias voltage is applied to a pn junction (diode) , the potential barrier of the pn junction is lowered allowing electrons and holes to flow across the depletion zone. When holes flow from the p-type material across the pn-junction into the n-type material they will then become minority carriers in the n-region. They will also be replenished by the positive terminal of the battery as they diffuse into the n-region. Similarly when electrons flow from the n-type material across the pn-junction into the p-type material they will then become minority carriers in the p-region. They will also be replenished by the negative terminal of the battery connected to the n-type material and a major diffusion of electrons to the p-region takes place



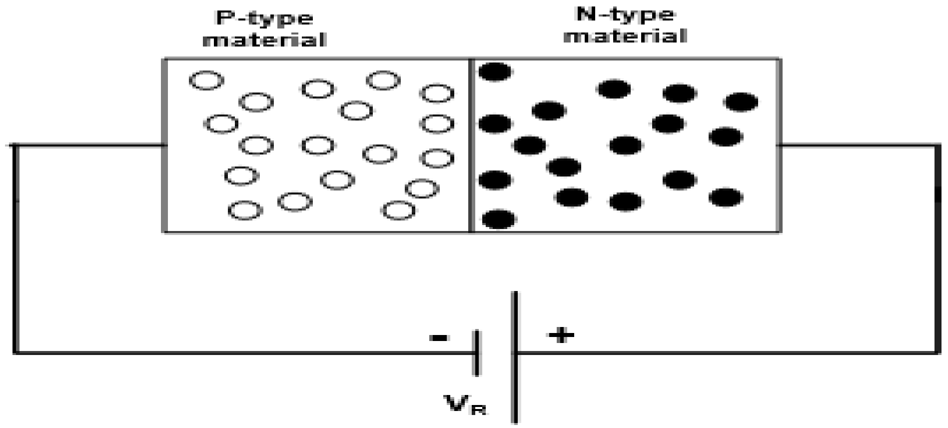
FORWARD BIASED PN JUNCTION



Notice how the potential barrier is much reduced and all the applied voltage is across the junction.

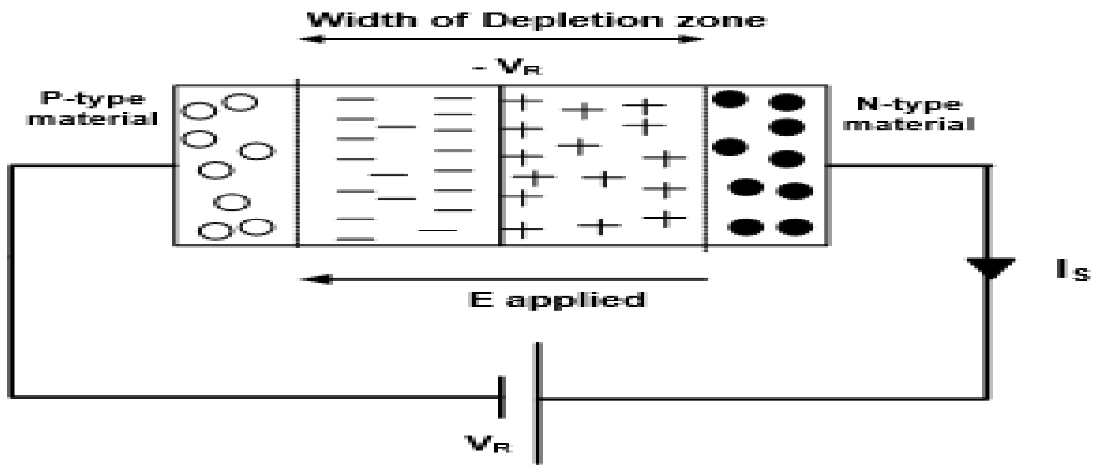
REVERSE BIASING THE PN JUNCTION

Consider the case where a positive voltage is applied to the n-region with respect to the p-region. In this case the diode is considered to have a reverse bias applied.

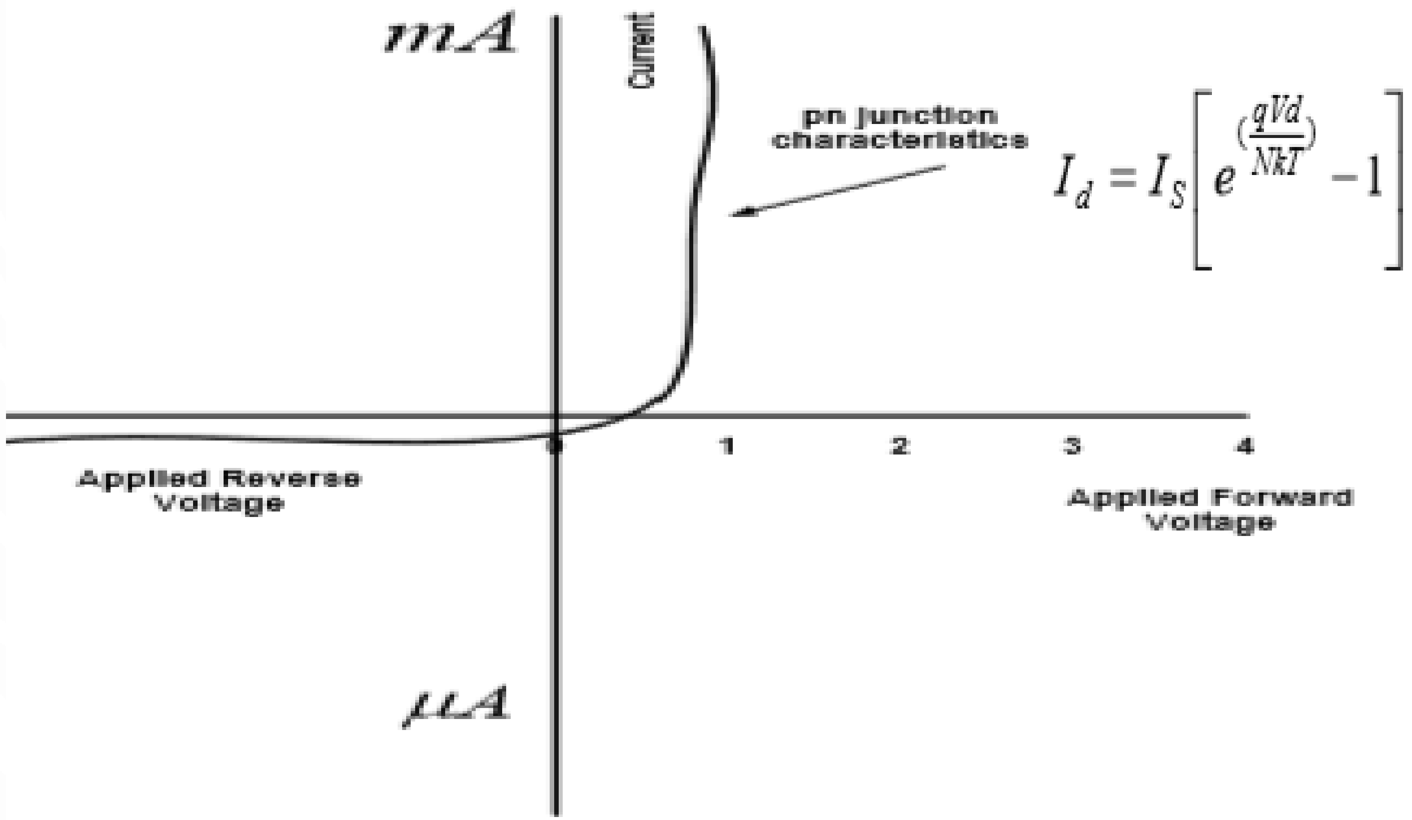


REVERSE BIASING THE PN JUNCTION

The negative potential will cause holes in the p-type material to move away from the junction and towards the contact which will result in more exposed negative Boron acceptor ions and thus creating a wider depletion zone. Similarly the positive potential will cause electrons in the n-type material to move away from the junction and towards the contact which will result in more exposed positive Phosphorous donor ions and thus creating a wider depletion zone on the n side as well



DIODE EQUATION



The pn-junction current-voltage characteristics

PN JUNCTIONS

The p-n junction serves an important role in electronic systems and in the understanding of the behaviour of semiconductor devices. It is used in rectification, switching, photonics, as well as being a building block of the Bipolar Junction Transistor (BJT), the Junction Field Effect Transistor (JFET) and the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) which we will cover in this course!

SOME QUESTIONS FOR YOU

- Q1: What is the difference between an intrinsic and extrinsic semiconductor
- Q2: If I add Phosphorous to a semiconductor what type of doping am I performing? How does it do this?
- Q3: What is meant by the term Band Gap Energy of a semiconductor?
- Q4: What is the valence band ?
- Q5: What is ionisation ?