



## Unit 3 solar energy - unit 3

B.tech (Dr. A.P.J. Abdul Kalam Technical University)

## Introduction to solar energy:

The solar energy is the energy obtained by capturing heat and light from the Sun. The method of obtaining **electricity** from sunlight is referred to as the Photovoltaic method. This is achieved using a semiconductor material.

Solar technology can be broadly classified as –

- **Active Solar** – Active solar techniques include the use of photovoltaic systems, concentrated solar power and solar water heating to harness the energy. Active solar is directly consumed in activities such as drying clothes and warming of air.
- **Passive Solar** – Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air.

## Conversion of Solar Energy

The solar energy is the energy obtained by capturing heat and light from the Sun. The method of obtaining electricity from sunlight is referred to as the Photovoltaic method. This is achieved using a semiconductor material.

The other form of obtaining solar energy is through thermal technologies, which give two forms of energy tapping methods.

- The first is solar concentration, which focuses solar energy to drive thermal turbines.
- The second method is heating and cooling systems used in solar water heating and air conditioning respectively.

The process of converting solar energy into electricity so as to utilize its energy in day-to-day activities is given below –

1. Absorption of energy carrying particles in Sun's rays called photons.
2. Photovoltaic conversion, inside the solar cells.
3. Combination of current from several cells. This step is necessary since a single cell has a voltage of less than 0.5 V.
4. Conversion of the resultant DC to AC.

## Solids:

Depending upon the electrical conductivities the solids are classified in given three types:-

### Conductors:-

The solids which have the conductivity in range  $10^4$  to  $10^7$  ohm $^{-1}$  are called the conductors metals are called the best conductors of electricity

### Insulators:-

The solids which have extremely low conductivities ranging between  $10^{-20}$  to  $10^{-10}$  ohm are called insulators.

▪ **Example:** Plastics, Wood, Rubber etc.

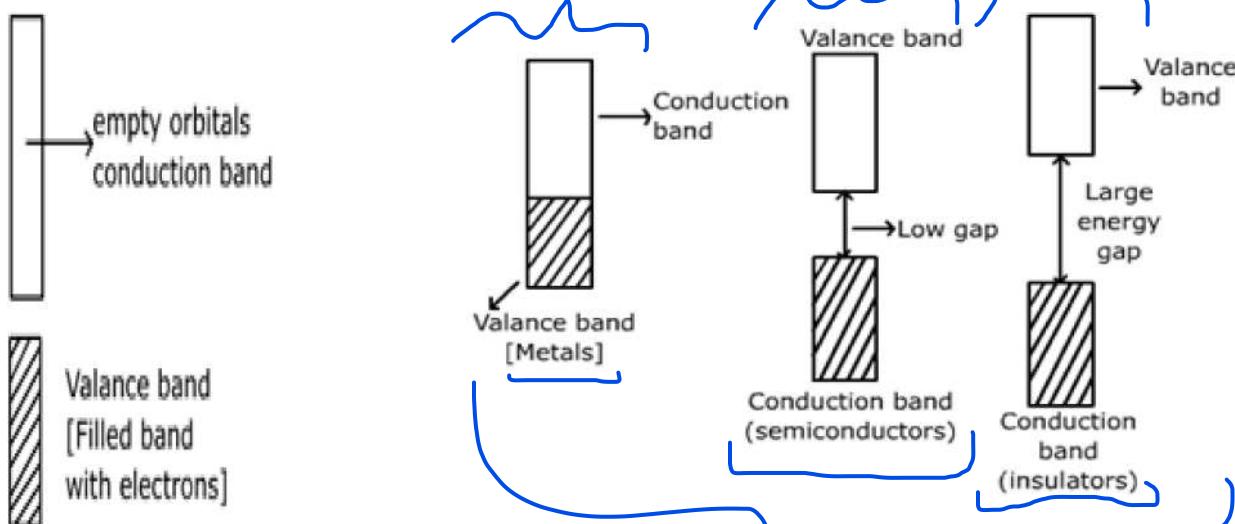
### Semiconductors:-

- The solids which have conductivity in between those of conductors and insulators are called the semiconductors.
- Example: Silicon, Germanium etc.

### BAND THEORY OF METALS:-

Metals conduct electricity with the help of valence electrons present in them.

- In metals orbital of atoms are so closed in energy that they overlap to form a large no. of molecular orbitals very close in energy. Thus set of molecular orbital is called a band.
- For example in case of lithium the lower half of molecular orbital is completely filled with electron while upper half is empty. On applying the electric current electrons can move into vacant levels. Thus electric current flows.
- Thus the band formed by lower energy valence orbital is called valence bond it generally contains electrons.
- And band formed by slightly higher energy orbital is called as the conduction band.



### Explanation of behavior of conductors, insulators and semiconductors on the basis of band theory:-

In case of metals there is no gap or very negligible band gap between the valence band and the conduction band thus electrons can easily move from valence band to conduction band thus electricity is conducted.

**1. In case of metals [conductor]:-** In conductor valance bond is partially filled with electrons and it overlaps with higher energy or unoccupied conduction band thus electrons can easily flow on application of electrical field thus metals have high conductivity.

**2. Insulators:-** In case of insulators the gap between the conduction band and valance band is too much that electron cannot jump from valance band to conduction band. Thus they not exhibit conductivity.

**3. Semiconductors:-** If the gap between valence band and conduction band is small (as in semiconductors) some electrons may jump from valence band to conduction band. Thus substance shows a moderate conductivity.

#### **Effect of temperature on conductivity:-**

1. The electrical conductivity of metals decreases with increase in the temperature or heating.
2. The electrical conductivity of semiconductors increases on heating, due to the fact that more electrons can jump from valence band to conduction band.

**On the basis of purity , semiconductors are of two types:**

(i) **Intrinsic Semiconductors** It is a pure semiconductor without any significant dopant species present  $n_e = n_h = n_i$  There is no doping in intrinsic semiconductors.  
where  $n_e$  and  $n_h$  are number densities of electrons and holes respectively and  $n_i$  is called intrinsic carrier concentration.

An intrinsic semiconductor is also called an undoped semiconductor or i-type semiconductor

(ii) **Extrinsic Semiconductors** Pure semiconductor when doped with the impurity, it is known as extrinsic semiconductor. The semiconductors which are doped with impurities to increase its conductivity.

Extrinsic semiconductors are basically of two types:

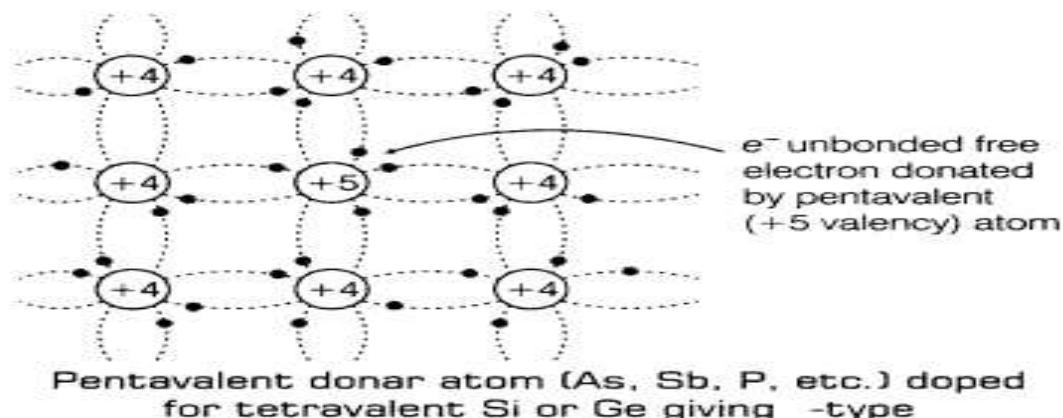
- (a) n-type semiconductors
- (b) p-type semiconductors

**NOTE:** Both the type of semiconductors are electrically neutral.

**In n-type semiconductor,** majority charge carriers are electrons and minority charge carriers are holes, i.e.  $n_e > n_h$ .

Here, we dope Si or Ge with a pentavalent element, then four of its electrons bond with the four silicon neighbours, while fifth remains very weakly bound to its parent atom.

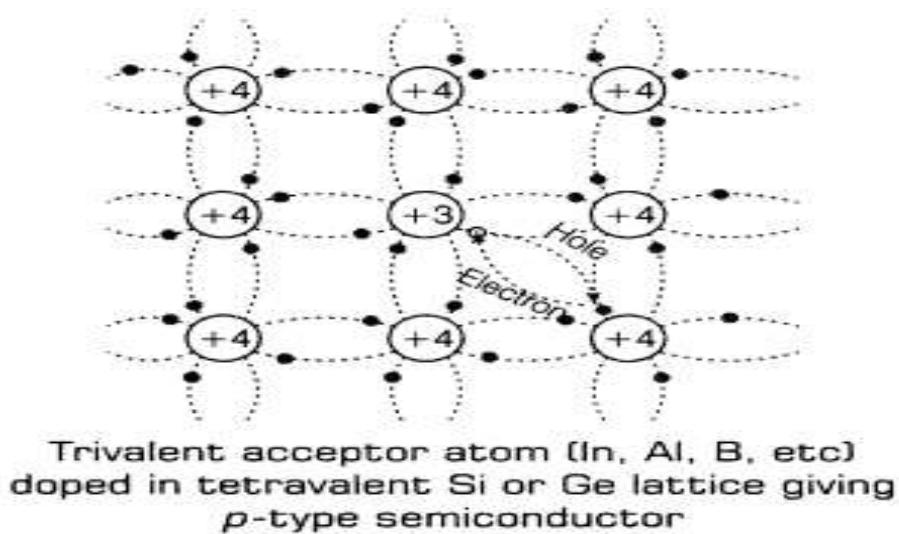
Formation of n-type semiconductor is shown below:



In p-type semiconductor, majority charge carriers are holes and minority charge carriers are electron i.e.  $n_h > n_e$ .

In a p-type semiconductor, doping is done with trivalent impurity atoms, i.e. those atoms which have three valence electrons in their valence shell.

Formation of p-type semiconductor is shown below:



At equilibrium condition,  $n_e n_h = n_i^2$

Minimum energy required to create a hole-electron pair,  $h\nu > E_g$  where,  $E_g$  is energy band gap.

Electric current,  $I = eA(n_e v_e + n_h v_h)$  where, A is area of cross-section.

where,  $v_e$  and  $v_h$  are speed of electron and hole respectively.

doping is the process of adding impurity in a semiconductor in order to increase its electrical conductivity

### P-N Junction diode:

A p-n junction is an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor.

The p-side or the positive side of the semiconductor has an excess of holes and the n-side or the negative side has an excess of electrons. In a semiconductor, the p-n junction is created by the method of doping.

### Formation of P-N Junction

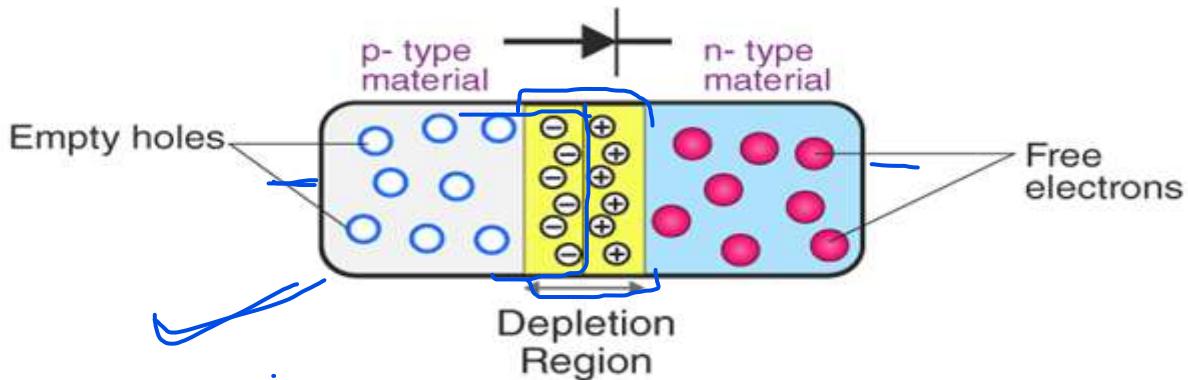
As we know if we use different semiconductor materials to make a p-n junction, there will be a grain boundary that would inhibit the movement of electrons from one side to the other by scattering the electrons and holes and thus we use the process of doping.

We will understand the process of doping with the help of this example. Let us consider a thin p-type silicon semiconductor sheet. If we add a small amount of penta-valent impurity to this, a part of the p-type Si will get converted to n-type silicon. This sheet will now contain both p-type region and n-type region and a junction between these two regions.

The processes that follow after the formation of a p-n junction are of two types – diffusion and drift. As we know, there is a difference in the concentration of holes and electrons at the two sides of a

junction, the holes from the p-side diffuse to the n-side and the electrons from the n-side diffuse to the p-side. These give rise to a diffusion current across the junction.

## ~~UNBIASED P-N JUNCTION~~



Also, when an electron diffuses from the n-side to the p-side, an ionized donor is left behind on the n-side, which is immobile. As the process goes on, a layer of positive charge is developed on the n-side of the junction. Similarly, when a hole goes from the p-side to the n-side, and ionized acceptor is left behind in the p-side, resulting in the formation of a layer of negative charges in the p-side of the junction.

This region of positive charge and negative charge on either side of the junction is termed as the depletion region. Due to this positive space charge region on either side of the junction, an electric field direction from a positive charge towards the negative charge is developed. Due to this electric field, an electron on the p-side of the junction moves to the n-side of the junction. This motion is termed as the drift. Here, we see that the direction of drift current is opposite to that of the diffusion current.

## Biasing conditions for the p-n Junction Diode

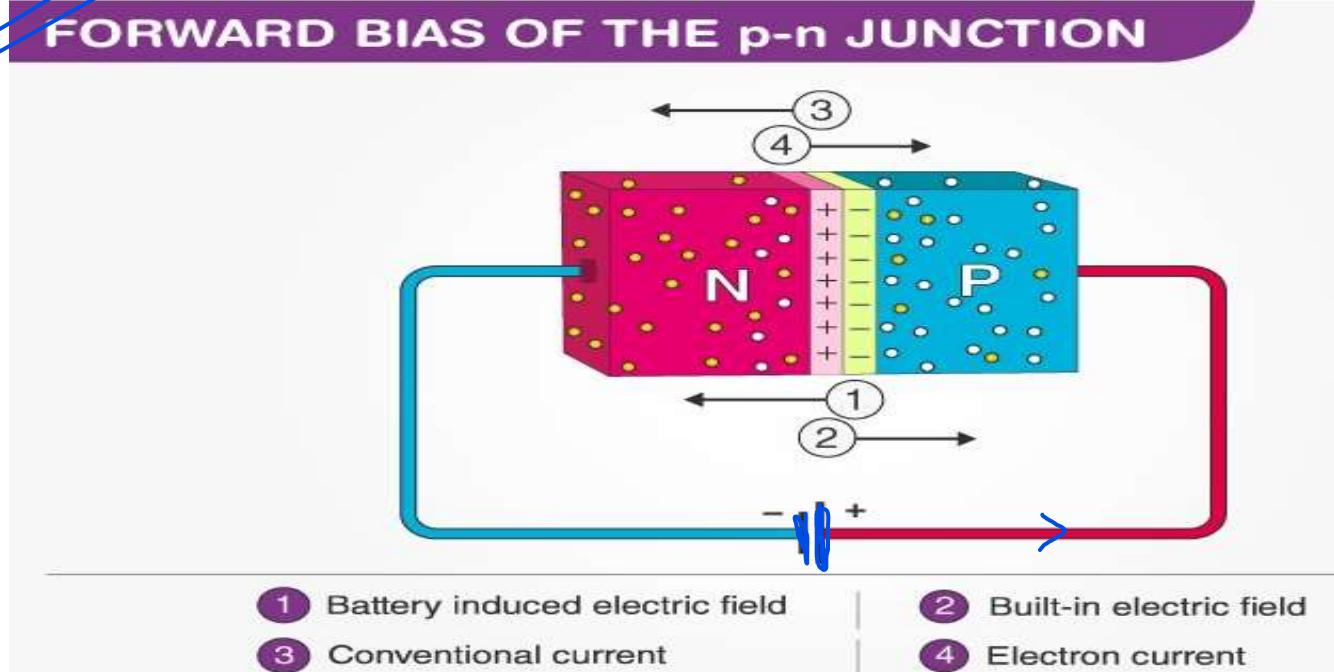
There are two operating regions in the p-n junction diode:

- P-type
- N-type

There are three biasing conditions for p-n junction diode and this is based on the voltage applied:

- **Zero bias:** There is no external voltage applied to the p-n junction diode.
- **Forward bias:** The positive terminal of the voltage potential is connected to the p-type while the negative terminal is connected to the n-type.
- **Reverse bias:** The negative terminal of the voltage potential is connected to the p-type and the positive is connected to the n-type.

## Forward Bias:



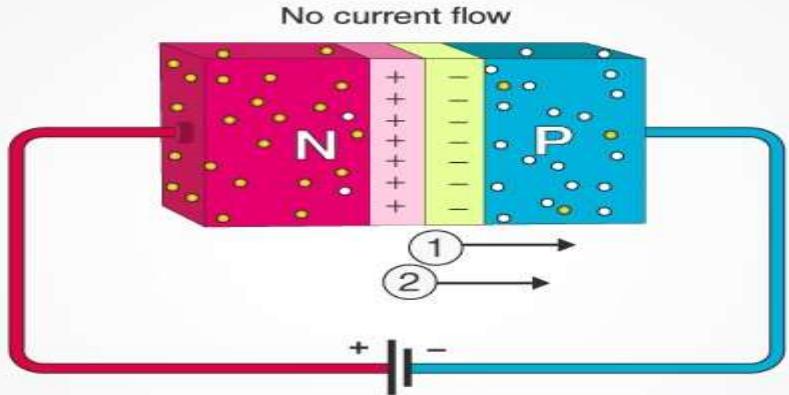
When the p-type is connected to the positive terminal of the battery and the n-type to the negative terminal then the p-n junction is said to be forward-biased. When the p-n junction is forward biased, the built-in electric field at the p-n junction and the applied electric field are in opposite directions. When both the electric fields add up the resultant electric field has a magnitude lesser than the built-in electric field. This results in a less resistive and thinner depletion region. The depletion region's resistance becomes negligible when the applied voltage is large. In silicon, at the voltage of 0.6 V, the resistance of the depletion region becomes completely negligible and the current flows across it unimpeded.

## Reverse Bias:

When the p-type is connected to the negative terminal of the battery and the n-type is connected to the positive side then the p-n junction is said to be reverse biased. In this case, the built-in electric field and the applied electric field are in the same direction.

When the two fields are added, the resultant electric field is in the same direction as the built-in electric field creating a more resistive, thicker depletion region. The depletion region becomes more resistive and thicker if the applied voltage becomes larger.

## REVERSE BIAS OF THE p-n JUNCTION



1 Battery induced electric field | 2 Built-in electric field

### P-N Junction Formula

The formula used in the p-n junction depends upon the built-in potential difference created by the electric field is given as:

$$E_0 = V_T \ln [N_D N_A / n_i^2]$$

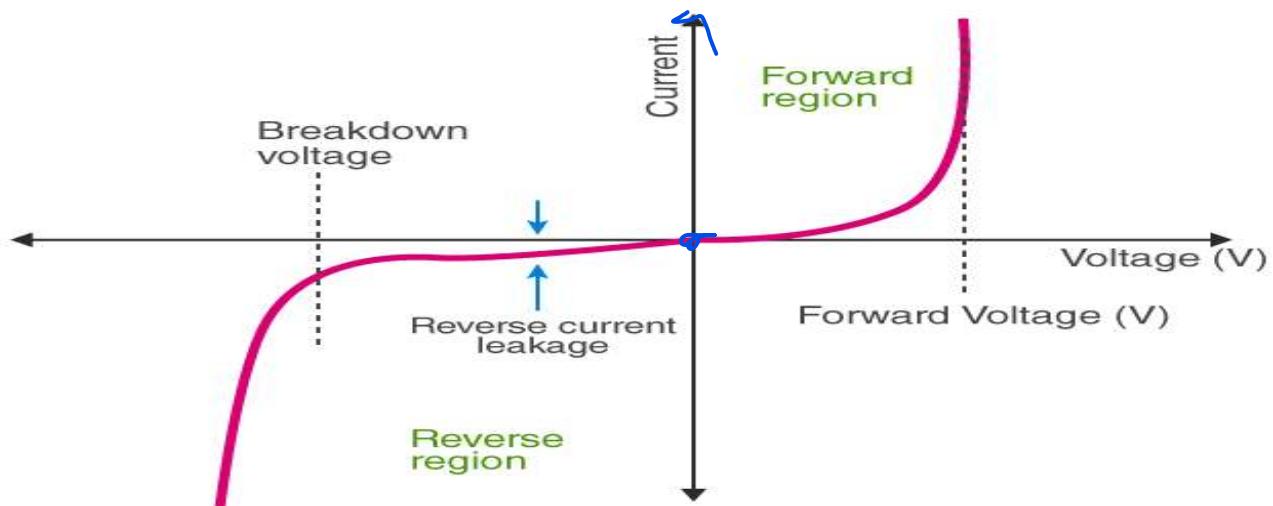
Where,

- $E_0$  is the zero bias junction voltage
- $V_T$  is the thermal voltage of 26mV at room temperature
- $N_D$  and  $N_A$  are the impurity concentrations
- $n_i$  is the intrinsic concentration.

### Current flow in PN junction diode:

The flow of electrons from the n-side towards the p-side of the junction takes place when there is an increase in the voltage. Similarly, the flow of holes from the p-side towards the n-side of the junction takes place along with the increase in the voltage. This results in the concentration gradient between both sides of the terminals. Because of the formation of the concentration gradient, there will be a flow of charge carriers from higher concentration regions to lower concentration regions. The movement of charge carriers inside the pn junction is the reason behind the current flow in the circuit.

## V-I Characteristics of PN Junction Diode:



VI characteristics of PN junction diode is a curve between the voltage and current through the circuit. Voltage is taken along the x-axis while the current is taken along the y-axis. The above graph is the VI characteristics curve of the PN junction diode. With the help of the curve we can understand that there are three regions in which the diode works, and they are:

- Zero bias
- Forward bias
- Reverse bias

When the PN junction diode is under zero bias condition, there is no external voltage applied and this means that the potential barrier at the junction does not allow the flow of current.

When the PN junction diode is under forward bias condition, the p-type is connected to the positive terminal while the n-type is connected to the negative terminal of the external voltage. When the diode is arranged in this manner, there is a reduction in the potential barrier. For silicone diodes, when the voltage is 0.7 V and for germanium diodes, when the voltage is 0.3 V, the potential barriers decreases and there is a flow of current.

When the diode is in forward bias, the current increases slowly and the curve obtained is non-linear as the voltage applied to the diode is overcoming the potential barrier. Once the potential barrier is overcome by the diode, the diode behaves normal and the curve rises sharply as the external voltage increases and the curve so obtained is linear.

When the PN junction diode is under negative bias condition, the p-type is connected to the negative terminal while the n-type is connected to the positive terminal of the external voltage. This results in an increase in the potential barrier. Reverse saturation current flows in the beginning as minority carriers are present in the junction.

When the applied voltage is increased, the minority charges will have increased kinetic energy which affects the majority charges. This is the stage when the diode breaks down. This may also destroy the diode.

## Applications of PN Junction Diode:

- p-n junction diode can be used as a photodiode as the diode is sensitive to the light when the configuration of the diode is reverse-biased.
- It can be used as a solar cell.
- When the diode is forward-biased, it can be used in LED lighting applications.
- It is used as rectifiers in many electric circuits and as a voltage-controlled oscillator in varactors.

## Available Solar Radiation and How It Is Measured:

Before talking about concentration of light for practical purposes, it would be good for us to review what kinds of natural radiation are available to us and how that radiation is characterized and measured.

The fraction of the energy flux emitted by the sun and intercepted by the earth is characterized by the **solar constant**.

The solar constant is defined as essentially the measure of the solar energy flux density perpendicular to the ray direction per unit area per unit time.

It is most precisely measured by satellites outside the earth atmosphere. The solar constant is currently estimated at **1367 W/m<sup>2</sup>**.

This number actually varies by 3% because the orbit of the earth is elliptical, and the distance from the sun varies over the course of the year. Some small variation of the solar constant is also possible due to changes in Sun's luminosity. This measured value includes all types of radiation, a substantial fraction of which is lost as the light passes through the atmosphere.

Solar Constant (Extraterrestrial solar flux intercepted by the Earth) = 1367 W/m<sup>2</sup>

As the solar radiation passes through the atmosphere, it gets absorbed, scattered, reflected, or transmitted. All these processes result in reduction of the energy flux density. Actually, the solar flux density is reduced by about 30% compared to extraterrestrial radiation flux on a sunny day and is reduced by as much as 90% on a cloudy day.

The following main losses should be noted:

- absorbed by particles and molecules in the atmosphere - 10-30%
- reflected and scattered back to space - 2-11%
- scattered to earth (direct radiation becomes diffuse) - 5-26%

As a result, the direct radiation reaching the earth surface (or a device installed on the earth surface) never exceeds 83% of the original extraterrestrial energy flux. This radiation that comes directly from the solar disk is defined as **beam radiation**. The scattered and reflected radiation that is sent to the earth surface from all directions (reflected from other bodies, molecules, particles, droplets,

etc.) is defined as **diffuse radiation**. The sum of the beam and diffuse components is defined as **total (or global) radiation**.

Only beam component of solar radiation can be effectively concentrated

**Short-wave radiation**, in the wavelength range from 0.3 to 3  $\mu\text{m}$ , comes directly from the sun. It includes both beam and diffuse components.

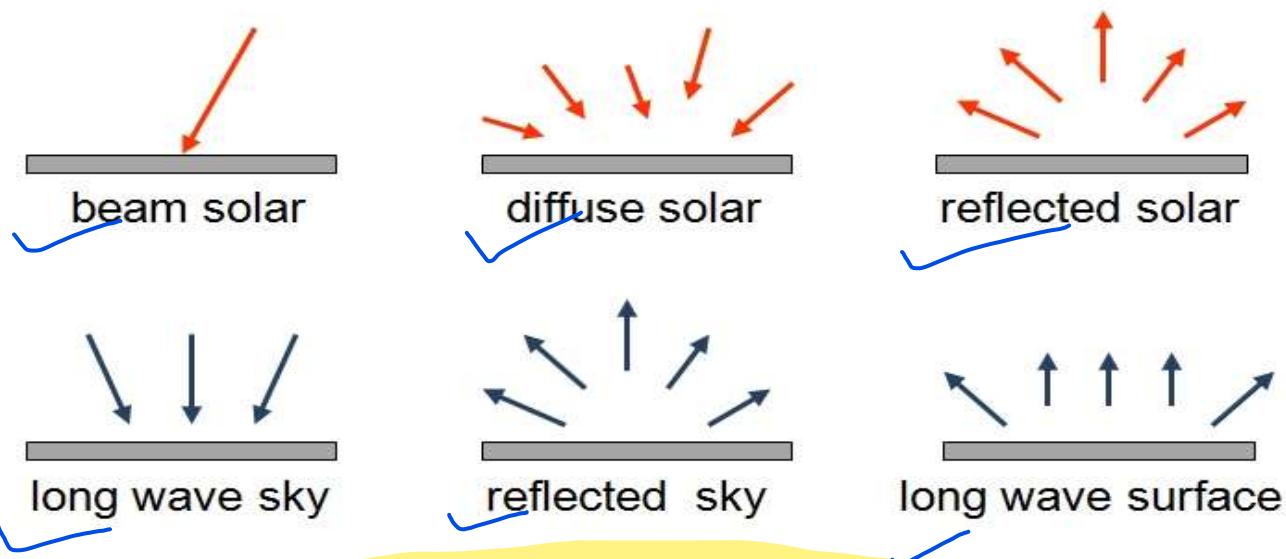
**Long-wave radiation**, with wavelength 3  $\mu\text{m}$  or longer, originates from the sources at near-ambient temperatures - atmosphere, earth surface, light collectors, other bodies.

The solar radiation reaching the earth is highly variable and depends on the state of the atmosphere at a specific locale. Two atmospheric processes can significantly affect the incident irradiation: **scattering** and **absorption**.

Scattering is caused by interaction of the radiation with molecules, water, and dust particles in the air. How much light is scattered depends on the number of particles in the atmosphere, particle size, and the total air mass the radiation comes through.

Absorption occurs upon interaction of the radiation with certain molecules, such as ozone (absorption of short-wave radiation - ultraviolet), water vapor, and carbon dioxide.

Due to these processes, out of the whole spectrum of solar radiation, only a small portion reaches the earth surface. Thus most of x-rays and other short-wave radiation is absorbed by atmospheric components in the ionosphere, ultraviolet is absorbed by ozone, and not-so abundant long-wave radiation is absorbed by CO<sub>2</sub>. As a result, the main wavelength range to be considered for solar applications is from 0.29 to 2.5  $\mu\text{m}$ .



The amount of solar radiation on the earth surface can be instrumentally measured, and precise measurements are important for providing background solar data for solar energy conversion applications.

There are two important types of instruments to measure solar radiation:

1. **Pyrheliometer** is used to measure direct beam radiation at normal incidence. There are different types of pyrheliometers. According to Duffie and Beckman, Abbot silver disc pyrheliometer and Angstrom compensation pyrheliometer are important primary standard instruments. Eppley normal incidence pyrheliometer (NIP) is a common instrument used for practical measurements in the US, and Kipp and Zonen actinometer is widely used in Europe. Both of these instruments are calibrated against the primary standard methods.  
Based on their design, the above listed instruments measure the beam radiation coming from the sun and a small portion of the sky around the sun. Based on the experimental studies involving various pyrheliometer design, the contribution of the circumsolar sky to the beam is relatively negligible on a sunny day with clear skies. However, a hazy sky or a uniform thin cloud cover redistributes the radiation so that contribution of the circumsolar sky to the measurement may become more significant.
2. **Pyranometer** is used to measure total hemispherical radiation - beam plus diffuse - on a horizontal surface. If shaded, a pyranometer measures diffuse radiation. Most of solar resource data come from pyranometers. The total irradiance ( $\text{W/m}^2$ ) measured on a horizontal surface by a pyranometer is expressed as follows:

$$I_{\text{total}} = I_{\text{beam}} \cos\theta + I_{\text{diffuse}}$$

where  $\theta$  is the zenith angle (i.e., angle between the incident ray and the normal to the horizontal instrument plane).

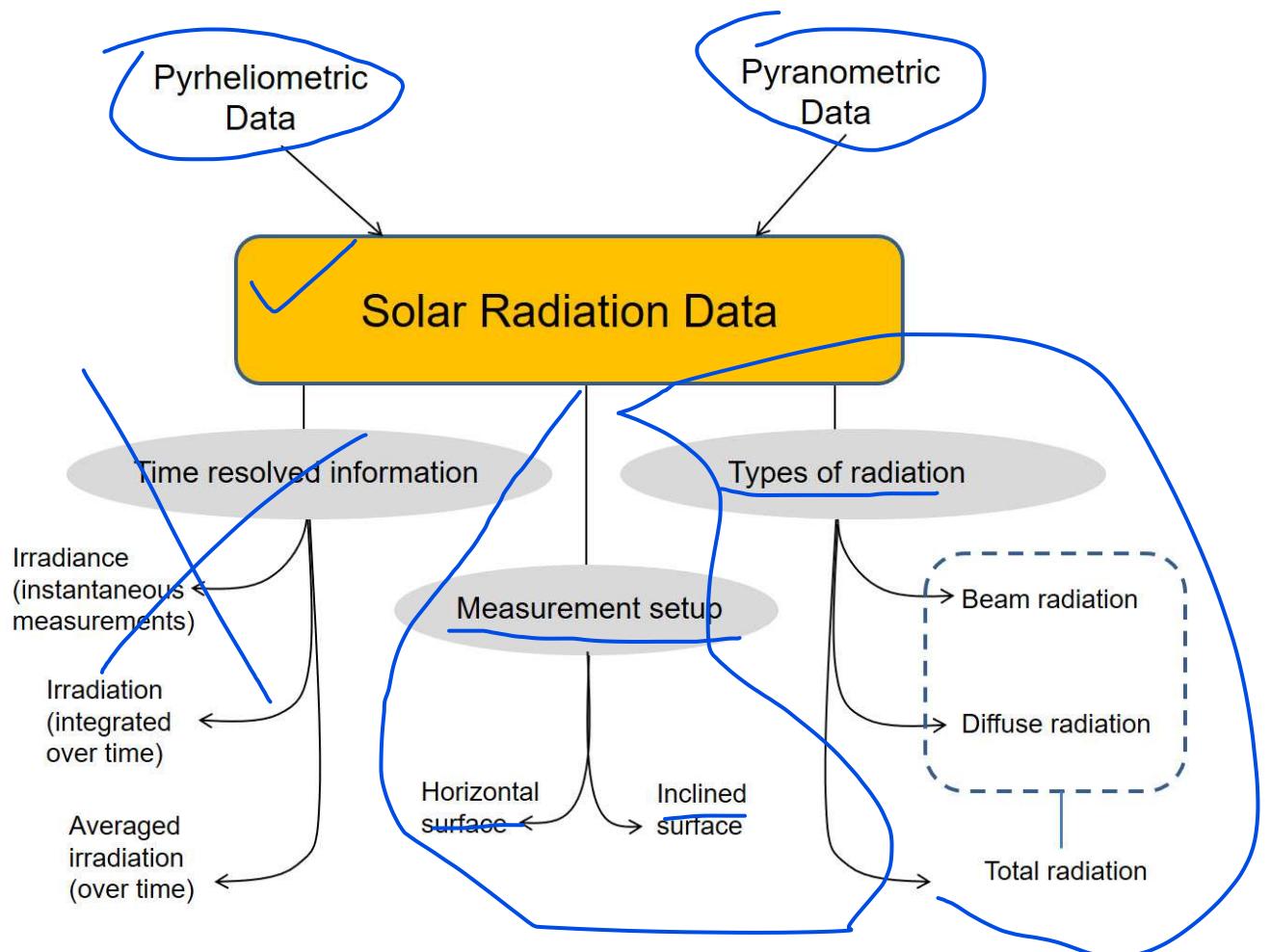
Examples of pyranometers are Eppley 180° or Eppley black-and-white pyranometers in the US and Moll-Gorczyński pyranometer in Europe. These instruments are usually calibrated against standard pyrheliometers.

There are pyranometers with thermocouple detectors and with photovoltaic detectors. The detectors ideally should be independent on the wavelength of the solar spectrum and angle of incidence. Pyranometers are also used to measure solar radiation on inclined surfaces, which is important for estimating input to collectors. Calibration of pyranometers depends on the inclination angle, so experimental data are needed to interpret the measurements.

3. **Photoelectric sunshine recorder.** The natural solar radiation is notoriously intermittent and varying in intensity. The most potent radiation that creates the highest potential for concentration and conversion is the bright sunshine, which has a large beam component. The duration of the bright sunshine at a locale is measured, for example, by a photoelectric sunshine recorder. The device has two selenium photovoltaic cells, one of which is shaded, and the other is exposed to the available solar radiation. When there is no beam radiation, the signal output from both cells is similar, while in bright sunshine, signal difference between the two cells is maximized. This technique can be used to monitor the bright sunshine hours.

More detailed explanation of how these instruments work and what kind of data are obtained from those measurements is available in the following Duffie and Beckman (2013) book referred below. Please spend some time acquiring basic knowledge on solar resource data. For

everyone who took EME 810 and is more or less familiar with this topic, this still may be a useful refresher.



**DIFFERENT GENERATIONS OF SOLAR SELLS:** Solar cells are usually divided into three main categories called generations up to recent years. *The first generation* contains solar cells that are relatively expensive to produce, and have a low efficiency. *The second generation* contains types of solar cells that have an even lower efficiency, but are much cheaper to produce, such that the cost per watt is lower than in first generation cells. The *third generation* is used about cells that are very efficient. Most technologies in this generation are not yet commercial, but there is a lot of research going on in this area. The goal is to make third generation solar cells cheap to produce.

**1st generation's solar cells:** These are the oldest and the mostly common used technology type due to high efficiencies. 1 st generation solar cells are produced on wafers. Each wafer can supply 2-3 watt power.

Generally there are two types of first generation solar cells (a) Single Crystal Solar Cells (b) Multi Crystal Solar Cells.

They differ by their crystallization levels. If the whole wafer is only one crystal, it is called single crystal solar cell. If wafer consist of crystal grains, it is called multi crystal solar cell. Anyone can see the boundaries between grains on the solar cell.

The efficiency of mono crystal solar cells is higher than multi crystal solar cells, production of multi crystal wafer is easier and cheaper. So they are competitive with mono crystals.

**2nd generation's solar cells:** These are (a) a-Si thin film solar cells (b) mc-Si solar cells (c) CdTe solar cells (d) CIS and CIGS solar cells.

Their efficiencies are less than 1st generation, their costs are also less than 1st generation. In addition they have an advantage in visual aesthetic. Since there are no fingers in front of the thin film solar cells for metallization, they are much more applicable on windows, cars, building integrations etc.

These thin films can also be grown on flexible substrates. As an advantage of thin film solar cells, they can be growth on large areas up to  $6\text{ m}^2$ . However wafer based solar cell can be only produced on wafer dimensions. The second generation solar cells include amorphous Si (a-Si) based thin films solar cells, Cadmium Telluride/Cadmium Sulfide (CdTe/CdS) solar cells and Copper Indium Gallium Selenide (CIGS) solar cells.

**3rd Generation solar cells:** These are (a) Nano-crystal based solar cells (b) Polymer based solar cells (c) Dye sensitized solar cells (d) concentrated solar cells.

These are the novel technologies which are promising but not commercially proven yet. Most developed 3rd generation solar cell types are dye sensitized and concentrated solar cell. Dye sensitized solar cells (DSSC) are based on dye molecules between electrodes. Electron hole pairs occur in dye molecules and transported through  $\text{TiO}_2$  nano-particles.

Their efficiency is very low, their cost is also very low. Their production is easy with respect to other technologies.

Dye sensitized solar cells can have variable colors. Concentrated PV solar cell is another promising technology. Main principle of concentrated cells is to concentrate large amount of solar radiation on to a small region where the PV cell is located. The amount of semiconductor material, which might be very expensive, is reduced in this way. In this system a perfect optical system should be integrated. Concentration levels starts from 10 sun to thousands suns. So, total cost can be lower than conventional systems. CPVs are promising technologies for near future.

**EFFICIENCY** - 1 st generation solar cells lab based efficiency was 24.7% and module based 22.7%. 2nd generation solar cells lab based efficiency 18.4% and module based 13.4%. 3rd generation solar cells has very high efficiency >30%.

#### Best efficiencies reported for different types of solar cells

Solar cell type	Efficiency	Laboratory/Institution
Crystalline Si	24.7	University of New south Wales
Multi Crystalline Si	20.3	Fraunhofer institute of solar energy system
Amorphous Si	10.1	Kaneka
HIT cell	23	Sanyo Corporation
GaAs cell	26.1	Radboud University Nijmegen
InP Cell	21.9	Spire Corporation
Multi junction cell	40.8	National Renewable Energy Laboratory
CdTe	16.5	National Renewable Energy Laboratory
CIGS	19.9	National Renewable Energy Laboratory
CuInS <sub>2</sub>	12.5	Hahn Meitner Institute
DSSC	11.1	Sharp
Organic solar cell	6.1	Gwangju Institute of Science and Technology

## LIMITATIONS OF DIFFERENT GENERATION'S SOLAR CELLS

For renewable energies, like solar energy, to compete with fossil fuels, there are two challenges to be met: (a) increase efficiencies (b) reduce production costs

Generally 1st generations solar cell based on Silicon (Si) solar cell. Though this technology has high conversion efficiency but the availability of Silicon is intricate because of its high cost. Also the fabrication process of the silicon based solar cell is complex. Several issues affect the efficiency of solar cells:

- ❖ The energy of the photons hitting the solar cell is less than the band gap, so the light cannot be converted into electricity and is lost.
- ❖ The energy of the incoming photons is greater than the band gap, so the excess energy is lost as heat.
- ❖ The Fermi levels of both n-type and p-type silicon are always inside the band gap of silicon so the open-circuit voltage is smaller than the band gap.

2<sup>nd</sup> generation solar cells based on thin film solar cells. Some advantages are illustrated below.

- ❖ It has high absorption co-efficient
- ❖ It can occupy both vacuum and non-vacuum process.
- ❖ Lower cost in comparison of Si based solar cell. Low cost substrate (Cu tape)

Disadvantages are:

- ❖ Environment Contamination starts from fabrication process.
- ❖ Materials are hard to find.

3rd generation solar cells (polymer) advantages are:

- ❖ Raw materials are easy to find
- ❖ Easier fabrication process rather than other two technology
- ❖ Cost is minimal

Disadvantages of 3rd generation solar cells (organic):

- ❖ Liquid electrolyte (low temperature)
- ❖ High cost, Ru (dye) and Pt (electrode)