Solar PV Systems :المـادة   المرحلة الثالثة

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Lecture 1: Properties of sunlight and solar irradiation

❖ **The Sun**: The sun is a hot sphere of gas whose internal temperatures reach over 20 million degree Kelvin.
Nuclear fusion reaction at the sun's core converts hydrogen to helium. A nuclear fusion releases a tremendous amount of thermal energy according to Einstein's formula:

$$E = mc^2$$

The radiation from the inner core is not visible since it is absorbed by a layer of hydrogen atoms closer to the sun's surface.
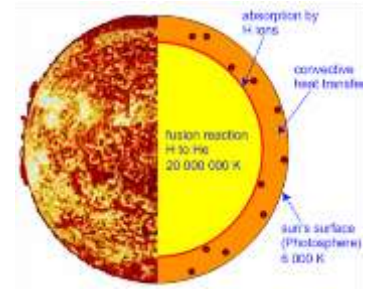
❖ Solar Radiation outside the Atmosphere

The spectrum of the radiation emitted by the sun is close to that of a black body at a temperature of 5.900 K.

8% of the energy is in the ultra-violet region,

44% is in the visible region, and

48% is in the infra-red region.

The spectral irradiance (E_λ): The blackbody sources which are of interest to photovoltaics emit light in the visible region. The spectral irradiance from a blackbody is given by Planck's1 radiation law, shown in the following equation:

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)}$$

- E: spectral irradiance (W/m^2/unit wavelength in m)
- h: Plank's constant = $6.63 \times 10^{-34} \, Ws^2$
- c: speed of light = $3 \times 10^8 \, m/s$
- T: temperature of black body (K)
- K: Boltzmann's constant = $1.38 \times 10^{-23} \, J/K$

❖ Stefan-Boltzmann law:

When E_λ is integrated over all possible values from zero to infinity, the result is the *irradiance* or the power per area.
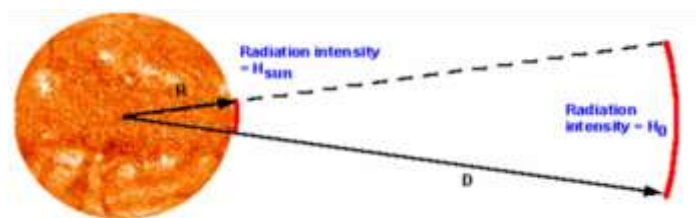
$$H = \int_0^\infty E_\lambda \, d\lambda = \frac{2\pi^5 K^4}{15h^3 c^2} T^4 = \sigma T^4$$

$$\sigma = \frac{2\pi^5 K^4}{15h^3 c^2} = 5.67 \times 10^{-8} \, W/m^2 K^4$$

σ *is called Stefan's constant*. So

$$H = \sigma T^4$$

Is *Stefan-Boltzmann law*. This is the irradiance per unit area.

❖ Solar radiation in space

• The energy radiated on an object in space decreases as the object moves further away from the sun.
• The energy density on an object some distance D from the sun is found by
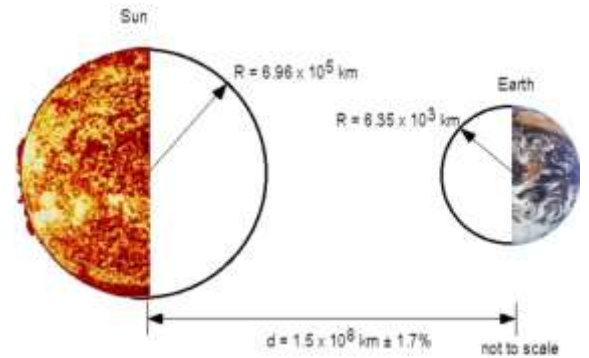
$$H_0 = \left(\frac{R}{D}\right)^2 H_{sun}$$

where:

$H_{sun} = 64 \times 10^6 \, W/m^2$ is the power density at the sun's surface
as determined by Stefan Boltzmann's blackbody equation;
$R = 695 \times 10^6 \, m$
is the radius of the sun in meters as shown in the figure below; and
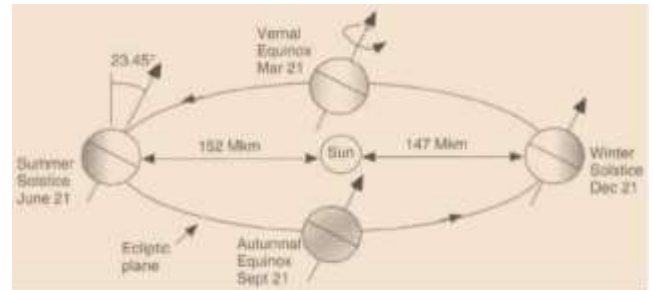D is the distance from the sun in meters as shown in the figure

Earth's orbit

• The earth revolves around the sun in an elliptical orbit once per year. The variation in distance between the sun and earth is given by

$$D = 150 \times 10^6 \left\{1 + 0.017sin\left[\frac{360(n-93)}{365}\right]\right\} km$$

• The maximum distance (152×10^6) occurs at summer solstice, and the minimum distance (147×10^6) occurs at winter solstice.

The actual power density varies slightly since the Earth-Sun distance changes as the Earth moves in its elliptical orbit around the sun, and because the sun's emitted power is not constant.
An equation which describes the variation throughout the year just outside the earth's atmosphere is:

$$\frac{H}{H_{constant}} = 1 + 0.033cos\left(\frac{360(n-2)}{365}\right)$$

where:

H is the radiant power density outside the Earth's atmosphere (in W/m^2);
$H_{constant}$ is the value of the solar constant, $1.353 \, kW/m^2$; and
n is the day of the year.

❖ Effect of Atmosphere on Sunlight

Atmospheric effects have several impacts on the solar radiation at the Earth's surface. The major effects for photovoltaic applications are:

- a reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere;
- a change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- the introduction of a diffuse or indirect component into the solar radiation; and

- local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality.

These effects are summarized in the figure below.
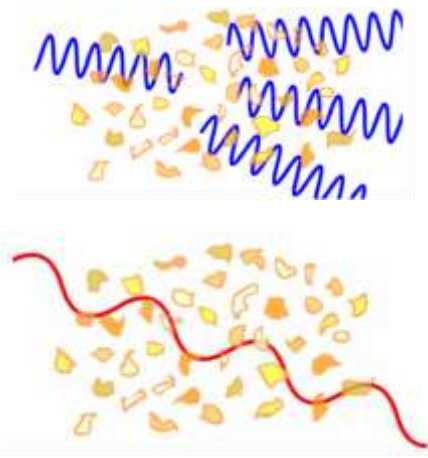
Blue light has a wavelength similar to the size of particles in the atmosphere – thus scattered.

Red light has a wavelength larger than most particles – thus unaffected
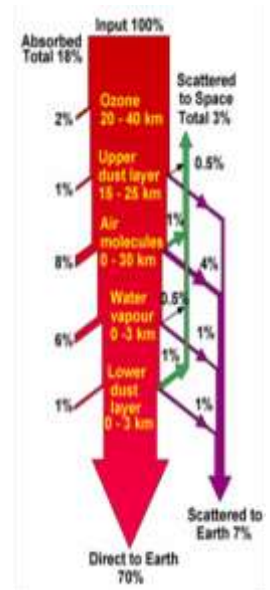
❖ Absorption in the Atmosphere

As solar radiation passes through the atmosphere, gasses, dust and aerosols absorb the incident photons. Specific gasses, notably ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O), have very high absorption of photons that have energies close to the bond energies of these atmospheric gases. This absorption yields deep troughs in the spectral radiation curve. For example, much of the far infrared light above 2 µm is absorbed by water vapor and carbon dioxide. Similarly, most of the ultraviolet light below 0.3 µm is absorbed by ozone (but not enough to completely prevent sunburn!).

While the absorption by specific gasses in the atmosphere change the spectral content of the terrestrial solar radiation, they have a relatively minor impact on the overall power. Instead, the major factor reducing the power from solar radiation is the absorption and scattering of light due to air molecules and dust. This absorption process does not produce the deep troughs in the spectral irradiance, but rather causes a power reduction dependent on the path length through the atmosphere. When the sun is overhead, the absorption due to these atmospheric elements causes a relatively uniform reduction across the visible spectrum, so the incident light appears white. However, for longer path lengths, higher energy (lower wavelength) light is more effectively absorbed and scattered. Hence in the morning and evening the sun appears much redder and has a lower intensity than in the middle of the day.

❖ Direct and Diffuse Radiation Due to Scattering of Incident Light

Light is absorbed as it passes through the atmosphere and at the same time it is subject to scattering. One of the mechanisms for light scattering in the atmosphere is known as Rayleigh scattering which is caused by molecules in the atmosphere. Rayleigh scattering is particularly effective for short wavelength light (that is blue light) since it has a λ-4 dependence. In addition to Rayleigh scattering, aerosols and dust particles contribute to the scattering of incident light known as Mie scattering.

Scattered light is undirected, and so it appears to be coming from any region of the sky. This light is called "diffuse" light. Since diffuse light is primarily "blue" light, the light that comes from regions of the sky other than where the sun is, appears blue. In the absence of scattering in the atmosphere, the sky would appear black, and the sun would appear as a disk light source. On a clear day, about 10% of the total incident solar radiation is diffuse.

Solar Radiation Spectrum
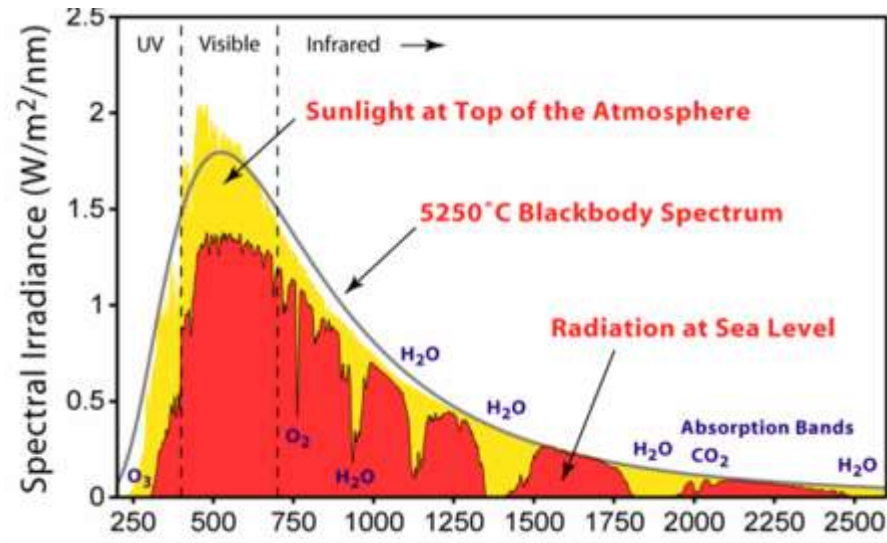
❖ Air Mass

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

$$AM = \frac{1}{cos\theta} = \frac{Y}{X}$$

Where θ is the angle from the vertical (zenith angle). When the sun is directly overhead, the Air Mass is 1. An easy method to determine the AM is from the shadow s of a vertical object. Air mass is the length of the hypotenuse k divided by the object height h:

$$AM = \frac{\sqrt{s^2 + h^2}}{h} = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$
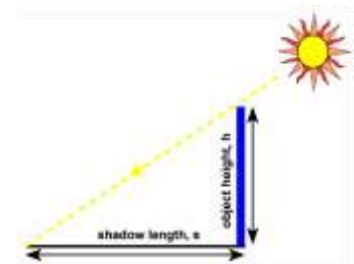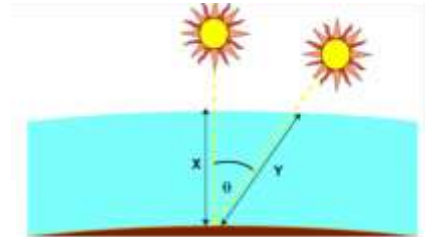
- By definition, the sea-level AM at the zenith is 1 (denoted AM1).
– AM increases as the angle between the sunbeam and the zenith increases, reaching a value of approximately 38 at the horizon.
– AM can be less than one at an elevation greater than sea level;
– The region above Earth's atmosphere, where there is no atmospheric attenuation of solar radiation, is considered to have "air mass zero" (AM0).
– Global solar radiation at AM0 is 1,367 W/m^2, and nearly 1000 W/m^2 at AM1 (i.e., about 70% of that corresponding to AM0)
– Note that AM0 and AM1 have different spectral content.

❖ Intensity Calculations Based on the Air Mass

The intensity of the direct component of sunlight throughout each day can be determined as a function of air mass from the experimentally determined equation

$$I_D = 1.353 \times (0.7)^{AM^{0.678}}$$

where I_D is the intensity on a plane perpendicular to the sun's rays in units of kW/m^2 and AM is the air mass.

- ❑ The value of 1.353 kW/m^2 is the solar constant and
- ❑ the number 0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth.
- ❑ The extra power term of 0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers.
- ❑ AM1.5 is chosen as the standard calibration spectrum for PV Cells.

Even on a clear day, the diffuse radiation is still about 10% of the direct component. Thus on a clear day the global irradiance I_G on a module perpendicular to the sun's rays is:

$$I_G = 1.1 \times I_D$$

Example: What is the direct and global irradiation intensity on a body at AM1.5 ?
Solution: Using

$$I_D = 1.353 \times (0.7)^{AM^{0.678}}$$

1. $1.5^{0678} = 1.316$
2. $0.7^{1.316} = 0.625$
3. $\therefore I_D = 1.353 \times 0.625 = 0.864 \; kW/m^2$
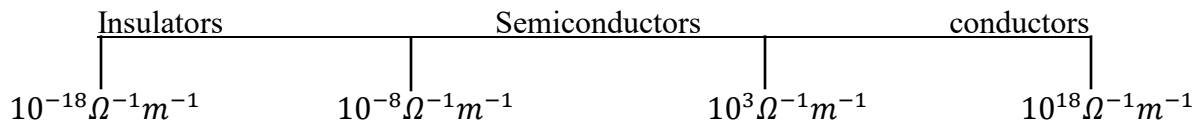4. $\therefore I_G = 1.1 \times 0.846 = 0.930$

   ➤ Some Facts
   • The hours of sunlight over a year are the same for every point on the earth (provided only the hours between sunrise and sunset are counted)
   • Why are the earth's poles cold? Because sunlight reaching these areas carries less energy, since it must pass through a greater air mass.

➤ **Irradiance and Irradiation**

• Irradiance: power density of sunlight (W/m^2). Often referred to as intensity of sunlight.
• Irradiation is a measure of energy density of sunlight (kW/m^2). It is the integral of irradiance over a period of time (usually 1 day)
• Irradiation is usually expressed in peak sun hours (*psh*), i.e., the length of time at an irradiance of 1 kW/m^2 needed to produce the daily irradiation obtained from integration of irradiance over a day.

Lecture 2: Semiconductors (intrinsic)

❖ <u>Introduction:</u>

> Semiconductors are materials whose electronic properties are intermediate between those of Metals and Insulators.

| Insulators | Semiconductors | conductors |

$$10^{-18}\Omega^{-1}m^{-1} \qquad 10^{-8}\Omega^{-1}m^{-1} \qquad 10^{3}\Omega^{-1}m^{-1} \qquad 10^{18}\Omega^{-1}m^{-1}$$

➤ $1\,S\,cm^{-1} = 1\,\Omega^{-1}m^{-1}$

➤ Remember: $\sigma\left[\frac{S}{cm}\right] = \frac{1}{\rho\,[\Omega.m]}$

- The interesting feature about semiconductors is that they are bipolar and current is transported by two charge carriers of opposite sign.
- These intermediate properties are determined by
  1. Crystal Structure bonding Characteristics.
  2. Electronic Energy bands.

❖ The electronic configuration in atoms

➤ Elemental semiconductors include antimony, arsenic, boron, carbon, germanium, selenium, silicon, sulfur, and tellurium. Silicon is the best-known of these. Common semiconductor compounds include gallium arsenide, indium antimonide, and the oxides of most metals. Of these, gallium arsenide (GaAs).

➤ It involves the specific arrangement of electrons in shells and sub-shells of Bohr's atomic model. This model has been widely accepted, and according to it, each atom has shells, which further have subshells. The shells are labeled K, L, M, N, and so on, from the innermost to the outermost shell.

➤ Each shell has subshells that are named for the type of emission lines produced from different states of angular momentum. They stand for sharp (S), principal (P), diffuse (D), and fundamental (F). The subshells have a distinct shape and configuration, in which the electrons move freely. Each shell and subshell has a limitation on the amount of electrons that it can carry. The maximum electrons that can be carried by the sub-shell S is 2, by P is 6, by D is 10, and the F sub-shell can carry 14. This decides the electron capacity of the shells. The K shell contains a 1s subshell hence it can carry 2 electrons; the L shell has 2s and 2p, and can carry 8 electrons. The M shell contains 3s, 3p, and 3d, and can carry 18 electrons. The N shell containing 4s, 4d, 4p and 4f, can carry 32 electrons. Such an arrangement helps explain the periodicity and periodic trends observed across the elements of the periodic table.

(a) Pictorial view   (b) Schematic View
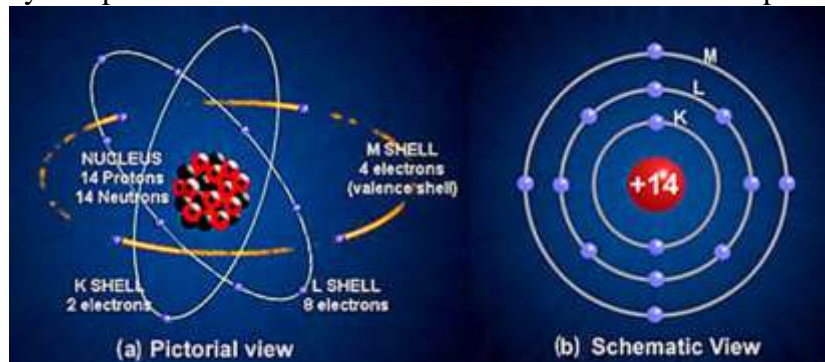
➢ Silicon and Germanium are elemental semiconductors and they have four valence electrons which are distributed among the outermost S and p orbitals.

Silicon (Si)	14	$1s^2 2s^2 2p^6 3s^2 3p^2$
Gallium (Ga)	31	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^1$

❖ <u>Semiconductors are mainly two types</u>
➢ Intrinsic (Pure) Semiconductors.
➢ Extrinsic (Impure) Semiconductors.

Intrinsic Semiconductor: A Semiconductor which does not have any kind of impurities, behaves as an Insulator at 0k and behaves as a Conductor at higher temperature

• Germanium and Silicon (4th group elements) are the best examples of intrinsic semiconductors and they possess diamond cubic crystalline structure
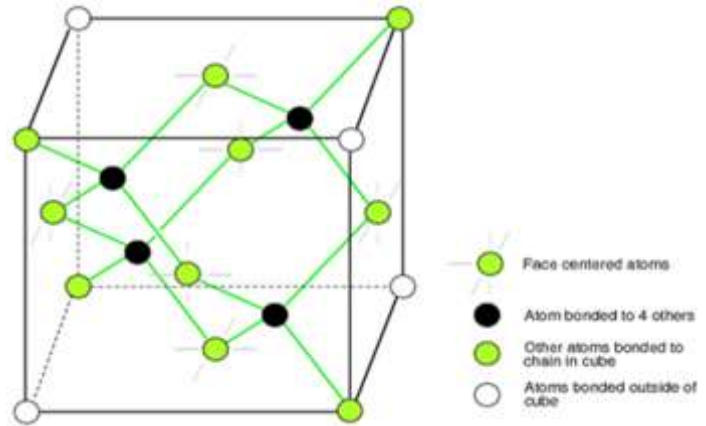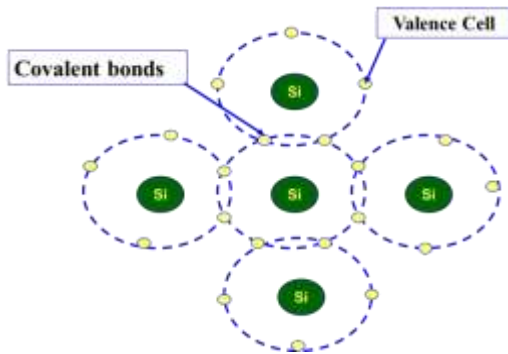
❖ **Carrier Concentration in Intrinsic Semiconductor**

When a suitable form of Energy is supplied to a Semiconductor then take transition from Valence band to Conduction band.
Hence a free electron in Conduction band and simultaneously free hole in Valence band is formed. This phenomenon is known as Electron - Hole pair generation.
In Intrinsic Semiconductor the Number of Conduction will be equal to the Number of Vacant sites or holes in the band.
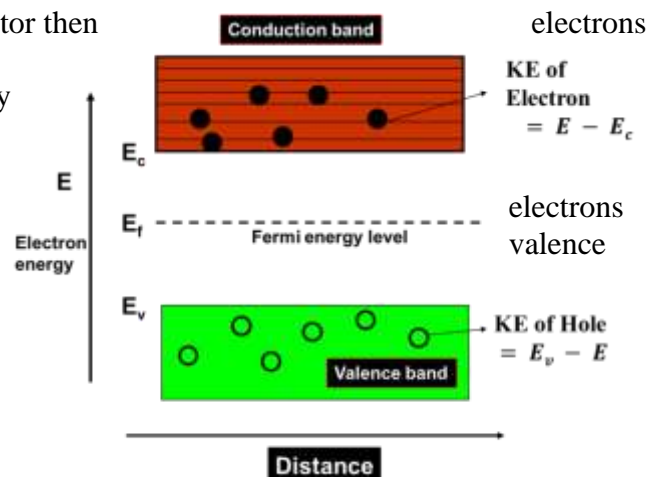
❖ **Calculation of Density of Electrons**

Let '*dn*' be the Number of Electrons available between energy interval '*E* and *E*+ *dE*' in the Conduction band

$$dn = Z(E)dE \ F(E)$$

$$n = \int\limits_{E_c}^{top\,of\,the\,band} z(E)F(E)dE...............(1)$$

Where $Z(E)\,dE$ is the Density of states in the energy interval E and $E + dE$ and $F(E)$ is the Probability of Electron occupancy.

➢ The density of states i.e., the number of energy states per unit volume within the energy interval E and $E + dE$ is given by

$$Z(E)dE = \frac{4\pi}{h^3}(2m)^{\frac{3}{2}}E^{\frac{1}{2}}dE$$

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}E^{\frac{1}{2}}dE$$

Since the E starts at the bottom of the Conduction band E_c

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}(E-E_c)^{\frac{1}{2}}dE$$

➢ **Probability of an Electron occupying an energy state E is given by**

$$F(E) = \frac{1}{1 + exp\left(\frac{E - E_F}{KT}\right)}$$

For all possible temperatures $E - E_c \gg KT$

$$F(E) = \frac{1}{exp\left(\frac{E - E_F}{KT}\right)} = exp - \left(\frac{E - E_F}{KT}\right) = exp\left(\frac{E_F - E}{KT}\right)$$

Substitute $Z(E)$ and $F(E)$ values in Equation (1)

$$n = \int\limits_{E_c}^{top\,of\,the\,band} z(E)F(E)dE$$

$$n = \int\limits_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}(E-E_c)^{\frac{1}{2}} \ exp(\frac{E_F - E}{kT})dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}\int\limits_{E_c}^{\infty}(E-E_c)^{\frac{1}{2}} \ exp(\frac{E_F - E}{kT})dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} exp(\frac{E_F}{kT})\int\limits_{E_c}^{\infty}(E-E_c)^{\frac{1}{2}} \ exp(\frac{-E}{kT})dE.....(2)$$

- Where m_e^* is the effective mass of electron

To solve equation 2, let us put

$$E - E_c = x$$
$$E = E_c + x$$
$$dE = dx$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}\exp(\frac{E_F}{kT})\int_0^\infty (E - E_c)^{\frac{1}{2}}\exp(\frac{-E}{kT})dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}\exp(\frac{E_F}{kT})\int_0^\infty (x)^{\frac{1}{2}}\exp-(\frac{E_c + x}{kT})dx$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}\exp(\frac{E_F - E_c}{kT})\int_0^\infty (x)^{\frac{1}{2}}\exp-(\frac{x}{kT})dx.....(3)$$

$we\ know\ that\ \int_0^\infty (x)^{\frac{1}{2}}\exp(\frac{-x}{kT})dE = (kT)^{\frac{3}{2}}\frac{\pi^{\frac{1}{2}}}{2}$

$substitute\ in\ equation\ (3)$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}}\exp(\frac{E_F - E_c}{kT})\ \{(kT)^{\frac{3}{2}}\frac{\pi^{\frac{1}{2}}}{2}\}$$

$$n = 2\ (\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}\ \exp(\frac{E_F - E_c}{kT})$$

- The above equation represents Number of electrons per unit volume of the Material

❖ <u>**Calculation of density of holes**</u>

Let 'dp' be the Number of holes or Vacancies available between energy interval 'E and E+ dE' in the valence band
$$dp = Z(E)dE\ \{1 - F(E)\}$$

$$p = \int_{bottom\ of\ the\ band}^{Ev} z(E)\{1 - F(E)\}dE...............(1)$$

Where $Z(E)\ dE$ is the density of states in the energy interval E and $E + dE$ and $1 - F(E)$ is the probability of existence of a hole.

➤ Density of holes in the Valence band is
$$Z(E)dE = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}E^{\frac{1}{2}}dE$$

Since E_v is the energy of the top of the valence band
$$Z(E)dE = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_v - E)^{\frac{1}{2}}dE$$

- Where m_h^* is the effective mass of hole

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➢ *Probability of an holes occupying an energy state E is given by*

$$1 - F(E) = 1 - \frac{1}{1 + exp\left(\frac{E - E_F}{KT}\right)} = 1 - \left\{1 + exp\left(\frac{E - E_F}{KT}\right)\right\}^{-1}$$

Neglecting higher order terms in this expansion for higher temperatures

$$1 - F(E) = exp\left(\frac{E - E_F}{KT}\right)$$

Substitute $Z(E)$ and $1 - F(E)$ values in Equation (1)

$$p = \int\limits_{bottom\,of\,the\,band}^{Ev} z(E)\{1 - F(E)\}dE$$

$$p = \int\limits_{-\infty}^{E_v} \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_v - E)^{\frac{1}{2}} \exp(\frac{E - E_F}{kT})dE$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} \exp(\frac{-E_F}{kT}) \int\limits_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} \exp(\frac{E}{kT})dE....(2)$$

To solve equation 2, let us put

$$E_v - E = x$$
$$E = E_v - x$$
$$dE = -dx$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} \exp(\frac{-E_F}{kT}) \int\limits_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} \exp(\frac{E}{kT})dE$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} \exp(\frac{-E_F}{kT}) \int\limits_{\infty}^{0} (x)^{\frac{1}{2}} \exp(\frac{E_v - x}{kT})(-dx)$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT}) \int\limits_{0}^{\infty} (x)^{\frac{1}{2}} \exp(\frac{-x}{kT})dx$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})(kT)^{\frac{3}{2}} \frac{\pi^{\frac{1}{2}}}{2}$$

$$p = 2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})$$

- **The above equation represents Number of holes per unit volume of the Material**

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❖ **Intrinsic Carrier Concentration**

In intrinsic Semiconductors $n = p$

Hence $n = p = n_i$ is called intrinsic Carrier Concentration

$$n_i^2 = np$$

$$n_i = \sqrt{np}$$

$$n_i = \sqrt{\{2\ (\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}\ \exp(\frac{E_F - E_c}{kT})\}\{2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})\}}$$

$$n_i = 2(\frac{2\pi kT}{h^2})^{\frac{3}{2}}(m_e^* m_h^*)^{\frac{3}{4}} \exp(\frac{E_v - E_c}{2kT})$$

$$n_i = 2(\frac{2\pi kT}{h^2})^{\frac{3}{2}}(m_e^* m_h^*)^{\frac{3}{4}} \exp(\frac{-E_g}{2kT})$$

❖ **Fermi level in intrinsic Semiconductors**

In intrinsic semiconductors n = p

$$2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT}) = 2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})$$

$$(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT}) = (\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})$$

$$\exp(\frac{2E_F}{kT}) = (\frac{m_h^*}{m_e^*})^{\frac{3}{2}} \exp(\frac{E_v + E_c}{kT})$$

taking logarithms on both sides
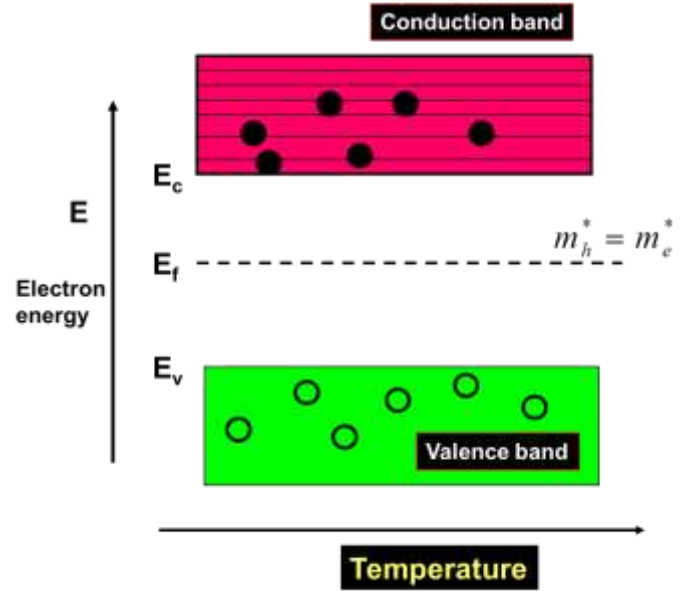
$$\frac{2E_F}{kT} = \frac{3}{2}\log(\frac{m_h^*}{m_e^*}) + (\frac{E_v + E_c}{kT})$$

$$E_F = \frac{3kT}{4}\log(\frac{m_h^*}{m_e^*})^{\frac{3}{2}} + (\frac{E_v + E_c}{2})$$

In intrinsic semiconductor we know that $m_e^* = m_h^*$

$$E_F = (\frac{E_v + E_c}{2})$$

• Thus the Fermi energy level E_F is located in the middle of the forbidden band.

Lecture 3: Semiconductors (extrinsic)

> **Extrinsic Semiconductors:** are those in which impurities of large quantity are present. Usually, the impurities can be either 3rd.group elements or 5th.group elements.

- Based on the impurities present in the Extrinsic Semiconductors, they are classified into two categories.
  1. N-type semiconductors
  2. P-type semiconductors
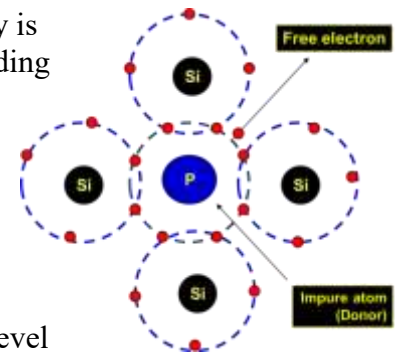- ❖ **N - type Semiconductors**

When any pentavalent element such as Phosphorous, Arsenic or Antimony is added to the intrinsic Semiconductor, four electrons are involved in covalent bonding with four neighboring pure Semiconductor atoms. The fifth electron is weakly bound to the parent atom. And even for lesser thermal energy it is released. Leaving the parent atom positively ionized.
The Intrinsic Semiconductors doped with pentavalent impurities are called N-type Semiconductors.

The energy level of fifth electron is called donor level.

The donor level is close to the bottom of the conduction band most of the donor level electrons are excited in to the conduction band at room temperature and become the Majority charge carriers. Hence in N-type Semiconductors electrons are Majority carriers and holes are Minority carriers.

❖ **Carrier Concentration in N-type Semiconductor**

- Consider N_d is the donor Concentration i.e., the number of donor atoms per unit volume of the material and E_d is the donor energy level.
- At very low temperatures all donor levels are filled with electrons.
- With increase of temperature more and more donor atoms get ionized and the density of electrons in the conduction band increases.

➢ Density of electrons in conduction band is given by

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT})$$

➢ The de_____ by

$$N_d\{1 - F(E_d)\} \approx N_d \exp(\frac{E_d - E_F}{kT})$$

➢ At very low temperatures, the Number of electrons in the conduction band must be equal to the Number of ionized donors.

$$2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT}) = N_d \exp(\frac{E_d - E_F}{kT})$$

Taking logarithm and rearranging we get

$$(\frac{E_F - E_c}{kT}) - (\frac{E_d - E_F}{kT}) = \log N_d - \log 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}$$
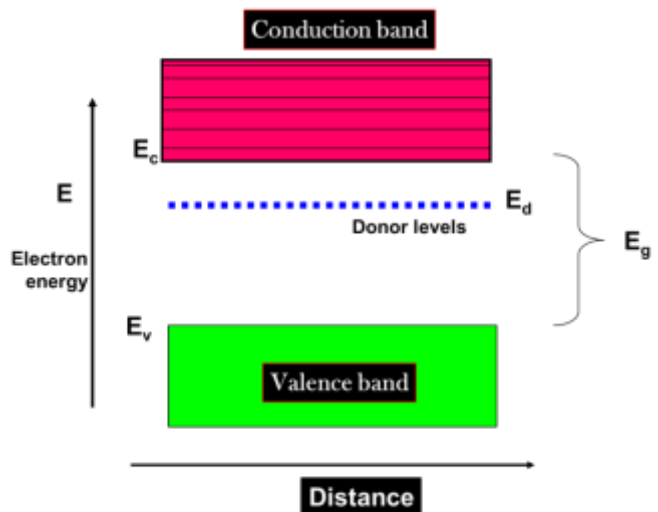
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At $0^c\ k$ Fermi level lies exactly at the middle of the donor level and the bottom of the Conduction band

> Density of electrons in the conduction band

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT})$$

$$\exp(\frac{E_F - E_c}{kT}) = \exp\{\frac{\{\frac{(E_d + E_c)}{2} + \frac{kT}{2}\log\frac{N_d}{2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}}\} - E_c}{kT}\}$$

$$\exp(\frac{E_F - E_c}{kT}) = \exp\{\frac{(E_d + E_c)}{2kT} + \log\frac{(N_d)^{\frac{1}{2}}}{[2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}]^{\frac{1}{2}}} - \frac{E_c}{kT}\}$$

$$\exp(\frac{E_F - E_c}{kT}) = \exp\{\frac{(E_d - E_c)}{2kT} + \log\frac{(N_d)^{\frac{1}{2}}}{[2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}]^{\frac{1}{2}}}\}$$

$$\exp(\frac{E_F - E_c}{kT}) = \frac{(N_d)^{\frac{1}{2}}}{[2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}]^{\frac{1}{2}}} \exp\frac{(E_d - E_c)}{2kT}$$

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT})$$

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}\{\frac{(N_d)^{\frac{1}{2}}}{[2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}]^{\frac{1}{2}}} \exp\frac{(E_d - E_c)}{2kT}\}$$

$$n = 2(N_d)^{\frac{1}{2}}(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{4}} \exp\frac{(E_d - E_c)}{2kT}$$

Thus we find that the density   the square root of the donor concentration at moderately low temperatures.

> **Variation of Fermi level with temperature**
- ❑ **To start with ,with increase of temperature E_f increases slightly.**
- ❑ **As the temperature is increased more and more donor atoms are ionized.**
- ❑ **Further increase in temperature results in generation of Electron - hole pairs due to breading of covalent bonds and the material tends to behave in intrinsic manner.**
- ❑ **The Fermi level gradually moves towards the intrinsic Fermi level E_i.**

❖ P-type semiconductors

▶ When a trivalent elements such as **Al, Ga or Indium** have three electrons in their outer most orbits , added to the intrinsic semiconductor all the three electrons of Indium are engaged in covalent bonding with the three neighboring Si atoms.

▶ Indium needs one more electron to complete its bond. this electron maybe supplied by Silicon , there by creating a vacant electron site or hole on the semiconductor atom.

▶ Indium accepts one extra electron, the energy level of this impurity atom is called **acceptor level** and this acceptor level lies just above the valence band.

▶ These type of trivalent impurities are called **acceptor impurities** and the semiconductors doped the acceptor impurities are called **P-type semiconductors**.
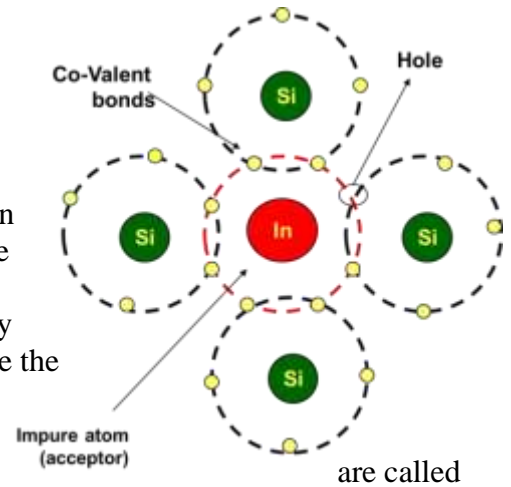
• Even at relatively low temperatures, these acceptor atoms get ionized taking electrons from valence band and thus giving rise to holes in valence band for conduction.

• Due to ionization of acceptor atoms only holes and no electrons are created.

• Thus holes are more in number than electrons and hence holes are majority carriers and electros are minority carriers in P-type semiconductors.
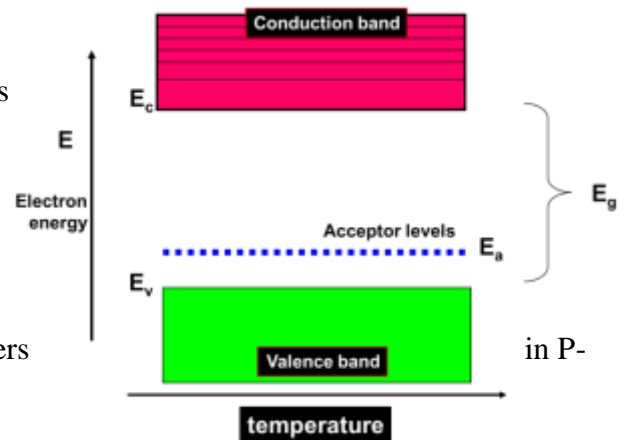
❖ Equation of continuity:

▶ As we have seen already, when a bar of **n**-type germanium is illuminated on its one face, excess charge carriers are generated at the exposed surface.

▶ These charge carriers diffuse throughout the material. Hence the carrier concentration in the body of the sample is a function of both time and distance.

▶ Let us now derive the differential equation which governs this fundamental relationship.

▶ Let us consider the infinitesimal volume element of area **A** and length **dx**.

▶ If t_p is the mean lifetime of the holes, the holes lost per sec per unit volume by recombination is p/t_p

▶ The rate of loss of charge within the volume under consideration

$$= eAdx\frac{p}{t_p}$$

If g is the thermal rate of generation of hole-electron pairs per unit volume, rate of increase of charge within the volume under consideration.

$$= eAdxg$$

▶ If i is the current entering the volume at x and $i + di$ the current leaving the volume at $x + dx$, then decrease of charge per second from the volume under consideration $= di$

$$= eAdx\frac{dp}{dt_p}$$

▶

▸ Because of the above stated three effects the hole density changes with time.
▸ Increase in the number of charges per second within the volume

<p style="color:red">Increase = generation - loss</p>

$$eAdx\frac{dp}{dt}_p = eAdxg - eAdx\frac{p}{t_p} - dI$$

Since the hole current is the sum of the diffusion current and the drift current

$$I = -AeD_p\frac{dp}{dx} + Ape\mu_h E$$

Where E is the electric field intensity within the volume. when no external field is applied, under thermal equilibrium condition, the hole density attains a constant value p_0.
Under these conditions

$$di = 0 \text{ and } \frac{p}{dt} = 0$$

$$g = \frac{P_0}{t_p}$$

this equation indicates that the rate of generation of holes is equal the rate of loss due to recombination ion under equilibrium conditions

$$\therefore \frac{dp}{dt} = -\frac{(p - p_0)}{t_p} + D_p\frac{\partial^2 p}{\partial x^2} - \mu_h\frac{d(pE)}{dx}$$

This is called equation of conservation of charge or the continuity equation.
If p is a function of both t and x then partial derivatives should be used

$$\frac{\partial p}{\partial t} = -\frac{(p - p_0)}{t_p} + D_p\frac{\partial^2 p}{\partial x^2} - \mu_h\frac{\partial(pE)}{\partial x}$$

If we considering holes in the n-type material

$$\frac{\partial p_n}{\partial t} = -\frac{(p_n - p_{0n})}{t_p} + D_p\frac{\partial^2 p_n}{\partial x^2} - \mu_h\frac{\partial(p_n E)}{\partial x}$$

If we considering electrons in the p-type material

$$\frac{\partial n_p}{\partial t} = -\frac{(n_p - n_{0p})}{t_e} + D_e\frac{\partial^2 n_p}{\partial x^2} - \mu_e\frac{\partial(n_p E)}{\partial x}$$

❖ **Direct band gap and indirect band gap semiconductors**:
In semiconductor physics, the band gap of a semiconductor is always one of two types,
(A) Direct band gap
(B) Indirect band gap
➤ **direct band gap semiconductor**

The band gap represents the minimum energy difference between the top of the valence band and the bottom of the conduction band
However, the top of the valence band (VB maxima) and the bottom of the conduction band (CB minima) are not generally at the same value of the electron momentum.
Minimum-energy state in the conduction band (CB -minima) and the maximum-energy state in the valence band (VB-maxima) are each characterized by a certain crystal momentum and k- vector (propagation constant or wave vector) in the Brillouin zone.

(a) Direct

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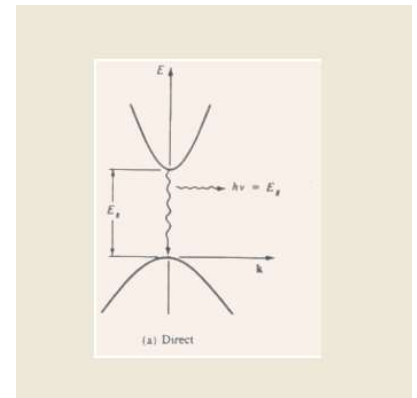
If the k-vectors are the same, for conduction band minima (CB-minima) and valence Band maxima (VB-maxima) it is called a "Direct band gap semiconductor"

The band gap is called "direct" if the momentum of electrons and holes is the same in both the conduction band and the valence band; an electron can directly emit a photon.

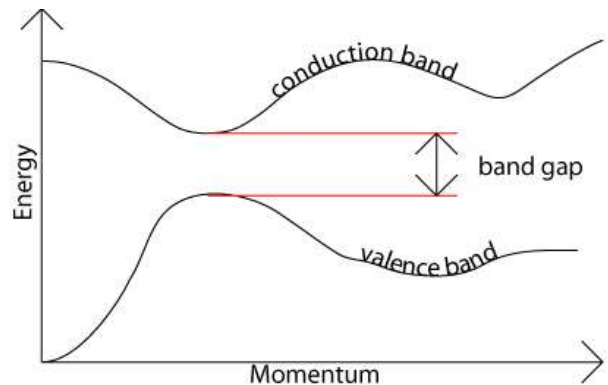In case of "direct band semiconductor " electron in conduction band (CB) minima ,recombine directly with the holes in valence band (VB) maxima without change in momentum as well as kinetic energy ,so energy will be emitted in the form of light , this phenomenon is called as "SPONTANEOUS EMISSION "

In direct band gap semiconductor Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

Relative carrier life time is small in case of direct band gap semiconductor

Best example of direct band gap semiconductors are GaAs InAs, InSb GaN InN ZnO CdSe ZnS

GaAs emits light in Infra-red region

➢ **indirect band gap semiconductor**

If the k-vectors (Propagation constant or wave vector) are different for conduction band minima (CB-minima) and valence Band maxima (VB-maxima) it is called a "Indirect band gap semiconductor"

In this case momentum is not same for conduction band minima (CB-minima) and valence band maxima (VB –maxima)

In an "indirect" gap, a photon cannot be emitted because the electron must pass through an intermediate state and transfer momentum to the crystal lattice.
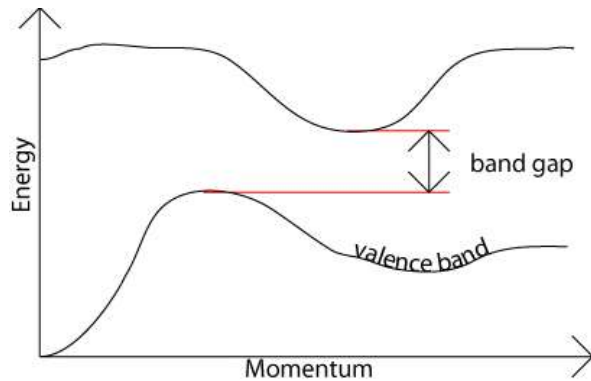
In case of indirect band gap semiconductors during excitation there is change in momentum, K.E. as well as direction and path of electron

In indirect band gap semiconductors energy emits in the form of heat.

Best examples of indirect band gap semiconductors are Si , Ge ,C (diamond) ,GaP

Differentiate between direct and indirect band gap semiconductors.

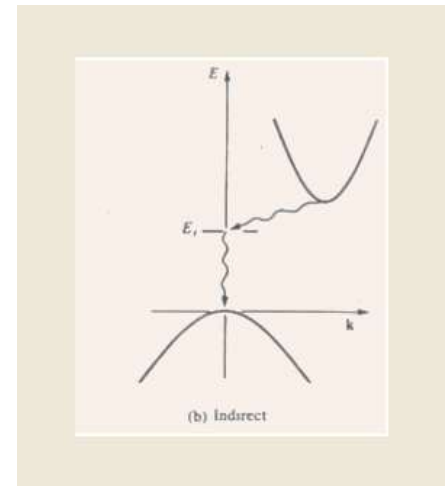| Direct band-gap (DBG) semiconductor	Indirect band-gap (IBG) semiconductor
1. A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	1. An Indirect band-gap (IBG) semiconductor is one in which the maximum energy level of the valence band and the minimum energy level of the conduction band are misaligned with respect to momentum.
2. In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	2. In case of a IBG semiconductor, due to a relative difference in the momentum, first, the momentum is conserved by release of energy and only after the both the momenta align themselves, a recombination occurs accompanied with the release of energy.
3. The probability of a radiative recombination is high.	3. The probability of a radiative recombination is comparatively low.
4. The efficiency factor of a DBG semiconductor is higher.	4. The efficiency factor of a IBG semiconductor is lower.
5. Energy is conserved by means of emitting a photon	5. Energy is not conserved as energy emits in the form of heat
6. Example, Gallium Arsenide (GaAs).	6. Example, Silicon and Germanium
7. DBG semiconductors are always preferred over IBG for making optical sources.	7. The IBG semiconductors cannot be used to manufacture optical sources.

Lecture 4: P-N junction

❖ **What is P-N Junction?**

Definition: *A p-n junction is an interface or a boundary between two semiconductor material types, 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. The process of doping is explained in further detail in the next section.

❖ **Formation of P-N Junction**

➢ To make a p-n junction, 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 pentavalent impurity to this (silicon, is doped with boron, phosphorus, or arsenic), 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. There will be a difference in the concentration of holes and electrons at the two sides of a junction, the holes (majority carriers) from the p-side diffuse to the n-side and the electrons (majority carriers) from the n-side diffuse to the p-side. These give rise to a diffusion current across the 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 (or space charge region). Due to this positive space charge region on either side of the junction, an electric field directed from a positive charge towards the negative charge is developed. Due to this electric field, an electron (minority carriers) on the p-side of the junction moves to the n-side of the junction. This motion is termed as the drift current. Here, we see that the direction of drift current is opposite to that of the diffusion current.
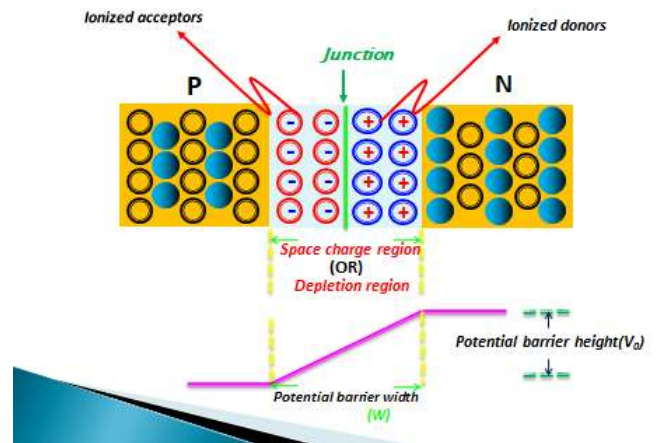
❖ Biasing conditions for the p-n Junction Diode

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.

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➤ **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.
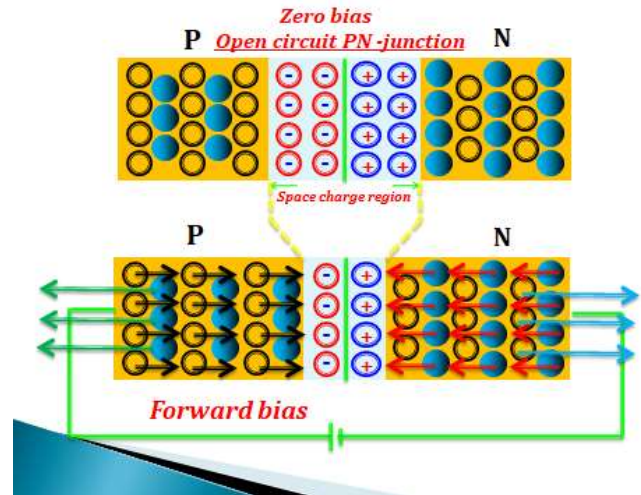
➤ **Reverse Bias**

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.
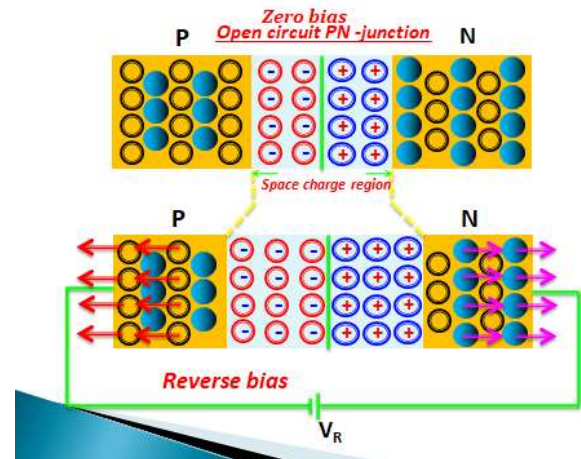
❖ **P-N Junction Formula**

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

$$E_0 = V_T ln \left[\frac{N_D - N_A}{n_i^2} \right]$$

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.

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❖ <u>**How does current flow in PN junction diode?**</u>

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 p-n junction is the reason behind the current flow in the circuit.

❖ <u>**V-I Characteristics of PN Junction Diode**</u>

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 graph shown 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 <u>forward bias condition</u>, there will be <u>a reduction in the potential barrier</u>. 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 <u>negative bias condition</u>, this results in an <u>increase in the potential barrier</u>. 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.
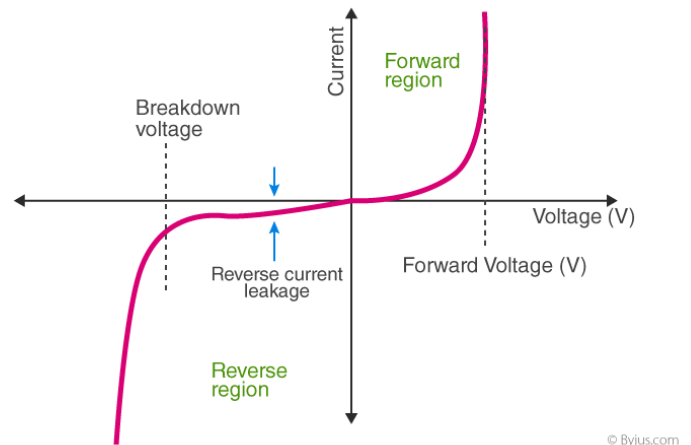
❖ <u>**Applications of PN Junction Diode**</u>
- p-n junction diode can be used as a photodiode as the diode is sensitive to the light when the configuration of the diode is reverse-biased.
- It can be used as a solar cell.
- When the diode is forward-biased, it can be used in LED lighting applications.
- It is used as rectifiers in many electric circuits and as a voltage-controlled oscillator in varactors
  - <u>**Varactor diodes**</u>
    - a reversed-biased diode has two conducting regions separated by an insulating depletion region
    - this structure resembles a capacitor

- variations in the reverse-bias voltage change the width of the depletion layer and hence the capacitance
- this produces a **voltage-dependent capacitor**
- these are used in applications such as **automatic tuning circuits**

Lecture 5: Solar Cell Parameters

❖ Solar Cell Parameters
➢ IV Curve

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current. The light has the effect of shifting the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$I = I_0[exp(qV/nkT) - 1] - I_L$$

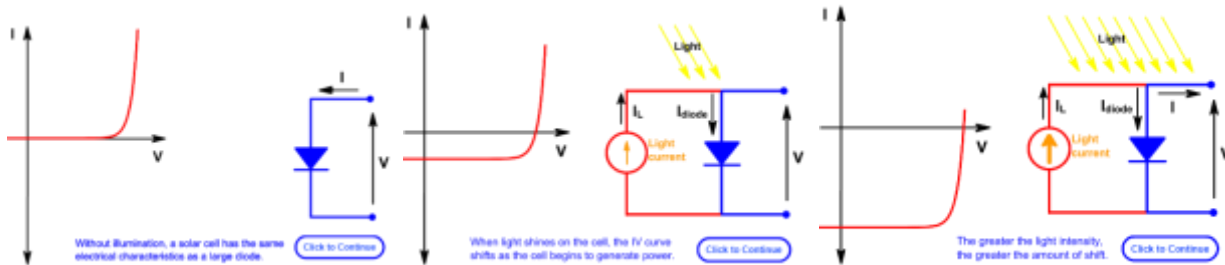Where I_L = light generated current.

Fig.1: The ideal short circuit flow of electrons and holes at a p-n junction. Minority carriers cannot cross a semiconductor-metal boundary and to prevent recombination they must be collected by the junction if they are to contribute to current flow.

• The effect of light on the current-voltage characteristics of a p-junction.

The equation for the IV curve in the first quadrant is:

$$I = I_L - I_0[exp(qV/nkT) - 1]$$

The -1 term in the above equation can usually be neglected. The exponential term is usually much greater than 1 except for voltages below 100 mV. Further, at low voltages, the light generated current I_L dominates the $I_0[exp(qV/nkT)]$ term so the -1 term is not needed under illumination.

$$I = I_L - I_0[exp(qV/nkT)]$$

Plotting the above equation gives the IV curve below with the relevant points on the curve labeled and discussed in more detail on the following pages. The power curve has a maximum denoted as P_{MP} where the solar cell should be operated to give the maximum power output. It is also denoted as P_{MAX} or maximum power point (MPP) and occurs at a voltage of V_{MP} and a current of I_{MP}.
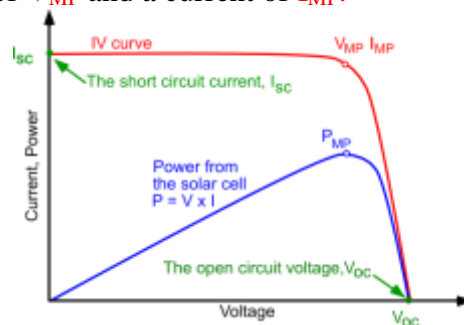
Fig.2: Current voltage (IV) curve of a solar cell. To get the maximum power output of a solar cell it needs to operate at the maximum power point, P_{MP}.

Several important parameters which are used to characterize solar cells are discussed in the following pages. The short-circuit current (I_{SC}), the open-circuit voltage (V_{OC}), the fill factor (FF) and the efficiency are all parameters determined from the IV curve.

Rearranging the equation above gives the voltage in terms of current:

$$V = \frac{nkT}{q} \, ln(I_L - I / I_0)$$

When $I > I_L$ the number in side the $ln(\ )$ is negative and undefined. So what happens in reality? The solar cell goes into reverse bias (negative voltage) and either the non-idealities in the solar cell limit the voltage or the supply limits the voltage. In either case, the solar cell will dissipate power. If there is no limit on the supply then a solar cell close to ideal (very high R_{SHUNT} in reverse bias) will be destroyed almost instantly. Other cells will be destroyed due to heating.

The problem of power dissipation in solar cells in reverse bias is covered in the module chapter and in particular the use of bypass diodes.

> ➤ Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited).

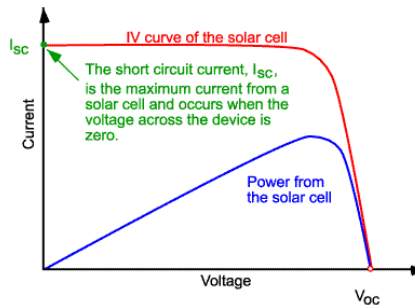Usually written as I_{SC}, the short-circuit current is shown on the IV curve below.

Fig3: IV curve of a solar cell showing the short-circuit current.

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell. The short-circuit current depends on a number of factors which are described below:

- **The area of the solar cell.** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{SC} in mA/cm^2) rather than the short-circuit current;
- **The number of photons** (i.e., the power of the incident light source). I_{SC} from a solar cell is directly dependent on the light intensity as discussed in Effect of Light Intensity;
- **The spectrum of the incident light.** For most solar cell measurement, the spectrum is standardized to the Air Mass 1.5 (AM1.5 spectrum);
- **The optical properties** (absorption and reflection) of the solar cell (discussed in Optical Losses); and
- **The collection probability** of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

When comparing solar cells of the same material type, the most critical material parameter is the diffusion length and surface passivation. In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current density can be approximated as:

$$J_{SC} = qG(L_n + L_p)$$

Where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively. Although this equation makes several assumptions which are not true for the conditions encountered in most solar cells, the above equation nevertheless indicates that the short-circuit current depends strongly on the generation rate and the diffusion length.

The short circuit current, I_{SC}, is the short circuit current density, J_{SC}, times the cell area:

$$I_{SC} = J_{SC}A$$

Silicon solar cells under an AM1.5 spectrum have a maximum possible current of 46 mA/cm². Laboratory devices have measured short-circuit currents of over 42 mA/cm², and commercial solar cell have short-circuit currents between about 28 mA/cm² and 35 mA/cm².
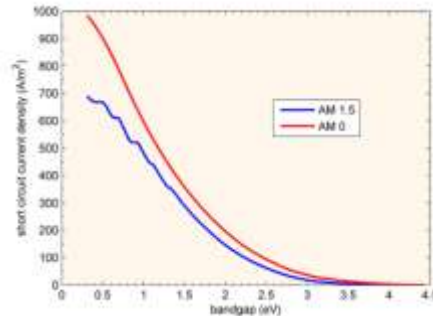

Fig.4: In an ideal device every photon above the bandgap gives one charge carrier in the external circuit so the highest current is for the lowest bandgap.

➤ Illuminated Current and Short Circuit Current (I_L or I_{SC} ?)

I_L is the light generated current inside the solar cell and is the correct term to use in the solar cell equation. At short circuit conditions the externally measured current is I_{SC}. Since I_{SC} is usually equal to I_L, the two are used interchangeably and for simplicity and the solar cell equation is written with I_{SC} in place of I_L. In the case of very high series resistance (> 10 Ω cm²) I_{SC} is less than I_L and writing the solar cell equation with I_{SC} is incorrect.

Another assumption is that the illumination current I_L is solely dependent on the incoming light and is independent of voltage across the cell. However, I_L varies with voltage in the case of drift-field solar cells and where carrier lifetime is a function of injection level such as defected multicrystalline materials.

➤ <u>Open-Circuit Voltage</u>

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the IV curve below.
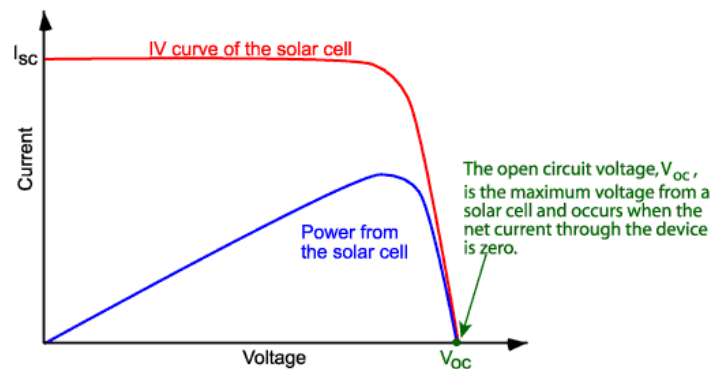
Fig.5: IV curve of a solar cell showing the open-circuit voltage.

An equation for *Voc* is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

A casual inspection of the above equation might indicate that V_{oc} goes up linearly with temperature. However, this is not the case as I_0 increases rapidly with temperature primarily due to changes in the <u>intrinsic carrier concentration n_i</u>. The effect of temperature is complicated and varies with cell technology. See the page "<u>Effect of Temperature</u>" for more details

V_{oc} **decreases** with temperature. If temperature changes, I_0 also changes.
The above equation shows that V_{oc} depends on the saturation current of the solar cell and the light-generated current. While I_{sc} typically has a small variation, the key effect is the saturation current, since this may vary by orders of magnitude. The saturation current, I_0 depends on recombination in the solar cell. Open-circuit voltage is then a measure of the amount of recombination in the device. Silicon solar cells on high quality single crystalline material have open-circuit voltages of up to 764 mV under one sun and AM1.5 conditions, while commercial devices on multicrystalline silicon typically have open-circuit voltages around 600 mV.
The V_{oc} can also be determined from the carrier concentration:

$$V_{oc} = \frac{kT}{q} ln\left(\frac{(N_A + \Delta n)\Delta n}{n_i{}^2}\right)$$

Where kT/q is the thermal voltage, N_A is the doping concentration, Δn is the excess carrier concentration and n_i is the intrinsic carrier concentration. The determination of V_{OC} from the carrier concentration is also termed Implied V_{OC}.

- V_{oc} as a Function of Bandgap, E_G

Where the short-circuit current (I_{SC}) decreases with increasing bandgap, the open-circuit voltage increases as the band gap increases. In an ideal device the V_{OC} is limited by radiative recombination and the analysis uses the principle of detailed balance to determine the minimum possible value for J_0.
The minimum value of the diode saturation current is given by:

$$J_0 = \frac{q}{k}\frac{15\sigma}{\pi^4}T^3 \int_u^\infty \frac{x^2}{e^x - 1} dx$$

Where q is the electronic charge, σ is the Stefan–Boltzmann constant, k is Boltzmann constant, T is the temperature and

$$u = \frac{E_G}{kT}$$

Evaluating the integral in the above equation is quite complex.

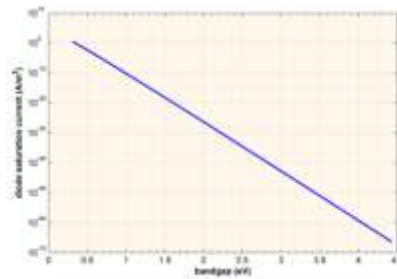*Fig.6: Diode saturation current as a function of band gap. The values are determined from detailed balance and place a limit on the open circuit voltage of a solar cell.*

The J calculated above can be directly plugged into the standard solar cell equation given at the top of the page to determine the V_{OC} so long as the voltage is less than the band gap, as is the case under one sun illumination.

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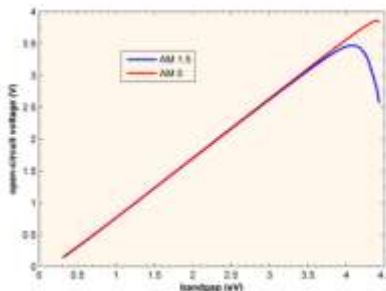
Fig.7: V_{OC} as function of bandgap for a cell with AM 0 and AM 1.5. The V_{OC} increases with bandgap as the recombination current falls. There is drop off in V_{OC} at very high band gaps due to the very low I_{SC}

❖ <u>Fill Factor</u>

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{SC}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{SC} so that:

$$FF = \frac{P_{MP}}{(V_{oc} \times I_{sc})} = \frac{V_{MP}I_{MP}}{V_{oc}I_{sc}}$$

Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below.
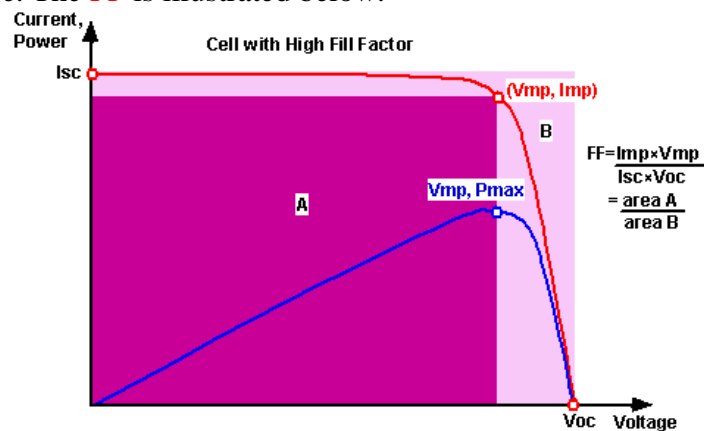

Fig.8: Graph of cell output current (red line) and power (blue line) as a function of voltage. Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{OC}) points, as well as the maximum power point (V_{mp}, I_{mp}). Click on the graph to see how the curve changes for a cell with low FF.

As FF is a measure of the "squareness" of the IV curve, a solar cell with a higher voltage has a larger possible FF since the "rounded" portion of the IV curve takes up less area. The maximum theoretical FF from a solar cell can be determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero. Hence:

$$\frac{d(IV)}{dV} = 0$$

Giving:

$$V_{MP} = V_{OC} - \frac{nkT}{q} \ln\left(\frac{qVmp}{nkT} + 1\right)$$

The equation above requires Lambert functions to solve (which is beyond this course) but a simpler approach is to use iteration to calculate V_{MP}. The equation above only relates V_{oc} to V_{MP} and extra equations are needed to find I_{MP} and FF. A more commonly used expression for the FF can be determined empirically as:

$$FF = \frac{v_{OC} - \ln(v_{OC} + 0.72)}{v_{OC} + 1}$$

Where v_{OC} is defined as a "normalized V_{OC}":

$$v_{OC} = \frac{V_{OC}}{\left(\frac{nkT}{q}\right)}$$

The above equations show that a higher voltage will have a higher possible FF. However, large variations in open-circuit voltage within a given material system are relatively uncommon. For example, at one sun, the difference between the maximum open-circuit voltage measured for a silicon laboratory device and a typical

commercial solar cell is about 120 mV, giving maximum FF's respectively of 0.85 and 0.83. However, the variation in maximum FF can be significant for solar cells made from different materials. For example, a GaAs solar cell may have a FF approaching 0.89.

The above equation also demonstrates the importance of the ideality factor, also known as the "n-factor" of a solar cell. The ideality factor is a measure of the junction quality and the type of recombination in a solar cell. For the simple recombination mechanisms discussed in Types of Recombination, the n-factor has a value of 1. However, some recombination mechanisms, particularly if they are large, may introduce recombination mechanisms of 2. A high n-value not only degrades the FF, but since it will also usually signal high recombination, it gives low open-circuit voltages.

A key limitation in the equations described above is that they represent a maximum possible FF, although in practice the FF will be lower due to the presence of parasitic resistive losses, which are discussed in Effects of Parasitic Resistances. Therefore, the FF is most commonly determined from measurement of the IV curve and is defined as the maximum power divided by the product of $I_{SC} \times V_{OC}$, i.e.:

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

❖ Solar Cell Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mp} V_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

Where:

V_{oc} is the open-circuit voltage;

I_{sc} is the short-circuit current;

FF is the fill factor and

η is the efficiency.

The input power P_{in} for efficiency calculations is 1 kW/m^2 or 100 mW/cm^2. Thus the input power for a 100×100 mm^2 cell is 10 W and for a 156×156 mm^2 cell is 24.3 W.

Lecture 6: Effect of temperature and shading on solar cells

❖ Effect of Temperature

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap.

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure below.
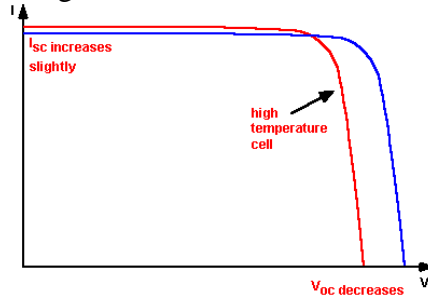

Fig.1: The effect of temperature on the IV characteristics of a solar cell.

The open-circuit voltage decreases with temperature because of the temperature dependence of I_0. The equation for I_0 from one side of a *p-n* junction is given by;

$$I_0 = qA \frac{D n_i^2}{L N_D}$$

where:

q is the electronic charge.

A is the area;

D is the diffusivity of the minority carrier

L is the minority carrier diffusion length;

N_D is the doping; and

ni is the intrinsic carrier concentration.

In the above equation, many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, n_i. The intrinsic carrier concentration depends on the band gap energy (with lower band gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations). The equation for the intrinsic carrier concentration is;

$$n_i^2 = 4 \left(\frac{2 \pi k T}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} exp \left(-\frac{E_{G0}}{kT} \right) = BT^3 exp \left(-\frac{E_{G0}}{kT} \right)$$

Where:

T is the temperature;

h and k are constants.

m_e^* and m_h^* are the effective masses of electrons and holes respectively;

E_{G0} is the band gap linearly extrapolated to absolute zero; and

B is a constant which is essentially independent of temperature.

Substituting these equations back into the expression for I_0, and assuming that the temperature dependencies of the other parameters can be neglected, gives;

$$I_0 = qA\frac{Dn_i^2}{LN_D}BT^3 exp\left(-\frac{E_{G0}}{kT}\right) \approx B'T^\gamma exp\left(-\frac{E_{G0}}{kT}\right)$$

Where, B' is a temperature independent constant. A constant, γ, is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters. For silicon solar cells near room temperature, I_0 approximately doubles for every 10 °C increase in temperature.

The impact of I_0 on the open-circuit voltage can be calculated by substituting the equation for I_0 into the equation for V_{OC} as shown below;

$$V_{OC} = \frac{kT}{q}ln\left(\frac{I_{SC}}{I_0}\right) = \frac{kT}{q}[lnI_{SC} - lnI_0] = \frac{kT}{q}lnI_{SC} - \frac{kT}{q}ln\left[B'T^\gamma exp\left(-\frac{qV_{G0}}{kT}\right)\right]$$

$$= \frac{kT}{q}\left(lnI_{SC} - lnB' - \gamma lnT + \frac{qV_{G0}}{kT}\right)$$

Where, $E_{G0} = qV_{G0}$. Assuming that dV_{OC}/dT does not depend on dI_{SC}/dT, dV_{OC}/dT can be found as;

$$\frac{dV_{OC}}{dT} = \frac{V_{OC} - V_{G0}}{T} - \gamma\frac{k}{q}$$

The above equation shows that the temperature sensitivity of a solar cell depends on the open circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature. For silicon, E_{G0} is 1.2, and using γ as 3 gives a reduction in the open-circuit voltage of about $2.2\ mV/°C$;

$$\frac{dV_{OC}}{dT} = -\frac{V_{OC} - V_{G0} + \gamma\frac{k}{q}}{T} \approx -2.2\ mV/°C\ for\ Silicon$$

The short-circuit current, I_{SC}, increases slightly with temperature, since the band gap energy, E_G, decreases and more photons have enough energy to create e-h pairs. However, this is a small effect and the temperature dependence of the short-circuit current from a silicon solar cell is;

$$\frac{1}{I_{SC}}\frac{dI_{SC}}{dT} \approx 0.0006\ /°C\ for\ Silicon$$

or 0.06% per °C for silicon.

The temperature dependency of FF for silicon is approximated by the following equation;

$$\frac{1}{FF}\frac{dFF}{dT} \approx \left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT} - \frac{1}{T}\right) \approx -0.0015/°C\ for\ Silicon$$

The effect of temperature on the maximum power output, P_{max}, is;

$$\frac{1}{P_{max}}\frac{dP_{max}}{dT} = \frac{1}{V_{OC}}\frac{dV_{OC}}{dT} + \frac{1}{FF}\frac{dFF}{dT} + \frac{1}{I_{SC}}\frac{dI_{SC}}{dT} \approx -(0.004\ to\ 0.005)/°C\ for\ Silicon$$

or 0.4% to 0.5% per °C for silicon.

- 300 K or 25 °C?

Most semiconductor modeling is done at 300 K since it is close to room temperature and a convenient number. However, solar cells are typically measured almost 2 degrees lower at 25 °C (298.15 K). In most cases the difference is insignificant (only 4 mV of V_{OC}) and both are referred to as room temperature. Occasionally, the modeled results need to be adjusted to correlate with the measured results.

❖ Hot Spot Heating

Hot-spot heating occurs when there is one low current solar cell in a string of at least several high short-circuit current solar cells, as shown in the figure below.
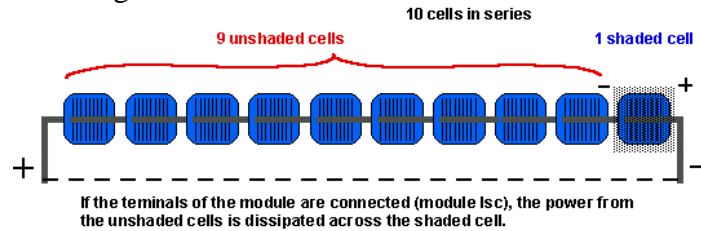
Fig.2: One shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell.

If the operating current of the overall series string approaches the short-circuit current of the "bad" cell, the overall current becomes limited by the bad cell. The extra current produced by the good cells then forward biases the good solar cells. If the series string is short circuited, then the forward bias across all of these cells reverse biases the shaded cell. Hot-spot heating occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. Essentially the entire generating capacity of all the good cells is dissipated in the poor cell. The enormous power dissipation occurring in a small area results in local overheating, or "hot-spots", which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell.

Fig.3: Heat dissipated in a shaded cell caused the module to crack.

❖ Effect of Light Intensity

Changing the light intensity incident on a solar cell changes all solar cell parameters, including the short-circuit current, the open-circuit voltage, the FF, the efficiency and the impact of series and shunt resistances. The light intensity on a solar cell is called the number of suns, where **1 sun corresponds to standard illumination at AM1.5, or 1 kW/m^2**. For example a system with 10 kW/m^2 incident on the solar cell would be operating at 10 suns, or at 10X. A PV module designed to operate under 1 sun conditions is called a "flat plate" module while those using concentrated sunlight are called "concentrators".

المرحلة الثالثة

د. وسام عبدالله لطيف
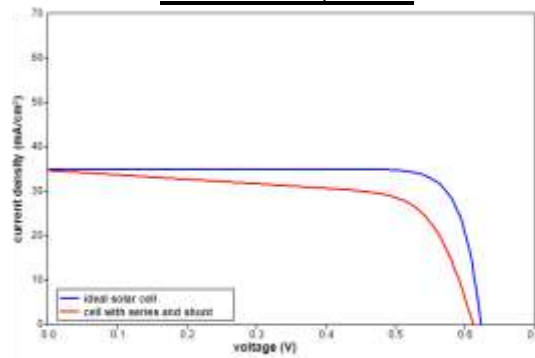
Ideal Cell: $V_{OC} = 0.623$ $I_{SC} = 35\ mA/cm^2$ $FF = 0.83$
Real Cell: $V_{OC} = 0.612$ $I_{SC} = 34.6\ mA/cm^2$ $FF = 0.67$
Cell shunt resistance, $R_{shunt} = 100.0\ \Omega\ cm^2$
Cell series resistance, $R_s = 1\ \Omega\ cm^2$
Concentration of light on solar cell, conc = 1 suns

Fig.4:The effect of concentration on the IV characteristics of a solar cell. The series resistance has a greater effect on performance at high intensity and the shunt resistance has a greater effect on cell performance at low light intensity.

- Concentrators

A concentrator is a solar cell designed to operate under illumination greater than 1 sun. The incident sunlight is focused or guided by optical elements such that a high intensity light beam shines on a small solar cell. Concentrators have several potential advantages, including a higher efficiency potential than a one-sun solar cell and the possibility of lower cost. The short-circuit current from a solar cell depends linearly on light intensity, such that a device operating under 10 suns would have 10 times the short-circuit current as the same device under one sun operation. However, this effect does not provide an efficiency increase, since the incident power also increases linearly with concentration. Instead, the efficiency benefits arise from the logarithmic dependence of the open-circuit voltage on short circuit. Therefore, under concentration, V_{OC} increases logarithmically with light intensity, as shown in the equation below;

$$V'_{OC} = \frac{nkT}{q} ln\left(\frac{XI_{SC}}{I_0}\right) = \frac{nkT}{q}\left[ln\left(\frac{I_{SC}}{I_0}\right) + lnX\right] = V_{OC} + \frac{nkT}{q} lnX$$

where *X* is the concentration of sunlight.
From the equation above, a doubling of the light intensity ($X = 2$) causes a 18 mV rise in V_{OC} .
The cost of a concentrating PV system may be lower than a corresponding flat-plate PV system since only a small area of solar cells is needed.
The efficiency benefits of concentration may be reduced by increased losses in series resistance as the short-circuit current increases and also by the increased temperature operation of the solar cell. As losses due to short-circuit current depend on the square of the current, power loss due to series resistance increases as the square of the concentration.

- Low Light Intensity

Solar cells experience daily variations in light intensity, with the incident power from the sun varying between 0 and 1 kW/m². At low light levels, the effect of the shunt resistance becomes increasingly important. As the light intensity decreases, the bias point and current through the solar cell also decreases and the equivalent resistance of the solar cell may begin to approach the shunt resistance. When these two resistances are similar, the fraction of the total current flowing through the shunt resistance increases, thereby increasing the fractional power loss due to shunt resistance. Consequently, under cloudy conditions, a solar cell with a high shunt resistance retains a greater fraction of its original power than a solar cell with a low shunt resistance.

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❖ Ideality Factor (*n*)

The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. The derivation of the simple diode equation uses certain assumption about the cell. In practice, there are second order effects so that the diode does not follow the simple diode equation and the ideality factor provides a way of describing them.

• Recombination mechanisms

The ideal diode equation assumes that all the recombination occurs via band to band or recombination via traps in the bulk areas from the device (i.e. not in the junction). Using that assumption the derivation produces the ideal diode equation below and the ideality factor, *n*, is equal to one.

$$I = I_L - I_0 \left[exp\left(\frac{qV}{nkT}\right) - 1 \right]$$

However recombination does occur in other ways and in other areas of the device. These recombination produce ideality factors that deviate from the ideal. Deriving the ideal diode equation by considering the number of carriers the need to come together during the process produces the results in the table below.

| Recombination Type	Ideality factor	Description
SRH, band to band (low level injection)	1	Recombination limited by minority carrier.
SRH, band to band (high level injection)	2	Recombination limited by both carrier types.
Auger	2/3	Two majority and one minority carriers required for recombination.
Depletion region (junction)	2	two carriers limit recombination.

❖ Effect of Shading

Shading is a problem in PV modules since shading just one cell in the module can reduce the power output to zero.

1. Shading one cell reduces the output of the whole string of cells or modules.
2. Excess power from the unshaded cells is dissipated in the shaded cell.
3. Bypass diodes isolate the shaded cell.

• Shading of a Single Cell

The output of a cell declines when shaded by a tree branch, building or module dust. The output declines proportionally to the amount of shading. For completely opaque objects such as a leaf, the decline in current output of the cell is proportional to the amount of the cell that is obscured.
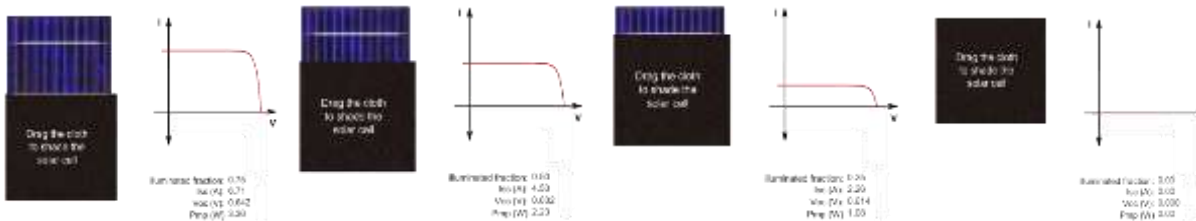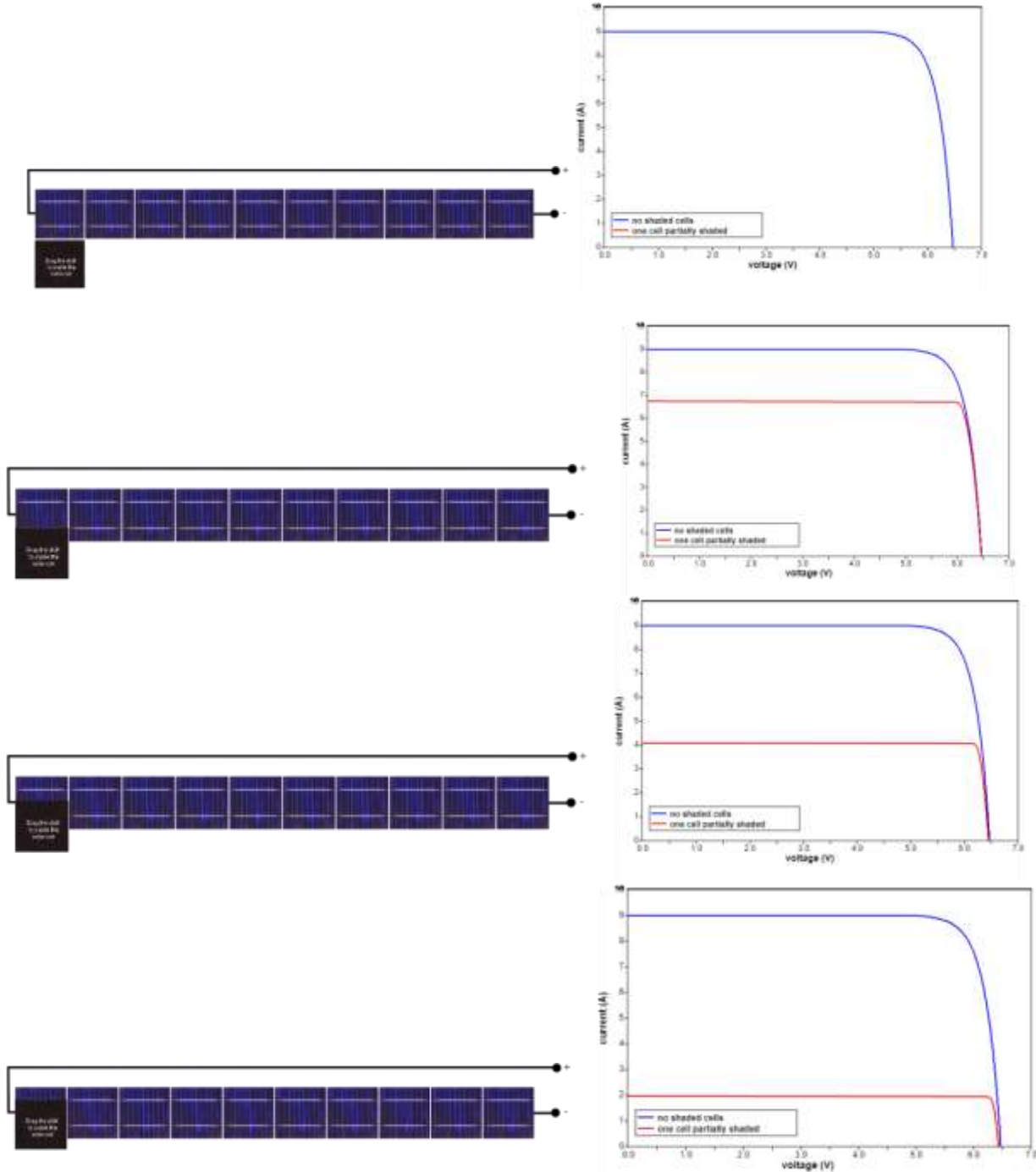

Move the grey rectangle over the solar cell. The current is reduced by the amount of shading.

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- Shading of a Cell in a Module

An individual solar cell has an output of 0.5 V. Cells are connected in series in a module to increase the voltage. Since the cells are in series, the current has to be the same in each cell and shading one cell causes the current in the string of cells to fall to the level of the shaded cell. Typically, the module I_{SC} is reduced to the **lowest** I_{SC} of all the cells in a string. Shading just one cell in a module to half causes the output power of the whole module to fall to half. No matter how many cells there are in the string, completely shading one cell causes the output power of the module to fall to zero. The lost output power of all the unshaded cells is dissipated in the shaded cell. It is even worse at the system level, where multiple modules are in series to increase the system voltage to 600 or 1000 V and shading one cell would affect the entire module string.
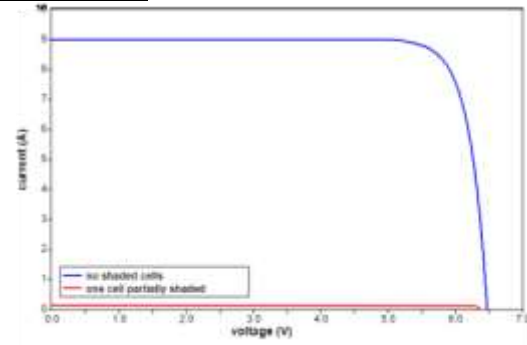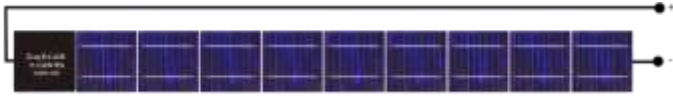
Move the black rectangle over the solar cell. The current is reduced by the amount of shading.

Lecture 7: Resistive effects on solar cells

❖ Resistive Effects
➤ Characteristic Resistance

The characteristic resistance of a solar cell is the output resistance of the solar cell at its maximum power point. If the resistance of the load is equal to the characteristic resistance of the solar cell, then the maximum power is transferred to the load and the solar cell operates at its maximum power point. It is a useful parameter in solar cell analysis, particularly when examining the impact of parasitic loss mechanisms. The characteristic resistance is shown in the figure below.
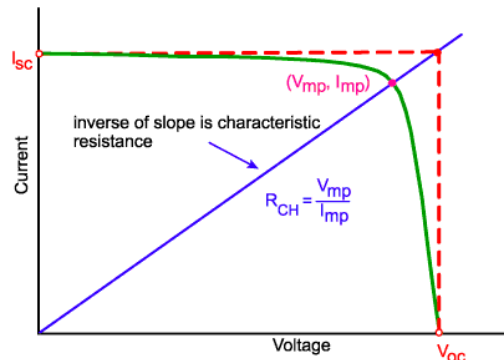
The characteristic resistance of a solar cell is the inverse of the slope of the line, shown in the figure above, which can be given as V_{MP} divided by I_{MP} for most cells it can be approximated by V_{OC} divided by I_{SC}:

$$R_{CH} = \frac{V_{MP}}{I_{MP}} \approx \frac{V_{OC}}{I_{SC}}$$

Commercial silicon solar cells are typically very high current and low voltage. A 156 mm (6 inch) square solar cell has a current of almost 9 amps and a maximum power point voltage of 0.6 volts giving a characteristic resistance of around 0.067 Ω. As a consequence, connections to a single cell require resistances in the milliohm range.
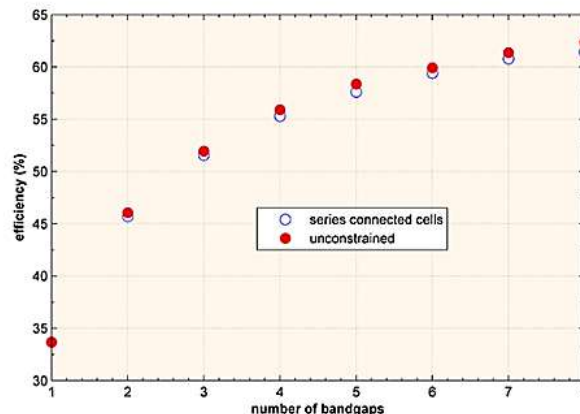
Fig.1: Efficiency of an ideal stack of solar cells as a function of the number of bandgaps. The spectrum used here is the direct spectrum (AM 1.5D) where the diffuse radiation is excluded.

➤ Effect of parasitic Resistances

Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances are series resistance and shunt resistance. The inclusion of the series and shunt resistance on the solar cell model is shown in the figure below.

Fig.2: Parasitic series and shunt resistances in a solar cell circuit.

In most cases and for typical values of shunt and series resistance, the key impact of parasitic resistance is to reduce the fill factor. Both the magnitude and impact of series and shunt resistance depend on the geometry of the solar cell, at the operating point of the solar cell. Since the value of resistance will dep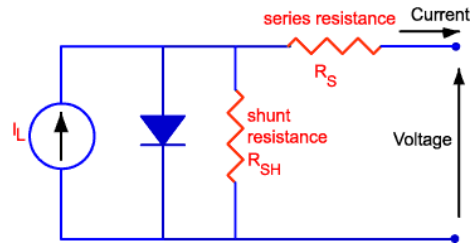end on the area of the solar cell, when comparing the series resistance of solar cells which may have different areas, a common unit for resistance is in Ωcm^2. This area-normalized resistance results from replacing current with current density in Ohm's law as shown below:

$$R'(\Omega\ cm^2) = \frac{V}{J}$$

The effects of series and shunt resistances are described in the following pages.

➤ Effect of Series Resistance

Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.
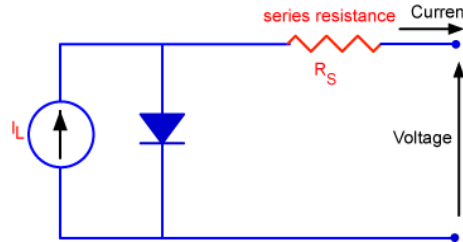
Fig.3: Schematic of a solar cell with series resistance.

$$I = I_L - I_0 exp\left[\frac{q(V + IR_s)}{nkT}\right]$$

where: I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are <u>constants</u>, n is the ideality factor, and R_S is the cell series resistance. The formula is an example of an implicit function due to the appearance of the current, I, on both sides of the equation and requires numerical methods to solve. The effect of the series resistance on the IV curve is shown below. To generate the plot the voltage across the diode is varied thereby avoiding the need to solve an implicit equation.

Cell series resistance, $R_S = 1\ \Omega\ cm^2$

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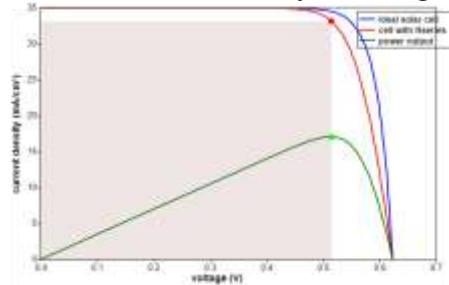
<u>د. وسام عبدالله لطيف</u>

Fig.4: The effect of series resistance on fill factor. The area of the solar cell is 1 cm^2 so that the units of resistance can be either ohm or ohm per cm^2. The short circuit current (I_{SC}) is unaffected by the series resistance until it is very large.

Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero. However, near the open-circuit voltage, the IV curve is strongly affected by the series resistance. A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the IV curve at the open-circuit voltage point.

An equation for the FF as a function of series resistance can be determined by noting that for moderate values of series resistance, the maximum power may be approximated as the power in the absence of series resistance minus the power lost in the series resistance. The equation for the maximum power from a solar cell then becomes:

$$P'_{MP} \approx V_{MP}I_{MP} - I^2_{MP}R_s = V_{MP}I_{MP}\left(1 - \frac{I_{MP}}{V_{MP}}R_s\right) = P_{MP}\left(1 - \frac{I_{SC}}{V_{OC}}R_s\right)$$

$$P'_{MP} = P_{MP}\left(1 - \frac{R_s}{R_{CH}}\right)$$

Defining a normalized series resistance as $r_s = \frac{R_s}{R_{CH}}$, gives the following equation which approximates the effect of series resistance on the output power of a solar cell;

$$P'_{MP} = P_{MP}(1 - r_s)$$

Assuming that the open-circuit voltage and short-circuit current are not affected by the series resistance allows the impact of series resistance on FF to be determined;

$$P'_{MP} = P_{MP}(1 - r_s)$$
$$V'_{OC}I'_{SC}FF' = V_{OC}I_{SC}FF(1 - r_s)$$
$$FF' = FF(1 - r_s)$$

In the above equation the fill factor which is not affected by series resistance is denoted by FF_0 and FF' is called FF_S. The equation then becomes;

$$FF_s = FF_0(1 - r_s)$$

An empirical equation, which is slightly more accurate for the relationship between FF_0 and FF_S is;

$FF_s = FF_0(1 - 1.1r_s) + \frac{r_s^2}{5.4}$, which is valid for $r_s < 0.4$ and $v_{oc} > 10$.

➤ Effect of Shunt Resistance

Significant power losses caused by the presence of a shunt resistance, R_{SH}, are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.

Fig.5: Circuit diagram of a solar cell including the shunt resistance.
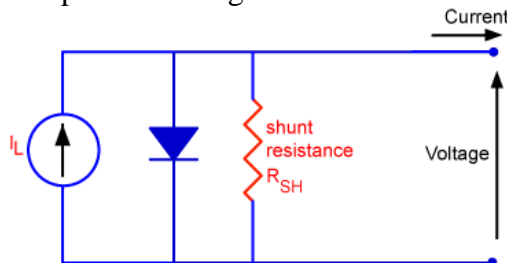
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The equation for a solar cell in presence of a shunt resistance is:

$$I = I_L - I_0 exp\left[\frac{qV}{nkT}\right] - \frac{V}{R_{SH}}$$

Where: I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_{SH} is the cell shunt resistance. The effect of a low shunt resistance is shown in the figure 6.
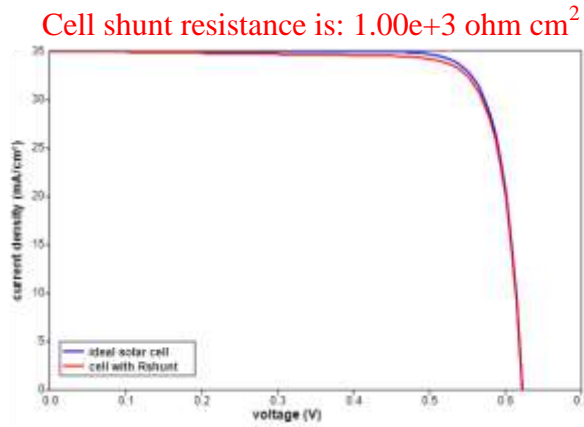
Cell shunt resistance is: 1.00e+3 ohm cm^2

Fig.6: The effect of shunt resistance on fill factor in a solar cell. The area of the solar cell is 1 cm^2, the cell series resistance is zero, temperature is 300 K, and I_0 is 1 x 10^{-12} A/cm^2.

An estimate for the value of the shunt resistance of a solar cell can be determined from the slope of the IV curve near the short-circuit's current point.

The impact of the shunt resistance on the fill factor can be calculated in a manner similar to that used to find the impact of series resistance on fill factor. The maximum power may be approximated as the power in the absence of shunt resistance, minus the power lost in the shunt resistance. The equation for the maximum power from a solar cell then becomes;

$$P'_{MP} \approx V_{MP}I_{MP} - \frac{V_{MP}^2}{R_{SH}} = V_{MP}I_{MP}\left(1 - \frac{V_{MP}}{I_{MP}}\frac{1}{R_{SH}}\right) = P_{MP}\left(1 - \frac{V_{OC}}{I_{SC}}\frac{1}{R_{SH}}\right)$$

$$P'_{MP} = P_{MP}\left(1 - \frac{R_{CH}}{R_s}\right)$$

Defining a normalized shunt resistance as $r_{SH} = \frac{R_{SH}}{R_{CH}}$

Assuming that the open-circuit voltage and short-circuit current are not affected by the shunt resistance allows the impact of shunt resistance on FF to be determined as;

$$P'_{MP} = P_{MP}\left(1 - \frac{1}{r_{SH}}\right)$$

$$V'_{OC}I'_{SC}FF' = V_{OC}I_{SC}FF\left(1 - \frac{1}{r_{SH}}\right)$$

$$FF' = FF\left(1 - \frac{1}{r_{SH}}\right)$$

In the above equation FF, the fill factor which is not affected by shunt resistance is denoted by FF_0 and FF' is called FF_{SH}. The equation then becomes;

$$FF_{SH} = FF_0\left(1 - \frac{1}{r_{SH}}\right)$$

An empirical equation, which is slightly more accurate for the relationship between FF$_0$ and FF$_{SH}$ is;

$FF_{SH} = FF_0\left(1 - \frac{V_{OC}+07}{V_{OC}}\frac{FF_0}{r_{SH}}\right)$, which is valid for $r_{sh} > 0.4$.

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➤ Impact of Both Series and Shunt Resistance

In the presence of both series and shunt resistances, the IV curve of the solar cell is given by;

$$I = I_L - I_0 exp\left[\frac{q(V + IR_s)}{nkT}\right] - \frac{V + IR_s}{R_{SH}}$$

and the circuit diagram of the solar cell is given as;
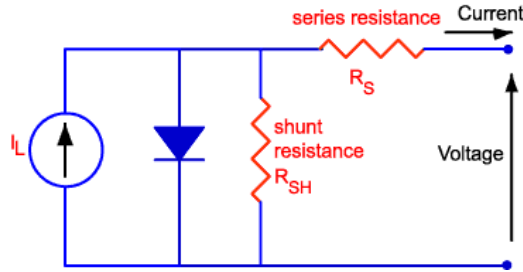
Fig.7: Parasitic series and shunt resistances in a solar cell circuit.

To combine the effect of both series and shunt resistances, the expression for *FF$_{sh}$*, derived above, can be used, with **FF$_0$** replaced by **FF$_s$**. The overall equation then becomes;

$$FF_{SH} = FF_S\left(1 - \frac{V_{OC} + 07}{V_{OC}} \frac{FF_S}{r_{SH}}\right)$$

Where **FF$_s$** is given by;

$$FF_s = FF_0(1 - 1.1r_s) + \frac{r_s^2}{5.4}$$

and by combining the above equations, the net equation for FF becomes;

$$FF = FF_0\left\{(1 - 1.1r_s) + \frac{r_s^2}{5.4}\right\}\left\{1 - \frac{V_{OC} + 07}{V_{OC}} \frac{FF_0}{r_{SH}}\left[(1 - 1.1r_s) + \frac{r_s^2}{5.4}\right]\right\}$$
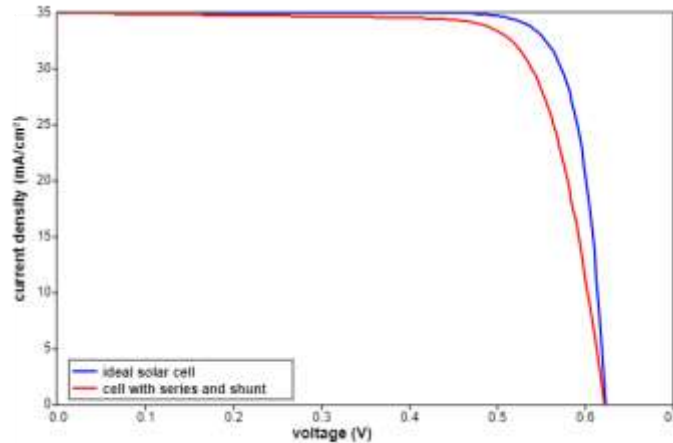
Series Resistance, R$_{series}$ = 1 Ω cm^2
Shunt Resistance, R$_{shunt}$ = 1000.0 Ω cm^2
Fig.8: the IV characteristics of a cell with the above resistors.

Lecture 8: Solar Cell Design Principles

❖ Solar Cell Design Principles

Solar cell design involves specifying the parameters of a solar cell structure in order to maximize efficiency, given a certain set of constraints. These constraints will be defined by the working environment in which solar cells are produced. For example in a commercial environment where the objective is to produce a competitively priced solar cell, the cost of fabricating a particular solar cell structure must be taken into consideration. However, in a research environment where the objective is to produce a highly efficient laboratory-type cell, maximizing efficiency rather than cost, is the main consideration.

The theoretical efficiency for photovoltaic conversion is in excess of 86.8%. However, the 86.8% figure uses detailed balance calculations and does not describe device implementation. For silicon solar cells, a more realistic efficiency under one sun operation is about 29%. The maximum efficiency measured for a silicon solar cell is currently 24.7% under AM1.5G.

The difference between the high theoretical efficiencies and the efficiencies measured from terrestrial solar cells is due mainly to two factors;

1. The theoretical maximum efficiency predictions assume that energy from each photon is optimally used, that there are no unabsorbed photons and that each photon is absorbed in a material which has a band gap equal to the photon energy. This is achieved in theory by modeling an infinite stack of solar cells of different band gap materials, each absorbing only the photons which correspond exactly to its band gap.

2. The high theoretical efficiency predictions assume a high concentration ratio. Assuming that temperature and resistive effects do not dominate in a concentrator solar cell, increasing the light intensity proportionally increases the short-circuit current. Since the open-circuit voltage (V_{oc}) also depends on the short-circuit current, V_{oc} increases logarithmically with light level. Furthermore, since the maximum fill factor (FF) increases with V_{oc}, the maximum possible FF also increases with concentration. The extra V_{oc} and FF increases with concentration which allows concentrators to achieve higher efficiencies.

In designing such single junction solar cells, the principles for maximizing cell efficiency are:

- increasing the amount of light collected by the cell that is turned into carriers;
- increasing the collection of light-generated carriers by the *p-n* junction;
- minimizing the forward bias dark current;
- extracting the current from the cell without resistive losses.

➢ Optical Losses

Optical losses chiefly effect the power from a solar cell by lowering the short-circuit current. Optical losses reduce the generation of an electron-hole pair, because the light is reflected from the front surface, or because it is not absorbed in the solar cell. For the most common semiconductor solar cells, the entire visible spectrum (350 - 780 nm) has enough energy to create electron-hole pairs and therefore all visible light would ideally be absorbed.
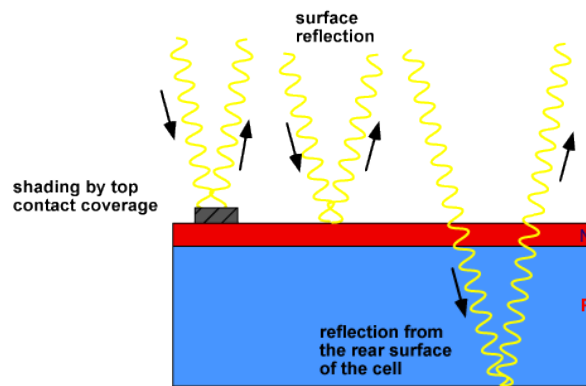

Fig.1: Sources of optical loss in a solar cell.

There are a number of ways to reduce the optical losses:
1. Top contact coverage of the cell surface can be minimized (although this may result in increased series resistance).
2. Anti-reflection coatings can be used on the top surface of the cell.
3. Reflection can be reduced by surface texturing.
4. The solar cell can be made thicker to increase absorption (although light that is absorbed more than a diffusion length from the junction has a low collection probability and will not contribute to the short circuit current).
5. The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

The reflection of a silicon surface is over 30% due to its high refractive index. The reflectivity, R, between two materials of different refractive indices is determined by:

$$R = \left(\frac{n_0 - n}{n_0 + n_{Si}}\right)^2$$

where n_0 is the refractive index of the surroundings and n_{Si} is the complex refractive index of silicon. For an unencapsulated cell $n_0 = 1$. For encapsulated cell $n_0 = 1.5$. The refractive index of silicon changes with wavelength.

❖ Anti-Reflection Coatings (ARC)

Bare silicon has a high surface reflection of over 30%. The reflection is reduced by texturing and by applying anti-reflection coatings (ARC) to the surface. Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses. They consist of a thin layer of dielectric material, with a specially chosen thickness so that interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy. In addition to anti-reflection coatings, interference effects are also commonly encountered when a thin layer of oil on water produces rainbow-like bands of color.
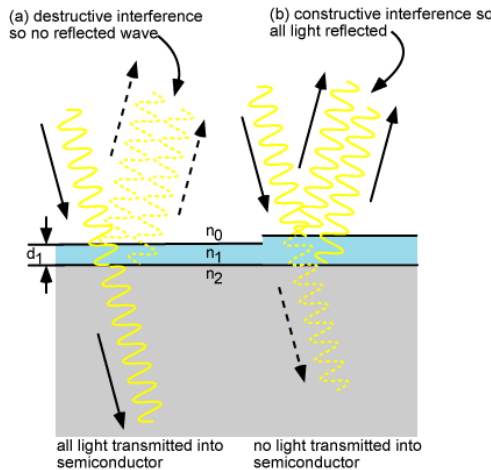
Fig.2: Use of a quarter wavelength anti-reflection coating to counter surface reflection.

The thickness of the anti-reflection coating is chosen so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave. For a quarter wavelength anti-reflection coating of a transparent material with a refractive index n_1 and light incident on the coating with a free-space wavelength λ_0, the thickness d_1 which causes minimum reflection is calculated by:

$$d_1 = \frac{\lambda_0}{4n_1}$$

Reflection is further minimized if the refractive index of the anti-reflection coating is the geometric mean of that of the materials on either side; that is, glass or air and the semiconductor. This is expressed by:

$$n_1 = \sqrt{n_0 n_2}$$

Where, n_0 is the refractive index of the surrounding material, and n_2 is the refractive index of the semiconductor.

For the reflectance at normal incidence we define a series of parameters: r_1, r_2, and θ. The surrounding region has a refractive index of n_0, the ARC has a refractive index of n_1 and a thickness of t_1, and the silicon has a refractive index of n_2.

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$$
$$r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$
$$\theta = \frac{2\pi n_1 t_1}{\lambda}$$

For a single layer ARC on a substrate the reflectivity is:

$$R = |r^2| = \frac{r_1^2 + r_2^2 + 2r_1 r_2 cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 cos 2}$$
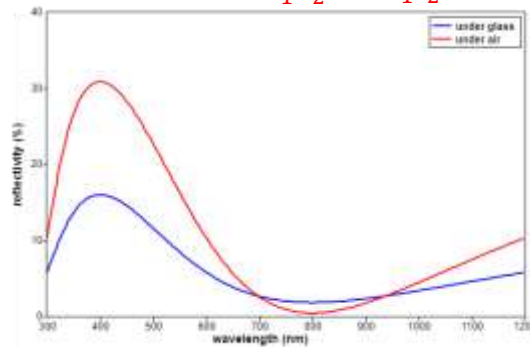
Fig.3: The graph shows the effect of a single layer anti-reflection coating on silicon, assuming a constant refractive index for silicon at 3.5. In reality the refractive index of silicon and the coating is a function of wavelength.

While the reflection for a given thickness, index of refraction, and wavelength can be reduced to zero using the equations above, the refractive index depends on wavelength and so zero reflection occurs only at a single wavelength. For photovoltaic applications, the refractive index, and thickness are chosen in order to minimize reflection for a wavelength of 0.6 μm. This wavelength is chosen since it is close to the peak power of the solar spectrum.

Fig.4: Comparison of surface reflection from a silicon solar cell, with and without a typical anti-reflection coating.
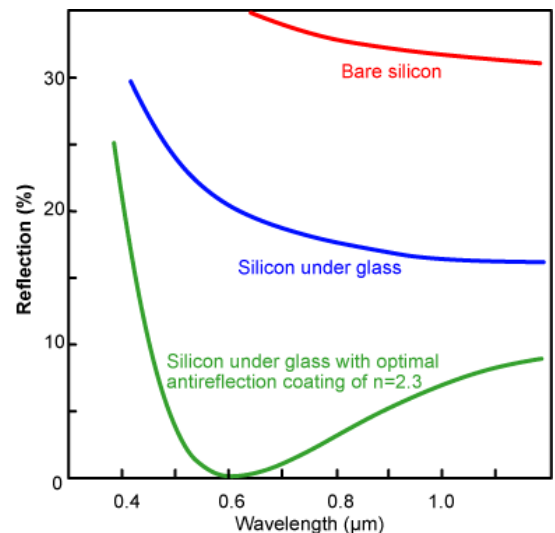
❖ Surface Texturing

Surface texturing, either in combination with an <u>anti-reflection coating</u> or by itself, can also be used to minimize reflection. Any "roughening" of the surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface, rather than out to the surrounding air.

Fig.5: Surface texturing can be accomplished in a number of ways. A single crystalline substrate can be textured by etching along the faces of the crystal planes. The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms. One such pyramid is illustrated in the drawing below. An electron microscope photograph of a textured silicon surface is shown in the photograph below. This type of texturing is called "random pyramid" texture, and is commonly used in industry for single crystalline wafers.
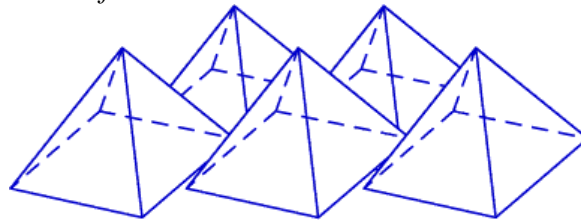
Fig.6: A square based pyramid which forms the surface of an appropriately textured crystalline silicon solar cell.
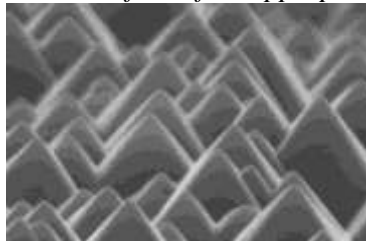
Fig.7: Scanning electron microscope photograph of a textured silicon surface.

Another type of surface texturing used is known as "inverted pyramid" texturing. Using this texturing scheme, the pyramids are etched down into the silicon surface rather than etched pointing upwards from the surface. A photograph of such a textured surface is shown below.
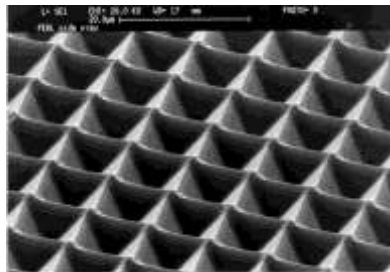
Fig.8: Scanning electron microscope photograph of a textured silicon surface.

For multicrystalline wafers, only a small fraction of the surface will have the required orientation of <100> and consequently these techniques are less effective on multicrystalline wafers. However, multicrystalline wafers

can be textured using a photolithographic technique as well as mechanically sculpting the front surface using dicing saws or lasers to cut the surface into an appropriate shape. A micrograph of a photolithographic texturing scheme is shown below.

Fig.9: Scanning electron microscope photograph of a textured multicrystalline silicon surface.

❖ Material Thickness

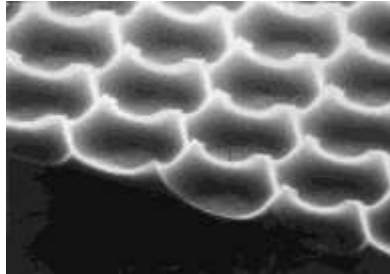While the reduction of reflection is an essential part of achieving a high efficiency solar cell, it is also essential to absorb all the light in the silicon solar cell. The amount of light absorbed depends on the optical path length and the absorption coefficient. Figure 10 below shows the dependence of photon absorption on device thickness for a silicon solar cell.

The device simulated is a cell with no front surface reflection losses so that the entire incident light enters the cell. The electronic properties are assumed to be perfect (infinite diffusion length) so that all light generated carriers are collected. Finally, the light only passes once through the cell. In reality, thin cells are usually designed with a reflector on the rear so that light makes multiple passes across the cell and the absorption is increased. In the case of ideal lambertian light trapping the path length is effectively increased by $4n^2$ where n is the index of refraction for the semiconductor. For silicon with a refractive index of 3.5, light trapping increases the path length by a factor of ~50. See light trapping section.
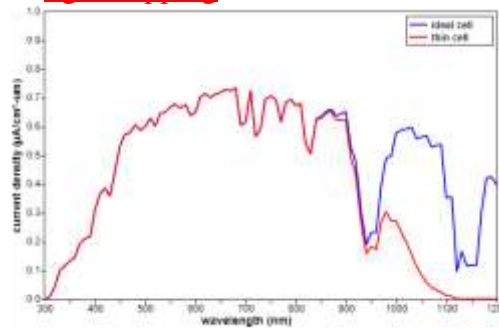
Cell thickness, t = 100 μm. In silicon J_{SC} = 0.0366 A/cm²

Fig.10: For silicon material in excess of 10 mm thick, essentially all the light with energy above the band gap is absorbed. The 100% of the total current refers to the fact that at 10 mm, all the light which can be absorbed in silicon, is absorbed. In material of 10 μm thick, only 30% of the total available current is absorbed. The photons which are lost are the orange and red photons.

❖ Light Trapping

The optimum device thickness is not controlled solely by the need to absorb all the light. For example, if the light is not absorbed within a diffusion length of the junction, then the light-generated carriers are lost to recombination. In addition, as discussed in the Voltage Losses Due to Recombination, a thinner solar cell which retains the absorption of the thicker device may have a higher voltage. Consequently, an optimum solar cell structure will typically have "light trapping" in which the optical path length is several times the actual device thickness, where the optical path length of a device refers to the distance that an unabsorbed photon may travel within the device before it escapes out of the device. This is usually defined in terms of device thickness. For example, a solar cell with no light trapping features may have an optical path length of one device thickness,

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while a solar cell with good light trapping may have an optical path length of 50, indicating that light bounces back and forth within the cell many times.

Light trapping is usually achieved by changing the angle at which light travels in the solar cell by having it be incident on an angled surface. A textured surface will not only reduce reflection as previously described but will also couple light obliquely into the silicon, thus giving a longer optical path length than the physical device thickness. The angle at which light is refracted into the semiconductor material is, according to Snell's Law, as follows:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

where θ_1 and θ_2 are the angles for the light incident on the interface relative to the normal plane of the interface within the mediums with refractive indices n_1 and n_2 respectively.

By rearranging Snell's law above, the angle at which light enters the solar cell (the angle of refracted light) can be calculated:

$$\theta_2 = sin^{-1}\left(\frac{n_2}{n_1} sin\theta_1\right)$$

In a textured single crystalline solar cell, the presence of crystallographic planes make the angle θ_1 equal to 36° as shown below.
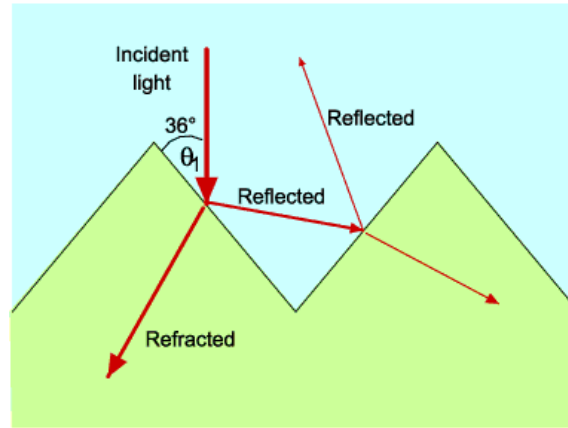
Fig.11: Reflection and transmission of light for a textured silicon solar cell.

The amount of light reflected at an interface is calculated from the Fresnel reflection formula. For light polarized in the parallel to the surface the amount of reflected light is:

$$R_\parallel = \frac{tan^2(\theta_1 - \theta_2)}{tan^2(\theta_1 + \theta_2)}$$

For light polarized perpendicular to the surface the amount reflected is:

$$R_\perp = \frac{sin^2(\theta_1 - \theta_2)}{sin^2(\theta_1 + \theta_2)}$$

For un-polarized light the reflected amount is the average of the two:

$$R_T = \frac{R_\perp + R_\parallel}{2}$$

If light passes from a high refractive index medium to a low refractive index medium, there is the possibility of total internal reflection (TIR). The angle at which this occurs is the critical angle and is found by setting $\theta_2 = 0$ in Snell's law.

$$\theta_1 = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Using total internal reflection, light can be trapped inside the cell and make multiple passes through the cell, thus allowing even a thin solar cell to maintain a high optical path length.
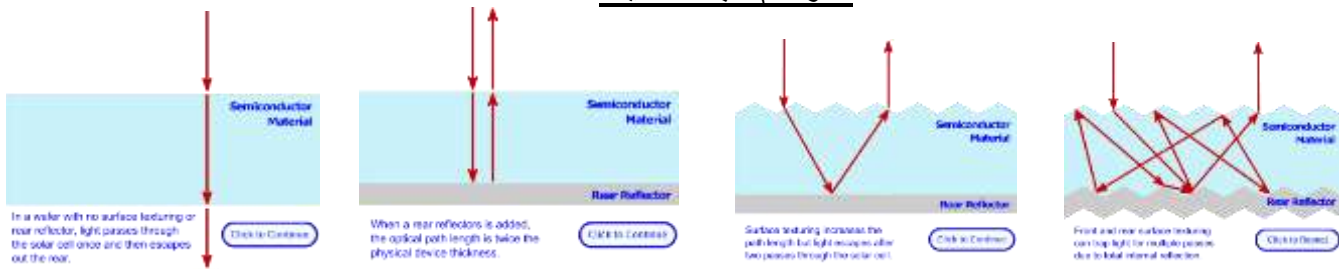
❖ Lambertian Rear Reflectors

A Lambertian back reflector is a special type of rear reflector which randomizes the direction of the reflected light.

- <u>Advantages of rear reflectors</u>
1. High reflection off the rear cell surface reduces absorption in the rear cell contacts or transmission from the rear, allowing the light to bounce back into the cell for possible absorption.
2. Randomizing the direction of light allows much of the reflected light to be totally internally reflected.
3. Light reaching the top surface at an angle greater than the critical angle for total internal reflection is reflected again towards the back surface. Light absorption can be dramatically increased in this way;
4. Since the path length of the incident light can be enhanced by a factor up to $4n^2$ where n is the index of refraction for the semiconductor. This allows an optical path length of approximately 50 times the physical devices thickness and thus is an effective light trapping scheme.

A Lambertian rear surface is illustrated in the figure below.
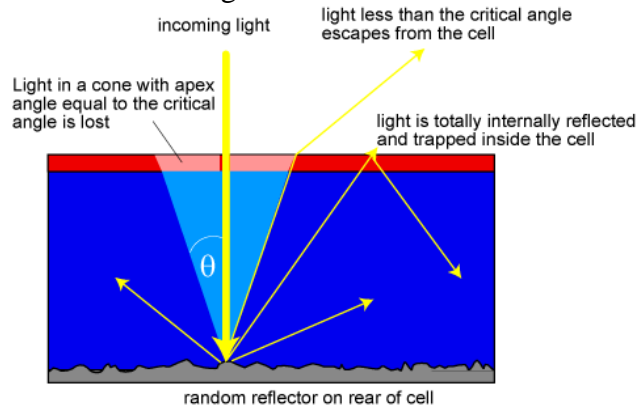
Fig.12: Light trapping using a randomized reflector on the rear of the cell. Light less than the critical angle escapes the cell but light greater than the critical angle is totally internally reflected inside the cell. In actual devices, the front surface is also textured using schemes such as the random pyramids mentioned earlier.

The graph below shows the short-circuit current of a silicon solar cell with and without light trapping. In the case without light trapping, the light makes only one pass through the solar cell with some of the light (particularly in the infrared) passing straight through the cell without being absorbed. In the case with ideal light trapping the path length is increased by $4n^2$ ($4 \times 3.5^2 \approx 50$) and the short-circuit current is much higher. In practice the level of light trapping is somewhere between these two limits.
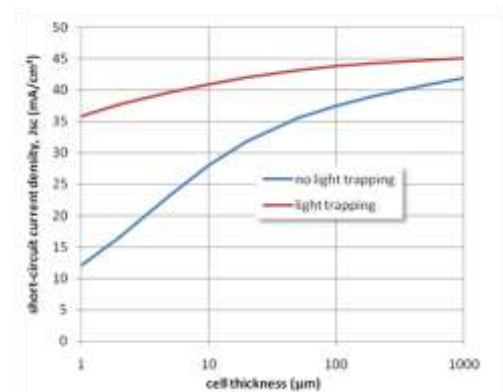
Light trapping increases the short-circuit current (J_{SC}) of the solar cell - particularly for thin devices.

Lecture 9: Recombination losses

❖ Recombination

Recombination is the opposite process to generation. An electron recombines with a hole and gives up the energy to produce either heat or light.

A device where the recombination is optimized to give off light is called a Light Emitting Diode (LED).

❖ Types of Recombination

Any electron which exists in the conduction band is in a meta-stable state and will eventually stabilize to a lower energy position in the valence band. When this occurs, it must move into an empty valence band state. Therefore, when the electron stabilizes back down into the valence band, it also effectively removes a hole. This process is called recombination. There are three basic types of recombination in the bulk of a single-crystal semiconductor. These are:

- Radiative recombination;
- Auger recombination; and
- Shockley-Read-Hall recombination.
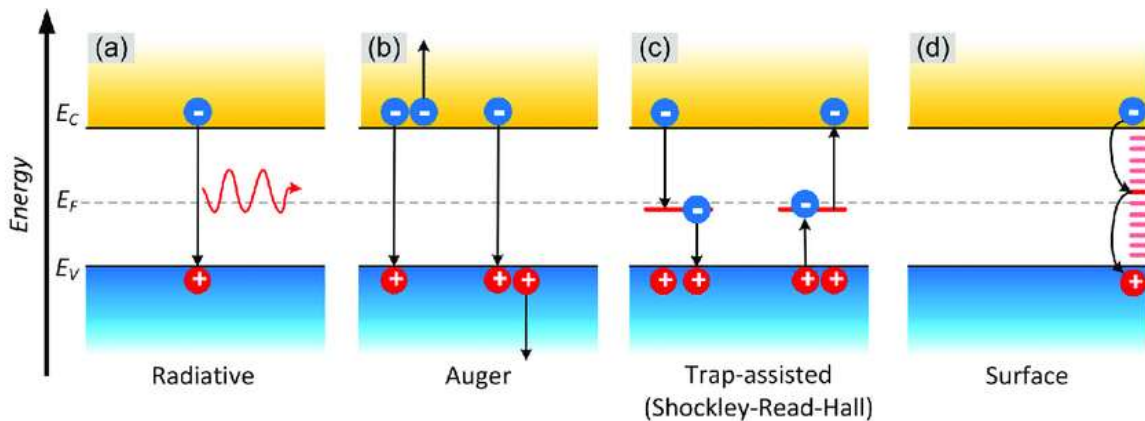
Fig.1: representation of recombination mechanisms.

➢ Radiative (Band-to-Band) Recombination

Radiative recombination is the recombination mechanism that dominates in *direct* bandgap semiconductors. The key characteristics of radiative recombination are:

- In radiative recombination, an electron from the conduction band directly combines with a hole in the valence band and releases a photon; and
- The emitted photon has energy similar to the band gap and is therefore only weakly absorbed such that it can exit the piece of semiconductor.
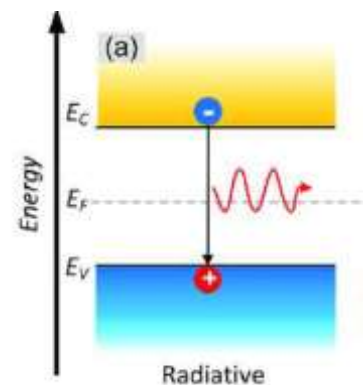
The light produced from a light emitting diode (LED) is the most obvious example of radiative recombination in a semiconductor device. Concentrator and space solar cells are typically made from direct bandgap materials (e.g. GaAs) and radiative recombination dominates. However, most terrestrial solar cells are made from silicon, which is an *indirect* bandgap semiconductor and radiative recombination is extremely low and usually neglected.

➤ Recombination through Defect Levels

Recombination through defects, also called Shockley-Read-Hall or SRH recombination does not occur in perfectly pure material.

> SRH recombination is a two-step process. The two steps involved are:
> * An electron (or hole) is trapped by an energy state in the forbidden region which is introduced through defects in the crystal lattice. These defects can either be unintentionally introduced or deliberately added to the material, for example in doping the material; and
> * If a hole (or an electron) moves up to the same energy state before the electron is thermally re-emitted into the conduction band, then it recombines.

The rate at which a carrier moves into the energy level in the forbidden gap depends on the distance of the introduced energy level from either of the band edges. Therefore, if energy is introduced close to either band edge, recombination is less likely as the electron is likely to be re-emitted to the conduction band edge rather than recombine with a hole which moves into the same energy state from the valence band. For this reason, energy levels near mid-gap are very effective for recombination.

➤ Auger Recombination

> Auger Recombination involves three carriers. An electron and a hole recombine, but rather than emitting the energy as heat or as a photon, the energy is given to a third carrier, an electron in the conduction band. This electron then thermalizes back down to the conduction band edge.

Auger recombination is most important at high carrier concentrations caused by heavy doping or high level injection under concentrated sunlight. In silicon-based solar cells (the most popular), Auger recombination limits the lifetime and ultimate efficiency. The more heavily doped the material is, the shorter the Auger recombination lifetime.

❖ Recombination Losses

Recombination losses effect both the current collection (and therefore the short-circuit current) as well as the forward bias injection current (and therefore the open-circuit voltage). Recombination is frequently classified according to the region of the cell in which it occurs. Typically, recombination at the surface (surface recombination) or in the bulk of the solar cell (bulk recombination) is the main areas of recombination. The depletion region is another area in which recombination can occur (depletion region recombination).

➤ Current Losses Due to Recombination

In order for the *p-n* junction to be able to collect all of the light-generated carriers, both surface and bulk recombination must be minimized. In silicon solar cells, the two conditions commonly required for such current collection are:

1. the carrier must be generated within a diffusion length of the junction, so that it will be able to diffuse to the junction before recombining; and
2. in the case of a localized high recombination site (such as at an unpassivated surface or at a grain boundary in multicrystalline devices), the carrier must be generated closer to the junction than to the recombination site. For less severe localized recombination sites, (such as a passivated surface), carriers can be generated closer to the recombination site while still being able to diffuse to the junction and be collected without recombining.
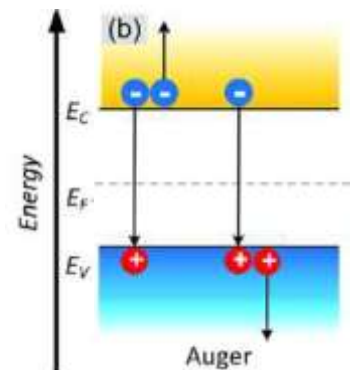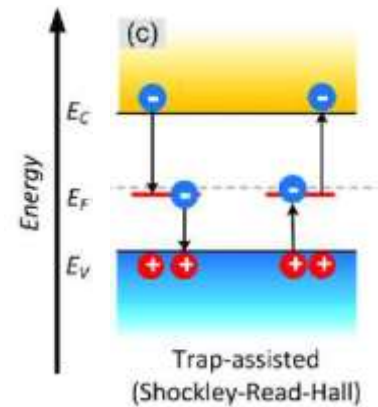
The presence of localized recombination sites at both the front and the rear surfaces of a silicon solar cell mean that photons of different energy will have different collection probabilities. Since blue light has a high absorption coefficient and is absorbed very close to the front surface, it is not likely to generate minority carriers that can be collected by the junction if the front surface is a site of high recombination. Similarly, a high rear surface recombination will primarily affect carriers generated by infrared light, which can generate carriers deep in the device. The quantum efficiency of a solar cell quantifies the effect of recombination on the light generation current. The quantum efficiency of a silicon solar cell is shown below.
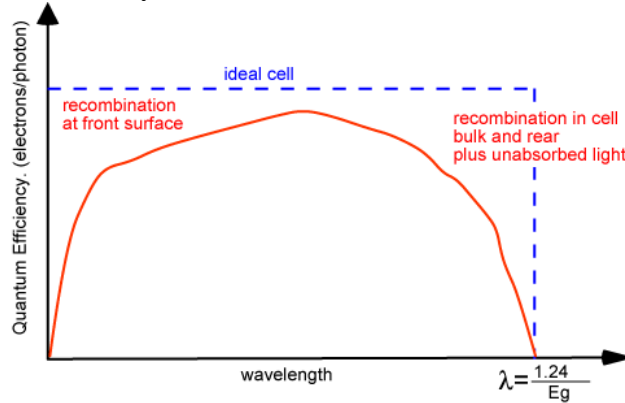
Fig.2: Typical quantum efficiency in an ideal and actual solar cell, illustrating the impact of optical and recombination losses.

➤ Voltage Losses due to Recombination

<u>The open-circuit voltage</u> is the voltage at which the forward bias diffusion current is exactly equal to the short circuit current. The forward bias diffusion current depends on the amount of recombination in a *p-n* junction and increasing the recombination increases the forward bias current. Consequently, high recombination increases the forward bias diffusion current, which in turn reduces the open-circuit voltage. The material parameter which gives the recombination in forward bias is the diode saturation current. The recombination is controlled by the number of minority carriers at the junction edge, how fast they move away from the junction and how quickly they recombine. Consequently, the dark forward bias current, and hence the open-circuit voltage is affected by the following parameters:

1. The number of minority carriers at the junction edge. The number of minority carriers injected from the other side is simply the number of minority carriers in equilibrium multiplied by an exponential factor which depends on the voltage and the temperature. Therefore, minimizing the equilibrium minority carrier concentration reduces recombination. Minimizing the equilibrium carrier concentration is achieved by **increasing the doping**;

2. The diffusion length in the material. A low diffusion length means that minority carriers disappear from the junction edge quickly due to recombination, thus allowing more carriers to cross and increasing the forward bias current. Consequently, to minimize recombination and achieve a high voltage, a **high diffusion length is required.**
   - The diffusion length depends on
     a) the types of material,
     b) the processing history of the wafer and
     c) the doping in the wafer.

   High doping reduces the diffusion length, thus introducing a trade-off between maintaining a high diffusion length (which affects both the current and voltage) and achieving a high voltage;

3. The presence of localized recombination sources within a diffusion length of the junction. A high recombination source close to the junction (usually a surface or a grain boundary) will allow carriers to

move to this recombination source very quickly and recombine, thus dramatically increasing the recombination current. The impact of surface recombination is reduced by **passivating the surfaces**. The net effect of previous trade-offs is shown in the graphs below.
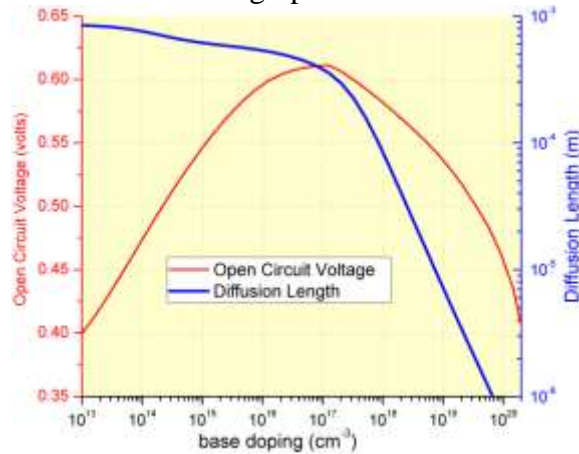
Fig.3: Effect of doping (N_D) on diffusion length and open-circuit voltage assuming well passivated surfaces.

➢ Surface Recombination

Surface recombination can have a major impact both on the short-circuit current and on the open-circuit voltage. High recombination rates at the top surface have a particularly detrimental impact on the short-circuit current since top surface also corresponds to the highest generation region of carriers in the solar cell. Lowering the high top surface recombination is typically accomplished by reducing the number of dangling silicon bonds at the top surface by using "passivating" layer on the top surface. The majority of the electronics industry relies on the use of a thermally grown silicon dioxide layer to passivate the surface due to the low defect states at the interface. For commercial solar cells, dielectric layers such as silicon nitride are commonly used.
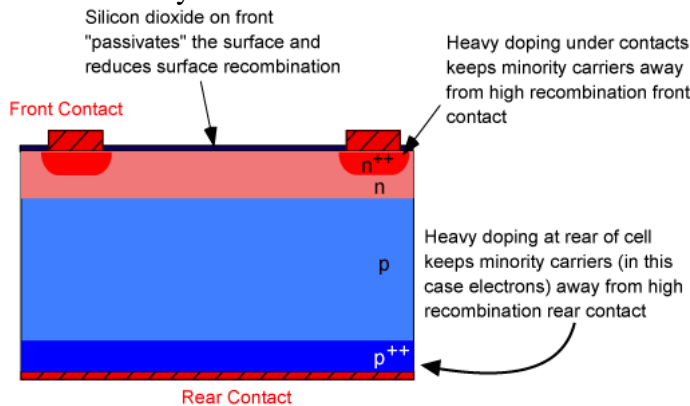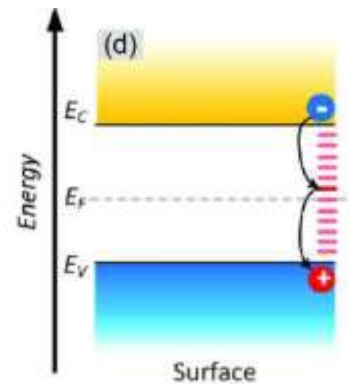
Fig.4: Techniques for reducing the impact of surface recombination.

Since the passivating layer for silicon solar cells is usually an insulator, any region which has an ohmic metal contact cannot be passivated using silicon dioxide. Instead, under the top contacts the effect of the surface recombination can be minimized by increasing the doping. While typically such a high doping severely degrades the diffusion length, the contact regions do not participate in carrier generation and hence the impact on carrier collection is unimportant. In addition, in cases where a high recombination surface is close to the junction, the lowest recombination option is to increase the doping as high as possible.

• Back Surface Field

A similar effect is employed at the rear surface to minimize the impact of rear surface recombination velocity on voltage and current if the rear surface is closer than a diffusion length to the junction. A "back surface field"

(BSF) consists of a higher doped region at the rear surface of the solar cell. The interface between the high and low doped regions behave like a *p-n* junction and an electric field forms at the interface which introduces a barrier to minority carrier flow to the rear surface. The minority carrier concentration is thus maintained at higher levels in the bulk of the device and the BSF has a net effect of passivating the rear surface.

Lecture 10: The Operation Principle of a Solar Cell (Part 1)

The Operation Principle of a Solar Cell

The working principle of solar cells is based on the photovoltaic effect, i.e. the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaic effect is closely related to the photoelectric effect, where electrons are emitted from a material that has absorbed light with a frequency above a material-dependent threshold frequency. In 1905, Albert Einstein understood that this effect can be explained by assuming that the light consists of well defined energy quanta, called photons. The energy of such a photon is given by

$$E_{ph} = hf \tag{1}$$

Where h is Planck's constant and f is the frequency of the light. The photovoltaic effect can be divided into three basic processes:

1. Generation of the charge carriers due to the absorption of photons in the materials that form a junction,

   In general, a solar cell structure consists of an absorber layer, in which the photons of an incident radiation are efficiently absorbed resulting in a creation of electron-hole pairs.

   Absorption of a photon in a material means that its energy is used to excite an electron from an initial energy level E_i to a higher energy level E_f , as shown in Fig. 1 (a). Photons can only be absorbed only if its energy equals the energy difference between the initial and final energy states.

   $$E_{ph} = E_f - E_i$$
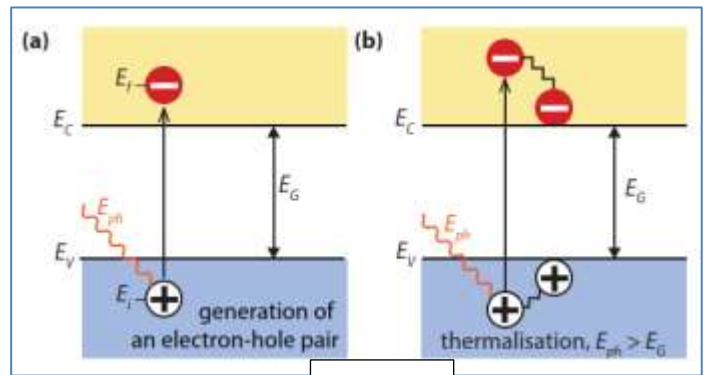
Figure 1

In an ideal semiconductor electrons can populate energy levels below the so-called valence band edge,E_V and above the so called conduction band edge, E_C. Between those two bands no allowed energy states exist, which could be populated by electrons. Hence, this energy difference is called the *bandgap*,

$$E_G = E_C - E_V$$

If a photon with energy smaller than E_G reaches an ideal semiconductor, it will not be absorbed but will traverse the material without interaction. If $E_{ph} > E_G$, a part of the energy is thermalized, fig.1 (b).

In a real semiconductor, the valence and conduction bands depend on the so-called *k-vector* that describes the momentum of an electron in the semiconductor. This means, that the energy of an electron is dependent on its momentum because of the periodic structure of the semiconductor crystal. If the maximum of the valence band and the minimum of the conduction band occur at the same *k-vector*, an electron can be excited from the valence to the conduction band without a change in the momentum. Such a semiconductor is called a direct bandgap material. If the electron cannot be excited without changing its momentum, we speak of an indirect bandgap material. The electron can only change its momentum by momentum exchange with the crystal, i.e. by receiving momentum from or giving momentum to vibrations of the crystal lattice called phonon. The absorption coefficient in a direct bandgap material is much higher than in an indirect bandgap material, thus the absorbing semiconductor, often just called the absorber.

If an electron is excited from E_i to E_f , a void is created at E_i. This void behaves like a particle with a positive elementary charge and is called a *hole*. The absorption of a photon therefore leads to the creation of an electron-hole pair, as illustrated in Fig. 2 ❶. The radiative energy of the photon is converted to the chemical energy of the electron-hole pair. The maximal conversion efficiency from radiative energy to

chemical energy is limited by thermodynamics. This thermodynamic limit lies in between 67% for non-concentrated sunlight and 86% for fully concentrated sunlight

2. Subsequent separation of the photo-generated charge carriers in the junction,
   Usually, the electron-hole pair will recombine, i.e. the electron will fall back to the initial energy level Ei, as illustrated in Fig. 2 ❷. The energy will then be released either as photon (Radiative recombination) or transferred to other electrons or holes or lattice vibrations (non-radiative recombination).

In order to separate the photo-generated electrons and holes from each other, the so-called "semi-permeable membranes" are attached to the both sides of the absorber. The semi-permeable membranes selectively allow only one type of charge carrier to pass through as illustrated in Fig. 2 ❸. An important issue for designing an efficient solar cell is that the electrons and holes generated in the absorber layer reach the membranes. This requires that the diffusion lengths of the charge carriers are larger than the thickness of the absorber. In most solar cells, these membranes are formed by n- and p-type materials. A membrane that let
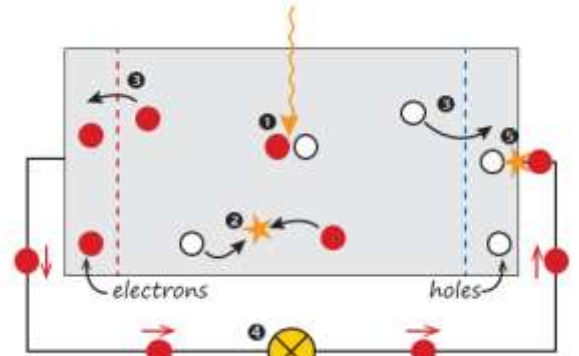

Figure 2

electrons go through and blocks holes is a material, which has a large conductivity for electrons and a small conductivity of holes. An example of such a material is an n-type semiconductor, in which a large electron conductivity with respect to the hole conductivity is caused namely by a large difference in electron and hole concentrations. Electrons can easily flow through the n-type semiconductor while the transport of holes, which are the minority carriers in such material, is due to the recombination processes very limited. The opposite holds for electrons in a p-type semiconductor, which is an example of the hole membrane.

3. Collection of the photo-generated charge carriers at the terminals of the junction.
   Finally, the charge carriers are extracted from the solar cells with electrical contacts so that they can perform work in an external circuit (Fig. 2 ❹). The chemical energy of the electron-hole pairs is finally converted to electric energy. After the electrons passed through the circuit, they will recombine with holes at a metal-absorber interface, as illustrated in Fig.2 ❺.

   ❖ <u>Electrostatic analysis - potential diagrams</u>
   In this section, we will show how to use the Poisson equation and current density equations to calculate the built-in electric field, ε, the electrostatic-potential, ψ, and the width of the depletion layer, W_d.

   ➢ Formation of a space-charge region in the p-n junction.
   Figure 3 shows schematically isolated pieces of a p-type and an n-type semiconductor and their corresponding band diagrams. In both isolated pieces the charge neutrality is maintained. In the n-type semiconductor the large concentration of negatively-charged free electrons is compensated by positively-charged ionized donor atoms N_D^+. In the p-type semiconductor holes are the majority carriers and the positive charge of holes is compensated by negatively-charged ionized acceptor atoms N_A^-. For the isolated n-type semiconductor we can write:
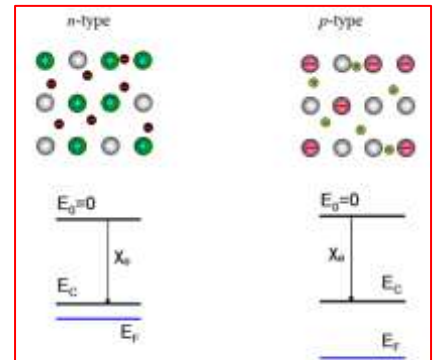

Figure 3. The electron affinity, denoted by χ (units: eV), of a semiconductor is the energy required to move an electron from the conduction band bottom to the vacuum level and is a material constant.

$$n = n_{n0} \approx N_D \qquad (1a)$$

$$p = p_{n0} \approx \frac{n_i^2}{N_D} \qquad (1b)$$

For the isolated p-type semiconductor

$$p = p_{p0} \approx N_A \qquad (2a)$$

Solar PV Systems :المادة

$$n = n_{p0} \approx \frac{n_i^2}{N_A} \qquad (2b)$$

When a p-type and an n-type semiconductor are brought together, a very large difference in electron concentration between n- and p-type semiconductors causes a diffusion current of electrons from the n-type material across the junction into the p-type material. Similarly, the difference in hole concentration causes a diffusion current of holes from the p- to the n-type material. Due to this diffusion process the region close to the junction becomes almost completely depleted of mobile charge carriers. The gradual depletion of the charge carriers gives rise to a space charge created by the charge of the ionized donor and acceptor atoms that is not compensated by the mobile charges any more. This region of the space charge is called the space-charge region or depleted region. The space charge around the junction results in the formation of an internal electric field which forces the charge carriers to move in the opposite direction than the concentration gradient. The diffusion currents continue to flow until the forces acting on the charge carriers, namely the concentration gradient and the internal electrical field, compensate each other. Regions outside the depletion region, in which the charge neutrality is conserved, are denoted as the quasi-neutral regions.

➢ Equilibrium conditions - p-n junction under zero bias.

Under equilibrium conditions the Fermi level has constant position in the band diagram of the p-n junction. Figure 4 shows the energy-band diagram of a p-n junction under equilibrium. The distance between the Fermi level and the valence and/or conduction bands does not change in the quasi-neutral regions and is the same as in the isolated n- and p-type semiconductors. Inside the space-charge region, the conduction and valence bands are not represented by straight horizontal lines any more but they are curved. This indicates the presence of an electric field in this region. Due to the electric field a difference in the electrostatic potential is created between the boundaries of the space-charge region. Across the depletion region the changes in the carrier's concentration are compensated by changes in the electrostatic potential. The electrostatic-potential profile is included in Figure 4.

Figure 4

The concentration profile of charge carriers in a p-n junction is schematically presented in Figure 5. In the quasi-neutral regions the concentration of electrons and holes is the same as in the isolated doped semiconductors. In the space-charge region the concentrations of majority charge carriers decrease very rapidly.

Figure 5

➢ The depletion approximation

The presence of the internal electric field inside the p-n junction means that there is an electrostatic potential difference, ψ_0, across the space-charge region. We shall determine a profile of the internal electric field and electrostatic potential in the p-n junction. First we introduce an approximation, which simplifies the calculation of the electric field and electrostatic-potential. This approximation (the depletion approximation) assumes that the space-charge density, ρ, is zero in the quasi-neutral regions and it is fully determined by the concentration of ionized dopants in the depletion region. In the depletion region of the n-type semiconductor it is the concentration of positively charged donor atoms, N_D which determines the space charge in this region. In the p-type semiconductor, the concentration of negatively charged acceptor atoms, N_A, determines the space charge in the depletion region. This is illustrated in Figure 6. Further, we assume that the p-n junction is a step junction; it means that there is an abrupt change in doping at the junction and the doping concentration is uniform both in the p-type and the n-type semiconductors.
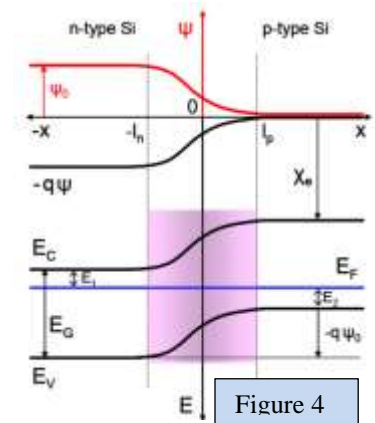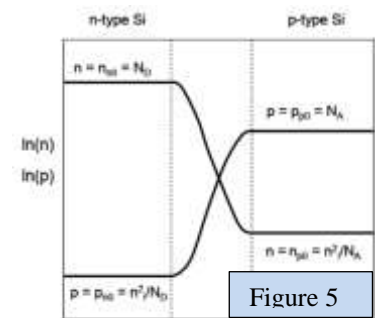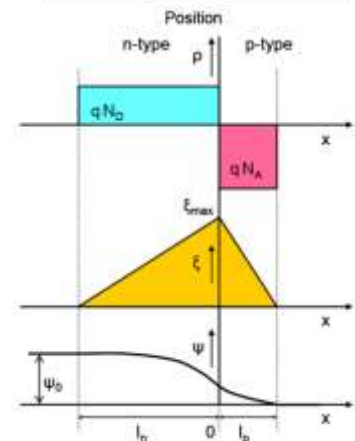

Figure 6

The position of the junction is placed at zero, the width of the space-charge region in the n-type material is denoted as l_n and the width of the space-charge region in the p-type material is denoted as l_p. The space-charge density is described by following equations:

$$\rho(x) = qN_D \qquad\qquad\qquad for -l_n \leq x \leq 0 \qquad\qquad (3a)$$
$$\rho(x) = -qN_A \qquad\qquad\qquad for \;\; 0 \leq x \leq l_p \qquad\qquad (3b)$$

Outside the space-charge region the space-charge density ρ is zero.

The electric field can be calculated from the Poisson's equation, which has the following form for one dimensional analysis:

$$\frac{d^2\psi}{dx^2} = -\frac{d\xi}{dx} = -\frac{\rho}{\varepsilon_r \varepsilon_0} \qquad\qquad (4)$$

Where ψ is the electrostatic potential, ξ is the electric field, ρ is the space-charge density, ε_r is the semiconductor dielectric constant and ε_0 is the permittivity of the vacuum. For crystalline Si $\varepsilon_r = 11.7$ and the permittivity of the vacuum $\varepsilon_0 = 8.854 \times 10^{-14} F/cm$. The electric field profile can be found by integrating the space-charge density across the space-charge region.

$$\xi = \frac{1}{\varepsilon_r \varepsilon_0} \int \rho \, dx \qquad\qquad (5)$$

Substituting eqns. (3a) and (3b) for the space-charge density and using the following boundary conditions:

$$\xi(-l_n) = \xi(l_p) = 0 \qquad\qquad (6)$$

The solution for the electric field is

$$\xi(x) = \frac{q}{\varepsilon_r \varepsilon_0} N_D(l_n + x) \qquad\qquad for -l_n \leq x \leq 0 \qquad\qquad (7a)$$
$$\xi(x) = \frac{q}{\varepsilon_r \varepsilon_0} N_A(l_p - x) \qquad\qquad for \;\; 0 \leq x \leq l_p \qquad\qquad (7b)$$

At the junction, $x = 0$ the electric field is continuous, which requires that the following condition has to be fulfilled

$$N_A l_p = N_D l_n \qquad\qquad (8)$$

Outside the space-charge region the material is electrically neutral and therefore the electric field is zero there. The profile of the electrostatic potential is calculated by integrating the electric field throughout the space-charge region and applying the boundary conditions.

$$\psi = -\int \xi \, dx \qquad\qquad (9)$$

We define the zero electrostatic potential level at the outside edge of the p-type semiconductor. Since we assume no potential drop across the quasi-neutral region the electrostatic potential at the boundary of the space-charge region in the p-type material is also zero

$$\psi(l_p) = 0 . \qquad\qquad (10)$$

Using Eqns. (7a) and (7b) for describing the electric field in the n-type and p-type parts of the space-charge region, respectively, and taking into account that at the junction the electrostatic potential is continuous, the solution for the electrostatic potential can be written as:

$$\psi(x) = -\frac{q}{2\varepsilon_r \varepsilon_0} N_D(x + l_n)^2 + \frac{q}{2\varepsilon_r \varepsilon_0}\left(N_D l_n^2 + N_A l_p^2\right) \qquad for -l_n \leq x \leq 0 \qquad (11a)$$
$$\psi(x) = \frac{q}{2\varepsilon_r \varepsilon_0} N_D\left(x - l_p\right)^2 \qquad\qquad\qquad\qquad for \;\; 0 \leq x \leq l_p \qquad (11b)$$

Under equilibrium a difference in electrostatic potential, ψ_0, develops across the space-charge region. The electrostatic potential difference across the p-n junction is an important characteristic of the junction and is denoted as the built-in potential or diffusion potential of the p-n junction. We can calculate ψ_0 as the difference between the electrostatic potential at the edges of the space-charge region:

$$\psi_0 = \psi(-l_n) - \psi(-l_p) = \psi(-l_n) \qquad\qquad (12)$$

Using Eq. (11a) we obtain for the built-in potential the following expression:

$$\psi_0 = \frac{q}{2\varepsilon_r \varepsilon_0}\left(N_D l_n^2 + N_A l_p^2\right) \tag{13}$$

Another way to determine the built-in potential ψ_0 is to use the energy-band diagram presented in Figure 4.

$$q\psi_0 = E_G - E_1 - E_2 \tag{14}$$

Using

$$E_G = E_C - E_V$$
$$E_1 = E_C - E_F = kT\ ln(N_C/N_D)$$
$$E_2 = E_F - E_V = kT\ ln(N_V/N_A)$$

We can write

$$q\psi_0 = E_G - kT\ ln(N_V/N_A) - kT\ ln(N_C/N_D) = E_G - kT\ ln\left(\frac{N_V N_C}{N_A N_D}\right) \tag{15}$$

Using the relationship between the intrinsic concentration, n_i and the band gap, E_G

$$n_i^2 = N_V N_C\ exp(-E_G/kT)$$

we can rewrite Eq. (15) to obtain

$$\psi_0 = \frac{kT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{16}$$

Eq. (16) allows us to determine the built-in potential of a p-n junction from the standard semiconductor parameters, such as doping concentrations and the intrinsic carrier concentration. When knowing the built-in potential we can calculate the width of the space charge region of the p-n junction in the thermal equilibrium. Substituting ψ_0 using Eq. (16) into Eq. (13) and taking the condition (7) into account, the resulting expressions for ln and lp are obtained.

$$l_n = \sqrt{\frac{2\varepsilon_r \varepsilon_0}{q}\ \psi_0\ \frac{N_A}{N_D}\left(\frac{1}{N_A + N_D}\right)} \tag{17a}$$

$$l_p = \sqrt{\frac{2\varepsilon_r \varepsilon_0}{q}\ \psi_0\ \frac{N_D}{N_A}\left(\frac{1}{N_A + N_D}\right)} \tag{17b}$$

The total space-charge width, W_d, is the sum of the partial space-charge widths in the n-type and p-type semiconductors

$$W_d = l_n + l_p = \sqrt{\frac{2\varepsilon_r \varepsilon_0}{q}\ \psi_0\left[\frac{1}{N_A} + \frac{1}{N_D}\right]} \tag{18}$$

The space-charge region is not uniformly distributed in the n-type and p-type regions.
By substituting lp expressed by Eq (17b) into Eq. (7b) we obtain the expression for the maximum value of the internal electric field.

$$\xi_{max} = \sqrt{\frac{2q}{\varepsilon_r \varepsilon_0}\left[\frac{N_A N_D}{N_A + N_D}\right]} \tag{19}$$

Example:
A crystalline silicon wafer is doped with 1×10^{16} acceptor atoms per cubic centimetre. A 1 micrometer thick emitter layer is formed at the surface of the wafer with a uniform concentration of 1×10^{18} donors per cubic centimetre. Assume a step p-n junction and that all doping atoms are ionized. The intrinsic carrier concentration in silicon at 300 K is $1.5 \times 10^{10} cm^{-3}$. For crystalline Si $\varepsilon_r = 11.7$.
Calculate the electron and hole concentrations in the p-type and n-type quasi-neutral regions at thermal equilibrium.

Solution:
       Use Eqs. (1a,b) and Eqs. (2a,b) to calculate the charge carrier concentrations.
P-type region:

$$p = p_0 \approx N_A = 1 \times 10^{16}\ cm^{-3}$$

$$n = n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{16}} = 2.25 \times 10^4 \, cm^{-3}$$

N-type region:

$$n = n_0 \approx N_D = 1 \times 10^{18} \, cm^{-3}$$

$$p = p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2 \, cm^{-3}$$

We can calculate the position of the Fermi energy in the quasi-neutral n-type and p-type regions, respectively, Let's assume that the reference energy level is the bottom of the conduction band, $E_C = 0 \, eV$.

N-type region:

$$E_F - E_C = -kT \, ln(N_C/n) = -0.0258 \, ln\left(\frac{3.32 \times 10^{19}}{1 \times 10^{18}}\right) = -0.09 \, eV$$

P-type region:

$$E_F - E_C = -kT \, ln(N_C/n) = -0.0258 \, ln\left(\frac{3.32 \times 10^{19}}{2.25 \times 10^4}\right) = -0.9 \, eV$$

The minus sign tells us that the Fermi energy is positioned below the E_C. The built-in voltage across the p-n junction is calculated using Eq. (16)

$$\psi_0 = \frac{kT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0258 \, ln\left(\frac{10^{16} \times 10^{18}}{(1.5 \times 10^{10})^2}\right) = 0.81 \, eV$$

A typical thickness of c-Si wafer is 300 μm. The depletion region is 0.3 μm which represents 0.1% of the thickness of the wafer. It is important to realize that almost the whole bulk of the wafer is a quasi-neutral region without the internal electrical field.

The maximum electric field is at the metallurgical junction and is calculated from Eq. (19).

$$\xi_{max} = \sqrt{\frac{2q}{\varepsilon_r \varepsilon_0}\left[\frac{N_A N_D}{N_A + N_D}\right]} = \sqrt{\frac{2 \times 1.6 \times 10^{-19}}{11.7 \times 8.85 \times 10^{-14}} \times 0.81 \times \left(\frac{10^{16} \times 10^{18}}{10^{16} + 10^{18}}\right)} = 50 \times 10^3 V/cm$$

Lecture 11: The Operation Principle of a Solar Cell (Part 2)

❖ <u>p-n junction under applied voltage</u>

When an external voltage, V_a, is applied to a p-n junction the potential difference between the n-type and p-type regions will change and the electrostatic potential across the space-charge region will become $(\psi_0 - V_a)$.

Remember that under equilibrium the built-in potential is negative in the p-type region with respect to the n-type region. When the applied external voltage is negative with respect to the potential of the p-type region, the applied voltage will increase the potential difference across the p-n junction. We refer to this situation as p-n junction under reverse-bias voltage. The potential barrier across the junction is increased under reverse-bias voltage, which results in a wider space-charge region.

Figure 1a shows the band diagram of the p-n junction under reverse-biased voltage. Under external voltage the concentrations of electrons and holes are described by the quasi-Fermi energy for electrons, E_{FC}, and the quasi-Fermi energy holes, E_{FV}, respectively. When the applied external voltage is positive with respect to the potential of the p-type region, the applied voltage will decrease the potential difference across the p-n junction. We refer to this situation as p-n junction under forward-bias voltage. The band diagram of the p-n junction under

Figure 1.

forward-biased voltage is presented in Figure 1b. The potential barrier across the junction is decreased under forward-bias voltage and the space charge region becomes narrower. The balance between the forces responsible for diffusion (concentration gradient) and drift (electric field) is disturbed. The lowering of the electrostatic potential barrier leads to a higher concentration of minority carriers at the edges of the space-charge region compared to the situation in equilibrium. This process is referred to as minority-carrier injection. This gradient in concentration causes the diffusion of the minority carriers from the edge into the bulk of the quasi-neutral region.

The diffusion of minority carriers into the quasi-neutral region causes a so-called ***recombination current***, J_{rec}, since the diffusing minority carriers recombine with the majority carriers in the bulk. The recombination current is compensated by the so-called ***thermal generation current***, J_{gen}, which is caused by the drift of minority carriers, which are present in the corresponding doped regions (electrons in the p-type region and holes in the n-type region), across the junction. Both, the recombination and generation currents have contributions from electrons and holes. When no voltage is applied to the p-n junction, the situation inside the junction can be viewed as the balance between the recombination and generation currents.

$$J = J_{rec} - J_{gen} = 0 \quad for \quad V_a = 0\ Volt \qquad (1)$$

It is assumed that when a moderate forward-bias voltage is applied to the junction the recombination current increases with the Boltzmann factor ($exp(qVa/\ kT)$) (the *Boltzmann approximation*):

$$J_{rec}(V_a) = J_{rec}(V_a = 0)exp\left(\frac{qV_a}{kT}\right) \qquad (2)$$

On the other hand, the generation current is almost independent of the potential barrier across the junction and is determined by the availability of the thermally-generated minority carriers in the doped regions.

$$J_{gen}(V_a) \approx J_{gen}(V_a = 0) \qquad (3)$$

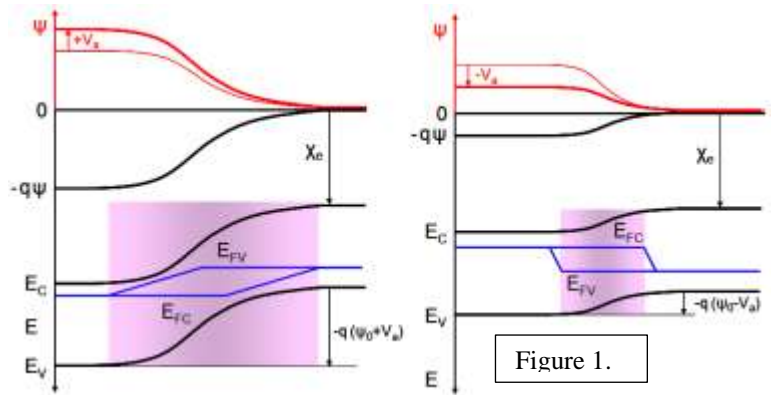The external net-current density can be expressed as

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$$J(V_a) = J_{rec}(V_a) - J_{gen}(V_a) = J_0\left[exp\left(\frac{qV_a}{kT}\right) - 1\right] \qquad (4)$$

Where J_0 is the saturation-current density of the p-n junction, given by

$$J_0 = J_{gen}(V_a = 0) \qquad (5)$$

Eq. (4) is known as the Shockley equation that describes the current-voltage behavior of an ideal p-n diode. It is a fundamental equation for microelectronics device physics.

The saturation-current density is expressed by Eq. (6)

$$J_0 = qn_i^2\left[\frac{D_n}{L_N N_A} + \frac{D_p}{L_p N_D}\right] \qquad (6)$$

The saturation-current density depends in a complex way on the fundamental semiconductor parameters. Ideally the saturation-current density should be as low as possible and this requires an optimal and balanced design of the p-type and n-type semiconductor properties. For example, an increase in the doping concentration decreases the diffusion length of the minority carriers, which means that the optimal product of these two quantities requires a delicate balance between these two properties.

The recombination of the majority carriers due to the diffusion of the injected minority carriers into the bulk of the quasi-neutral regions results in a lowering of the concentration of the majority carriers compared to the one under equilibrium. The drop in the concentration of the majority carriers is balanced by the flow of the majority carriers from the electrodes into the bulk. In this way the net current flows through the p-n junction under forward-bias voltage. For high reverse-bias voltage, the Boltzmann factor in Eq. (4) becomes very small and can be neglected. The net current density is given by

$$J(V_a) = -J_0 \qquad (7)$$

and represents the flux of thermally generated minority carriers across the junction. The current density-voltage (J-V) characteristic of an ideal p-n junction is schematically shown in Figure 2.
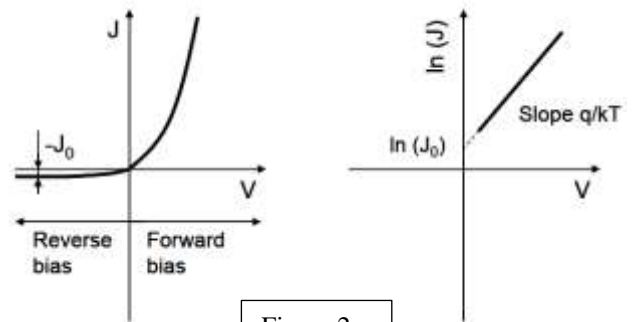

Figure 2

❖ p-n junction under illumination.

When a p-n junction is illuminated the additional electron-hole pairs are generated in the semiconductor. The concentration of minority carriers (electrons in the p-type region and holes in the n-type region) strongly increases. This increase in the concentration of minority carriers leads to the flow of the minority carriers across the depletion region into the quasi-neutral regions. Electrons flow from the p-type into the n-type region and holes from the n-type into the p-type region. The flow of the photo-generated carriers causes the so-called photo-generation current, J_{ph}, which adds to the thermal-generation current, J_{gen}. When no external contact between the n-type and the p-type regions is established, which means that the junction is in the open-circuit condition, no net current can flow inside the p-n junction. It means that the current resulting from the flux of photo-generated and thermally-generated carriers has to be balanced by the opposite recombination current. The recombination current will increase through lowering of the electrostatic potential barrier across the depletion region. This situation of the illuminated p-n junction under open-circuit condition using the band diagram is presented in Figure 3a. The electrostatic-potential barrier across the junction is lowered by an amount

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of V_{oc}. We refer to V_{oc} as the open-circuit voltage. Under non-equilibrium conditions the concentrations of electrons and holes are described by the quasi-Fermi energy levels. It is illustrated in Figure 3a that the electrochemical potential of electrons, denoted by E_{FC}, is higher in the n-type region than in the p-type region by an amount of qV_{oc}. This means that a voltmeter will measure a voltage difference of V_{oc} between the contacts of the p-n junction. Under illumination, when the n-type and p-type regions are short circuited, the photo-generated current will also flow through the external circuit. This
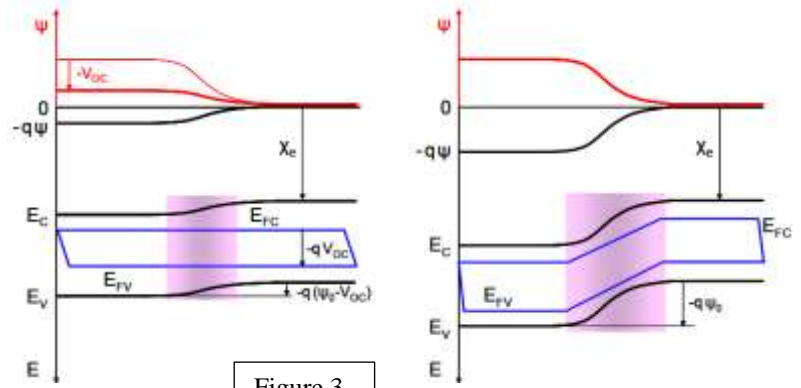

Figure 3

situation is illustrated in Figure 3b. Under the short-circuit condition the electrostatic-potential barrier is not changed, but from a strong variation of the quasi-Fermi levels inside the depletion region one can determine that the current is flowing inside the semiconductor.

When a load is connected between the electrodes of the illuminated p-n junction, only a fraction of the photo-generated current will flow through the external circuit. The electro-chemical potential difference between the n-type and p-type regions will be lowered by a voltage drop over the load. This in turn lowers the electrostatic potential ψ over the depletion region which results in an increase of the recombination current. The net current flowing through the load is determined as the sum of the photo- and thermal generation currents and the recombination current (the superposition approximation). The voltage drop at the load can be simulated by applying a forward-bias voltage to the junction, therefore Eqs. (4), which describe the behavior of the junction under applied voltage, is included to describe the net current of the illuminated p-n junction:

$$J(V_a) = J_{rec}(V_a) - J_{gen}(V_a) - J_{ph} = J_0\left[exp\left(\frac{qV_a}{kT}\right) - 1\right] - J_{ph} \qquad (8)$$

The dark and illuminated J-V characteristics of the p-n junction are represented in Figure 4. Note, that the superposition principle is reflected in Figure 4.

The illuminated J-V characteristic of the p-n junction is the same as the dark J-V characteristic, but it is shifted down by the photo-generated current density J_{ph}. The photo-generated current density of the p-n junction under uniform generation rate, G, is

$$J_{ph} = qG\left(L_N + W_d + L_p\right) \qquad (9)$$

Where L_N and L_p is the minority-carrier-diffusion length for electrons and holes, respectively, and W_d is the width of the depletion region. It means only carriers generated in the depletion region and in the regions up to the minority-carrier-diffusion length from the

Figure 4.

depletion region contribute to the photo-generated current. Eq. (9) is useful when designing the thickness of a solar cell. The thickness of the absorber should not be thicker than the region from which the carriers contribute to the photo-generated current.
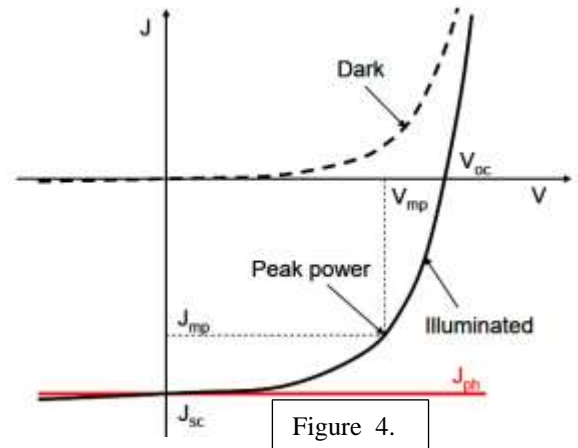
❖ Solar cell external parameters

The main parameters that are used to characterize the performance of solar cells are the short-circuit current density, J_{sc}, the open-circuit voltage, V_{oc} and the fill factor, FF. These parameters are determined from the illuminated J-V characteristic as illustrated in Figure 4. The conversion efficiency, η, is determined from these parameters. The short-circuit current is the current that flows through the external

circuit when the electrodes of the solar cell are short circuited. In the ideal case, J_{sc} is equal to the photo-generated current density J_{ph}. The open-circuit voltage is the voltage at which no current flows through the external circuit. In this case the dark current compensates the photo-current. The open-circuit voltage depends on the photo-generated current density and can be calculated from Eq. (7) assuming that the net current is zero.

$$V_{oc} = \frac{kT}{q} \, ln\left(\frac{J_{ph}}{J_0} + 1\right) \qquad (10)$$

The fill factor is the ratio between the maximum power ($P_{max} = J_{mp} \times V_{mp}$) deliverable by a solar cell and the product of V_{oc} and J_{sc}.

$$FF = \frac{J_{mp} \times V_{mp}}{V_{oc} \times J_{sc}} \qquad (11)$$

In case that the solar cell behaves as an ideal diode the fill factor can be expressed as a function of open-circuit voltage.

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \qquad (12)$$

Where $v_{oc} = \frac{V_{oc}}{(kT/q)}$ is a normalized voltage.

The conversion efficiency is calculated as the ratio between the generated maximum power and the incident power. The irradiance value, P_{in} , of $1000 \, W/m^2$ of AM1.5 spectrum has become a standard for measuring the conversion efficiency of solar cells.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{J_{mp} \, V_{mp}}{P_{in}} = \frac{V_{oc} \, J_{sc} \, FF}{P_{in}} \qquad (13)$$

Typical external parameters of a crystalline silicon solar cell are;
- J_{sc} of 35 mA/cm^2,
- V_{oc} up to 0.65 V and
- FF in the range 0.75 to 0.80.
- The conversion efficiency η lies in the range of 17 to 18%.

Example
A crystalline silicon solar cell generates a photo-current density $J_{ph} = 35 \, mA/cm^2$. The wafer is doped with 1×10^{17} acceptor atoms per cubic centimeter and the emitter layer is formed with a uniform concentration of 1×10^{19} donors per cubic centimeter. The minority-carrier diffusion length in the p-type region and n-type region is $500 \times 10^{-6}m$ and $10 \times 10^{-6}m$, respectively.
The intrinsic carrier concentration in silicon at 300 K is $1.5 \times 10^{10} cm^{-3}$, the mobility of electrons in the p-type region is $\mu_n = 1000 \, cm^2 Vs^{-1}$ and holes in the n-type region is $\mu_p = 100 cm^2 Vs^{-1}$.
Assume that the solar cell behaves as an ideal diode. Calculate the open-circuit voltage and the conversion efficiency of the cell.

Solution:
Given information: <u>convert to SI units</u>
$J_{ph} = 350 \, A/m^2$
$N_A = 1 \times 10^{17} cm^{-3} = 1 \times 10^{23} m^{-3}$
$N_D = 1 \times 10^{19} cm^{-3} = 1 \times 10^{25} m^{-3}$
$L_N = 500 \times 10^{-6}m$
$L_P = 10 \times 10^{-6}m$

$D_N = (kT/q)\mu_n = 0.0258V \times 1000 \times 10^{-4}\ m^2 V s^{-1} = 2.58 \times 10^{-3}\ m^2 s^{-1}$

$D_P = (kT/q)\mu_p = 0.0258V \times 100 \times 10^{-4}\ m^2 V s^{-1} = 2.58 \times 10^{-3}\ m^2 s^{-1}$

According to the assumption the solar cell behaves as an ideal diode, it means that the Shockley equation describing the J-V characteristic is applicable. Using Eq. (6) we determine the saturation-current density:

$$J_0 = q n_i^2 \left[\frac{D_n}{L_N N_A} + \frac{D_p}{L_p N_D} \right]$$

$$J_0 = 1.602 \times 10^{-19} C \times (1.5 \times 10^{16})^2 m^{-6} \times \left[\frac{2.58 \times 10^{-3}}{500 \times 10^{-6} \times 1 \times 10^{23}} + \frac{2.58 \times 10^{-3}}{10 \times 10^{-6} \times 1 \times 10^{25}} \right]$$

$$= 3.6 \times 10^{13} C m^{-6} \times [5.16 \times 10^{-23} + 2.58 \times 10^{-24}] = 1.95 \times 10^{-9} C s^{-1} m^{-2} = 1.95 \times 10^{-9} A m^{-2}$$

Using Eq. (10) we determine the open-circuit voltage:

$$V_{oc} = \frac{kT}{q}\ ln\left(\frac{J_{ph}}{J_0} + 1\right) = 0.0258 \times ln\left(\frac{350}{1.95 \times 10^{-9}} + 1\right) = 0.67\ V$$

The fill factor of the cell can be calculated from Eq. (12). First we normalize the V_{oc} .

$$v_{oc} = \frac{V_{oc}}{(kT/q)} = \frac{0.67}{0.0258} = 26.8$$

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} = \frac{26.8 - ln(26.8 + 0.72)}{(26.8 + 1)} = 0.84$$

The conversion efficiency is determined using Eq. (13)

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{in}} = \frac{350\ A m^{-2} \times 0.67\ V \times 0.84}{1000\ W m^{-2}} = 0.197 \times 100\% = 19.7\%$$

Lecture 12: Module Design

Module Design

❖ Module Structure

A PV module consists of a number of interconnected solar cells encapsulated into a single, long-lasting, stable unit. The key purpose of encapsulating a set of electrically connected solar cells is to protect them and their interconnecting wires from the harsh environment in which they are used.

1. Prevent mechanical damage to the solar cells.
2. Prevent water or water vapor from corroding the electrical contacts.

Many different types of PV modules exist and the module structure is often different for different types of solar cells or for different applications. For example, amorphous silicon solar cells are often encapsulated into a flexible array, while bulk silicon solar cells for remote power applications are usually rigid with glass front surfaces.

The most common modules have either 60 cells or 72 cells with three bypass diodes.

❖ Module Materials

Most PV bulk silicon PV modules consist of a transparent top surface, an encapsulant, a rear layer and a frame around the outer edge. In most modules, the top surface is glass, the encapsulant is EVA (ethyl vinyl acetate) and the rear layer is Tedlar.

• Front Surface Materials

The front surface of a PV module must have a high transmission in the wavelengths which can be used by the solar cells in the PV module. For silicon solar cells, the top surface must have high transmission of light in the wavelength range of 350 nm to 1200 nm. In addition, the reflection from the front surface should be low. While theoretically this reflection could be reduced by applying an anti-reflection coating to the top surface, in practice these coatings are not robust enough to withstand the conditions in which most PV systems are used. An alternative technique to reduce reflection is to "roughen" or texture the surface. However, in this case the dust and dirt is more likely to attach itself to the top surface, and less likely to be dislodged by wind or rain.

In addition to its reflection and transmission properties, the top surface material should be

• waterproof,
• have good impact resistance,
• stable under prolonged UV exposure and
• have a low thermal resistivity.

Water or water vapor access into a PV module will corrode the metal contacts and interconnects, and consequently will dramatically reduce the lifetime of the PV module. In most modules the front surface is used to provide the mechanical strength and rigidity, therefore either the top surface or the rear surface must be mechanically rigid in order to support the solar cells and the wiring.

There are several choices for a top surface material including acrylic, polymers and glass. Tempered, low iron-content glass is most commonly used as it is low cost, strong, stable, highly transparent, and waterproof.

Encapsulant

An encapsulant is used to provide adhesion between the solar cells, the top surface and the rear surface of the PV module. The encapsulant should be

• stable at elevated temperatures and high UV exposure.
• It should also be optically transparent and
• should have a low thermal resistance.
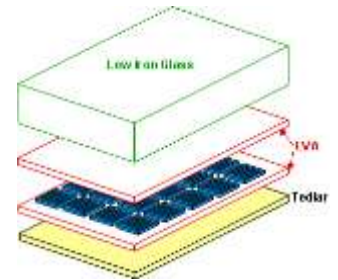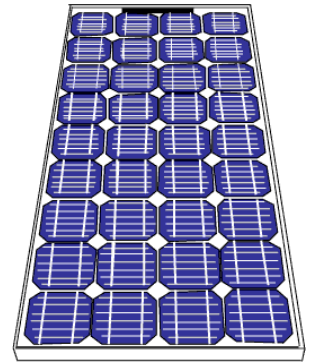
EVA (ethyl vinyl acetate) is the most commonly used encapsulant material. EVA comes in thin sheets which are inserted between the solar cells and the top surface and the rear surface. This sandwich is then heated to 150 °C to polymerize the EVA and bond the module together.

- Rear Surface

The key characteristics of the rear surface of the PV module are that it must have low thermal resistance and that it must prevent the access of water or water vapor. In most modules, a thin polymer sheet, typically Tedlar, is used as the rear surface.

- Frame

A final structural component of the module is the framing of the module. A conventional PV module frame is typically made of aluminum.

❖ Interconnection Effects

➢ Module Circuit Design

A bulk silicon PV module consists of multiple individual solar cells connected, nearly always in series, to increase the power and voltage above that from a single solar cell. The voltage of a PV module is usually chosen to be compatible with a 12V battery. An individual silicon solar cell has a voltage at the maximum power point around 0.5V under 25 °C and AM1.5 illumination. Taking into account an expected reduction in PV module voltage due to temperature and the fact that a battery may require voltages of 15V or more to charge, most modules contain 36 solar cells in series. This gives an open-circuit voltage of about 21V under standard test conditions, and an operating voltage at maximum power and operating temperature of about 17 or 18V. The remaining excess voltage is included to account for voltage drops caused by other elements of the PV system, including operation away from maximum power point and reductions in light intensity.
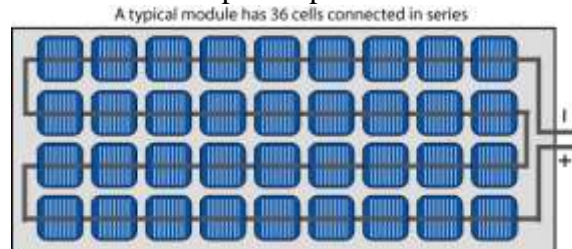

Fig.1: In a typical module, 36 cells are connected in series to produce a voltage sufficient to charge a 12V battery.

- The voltage from the PV module is determined by the number of solar cells.
- The current from the module depends primarily on the size of the solar cells.

If all the solar cells in a module have identical electrical characteristics, then all the cells will be operating at exactly the same current and voltage. In this case, the IV curve of the PV module has the same shape as that of the individual cells, except that the voltage and current are increased. The equation for the circuit becomes:

$$I_T = M \cdot I_L - M \cdot I_0 \left[exp\left(\frac{q \frac{V_T}{N}}{nkT} \right) - 1 \right]$$

where:
N is the number of cells in series;
M is the number of cells in parallel;
I_T is the total current from the circuit;
V_T is the total voltage from the circuit;
I_0 is the saturation current from a single solar cell;
I_L is the short-circuit current from a single solar cell;
n is the ideality factor of a single solar cell;
and q, k, and T are constants.

The overall IV curve of a set of identical connected solar cells is shown below. The total current and the total voltage are simply:

$$I_{SC}(total)=I_{SC}(cell)\times M$$
$$I_{MP}(total)=I_{MP}(cell)\times M$$
$$V_{OC}(total)=V_{OC}(cell)\times N$$
$$V_{MP}(total)=V_{MP}(cell)\times N$$

If the cells are identical then the fill factor (FF) does not change when the cells are in parallel or series.
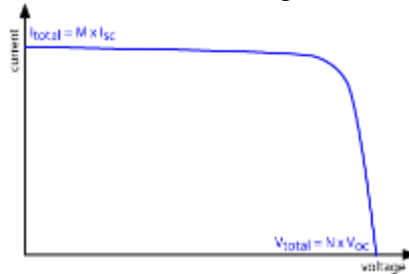

Fig.2: I-V curve for N cells in series x M cells in parallel.

❖ Mismatch Effects

Mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties or which experience different conditions from one another. Mismatch losses are a serious problem in PV modules and arrays under some conditions because the output of the entire PV module under worst case conditions is determined by the solar cell with the lowest output. For example, when one solar cell is shaded while the remainder in the module are not, the power being generated by the "good" solar cells can be dissipated by the lower performance cell rather than powering the load. This in turn can lead to highly localized power dissipation and the resultant local heating may cause irreversible damage to the module.

✓ *Shading of one region of a module compared to another is a major cause of mismatch in PV modules.*
Mismatch in PV modules occurs when the electrical parameters of one solar cell are significantly altered from those of the remaining devices. The impact and power loss due to mismatch depend on:
- the operating point of the PV module;
- the circuit configuration; and
- the parameters which are different from the remainder of the solar cells.

The impact of the mismatch depends on both the circuit configuration and on the type of mismatch.

➢ Mismatch for Cells Connected in series

As most PV modules are series-connected, series mismatches are the most common type of mismatch encountered. Of the two simplest types of mismatch considered (mismatch in short-circuit current or in open-circuit voltage), a mismatch in the short-circuit current is more common, as it can easily be caused by shading part of the module. This type of mismatch is also the most severe.
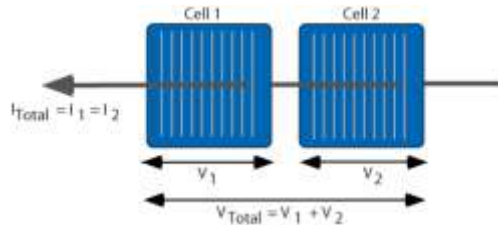

Fig.4: For two cells connected in series, the current through the two cells is the same. The total voltage produced is the sum of the individual cell voltages. Since the current must be the same, a mismatch in current means that the total current from the configuration is equal to the lowest current.

- Open Circuit Voltage Mismatch for Cells Connected in Series

A mismatch in the open-circuit voltage of series-connected cells is a relatively nonthreatening form of mismatch. At short-circuit current, the overall current from the PV module is unaffected. At the maximum power point, the overall power is reduced because the poor cell is generating less power. As the two cells are connected in series, the current through the two solar cells is the same, and the overall voltage is found by adding the two voltages at a particular current.
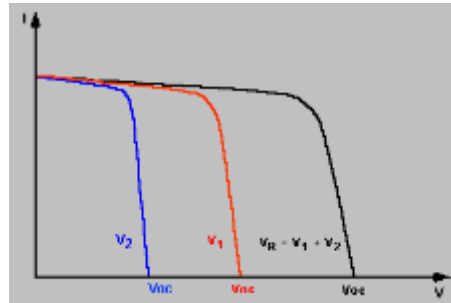

Fig.5: In the animation, cell 2 has a lower output voltage than cell 1.

- Short-Circuit Current Mismatch for Cells Connected in Series

A mismatch in the short-circuit current of series connected solar cells can, depending on the operating point of the module and the degree of mismatch, have a drastic impact on the PV module. As the current through the two cells must be the same, the overall current from the combination cannot exceed that of the poor cell. At low voltages where this condition is likely to occur, the extra current-generating capability of the good cells is not dissipated in each individual cell (as would normally occur at short circuit), but instead is dissipated in the poor cell.

Overall, in a series connected configuration with current mismatch, severe power reductions are experienced if the poor cell produces less current than the maximum power current of the good cells and also if the combination is operated at short circuit or low voltages, the high power dissipation in the poor cell can cause irreversible damage to the module. These effects are illustrated in the two animations below.
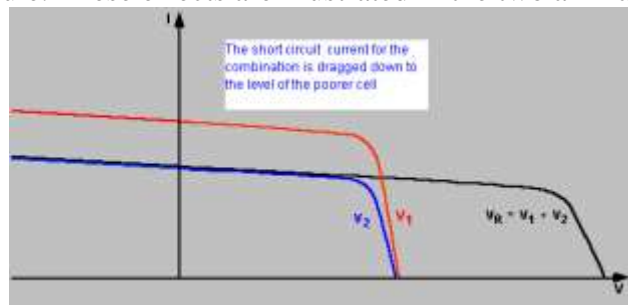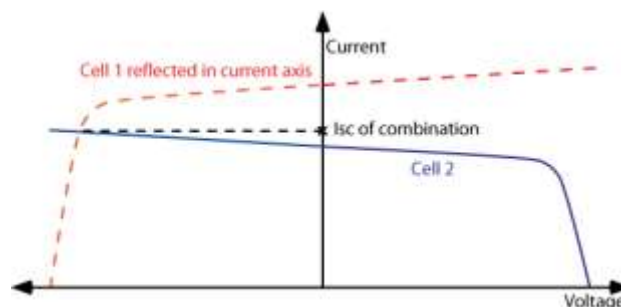

Fig.6: Current mismatch for two cells in series can be quite serious and quite common. The I_{sc} of the combination is limited to the I_{sc} of the lowest cell.

Fig.7: An easy method of calculating the combined short-circuit current of series connected mismatched cells. The current at the point of intersection represents the short-circuit current of the series combination (ie. V1+V2=0).
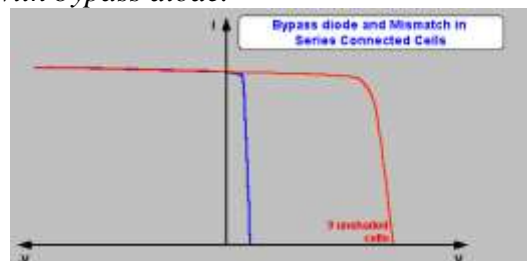
> ## Bypass Diodes

The destructive effects of hot-spot heating may be circumvented through the use of a bypass diode. A bypass diode is connected in parallel, but with opposite polarity, to a solar cell as shown below. Under normal operation, each solar cell will be forward biased and therefore the bypass diode will be reverse biased and will effectively be an open circuit. However, if a solar cell is reverse biased due to a mismatch in short-circuit current between several series connected cells, then the bypass diode conducts, thereby allowing the current from the good solar cells to flow in the external circuit rather than forward biasing each good cell. The maximum reverse bias across the poor cell is reduced to about a single diode drop, thus limiting the current and preventing hot-spot heating. The operation of a bypass diode and the effect on an IV curve are shown in the illustration.

Current flow for two cells in series and the effect of a bypass diode. The animation progresses automatically from one condition to another.

The effect of a bypass diode on an IV curve can be determined by first finding the IV curve of a single solar cell with a bypass diode and then combining this curve with other solar cell IV curves. The bypass diode affects the solar cell only in reverse bias. If the reverse bias is greater than the knee voltage of the solar cell, then the diode turns on and conducts current. The combined IV curve is shown in the figure below.
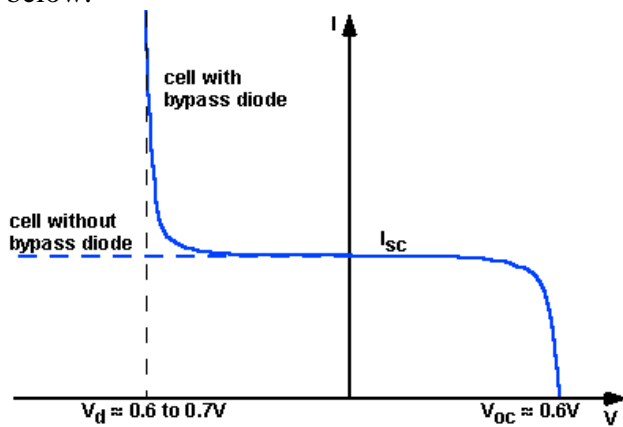
IV curve of solar cell with bypass diode.

Preventing hot-spot heating with a bypass diode. For clarity, the example uses a total of 10 cells with 9 unshaded and 1 shaded. A typical module contains 36 cells and the effects of current mismatch are even worse without the bypass diode, but are less important with the bypass diode. The animation moves automatically. You do not need to click to continue.
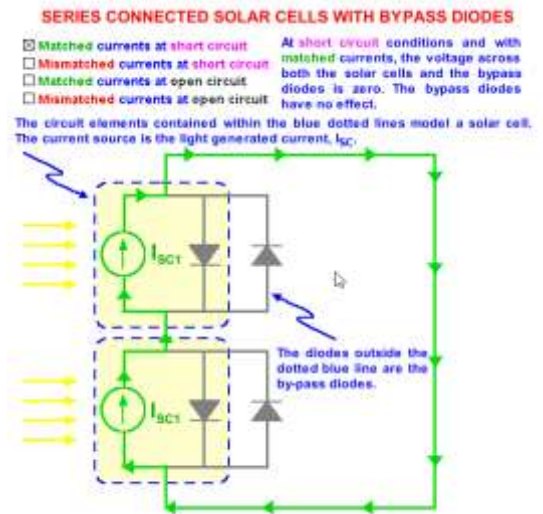
In practice, however, one bypass diode per solar cell is generally too expensive and instead bypass diodes are usually placed across groups of solar cells. The voltage across the shaded or low current solar cell is equal to the forward bias voltage of the other series cells which share the same bypass diode plus the voltage of the bypass diode. This is shown in the figure below. The voltage across the unshaded solar cells depends on the degree of shading on the low current cell. For example, if the cell is completely shaded, then the unshaded solar cells will be forward biased by their short circuit current and the voltage will be about 0.6V. If the poor cell is only partially shaded, the some of the current from the good cells can flow through the circuit, and the remainder is used to forward bias each solar cell junction, causing a lower forward bias voltage across each cell. The maximum power dissipation in the shaded cell is approximately equal to the generating capability of all cells in the group. The maximum group size per diode, without causing damage, is about 15 cells/bypass diode, for silicon cells. For a normal 36 cell module, therefore, 2 bypass diodes are used to ensure the module will not be vulnerable to "hot-spot" damage.
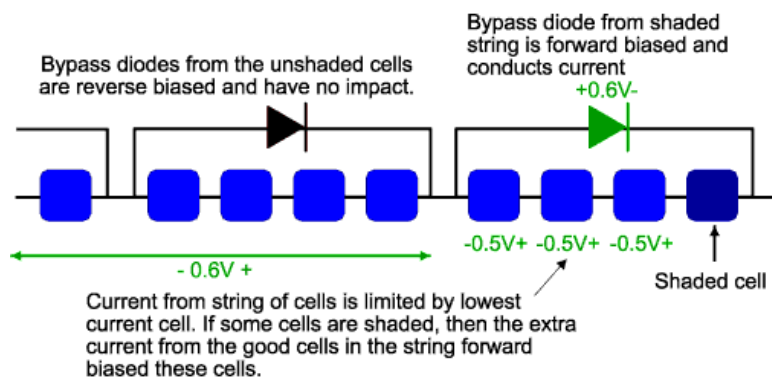
Bypass diodes across groups of solar cells. The voltage across the unshaded solar cells depends on the degree of shading of the poor cell. In the figure above, 0.5V is arbitrarily shown.

➢ <u>Mismatch for Cells Connected in Parallel</u>

In small modules, the cells are placed in series so parallel mismatch is not an issue. Modules are paralleled in large arrays so the mismatch usually applies at a module level rather than at a cell level. For cells or modules in parallel:

$$V_1 = V_2 \ and \ I_T = I_1 + I_2$$
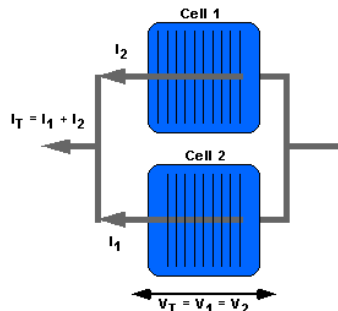
Cells connected in parallel. The voltage across the cell combination is always the same and the total current from the combination is the sum of the currents in the individual cells.

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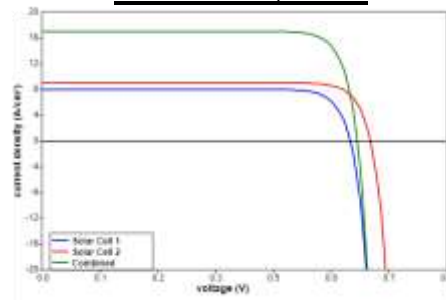
Cell1 V_{OC}, = 0.61 volts
Cell2 V_{OC}, = 0.65 volts

Voltage mismatch for two cells in parallel. The individual cells are in red and blue. The green curve is the IV curve of the combination. The V_{OC} of the combination lies between the V_{OC}'s for the individual cells.

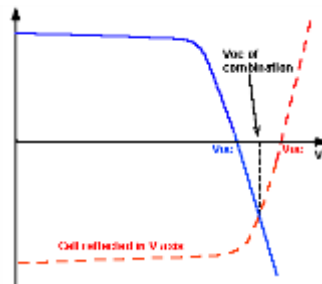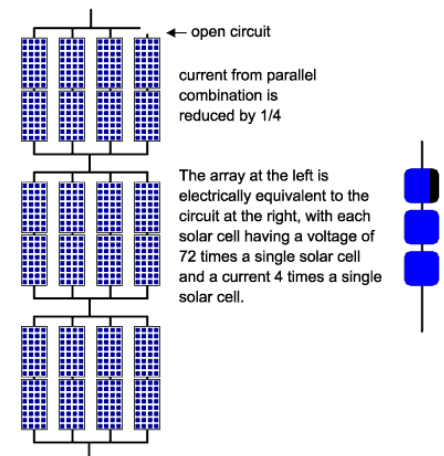*An easy method of calculating the combined open circuit voltage (Voc) of mismatched cells in parallel. The curve for one of the cells is reflected in the voltage axis so that the intersection point (where I1+I2=0) is the Voc of the parallel configuration.*
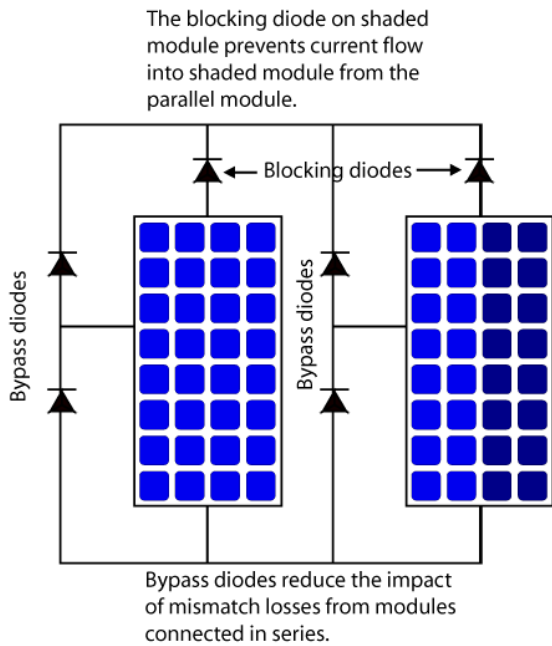
❖ Mismatch Effects in Arrays

In a larger PV array, individual PV modules are connected in both series and parallel. A series-connected set of solar cells or modules is called a "string". The combination of series and parallel connections may lead to several problems in PV arrays. One potential problem arises from an open-circuit in one of the series strings. The current from the parallel connected string (often called a "block") will then have a lower current than the remaining blocks in the module. This is electrically identical to the case of one shaded solar cell in series with several good cells, and the power from the entire block of solar cells is lost. The figure below shows this effect.

Parallel connections in combination with mismatch effects may also lead to problems if the by-pass diodes are not rated to handle the current of the entire parallel connected array. For example, in parallel strings with series connected modules, the by-pass diodes of the series connected modules become connected in parallel, as shown in the figure below. A mismatch in the series connected modules will cause current to flow in a by-pass diode, thereby heating this diode. However, heating the by-pass diode reduces the effective resistance. Most of the current will now flow through the slightly hotter set of by-pass diodes. These by-pass diodes then become even hotter, further reducing their resistance and increasing the current flow. Eventually almost all the current may flow through one set of by-pass diodes. If the diodes are not rated to handle the current from the parallel combination of modules, they will burn out and allows damage to the PV modules to occur.

Solar PV Systems :المـادة

د. وسام عبدالله لطيف

One set of by-pass
diodes may have
lower resistance

Lower resistance
diodes have higher
current flow.

shaded module

The blocking diode on shaded
module prevents current flow
into shaded module from the
parallel module.

← Blocking diodes →

Bypass diodes

Bypass diodes

Bypass diodes reduce the impact
of mismatch losses from modules
connected in series.

In addition to the use of by-pass diodes to prevent mismatch losses, an additional diode, called a blocking diode, may be used to minimize mismatch losses. A blocking diode, shown in the figure below, is typically used to prevent the module from loading the battery at night by preventing current flow from the battery through the PV array. With parallel connected modules, each string to be connected in parallel should have its own blocking diode. This not only reduces the required current carrying capability of the blocking diode, but also prevents current flowing from one parallel string into a lower-current string and therefore helps to minimize mismatch losses arising in parallel connected arrays.
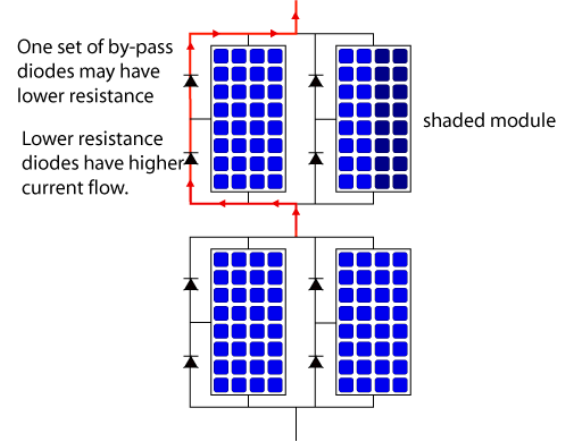
Impact of blocking diodes in parallel connected modules.

Lecture 13: Design and installation of Solar PV Systems

Design and installation of Solar PV Systems

Today our modern world needs energy for various day to day applications such as industrial manufacturing, heating, transport, agricultural, lightning applications, etc. Most of our energy need is usually satisfied by non-renewable sources of energy such as coal, crude oil, natural gas, etc. But the utilization of such resources has caused a heavy impact on our environment.

Also, this form of energy resource is not uniformly distributed on the earth. There is an uncertainty of market prices such as in the case of crude oil as it depends on production and extraction from its reserves. Due to the limited availability of non-renewable sources, the demand for renewable sources has grown in recent years.

Solar energy has been at the center of attention when it comes to renewable energy sources. It is readily available in an abundant

form and has the potential to meet our entire planet's energy requirement. The solar standalone PV system as shown in fig 1 is one of the approaches when it comes to fulfilling our energy demand independent of the utility. Hence in the following, we will see briefly the planning, designing, and installation of a standalone PV system for electricity generation.

❖ Planning of a Standalone PV system

Site assessment, surveying & solar energy resource assessment:

Since the output generated by the PV system varies significantly depending on the time and geographical location it becomes of utmost importance to have an appropriate selection of the site for the standalone PV installation. Thus, the following points must be considered for the assessment and selection of locations for installation.

1. **Minimum Shade:** It must be made sure that the selected site either at rooftop or ground should not have shades or should not have any structure that intercepts the solar radiation falling on the panels to be installed.
2. **Surface Area:** The surface area of the site at which the PV installation is intended should be known, to have an estimation of the size and number of panels required to generate the required power output for the load. This also helps to plan the installation of inverter, converts, and battery banks.
3. **Rooftop:** In the case of the rooftop installation the type of roof and its structure must be known. In the case of tilt roofs, the angle of tilt must be known and necessary mounting must be used to make the panels have more incidents of solar radiation i.e. ideally the radiation angle must be perpendicular to the PV panel and practically as close as to 90 degrees.
4. **Routes:** Possible routes for the cables from an inverter, battery bank, charge controller, and PV array must be planned in a way that minimizes number of cables and lower voltage drop in cables. The designer should choose between the efficiency and the cost of the system.

To estimate the output power the solar energy assessment of the selected site is of foremost significance. Insolation is defined as the measure of the sun's energy received in a specified area over a period of time. You can find this data using a **pyranometer**, while assessing the solar energy the data can be measured in two ways as follows:

- **Kilowatt-hours per square meter per day (KWh/m²/day):** It is a quantity of energy measured in kilowatt-hours, falling on square meter per day.
- **Daily Peak Sun Hours (PSH):** Number of hours in a day during which irradiance averages to 1000 W/m².

Peak sun hours are most commonly used as they simplify the calculations. Do not get confused with the "**Mean Sunshine Hours**" and "**Peak Sun Hours**" which you would collect from the meteorological station. The "Mean sunshine hours" indicates the number of hours the sunshine's were as the "Peak sun hours" is the actual amount of energy received in KWh/m²/day. Amongst all months over a period of year use the lowest mean daily
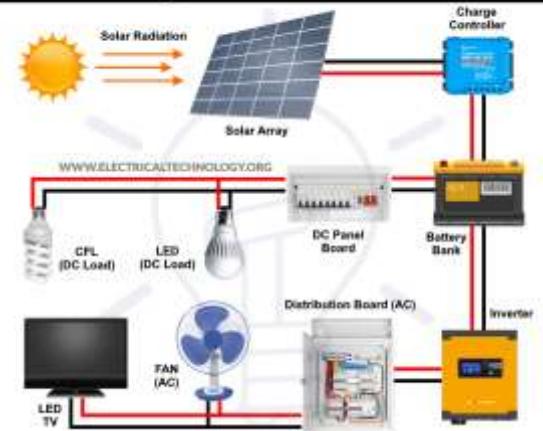
insolation value as it will make sure that the system will operate in a more reliable way when the sun is least due to unsuitable weather conditions.

<div align="center">

Considerations for Standalone PV system
</div>

❖ Calculation of Energy Demand

The size of the standalone PV system depends on the load demand. The load and its operating time vary for different appliances; therefore special care must be taken during energy demand calculations. The energy consumption of the load can be determined by multiplying the power rating (W) of the load by its number of hours of operation. Thus, the unit can be written as watt × hour or simply Wh.

$$Energy\ demand\ Watt - hour\ =\ Power\ rating\ in\ Watt\ \times\ Duration\ of\ operation\ in\ hours.$$

Thus, the daily total energy demand in Wh is calculated by adding the individual load demand of each appliance per day.

$$Total\ energy\ demand\ Watt - hour$$
$$=\ \sum (Power\ rating\ in\ Watt\ \times\ Duration\ of\ operation\ in\ hours).$$

A system should be designed for the worst-case scenario i.e. for the day when the energy demand is highest. A system designed for the highest demand will ensure that the system is reliable. If the system meets the peak load demand it will meet the lowest demand. But designing the system for the highest demand will increase the overall cost of the system. On the other hand, the system will be fully utilized only during the peak load demand. So, we have to choose between cost and reliability of the system.

❖ Inverter & Converter (Charge Controller) Ratings

For choosing the proper inverter both the input and output voltage and current rating should be specified. The inverter's output voltage is specified by the system load, it should be able to handle the load current and the current taken from the battery bank. Based on the total connected load to the system the inverter power rating can be specified.

Let's consider 2.5 kVA in our case, hence an inverter with power handling capacity having a size of 20-30% higher than the power running the load should be chosen from the market. In the case of motor load, it should be 3-5 times higher than the power demand of such an appliance.

In the case of the converter, the charge controller is rated in current and voltage. Its current rating is calculated by using the short-circuit current rating of the PV module. The value of voltage is the same as the nominal voltage of batteries.

• Converter and Charge Controller Sizing

The charge controller rating should be 125% of the photovoltaic panel short circuit current. In other words, It should be 25% greater than the short circuit current of solar panel.

$$size\ of\ solar\ charge\ controller\ in\ amper = Short - circuit\ current\ of\ PV\ \times\ \mathbf{1.25}\ (Safety\ factor).$$

For example, we need a 6 numbers each of 160W solar panels for our system. Following are the related date of PV panel. Suppose the PV module specification is as follow.

- $P_M\ =\ 160\ W_{Peak}$
- $V_M\ =\ 17.9\ V_{DC}$
- $I_M\ =\ 8.9\ A$
- $V_{OC}\ =\ 21.4\ V$
- $I_{SC}\ =\ 10\ A$

The required rating of solar charge controller is = (4 panels x 10 A) x 1.25 = 50 A

Now, a 50A charge controller is needed for the 12V DC system configuration.

Note: This formula is not applicable on MPPT Solar chargers. Please refer to the user manual or check the nameplate data rating for proper sizing.

- **Inverter Sizing**

The size of Inverter should be 25% bigger than the total load due to losses and efficiency problem in the inverter. For example, if the required wattage is 2400W, than the size of inverter should be:

2400W x 1.25

3000 Watts.

So we need a 3kW of inverter in case of 2400W load.

- ## Daily Energy Supplied to Inverter

Let us consider the daily energy consumption by the load is 2700 Wh. The energy supplied to the inverter should be more than the energy used by the load, so the losses in the inverter can be compensated. Assuming 90% efficiency, the total energy supplied by the battery to the inverter would be given as;

Energy supplied by the battery to the inverter input = 2700 / 0.90 = 3000 Wh/per day.

- ## System Voltage

The inverter input voltage is referred to as the system voltage. It is also the overall battery pack voltage. This system voltage is decided by:

- the selected individual battery voltage,
- line current,
- maximum allowable voltage drop, and
- power loss in the cable.

Usually, the voltage of the batteries is 12 V so will be the system voltage. But if we need higher voltage it should be multiples of 12 V. i.e. 12 V, 24 V, 36 V, and so on.

By decreasing the current, power loss and voltage drop in the cable can be reduced; this can be done by increasing the system voltage. This will increase the number of batteries in the series. Therefore, one must choose between power loss and system voltage.

Now, let us consider the system voltage of 24 V.

- ## Sizing of the Batteries

When sizing the battery some parameters are needed to be considered as follows:

1. Depth of Discharge (DOD) of the battery.
2. Voltage and ampere-hour (Ah) capacity of the battery.
3. The number of days of autonomy (It is the number of days required to power up the whole system (backup power) without solar panels in case of full shading or rainy days.) to get the needed Ah capacity of batteries.

24V, 200Ah (Ideally)

12V, 100Ah   12V, 100Ah

12V, 100Ah   12V, 100Ah

Parallel Set of 2 Batteries Connected in Series

- Let us consider we have batteries of 12 V, 100 Ah with DOD of 70%. Thus, the usable capacity is 100 Ah × 0.70 = 70 Ah.
- Therefore, the charged capacity that is required is determined as follows;

$Required\ charge\ capacity\ =\ energy\ supplied\ by\ the\ battery\ to\ the\ inverter\ input/system\ voltage$

$Required\ charge\ capacity\ =\ 3000\ Wh/\ 24\ V\ =\ 125\ Ah$

From this, the number of batteries required can be calculated as;

$No.\ of\ batteries\ required\ =\ required\ charge\ capacity\ /\ (100\ \times\ 0.7)$

$No.\ of\ batteries\ required\ =\ 125\ Ah\ /\ (100\ \times\ 0.7)\ =\ 1.78\ (round\ off\ 2\ batteries)$

Thus, 2 batteries of 12 V, 100 Ah are required. But due to round off 140 Ah instead of 125 Ah is required.

$Required\ charge\ capacity\ =\ 2\ \times\ 100Ah\ \times\ 0.7\ =\ 140\ Ah$

Therefore, two 12 V, 100 Ah batteries in parallel to meet the above charge capacity. But as the individual battery is of 12 V, 100 Ah only and the system voltage requirement is of 24 V we need to connect two batteries in series to get the system voltage of 24 V as shown in figure 2 below:

- **Battery Bank**
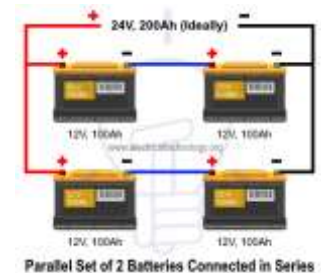
So, in total there will be four batteries of 12 V, 100 Ah. Two connected in series and two connected in parallel. Also, the required capacity of batteries can be found by the following formula.

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Wh per Day used by Appliances x Days of Autonomy}}{(0.85 \times 0.6 \times \text{Nominal Battery Voltage})}$$

- **Sizing of the PV Array**

One of the most common way to determine the sizing of the PV array is to use the lowest mean daily insolation (Solar irradiance) in peak sun hours as follows;

$$\textit{The total size of PV array (W)} = (\textit{Energy demand per day of a load (Wh)} / T_{PH}) \times 1.25$$

Where T_{PH} is the lowest daily average peak sun hours of a month per year & 1.25 is the scaling factor. With this the number of PV modules $N_{modules}$ required can be determined as;

$$N_{modules} = \textit{Total size of the PV array (W) / Rating of selected panels in peak} - \textit{watts.}$$

Suppose, the load is 3000 Wh/per day. To know the needed total W_{Peak} of a solar panel capacity, we use PFG factor i.e.

$$\text{Total } W_{Peak} \text{ of PV panel capacity} = 3000 / \textbf{3.2 (PFG)} = 931 \text{ } W_{Peak}$$

Now, the required number of PV panels are = 931 / 160W = 5.8.

This way, we need 6 numbers of solar panels each rated for 160W. You can find the exact number of solar panels by dividing the W_{Peak} by other rating i.e. 100W, 120W 150W etc based on the availability.

Note: The value of **PFG (Panel Generation Factor)** is varying (due to climate and temperature changes) in different regions e.g, PFG in USA = 3.22, EU = 293, Thailand = 3.43 etc.

Moreover, the additional losses should be considered to find the exact panel generation factor (PGF). These losses (in %) occur due to :

- Sunlight not striking the solar panel straight on (5%)
- Not receiving energy at the maximum power point (excluded in case of MPPT charge controller). (10%)
- Dirt on solar panels (5%)
- PV panels aging and below specification (10%)
- Temperature above 25°C (15%)

- **Sizing of the Cables**

The sizing of the cables depends on many factors such as

- Maximum current carrying capacity.
- It should have a minimum voltage drop (typically less than 2%)
- Have minimum resistive losses.
- As the cables would be placed in the outdoor environment it should be water-resistant and ultraviolet.

The cable must behave minimum voltage drop typically less than 2% as there is an issue of voltage drop in low voltage system. Under sizing of the cables will result in energy loss and sometimes can even lead to accidents, whereas the oversizing is not economically affordable.

The cross-sectional area of the cable is given as;

$$A = (\rho I_M L / V_D) \times 2$$

Where

- ρ is the resistivity of the conducting wire material (ohm-meters).
- L is the length of cable.
- V_D is the maximum permissible voltage drop.
- I_M is the maximum current carried by the cable.

In addition, you may use this <u>cable and wire size calculator.</u> Also, use the <u>proper sized circuit breaker</u> and <u>rated plugs and switches</u>.

Let's have a solved example for the above example.

Example:

Suppose we have the following electrical load in watts where we need a 12V, 120W solar panel system design and installation.

- An LED lamp of 40W for 12 Hours per day.
- A refrigerator of 80W for 8 Hours per day.
- A DC Fan of 60W for 6 Hours per day.

Now let's find the number of solar panels, rating and sizing of charge controller, inverter and batteries etc.

Finding the Total Load

Total Load in Wh / day = (40W x 12 hours) + (80W x 8 hours) + (60W x 6 hours) **= 1480 Wh / day**

The required wattage by Solar Panels System= 1480 Wh x 1.3 **= 1924 Wh/day**

(1.3 is the factor used for energy lost in the system)

Finding the Size and No. of Solar Panels

W_{Peak} Capacity of Solar Panel= 1924 Wh /3.2= 601.25 W_{Peak}

Required No of Solar Panels = 601.25 / 120W

No of Solar Panels = 5 Solar Panel Modules

This way, the 5 solar panels each of 120W will capable to power up our load requirements.

Find the Rating and Size of Inverter

As there is only AC loads in our system for specific time (i.e. no additional & direct DC load connected to the batteries) and our total required wattage is:

= 40W + 80W + 60W

= 180W

Now, the rating of inverter should be 25% greater than the total load due to losses in the inverter.

= 180W x 2.5

Inverter Rating & Size = 225 W

Related Posts:

- <u>Series Connection of Solar Panel with Auto UPS System</u>
- <u>Parallel Connection of Batteries with Solar Panel</u>

Find the Size, Rating & No of Batteries

Our load wattage and operational time in hours

= (40W x 12 hours) + (80W x 8 hours) + (60W x 6 hours)

Nominal Voltage of Deep Cycle Battery = 12V

Required Days of Autonomy (Power by batteries without solar panel power) = 2 days.

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Wh per Day used by Appliances} \times \text{Days of Autonomy}}{(0.85 \times 0.6 \times \text{Nominal Battery Voltage})}$$

$$= \frac{(40W \times 12 \text{ hours}) + (80W \times 8 \text{ hours}) + (60W \times 6 \text{ hours})}{(0.85 \times 0.6 \times 12V)} \times 2 \text{ Days}$$

The required capacity of batteries in Ampere-hour = 483.6 Ah

This way, we need a 12V 500Ah battery capacity for 2 days of autonomy.

In this case, we may use 4 numbers of batteries each of 12 V, 125Ah connected in parallel.

If the available battery capacity is 175Ah, 12 V, we may use 3 numbers of batteries. You can get the exact number of batteries by dividing the required capacity of batteries in Ampere-hour by the available battery Ah rating.

Required Number of batteries = Required capacity of batteries in Ampere-hour / Available battery Ah rating

Find the Rating and Size of Solar Charge Controller

The charge controller should be 125% (or 25% greater) than the solar panel short circuit current.

Size of solar charge controller in Amp = Short circuit current of PV × 1.25

<u>PV module specification</u>

- $P_M = 120\ W_{Peak}$
- $V_M = 15.9\ V_{DC}$
- $I_M = 7.5\ A$
- $I_{SC} = 8.8\ A$

The required rating of solar charge controller is = (5 panels x 8.8 A) x 1.25 = 44 A

So you can use the next nearest rated charge controller which is 45A.

Note that this method can't be used to find the exact size of MPPT solar chargers. Please refer to the user manual provided by the manufacturer or see the nameplate rating printed on it.