PhotoVoltaic 1st slide

28 January 2024 17:28

1.1.4 Energy Source Categories

	Non renewable	**Renewable**
Conventional	Coal Oil Gas Nuclear Fission	Wood Hydro Human/Animal Wind Water Pumping
Alternative	Geothermal Oil Shale, CTL Tar Sands Methane Hydrates	Wind Solar Biomass Wave/Tide Ocean Current

•Sustainable means using less than is renewed; if water is withdrawn from a dam faster than it is refilled, the level drops and hydro power is lessened, and finally fails

- **total energy density (u):** total radiant energy per unit volume for all wavelength radiating at any point
- **total emissive power (E):** radiant energy per unit time per unit surface area of body for all wavelength

$$u = \int_0^\infty u_\lambda d\lambda \quad and \quad E = \int_0^\infty E_\lambda d\lambda$$

Planck's radiation law $\boxed{u(\nu)d\nu = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{(e^{h\nu/kT}-1)}d\nu}$

Wien's displacement law $\lambda_{max}T = 2.898\times10^{-3} m - K = const.$

Stefan-Boltzmann Law. $E = e\sigma T^4$

Stefan boltzman constant value

5.67x10^{-8}

Assuming sun surface temperature 5800^0 K and sun radius R_s=7x10^{8}m , total energy radiated by sun and energy received by earth. Distance b/w sun and earth is r = 1.5x10^{11}m

Total energy radiation from sun $U = \sigma A_s T^4$
$= 5.67\times10^{-8} \times 4\pi R_s^2 \times (5800)^4$
$= 3.95\times10^{26}$J

At earth atmosphere = $U/4\pi r^2$
$= 3.95\times10^{26}J / 4\pi\times(1.5\times10^{11})^2$
$= 1400 W/m^2$

Solar Energy at Earth surface

- Incoming sunlight = I_{in} = 1400 W/m^2
  - solar constant

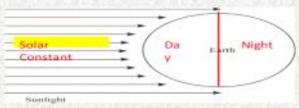
- Albedo = reflected light = α
- Not absorbed and re-radiated as IR
- Just 'bounces' back

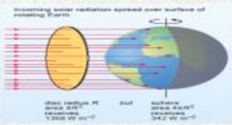
•Albedo = reflected light = α= 30%

- 1400 W/m^2 (1 - α) = 980 W/m^2
- Want flux for the whole planet (no m^2)
- F_{in}(W) = I_{in}(W/m^2) x Area(m^2)

Sunlight hits Earth from same direction, makes a circular shadow, use the area of a circle, not a sphere.

Earth receives influx of energy equal to the intensity of sunlight multiplied by the area of a circle $= \pi r^2_{earth}$





Area (m^2) = πr^2_{earth}

Put them together, total incoming flux is:

$$\boxed{F_{in} = \pi r^2_{earth} (1 - \alpha)\, I_{in}}$$

- I_{in} = 1400 W/m^2
- Reduce by albedo to 1000 W/m^2
- Multiply by area of circle to get solar Flux (W)

Properties of Light

There are several key characteristics of the incident solar energy which are critical in determining how the incident sunlight interacts with a photovoltaic converter or any other object. The important characteristics of the incident solar energy are:

- the spectral content of the incident light;
- the radiant power density from the sun;
- the angle at which the incident solar radiation strikes a photovoltaic module;
- and the radiant energy from the sun throughout a year or day for a particular surface.

Energy of Photon

Photons – Quanta of Light

Quantum theory describes the frequency dependence of photon energy.

Particle-wave duality:
Photons have discrete quanta of energy.
Photons have momentum.
Light can be polarized.
Light can be diffracted.

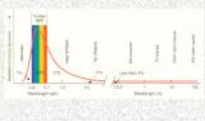
Relevant Equations:

$$E_{ph} = h\nu = \frac{hc}{\lambda}$$

$$P_{ph} = \hbar k = \frac{h}{\lambda}$$

A photon is characterized by either a wavelength, denoted by λ or equivalently an energy, denoted by *E*.

where $h = 6.626\times10^{-34}$ joule·s and $c = 2.998\times10^8$ m/s



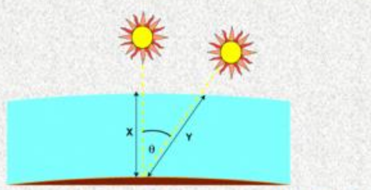
High energy photon for blue light.

Lower energy photon for red light.

Low energy photon for infrared light. Should be invisible!

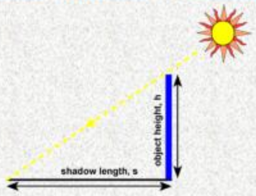
Air mass is a measure of how much atmosphere sunlight has to travel through. It helps us understand how sunlight is absorbed and scattered as it passes through the Earth's atmosphere.

$$AM = \frac{1}{\cos\theta} = \frac{\text{optical path length to sun}}{\text{optical path length if sun directly overhead}}$$



The air mass represents the proportion of atmosphere that the light must pass through before striking the Earth relative to its overhead path length, and is equal to Y/X.

An easy method to determine the air mass is from the shadow of a vertical pole.



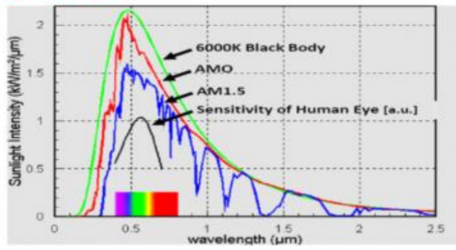
Air mass is the length of the hypotenuse divided by the object height h, and from Pythagoras's theorem we get:

$$AM = \sqrt{1+(\frac{s}{h})^2}$$

Standardised Solar Spectrum and Solar Irradiation

However, the standard AM1.5G spectrum has been normalized to give $1kW/m^2$ due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation.

SOLAR SPECTRUM



INSOLATION

Insolation: Incoming Solar Radiation

Typically given in units of:
Energy per Unit Area per Unit Time
($kWh/m^2/day$)

Helpful when designing or projecting PV systems: Expected yield

Affected by: latitude, local weather patterns, etc.

Estimating System Output from Insolation Maps

$$Energy\ output = \frac{(System\ size)\ x\ (insolation\ at\ site\ of\ installation)}{AM1.5G}$$

Estimating Solar Land Area Requirements

Here's the equation to use, when calculating the area of land needed to produce a certain amount of energy over a year, given a technology with a certain conversion efficiency.

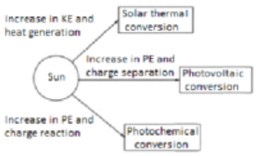
How much energy (kWh) will be produced by the solar system over the course of a year.

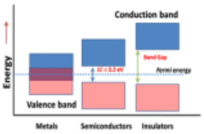
$$Land\ Requirements\ (m^2) = \frac{Energy\ Burn\ Rate\ (kWh/yr)}{Solar\ Resource(\frac{kWh}{m^2 \cdot yr})\ x\ Conversion\ Efficiency}$$

How much energy from the sun is available

The ability of a given technology to convert Sun light in a usable form. This is the conversion efficiency for entire system for just for device.

Light matter interaction (absorption)





- **Insulators:**
  - Large energy gap between valence and conduction bands.
  - Sunlight photons lack the energy to move electrons across the gap.
- **Conductors:**
  - Valence and conduction bands almost overlap.
  - Free electrons move randomly, hindering current flow.
  - Lack a structure like a PN junction.
- **Semiconductors:**
  - Moderate energy gap allows photons to excite electrons.
  - Presence of PN junction creates a small electric field.
  - Electrons move in one direction, crucial for solar cells.

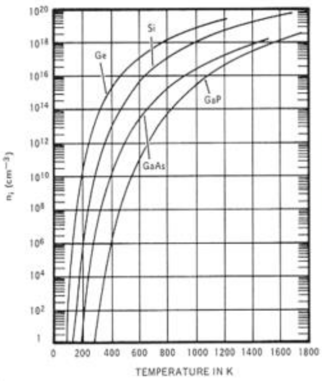
PN Junction in Semiconductors:
- Electrons and holes attempt to mix but don't completely.
- Formation of a potential barrier due to combining electrons and holes.
- Equilibrium results in a small electric field, driving free electrons.

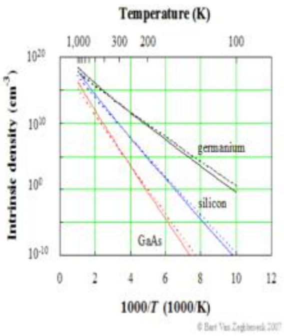
Conductors vs. Semiconductors:
- Conductors lack the PN junction structure and small electric field.
- Random electron movement in conductors makes them unsuitable for solar cells.

The band gap is the minimum amount of energy required for an electron to break free of its bound state.

- **Solar Cells:**
  - Work on the photoelectric effect.
  - Photon absorption creates electron-hole pairs.
- **Working Principle:**
  - Electron-hole pairs, when separated across the PN junction, generate voltage.
  - This voltage can drive current in an external circuit, extracting power from the solar cell.
- **Solar Cell Types:**
  - Silicon wafer-based (first solar cell).
  - Thin-film amorphous Si, crystalline Si, Cadmium Telluride (CdTe), and Copper Gallium Selenide (CIGS).

Temperature Dependence of Intrinsic Carrier Concentration





Doping creates N-type material when semiconductor materials from group IV are doped with group V atoms. P-type materials are created when semiconductor materials from group IV are doped with group III atoms.

N-type materials increase the conductivity of a semiconductor by increasing the number of available electrons; P-type materials increase conductivity by increasing the number of holes present.

Doping can increase conductivity or decrease it

Photovoltaic effect likhna hai

Absorption of Light

When the energy of a photon is equal to or greater than the band gap of the material, the photon is absorbed by the material and excites an electron into the conduction band.

Both minority and majority carriers are generated when a photon is absorbed.

Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap:

$E_{ph} < E_G$ Photons with energy E_{ph} less than the band gap energy E_G interact only weakly with the semiconductor, passing through it as if it were transparent.

$E_{ph} = E_G$ have just enough energy to create an electron hole pair and are efficiently absorbed.

$E_{ph} > E_G$ Photons with energy much greater than the band gap are strongly absorbed. However, for photovoltaic applications, the photon energy greater than the band gap is wasted as electrons quickly thermalize back down to the conduction band edges.

Absorption Coefficient

α : reflects how strongly photon get absorbed by material

Generation Rate

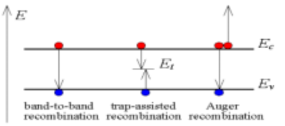
The generation of an electron-hole pair can be calculated at any location within the solar cell, at any wavelength of light, or for the entire standard solar spectrum.

Generation is the greatest at the surface of the material, where the majority of the light is absorbed.

Because the light used in PV applications contains many different wavelengths, many different generation rates must be taken into account when designing a solar cell.

The generation rate gives the number of electrons generated at each point in the device due to the absorption of photons. Generation is an important parameter in solar cell operation.

Types of Recombination



- Radiative recombination (Unavoidable recombination): spontaneous
  - when an electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of a photon
- Auger recombination (Unavoidable recombination): non-radiative
  - the energy is given to a third carrier which is excited to a higher energy level without moving to another energy band
- Shockley-Read-Hall recombination (avoidable recombination): non-radiative and due to defects and imperfection in the crystal:
  - the electron in transition between bands passes through a new energy state (localized state) created within the band gap by a dopant or a defect in the crystal lattice; such energy states are called traps.

1. **Radiative Recombination:**
   - **Description:** In radiative recombination, an electron and a hole recombine, releasing energy in the form of light (photons).
   - **Significance:** This process is crucial for devices like light-emitting diodes (LEDs) and lasers, where the emission of light is desired.
2. **Auger Recombination:**
   - **Description:** Auger recombination involves the transfer of energy from an electron and a hole to a third charge carrier (either an electron or a hole).
   - **Significance:** More pronounced at high carrier concentrations, it can impact the efficiency of semiconductor devices, particularly at elevated carrier densities.
3. **Trap-Assisted Recombination:**
   - **Description:** Charges are captured by defects or impurities in the semiconductor material, leading to recombination with opposite carriers.
   - **Significance:** Defects in the semiconductor lattice can reduce the efficiency of devices by facilitating non-radiative recombination processes.
4. **Shockley-Read-Hall Recombination:**
   - **Description:** This type of recombination is associated with defects in the semiconductor crystal lattice.
   - **Significance:** Electrons and holes can become trapped at these defects, contributing to non-radiative recombination processes, affecting the performance of semiconductor devices.

Diffusion Length

- Diffusion length is the average length a carrier moves between generation and recombination.
- Semiconductor materials that are heavily doped have greater recombination rates and consequently, have shorter diffusion lengths.
- Higher diffusion lengths are indicative of materials with longer lifetimes, and is therefore an important quality to consider with semiconductor materials.

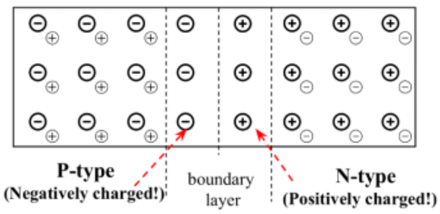
The diffusion length is related to the carrier lifetime by the diffusivity according to the following formula:

$$L = \sqrt{D\tau}$$

here:
L is the diffusion length in meters;
D is the diffusivity in m²/s and
τ is the lifetime in seconds.

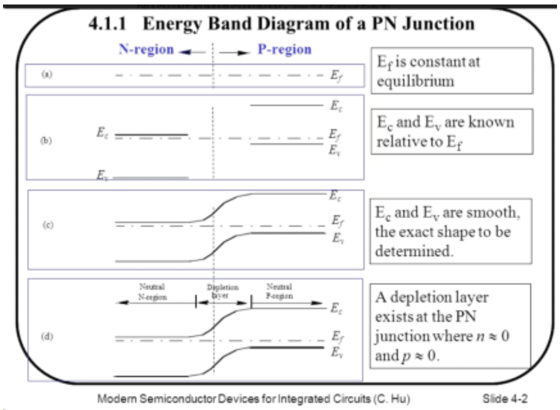
PN-Junction diode and solar cell

Joining n-type and p-type materials creates a PN junction, where excess electrons from the n-type material diffuse to the p-type side, and excess holes from the p-type material diffuse to the n-type side. This movement creates a depletion region and an electric field at the junction, resulting in a voltage.



- Equilibrium condition, no bias voltage
- diffusion current opposite to the E-field
- diffusion voltage V_0 with $\Delta E = eV_0$ at diffusion force = E-field force

V_0 is the electrial voltage at the equlibrium state = diffusion voltage



Semiconductor devices have three modes of operation:

- 1. Thermal Equilibrium

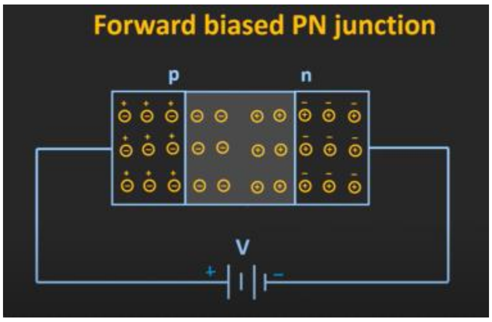
At thermal equilibrium there are no external inputs such as light or applied voltage. The currents balance each other out so there is no *net* current within the device.

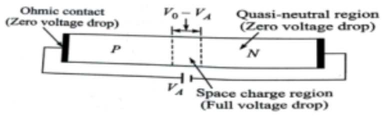
- 2. Steady State

Under steady state there are external inputs such as light or applied voltage, but the conditions do not change with time. Devices typically operate in steady state and are either in forward or reverse bias.

- 3. Transient

If the applied voltage changes rapidly, there will be a short delay before the solar cell responds. As solar cells are not used for high speed operation there are few extra transient effects that need to be taken into account.





junction potential

$V_0 - V_A$ in forward bias

$V_0 + V_A$ in reverse bias

Forward Bias:
- In forward bias, the electric field across the PN junction decreases.
- The positive voltage on the P-type side repels holes toward the junction, while the negative voltage on the N-type side repels electrons toward the junction.
- This reduction in the electric field allows for easier movement of charge carriers across the junction, enabling current flow.

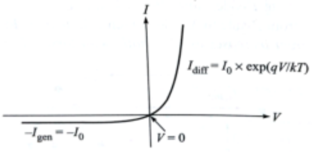
Reverse Bias:
- In reverse bias, the electric field across the PN junction increases.
- The positive voltage on the N-type side attracts electrons away from the junction, and the negative voltage on the P-type side attracts holes away.
- The increased electric field strengthens the barrier, making it difficult for charge carriers to cross the junction, minimizing current flow.

Diode Equation

Ideal Diodes

The diode equation gives an expression for the current through a diode as a function of voltage. The *Ideal Diode Law*, expressed as:

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



where:
I = the net current flowing through the diode;
I_0 = "dark saturation current", the diode leakage current density in the absence of light;
V = applied voltage across the terminals of the diode;
q = absolute value of electron charge;
k = Boltzmann's constant; and
T = absolute temperature (K).

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

Note that:
I_0 increases as T increases; and
I_0 decreases as material quality increases.
At 300K, kT/q = 25.85 mV, the "thermal voltage".

Non-Ideal Diodes

For actual diodes, the expression becomes:

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

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

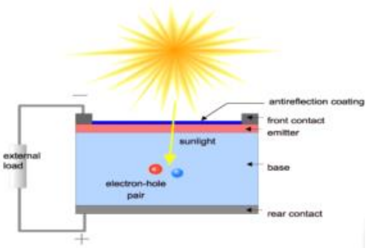
PN Junction under illumination: Solar cell

- Charge carriers generated in space charge and quasi-neutral regions.
- Electric field in space charge region sweeps carriers: electrons to N, holes to P.
- Minority carriers drift in the quasi-neutral region, creating a potential across the P-N junction (photovoltage).
- Diffusion length (Ln or Lp) represents the distance carriers can travel before recombination.
- Carriers within Ln and Lp contribute to the photovoltage.
- Carriers beyond (Ln + W + Lp) don't contribute due to recombination.
- Minority carriers' generation rate depends on light intensity.
- Light generates a current (IL) as carriers create a drift current.
- Photovoltage in forward bias reduces the potential barrier, increasing diffusion current.
- IL > Diffusion Current (Idiff), resulting in a net current from N to P.
- Positive voltage, negative current means extractable power from the solar cell.

Solar Cell Structure

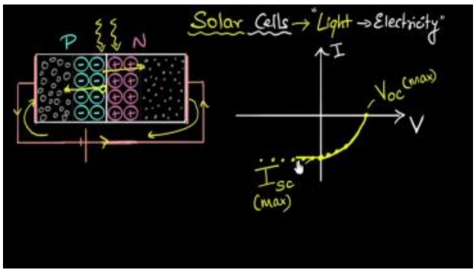
The basic steps in the operation of a solar cell are:

- the generation of light-generated carriers;
- the collection of the light-generated carries to generate a current;
- the generation of a large voltage across the solar cell; and
- the dissipation of power in the load and in parasitic resistances.



In a solar cell, **light-generated current** involves two processes:
1. **Photon Absorption**: Incident photons create electron-hole pairs if their energy exceeds the band gap, but these pairs are meta-stable.
2. **Carrier Collection by P-N Junction**: A p-n junction separates and prevents recombination of carriers. The electric field at the junction sweeps minority carriers across, generating current if the cell is short-

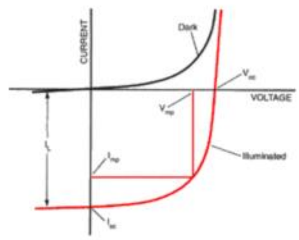
circuited.

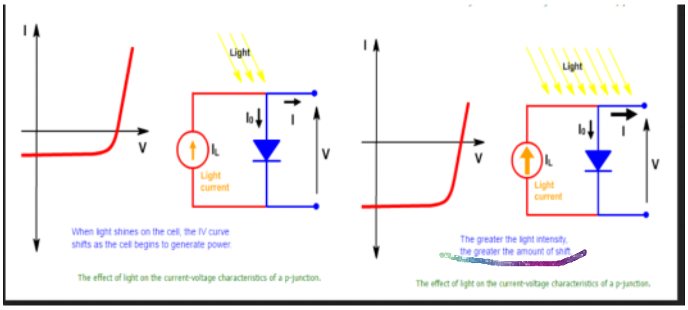


The equation for the IV curve in the first quadrant is:

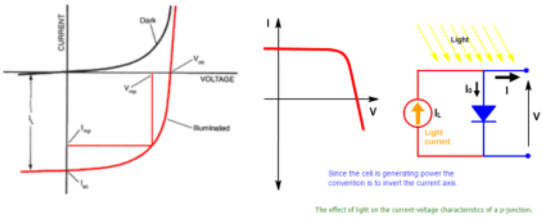
$$I = I_L - I_O\left[\exp\left(\frac{qV}{kT}\right)\right]$$

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.





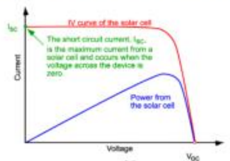
Solar cell I-V curve



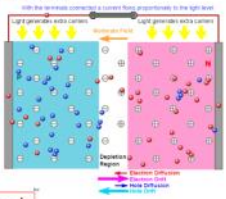
$$I = I_O\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$$

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.



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



$I_{sc} = -I_L$

The short-circuit current depends on a number of factors which are described below:

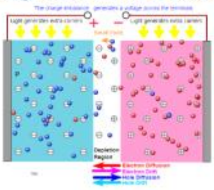
- **the area of the solar cell.** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in mA/cm²) rather than the short-circuit current;
- **the number of photons** (i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity;
- **the spectrum of the incident light.** For most solar cell measurement, the spectrum is standardised to the 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.

V max means no resistance

Isc max means short circuit means zero resistance

Open-Circuit Voltage

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.



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

- 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.

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}.

Voc as a Function of Band gap, 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–Boltzman constant, k is Boltmann constant, T is the temperature and

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

Fill Factor

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.

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \quad \text{or} \quad \frac{d(IV)}{dV} = 0$$

Solar Cell Efficiency

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC}I_{SC}FF$$

$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}}$$

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.

A solar cell is operating 27°C with J_{sc} = 50 mA/cm^2 under AM1.5G. Calculate the efficiency of the cell if $J_0 = 10^{-9}$mA/cm^2 and FF = 0.75.

A solar cell is operating 27 C with 50 mA/cm2 under AMI.5G. Calculate the efficiency of the cell if Jo = 10^-9mA/cm2 and FF 0.75.

Quantum Efficiency

The "quantum efficiency" (Q.E.) is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell.

Spectral Response

$$SR(A/W) = \frac{QE.\lambda(nm)}{1239.8}$$

Tandem Cells

One method to increase the efficiency of a solar cell is to split the spectrum and use a solar cell that is optimised to each section of the spectrum.