4.1 SOLAR CELL OPERATION

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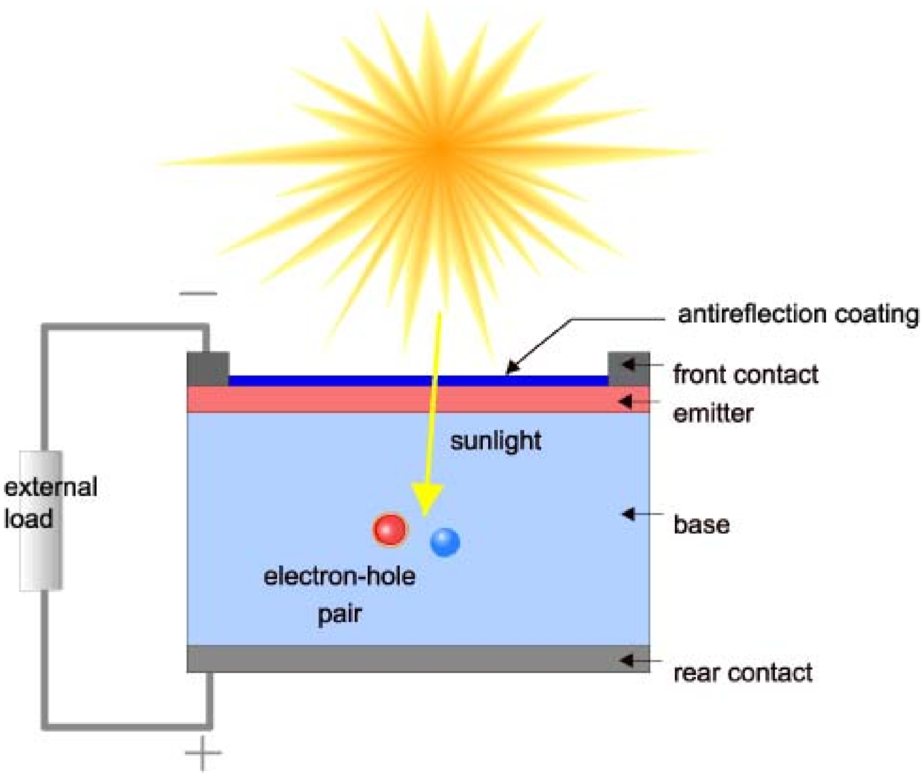
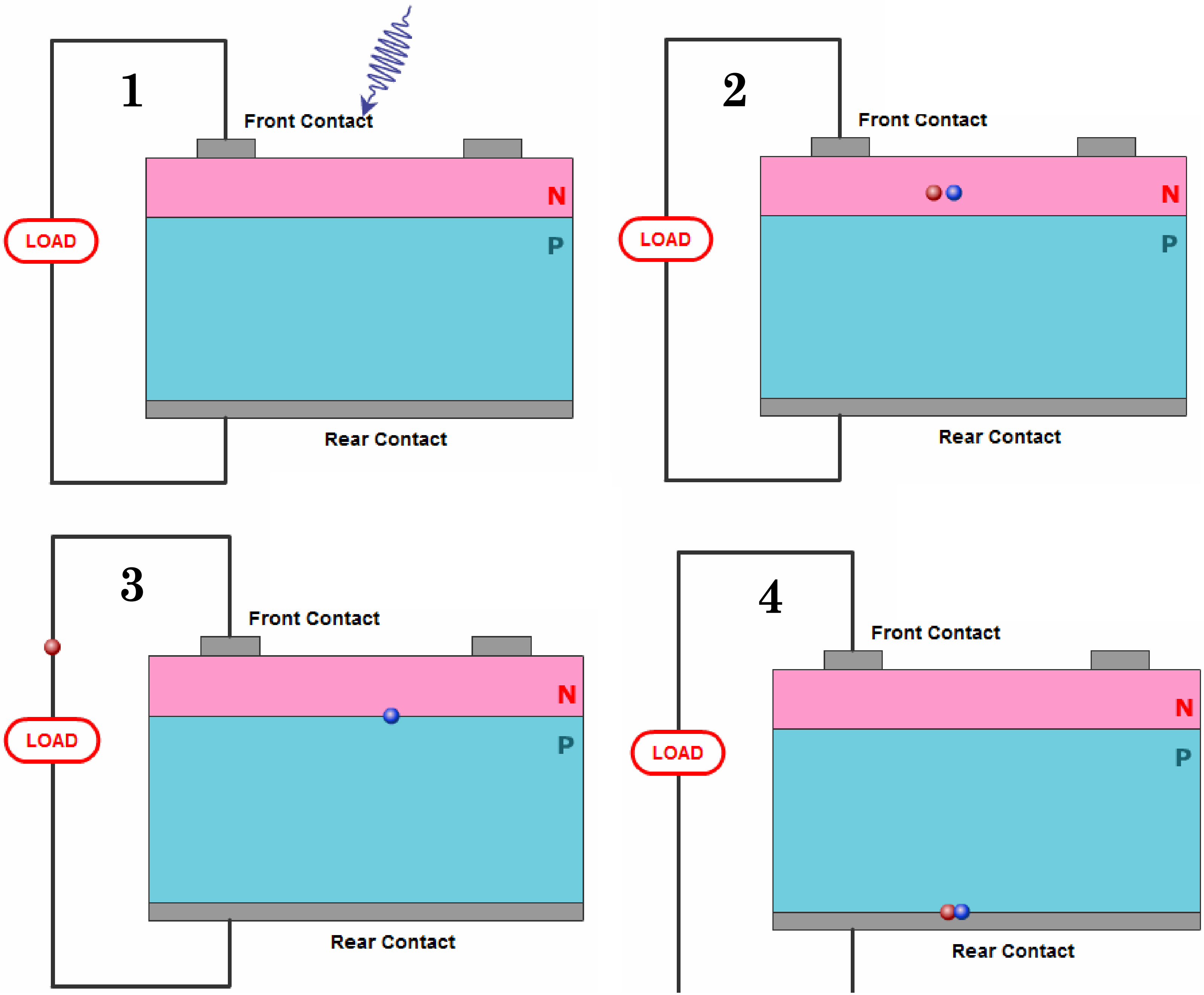
SOLAR CELL STRUCTURE

- Light shining on the solar cell produces both a current and a voltage to generate electric power.
- This process requires a material in which the absorption of light raises an electron to a higher energy state, and the movement of this higher energy electron from the solar cell into an external circuit.
- The electron then dissipates its energy in the external circuit and returns to the solar cell.
- A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p-n* junction.



BASIC OPERATION STEPS

- 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 voltage across the solar cell; and
  - the dissipation of power in the load.
- The generation of current in a solar cell, known as the "**light-generated current**", involves two key processes.
  - The first process is the absorption of incident photons to create electron-hole pairs. If the carrier recombines, then the light-generated electron-hole pair is lost and no current or power can be generated.
  - A second process, the carriers are separated by the action of the electric field existing at the *p-n* junction. If the emitter and base of the solar cell are connected together through an electric load, the light-generated electrons flow through the external circuit.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Front Contact
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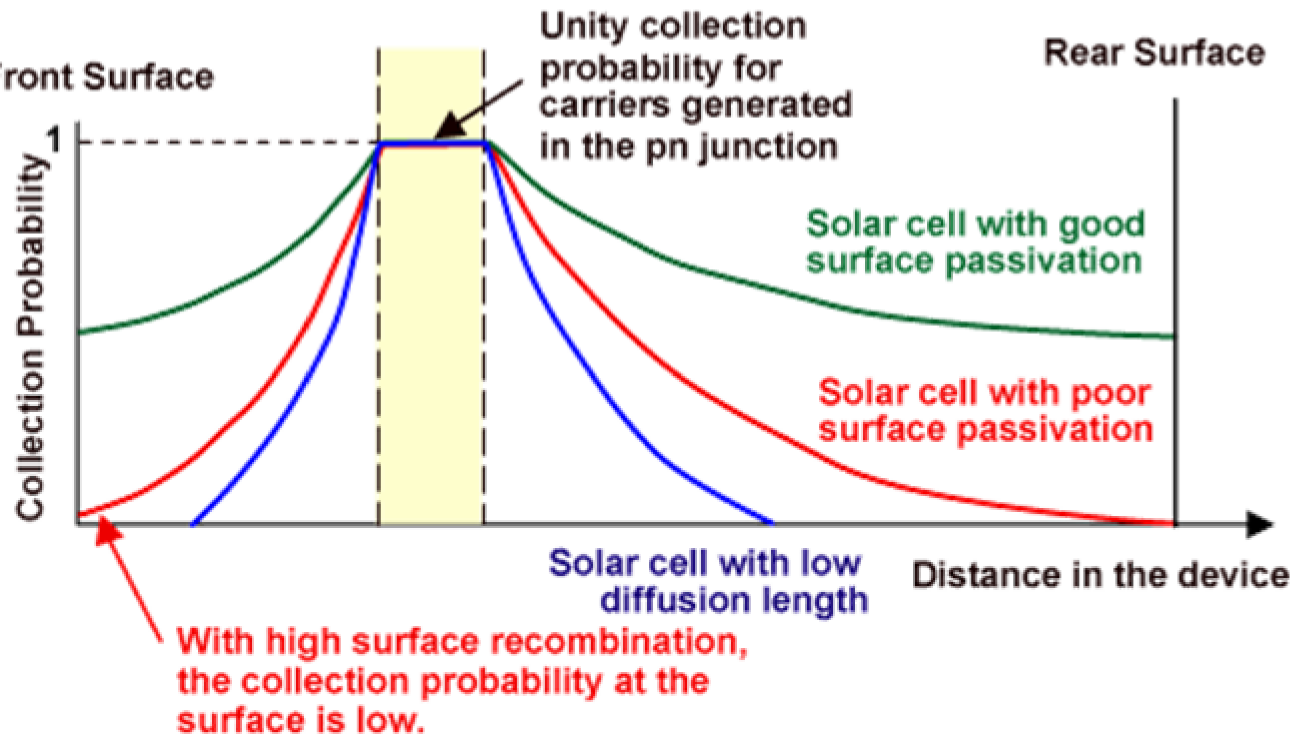
Rear Contact

COLLECTION PROBABILITY

- The "**collection probability**" describes the probability that a light generated carrier absorbed in a certain region of the device will be collected by the *p-n* junction and therefore contribute to the light-generated current.
- This probability depends on
  - the distance that a light-generated carrier must travel compared to the diffusion length.
  - the surface properties of the device.
- Collection probability of carriers generated in the depletion region is unity as the electron-hole pair are quickly swept apart by the electric field and are collected.
- Away from the junction, the collection probability drops.
  - If the carrier is generated more than a diffusion length away from the junction, then the collection probability of this carrier is quite low.
  - Similarly, if the carrier is generated closer to a region such as a surface with higher recombination than the junction, then the carrier will recombine.

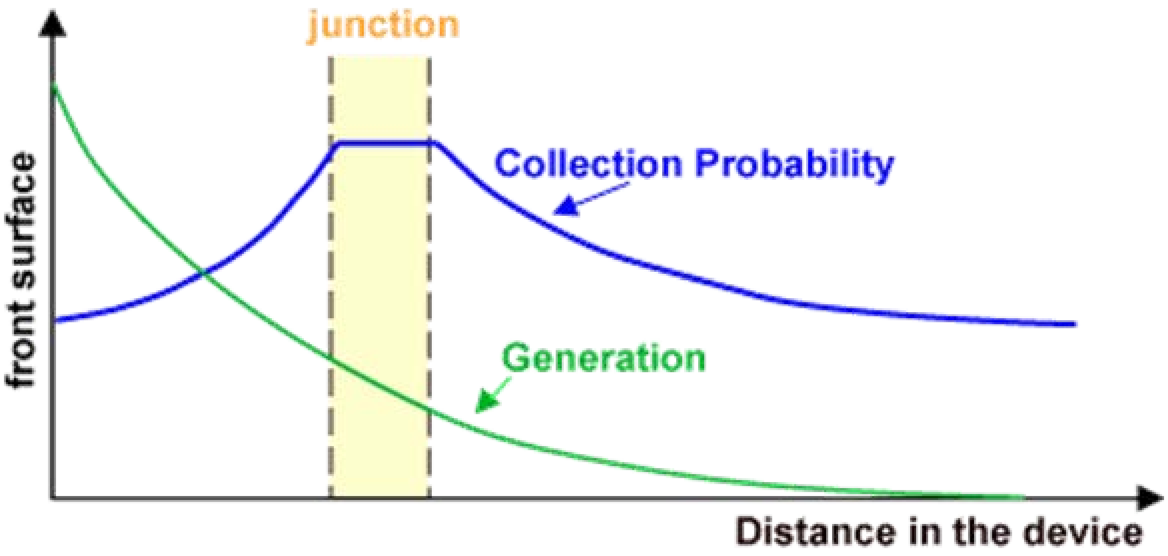


- The collection probability in conjunction with the generation rate in the solar cell determine the light-generated current from the solar cell.
- The light-generated current is the integration over the entire device thickness of the generation rate at a particular point in the device, multiplied by the collection probability at that point.

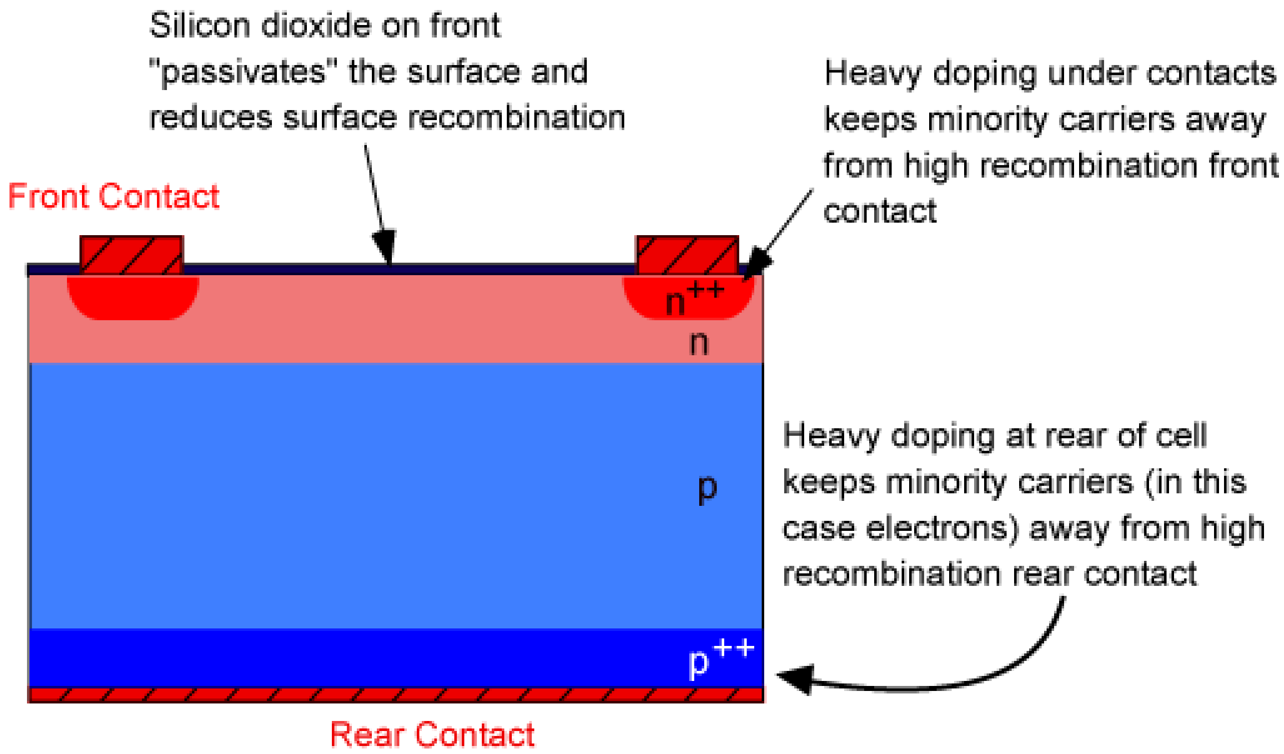
- The equation for the light-generated current density (J_L), with an arbitrary generation rate G(x) and collection probability CP(x), is shown below, as is the generation rate in silicon due to the AM1.5 solar spectrum:

$$J_L = q\int_0^W G(x)CP(x)dx = q\int_0^W \left[\int \alpha(\lambda)H_0 \exp(-\alpha(\lambda)x)\, d\lambda\right] CP(x)dx$$

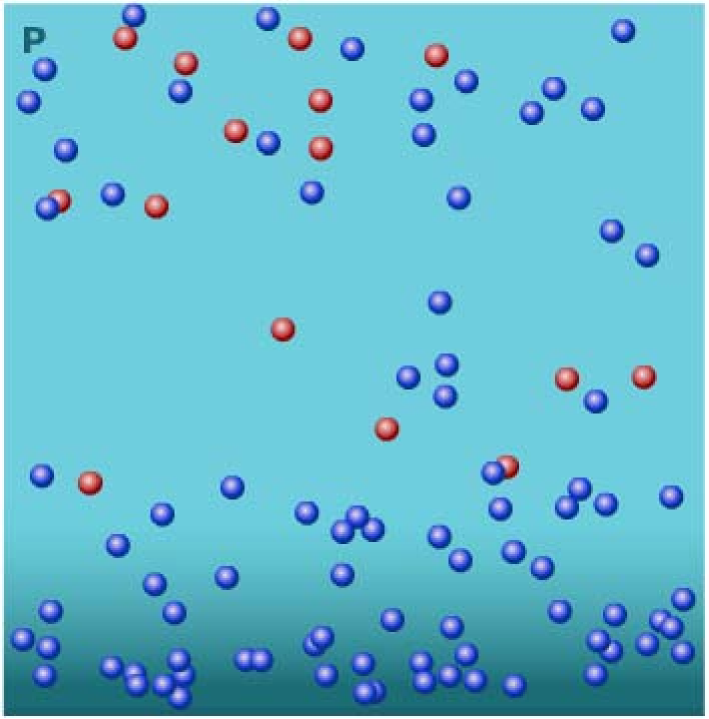
where:
q is the electron charge;
W is the thickness of the device;
$\alpha(\lambda)$ is the absorption coefficient;
H_0 is the number of photons at each wavelength.



- 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 growing a "passivating" layer (usually silicon dioxide – an insulator) on the top surface.
  - Under the top contacts, surface recombination can be minimized by increasing the doping as high as possible.

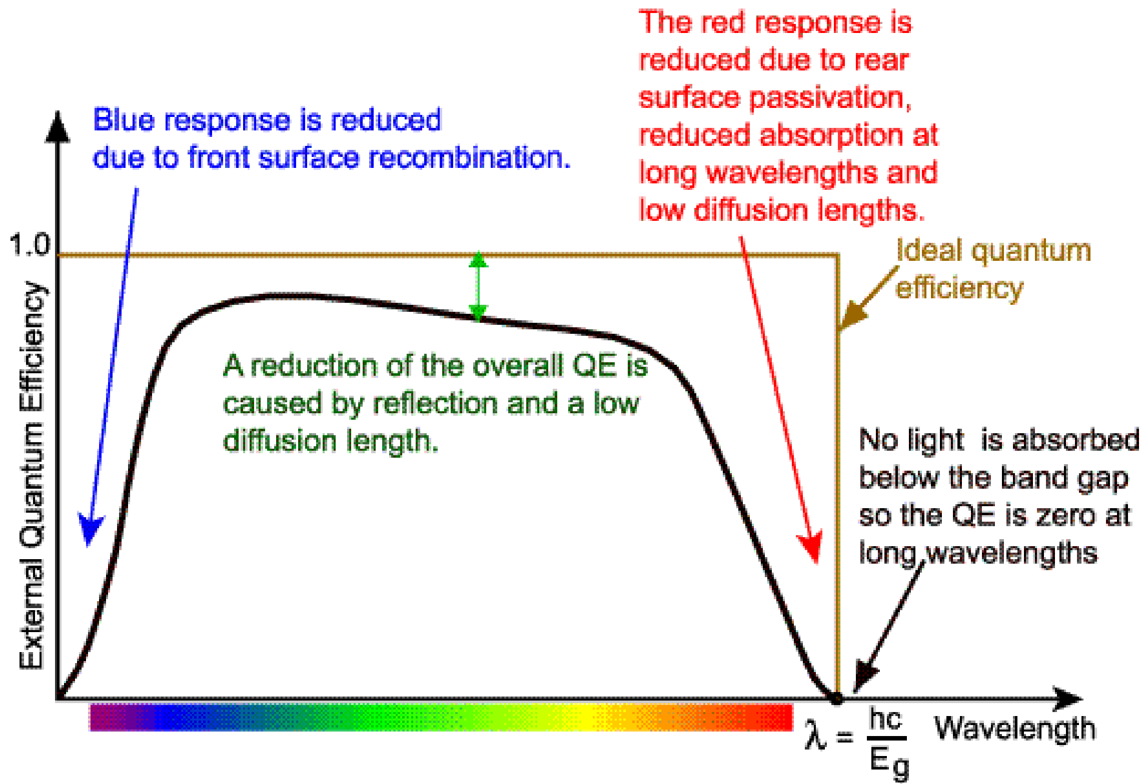


- A similar effect is employed at the rear surface to minimize the impact of rear surface recombination, if the rear surface is closer than a diffusion length to the junction.
- A "back surface field" (BSF) consists of a higher doped region at the rear surface of the solar cell. The interface between the high and low doped region behaves 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 BSF has a net effect of passivating the rear surface.



QUANTUM EFFICIENCY

- The "quantum efficiency" (QE) 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.
- QE may be given either as a function of wavelength or as energy. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is unity. The quantum efficiency for photons with energy below the band gap is zero

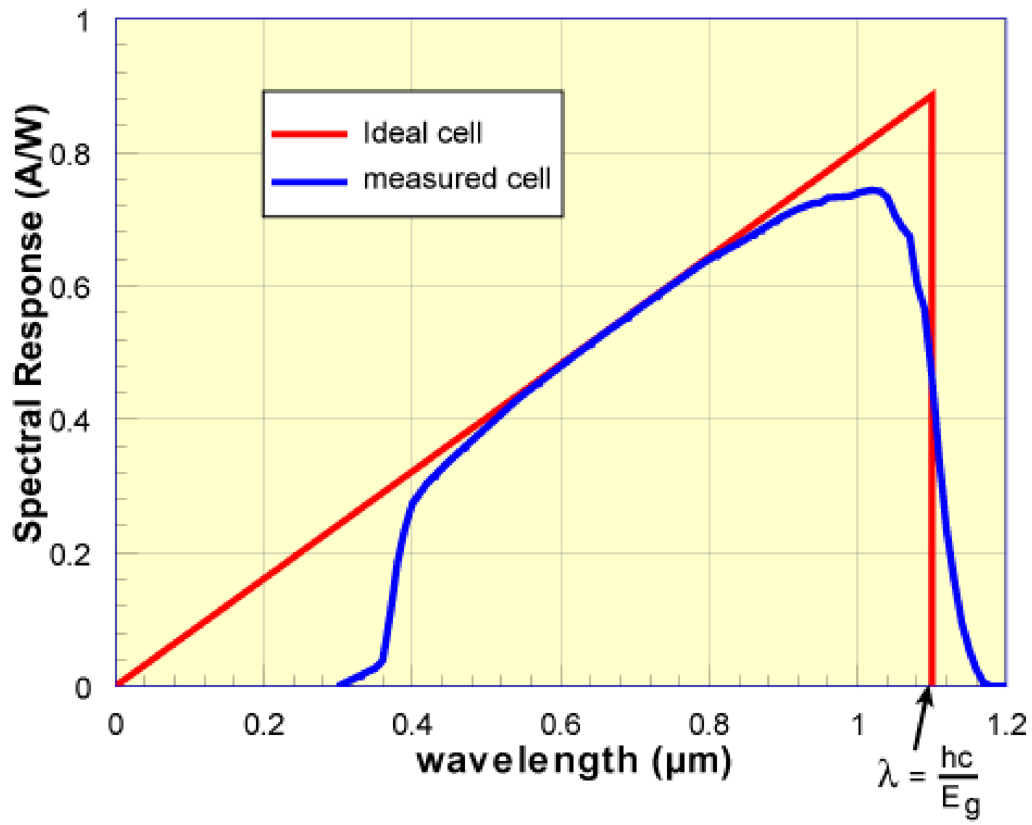


QUANTUM EFFICIENCY

- While quantum efficiency ideally has the square shape, the quantum efficiency for most solar cells is reduced due to recombination effects.
- The same mechanisms which affect the collection probability also affect the quantum efficiency.
  - For example, front surface passivation affects carriers generated near the surface, and since blue light is absorbed very close to the surface, high front surface recombination will affect the "blue" portion of the quantum efficiency.
- The quantum efficiency can be viewed as the collection probability due to the generation profile of a single wavelength, integrated over the device thickness and normalized to the incident number of photons.
- The "external" quantum efficiency of a silicon solar cell includes the effect of optical losses such as transmission and reflection. However, it is often useful to look at the quantum efficiency of the light left after the reflected and transmitted light has been lost.

SPECTRAL RESPONSE

- The spectral response is conceptually similar to the quantum efficiency. The quantum efficiency gives the number of electrons output by the solar cell compared to the number of photons incident on the device, while the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell.
- The spectral response of a silicon solar cell under glass is shown below:



SPECTRAL RESPONSE

- The ideal spectral response is limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap.
- However, unlike the square shape of QE curves, the spectral response decreases at small photon wavelengths. At these wavelengths, each photon has a large energy, and hence the ratio of photons to power is reduced. Any energy above the band gap goes to heating the solar cell.
- The inability to fully utilize the incident energy at high energies, and the inability to absorb low energies of light represents a significant power loss in solar cells with one *p-n* junction.
- Spectral response is important since it is the spectral response that is measured from a solar cell, and from this the quantum efficiency is calculated. The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength.

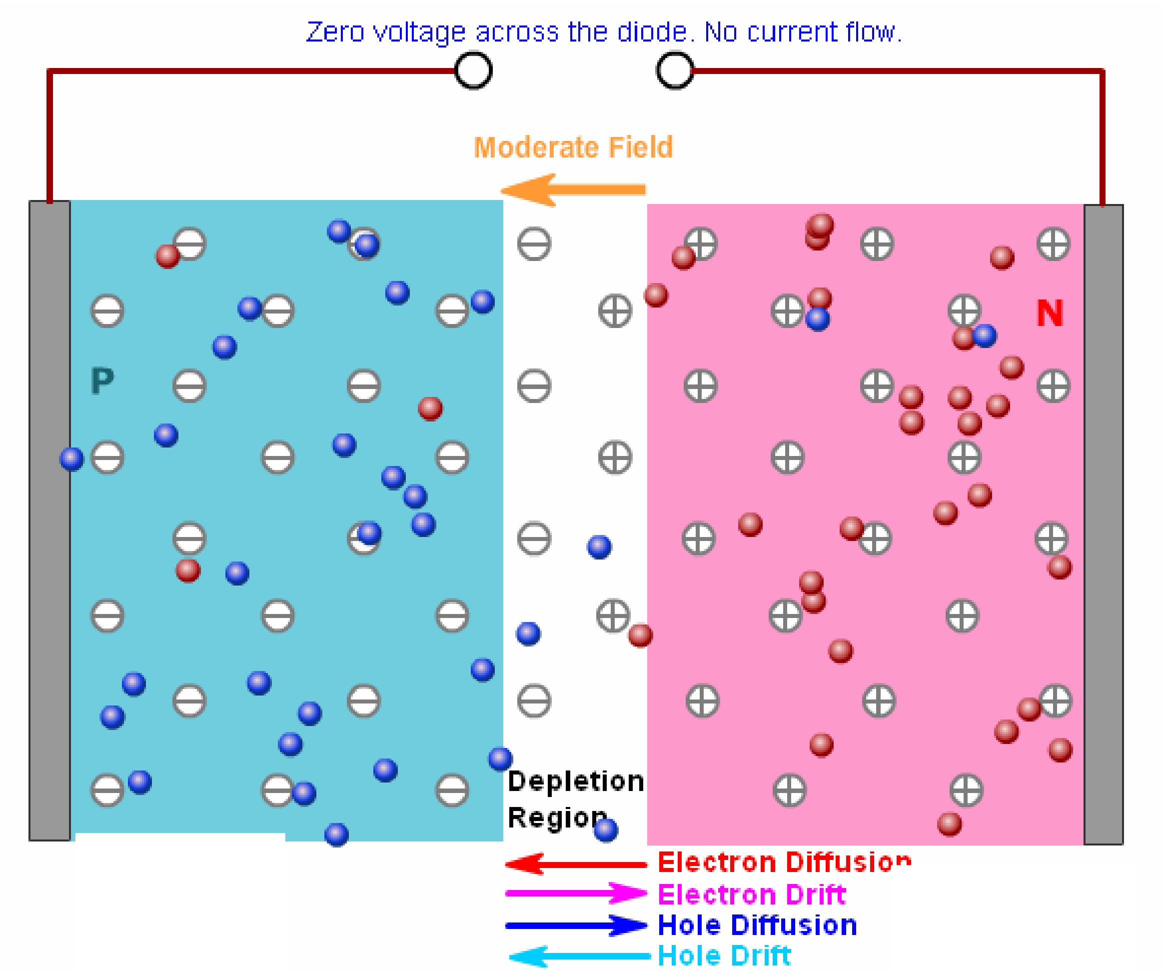
PHOTOVOLTAIC EFFECT

- The collection of light-generated carriers does not by itself give rise to power generation. In order to generate power, a voltage must be generated as well as a current.
- Voltage is generated in a solar cell by a process known as the "photovoltaic effect". The collection of light-generated carriers by the *p-n* junction causes a movement of electrons to the *n*-type side and holes to the *p*-type side of the junction.
- Under short circuit conditions, there is no build up of charge, as the carriers exit the device as light-generated current.
- However, if the light-generated carriers are prevented from leaving the solar cell, then the collection of light-generated carriers causes an increase in the number of electrons on the *n*-type side of the *p-n* junction and a similar increase in holes in the *p*-type material.

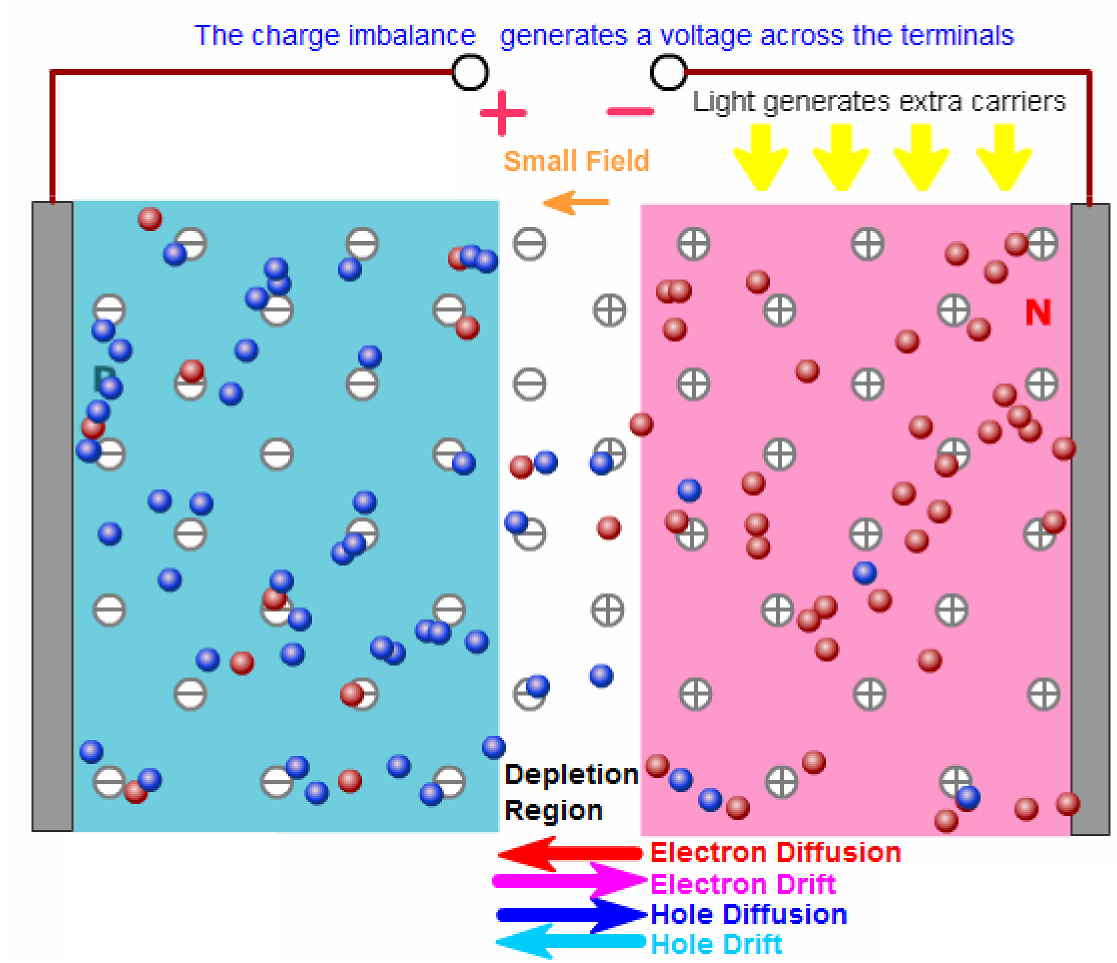
PHOTOVOLTAIC EFFECT

- This separation of charge creates an electric field at the junction which is in opposition to that already existing at the junction, thereby reducing the net electric field.
- Since the electric field represents a barrier to the flow of the forward bias diffusion current, the reduction of the electric field increases the diffusion current.
- A new equilibrium is reached in which a voltage exists across the *p-n* junction. The current from the solar cell is the difference between the light-generated and the forward bias current.
- Under open circuit conditions, the forward bias of the junction increases to a point where the light-generated current is exactly balanced by the forward bias diffusion current, and the net current is zero.
- The voltage required to cause these two currents to balance is called the "open-circuit voltage".

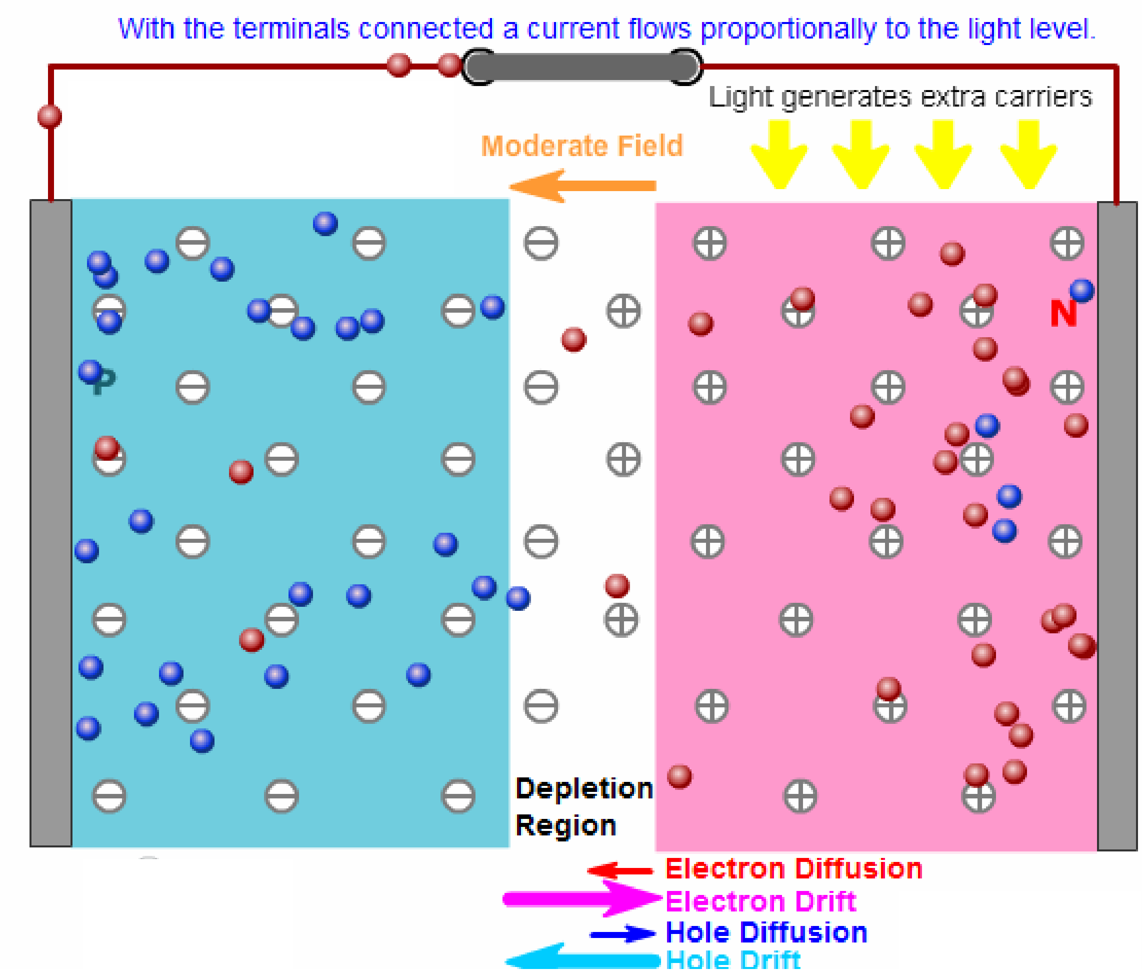
- In equilibrium (i.e. in the dark) both the diffusion and drift current are small.



- Under open circuit conditions, the light-generated carriers forward bias the junction, thus increasing the diffusion current. Since the drift and diffusion current are in opposite direction, there is no net current from the solar cell at open circuit.



- Under short circuit conditions, the minority carrier concentration on either side of the junction is increased and the drift current, which depends on the number of minority carriers, is increased.



I-V CURVE

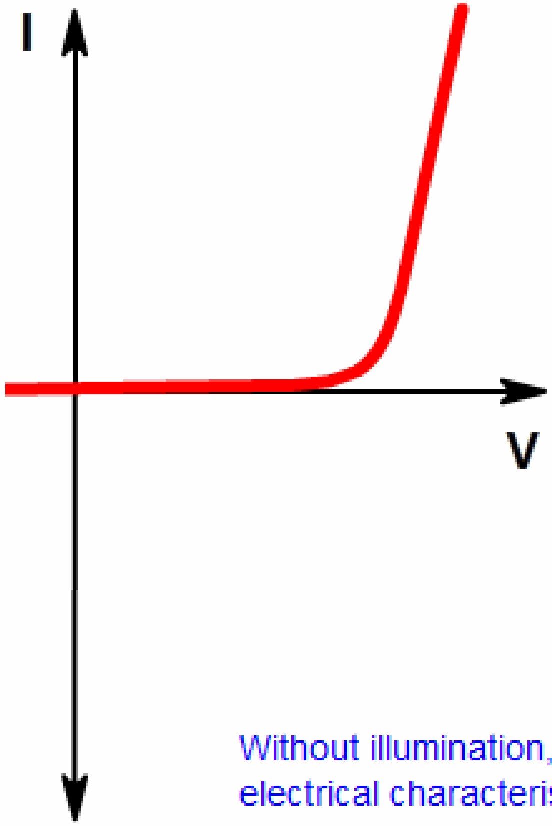
- The I-V curve of a solar cell is the superposition of the I-V curve of the solar cell diode in the dark with the light-generated current I_L. The light has the effect of shifting the I-V curve down into the fourth quadrant where power can be extracted from the diode. The equation for the I-V curve in the first quadrant is:

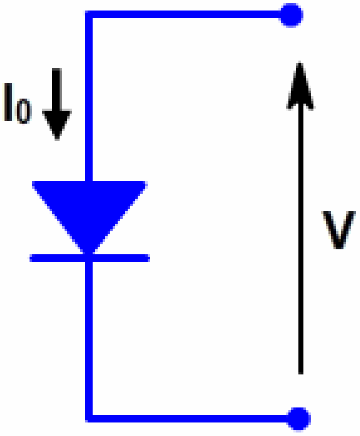
$$I = I_L - I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$

where I_L = light generated current.

- The -1 term in the above equation can usually be neglected. The exponential term is usually >> 1 except for voltages below 100 mV. Further, at low voltages, the light generated current I_L dominates the second term so the -1 term is not needed under illumination.

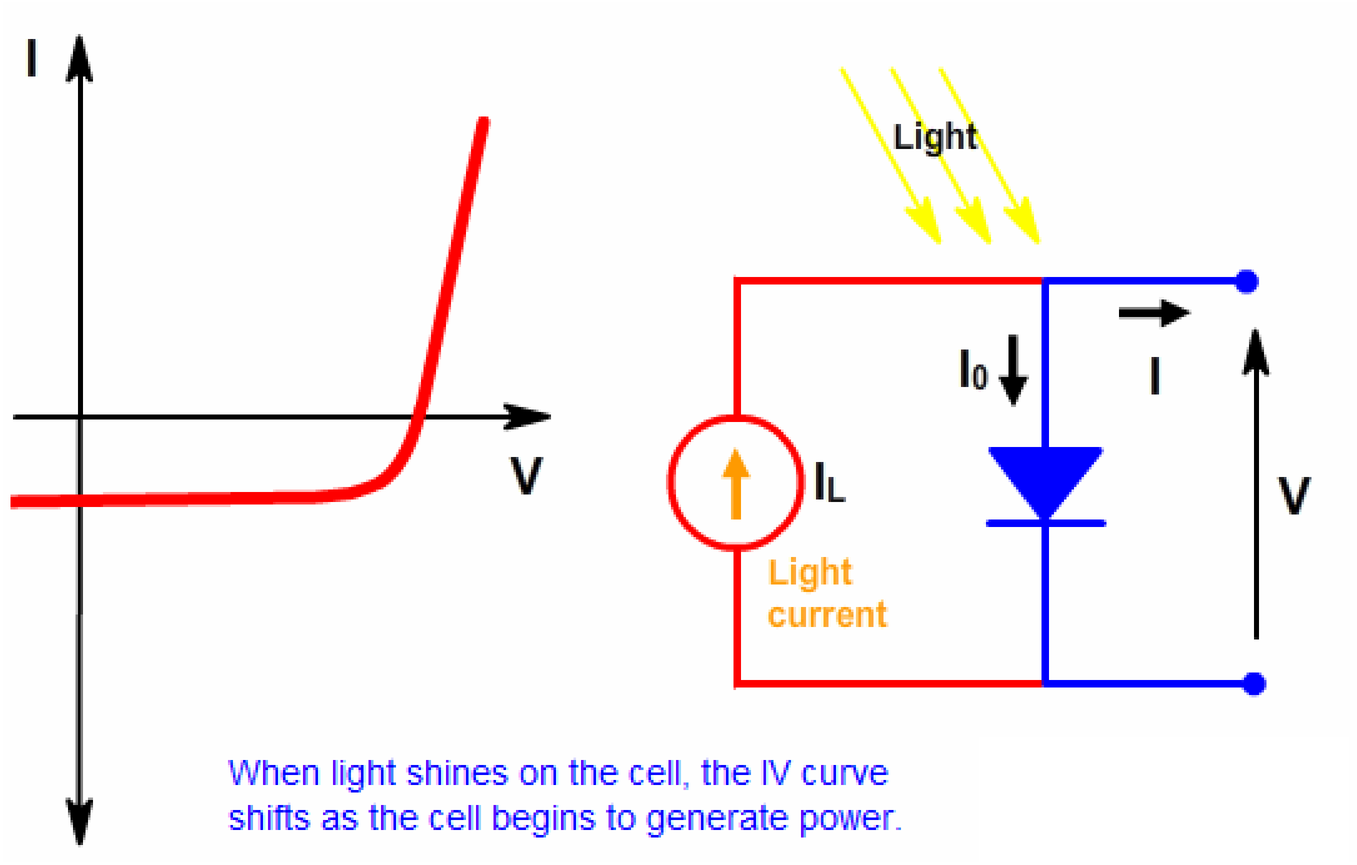
DIODE I-V CURVE



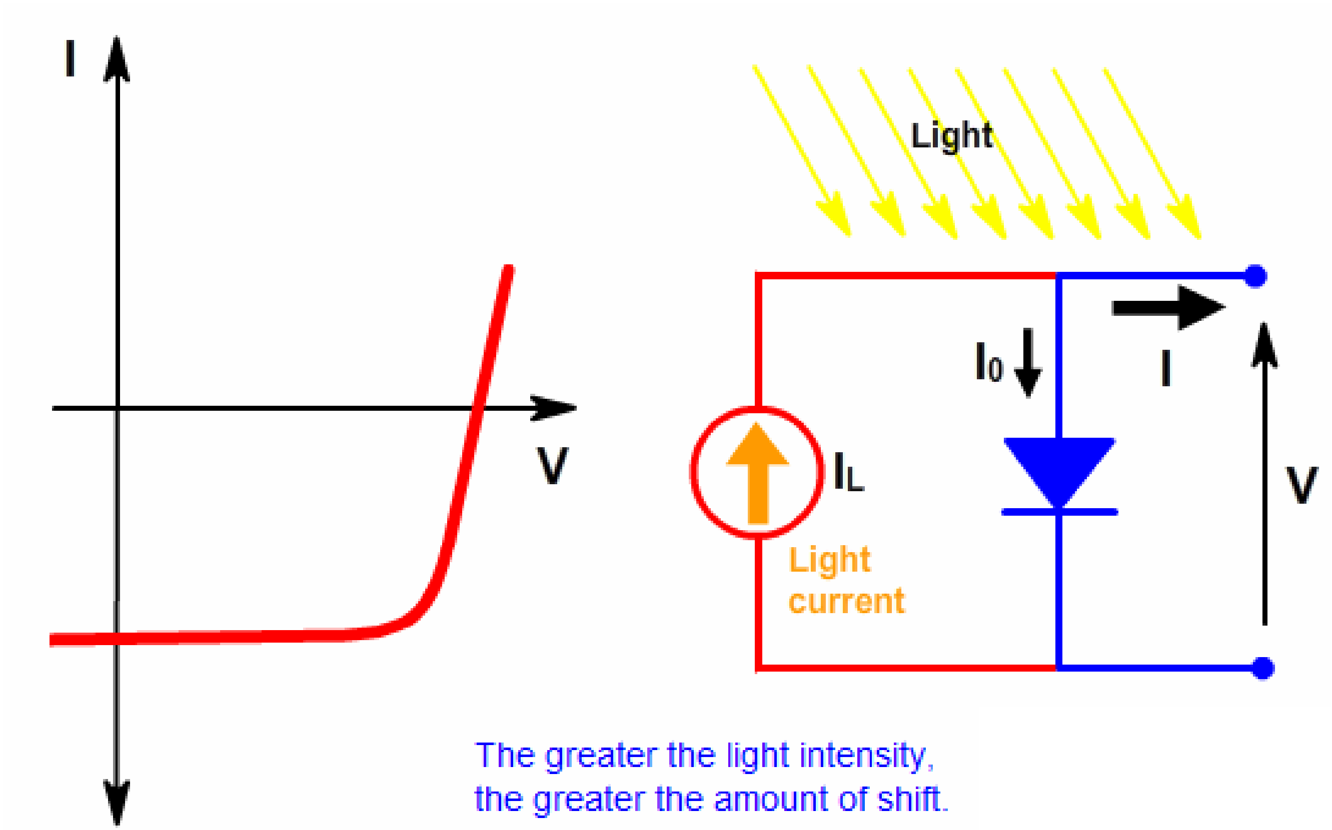


Without illumination, a solar cell has the same electrical characteristics as a large diode.

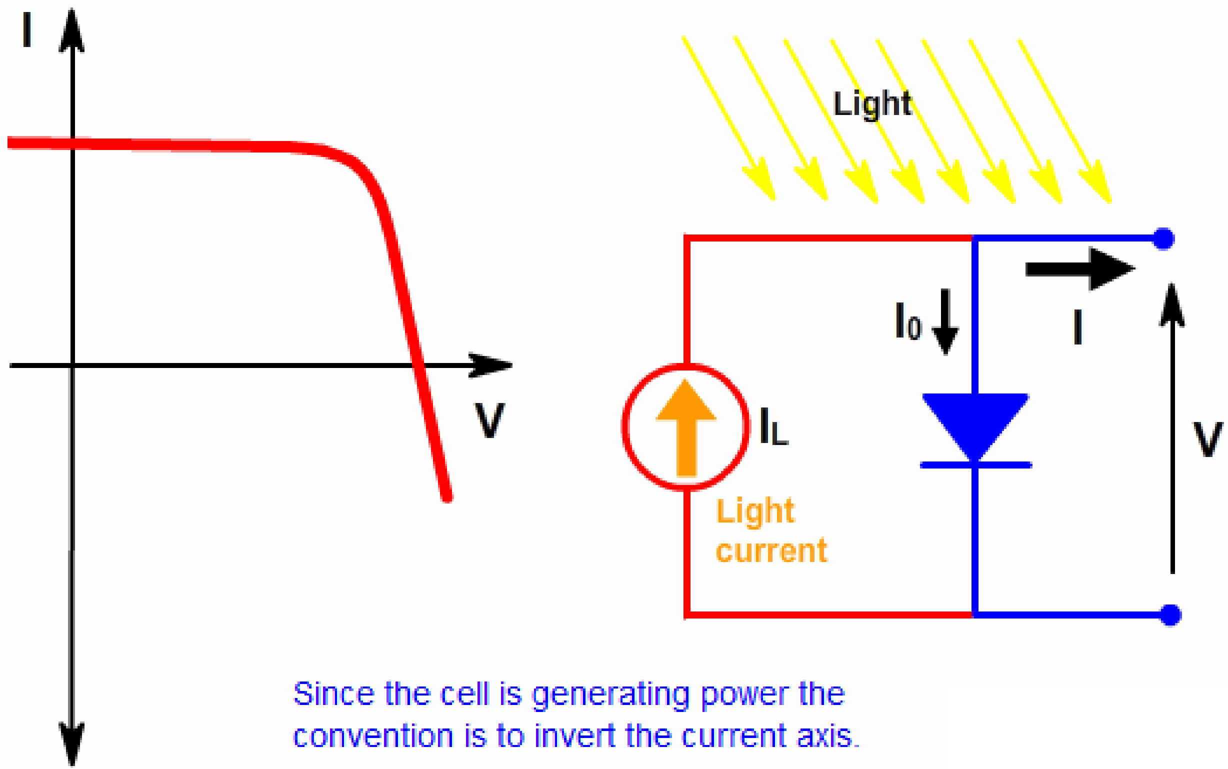
SHIFT OF I-V CURVE



SHIFT OF I-V CURVE

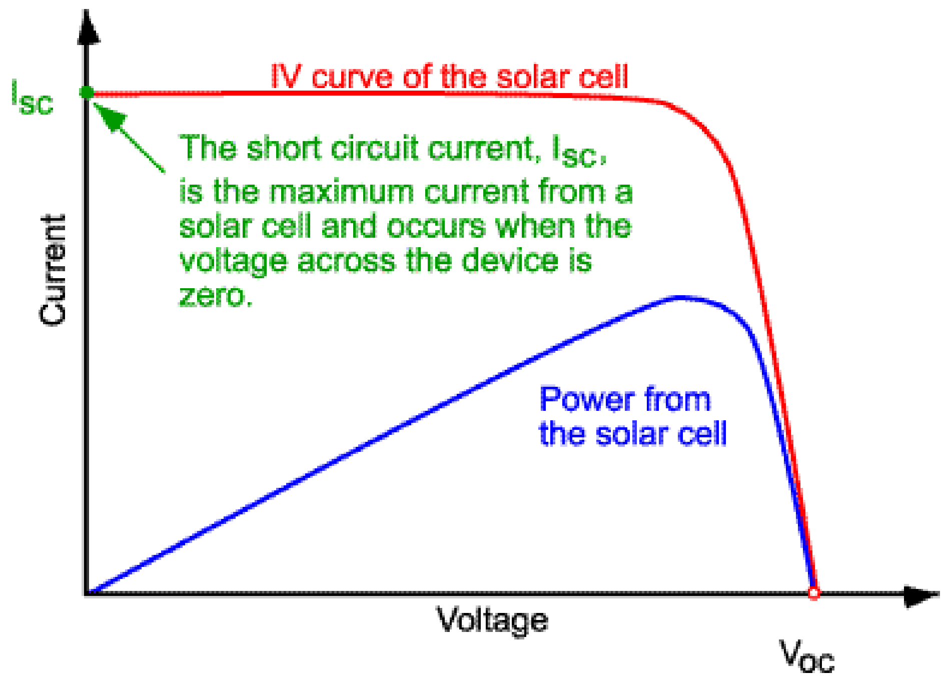


Final I-V Curve



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).
- The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell, 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 :
  - **the area of the solar cell**
  - **the number of photons**
  - **the spectrum of the incident light.**
  - **the optical properties**
  - **the collection probability**
- 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 can be approximated as:

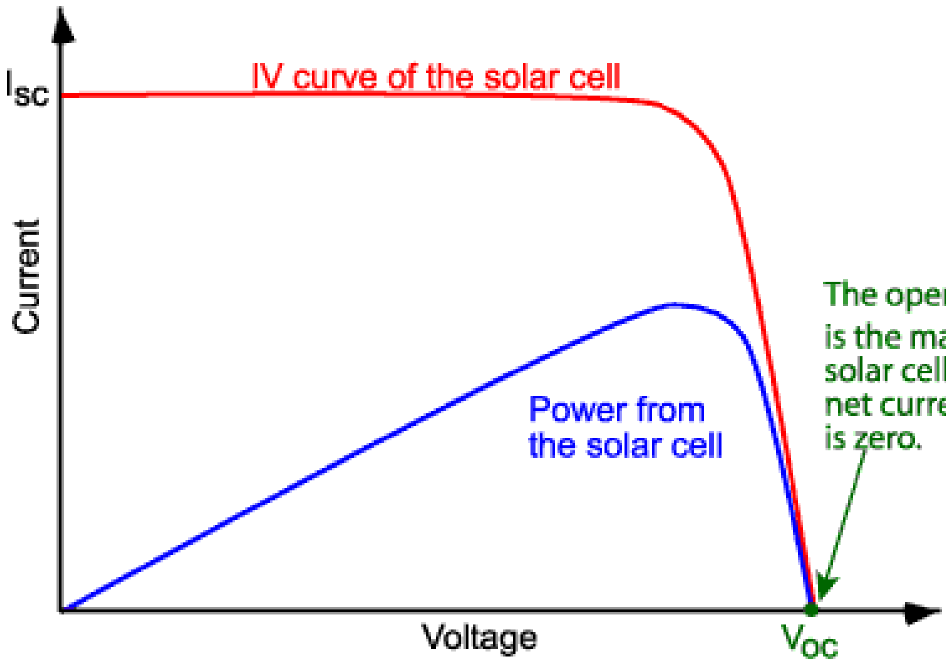
$$J_{SC} = qG\left(L_n + L_p\right)$$

  where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively.
- Silicon solar cells under an AM1.5 spectrum have a maximum possible current of 46 mA/cm^2. Laboratory devices have measured short-circuit currents of over 42 mA/cm^2, and commercial solar cell have short-circuit currents between about 28 and 35 mA/cm^2.

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.
- An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

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



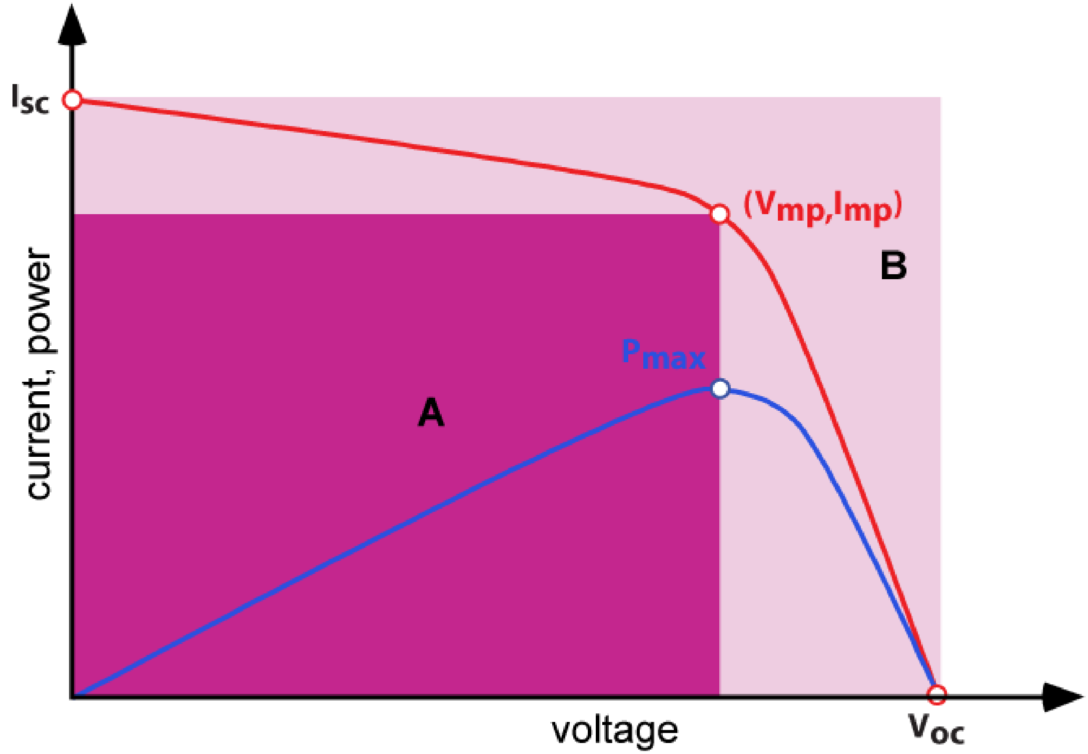
- The above equation shows that V_{oc} depends on the saturation current of the solar cell and the light-generated current. The saturation current, I_0 depends on recombination in the solar cell.
- Open-circuit voltage is then a measure of the amount of recombination in the device.
- Silicon solar cells on high quality single crystalline material have open-circuit voltages of up to 730 mV under one sun and AM1.5 conditions, while commercial devices on multi-crystalline 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.

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.
- The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and 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 defined as the maximum power divided by the product of I_{sc}*V_{oc}, i.e.:

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

- 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. i.e.,

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

- giving

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

- However, the above technique does not yield a simple or closed form solution. 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}"

$$v_{oc} = \frac{q}{nkT} V_{oc}$$

- Silicon cells have a FF ranging between 0.82 and 0.85.
- GaAs solar cell may have a FF approaching 0.89.

CELL EFFICIENCY

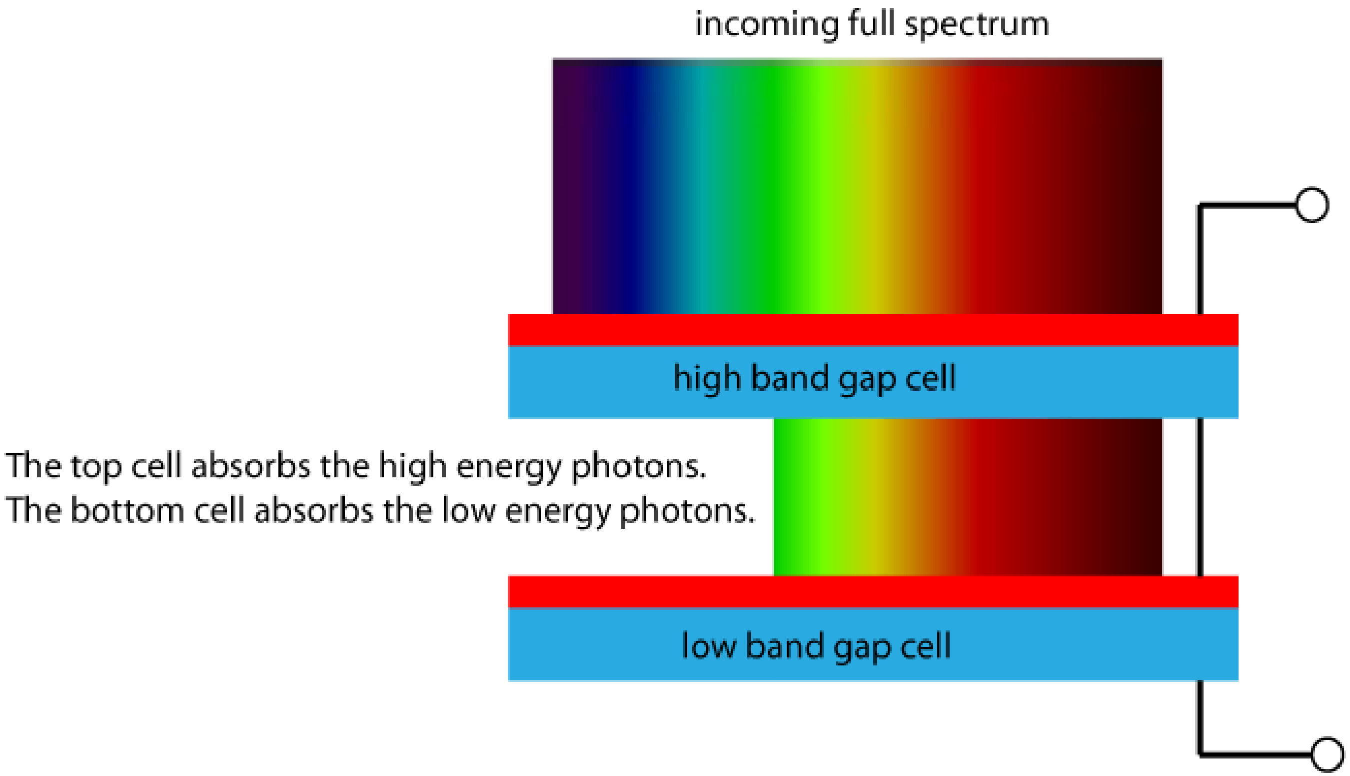
- The efficiency is the most commonly used parameter to compare the performance of one solar cell to another.
- Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends 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.
- The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

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

where V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current; and *FF* is the fill factor.

TANDEM CELLS

- One method to increase the efficiency of a solar cell is to split the spectrum and use a solar cell that is optimized to each section of the spectrum.
- The most common arrangement for tandem cells is to grow them monolithically so that all the cells are grown as layers on the on substrate and tunnel junctions connect the individual cells.



TANDEM CELLS

- The maximum theoretical efficiency for a two junction tandem under AM1.5 is 47%. At the peak efficiency the top cell has a bandgap of 1.63 eV and the bottom cell has a bandgap of 0.96 eV.
- As the number of bandgaps increases, the efficiency of the stack also increases. In reality however, semiconductor materials that for arbitrary bandgaps and of high quality do not exist.