Photovoltaic Effect: An Introduction to Solar Cells

Text Book: Sections 4.1.5 & 4.2.3

References:
Solar Cells by Martin A. Green, The University of New South Wales, 1998.
Silicon Solar Cells by Martin A. Green, The University of New South Wales, 1995.
Photovoltaic Effect

Solar photovoltaic energy conversion: Converting sunlight directly into electricity.

When light is absorbed by matter, photons are given up to excite electrons to higher energy states within the material (the energy difference between the initial and final states is given by $h\nu$). Particularly, this occurs when the energy of the photons making up the light is larger than the forbidden band gap of the semiconductor. But the excited electrons relax back quickly to their original or ground state. In a photovoltaic device, there is a built-in asymmetry (due to doping) which pulls the excited electrons away before they can relax, and feeds them to an external circuit. The extra energy of the excited electrons generates a potential difference or electron motive force (e.m.f.). This force drives the electrons through a load in the external circuit to do electrical work.
The solar cell is the basic building block of solar photovoltaics. The cell can be considered as a two terminal device which conducts like a diode in the dark and generates a photovoltage when charged by the sun.

When the junction is illuminated, a net current flow takes place in an external lead connecting the p-type and n-type regions.

The light generated current is superimposed upon the normal rectifying current-voltage characteristics of the diode. The power can be extracted from the device in a region shown in the fourth quadrant.
The solar cell is the basic building block of solar photovoltaics. When charged by the sun, this basic unit generates a dc photovoltage of 0.5 to 1.0 V and, in short circuit, a photocurrent of some tens of mA/cm². Since the voltage is too small for most applications, to produce a useful voltage, the cells are connected in series into modules, typically containing about 28 to 36 cells in series to generate a dc output of 12 V. To avoid the complete loss of power when one of the cells in the series fails, a blocking diode is integrated into the module. Modules within arrays are similarly protected to form a photovoltaic generator that is designed to generate power at a certain current and a voltage which is a multiple of 12 V.
**Solar Cell - Definitions**

*Open circuit voltage* \( V_{oc} *: \) When light hits a solar cell, it develops a voltage, analogous to the e.m.f. of a battery in a circuit. The voltage developed when the terminals are isolated (infinite load resistance) is called the open circuit voltage.

*Short circuit current* \( I_{sc} *: \) The current drawn when the terminals are connected together is the short circuit current.

For any intermediate load resistance \( R_L \) the cell develops a voltage \( V \) between 0 and \( V_{oc} \) and delivers a current \( I \) such that \( V = IR_L \), and \( I(V) \) is determined by the Current-voltage characteristic of the cell under that illumination.

Both \( I \) and \( V \) are determined by the illumination as well as the load.

The current is approximately proportional to the illumination area, the *short circuit current density*, \( J_{sc} \) is a useful quantity for comparison.
Photocurrent and Quantum Efficiency

The photocurrent density, $J_{sc}$, generated by a solar cell under illumination at short circuit is dependent on the incident light spectrum.

**Quantum efficiency (QE):** It is the probability that an incident photon of energy $E$ will deliver one electron to the external circuit.

$$J_{sc} = q \int b_s(E)QE(E) \, dE$$

Where $b_s(E)$ is the incident spectral photon flux density, the number of photons of energy in the range $E$ to $E+dE$ which are incident on unit area in unit time and $q$ is the electronic charge.

$$E = \frac{hc}{\lambda} = \frac{1240}{\lambda}$$

QE depends on the solar cell material and electronic characteristics, but does not depend on the incident spectrum.
Photocurrent and Quantum Efficiency

A battery normally delivers a constant e.m.f. at different levels of current and will deteriorate when it is heavily discharged. The solar cell delivers a constant current for any given illumination level while the voltage is determined largely by the load resistance.

The short circuit photocurrent is obtained by integrating the product of the photon flux density and QE over photon energy. It is desirable to have a high QE at wavelengths where the solar flux density is high.
Consider a beam of red light with a wavelength $\lambda = 6000$ Å. Its energy in electron volts is

$$E = h \nu = \frac{hc}{\lambda} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{6000 \times 10^{-10}} = 2.08eV$$

$$eV = 1.6 \times 10^{-19} \text{ joule}$$

The *photon flux* is a quantity useful in solar cell calculations: it is defined as the number of photons crossing a unit area perpendicular to the light beam per second. If we let $\Phi$ denote the intensity of the light in $\text{w/cm}^2$ then we have

$$\Phi = N_{ph} E = \frac{N_{ph} hc}{\lambda_{av}}$$

where $N_{ph}$ is the number of photons carrying the energy.
The path length of the solar radiation through the Earth’s atmosphere in units of Air Mass (AM) increases with the angle from the zenith. The AM 1.5 spectrum is the preferred standard spectrum for solar cell efficiency measurements.

The easiest way to estimate the air mass in practice is to measure the length of the shadow $s$ cast by a vertical structure of height $h$ using

$$AM = \sqrt{1 + \left( \frac{s}{h} \right)^2}$$
Solar irradiance: The amount of radiant energy received from the Sun per unit area per unit time. It is a function of wavelength at a point outside the Earth’s atmosphere. Solar irradiance is greatest at wavelengths, 300-800 nm.

The extraterrestrial spectrum resembles the spectrum of a black body radiation at 5760 K. The black body emits photons with a distribution of energies determined by it’s surface temperature.
Solar Radiation Spectrum

The global spectrum comprises the direct plus the diffused light.
Silicon solar cells with a bandgap of 1.13ev can maximally absorb 77% of the terrestrial solar energy.
Irradiance

The emitted energy flux density or irradiance, $L(E)$ is related to the photon flux density through

$$L(E) = Eb_s(E)$$

Integrating over $E$ gives the total emitted power density, $\sigma_s T_s$, where $\sigma_s$ is Stefan’s constant that is given by

$$\sigma_s = \frac{2\pi^5 k^4}{15c^2h^3}$$

At the sun’s surface, the power density is 62 MW/m$^2$
Outside the Earth’s atmosphere, the power density is 1353 W/m$^2$
Photon Flux Calculation

Let $\Phi$ denote intensity of the light in W/cm$^2$ and the number of photons carrying that energy $N_{ph}$ is computed from the expression

$$\Phi = N_{ph} E = N_{ph} h \nu_{av} = \frac{N_{ph} hc}{\lambda_{av}}$$

For example, if outside the atmosphere the solar spectrum has an intensity of 0.135 W/cm$^2$ and each photon carries on the average 1.48 eV, then the photon flux is

$$N_{ph} = \frac{0.135 \text{ W/cm}^2}{1.48 \text{ eV}} \times \frac{1.48 \text{ eV}}{1.60 \times 10^{-19} \text{ joule/W-sec}} = 5.8 \times 10^{17} \text{ 1/cm}^2\text{-sec}$$

$m=1/\cos \theta$

$w= \text{number of cm of perceptible water vapor}$

Note: $N_{ph}$ is computed by summing the number of photons in the energy range from 0 up to 4 eV found in the solar spectrum
Motion of the Sun

Apparent motion of the sun relative to a fixed observer at latitude 35° in the northern hemisphere. The position of the sun is shown at solar noon and shaded circles represent the sun’s position 3 h before and after solar noon.
Sustainable Energy Science and Engineering Center

**Spectral Photon Flux Density**

The *spectral photon flux* $\beta (E, s, \theta, \phi)$ - number of photons of given energy passing through unit area in unit time per unit solid angle. It is defined on an element of surface area with its direction is defined by the angle to the surface normal, $\theta$, and an azimuthal angle, $\phi$, projected on the plane of the surface element. The photon flux density resolved along the normal to the surface is denoted by $b$, which is obtained by integrating the components of $\beta$ normal to the surface over solid angle.

$\beta$ is given by

$$\beta_s d\Omega ds dE = \frac{2}{h^3 c^2} \left( \frac{E^2}{e^{E/k_B T_s} - 1} \right) d\Omega ds dE$$

$$b_s ds dE = \int_{\Omega} \beta_s(E, s, \theta, \phi) \cos \theta d\Omega ds dE$$

$$b_s ds dE = \frac{2 F_s}{h^3 c^2} \left( \frac{E^2}{e^{E/k_B T_s} - 1} \right) ds dE$$

$$F_s = \pi \sin^2 \theta_{\text{sun}}$$

Where $\theta_{\text{sun}}$ is the half angle subtended by the radiating body to the point of the flux measurement. For the sun as seen from the Earth $\theta_{\text{sun}} = 26^\circ$
Current Density at Ambient Temperature

The spectral photon flux at a point \( s \) on the surface of a solar cell at ambient temperature, \( T_a \) is

\[
\beta_a d\Omega ds dE = \frac{2}{h^3 c^2} \left( \frac{E^2}{e^{\frac{k_B T_a}{E}} - 1} \right) d\Omega ds dE
\]

With appropriate integration of the above expression, we obtain the incident flux of thermal photons normal to the surface of a flat flat solar cell as

\[
b_a(E) = \frac{2F_a}{h^3 c^2} \left( \frac{E^2}{e^{\frac{k_B T_a}{E}} - 1} \right)
\]

Where \( F_a = \pi \) for the ambient radiation received over a hemisphere. The equivalent current density absorbed from the ambient is

\[
j_{abs} = q(1 - R(E)a(E)b_a(E))
\]

Where \( a(E) \) (known as the absorbance that is determined by the absorption coefficient of the material and by the optical path length through the device) is the probability of absorption of a photon of energy \( E \) and \( R(E) \) is the probability of photon reflection. \( j_{abs} \) \( (E) \) is the electron current density equivalent to the absorbed photon flux if each photon of energy \( E \) generates one electron.
Current Density Under Illumination

Under illumination by a solar photon flux \( b_s(E) \), the cell absorbs solar photons of energy \( E \) at a rate

\[
(1 - R(E)a(E)b_s(E))
\]

The current density for photon emission is given by

\[
j_{rad} = q(1 - R(E)a(E)b_e(E))
\]

\[
j_{rad} = q(1 - R(E)a(E)(b_e(E) - b_a(E)))
\]

The net equivalent current density or radiative recombination current density is then given by

\[
j_{abs} - j_{rad} = q((1 - R(E)a(E))(b_e(E) - b_a(E)))
\]

The output is determined by a balance between light absorption, current generation and recombination. Generation is an electronic excitation event which increases the number of free carriers available to carry charge, which requires an input of energy. Recombination is an electronic relaxation event which reduces the number of free carriers and releases energy. For every generation process there is an equivalent recombination processes.

Generation, by the absorption of a photon, is the promotion of an electron from valance to conduction band, which creates an electron-hole pair. Recombination is the loss of an electron or hole through the decay of an electron to a lower energy state.
Consider a two band system: the ground state is initially full and the excited state empty.

Band gap, $E_g$: The bands are separated by a band gap.

Photons with energy $E < E_g$ cannot promote an electron to the excited state. Photons with $E \geq E_g$ can raise the electron but any excess energy is quickly lost as heat as the carriers relax to the band edges. We will assume that electrons in each band are in quasi thermal equilibrium at the ambient temperature $T_a$ and the chemical potential for that band is $\mu_i$. An absorbed photon with $E \gg E_g$ achieves the same result as the photon with $E = E_g$. Hence it is the photon flux and not the photon energy density which determines the photo generation. Once excited, the electrons remain in the excited state for a relatively long time.
For the case of the most efficient solar cell we have perfectly absorbing, non-reflecting material so that all incident photons of energy \( E > E_g \) are absorbed to promote exactly one electron to the upper band. We also have perfect charge separation so that all electrons which survive radiative recombination are collected by the negative terminal of the cell and delivered to the external circuit. This gives maximum photocurrent for that band gap. Then

\[
QE(E) = \begin{cases} 
1 & E \geq E_g \\
0 & E < E_g 
\end{cases}
\]

and

\[
J_{sc} = q \int_{E_g}^{E} b_s(E) dE
\]

Photocurrent is then a function of only of the band gap and the incident spectrum. Lower the \( E_g \), the greater will be \( J_{sc} \).
The net electron current is due to the difference between the two photon flux densities: the absorbed flux, which is distributed over a wide range of photon energies above the threshold \( E_g \), and the emitted flux, which is concentrated on photon energies near \( E_g \). As \( V \) increases, the emitted flux increases and the net current decreases. At \( V_{oc} \) the total emitted flux exactly balances the total absorbed flux and net current is zero.
When load is present, a potential difference develops between terminal and it generates a current which acts in the opposite direction to the photocurrent. Therefore the net current is reduced from its short circuit value. The reverse current is called the dark current $I_{dark}(v)$ which flows across the device under an applied voltage or bias voltage, $V$ in the dark.

Most solar cells behave like a diode in the dark, admitting much larger current under forward bias ($V>0$) than under reverse bias ($V<0$). This rectifying behavior is a feature of photo voltaic devices, since an asymmetric junction is needed to achieve charge separation. For an ideal diode the dark current density is given by

$$J_{dark}(V) = J_0 \left( e^{\frac{qV}{k_BT}} - 1 \right)$$

Where $J_0$ is a constant, $k_B$ is Boltzmann’s constant and $T$ is temperature in K.
Superposition Approximation

The overall current voltage response of the cell, its *current-voltage characteristic*, can be approximated as the sum of short circuit photocurrent (positive) and the dark current.

The overall current voltage response of the cell, its *current-voltage characteristic*, can be approximated as the sum of short circuit photocurrent and the dark current. The net current density in the cell is

\[ J(V) = J_{sc} - J_{dark}(V) \]

For an ideal diode,

\[ J = J_{sc} - J_0 \left( e^{\frac{qV}{k_B T}} - 1 \right) \]

When the dark current and short circuit photocurrent exactly cancel out, we have for the ideal diode (forward bias \( V > 0 \))

\[ V_{oc} = \frac{kT}{q} \ln \left( \frac{J_{sc}}{J_0} + 1 \right) \]
When illuminated, the ideal cell produces a photocurrent to the light intensity. That photocurrent is divided between the variable resistance of the diode and the load, in a ratio which depends on the resistance of the load and illumination level. For higher resistances, more of the photocurrent flows through the diode, resulting in higher potential difference between the cell terminals but a smaller current through the load. The diode thus provides the photo voltage. Without the diode, there is nothing to drive the photocurrent through the load.

When the current-voltage product is positive and the voltage is between 0 and $V_{oc}$, the cell generates power. At $V>V_{oc}$ the device consumes power and it is the regime where light emitting diodes operate. At $V<0$, the illuminated device acts as a photodetector, consuming power to generate a photocurrent.
The cell power density is given by

\[ P = JV \]

\( P \) reaches maximum at the cell’s operating point or maximum power point (MPP).

The fill factor is defined as

\[ FF = \frac{J_m V_m}{J_{sc} V_{oc}} \]
The efficiency $\eta$ of the cell is the power density delivered at the operating point as a fraction of the incident light power density, $P_s$.

$$\eta = \frac{J_m V_m}{P_s} = \frac{J_{oc} V_{oc} FF}{P_s}$$

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Area (cm$^2$)</th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>FF</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>crystalline Si</td>
<td>4.0</td>
<td>0.706</td>
<td>42.2</td>
<td>82.8</td>
<td>24.7</td>
</tr>
<tr>
<td>crystalline GaAs</td>
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<td>1.022</td>
<td>28.2</td>
<td>87.1</td>
<td>25.1</td>
</tr>
<tr>
<td>poly-Si</td>
<td>1.1</td>
<td>0.654</td>
<td>38.1</td>
<td>79.5</td>
<td>19.8</td>
</tr>
<tr>
<td>a-Si</td>
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<td>0.887</td>
<td>19.4</td>
<td>74.1</td>
<td>12.7</td>
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<tr>
<td>CuInGaSe$_2$</td>
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<td>35.7</td>
<td>77.0</td>
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</tr>
<tr>
<td>CdTe</td>
<td>1.1</td>
<td>0.848</td>
<td>25.9</td>
<td>74.5</td>
<td>16.4</td>
</tr>
</tbody>
</table>
Current Density and Efficiency

The current density is calculated from the multiplication of $q$ and integrated net photon flux.

The power conversion efficiency is calculated from the incident and extracted power from photon fluxes. The incident power density is obtained from

$$P_s = \int_0^\infty E_b s(E_s) dE$$

The extracted power density is given by

$$P = V J(V)$$

The power conversion efficiency:

$$\eta = \frac{V J(V)}{P_s}$$
The *power conversion efficiency* of the ideal two band photoconverter is a function only of $E_g$ and the *incident spectrum*. If the incident spectrum is fixed, then efficiency depends only on the band gap.

Limiting efficiency for single band gap solar cell in AM 1.5. The maximum efficiency for a standard solar spectrum is around 33% at a band gap of 1.4 eV.

The available power spectrum for an optimum band gap cell at maximum power point is compared with incident power from a black body sun.
Power conversion efficiency limits

![Graph showing power conversion efficiency limits for different semiconductor materials and their band gaps.](image-url)
Parasitic Resistances

*Real cells:* Resistance of the contacts and leakage currents around the sides of the device.

Series resistance: it arises from the resistance of the cell material to current flow, particularly through the front surface to the contacts and from resistive contacts. It is a particular problem at high current densities, i.e. under concentrated light.

Shunt resistance: It arises from the leakage of the current through the cell around the edges of the device and between contacts of different polarity. It is a problem with poorly rectifying devices.

The diode equation becomes

\[
J = J_{sc} - J_0 \left( e^{\frac{q(V+JAR_s)}{kT}} - 1 \right) - \frac{V + JAR_s}{R_{sh}}
\]

Where \( A \) is the cell area.
The effect of resistances is to reduce the area of the maximum power rectangle compared to $J_{sc} \times V_{oc}$. 

Parasitic Resistances
The bulk of the energy converter is composed of p-type material. Only a front surface layer of the wafer has n-type conductivity. The n-layer is called the emitter and the p-region is called the base. When forming such a so called pn-junction diode structure, electrons from the emitter diffuse instantaneously into the base, and holes from the p-region diffuse into the emitter. This is due to the fact that emitter contains a very high concentration of electrons compared to the base, whereas the base is rich in holes. This diffusion of charge carriers leads to the build up of an electric field, resulting internal voltage in the vicinity of the pn-junction. Under equilibrium conditions, the electrical forces due to this field compensate the forces driving the diffusion -thus no electric current flows.

Ref: Photovoltaic guidebook for decision makers, Ed: A. Bubenzer & J. Luther, 2002
Real Solar Cells

The real solar cells do not achieve ideal performance due to following reasons:

1. Incomplete absorption of the incident light. Photons are reflected from the front surface or pass through the cell without being absorbed. This reduces the photocurrent.

2. Non-radiative recombination of photogenerated carriers. Excited charges are trapped at defect sites and subsequently recombine before being collected. This happens, for example, near junctions. It reduces both the photocurrent, through the probability of carrier collection and the voltage by increasing the dark current.

3. Voltage drop due to series resistance between the point of photogeneration and the external circuit. This reduces the available power.
Summary

1. The current size generated by the cell in short circuit depends upon the incident light intensity and the energy spectrum.

2. The photocurrent is related to incident spectrum by the quantum efficiency of the cell.

3. When a load is present, a potential difference is created between the terminals of the cell and this drives a current, dark current, in the opposite direction to photocurrent. As the load resistance is increased the potential difference increases and the net current decreases until the photocurrent and dark current exactly cancel out. The potential difference at this point is called the open circuit voltage.

4. At some point before the open circuit voltage is reached the current-voltage product is maximum. The cell should be operated with a load resistance which corresponds to this point.

5. In real cells, the current-voltage characteristic behavior is degraded by the presence of series and parallel or shunt resistances.