

Chapter 5.

SOLAR CELL CONVERSION-EFFICIENCY LIMITS

5.1 Solar cell conversion efficiency and radiation spectrum

The conversion efficiency, η , of solar cells is calculated as the ratio between the generated maximum power, P_m , generated by a solar cell and the incident power, P_{in} . The incident power is equal to the irradiance of AM1.5 spectrum, normalized to 1000 W/m^2 . The η is determined from the I - V measurement using Eq. (4.32).

$$\eta = \frac{P_m}{P_{in}} = \frac{J_{mp} V_{mp}}{P_{in}} = \frac{J_{sc} V_{oc} FF}{P_{in}}$$

The irradiance of AM1.5 spectrum can be calculated from the spectral power density, $P(\lambda)$, (see Figure 5.1) using the following equation:

$$P_{in} = \int_0^{\infty} P(\lambda) d\lambda \quad (5.1)$$

Using Eq. (2.3) that relates the photon flux density, $\Phi(\lambda)$, to the spectral power density, Eq. (5.2) can be written as:

$$P_{in} = \int_0^{\infty} \Phi(\lambda) \frac{hc}{\lambda} d\lambda \quad (5.2)$$

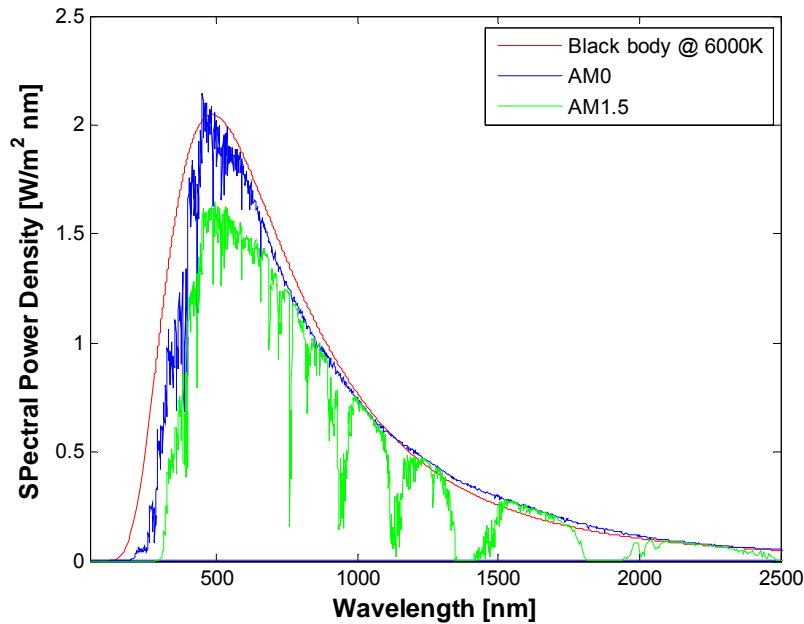


Figure 5.1. Spectral power density of black-body radiation at 6000 K, AM0 and AM1.5 spectra.

5.2 Conversion efficiency limiting factors

5.2.1 Spectral mismatch

There are two principal losses that strongly reduce the energy conversion efficiency of today's solar cells. As discussed in Chapter 4, an important part of a solar cell is the absorber layer, in which the photons of the incident radiation are efficiently absorbed resulting in a creation of electron-hole pairs. The absorber layer of the solar cells is in most cases formed by a semiconductor material, which has its distinct optical properties characterized by the band gap energy, E_G , and the complex refractive index, $\tilde{n} = n - ik$. In principle, only photons with energy higher than the band gap energy of the absorber generate electron-hole pairs. Since the electrons and holes tend to occupy energy levels at the bottom of the conduction band and the top of the valence band, respectively, the extra energy that the electron-hole pairs receive from the photons is released as heat into the semiconductor lattice in the **thermalization** process. Photons with energy lower than the band gap energy of the semiconductor absorber are in principle not absorbed and cannot generate electron-hole pairs. Therefore these photons are not involved in the energy conversion process. The **non-absorption** of photons carrying less energy than the semiconductor band gap and the excess energy of photons, larger than the band gap, are the two main losses in the energy conversion process using solar cells. Both of these losses are thus related to the **spectral mismatch** of the energy distribution of photons in the solar spectrum and the band gap of a semiconductor material

We can determine the fraction of energy of the incident radiation spectrum that is absorbed by a single junction solar cell. When we denote λ_G as the wavelength of photons that corresponds to the band gap energy of the absorber of the solar cell, only the photons with the energy higher than the band gap are absorbed, it means photons with $\lambda \leq \lambda_G$. The fraction of the incident power, p_{abs} that is absorbed by a solar cell and used for energy conversion is expressed as:

$$P_{abs} = \frac{\int_0^{\lambda_G} \Phi(\lambda) \frac{hc}{\lambda} d\lambda}{\int_0^{\infty} \Phi(\lambda) \frac{hc}{\lambda} d\lambda} \tag{5.3}$$

A part of the absorbed energy, the excess energy of photons, is lost due to the thermalization of photo-generated electrons and holes in the absorber material. The fraction of the absorbed energy that the solar can deliver as useful energy, P_{use} , is described by Eq. (5.4):

$$P_{use} = \frac{E_G \int_0^{\lambda_G} \Phi(\lambda) d\lambda}{\int_0^{\lambda_G} \Phi(\lambda) \frac{hc}{\lambda} d\lambda} \tag{5.4}$$

We can determine the conversion efficiency limited by the spectral mismatch:

$$\eta = P_{abs} P_{use} = \frac{\int_0^{\lambda_G} \Phi(\lambda) \frac{hc}{\lambda} d\lambda}{\int_0^{\infty} \Phi(\lambda) \frac{hc}{\lambda} d\lambda} \frac{E_G \int_0^{\lambda_G} \Phi(\lambda) d\lambda}{\int_0^{\lambda_G} \Phi(\lambda) \frac{hc}{\lambda} d\lambda} \tag{5.5}$$

Figure 5.2 illustrates the fraction of the AM1.5 spectrum that can be converted into a usable energy by a crystalline silicon solar cell.

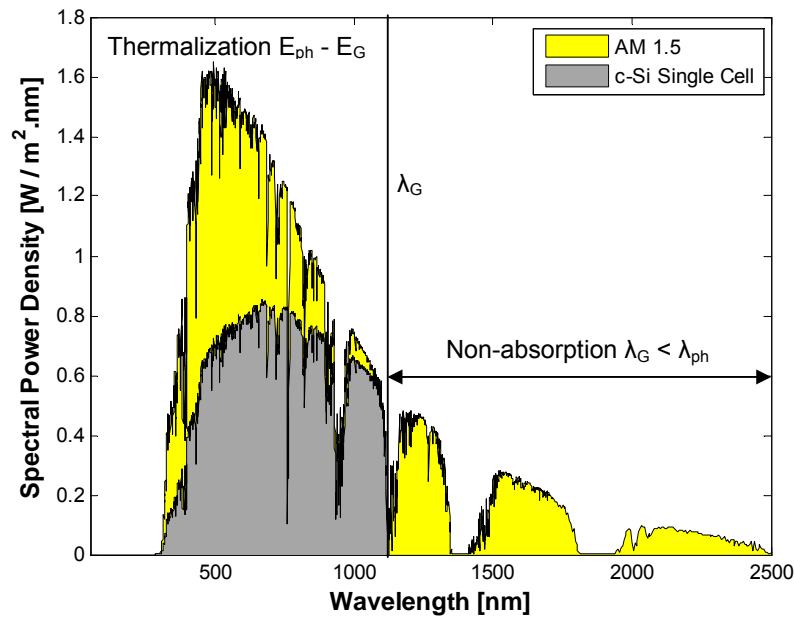


Figure 5.2. The fraction of the AM1.5 spectrum that can be converted into a usable energy by a crystalline silicon solar cell.

Figure 5.3 shows the conversion efficiency of a solar cells limited only by spectral mismatch as a function of the band gap of a semiconductor absorber for three different radiation spectra, black-body radiation at 6000 K, AM0 and AM1.5 solar radiation spectra. The figure demonstrates that in the case of a crystalline silicon solar cell ($E_G = 1.1$ eV) the losses due to the spectral mismatch account for almost 50 %. It also shows that an optimal absorber material for a single junction solar cell has a band gap of 1.1 eV and 1.0 eV for AM0 and AM1.5 spectrum, respectively. Note that the maximum conversion efficiency for the AM1.5 spectrum is higher than that for AM0, while the AM0 spectrum has a higher overall power density. This is caused by the fact that the AM1.5 spectrum has a lower power density in parts of the spectrum that are not contributing to the energy conversion process as can be seen in Fig. 5.2. The dips in the AM1.5 spectrum also result in the irregular shape of the maximum conversion efficiency as function of the band gap.

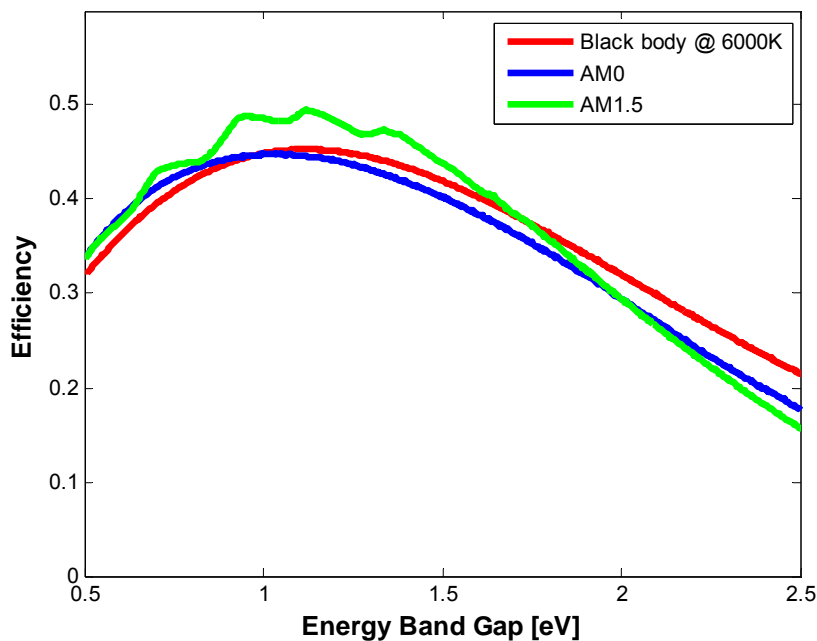


Figure 5.3. Maximum conversion efficiency for the black body spectrum at 6000 K, the AM0 and AM1.5 solar radiation spectra, limited only by the spectral mismatch as a function of the band gap of a semiconductor absorber in single junction solar cells.

5.2.2 Solar cell optical properties

As mentioned in the previous section there are also other optical parameters than E_G that have influence on the conversion efficiency of a solar cell. These are optical constants of the individual layers, that are expressed in the complex refractive index $\tilde{n} = n - ik$. The optical constants, refractive index, n , and extinction coefficient, k , are function of the wavelength.

In general, when light arrives on an interface between two media, a part of the light is reflected from and the other part is transmitted through the interface. The interface is therefore characterized by the wavelength dependent reflectance, $R(\lambda)$, and transmittance, $T(\lambda)$. Reflectance is the ratio of the energy reflected from the surface of the interface to the total

incident energy. There is a reflection of light at the interface between the first layer of a solar cell and the incident medium, usually air, and there is also reflection at the interfaces between the individual layers within the solar cell. All these processes result in a total reflectance between the solar cell and air. This means that a part of the incident energy that can be converted into a usable energy by the solar cell is lost by **reflection**. We shall denote the total reflectance as R^* , which can be considered as the effective reflectance in the wavelength range of interest.

In most c-Si solar cells one of the metal electrodes is placed on the front side of the cell. The metal-covered area does not allow the light to enter the solar cell because it totally reflects the light in wavelength range of interest. The area that is covered by the electrode effectively decreases the active area of the solar cell through which the light enters the solar cell. When we denote the total area of the cell A_{tot} and the cell area that is not covered by the electrode A_f , the active area of the cell is determined by the ratio of A_f/A_{tot} . This ratio is called the **coverage factor** and determines the so called **shading losses**. The design of the front electrode is therefore of great importance since in order to minimize the losses due to the series resistance of the front electrode, it should be designed with sufficient cross-section. The optimal design of the front electrode is a trade-off between a high coverage factor and a sufficiently low series resistance of the front electrode.

When light penetrates into a material, it will be absorbed as it propagates through the material. The absorption of light in the material depends on its absorption coefficient which is related to the extinction coefficient through Eq. (3.32). In general, light is absorbed in all layers that form the solar cell. However, the solar cell is optimally designed when most of the incident light is absorbed in the absorber layer. Due to the limited thickness of the absorber layer, not all the light entering the absorber layer is absorbed. **Incomplete absorption** in the absorber due to its limited thickness is an additional loss that lowers the efficiency of the energy conversion. The incomplete absorption loss can be described by the internal optical quantum efficiency, QE_{op} , which is the probability of a photon being absorbed in a material. Since there is a chance that a high energetic photon can generate more than one electron-hole pair, we define the quantum efficiency for carrier generation, η_g , which represents the number of electron-hole pairs generated by one absorbed photon. Usually η_g is assumed to be unity.

5.2.3 Solar cell collection losses

Not all charge carriers that are generated in a solar cell are collected at the electrodes. The photo-generated carriers are the excess carriers with respect to the thermal equilibrium and are subjected to the **recombination**. The carriers recombine in the bulk, at the interfaces, and/or at the surfaces of the junction. The recombination is determined by the electronic properties of materials that form the junction, such as density of states introduced into the band gap by the R-G centers. The concentration of R-G centers strongly influences the minority-carrier lifetimes as discussed in Chapter 3.

The contributions of both the electronic and optical properties of the solar cell materials to the photovoltaic performance are taken into account in the absolute external quantum efficiency. The absolute external quantum efficiency is defined as the number of charge carriers collected (from all layers of the device) per incident photon at each wavelength λ . This quantum efficiency can be approximated as

$$QE(\lambda) = (1 - R^*)QE_{op}(\lambda)\eta_g(\lambda)QE_{el}(\lambda), \quad (5.6)$$

Where the QE_{el} is the electrical quantum efficiency and is defined as the probability that a photo-generated carrier is collected. When we combine the absolute external quantum efficiency (Eq. (5.6)) and shading losses with the photon flux density of the spectrum of incident radiation we can determine the expected short-circuit current density that a solar cell can deliver. The maximal current density that the solar cell can deliver is determined by the band gap of the absorber layer that determines which photons of the incident radiation can generate electron-hole pairs. When we assume that all these photons are absorbed and all generated carriers are collected the maximum current density, J_{max} , is described as:

$$J_{max} = q \int_0^{\lambda_G} \Phi(\lambda) d\lambda \quad (5.7)$$

The short-circuit current density is determined by the absolute external quantum efficiency and the shading loss:

$$J_{sc} = J_{max} (1 - R^*) QE_{opt} \eta_G QE_{el} \frac{A_f}{A_{tot}} \quad (5.8)$$

Combining Eq. (5.7) and Eq. (5.8) we obtain:

$$J_{sc} = q (1 - R^*) QE_{opt} \eta_G QE_{el} \frac{A_f}{A_{tot}} \int_0^{\lambda_G} \Phi(\lambda) d\lambda \quad (5.9)$$

Note that the upper limit of the integration is set at the wavelength corresponding to the band gap of the absorber layer. Photons with larger wavelength (lower energy) cannot generate electron hole pairs. Therefore QE_{op} equals zero larger wavelengths.

5.2.4 Additional limiting factors

In chapter 4 we discussed that the V_{oc} of a solar cell depends on the saturation current and the photo-generated current (Eq. (4.29)) of the solar cell. The saturation current density depends on the recombination in the solar cell that cannot be avoided and is referred to as the **fundamental recombination**. This fundamental recombination depends on the doping of the different regions (n-type and p-type regions) of a junction and the electronic quality of materials forming the junction. The doping levels and the recombination determine the **voltage factor**, qV_{oc}/E_G , that is the ratio of the maximum voltage developed by the solar cell (V_{oc}) to the voltage related to the band-gap of the absorber (E_G/q).

The maximum power generated by a solar cell is dependent on the **fill factor**, FF . In case of a solar cell that behaves as an ideal diode only direct recombination occurs and the maximal FF is a function of V_{oc} and can be approximated by Eq. (4.31). In a practical solar cell the FF is lower than the ideal value due to following reasons:

- The voltage drop due to the series resistance R_s of a solar cell. The series resistance is introduced by the resistance of the main current path through which the photo-generated carriers arrive to the external circuit. The contributions to the series resistance come from the bulk resistance of the junction, the contact resistance between the junction and electrodes, the resistance of the electrodes.

- The voltage drop due to the leakage current and characterized by the shunt resistance R_p of a solar cell. The leakage current is caused by the current through local defects in the junction or due to the shunts at the edges of solar cells.
- The recombination in a non-ideal solar cell results in a decrease of the FF .

5.2.5 Conversion efficiency

The conversion efficiency determined from the I-V measurement can be expressed as:

$$\eta = \frac{J_{sc} V_{oc} FF}{P_{in}}$$

Using Eq. (5.2) and Eq. (5.9) we can rewrite the expression for the conversion efficiency as

$$\eta = \frac{q \int_0^{\lambda_G} \Phi^0(\lambda) d\lambda}{\int_0^{\infty} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda} (1 - R^*) QE_{opt} \eta_G QE_{el} \frac{A_f}{A_{tot}} V_{oc} FF \tag{5.10}$$

We can introduce the voltage factor (qV_{oc}/E_G) into Eq. (5.10) by expressing the V_{oc} as:

$$V_{oc} = \frac{qV_{oc}}{E_G} \frac{E_G}{q} \tag{5.11}$$

$$\eta = \frac{q \int_0^{\lambda_G} \Phi^0(\lambda) d\lambda}{\int_0^{\infty} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda} (1 - R^*) QE_{opt} \eta_G QE_{el} \frac{A_f}{A_{tot}} \frac{qV_{oc}}{E_G} \frac{E_G}{q} FF \tag{5.12}$$

By introducing a term $\frac{\int_0^{\lambda_G} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda}{\int_0^{\lambda_G} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda}$ into the right side of Eq. (5.12) and manipulating it, the

conversion efficiency can be now written as¹

$$\eta = \underbrace{\frac{\int_0^{\lambda_G} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda}{\int_0^{\infty} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda}}_1 \underbrace{\frac{E_G \int_0^{\lambda_G} \Phi^0(\lambda) d\lambda}{\int_0^{\lambda_G} \Phi^0(\lambda) \frac{hc}{\lambda} d\lambda}}_2 \underbrace{(1 - R^*)}_3 \underbrace{QE_{opt}^* \eta_G^*}_4 \underbrace{QE_{el}^*}_5 \underbrace{\frac{A_f}{A_{tot}}}_6 \underbrace{\frac{qV_{oc}}{E_G}}_7 \underbrace{FF}_8 \tag{5.13}$$

¹ R.J. van Overstraeten, R.P. Mertens, Physics, Technology and Use of Photovoltaics, Adam Hilger Ltd, 1986.

Eq. (5.13) describes the conversion efficiency of a solar cell in terms of components that represent particular losses in energy conversion.

1. Loss due to non-absorption of long wavelengths
2. Loss due to thermalization of the excess energy of photons
3. Loss due to the total reflection
4. Loss by incomplete absorption due to the finite thickness
5. Loss due to recombination
6. Loss by metal electrode coverage, shading losses
7. Loss due to voltage factor
8. Loss due to fill factor

Figure 5.4 shows the efficiency as a function of the band gap of the absorber of an ideal solar cell, such that losses due to 3, 4, 6 are eliminated.

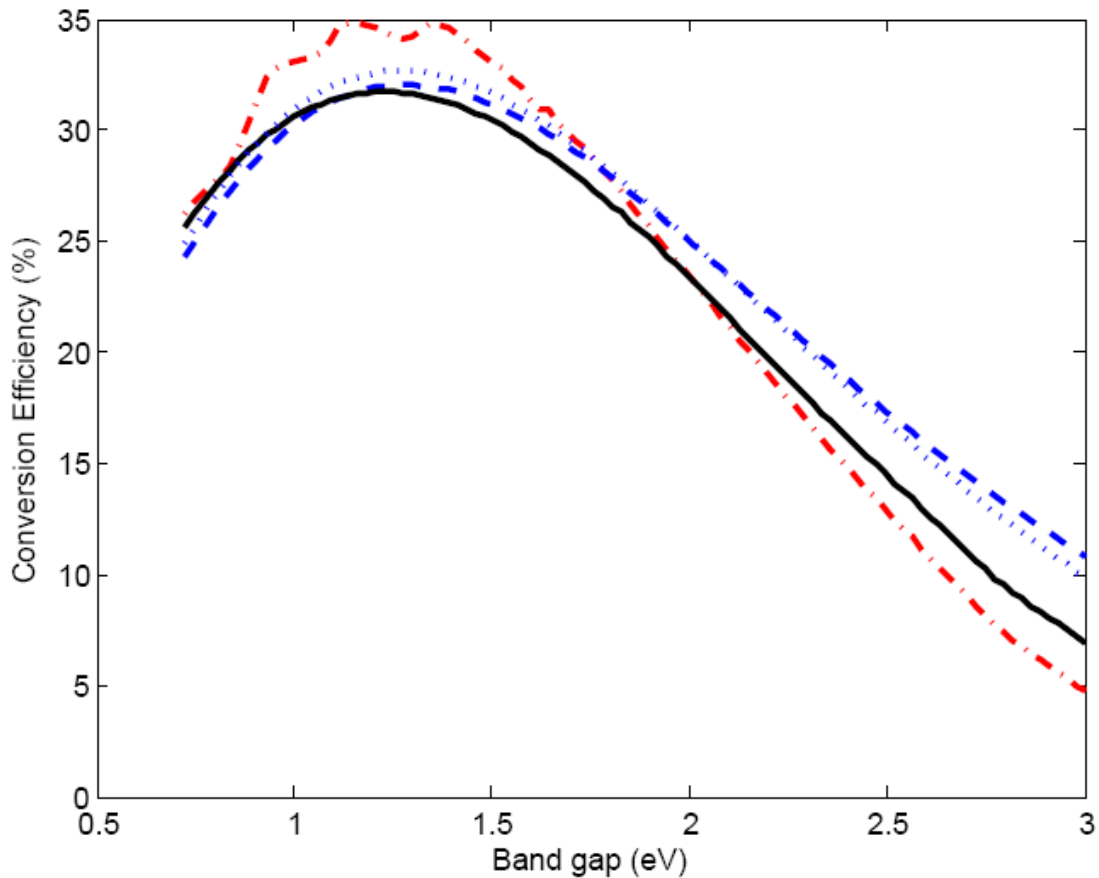


Figure 5.4. The detailed balance efficiency limit as a function of the band gap of a solar cell illuminated by different incident spectra: Black body radiator at 6000K (blue dots); sampled black body radiator (blue dashes); AM0 (black solid line); AM1.5 (red dash-dot).

5.3 Equivalent circuit

The J - V characteristic of an illuminated solar cell that behaves as the ideal diode is described by Eq. (4.27):

$$J = J_0 \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] - J_{ph}$$

This behaviour can be described by a simple equivalent circuit, in which a diode and a current source are connected in parallel. The equivalent circuit is shown in Figure 5.5a. The diode is formed by a p-n junction. The first term in Eq. (4.27) describes the dark diode current density and the second term describes the photo-generated current density. In practice the FF is influenced by the series resistance, R_s , and the shunt resistance, R_p , of a solar cell. The influence of these parameters on the J - V characteristic of the solar cell can be studied using the equivalent circuit presented in Figure 5.5b. The J - V characteristic of the one-diode equivalent circuit with the series resistance and the shunt resistance is described by (A is the area of the solar cell):

$$J = J_0 \left[\exp\left(\frac{q(V - AJR_s)}{kT}\right) - 1 \right] + \frac{V - AJR_s}{R_p} - J_{ph} \quad (5.14)$$

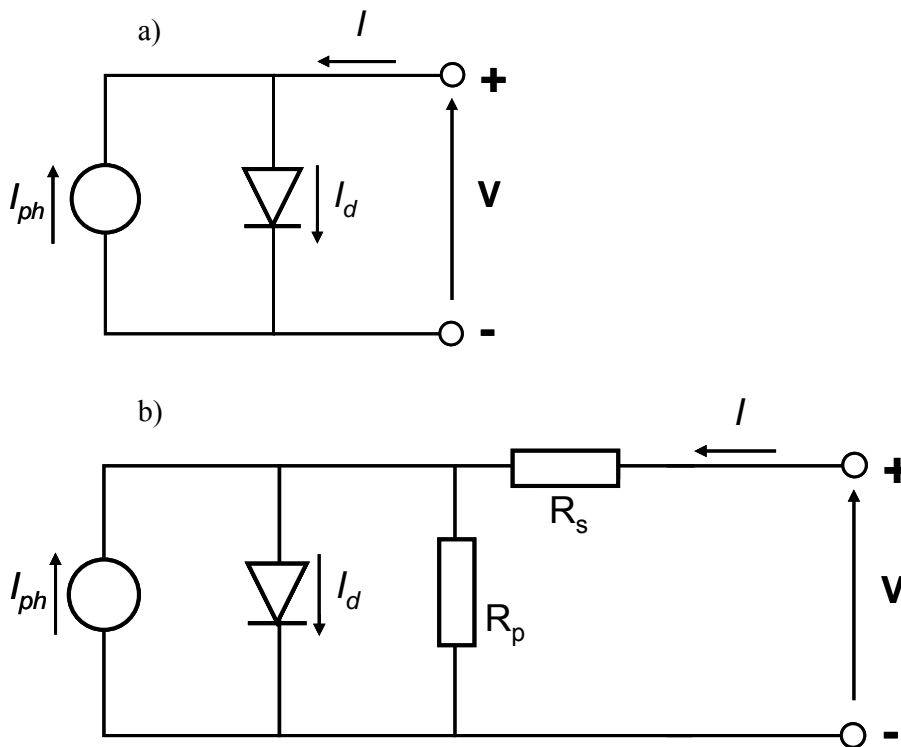


Figure 5.5. a) The equivalent circuit of an ideal solar cell. b) The equivalent circuit of a solar cell with series and shunt resistance. R_s is the series resistance, R_p is the shunt resistance.

The effect of R_s and R_p on the J - V characteristic is illustrated in Figure 5.6a and 5.6b, respectively.

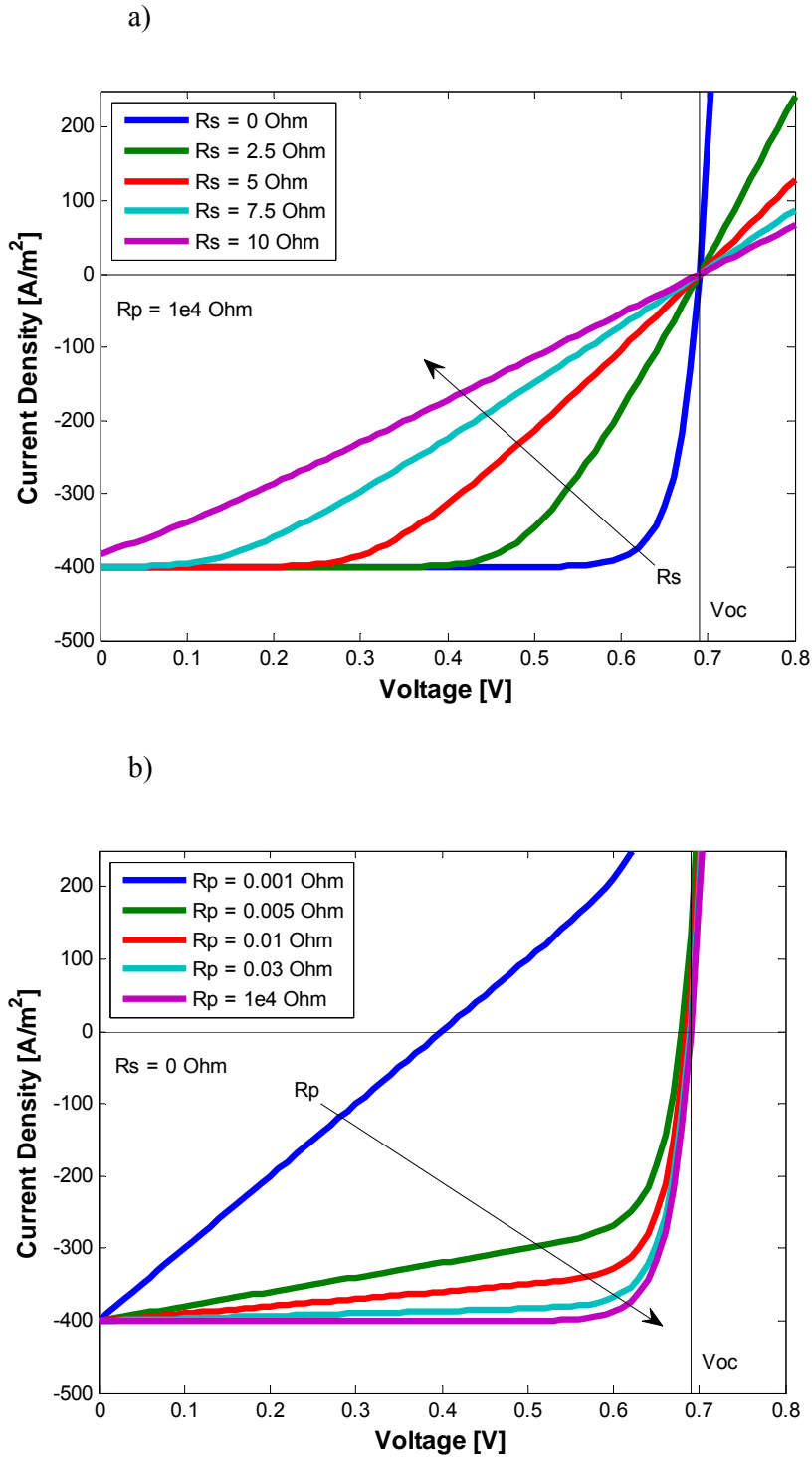


Figure 5.6. Effect of parasitic resistances on the J - V characteristic of a solar cell.

In practical solar cells the FF is influenced by the additional recombination occurring in the p-n junction. This non-ideal diode is often represented in the equivalent circuit by two diodes, an ideal one with an ideality factor equal to unity and a non-ideal diode with an ideality factor larger than unity. The equivalent circuit of a practical solar cell is presented in Figure 5.7. The J - V characteristic of the two-diode equivalent circuit is described by:

$$J = J_{01} \left[\exp\left(\frac{q(V - AJR_s)}{n_1 kT}\right) - 1 \right] + J_{02} \left[\exp\left(\frac{q(V - AJR_s)}{n_2 kT}\right) - 1 \right] + \frac{V - AJR_s}{R_p} - J_{ph} \quad (5.15)$$

The J_{01} and J_{02} are the saturation currents of the two diodes, respectively, and n_1 and n_2 are the ideality factors of the two diodes.

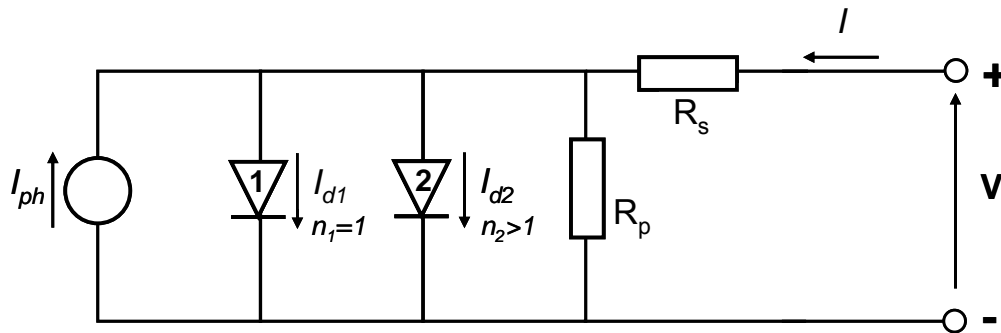


Figure 5.7. The equivalent circuit of a solar cell based on a two-diode model.

EXAMPLE.

A commercial multi-crystalline silicon solar cell with a so-called H-pattern as a front contact design (see figure) has the following specifications:

- $V_{oc}=605\text{ mV}$, $I_{sc}=5.0\text{ A}$,
- $V_{mpp}=500\text{ mV}$, $I_{mpp}=4.6\text{ A}$,
- size: 156 cm^2 ,
- 9% metallization coverage.

V_{mpp} and I_{mpp} are the voltage and current, respectively, at the maximum power point

a) Calculate the total area and active area efficiency of the cell, respectively (irradiance: 100 mW/cm^2)

$$\eta_{ta} = V_{mpp} \times I_{mpp} / (156\text{ cm}^2 \times 0.1\text{ Wcm}^{-2}) \times 100\% = 0.5 \times 4.6 / (156 \times 0.1) \times 100\% = 14.7\%$$

$$\eta_{aa} = V_{mpp} \times I_{mpp} / (156\text{ cm}^2 \times 0.91 \times 0.1\text{ Wcm}^{-2}) \times 100\% = 0.5 \times 4.6 / (156 \times 0.91 \times 0.1) \times 100\% = 16.2\%$$

b) Calculate the fill factor FF of the cell

$$FF = V_{mpp} \times I_{mpp} / (V_{oc} \times I_{sc}) = 0.5 \times 4.6 / (0.605 \times 5) = 0.760.$$

Cells with these characteristics will be interconnected with strips (see figure). This will result in an additional $2\text{ m}\Omega$ series resistance loss.

c) Calculate the lower FF due to this higher series resistance (Hint: use the voltage drop at the maximum power point to calculate the lower FF)

$$\Delta V = I_{mpp} \Delta R = 4.6 \times 2 \cdot 10^{-3} = 9.2 \cdot 10^{-3}\text{ V} = 9.2\text{ mV}$$

$$\Delta FF = \Delta V / V_{mpp} \times FF = 9.2 / 500 \times 0.760 = 0.014; FF_{new} = 0.760 - 0.014 = 0.746$$

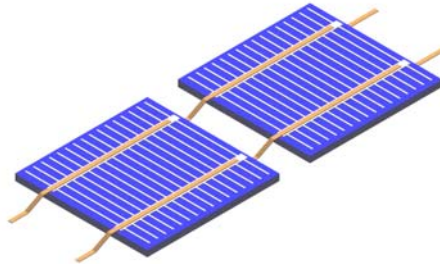


Figure: Standard cells with H pattern and interconnection strips