An introduction to solar cells and photodiodes

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Contents

1 Solar cells

Solar cells are devices used for both space and terrestrial applications. They furnish the long-duration power supply for satellites. They are good terrestrial sources because they convert sunlight directly to electricity with reasonable conversion efficiency and provide nearly permanent power at low operating cost. Moreover, solar cells are virtually non-polluting. In this short introduction, after giving the motivation for solar cells' production (Section 2.1), the physics beyond these devices will be discussed (Section 2.2). Materials used in solar cells' production will be shortly presented in Section 1.3 and then the efficiency of a solar cell will be discussed widely in Section 1.4. This is in fact the most important parameter to quantify the goodness of a solar cell, hence related to solar cells' applications (Section 1.5).

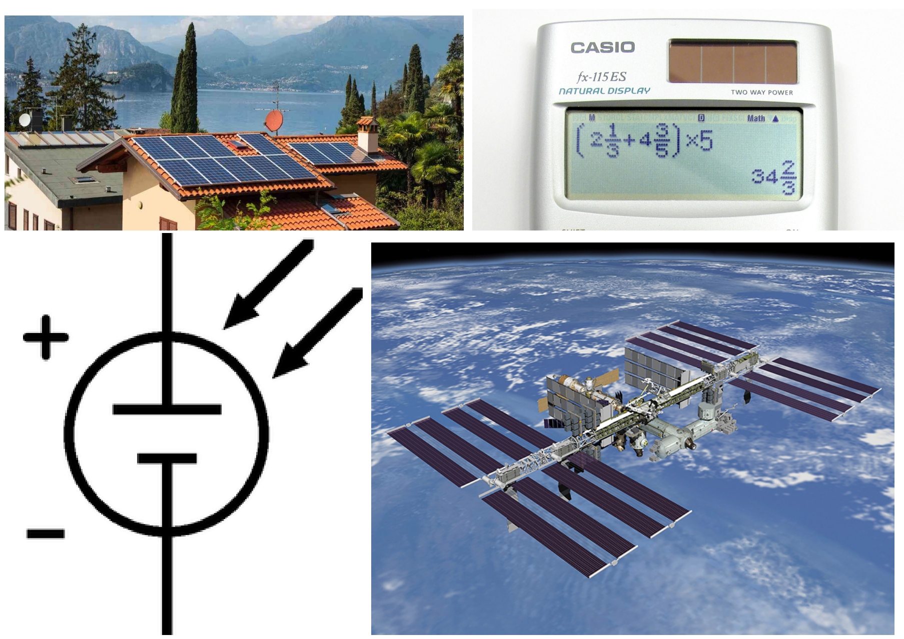

Figure 1: Some common examples of solar devices: solar panels on the roof of a building (a), small solar cells in a pocket calculator (b), the solar cell symbol in an electronic circuit (c) and solar arrays powering the International Space Station (d).

1.1 Motivation

Before analysing how a solar cell works, we should be aware of the reason that motivate the development and production of solar cells. The reason all sits in the huge amount of energy produced by our Sun, which we would like to exploit in some way. In order to understand what's the most efficient way possible, a short discussion regarding how the Sun is emitting light is needed. What happens in the Sun is the process of nuclear fusion, which can be described by a few reactions starting from the fusion of two hydrogen nuclei in a deuterium nucleus.

$$^1H +^1 H \rightarrow^2 H + e^+ + \nu_e + 3.27MeV \tag{1}$$

$$^2H +^1 H \rightarrow^3 H + \gamma + 4.03MeV \tag{2}$$

$$^3H +^3 H \rightarrow^4 He + 2^1H + 17.59MeV \tag{3}$$

The rate of hydrogen burned in the Sun is $6 \cdot 10^{11}$kg/s, but as most of the hydrogen nuclei re-enter the cycle, the net mass loss rate $4 \cdot 10^3$kg/s. This seems to be a big quantity of mass, but the expected lifetime of the Sun can be computed and it turns out that the Sun will shine for 10^{10} years more. This rate can be translated in an energy production rate by using Einstein equation $E = mc^2$; the result is the emission of $4 \cdot 10^{20}$J/s. This is the motivation why to focus on solar cells.

This energy is emitted as radiation in a range of frequencies between infrared and ultraviolet, thus involving energies in the range $1-10$eV and wavelengths of $250-2500$nm. Most of the radiation is emitted in the visible spectrum and UV spectrum, as we can see from Figure 2, showing the solar irradiance reaching the Earth.

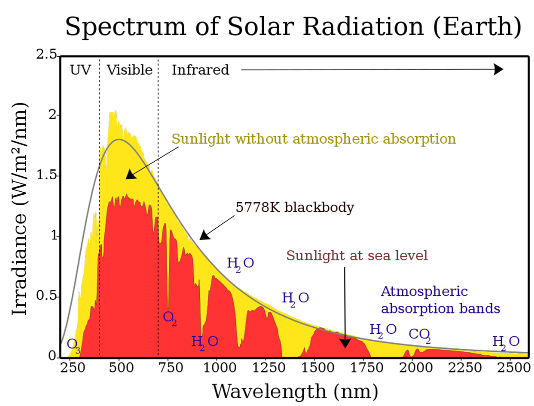

Figure 2: Solar irradiance as a function of the wavelength of the incoming radiation. The yellow area represents the Sunlight without any attenuation by atmosphere, which is consistent with the irradiance spectrum of a blackbody at a temperature $T = 5778$ K. The red area represents the effective power reaching the Earth, considering the atmosphere absorption.

A quantity that should be mentioned when talking about solar irradiance is the solar constant $G_{SC} = 1367\,\text{W/m}^2$. This is the total amount of power reaching the Earth, integrating over all the wavelengths, computed without considering any attenuation, just taking into account the average distance between the Sun and the Earth's orbit.

The presence of atmosphere is anyway not negligible; it reduces significantly the quantity of sunlight reaching the Earth's surface. The level of attenuation is quantified defining the Air Mass (AM), which is nothing else than the reciprocal of the cosine of the angle between the direction of the incoming light and the zenith direction.

$$AM = \frac{1}{\cos\theta} \tag{4}$$

This indicator takes into account the length of the light's path through the atmosphere, or the mass of air through which it passes.
As can be seen in Figure 3, when the Sun is at the Zenith position the Air Mass indicator will be equal to 1, while going to higher angles positions the indicator will increase. Of course, outside the atmosphere, the Air Mass is zero because no attenuation occurs.

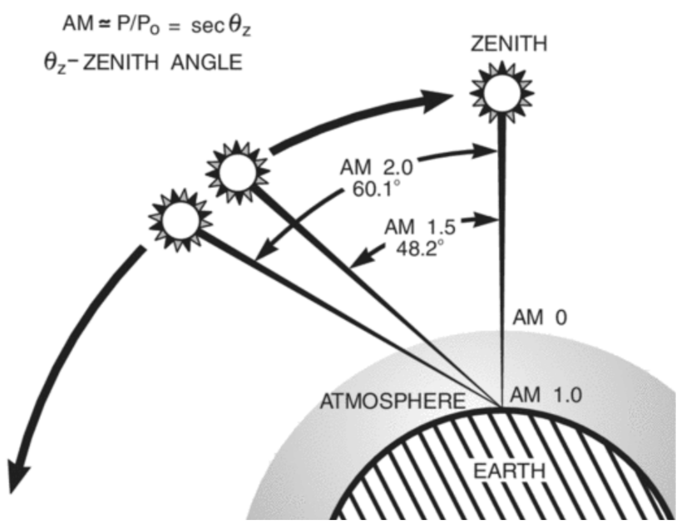

Figure 3: Air Mass definition

In solar cells physics, the interest is in two different regimes of Air Mass: $AM = 0$ is relevant for space applications, while $AM = 1.5$ is considered to study terrestrial applications.

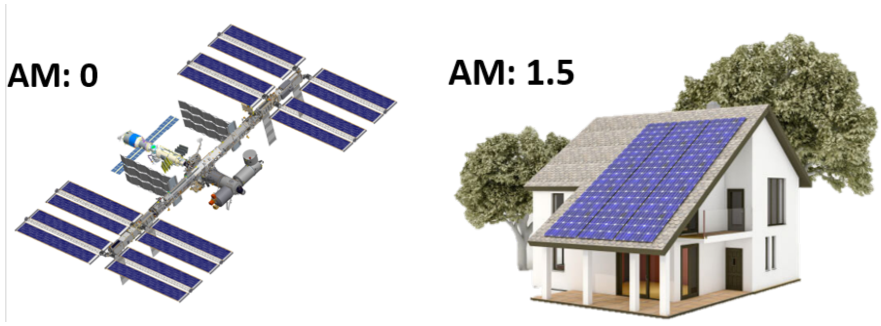

Figure 4: Air Mass regime for spatial and terrestrial applications

1.2 Mechanism

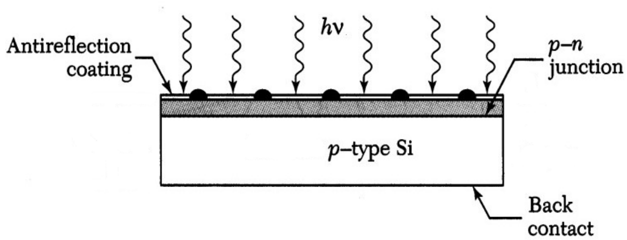

Figure 5: Sketch of a solar cell

The simple scheme in Figure 6 can be used as a guide in the comprehension of the physics beyond solar cells. Different elements can be recognized: a p-n junction, the incoming radiation characterized by its frequency $h\nu$, the metal contacts and an anti-reflection coating.

The main body of this solar cell is a shallow p-n junction, with a p-type silicon portion bigger than the n-type silicon portion. The thickness of such a device is usually about 0,5 mm; the only n-doped layer at the top is usually $1\,\mu$m thick. A p-n junction is a device made out of two pieces of semiconductor material, with different doping. When these are brought together, electrons and holes migrate through the junction. So a spatial charge layers are created in the junction and hence an electrical potential appears, the so-called junction potential.

The other important element is the incoming light. When a photon arrives at the surface of a solar cell, it produces a so-called exciton, which is an electron-hole couple. The electron and the hole are then respectively swallowed up in the n-type and p-type side, producing some electric current in the circuit. This process only takes place when the energy of the incoming photon E_γ is at least as big as the energy gap E_G of the semiconductor ($E_\gamma \geq E_G$). In fact, if the incoming photon energy is lower than the energy gap ($E_\gamma < E_G$), the photon will give no contribution to the cell output. If the incoming photon has an energy greater than the energy gap ($E_\gamma > E_G$), the extra amount of energy is wasted as heat. That's why the energy bandgap of the semiconductor plays an important role in a p-n junction solar cell. Silicon happens to have an energy bandgap functional to solar light collection and it is hence the most used material in solar cells' production (cfr. Section 1.3).

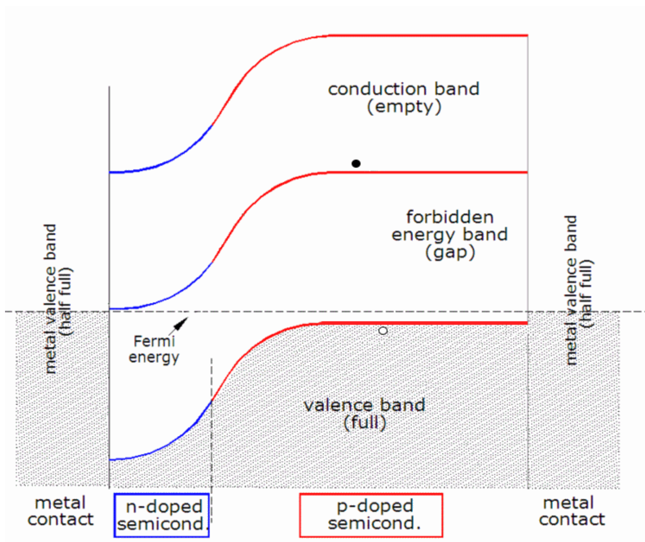

Figure 6: Exciton production by the incoming radiation in the energy levels structure of a pn-junction

In order to collect this current, we need a back and a front contact. The shape of the front contact is quite important as it influences the resistance that the incoming photons are facing when going through the electrode. A common shape is a stripe with some fingers, in order to reduce the area occupied by the contact and increase the one useful to collect photons.

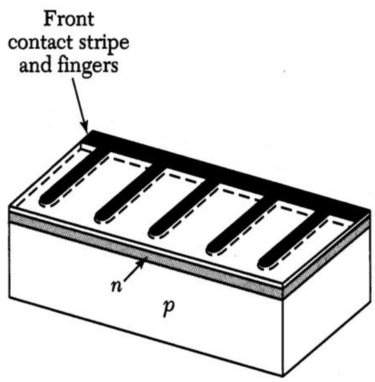

Figure 7: Front contact of a solar cell

The anti-reflection coating is applied on the solar cell in order to reduce the reflection of the incoming light, which is one of the factors making the efficiency decrease (cfr. Section 1.4). In fact, $\sim 31\%$ of the incident photons are reflected and will not give any contribution to electric current production. This value can be computed using air refraction index ($n_{air} = 1$) and the silicon refraction index ($n_{Si} = 3.5$).

1.3 Materials and Production

In solar cells' production, three categories can be distinguished, depending on which kind of silicon is used and how it is assembled in the solar cell production. The three categories are:

- monocrystalline solar cells
  Monocrystalline solar cells are made of one single crystal; these are the ones providing the highest efficiency, the ones with the longest lifetime, even if the most expensive.

- polycrystalline solar cells
  Polycrystalline solar cells are indeed produced starting from liquid silicon that is subjected to solidification process, so they are made of different crystals of different dimensions. The efficiency decreases, even if not dramatically.

- amorphous or thin films solar cells
  They are made of a thin layer of silicon deposited on a substrate. These are the ones with the lowest efficiency and hence the cheapest of all.

Figure 8: Different types of solar cells: structure

Figure 9 summarizes the features of each solar cell kind. As expected, going from ordered structure to less ordered structures, the efficiency decreases due to higher losses caused by recombination currents and resistances.

	Monocrystalline	Policrystalline	Amorphous
Efficiency	14%-18%	12%-14%	5%-6%
Lifespan	25-30 years	20-25 years	15-20 years
Cost	Very expensive	Expensive	Cheap

Figure 9: Different types of solar cells: efficiency

Silicon is nowadays the most used element in solar cell production. Reasons for this are related to its bandgap energy, in the range $1-1{,}8\,\text{eV}$, which happens to be compatible with the energy of photons in visible spectrum, which is in the range $1-3\,\text{eV}$. In general, all the semiconductor materials with bandgaps between $1-2\,\text{eV}$ can be considered solar cell materials. Then, silicon is an easily available material as it is the second most rich in the earth's crust, constituting the 30% of it, second only to oxygen. Moreover, looking at the efficiency plot as a function of energy bandgap (Figure 10), the crystalline silicon is the material providing the highest efficiency. This curve is the result of two competing effects: increasing the bandgap the saturation current will increase and hence the voltage, but at the same time a higher bandgap will reduce the number of photons that can produce an electron-hole pair.

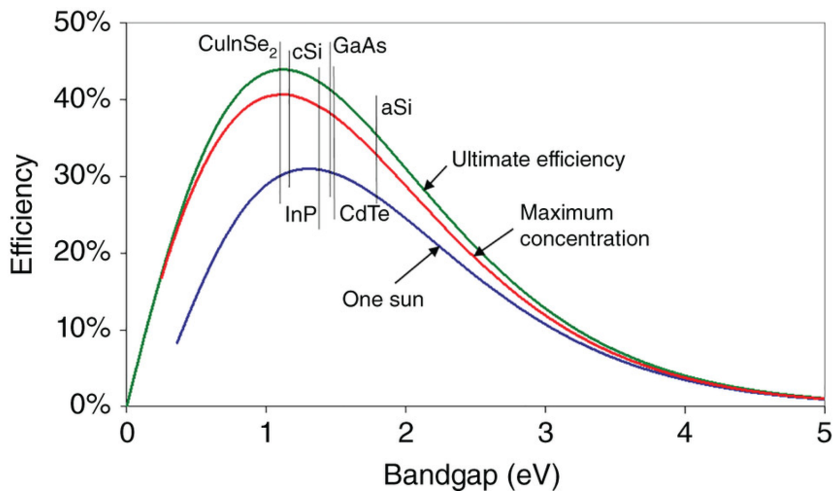

Figure 10: Efficiency of a solar cell as a function of the bandgap energy

Solar cells have a surface of around $13\,\mathrm{mm}^2$ and produce $1-2\,\mathrm{W}$ of power. These are not used alone: solar panels can be simply obtained from solar cells by connecting many solar cells together.
First, modules can be produced by linking solar cells in series; this way the device will have a surface of around half square meter and will emit a power of $50-80\,\mathrm{W}$. Then solar arrays or strings can be produced by connecting in series many solar modules, usually from 3 to 6 solar models. A solar string has a typical dimension of $1\,\mathrm{m}^2$ and an emitted power of $200-300\,\mathrm{W}$. Finally, a solar panel is obtained connecting in parallel solar arrays.

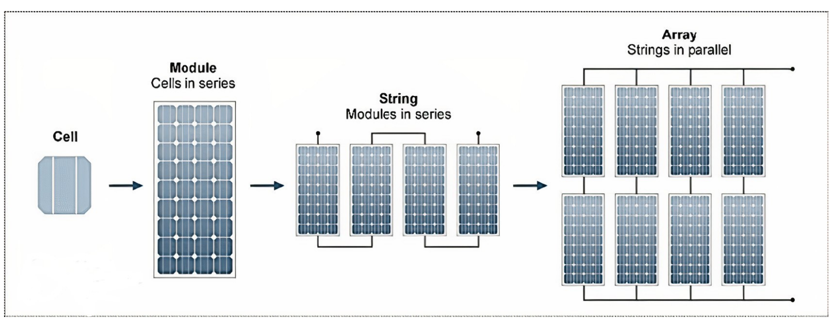

Figure 11: Solar cells arrangement

1.4 Efficiency

In order to discuss the efficiency of an ideal solar cell, an electronic circuit is needed for such a device. A simple model is sketched in Figure 12.

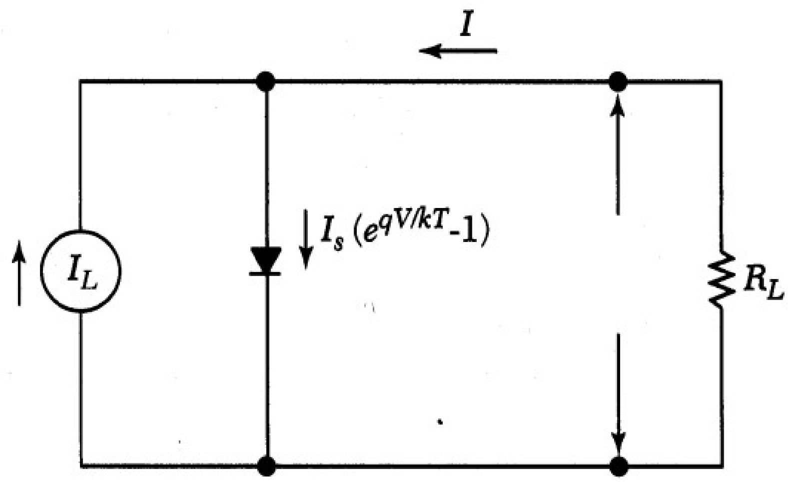

Figure 12: Electronic circuit for a solar cell

The incoming light from the Sun can be modelled as a current source I_L; the other element is the p-n junction, with a saturation current I_S and a load resistance R_L. Hence the total current going through the circuit is given by this simple formula:

$$I = I_S(e^{qV/kT} - 1) - I_L \tag{5}$$

As mentioned in the previous section, the saturation current depends on the energy gap, with an exponential of the ratio between energy gap and the thermal energy, while the light current depends on the quantity of photons with energy higher than the energy gap available.

With this model, it is possible to plot the I-V curve of a solar cell. The first thing that can be noticed is that the curve is passing through the fourth quadrant: this means that it is possible to extract power from a solar cell. The important parameters are I_m and V_m; multiplying them, the maximum value of power that can be extracted from the solar cell is obtained. This is represented in Figure 13 by the rectangle in the fourth quadrant.

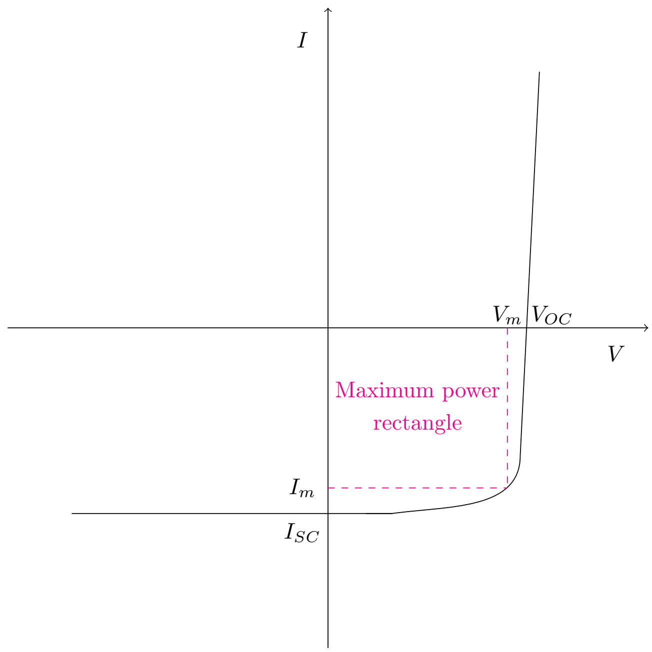

Figure 13: I-V curve of an ideal solar cell

Efficiency is then defined as the ratio between the maximum power that can be extracted from the solar cell and the input power.

$$\eta = \frac{I_m V_m}{P_{in}} \tag{6}$$

The incoming power is the integral of the irradiance spectrum showed in Figure 2 over all the wavelengths absorbed by the p-n junction. For an ideal solar cell, considering an Air Mass of 1.5, the efficiency is about 29%. In real world, other loss effects than the band-band recombination as to be considered, hence a more realistic value of the efficiency is around 10-15%.

Efficiency losses in a real solar cell are mainly due to series resistances, reflection and recombination current; the three effects all together provides a decrease of efficiency up to $\sim 40\%$ of its ideal value. Series resistance can be easily added to the electronic circuit model by adding a resistor in series R_s. The current in the circuit will become:

$$I = I_S(e^{q(V-IR_S)/kT} - 1) - I_L \tag{7}$$

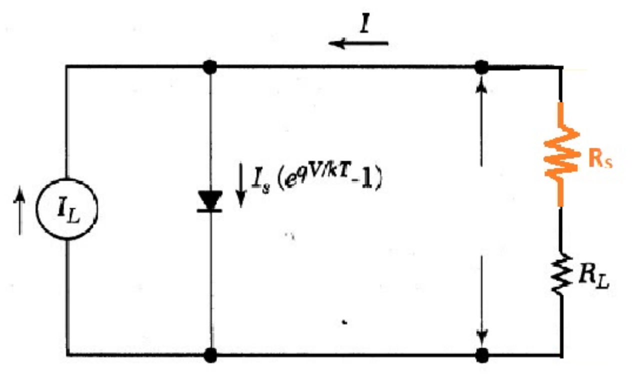

Figure 14: Series resistance included in the electronic model for a solar cell

The series resistance depends on the junction depth, the impurity concentrations of p-type and n-type regions and the arrangement of the front-surface ohmic contacts. As an example, if the finger electrodes in Figure 7 are very thin, the series resistance will be further increased. The maximum power rectangle will be hence reduced. As can be seen in Figure 15, the higher the resistance, the more the power rectangle will be reduced. A typical value of the resistance reduces the solar cell efficiency to $\sim 60\%$ of its ideal value.

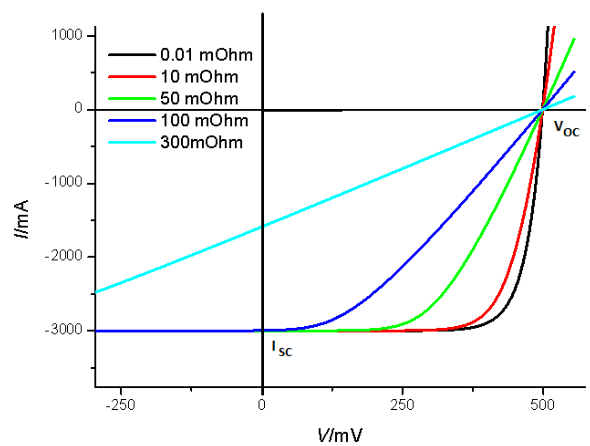

Figure 15: Series resistance effect on the I-V plot

Reflection losses can be avoided by applying an anti-reflection coating to the solar cell surface. A destructive interference between the reflected waves can be obtained and the reflected light fraction can be highly reduced by choosing the optimal refraction index and thickness of the coating, as shown in Figure 16.

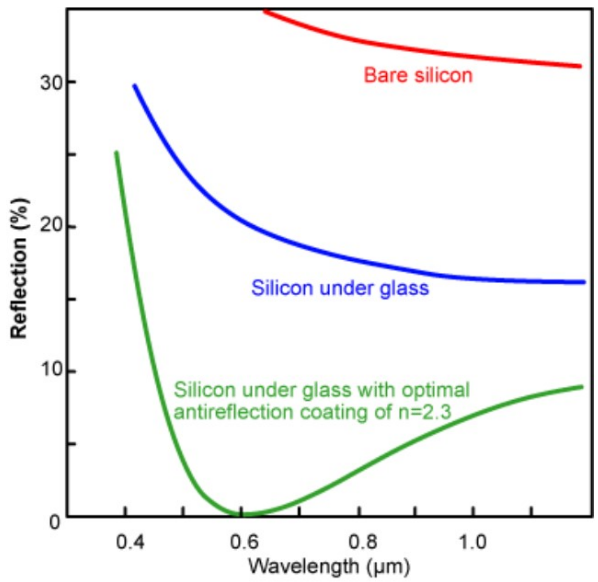

Figure 16: Reflection percentage as a function of wavelength with and without anti-reflection coating

Effects that provide an efficiency gain can also be discussed. One first method is the so-called "spectrum splitting technique". The idea is to reduce the input power and in order to do so to reduce the wavelength range. This can be done by splitting sunlight into narrow wavelength bands and directing each band to a cell that has a bandgap optimally chosen to convert just this band. A simple solution is stacking cells on top of one another with the highest bandgap cell uppermost automatically achieves a suitable spectral-splitting effect.

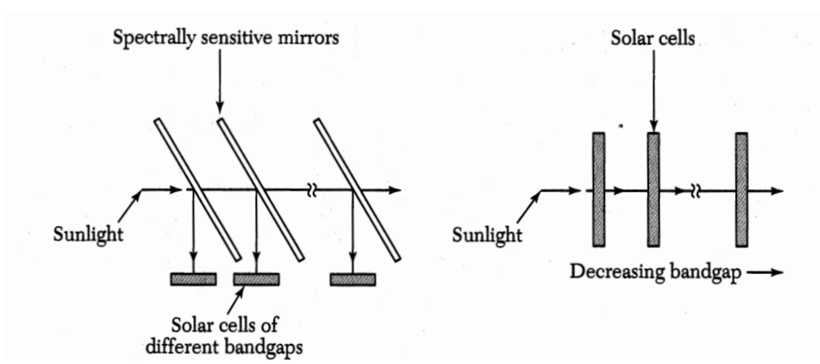

Figure 17: Splitting spectrum technique: lens configuration

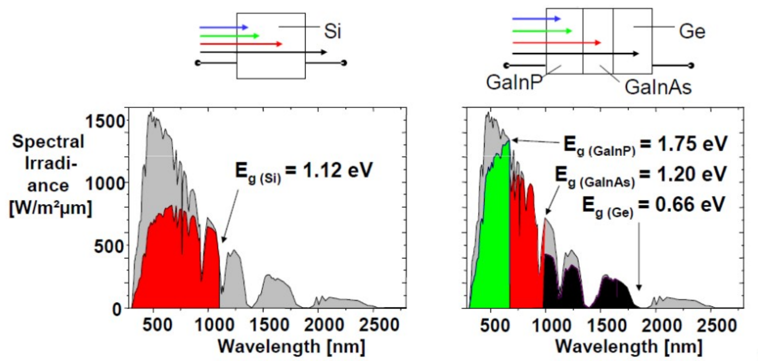

Figure 18: Splitting spectrum technique: intensity spectrum

Another option is to increase the light concentration on the solar cell surface and hence collecting a higher quantity of photons in the cell. This can be done using a Fresnel lens, which is shaped in such a way to convey the light towards the solar cell. Increasing the concentration up to $C = 1000$, the equivalent of one thousand suns, at $AM = 1.5$ and $T = 300\,\mathrm{K}$, will make the efficiency raise to $\sim 130\%$ of its ideal value.

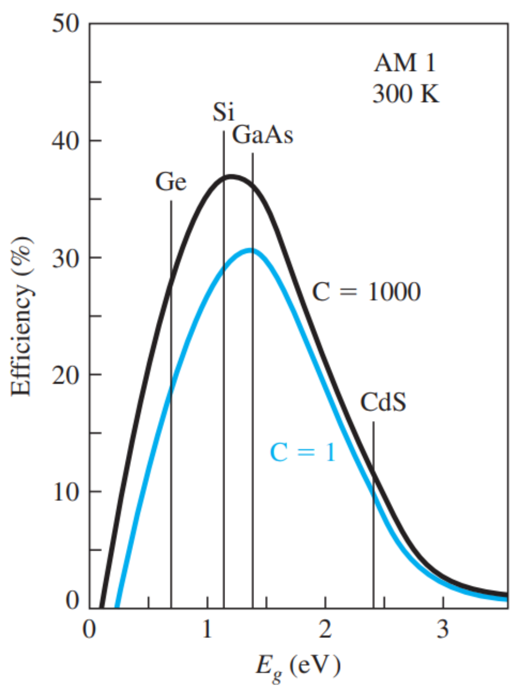

Figure 19: Optical lensing technique

1.5 Applications

Figure 20: Some more examples of solar devices: solar panels on the top of traffic lights (a), in charging stations for electric cars (b), in telecommunication systems (c) and a fully solar-cells-powered car(d).

Some other more fancy applications of solar cells are presented here. For example, many countries are now using road signs powered by solar cells. It is also not rare to find charging stations powered by solar cells where electric cars can be charged. Solar cells are often used in telecommunication systems. Finally, there is an annual international competition held in Australia where only fully solar cells powered cars are admitted. The car pictured in Figure 20 won the race in 2017 and is able to carry up to 3 people at a maximum speed of 70 km/s.

2 Photodiodes

A photodiode is a semiconductor p–n junction device working in the reverse bias mode that converts light into an electrical current. The current is generated when photons are absorbed in the photodiode.

Efficiency and responsivity highly depend on wavelength; response speed can be enhanced choosing the proper junction thickness. Applications can be found in different fields, such as safety electronics and defence applications.

2.1 Motivation

Photodiodes are produced with the aim of developing devices able to detect the presence of light. The goal is to have a simple device that, when hit by some external radiation, will switch on a signal or an alarm. Such devices could be useful in many fields, e.g. particle physics detection or safety systems, and some applications are showed in the last subsection.

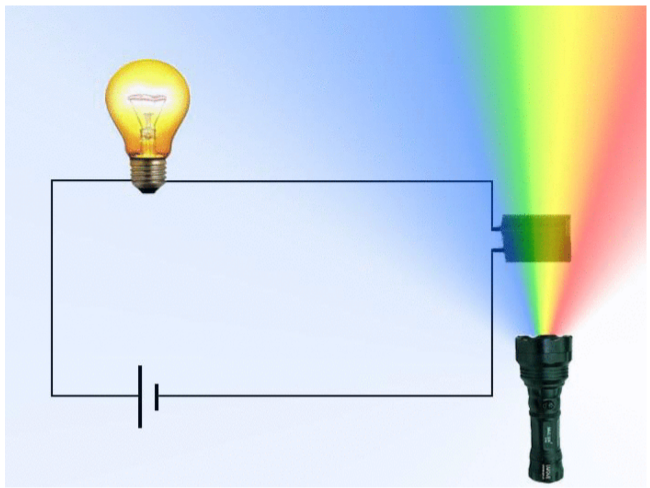

Figure 21: Schematic view of a photodiode

2.2 Mechanism

The physics beyond photo-diodes is the same as solar cells, with an important difference: these devices are working in reverse mode bias. Hence, the working point will be located in the third quadrant of the I-V curve.

The goal of photo-diodes is to detect incoming light, so there is the need to be in a region where a variation of voltage is followed by a slight variation of current. Unfortunately, even if there is no illuminance, there will still be some current in the device. This is due to the so-called “dark current”, which arises due to thermal energy and consequent random generation of electron-hole pairs.

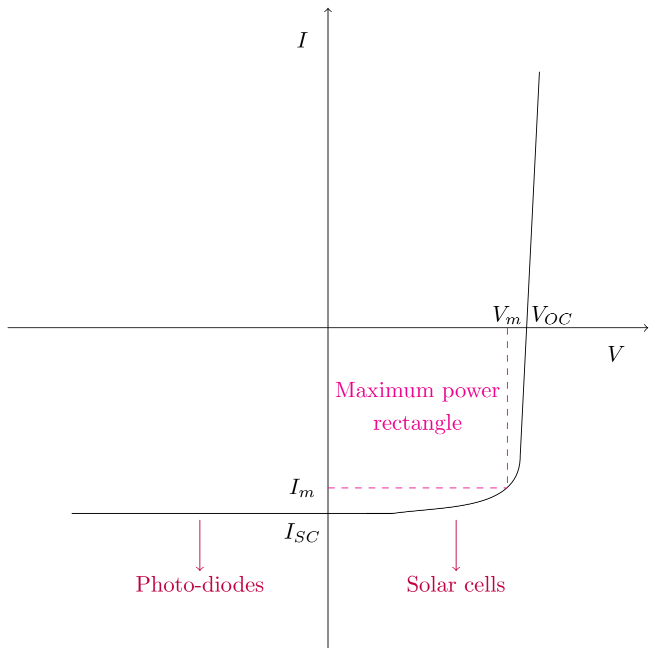

Figure 22: I-V curve for a photodiode

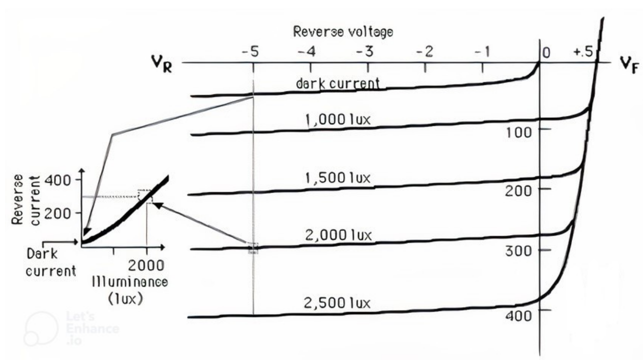

Figure 23: I-V curve for a photodiode for different illuminance regimes. Notice that the current-illuminance curve is not passing from the origin, i.e. there is some "dark current" even when there are no photons coming from outside.

2.3 Efficiency

As for solar cells, it is quite important to have appropriate parameters to quantify the goodness of a photodiode device. In this case, three figures of merit are the most used: quantum efficiency, responsivity and response speed.

Quantum efficiency η is easily defined as the ratio between the number of collected electron-hole pairs per second and the number of incident photons per second. It can be expressed as a function of the energy of the incoming radiation $h\nu$, the generated photocurrent I_p and the incident optical power P_{opt} as well.

$$\eta = \frac{collected\ e/h\ per\ second}{incident\ photons\ per\ second} = \frac{I_p}{q}\frac{h\nu}{P_{opt}} \tag{8}$$

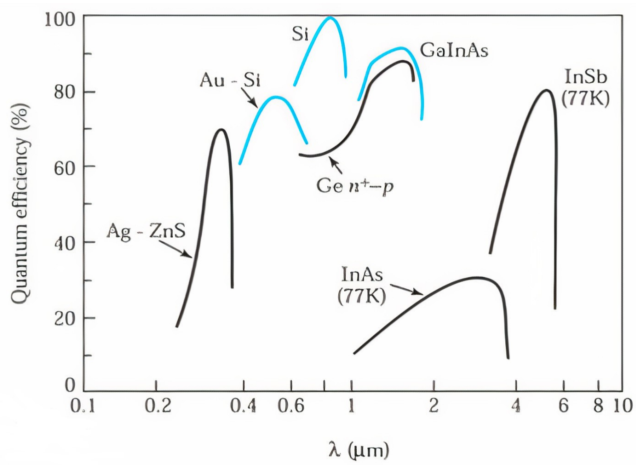

Figure 24: Quantum efficiency of a photodiode

The responsivity $\mathcal{R}$ of a photodiode is defined as the generated photocurrent I_p per incident optical power P_{opt}.

$$\mathcal{R} = \frac{I_p}{P_{opt}} = \eta\frac{q}{h\nu} \tag{9}$$

$\mathcal{R}$ is also called the spectral responsivity or radiant sensitivity. If a photodiode has an ideal quantum efficiency of 100%, then $\mathcal{R}$ should be linearly proportional to the wavelength λ. In practice, the relationship of R and λ is shown in Figure 26. The quantum efficiency limits the responsivity below the ideal photodiode.

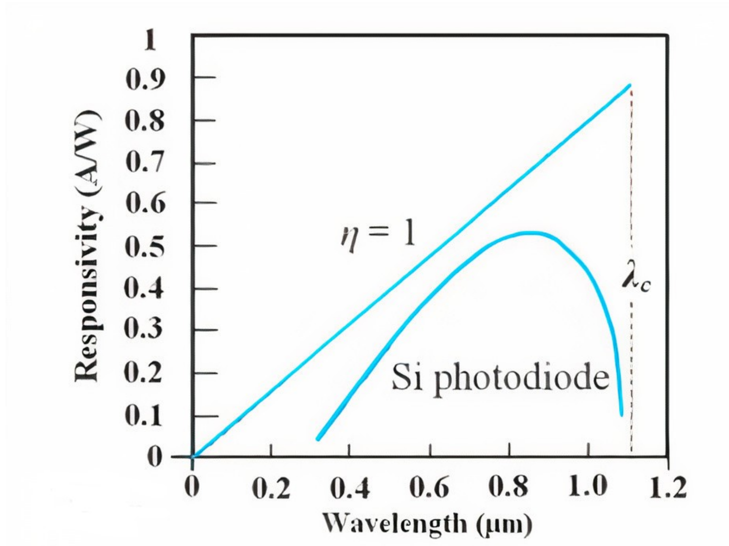

Figure 25: Responsivity of a photodiode

Response speed, instead, depends on three main parameters:

- diffusion of carriers; for this reason, the junction is located very close to the surface.
- drift time in the depletion region; for this reason, it is better not to have a too wide depletion region.
- capacitance of the depletion region; for this reason, it is better not to have a too thin depletion region as $C \propto A/d$.

The thickness of the device should hence be tuned carefully to compensate the drift time and capacitance effects and gain the desired response speed.

2.4 Applications

Applications oh photodiodes can be found in many different fields. A couple of examples are presented here: a remote control works thanks to some photodiode in the TV detection, which detect the electromagnetic waves emitted by it, and a smoke detector is switched on when there are some smoke particles inside it thanks to a photodiode which will receive photons scattered by the light particles.

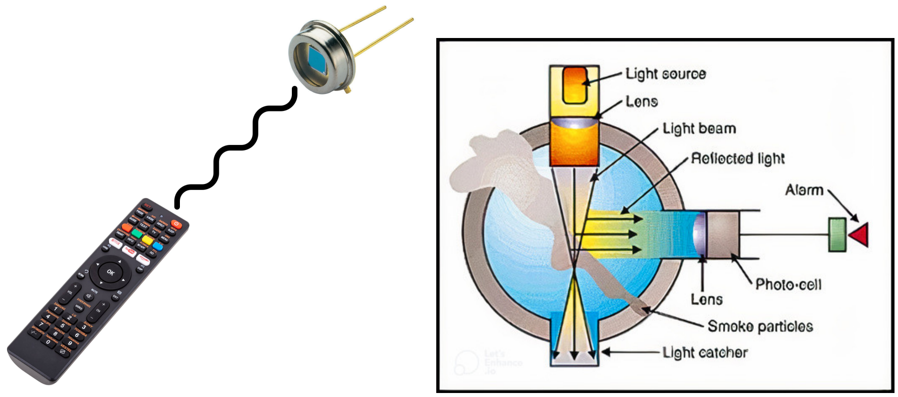

Figure 26: Some examples of photodiodes applications in commonly used objects

3 Comparison

As a conclusion, a short comparison between the two devices can be presented. Main differences are in the dimensions of the junction area, the voltage applied to the junction and the applications in which these devices can be used.

	Solar cells	**Photo-diodes**
Junction area	Larger	Smaller
Biasing	No voltage	Reverse bias
Main application	Light to electric energy converter	Light detector

Figure 27: Comparison between solar cells and photodiodes

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