ET3034TU: Solar Cells

TU Delft Delft University of Technology

Challenge the future

Contents

Introduction to PV and solar radiation

Introduction to Photovoltaic Solar Energy

The Energy Problem

During the last decades the energy problem on the planet has been growing steadily. The reason for that is a growing world population and increasing living standard. This has led to increasing fossil fuel prices due to more expensive and more risky fossil fuel depletion.

To overcome those problems it is necessary to change the energy infrastructure within this century. The higher energy consumption can be compensated by an increase in usage of solar power.

Electricity

Electricity is a secondary form of energy. For the last 100 year it has become more and more important in practical use and nowadays is a symbol of modernity and progress. However over 2 billion people do not have access to it.

Electricity can be generated in various ways. It can be directly created through Photovoltaic's which take the energy from the sun. Other methods are to create thermal energy first which is then converted into mechanical and eventually into electrical. When Electricity is generated roughly 66 % is lost in conversion / efficiencies and only 33 % is used for consumption.

The Sun as sustainable energy source

The sun is a gas sphere with a diameter of 1.5 million km. For us it is the source of all thermonuclear reactions and its surface temperature are 5800 K. The energy from the sun can be split up in light and heat or electromagnetic radiation / photons. White light refers to composition of colors and heat to long, invisible radiation.

When the solar radiation of the sun reaches the earth only a part of the entire radiation reaches the earth due to reflection / absorption in the atmosphere. The peak radiance is in the visible area. 98 % of the energy is between 200 and 3000 nm.

- ultraviolet radiation (<400 nm, 9% energy)
- visible light (400 – 750 nm, 44% energy)
- infrared radiation (>750 nm, 47% energy)

Considering that the earth uses 16 TW now and the global demand will reach 32 TW in 2050 one could use the solar energy which is 120.000 TW for that an area of 1250km² would be needed.

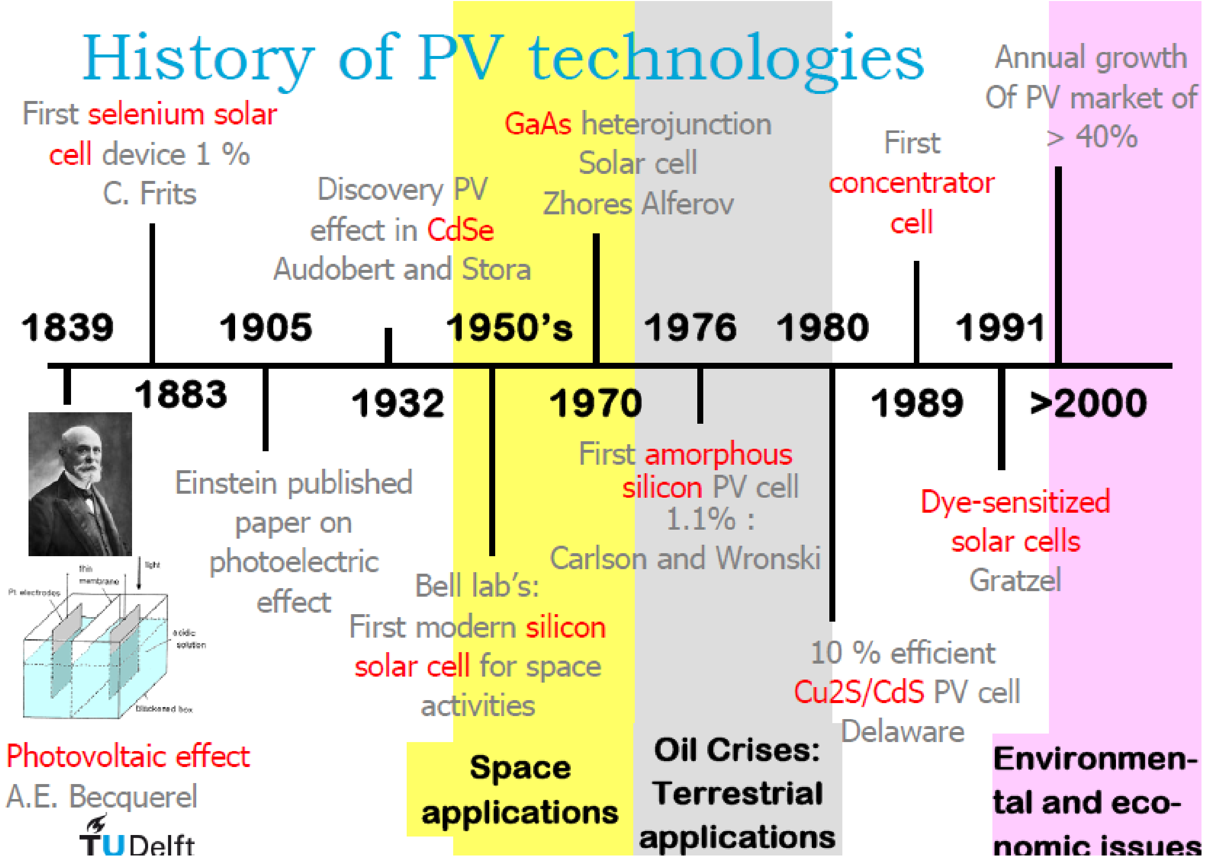
Photovoltaic

Literally Photvoltaics (PV) means "light electricity". It is a direct conversion of light into electricity using semi conductor materials. Advanced semiconductor devices are solar cells. The reasons for PV are the energy problem, ecological reason (climate change)and economic reason (new job creation, added value for buildings)

Advantages:	Disadvantages:
• environmentally friendly	• PV cannot operate without light

• no noise, no moving parts • no emissions • no use of fuels and water • minimal maintenance requirements • long lifetime, up to 30 years • electricity is generated where ever there is light, solar or artificial • PV operates even in cloudy weather conditions • modular “custom-made” energy can be sized for any application from watch to a multi-megawatt power plant	• high initial costs that at the moment overshadow the low maintenance costs and lack of fuel costs • large area needed for large scale applications • PV generates direct current special DC appliances or an inverter are needed • in off-grid applications energy storage is needed

History, Status and future of PV technology



History of PV technologies

1839
Photovoltaic effect
A.E. Becquerel

1883
First selenium solar cell device 1 %
C. Frits

1905
Einstein published paper on photoelectric effect

1932
Discovery PV effect in CdSe
Audobert and Stora

1950’s
Bell lab’s:
First modern silicon solar cell for space activities

Space applications

1970
GaAs heterojunction Solar cell
Zhores Alferov

1976
First amorphous silicon PV cell
1.1% :
Carlson and Wronski

Oil Crises:
Terrestrial applications

1980
10 % efficient Cu2S/CdS PV cell
Delaware

1989
First concentrator cell

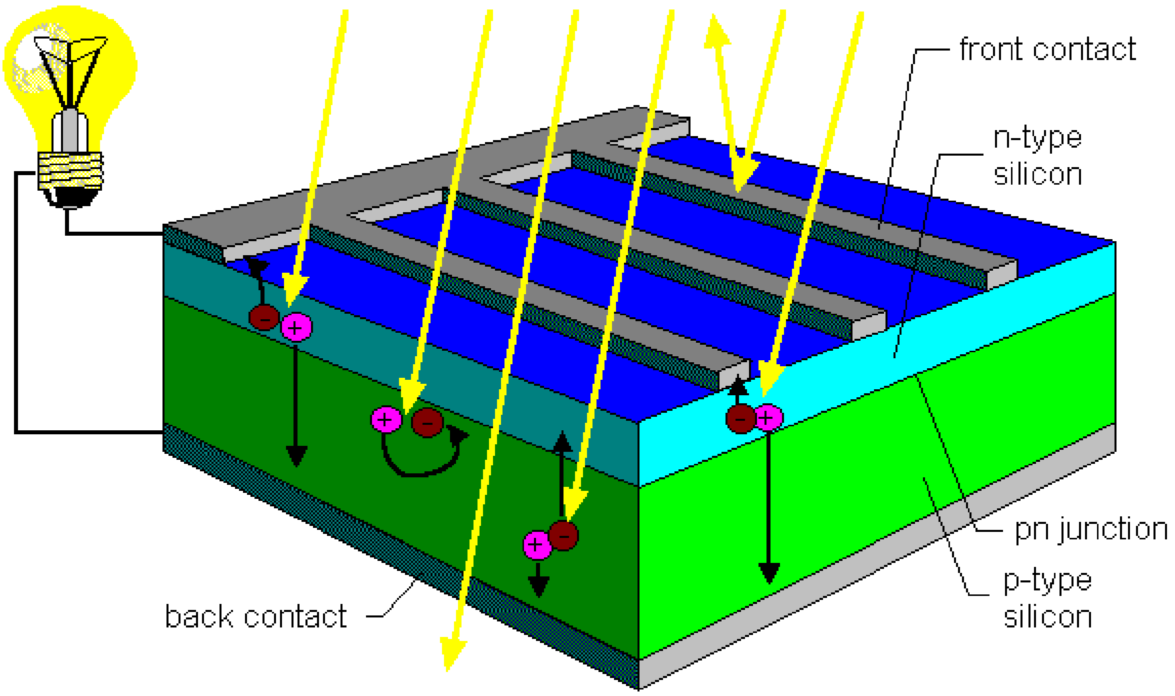
1991
Dye-sensitized solar cells
Gratzel

>2000
Annual growth Of PV market of > 40%

Environmental and economic issues

Solar cell operation

The solar cell operation is based on the photovoltaic effect: The generation of a voltage difference at the junction of two different materials in response to visible or other radiation. First of all the absorption of light generates charge carriers which es followed by the separation of charge carriers, eventually the collection of the carriers take place at the electrode.

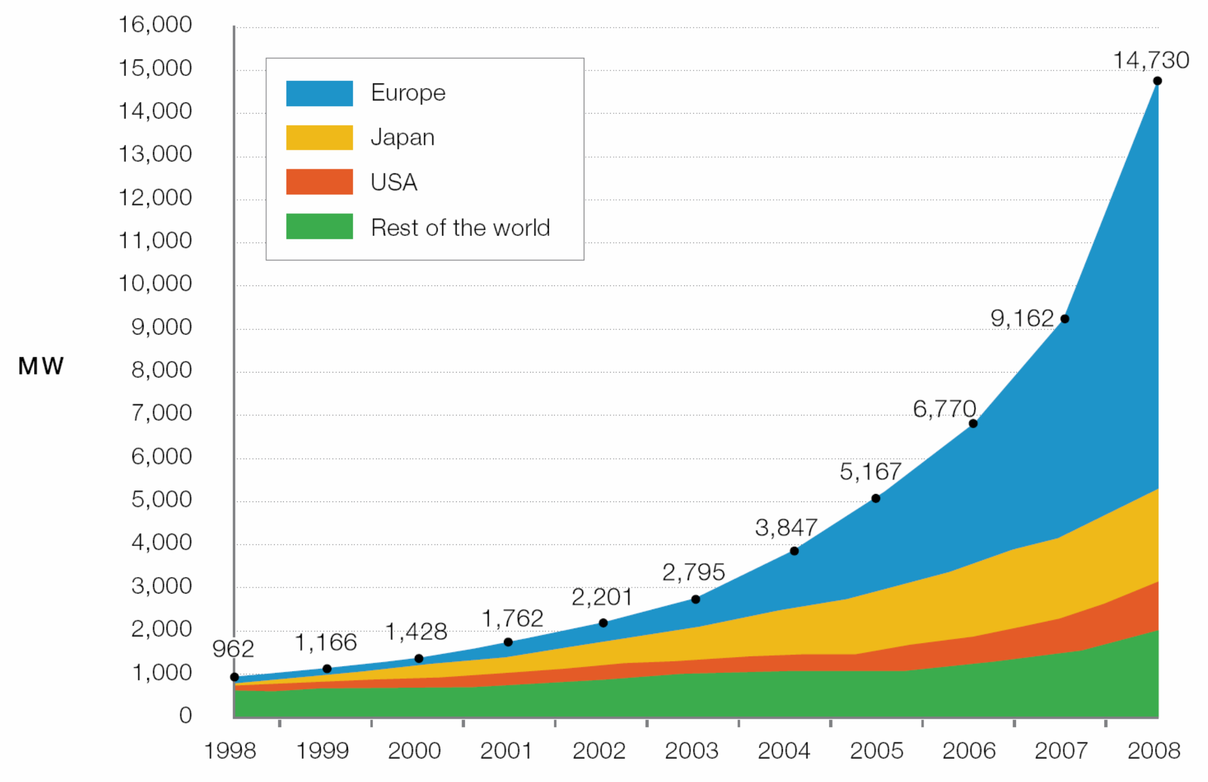


External parameters for solar cells are the short circuit current, open circuit voltage and the fill factor, also the maximum peak power and the efficiency. When performing IV measurements standard conditions need to be applied: AM1.5 spectrum, Irradiance 1000W and temperature of 25 degrees Celsius.

When looking at PV technologies one can separate the progress in technology in 3 different generations of solar cells:

1. 1st Generation which are high quality materials (high production costs) and relative high efficiencies. Usually they are wafer based SI. They cover 90 % of the market however the manufacturing cost is the major challenge. The efficiencies lie between 12 and 20 %
2. 2nd Generation are thin films with lower efficiencies but also low production costs. The Cost per m² is higher than those for the 1.st generation. Those ones are low cost and make new applications possible the enhancement of the efficiency is the major challenge. Efficiency range between 6 and 9 percent.
3. 3rd For the future the industry aims at new concepts which lower the production costs and give higher efficiencies.

Photovoltaics will be increasingly used in the future as the tables displays:



PV System

The term solar cells stands for the semiconductor device. A solar cell connected in series is then a PV module. A collection of those modules is called a solar array. The solar system is the built up from the PV module, inverter, battery, appliances etc.

Definitions:

- Power (of cells, modules and systems) in Watt-peak (Wp)
- The performance ration is equal to the average ac system over the dc module efficiency
- The electricity yield in KW/kWp
- The capacity factor is the amount of ac peak divided by the amout of hours per year.

The Sun and its Radiation

The Sun

The solar constand is 1367 Wm^{-2} outside the atmosphere , also roughly 98 % of the energy is within a spectrum of 200-3000 nm. From that 9 % of the energy is within the ultraviolet area, 44 % is visible light and infrared is 47 % of the energy.

There are several quantities and units in which radiation is measured:

- Spectral power density P(λ): incident power per unit area per unit wavelength
- Spectral photon flux Φ(λ): Number of photons per unit area, per unit time and per unit wavelength:
  $P(\lambda) = \Phi(\lambda)\frac{\mathrm{hc}}{\lambda}$
- Photon flux Φ: Number of photons per unit area per unit.

- Irradiance I: Incident total power from a radiant source per unit $I = \int P(\lambda)d\lambda$
- Irradiation F: irradiance integrated over a period of time $F = \int Idt = I\ x\ time$
- Air mass: The ratio of the path length which light takes through the atmosphere to the shortest possible path length: Air mass = 1 / cos (θ)

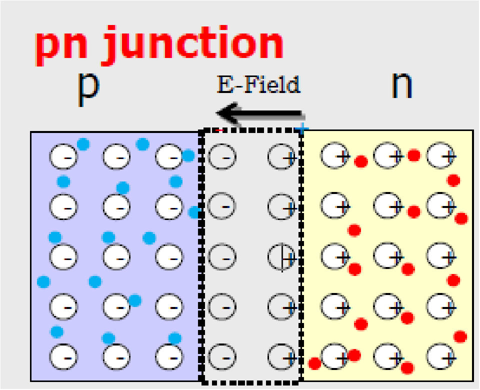
From the solar radiation that comes from the sun 6 % is reflected by the atmosphere, 20% by clouds and 4 % from the surface. Also 19 % is absorbed by atmosphere and clouds leading to only 51 % that is absorbed by the surface.

Solar Cell operation

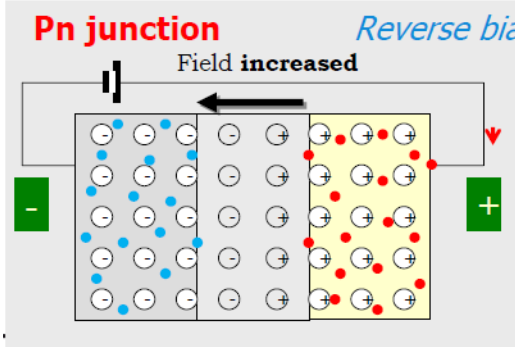
Summary of internal process

When a material is either p or n doped it means that the majority carriers control the diffusion, additionally by light absorption electron hole pairs do not affect the density. In the minority carriers the light absorption does significantly affect the density. The diffusion is governed by the density in the material. This is called diffusion, also transport can be done by drift and an electric field is created.

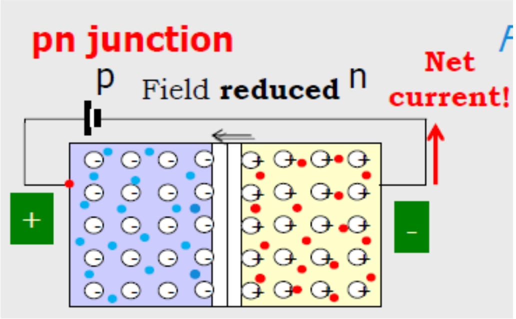
In a pn junction the diffusion of majority carriers and the recombination creates a space charge zone. Then there is a net transport competition between both the diffusion of the majority carriers and the drift of minority carriers by the electric field through the depletion zone.



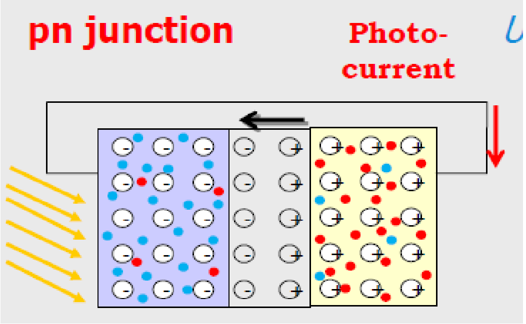
In the **reverse bias in the dark** the contribution of the majority carriers due to the large width of the depletion zone is surpressed. The drift of the minority carriers controls the net current.



In the forward bias in the dark the width of the depletion zone is suppressed and the contribution of the diffusion increases, the net transport is controlled by diffusion of the majority carriers.



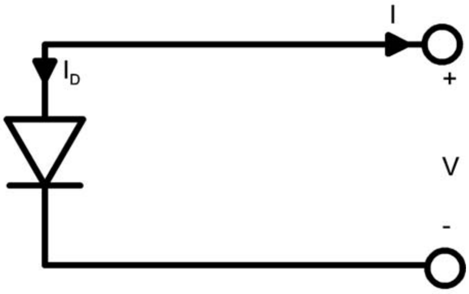
Under illumination the density of the minority charge carriers is increased a significant order of magnitude. This does not affect the diffusion but increases the drift current of minority carriers through the depletion zone.



The IV Curve of solar cells

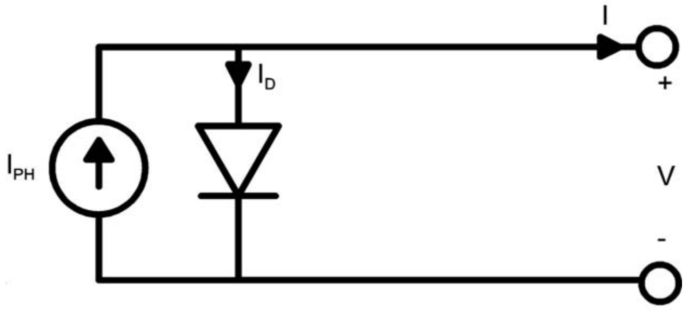
IV Curve in the dark and illuminated

The dark current



The current of the pn junction is equal to the dark current which is given by: $I = I_{DARK} = I_0(\exp\left(\frac{qV}{k_bT}\right) - 1)$ in which q is the charge of the electron, k is the Boltzman constand and T the Temperature.

The illuminated ideal pn junction



In addition to the dark current there is the photon in the reverse direction leading to the equation: $I = I_{PH} -$ $IDARK=IPH-I0(\exp qVkbT-1)$

Now additionally the unit J is introduced which is the current per area, which is the current density. Using the unit one can derive new external parameters.

Open circuit voltage Voc

When considering an open circuit there is a certain open circuit voltage which builds up. When rearranging the previous equation it leads to $V_{oc} = \frac{kT}{q} ln\,(\frac{J_{PH}}{J_0} + 1)$. Increasing the voltage over solar cell increases the forward diode current

At a certain voltage the forward current is so high that it cancels out the light generated current.

Short circuit current Jsc

There is the possibility of a current using the short circuit. The equation for that can be derived from the basic equation:

$$J = J_{PH} - J_0\left(\exp\left(\frac{qV}{k_B T}\right) - 1\right)$$

$$J_{SC} \quad \Rightarrow \quad V = 0$$

$$J_{SC} = J_{PH}$$

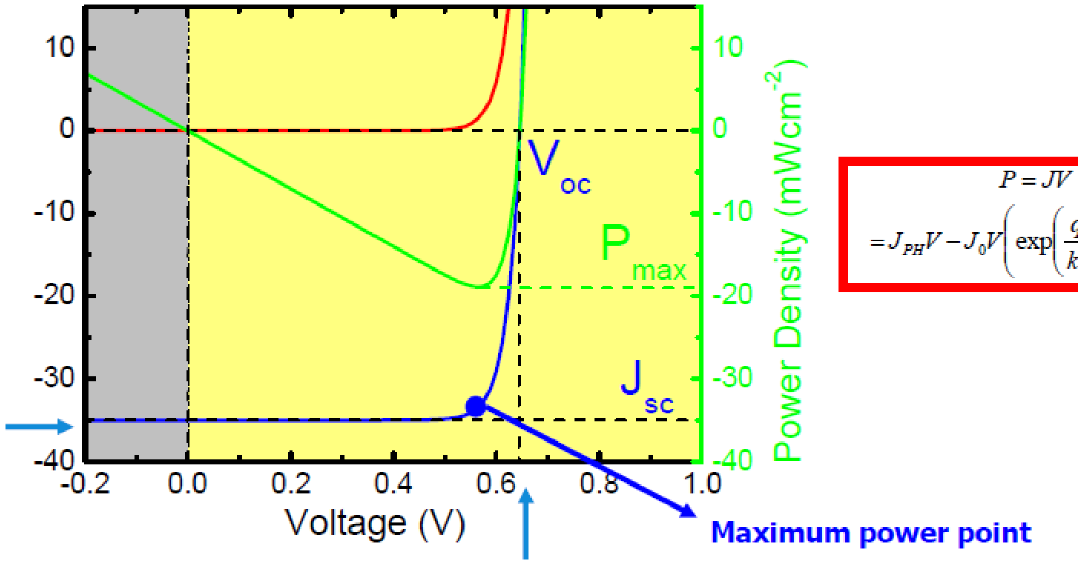
To remove the dependence of the solar cell area, it is more common to list the short-circuit current density (Jsc in mA/cm2) rather than the short-circuit current;
(i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity as discussed in Effect of Light Intensity
For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum; ;
(absorption and reflection) of the solar cell (discussed in Optical Losses); and
of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

The Power density

Power is equalt to the product of current and voltage. It is given by equation:

$$P = JV$$
$$= J_{PH}V - J_0 V\left(\exp\left(\frac{qV}{k_B T}\right) - 1\right)$$

In the graph below one can the see the Diagram which includes all the external parameters described above.

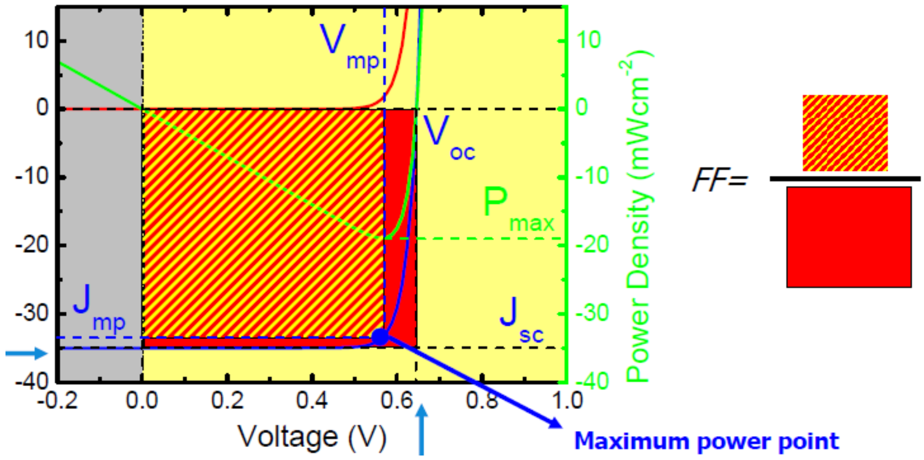


In order to find the maximum power output P one introduces a fill facot FF which is given in the equation below. The actual power is given by the yellow shaded area and the possible power given by the red area.

Maximal power output P_{max}

Introduction of external parameter FF:

$$FF = \frac{P_{\max}}{J_{sc} V_{oc}} = \frac{J_{mp} V_{mp}}{J_{sc} V_{oc}}$$



Furthermore the efficiency can now be determined by using the fill factor:

Efficiency η

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{max}}{P_{in}} = \frac{J_{mp} \cdot V_{mp}}{P_{in}} = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$$

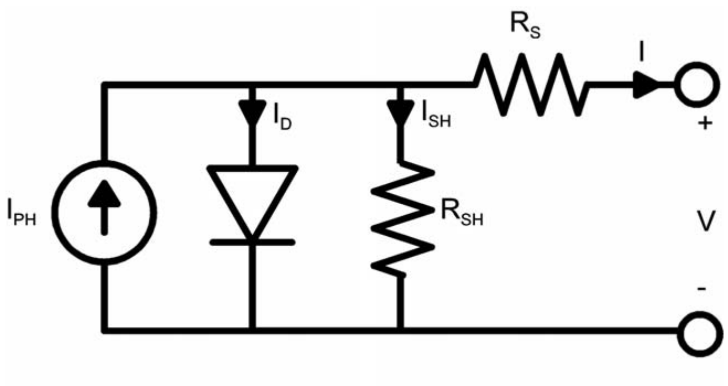
$$FF = \frac{J_{mp} V_{mp}}{J_{sc} V_{oc}} \Rightarrow J_{mp} V_{mp} = J_{sc} V_{oc} FF$$

efficiency is expressed in all external parameters!

η, V_{oc}, J_{SC}, FF, P_{max}

The measurements are done in standard test condition which means that Pin is equal to 1000W/m².

Now lets consider the non ideal pn junction:



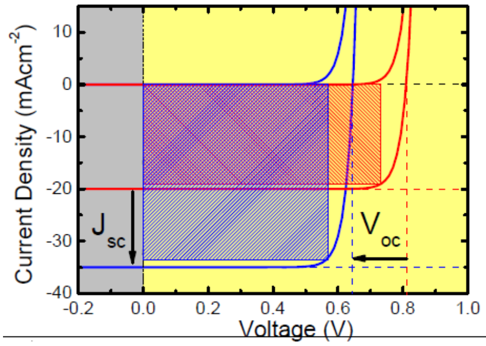
Rs in the resistance due to the contacts on the solar cell and Rh the shunt resistance which is due to material improperties. . Decreasing Rsh means that the fill factor decreases as well. It can be derived from the diagram that Rsh should be large and Rs slmall. From the circuit diagram a neq eaution can be derived:

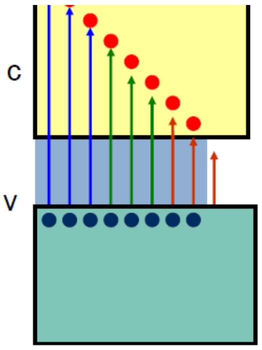
$$\boxed{\begin{aligned} J &= \frac{I}{A} \\ J &= J_{PH} + J_{DARK} = \\ &= J_{PH} + J_0\left(\exp\left(\frac{q(V + JR_S)}{k_B T}\right) - 1\right) - \frac{V + JR_S}{R_{SH}} \end{aligned}}$$

JV Characteristics

Dependence on the material:

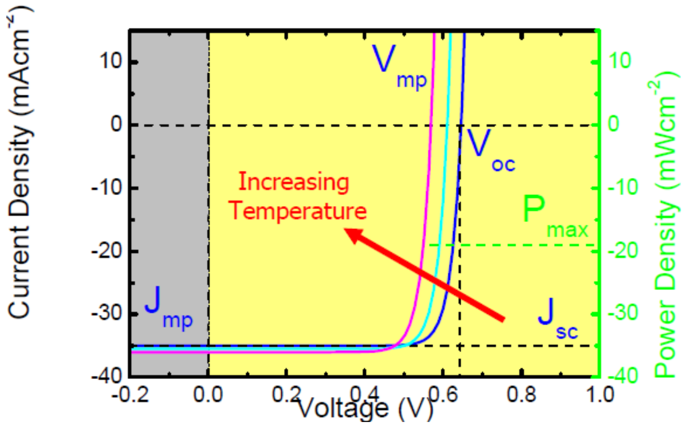
A larger band gap leads to only high energetic photons generating a current which means that Jsc is smaller but a higher Voc is generated. A smaller band gap leads to a higher Jsc but smaller Voc





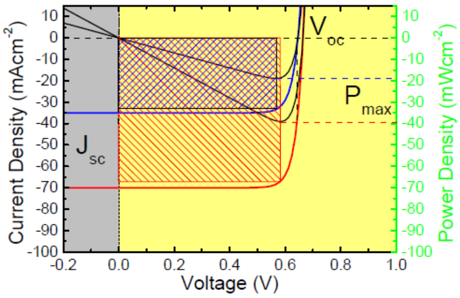
The effect of temperature:

An increase in temperature leads to an increase in J0 and a decrease in Voc which eventually leads to a lower efficiency.



The effect of light intensity

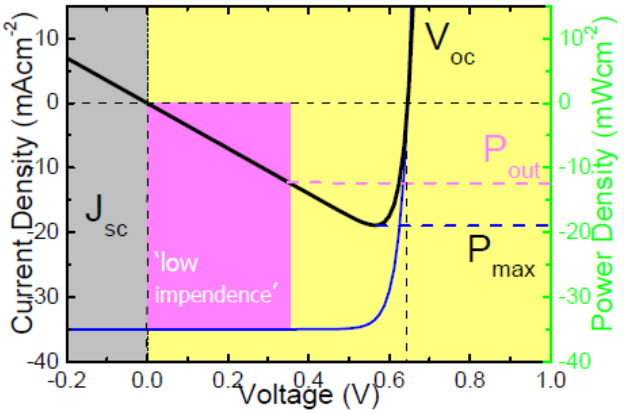
A higher light intensity means a higher Voc as it can be seen in the equation for the Voc.

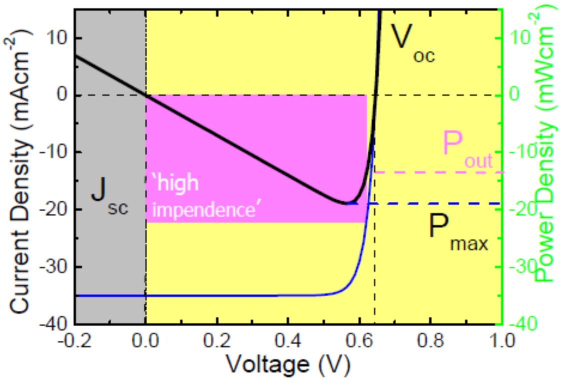


$$V_{OC} = \frac{k_B T}{q} \ln\left(\frac{J_{PH}}{J_0} + 1\right)$$

The load versus output

Additionally it needs to be taken into account which load should be taken. A wrong load can lead to a loss in output. Examples for a too low load or a too hugh load are given below:



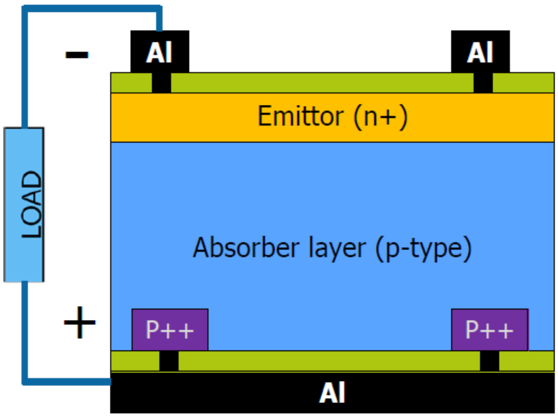


Operation of solar cell: fundamentals

Charge carrier transport

Solar cell structure:

the generation of positive and negative charge carrier pairs;
the collection of the charge carries at the corresponding contact generating a current;
the dissipation of power in the load and in parasitic resistances



Recombination

Radiative Recombination

Radiative recombination is the recombination mechanism which dominates in devices such as LEDs and lasers. However, for photovoltaic devices which for terrestrial applications are made out of silicon, it is unimportant since silicon's band gap is an "indirect" band gap which does allow a direct transition for an electron in the valence band to the conduction band. The key characteristics of radiative recombination are:

In radiative recombination, an electron directly combines with a hole in the conduction band and releases a photon; and

The emitted photon has an energy similar to the band gap and is therefore only weakly absorbed such that it can exit the piece of semiconductor.

Recombination Through Defect Levels

Recombination through defects, also called Shockley-Read-Hall or SRH recombination, does not occur in perfectly pure, undefected material. SRH recombination is a two-step process. The two steps involved in SRH recombination are:

An electron (or hole) is trapped by an energy state in the forbidden region which is introduced through defects in the crystal lattice. These defects can either be unintentionally introduced or can have been deliberately added to the material, for example in doping the material; and

If a hole (or an electron) moves up to the same energy state before the electron is thermally re-emitted into the conduction band, then it recombines.

The rate at which a carrier moves into the energy level in the forbidden gap depends on the distance of the introduced energy level from either of the band edges. Therefore, if an energy is introduced close to either band edge, recombination is less likely as the electron is likely to be re-emitted to the conduction band edge rather than recombine with a hole which moves into the same energy state from the valence band. For this reason, energy levels near mid-gap are very effective for recombination.

Auger Recombination

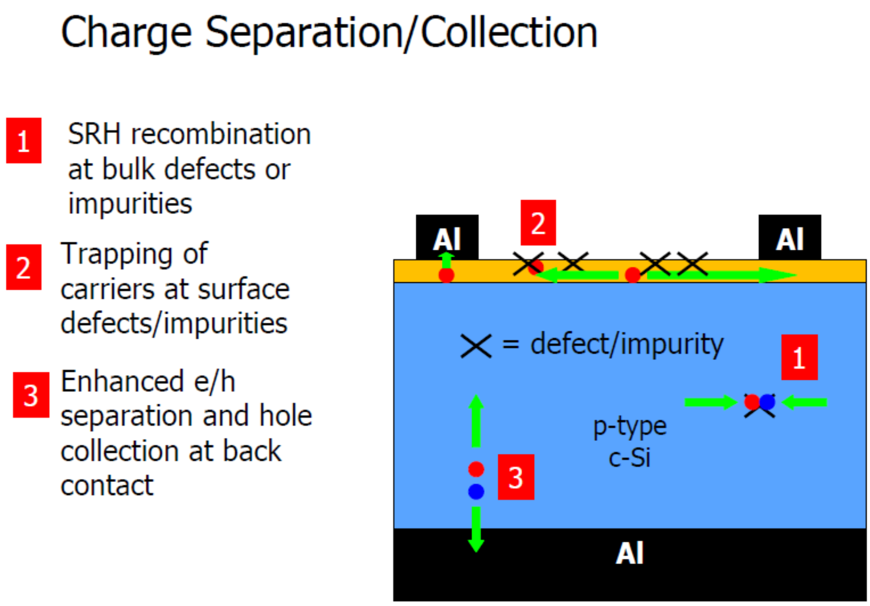
An Auger Recombination involves three carriers. An electron and a hole recombine, but rather than emitting the energy as heat or as a photon, the energy is given to a third carrier, an electron in the conduction band. This electron then thermalizes back down to the conduction band edge.

Auger recombination is most important in heavily doped or heavily excited material.

Diffusion Length

If the number of minority carriers is increased above that at equilibrium by some transient external excitation, the excess minority carrier will decay back to the equilibrium carrier contraction due to recombination processes. A critical parameter in a solar cell is the rate at which recombination occurs. Such a process, known as the "recombination rate" depends on the number of excess minority carriers. If for example, there are no excess minority carriers, then the recombination rate must be zero. The "minority carrier lifetime" of a material, denoted by tn or tp, is the average time which a carrier can spend in an excited state after electron-hole generation before it recombines. A related parameter, the "minority carrier diffusion length" is the average distance a carrier can move from point of generation until it recombines.

The minority carrier lifetime and the diffusion length depend strongly on the type and magnitude of recombination processes in the semiconductor. For many types of silicon solar cell, SRH recombination is the dominant recombination mechanism. The recombination rate will depend on the number of defects present in the material, so that as doping the semiconductor increases the defects in the solar cell, doping will also increase the rate of SRH recombination. In addition, since Auger recombination is more likely in heavily doped and excited material, the recombination process is itself enhanced as the doping increases. The method used to fabricate the semiconductor wafer and the processing also have a major impact on the diffusion length.



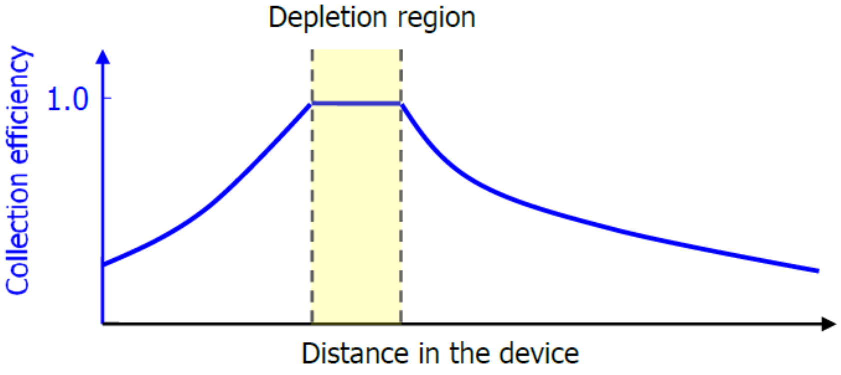
Charge Separation/Collection

1 SRH recombination at bulk defects or impurities

2 Trapping of carriers at surface defects/impurities

3 Enhanced e/h separation and hole collection at back contact

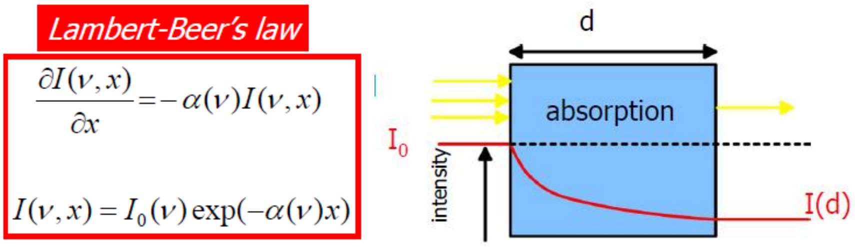
The distance in the device and the collection efficiency can now be plotted in a diagram to see where the most efficient collection takes place:



Light absorption

lambert-Beers law:

It states that the absorbing film with thickness d and absorption coefficient a(v) at frequency v is equal to:



Lambert-Beer's law

$$\frac{\partial I(\nu,x)}{\partial x} = -\alpha(\nu) I(\nu,x)$$

$$I(\nu,x) = I_0(\nu)\exp(-\alpha(\nu)x)$$

For that also the transmission and the absorption are given:

Transmission

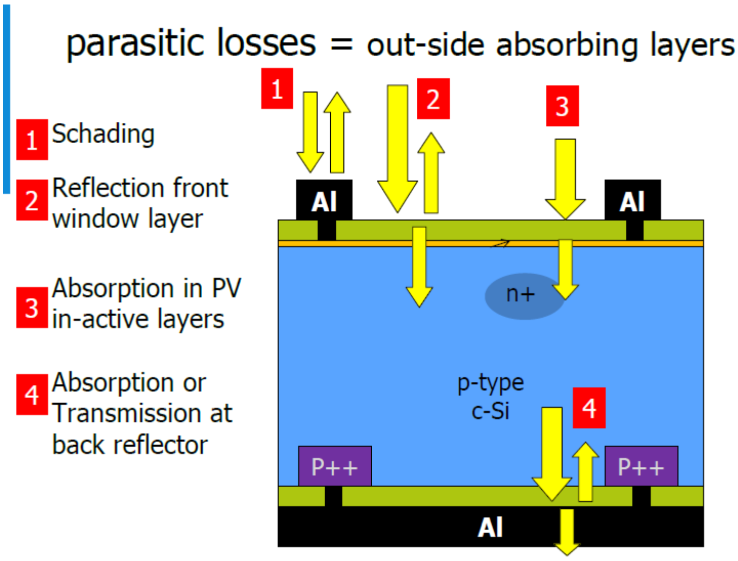
$$T(\nu)=\frac{I(\nu,d)}{I_0(\nu)}=\exp(-\alpha(\nu)d)$$

Absorption

$$A(\nu)=I_0(\nu)-I(\nu,d)=I_0(\nu)\left(1-\exp(-\alpha(\nu)d)\right)$$

$\alpha(\nu)$ expressed in cm^{-1}

The absorption length is given by $L=\frac{1}{\alpha(\nu)}$



parasitic losses = out-side absorbing layers

1 Schading

2 Reflection front window layer

3 Absorption in PV in-active layers

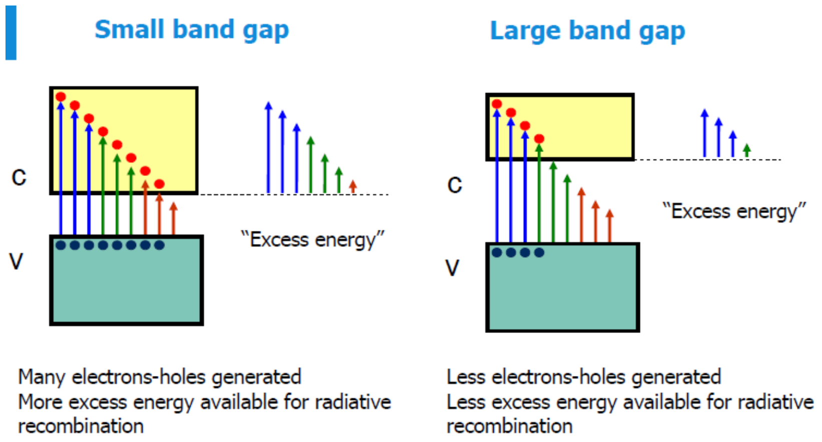
4 Absorption or Transmission at back reflector

An option to overcome the absorption length is to use a zig zag structure.

Spectral mismatch

Because of the AM 1.5G region only roughly 50 % of the sunlight can be used. Also light absorption can be done with the sceneraios: Photons incident on the surface of a semiconductor will be either reflected from the top surface, will be absorbed in the material or, failing either of the above two processes, will be transmitted through the material. For photovoltaic devices, reflection and transmission are typically considered loss mechanisms as photons which are not absorbed do not generate power. If the photon is absorbed it will raise an electron from the valence band to the conduction band. A key factor in determining if a photon is absorbed or transmitted is the energy of the photon. Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap.

If now one uses a thermodynamic approach one can see that energy is lost for a small and a large band gap:



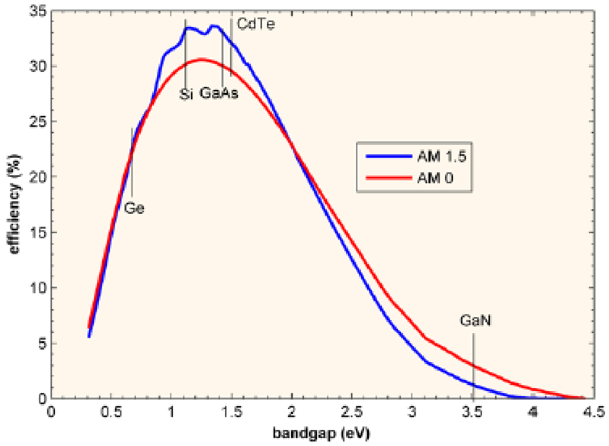
Small band gap

Large band gap

Many electrons-holes generated
More excess energy available for radiative recombination

Less electrons-holes generated
Less excess energy available for radiative recombination

From that it can be derived that only 50 % of the energy can be used which is known as the Schockley Queisser limit. The optimum occurs between a gap of 1 and 1.5 ev



Operation of solar cell: outdoors and characterization

Manufacturing and high efficiencies

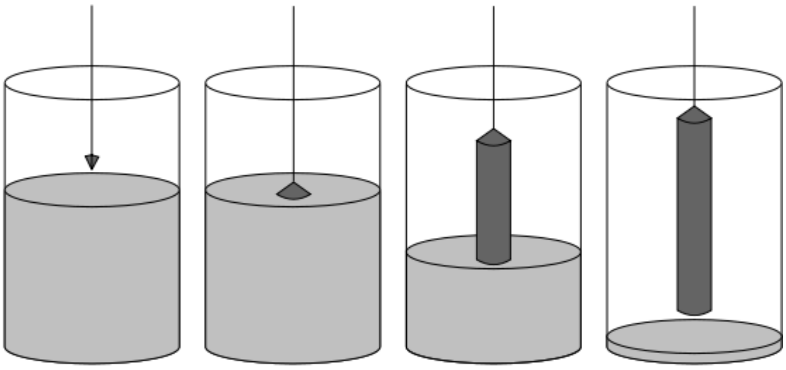
Processing of silicon and silicon solar cells

Solar cell material

The silicon is roughly 40 percent of the total cost of the solar module. Common materials that are used are mono crystalline, multi crystalline and amorphous silicon. The material has a cubic diamond structure and one can state that the main material used is the multi crystalline silicon.

Processing and refining

Silicon in its basic form is sand. In a furnace of roughly 1900 degrees Celsius the SiO2 is added with 2 C atoms leading to SI and 2 CO. This already gives a purity of roughly 98 %. This is however not enough, to further refine the metallurgical silicon the silicon is converted into compound and then this is converted back to pure silicon. Further refining can be done by using **czochralski casting** which first melts down the silicon in a crucible, then a seed crystal is dipped into the silicond, the slowly the seed is pulled upwards and rotated at the same time. This results in a large singly crystal ingot.



Czochralski casting

Another process is **zone float pulling** in which oxygen impurities reduce the minority carriers lifetime. The impurities stay in the molten region, thereby purifying the material.

Also multi crystalline ingot casting can be used in which crucibles are are filled with silicon and the required dpoants (boron), the molten silicon is slowly cooled down to get large grain.

Another highly effective method is silicon ribbon in which a temperature resistand wire is pulled through a crucible of molten silicon, however this leads to more defects.

Description	Symbol	Grain Size	Common Growth Techniques
Single crystal	Sc-Si	>10cm	Czochralski Float zone
Multicrystalline	mc-Si	1mm – 10cm	Cast Sheet Ribbon
Polycrystalline	pc-Si	1μ – 1mm	Chemical vapour deposition
Microcrystalline	μc-Si	<1 μm	Plasma deposition

Cutting of material

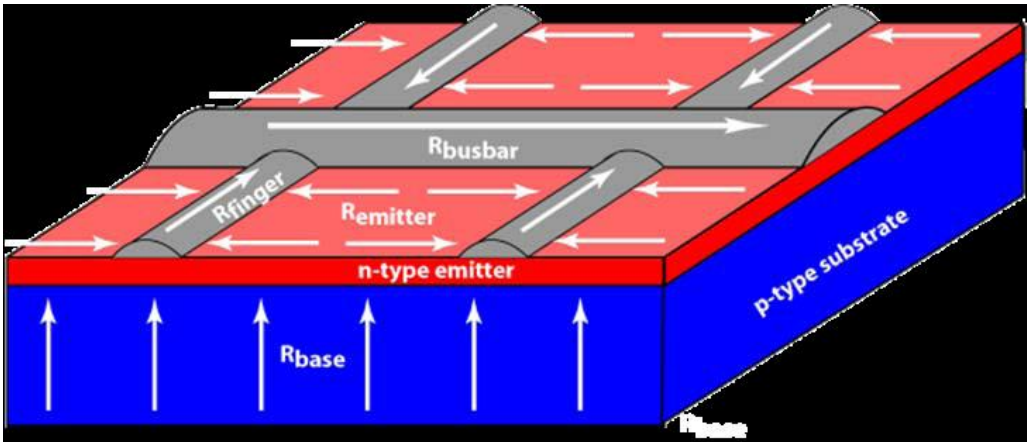
After the material has been purified it needs to be cut. One method is using wire cutting in which the brick is cut into wafers. Afterwards the damage from the cutting is removed by a hot solution of sodium hydroxide which removes surface contamination and the first 10 μm

Wafers

The wafers are usually doped with boron or a solid state diffusion for p-type doping. For N-type doping the emitter layer is formed through phosphorous doping by solid state diffusion from gas phase. Afterwards the edge isolation process removes diffusion around the edge of the cell so that from emitter is electrically isolated from the rear of the cell. Afterwards the edges are isolated so that the front emitter is electrically isolated.

Metallisation

Next to the wafers the metal contacts needs to be placed on the solar cell. The current flows perpendicular to the cell surface and from the bulk of the cell through the top doped layer to the top of the surface.



Afterwards the contact collects the current. The busbars collect the current from the fingers and delivers it to the outside. It is necessary to minimize the finger and busbar resistance, furthermore the overall losses are due to resistive losses and shading losses. Critical features to overcome those losses are finger and busbar spacing, metal height to width ratio, minimum metal line width and the resistivity of the metal.

The c-Si solar module

A PV module consists of a module of number of interconnected solar cells.A set of solar cells that is connected in series is referred to as string. When the solar cells are connected in series, the voltages add up otherwise if connected in parallel the currents add up. The equation for the circuit becomes:

$$I_T = M \cdot I_L - M \cdot I_0 \left[\exp\left(\frac{q \frac{V_T}{N}}{nkT} \right) - 1 \right]$$

In which:

N is the number of cells in series;
M is the number of cells in parallel;
IT is the total current from the circuit;
VT is the total voltage from the circuit;
I0 is the saturation current from a single solar cell;
IL is the short-circuit current from a single solar cell;
n is the ideality factor of a single solar cell

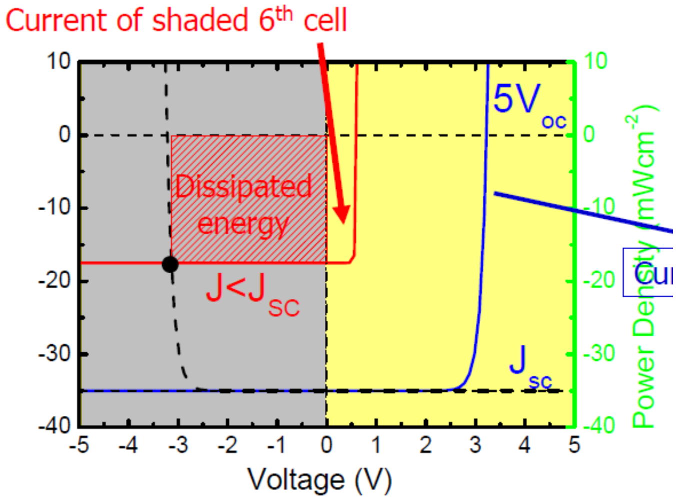
For the entire PV modules it can be stated that:

- STC conditions are rare during operation

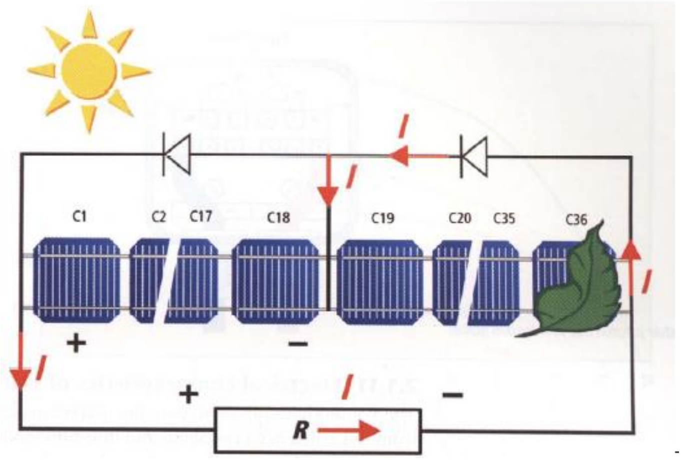
- Current is proportional to irradiance
- Voltage is affected by temperature
- Lower voltage in summer, higher voltage in winter
- Important during sizing (winter – high voltages)
- Power reduction in summer (35 %) => ventilation
- Temperature coefficients have to be specified

Shading

Shading can lead to the point where a cell turns into a load, it reverses the current and induces hot spods which can damage the material.



The solution for that is are bypass diodes:



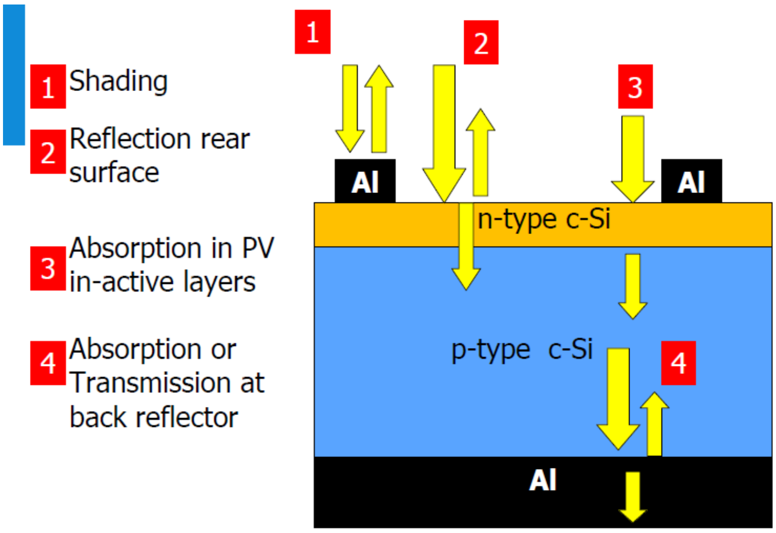
Encapsulation

Through encapsulation material damage is prevented and also water or vapour is stopped from corroding.

Increasing the absorption in c-Si solar cells

Reduction of losses in carrier transport and separation

The main losses are due to shading, reflection rear surface, absorption in PC in active layers and absorption or transmission at back reflector.



The reflection front surface is given by $Rs = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$. However when a transparent film with $n1 = \sqrt{n_0 n_s}$between media with n0 and ns is put on it reduces the reflection with approximately a half. Also when a film with optical thickness $n1d = 0.25\lambda$between n0 and ns will cancel out the reflected intensity due to destructive interference. Furthermore through a textured surface less light is reflected.

Shading by contacts

The next thing we are about to discuss is how to reduce the reflection on the metal.

This is a 3D picture of solar cells we can see p-type c-Si, n-type c-Si antireflection coating, contact on the both side. L is the length of the contact. This picture shows the cross-section of the contact. W is the width, H is the hight.

Light hitting on the metal won’t contribute to absorption in the semiconductor. So clearly reduce the coverage of metal will be helpful. In our case, it is to decrease W, nomally L is constant, in order to decrease the area where metal contact cover the surface. But we know resistance of this contact is calculated by this formula so if W decrease then R will increase. This is bad for the solar cells. How to compromise those two opposite effects is an artist’s work.

The equation for the resistance is: $R = \rho \frac{L}{WH}$.

Another important aspect is the improve the aspect ration W/H. This leads to a decrease in losses as depicted in the diagram below:

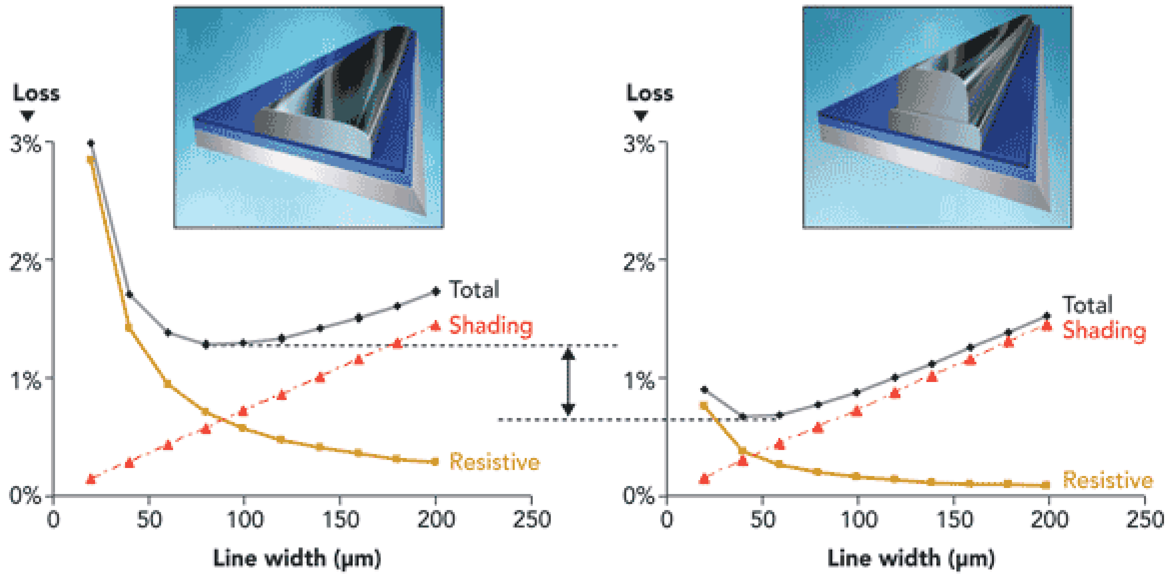


Figure 4. Esatto technology for double printed contact lines can increase absolute cell efficiency by 0.5% (experimental values may vary with a range of 0.3-0.5%).

Furthermore grooves can be used in which the contacts are buried in the solar cells. Lastly the point contacts can be situated at the back of the solar cell.

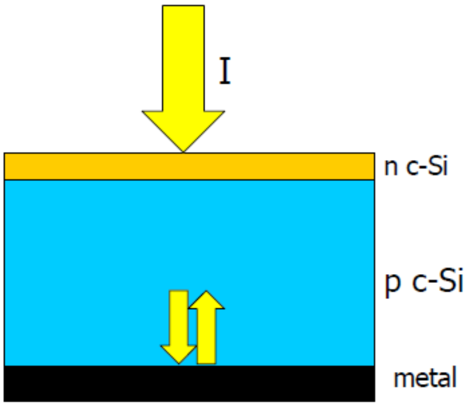
Preventing transmission of light rear surface

We have already discussed about how to reduce reflection on the interface between semiconductor and air and how to reduce front metal contact coverage. To increase the light absorption and increase e/h generation, we still need to reduce the transmission loss.

The simplest method is to increase absorber thickness. Certainly, the thicker the absorber is, more light will be absorbed. According to measurement, 1mm thick c-Si will absorb all the light. Why we normally use 300~500micrometer thicker wafer. Of coursely, material will be saved. If we neglect cost issue, will the thicker wafer benefit the current or efficiency.

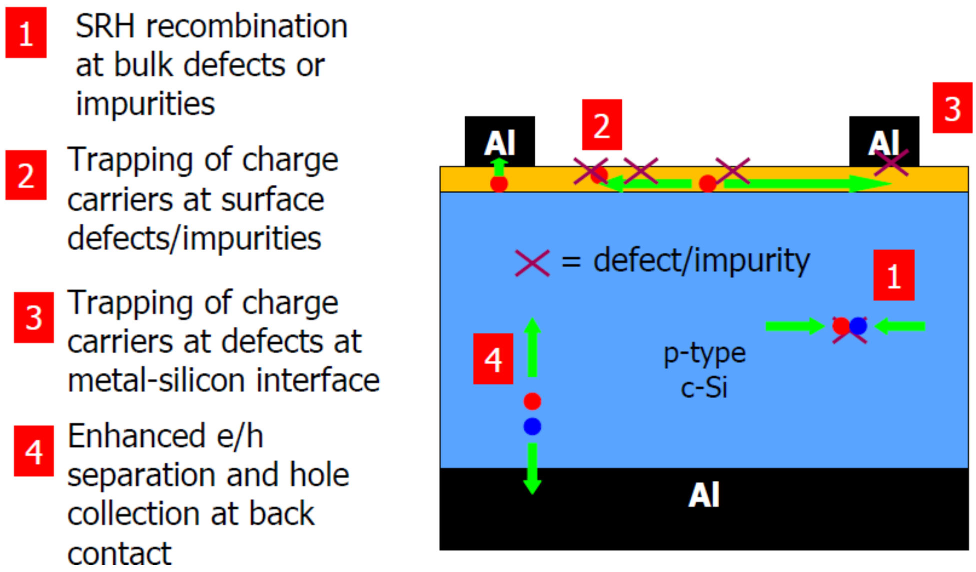
Increasing the thickness of wafer is aiming to increase the path length which light travels inside the c-Si. but that is not the only solution, we can increase the path by manipulating the light traveling.

One method is to use back reflection. If we back reflection is 100%, it is equivalent to double the thickness of wafer.



When decreasing the thickness of the material it is necessary to use an appropriate light management within the solar cell. The absorption path length can be increased by scattering the texture at the front surface.

The losses in charge collection can be summarized as followed:



1 SRH recombination at bulk defects or impurities

2 Trapping of charge carriers at surface defects/impurities

3 Trapping of charge carriers at defects at metal-silicon interface

4 Enhanced e/h separation and hole collection at back contact

Loss in charge collection and speartion.

1. Defects and impurities in silicon bulk can be overcome by improving the material quality.
2. Defecs and impurities in silicon surface can be overcome by optimizing the surface condition
3. Defects in silicon-metal interface can be solved by reducing the area of metal contact

Reduction of bulk defects

In reality, crystalline structure can not be perfect. There always are some defects. There are three kinds of defects. Point defects: vacancy: some atoms are missing. Or some impurity will be inserted to the crystalline structure. Some small atoms are squeezed into space between atoms. Some large impurity could replace some atoms.
Linear defect: a line of atoms are missing here. Planar defects: atomic arrangement is suddenly changed from different parts. All defects can serve a trap for recombination

Reduction of surface defects

Only using high quality material is not enough. We still need to consider the surface of material because the surface has different properties from the inside bulk.
At first, the surface contacts with environment, also during processes, inevitably, it is very easy to get some dirt on the surface. Secondly, every atom inside the bulk is surrounded by the same atom. But on the surface, atom at least on one side, there are no atoms , so the atom is not satisfied so there are a lot of dangling bond which is not conneted to other atoms. What we normally do is to grow a layer on both side of wafer. This layer will saturate those dangling bonds to prevent recombination.
2. Conventionally SiO2 is thermally formed on very high temperature.this layer could also be SiNx sometime.

Reduction of defects at metal-silicon interface

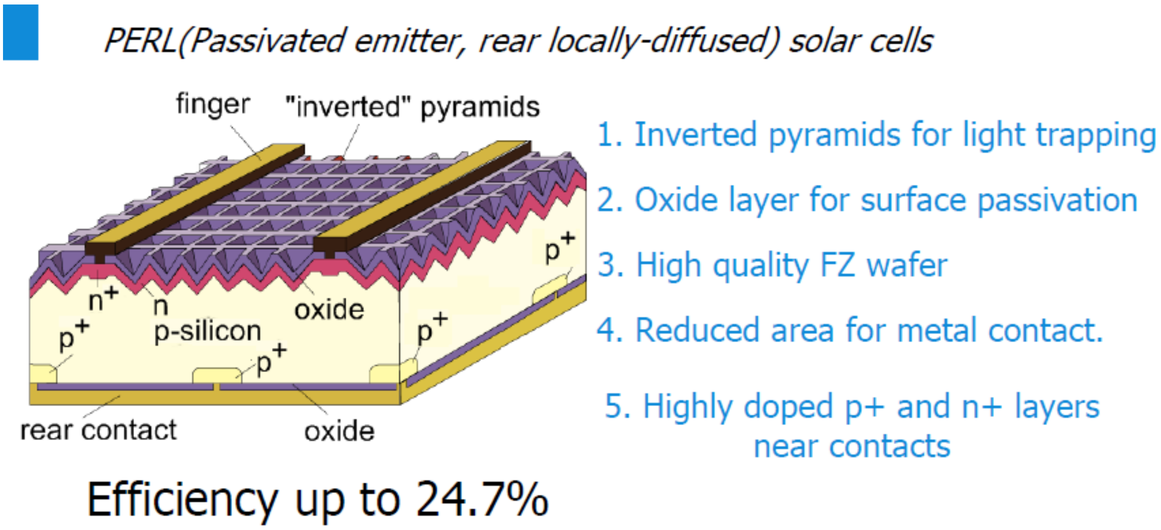
In the area where the metal contact with semiconductor, electron also get lost easily since when two material contact to each other, they can never bond to each other perfectly.
So we use this design, we make the contact area smaller , but make this part biger to keep low resistance.
Enhanced e/h separation and hole collection at back contact

This approach to reduce the e/h loss is not directly related to traps.
The electrostatic field created by pn juntion is only hundreds of nanometer thick around the pn junction interface. But the wafer is about hundreds of micrometer thickness. So most of e/h do not feel that electrostatic field, they just move around randomly. Some are lucky, they reach the pn junction interface and they get seperated and cellected. But some maybe move to the oppsite dirrection, they are just very stupid.
E.g. electrons here. They are supposed to move upwards but some of them are move downwards. What will happen to those who are moving downwards. In bottom here there are full of holes. Electron wll recombine easily here.
The solution is to put anther electrostatic field to seperate e/h pair, the field has a special name back surface field.

Reduction of series resistance

High efficient solar cells

Examples of high efficiency c-Si solar cells are the PERL solar cells and the Swanson solar cell.



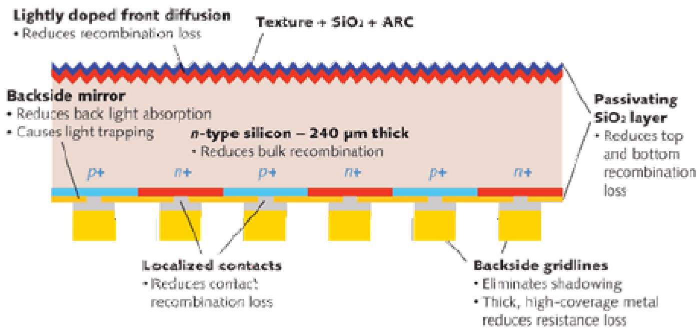
PERL(Passivated emitter, rear locally-diffused) solar cells

1. Inverted pyramids for light trapping
2. Oxide layer for surface passivation
3. High quality FZ wafer
4. Reduced area for metal contact.
5. Highly doped p+ and n+ layers near contacts

Efficiency up to 24.7%

Swanson (Sunpower Corp. USA): record c-Si solar cells

Point contact solar cells



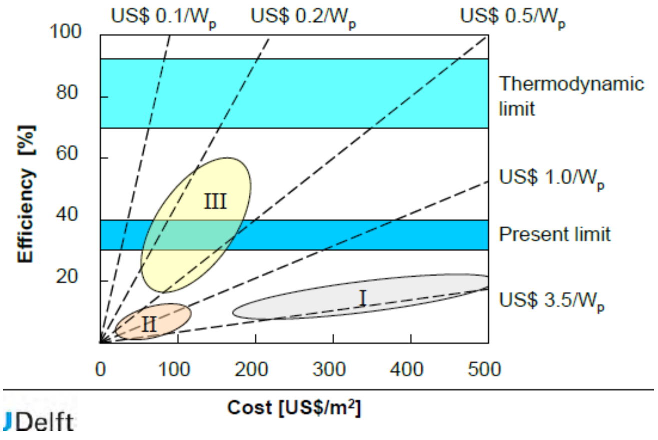
Efficiency up to 24.2 %

1. Texture for light trapping
2. Oxide layer for surface passivatio
3. Back contacts: prevents shading
4. Localized contacts: reduction recombination loss
5. n-type c-Si: higher lifetimes for holes: longer diffusion lengths.

2nd Generation technology: Thin silicon film solar cells

The PV technologies

There are three generation of solar cells. On a diagram which measures efficiency as a function of cost one can clearly see where those 3 generations are situated:

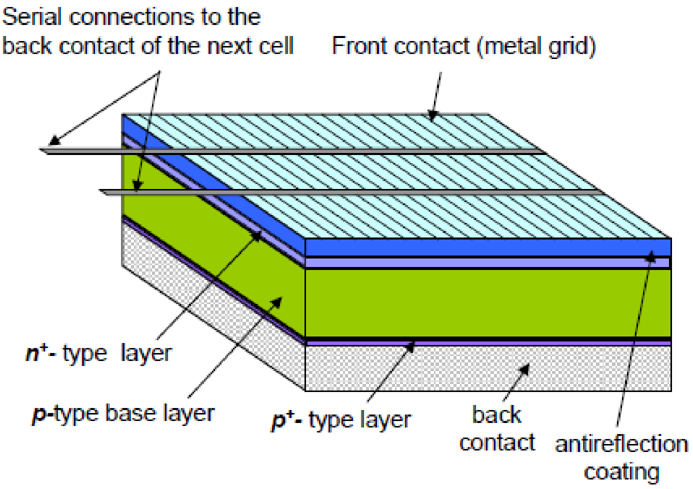


The slope of the graph gives the Wp per $, meaning the the inverse slope gives $ per Wp

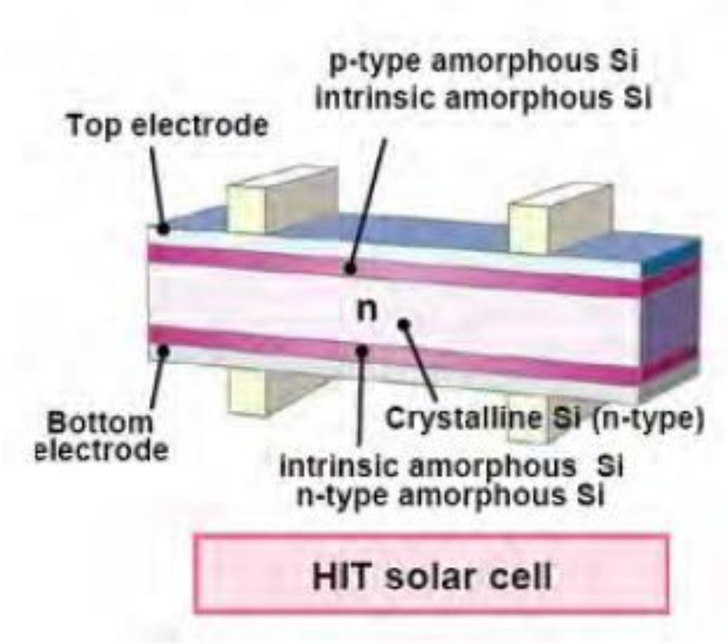
1st generation

The first generation of solar cells consists of high quality materials with high production cost and relative high efficiencies

Bulk c-Si modules with efficiencies of 17% consist of:



Hetero-junction based on c-Si module have roughly 18 % efficiency and is composed of thin single crystalline SI wafer sandwiched by ultra thin a-SI layers:



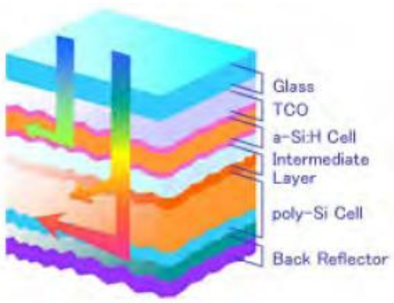
2nd generation: thin film solar cells, high efficient solar cells

The second generation consists of lower efficiencies but has far lower production costs.

Thin-film solar cells

Thin film solar cells can be made from silicon thin films, II-IV compounds, II-IV-VI compounds, thin film crystalline or organic solar cells. Various options are:

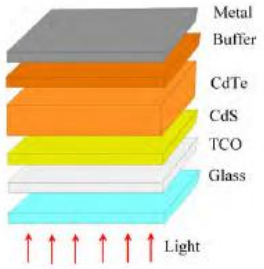
Si:H (η~9%)



CIGS (η~11%)

$Cu(In,Ga)(S,Se)_2$

CdTe (η~10%)



Besides those rigid options it is possible to have DSSC – Die Sensitized Solar cells with efficiencies of roughly 6 %

3rd generation: new concepts

The third generation consists of low production costs and new concepts with higher efficiencies.

Noval concepts

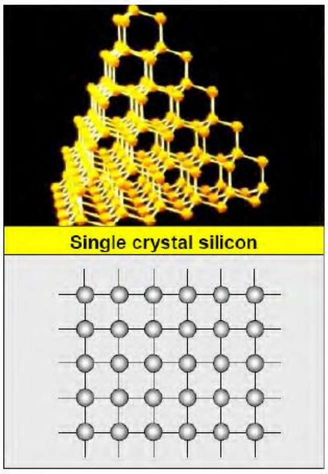
Some of the new concepts for cheap and efficient solar cells are:

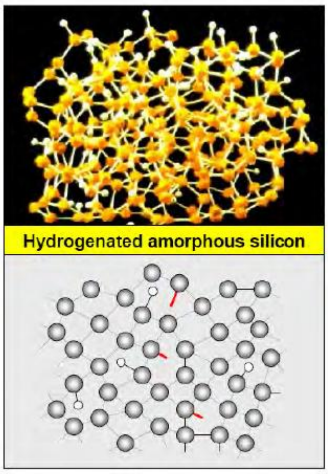
- Up and down conversion
- Intermediate band
- Hot carriers
- Superlattices
- Quantum dots
- Nanotubes

Thin silicon solar cells

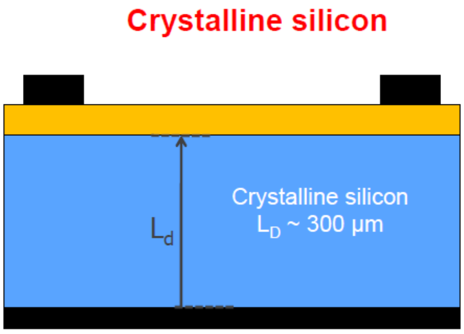
The a-Si:H solar cell

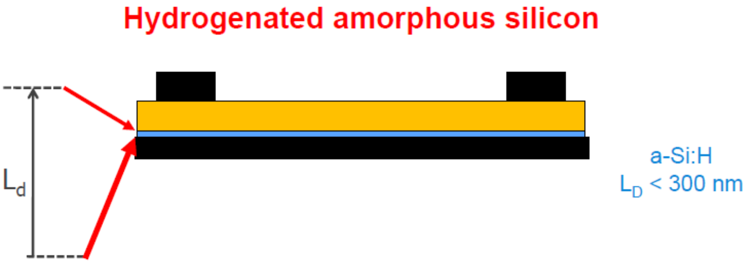
The A-SI or amorphous silicon has a different lattice structure than a single C-SI:



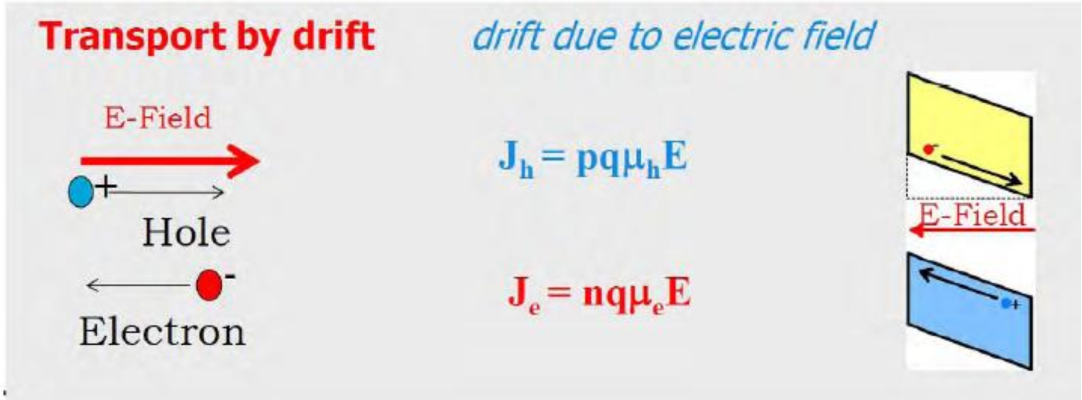


The **hydrogenated amorphous silicon** has an active material. The semiconductor has a direct band gap. The band gap varies between 1.6 and 1.9 eV. The electron and hole diffusion length is small than c-Si material (100-300 nm). In terms of optical properties it can be stated the in the visible part of spectrum a-Si:H is 70 times higher tan c-Si and thin film absorb 90 % of usable solar energy:





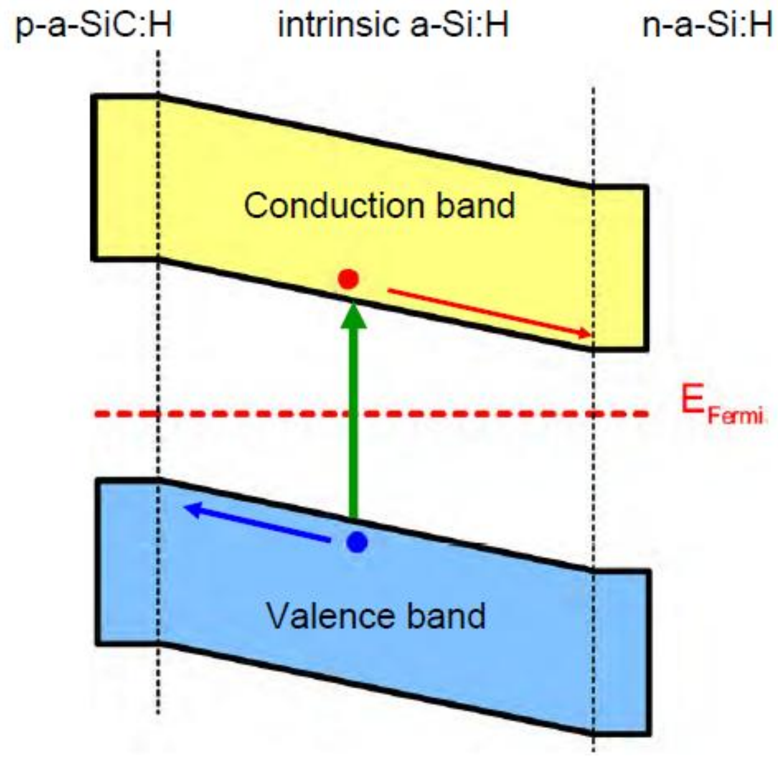
The Length sales of absorption path length and diffusion length are not competitive. The charge carrier transport can only be established by means of **drift**.

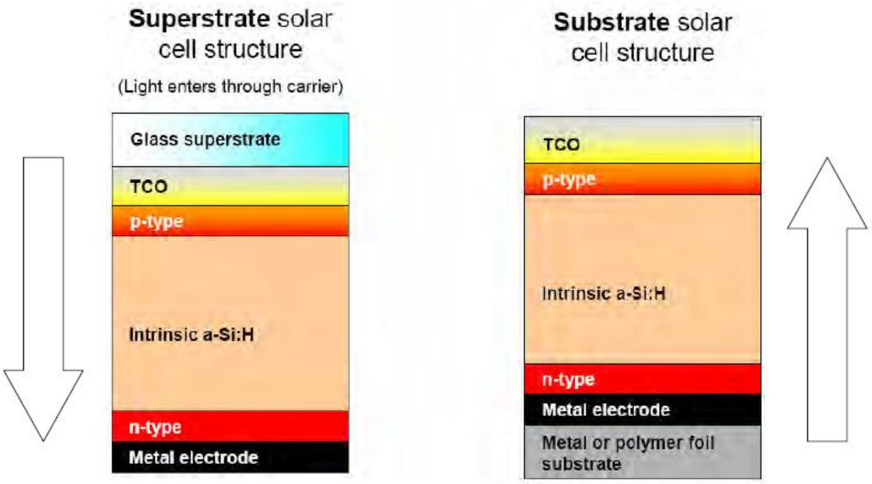


In principal an intrinsic layer o a Si:H (200-300mm) is sandwiched between a thin boron doped p-layer (6-10nm) a-SiC:H and a thin phosphorous doped n-ayer a-Si:H (20-40nm). Light absorption creates electrons and holes in the intrinsic film. (Note, no majority and minority carriers)

The build in field caused by the p and n layer separates the holes and electrons via electrical drift. The holes drift to the p-layer and the electrons drift to the n-layer.

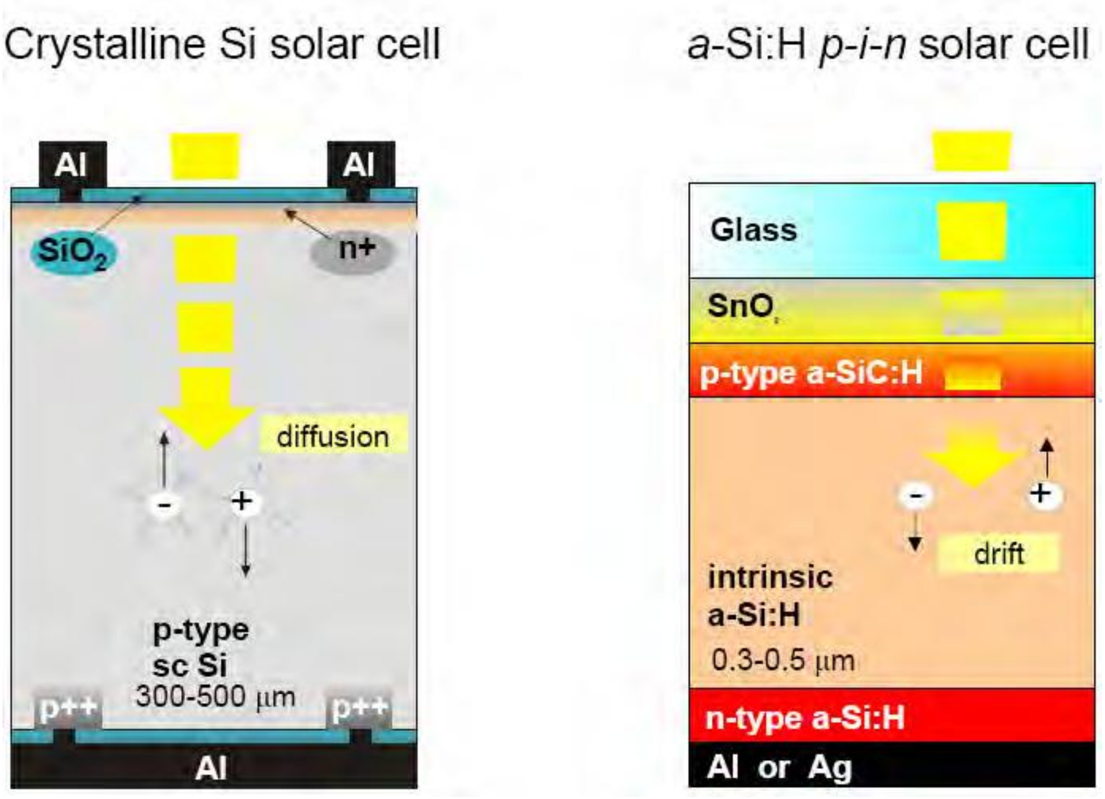
In the p-layer and n-layer the holes and electrons are respectively the majority carriers and diffusion is the dominant transport mechanism Drift versus diffusion device. This creates a high internal electric field.

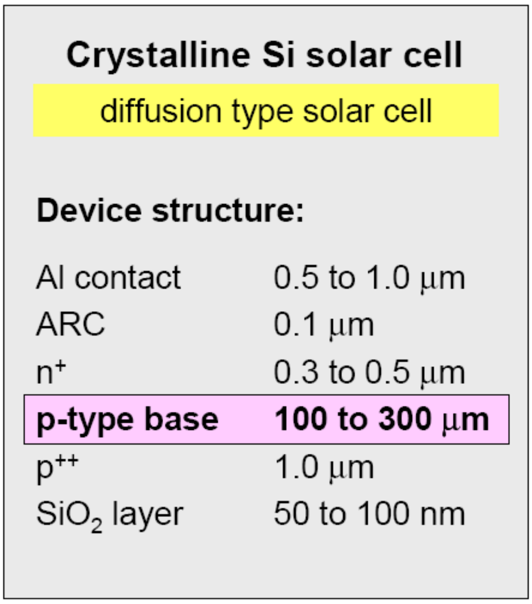




Superstrate solar cell structure (Light enters through carrier	Substrate solar cell structure
-High quality top TCO electrode which is deposited at 550 C +carriers must withstand high temperature	-lower quality top TCO electrode which is deposited at T = 200 C + use of flexible carriers (roll to roll process)

Comparison with c-Si: structure



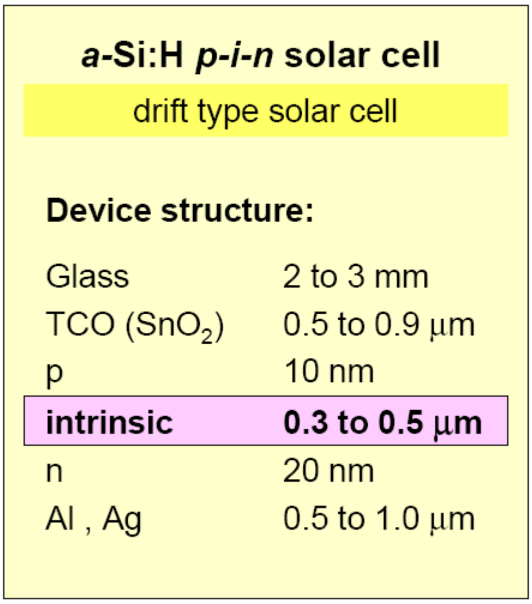


Crystalline Si solar cell

diffusion type solar cell

Device structure:

Al contact	0.5 to 1.0 µm
ARC	0.1 µm
n^+	0.3 to 0.5 µm
p-type base	**100 to 300 µm**
p^{++}	1.0 µm
SiO_2 layer	50 to 100 nm



***a*-Si:H *p-i-n* solar cell**

drift type solar cell

Device structure:

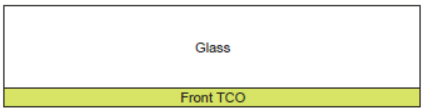
Glass	2 to 3 mm
TCO (SnO_2)	0.5 to 0.9 µm
p	10 nm
intrinsic	**0.3 to 0.5 µm**
n	20 nm
Al , Ag	0.5 to 1.0 µm

Processing cell

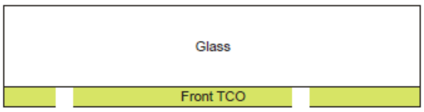
Processing module

1. Glass plates used as substrate carrier

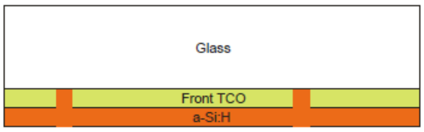
2. Front TCO deposition



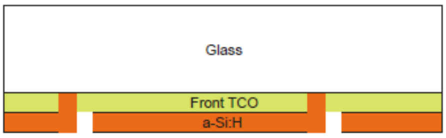
3. Laser scribing: L1



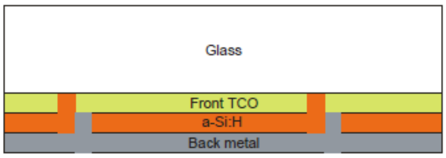
4. Si:H layers deposition



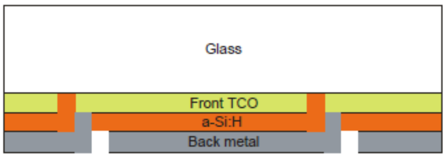
5. Laser scribing: L2



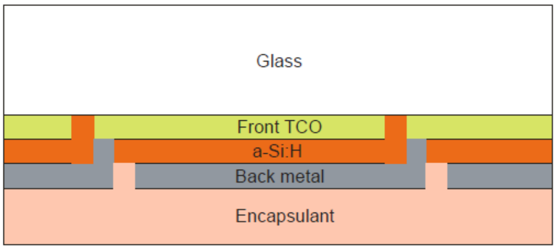
6. Back metal deposition

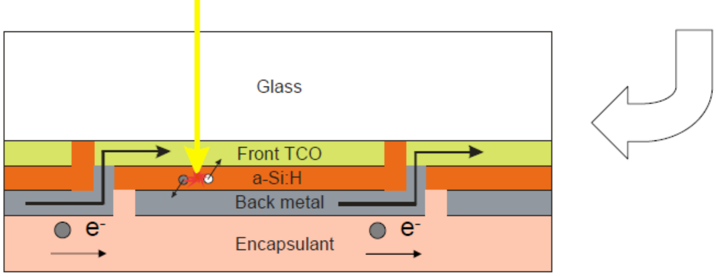


7. Laser scribing: L3



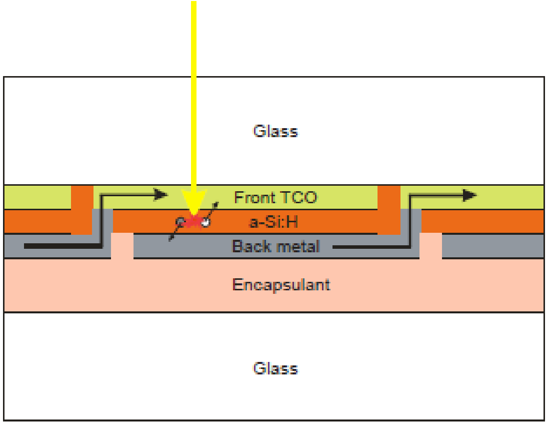
8. Encapsulant





Here we can see quite some difference compared to the c-SI modules which are connected in individual cells.

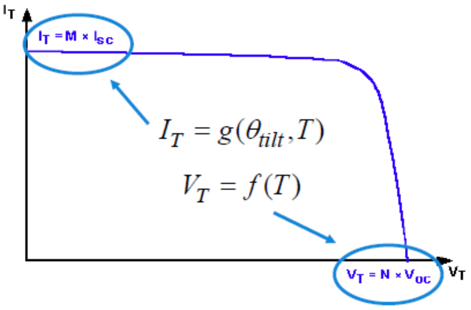
9. Second glass



Many solar cells deposited at once and laser-scribed in series.

The IV curve

$$I_T = M \cdot I_{SC} - M \cdot I_0 \left\{ \exp\left[\frac{q(V_T / N)}{nkT} \right] - 1 \right\}$$



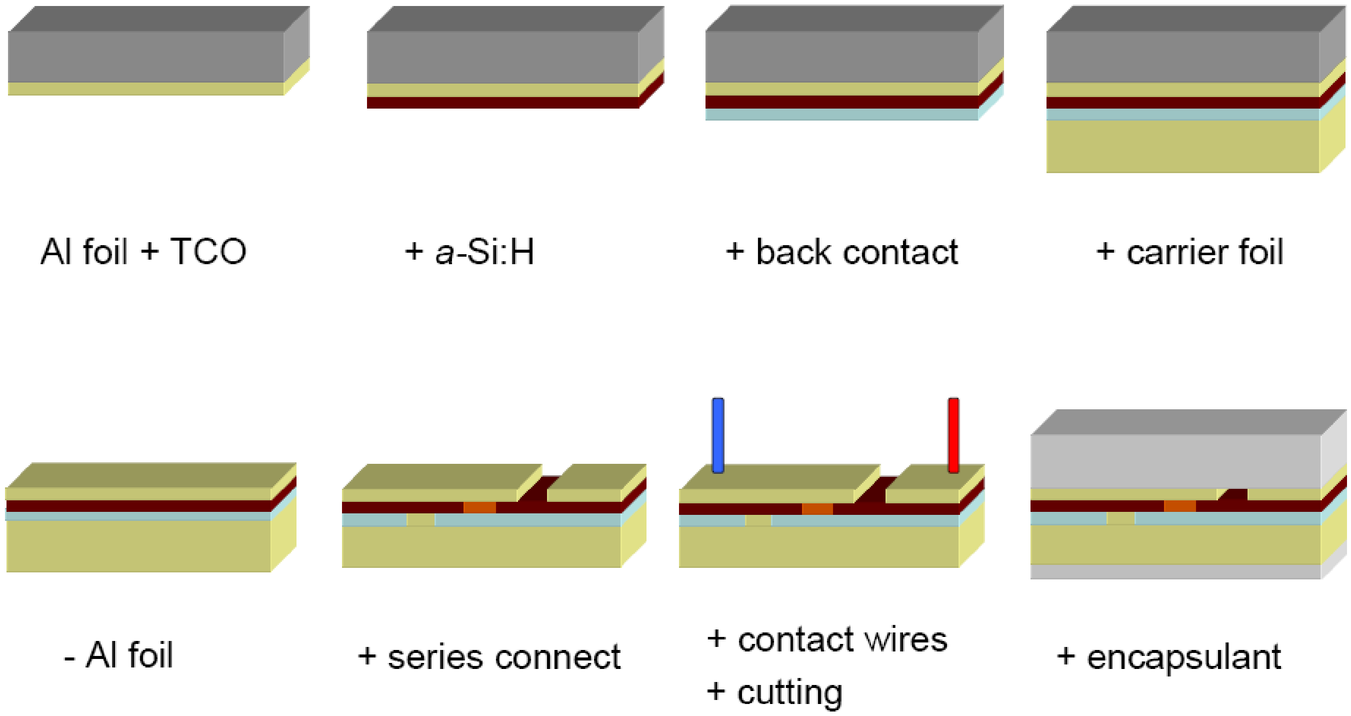
where
- **N** = number of cells in series
- **M** = number of cells in parallel
- $\mathbf{I_T}$ = the total current from the circuit
- $\mathbf{V_T}$ = total voltage from the circuit
- $\mathbf{I_0}$ = saturation current from a single solar cell
- $\mathbf{I_{SC}}$ = the short-circuit current from a single solar cell
- **n** = the ideality factor of a single solar cell

and **q**, **k**, and **T** are constants

How can the cost be reduced?

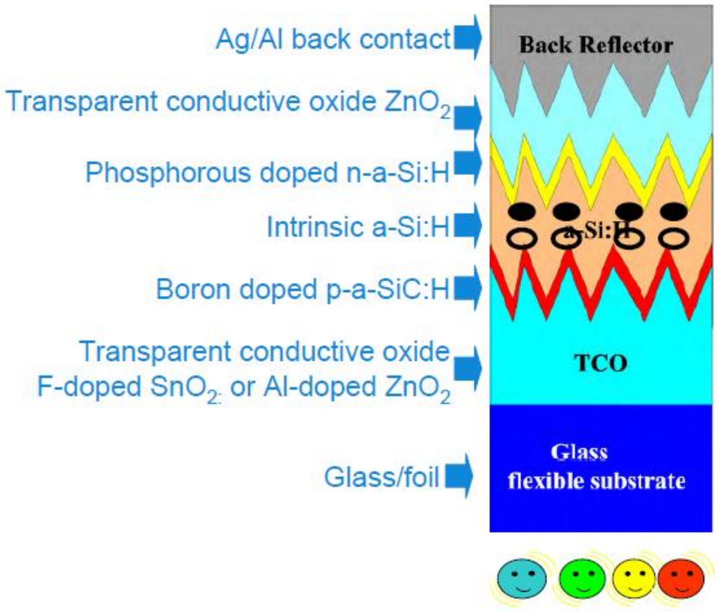
- Roll-to-roll deposition technology - foil substrate
- Scale of production (1.30 m foil width, >106 m2/year)
- Amorphous and/or thin-film silicon active layers
- Proprietary manufacturing process
- Applications development with partners

What is the manufacturing sequence:



Important issues in increasing the efficiency of thin cells

Lets start looking at the a-Si:H p-i-n junction:

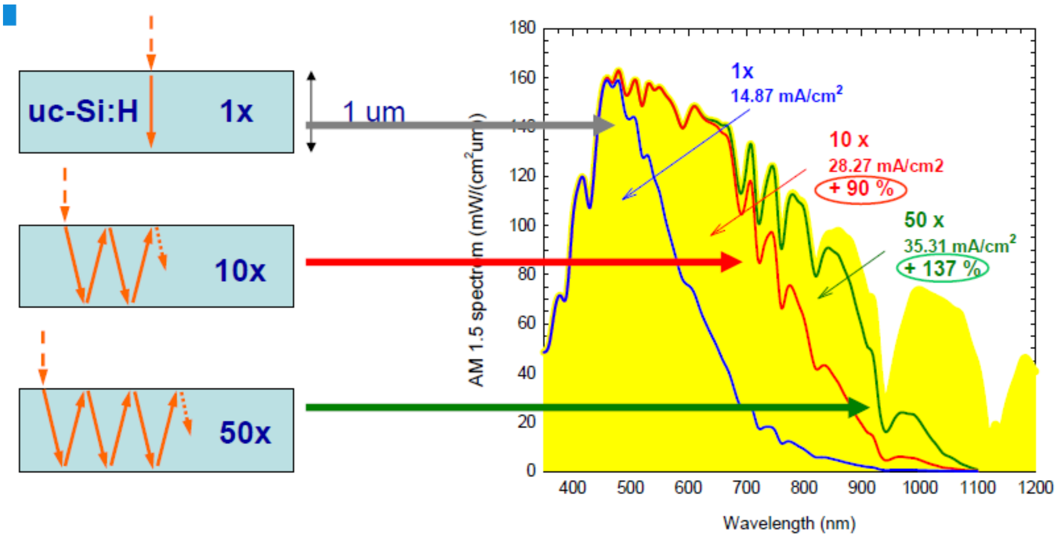


Now lets think about methods to increase the efficiency to about 15 %.

Spectrum matching / multi-junctions

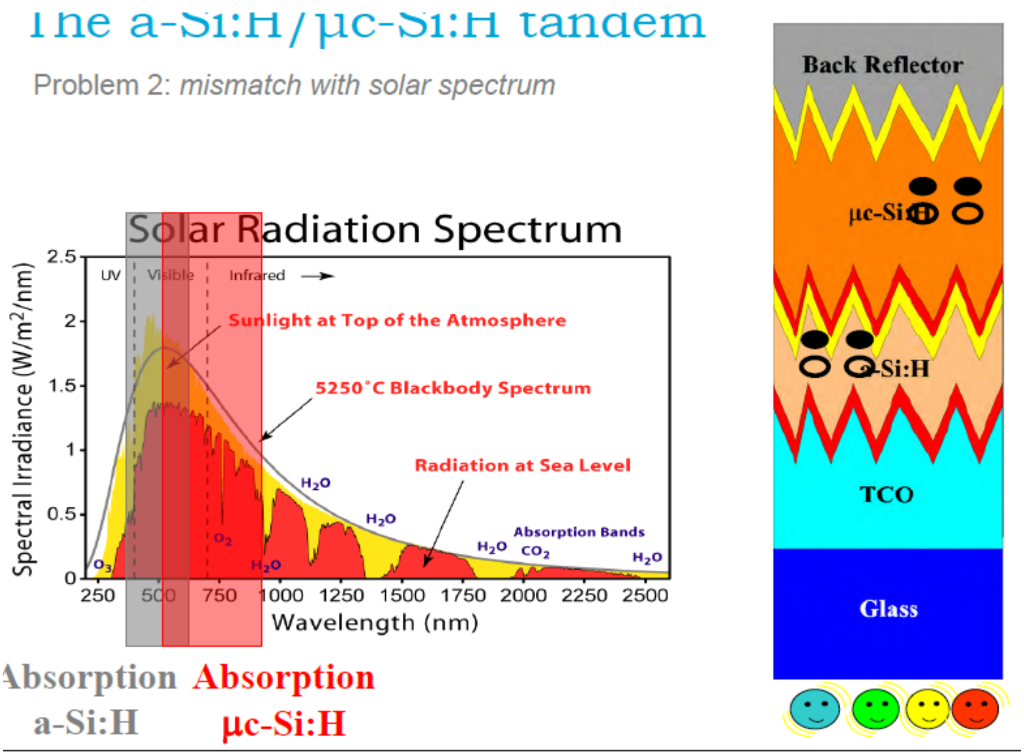
Problem 3: light confinement

With thin films the absorption path length is too short for red and blue spectrum. The answer to that is confinement of photons, which means increasing the absorption path length using light trapping. Now what is the result of light trapping:



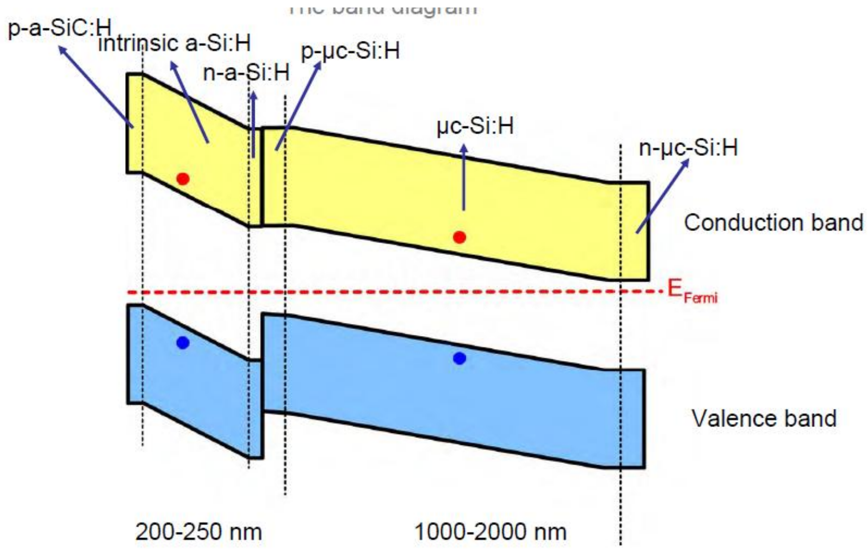
Problem 2: mismatch single junction with solar spectrum

A single junction would not cover the entire spectrum. Therefore a-Si:H and uc-Si:H are used which cover a far broader area of the spectrum:

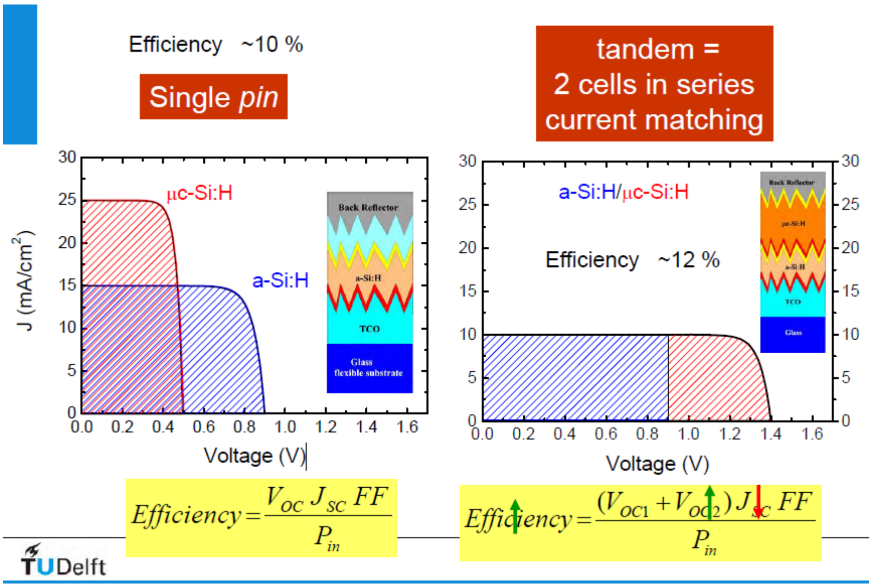

The a-Si:H/µc-Si:H tandem

Problem 2: *mismatch with solar spectrum*

The tandem band diagram:



Comparison of Single pin and tandem:


Efficiency ~10 %

Single *pin*

tandem =
2 cells in series
current matching

Efficiency ~12 %

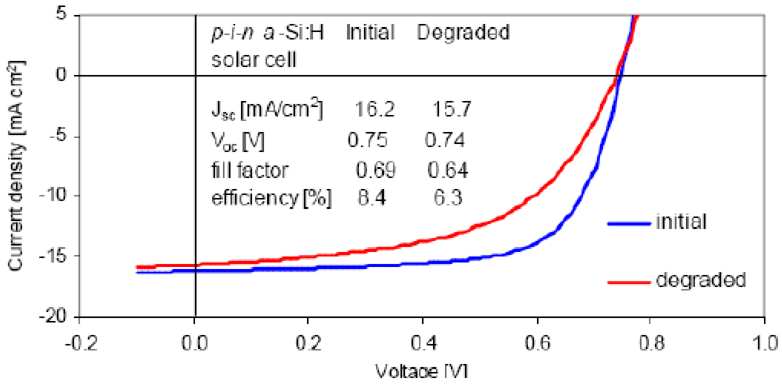
$$\text{Efficiency} = \frac{V_{OC}\, J_{SC}\, FF}{P_{in}}$$

$$\text{Effi}{\uparrow}\text{ciency} = \frac{(V_{OC1} + V_{OC2}{\uparrow})\, J_{SC}{\downarrow}\, FF}{P_{in}}$$

Stability a-Si:H

Problem 1: instability a-Si-H film

During exposure to light, additional defects are created in the a-Si H. Also an enhanced Shockley-reed hall recombination of charge carriers occurs then. The plot below shows the initial verses stabilized efficiency:



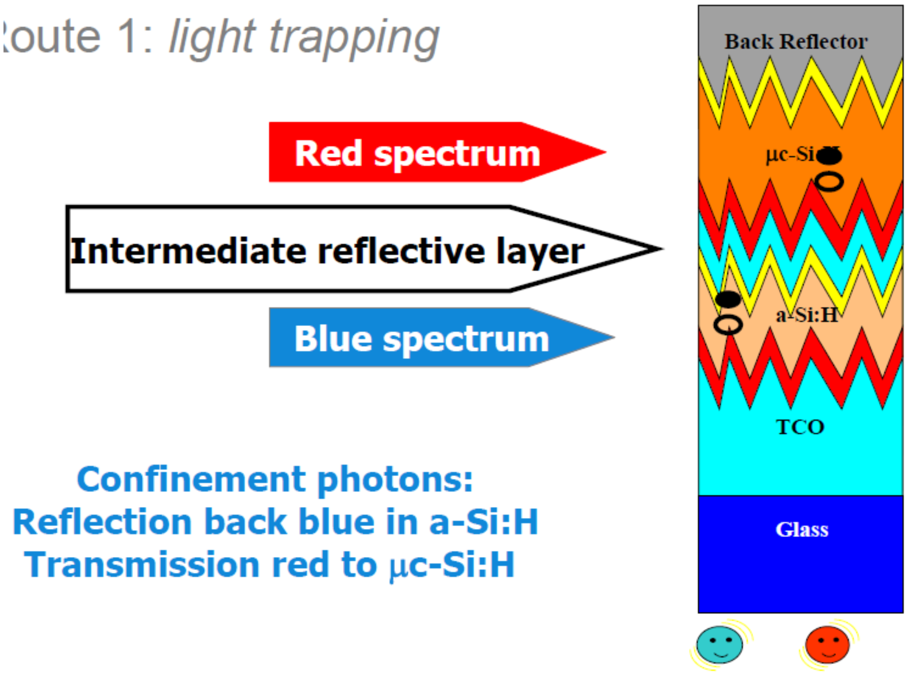
Also once can conclude that the thicker the a-Si:H layer is the higher is the degradation of performance from the initial state. After roughly 1000 hours of light soaking a-Si:H based solar cells start exhibit constant behavior.

Light management

Now lets think about various method that can be used in order to increase the efficiency:

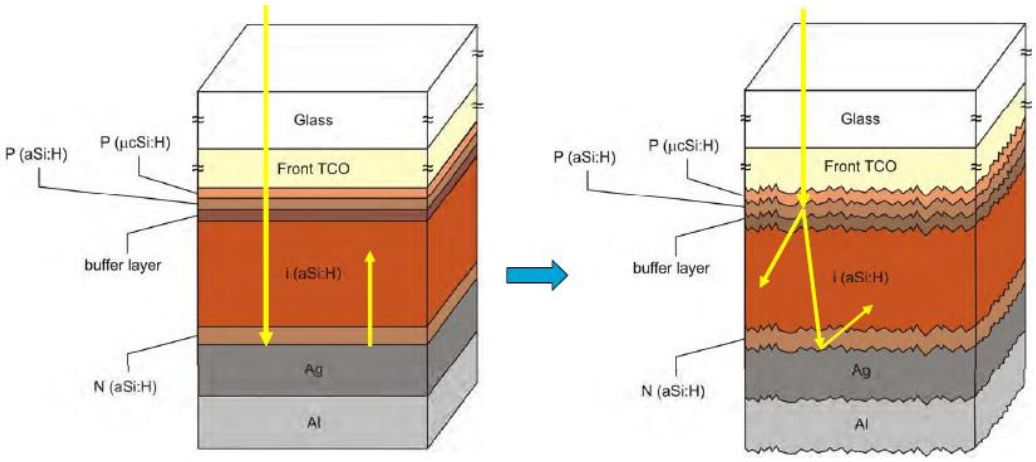
Route 1: Light trapping:

Through an intermediate reflective layer the photons are are trapped in the cell:



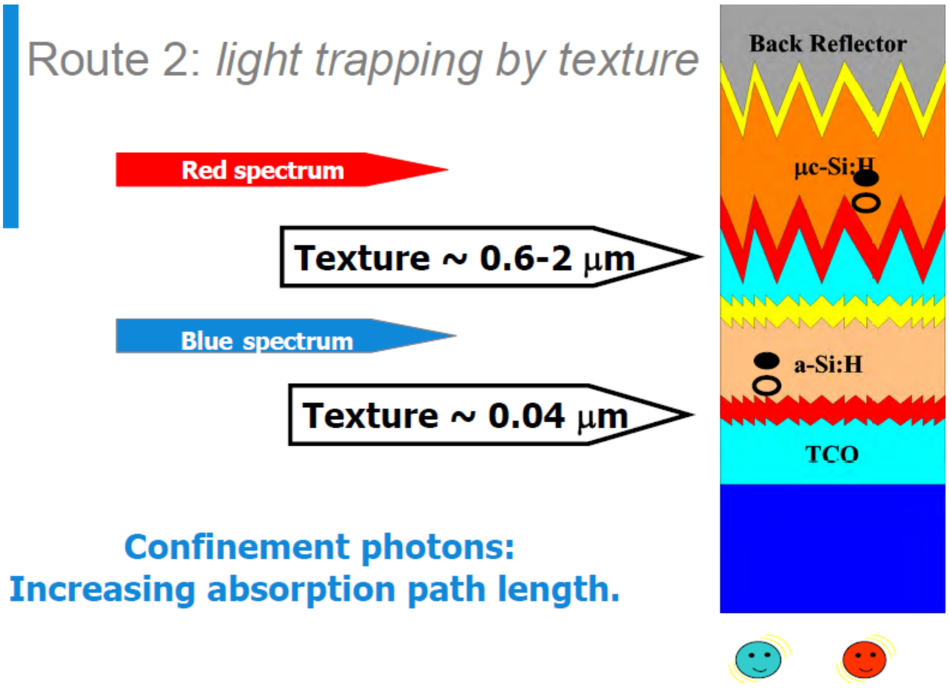
Confinement photons:
Reflection back blue in a-Si:H
Transmission red to μc-Si:H

This layer increases the photo current in a-Si:H cell and thinner films can be processed. It also enhances the stability of the cell. This is done via scattering at textured interfaces:



Route 2: selective light scattering

For red and blue scattering one can use Rayleight and Mie scattering. Rayleight scatters blue light with particles << then the wavelength and Mie scatters particles which are roughly the same wavelength.



Route 2: *light trapping by texture*

Red spectrum

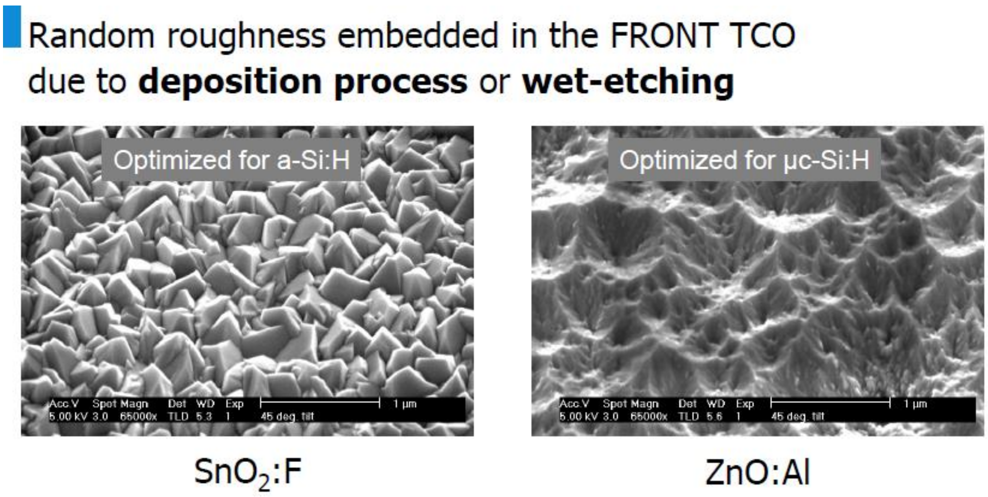
Texture ~ 0.6-2 μm

Blue spectrum

Texture ~ 0.04 μm

Confinement photons:
Increasing absorption path length.

Random roughness can be embedded in the FRONT TCO due to deposition process or wet-etching:

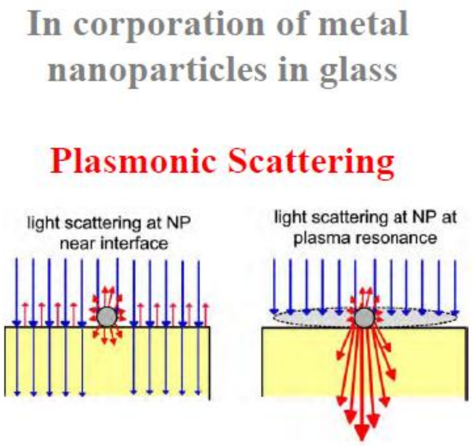


Random roughness embedded in the FRONT TCO due to **deposition process** or **wet-etching**

$SnO_2:F$ $ZnO:Al$

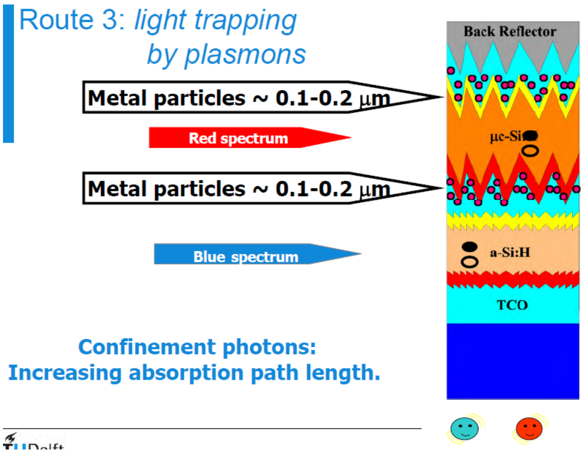
Route 3: selective light scattering.

Through small nana particles more light can be scattered:



In corporation of metal nanoparticles in glass

Plasmonic Scattering



Route 3: *light trapping by plasmons*

Metal particles ~ 0.1-0.2 µm

Red spectrum

Metal particles ~ 0.1-0.2 µm

Blue spectrum

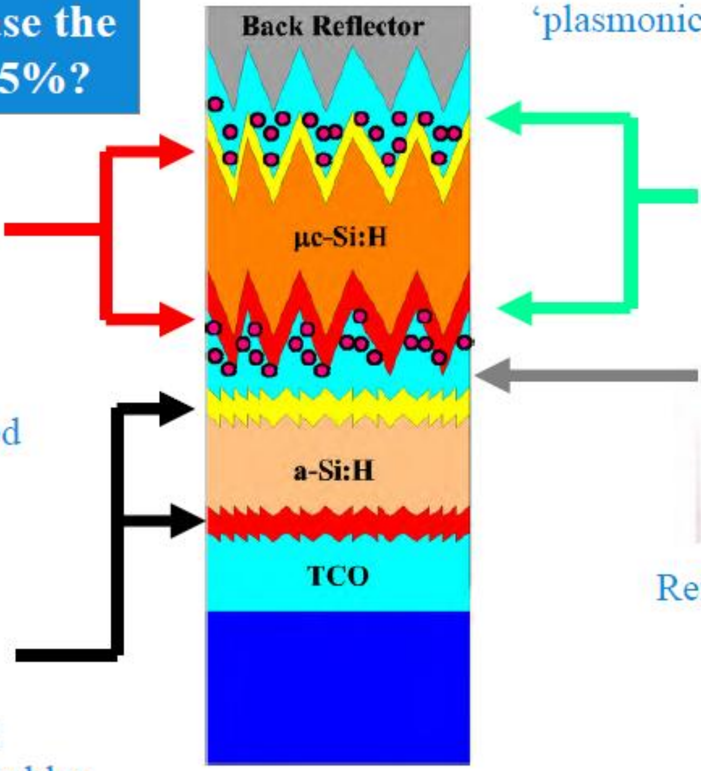
Confinement photons:
Increasing absorption path length.

So lets summarize:

Summary

How to increase the efficiency to 15%?

Multi-junction



Enhanced scattering
'plasmonic' metal particle

Textured surfaces:
'Mie' scattering for Red

Reflective layers

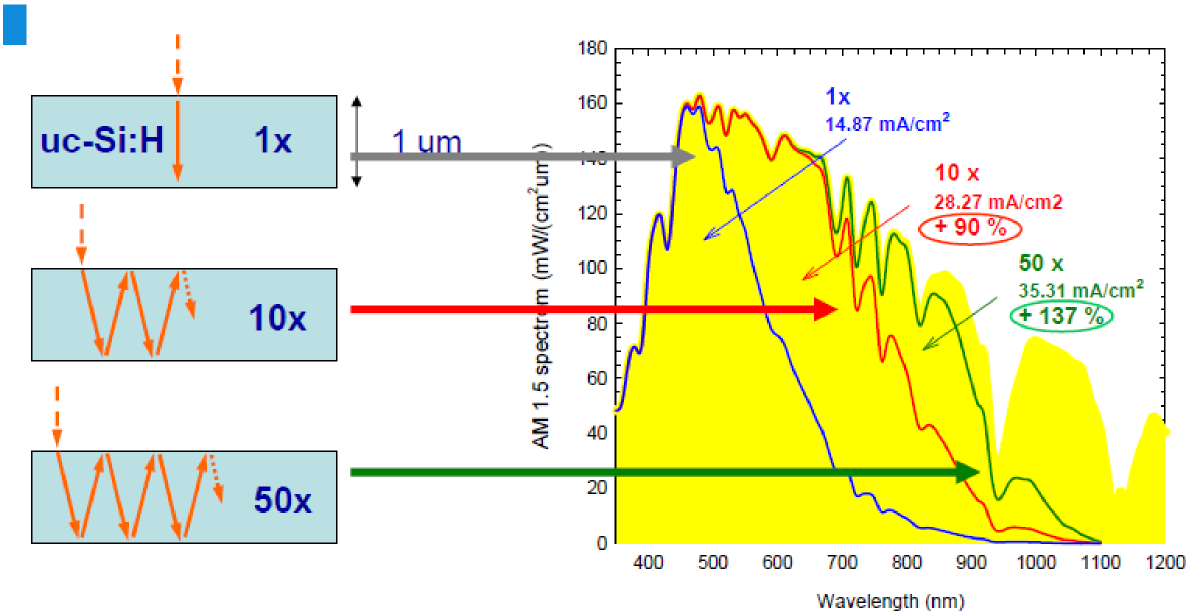
Textured surfaces:
'Rayleigh' scattering for blue

2nd Generation Technology: Thin film solar cells

Light trapping in thin silicon solar cells

Increasing the absorption path length

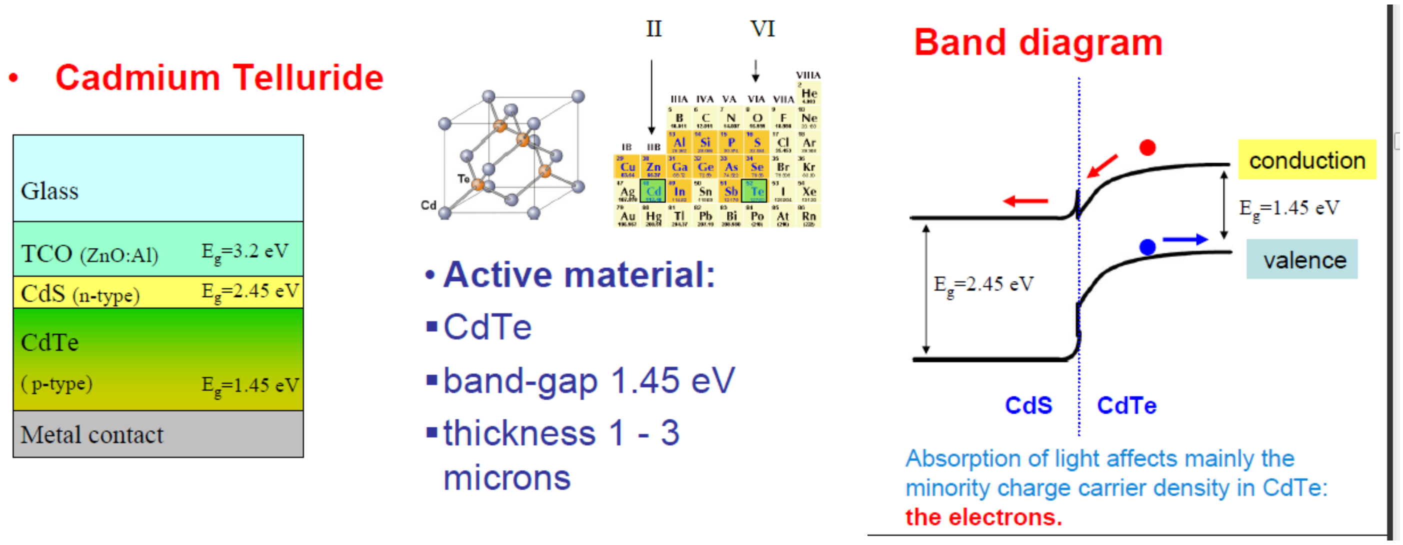
The answer to the problems displayed before is light trapping. When light reflected 10 times it can lead to an increase in ma/cm^2 by roughly 90 %, further 59 reflection can lead to 137% increase in ma/cm^2



Thin film silicon solar cell

CdTe

Cadmium Telluride is a second generation PC technology. It has a great low-cost potential and positive impact of development of take-back and recycling systems. However the efficiency is the major challenge. Currently it is between 7 and 11 % but it will probably rise to 15 % in the future.



- **Cadmium Telluride**

- **Active material:**
  - CdTe
  - band-gap 1.45 eV
  - thickness 1 - 3 microns

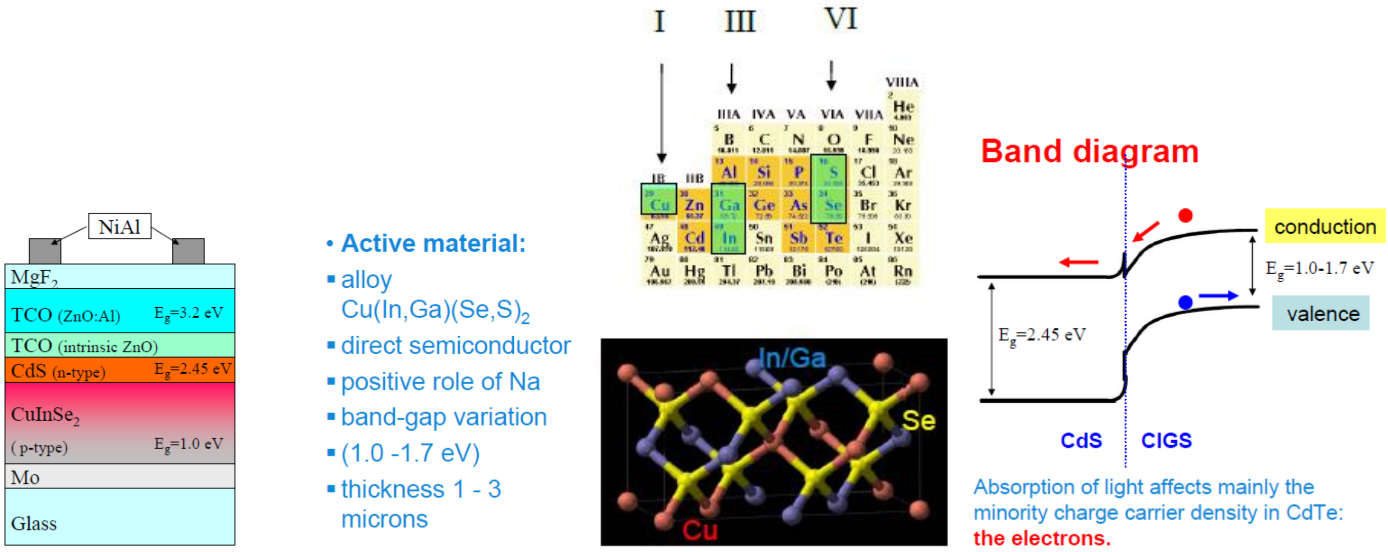
Band diagram

Absorption of light affects mainly the minority charge carrier density in CdTe: **the electrons.**

The advantages of the technology are the extreme low cost-price per Wp. However Cd is toxic and Te is not abundantly available which limits the up scaling to Terawatt production,

CIGS

Copper-indium/gallium-selenide stands out through high performance and possibilities for multi junction devices. However the reduction of manufacturing costs is still the biggest challenge. There is work going on on low cost varieties. The current efficiencies are around 9 -12 % and for the future they will reach 15 to 18%.



- **Active material:**
  - alloy $Cu(In,Ga)(Se,S)_2$
  - direct semiconductor
  - positive role of Na
  - band-gap variation
  - (1.0 -1.7 eV)
  - thickness 1 - 3 microns

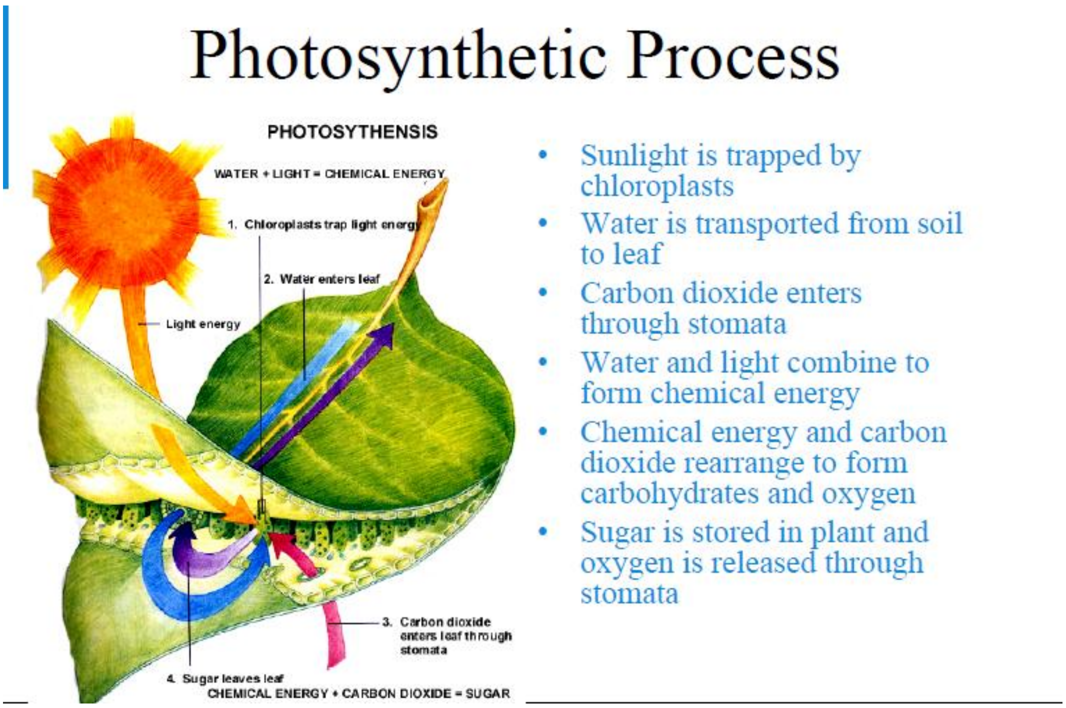
Band diagram

Absorption of light affects mainly the minority charge carrier density in CdTe: **the electrons.**

The disadvantages are that Cd in the CdS layer is toxic and In is not an abundant available material

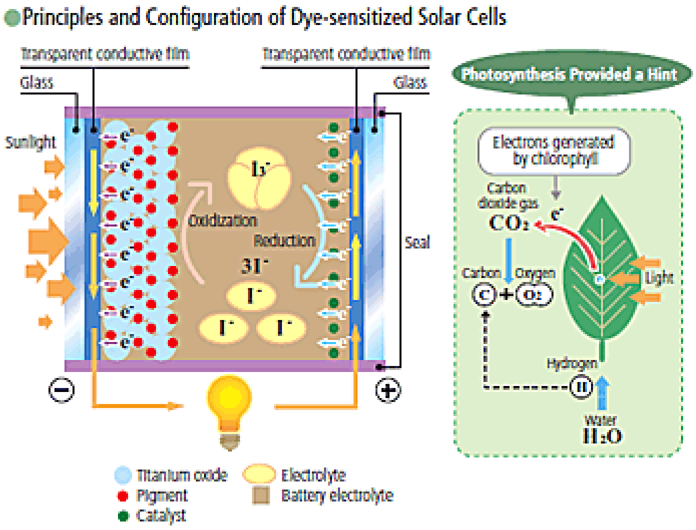
Dye-Sensitized

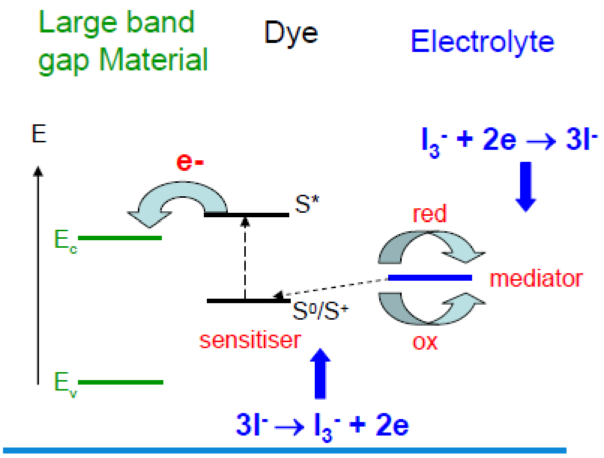
Dye Sensitized Solar Cells or DSSC can have an efficiency of up to 6 percent. Within them the photosynthetic effect know from nature is going on:



Photosynthetic Process

- Sunlight is trapped by chloroplasts
- Water is transported from soil to leaf
- Carbon dioxide enters through stomata
- Water and light combine to form chemical energy
- Chemical energy and carbon dioxide rearrange to form carbohydrates and oxygen
- Sugar is stored in plant and oxygen is released through stomata





Lets summarize the most important steps in a dye sensitized solar cell:

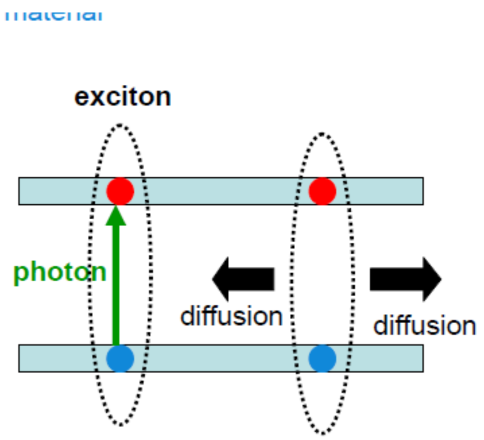
1. Absorption creats excited electron dye
2. Electron is injected in the conduction band of titanium oxide particles. Dye molecules remains positively charged
3. Diffusion electron to TCO
4. At Pt/TCO contact electrons are consumed
5. I3- + 2e →3I-
6. Diffusion 3I- → to dye
7. 3I- → I3 +

The advantages are the the solar cells are cheap and can be manufactured in a straightforward way. They are easily processed on flexible substrates. The disadvantage is the liquid electrolyte which has temperature stability problems:

At low temperatures the electrolyte can freeze, ending power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem. Furthermore the electrolyte solution is a problem since it contains volatile organic solvents and must be carefully sealed. The solvents permeate plastics, has precluded large-scale outdoor application and integration into flexible structure. Pt-contact is essential: Pt expensive and not abundantly available.

Organic solar cell

Organic cells are made of organic polymers. An Exciton which is a coupled electron-hole pair is the neutral entity which is able to diffuse through the polymer material. Exciton requires separation at hetero junction interface.



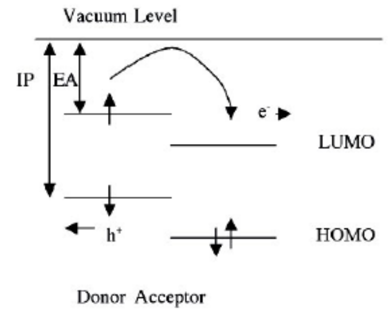
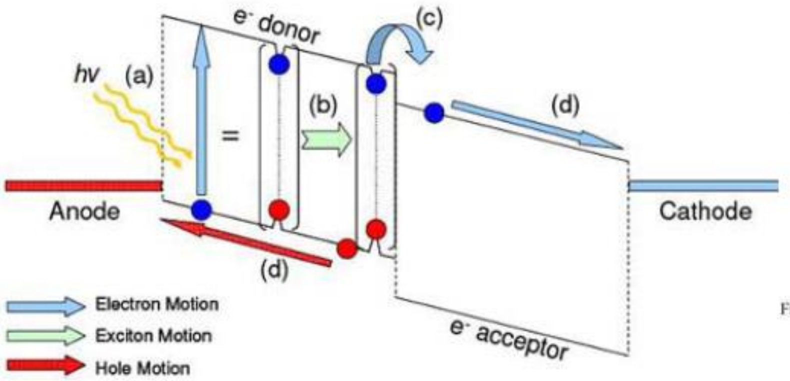


Figure 4: Charge separation of an exciton into a free electro/hole pair at a donor acceptor interface.

The absorption creates an exciton. The diffusion exciton then goes to the donor surgace. Then there is a sparation hole and electron at donor surface. The electron and hole diffusion go then to electrodes.



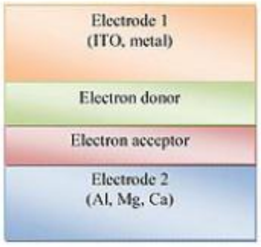


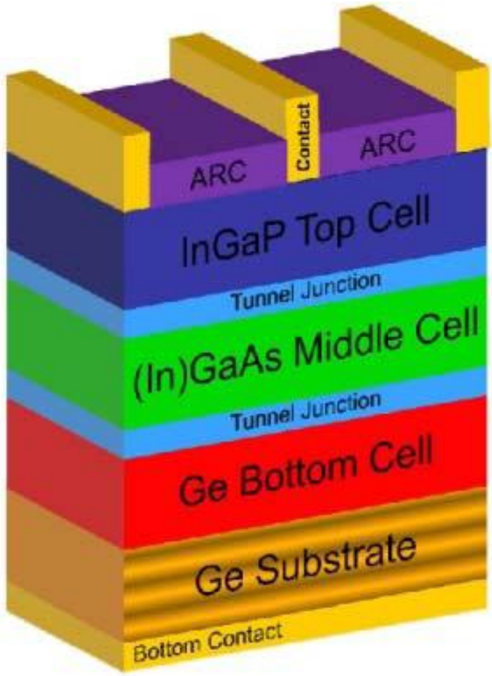
Fig 3 sketch of multilayer organic photovoltaic cell

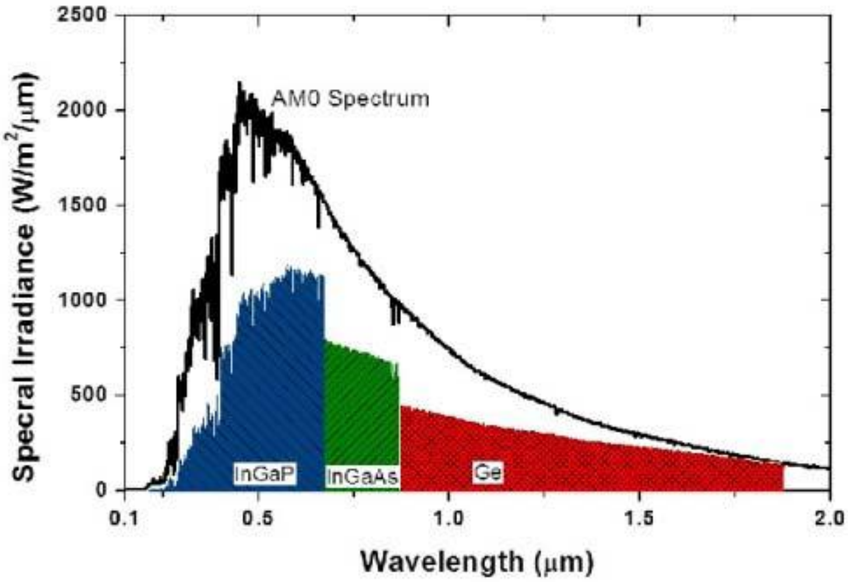
The challenges for organic cells are the instabilities against oxidation and reduction, recrystallization and temperature variations can also lead to device degradation and decreased performance over time. Difficulties associated with organic photovoltaic cells include their low quantum efficiency (~3%) in comparison with inorganic photovoltaic devices; due largely to the large band gap of organic materials. •Other important factors include the exciton diffusion length; charge separation and charge collection; and charge transport and mobility, which are affected by the presence of impurities.

Novel concepts

Multi-junction and QDs

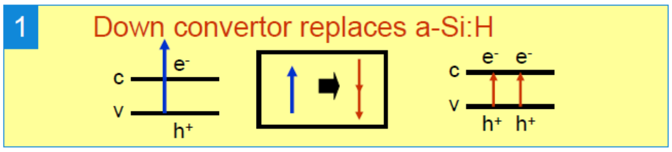
The advantage of multi-junction solar cell is that it improves the match between junction and solar spectrum.



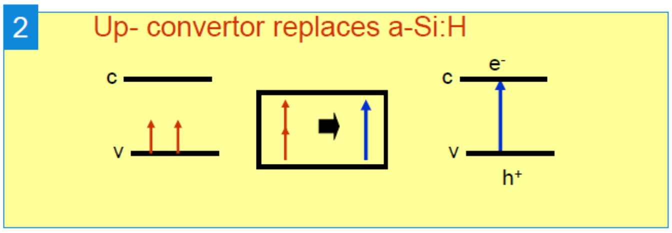


Furthermore one can use Quantum dots (GDs) which give variable bad gaps depending on the size of the QDs. Smaller QD lead to a larger band gap.

Down and up conversion

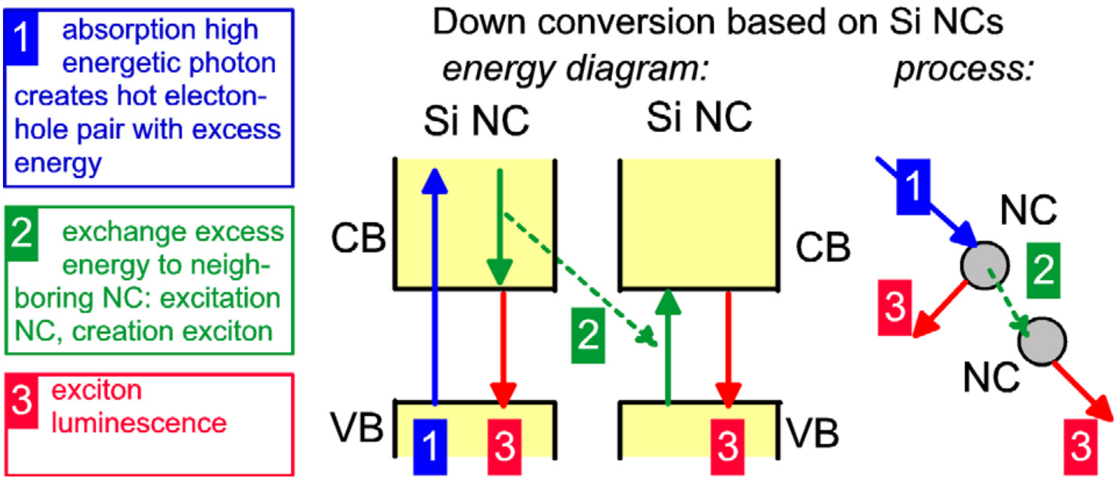


In Down conversion one larger photon is replaced by two smaller one in order to match the appropriate band gape length.



In up conversion two smaller photons are combined to one larger one in order to match the band gap size,

For that a film with high density of silicon nanocrystals (NCs) can act like down convertor.



Down conversion based on Si NCs

1 absorption high energetic photon creates hot electon-hole pair with excess energy

2 exchange excess energy to neighboring NC: excitation NC, creation exciton

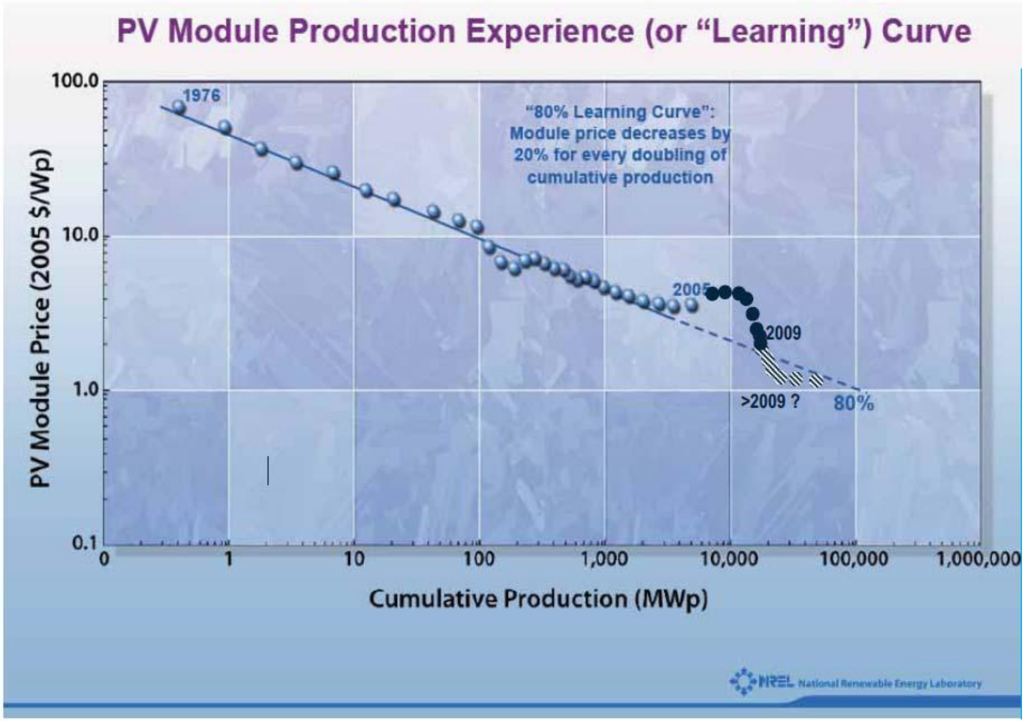
3 exciton luminescence

The economics of PV technology

The learning curves

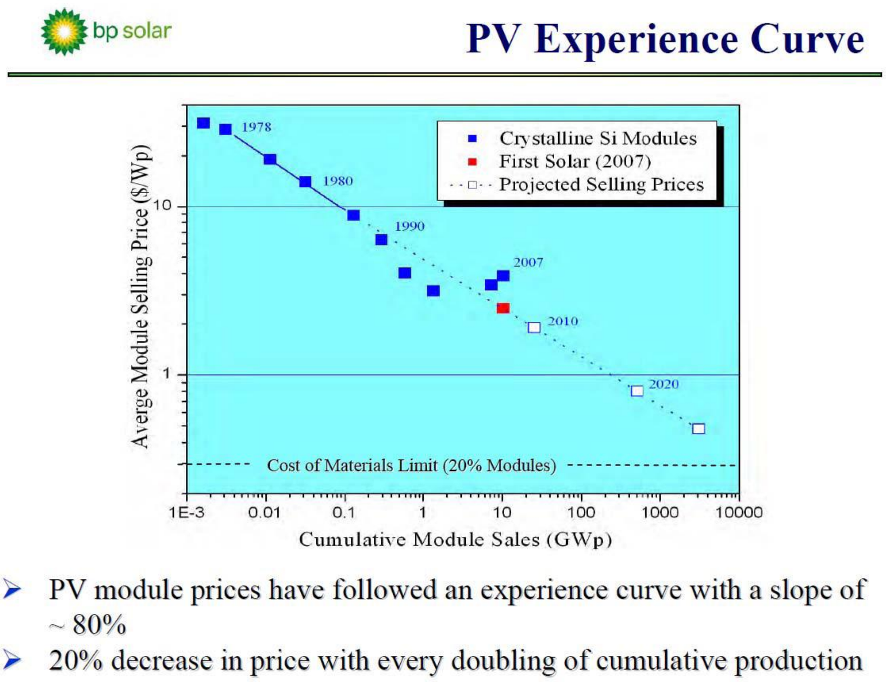
In order to become competitive with conventional electricity the costs need to be reduced by a factor of 5. Today the prices are roughly 2 Euros per Wp

In order to reduce the cost the raw material, labor and investment costs should be reduced and the efficiency and lifetime increased. Furthermore the system integration should be optimized by are and power related cots.



PV Module Production Experience (or "Learning") Curve

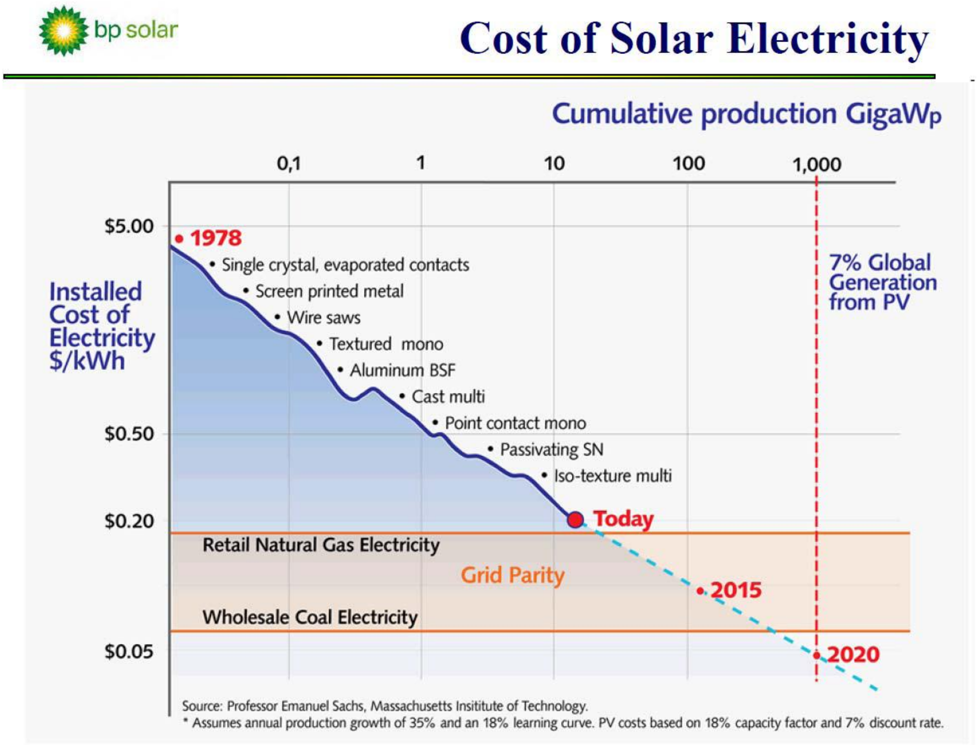
"80% Learning Curve": Module price decreases by 20% for every doubling of cumulative production



PV Experience Curve

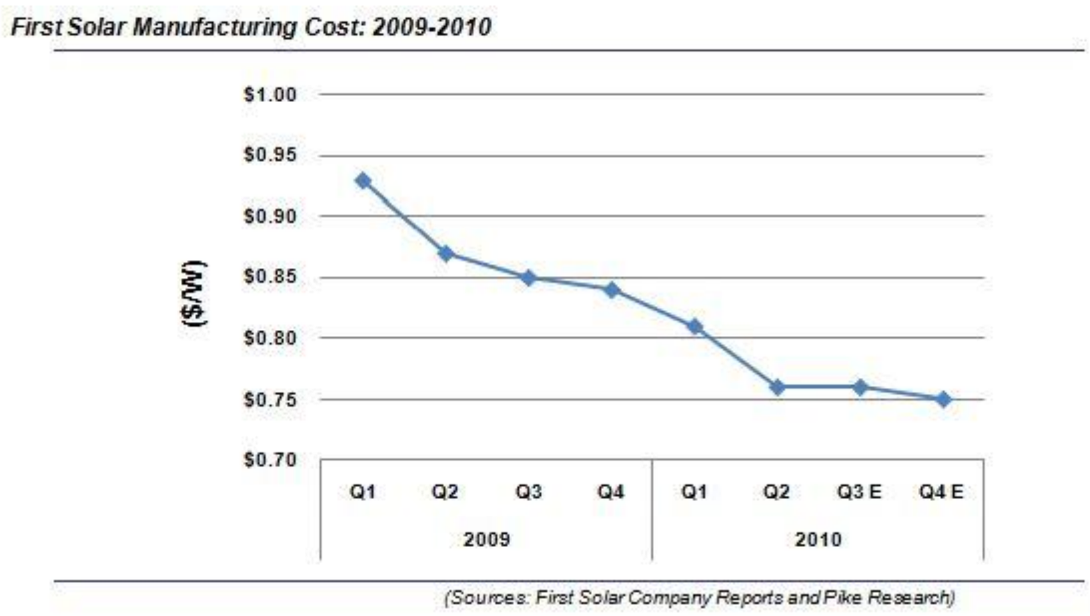
- PV module prices have followed an experience curve with a slope of ~ 80%
- 20% decrease in price with every doubling of cumulative production

Retailing price



Cost of Solar Electricity

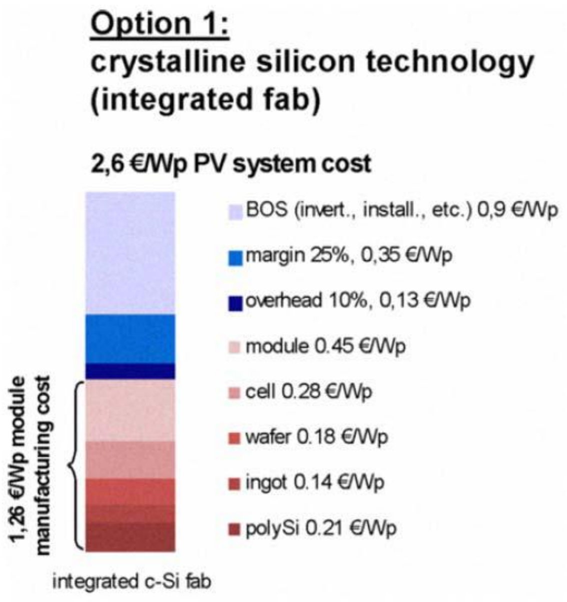
Source: Professor Emanuel Sachs, Massachusetts Institute of Technology.
* Assumes annual production growth of 35% and an 18% learning curve. PV costs based on 18% capacity factor and 7% discount rate.



First Solar Manufacturing Cost: 2009-2010

(Sources: First Solar Company Reports and Pike Research)

Cost price of PV modules



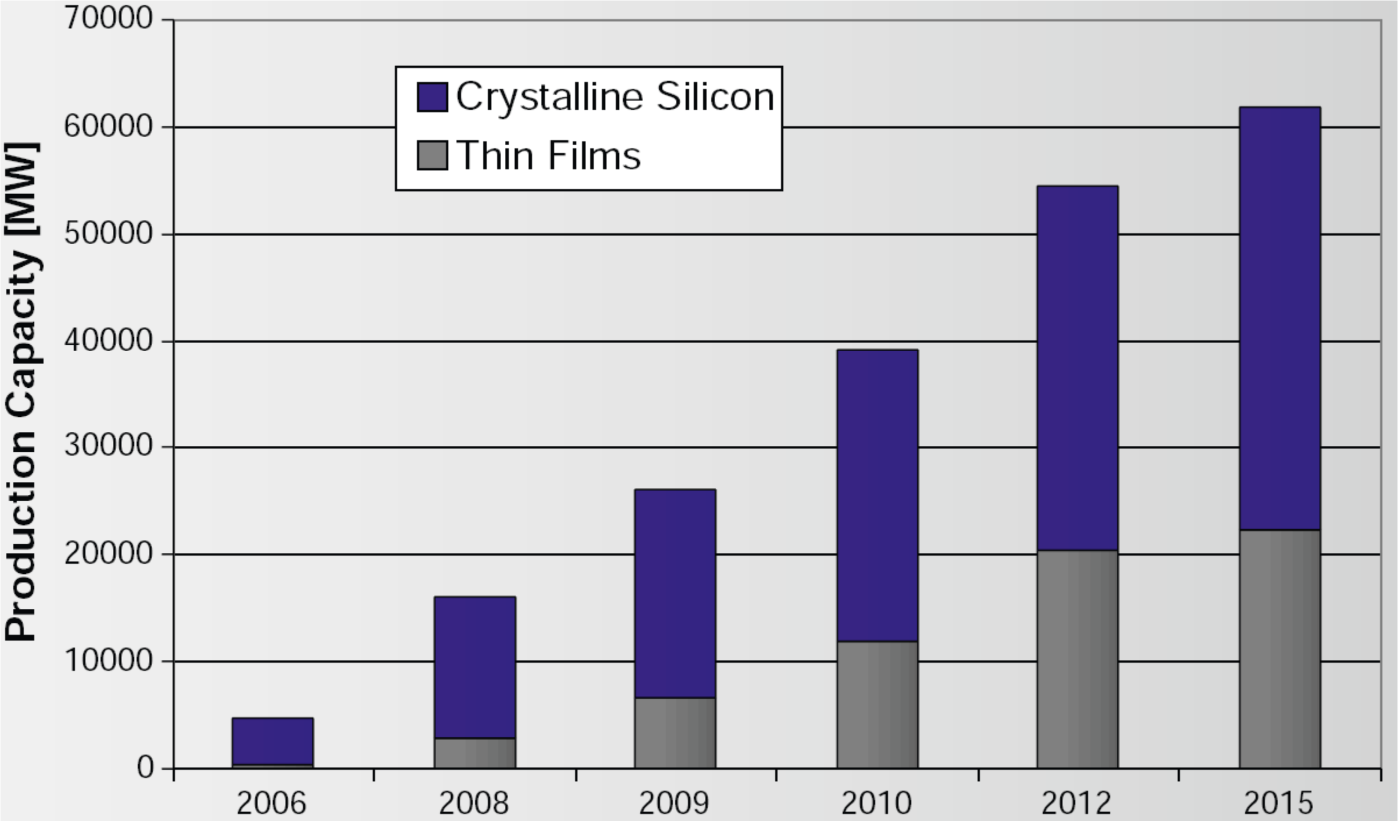
Option 1:
crystalline silicon technology (integrated fab)

2,6 €/Wp PV system cost

The advantages of thin film PV technologies are:

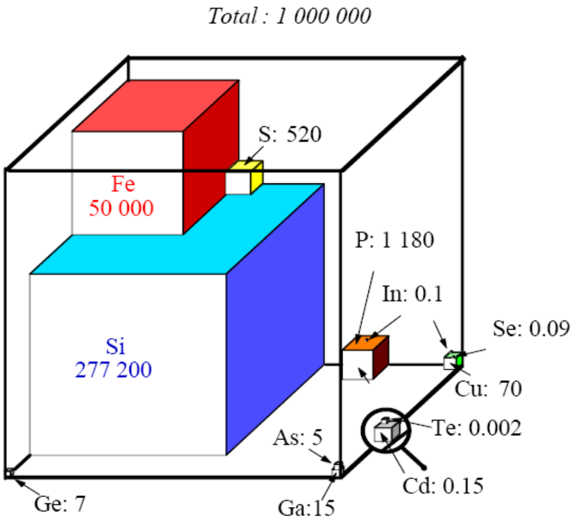
- Savings in material and energy consumption
- Large area deposition
- Monolithic integration
- Energy pay-back time
  ~ 2 years (c-Si) VS< ~ 1.4 years (thin-films)
- Implementation in building industry

Up scaling PV technology to terawatts

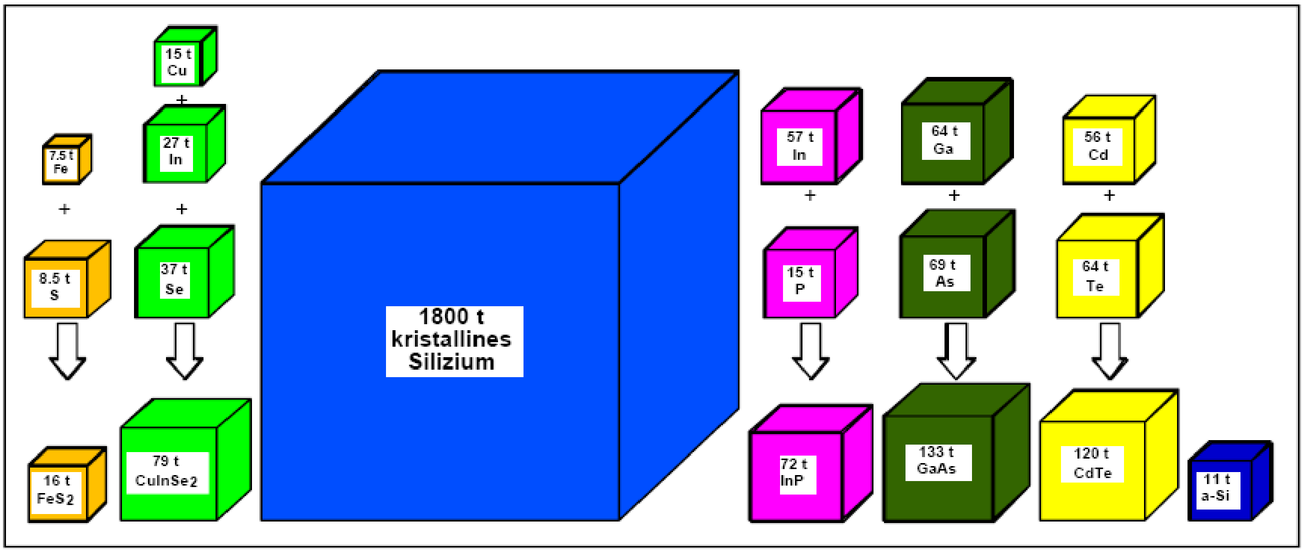


The abundance of the source materials

The composition of the earths crust

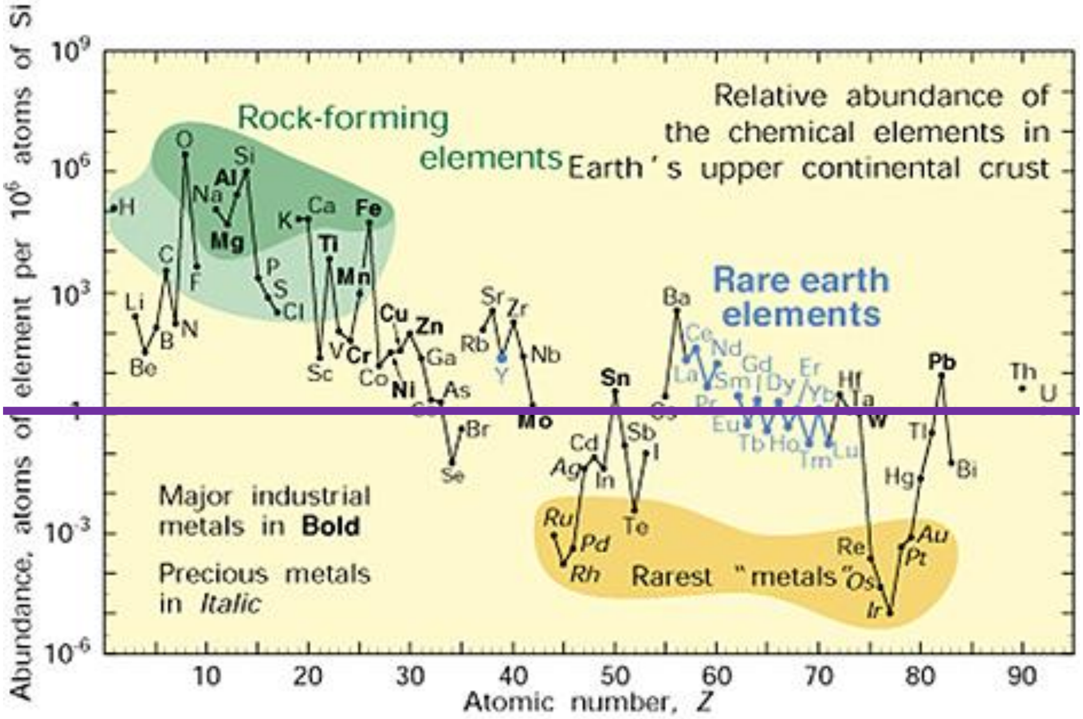


Now lets think about upscaling to 1MWp for the materials listed below:



	16 t FeS_2	79 t $CuInSe_2$	1800 t c-Si	72 t InP	133 t GaAs	120 t CdTe	11 t a-Si
$\eta(\%)$	3	12	20	20	20	10	10
$d(\mu m)$	0.1	2	150	3	5	2	0.5

The figure below shows the availability of materials in the earth crust. The horizontal line indicates whether materials are abundant or not.



CdTe: Cd,Te,S,Al,Zn,O

GaAs: Ga,As,Al,In,P,Ge

CIGS: Cu,In,Se,Ga,Al,Zn,O,Cd,S

Dye-sensitized; Ti,O,Sn,Pt,C,O,H,N,S,Ru,I

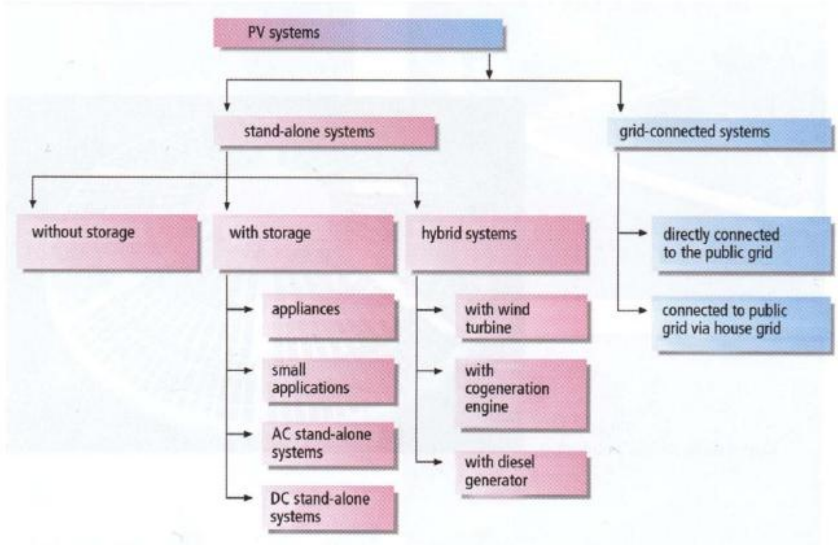
a-SI:H: H,Si,O,Zn,Al,B,P

PV systems and module issues

Classification of PV systems

The entire PV system is more than just the PV array (1.). The PV array is connected to a PV array combiner (2). From there it is connected to the grid-tied inverter (3.). Connected to that it is also the import / export meter and lastly the connection to the grid.

Now lets have a look at the planning and installing of a PV system:



Stand alone

Stand alone system can be simple connected to a DC engine which does work. Additionally a battery can be added to that system which saves not consumed energy. Besides a battery an inverter can be used so that AC machines can be connected.

Grid connected

Grid connected systems don't need on site energy storage. They consist of the solar arrays, an inverter, ac machines and a connection to the grid. The ac machine however is not necessary. Furthermore hybrid systems can exist for example in combination with a windmill.

PV system components

The components of the PV system can be listes as follows:

PV device

- Cell, panel, array
- Dc electricity

Balance of system (BOS)

- Mounting structures, tracking
- Storage devices
- Power conditioners

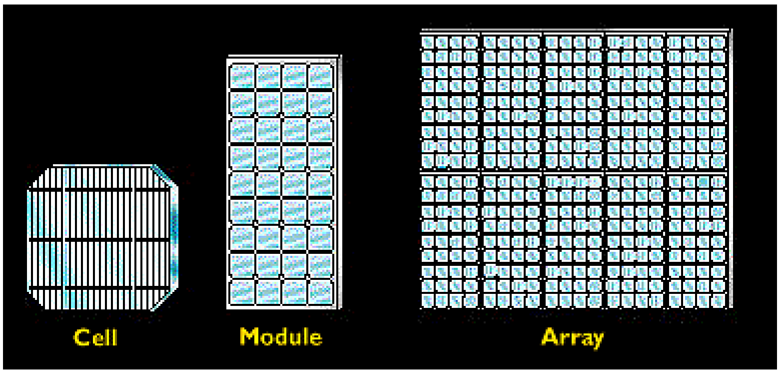
Load (dc or ac)

Modules

Cell (c-Si 12.5×12.5 cm2 η=15% P=2.5Wp V=0.6V I=5.5A)

Solar panel (36 c-Si cells P=95Wp I=5.5A V=23V)

Solar array



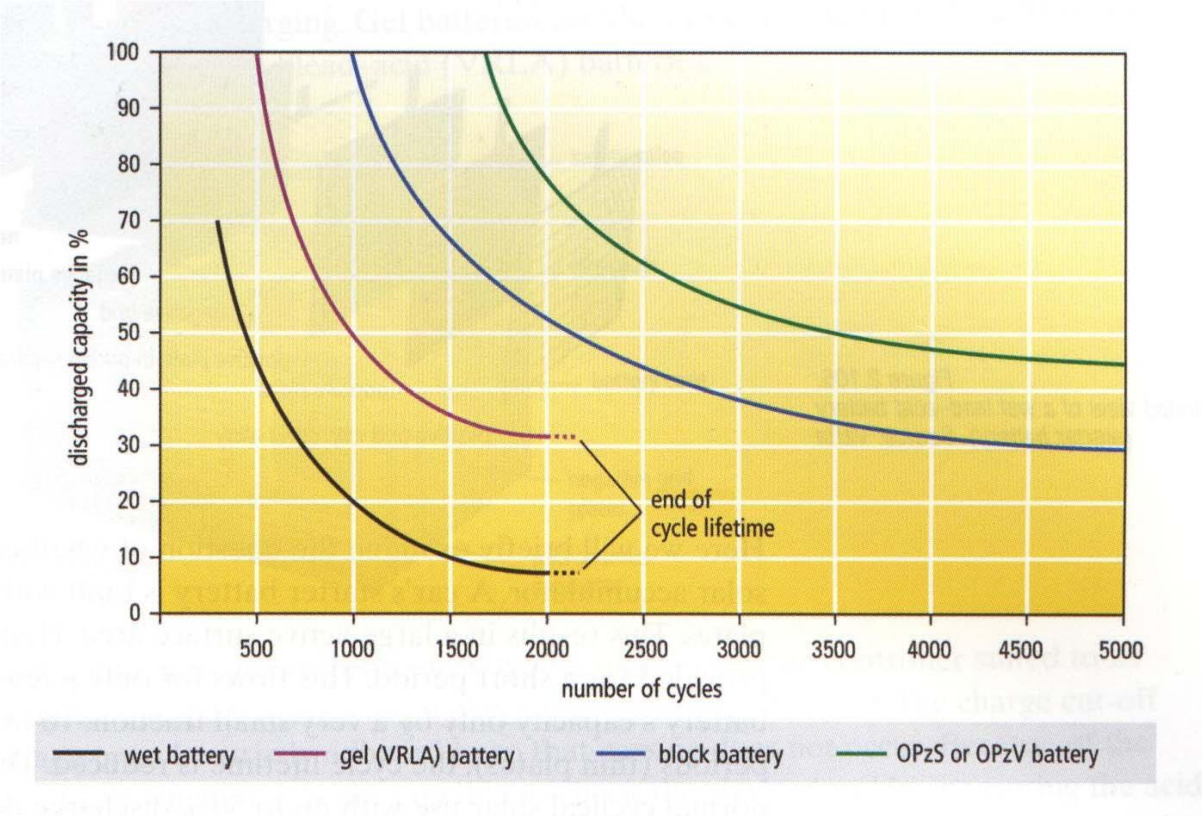
- STC conditions are rare during operation
- Current is proportional to irradiance
- Voltage is affected by temperature
- 50 W module: -8 V in summer, +10 V in winter
- Important during sizing (winter – high voltages)
- Power reduction in summer (35 %) => ventilation
- Temperature coefficients have to be specified
- vOC -0.40%/°C, ISC +0.05%/°C, P -0.45%/°C

Encapsulation of the cells can be done via EVA, Teflon or Casting resin

Batteries

The advantage of batteries is that it is a reliable energy source available at night or on cloudy days. However the disadvantages are the it decreases the efficiency of the PV system, roughly 80% can be reclaimed. Using batteries adds to the expense of the overall system. Furthermore batteries need to be replaced every 5 – 10 years. Also floor space, safety concerns and periodic maintenance are needed.

There are different kind of batteries available at the market ranging from lead-acid batteries to Ni-Cd, NiMH and Li-ion batteries. The cycle lifetime is different for the various battieres:



Inverters

Power conditioners

Charge controller	Stand-alone inverter
• Optimum charge to the batteries • Overcharge protection • Preventing unwanted discharging • Deep discharge protection • Information on the state of charge of the batteries	• AC current with sinusoidal form • High conversion efficiency • High overload capacity for switch-on • Tolerance against battery voltage fluctuations • Economical standby state with automatic load detection

Inverter parameters:

- conversion efficiency ηCON = AC power out / DC power in
- tracking efficiency ηTR = DC instant power / DC maximum power
- static efficiency $\eta INV = \eta CON \times \eta TR$
- nominal power, voltage, current
- turn on / off power

- MPP voltage range

Overload behavior

- shift the operating point
- power limitation
- switch off

Additionally charge controllers are implements which take care of optimum charging, protect from an overcharge and prevents from unwanted discharging. Different systems for that are series controllers, shunt controllers and mpp charge controllers.

Design and sizing

PV system design rules:

1. Determining the total load current and operating time requirements in Ampere-hours
2. Taking care of system losses and safety factors
3. Determining the worst case (wintertime) equivalent sun hours
4. Determining total solar array current requirements
5. Determining optimum module arrangement for solar array
6. Determining battery size for recommended reserve time

1.Determining the total load current and operating time requirements in Ampere hours:

- Decide the nominal voltage (12 or 24 V)
- nominal power of loads
- average time they are operated each day

example:

- appliance A: 15 W, 6 hours
- appliance B: 20 W, 3 hours

total energy consumption per day:
15W x 6h + 20W x 3h = 150Wh

expressed in Ah: 150Wh/12V = 12.5 Ah

What about AC appliances ?

- Typical inverter effieciency 85 %

example:

- appliance C: 40 W, 2 hours
- appliance D: 60 W, 3 hours

total energy consumption per day:

- 40W x 2h + 60W x 3h = 260Wh
- DC requirement 260Wh/0.85 = 306Wh
- expressed in Ah: 306Wh/12V = 25.5 Ah

2. Taking care of system losses and safety factors

- Generated solar power is not fully available for loads
- Cable losses (6% loss)

- Reduce the PV array yield by a factor of $V_L=0.94$

- Conversion losses in the battery (10% loss)

- Reduction factor of $V_u=0.90$

- Mismatching losses (10% loss)

- Reduction factor of $V_a=0.90$ (can be suppressed by MPP tracking)

- Resulting overall losses are $V= V_L \times V_u \times V_a = 0.76$
- Power available for the loads is:

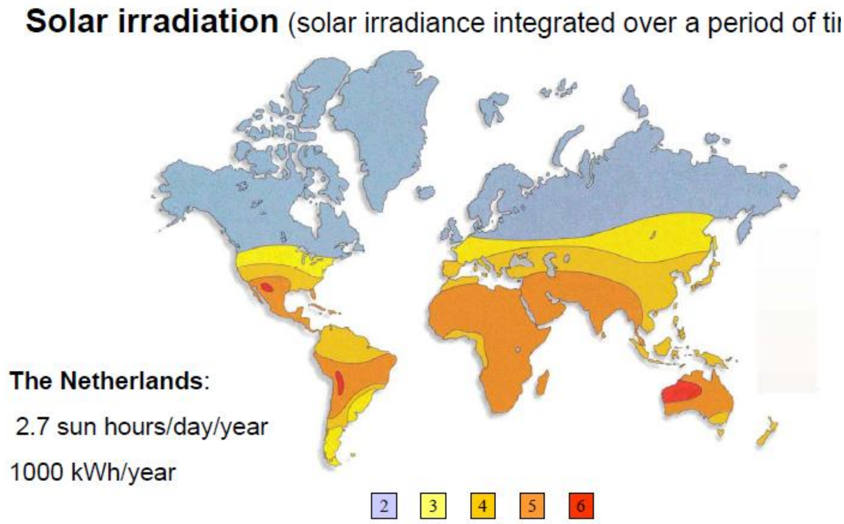
$Pload = PPV \times V = PPV \times VL \times Vu \times Va$

Example:

- Total DC requirements of loads:
- 12.5Ah + 25.5Ah = 38Ah
- To compensate for system losses (20% - 30%):
- 38Ah x 1.2 = 45.6Ah

3. Determine the solar irradiation in daily equivalent sun hours

- The yield of the PV module depends on several factors:
- Local weather, temperature, season, tilt angle.
- 1 equivalent sun – 1000 W/m^2
- on average 2740 Wh/m^2 each day (Netherlands)
- or 2.74 hours of 1 sun each day



Annual average of daily hours of sunlight

4. Determining the total solar array current requirements

- Total DC requirements of loads plus losses: 45.6 Ah
- Daily EHS for The Netherlands ~ 3h
- Total required current: 45.6 Ah / 3 h = 15.2 A

5. Determining optimum module arrangement for solar aray

- Check the specifications of PV modules
- Compare with the system specifications (voltage, current requirements)
- Number of modules in parallel = total current / module current
- Number of modules in series = nominal voltage / module voltage

- Example:
- We have Shell50-H, IMPP = 3.15 A, VMPP = 15.9 V
- In parallel: 15.2A/3.15A = 4.8
    - ⇨ 5 modules connected in parallel

6. Determing battery size for recommended reserve time:

- Load operation during night, limited sunlight
- PV system autonomy (from batteries)
- Telecommunications ~ 10 days
- Residential ~ 5 days
- battery capacity = DC energy requirement X reserve time
- example: 45.6 Ah x 5 = 228 Ah

- To save battery – use only 80 % of the capacity
- That is 228 Ah / 0.80 = 285 Ah