

Alexandre-Edmond Becquerel

(24 March 1820 – 11 May 1891)

- He was a French physicist born in Paris in 1820.
- He was in turn the pupil, assistant and successor of his father at the Musee d'Histoire Naturelle.
- In 1849 at the age of 29 he was appointed professor at the Agronomic Institute at Versailles.
- In 1853 he received the Chair of Physics at the Conservatoire des Arts et Metiers.



Alexandre-Edmond Becquerel studied light in great detail; investigating the photochemical effects and spectroscopic characteristics of solar radiation and the (electric) light, and the phenomena of phosphorescence, particularly as displayed by sulfides and compounds of uranium.

Like many physicists of his day Becquerel worked on a wide variety of topics, including magnetism, electricity, and optics.

He was especially interested in phosphorescence and luminescence – photo-chemical reactions caused by exposing certain substances to light.

Unlike fluorescence, phosphorescence, is characterised by emission of light, sometime after the illuminating source is removed.

Becquerel's research resulted in the design of an instrument known as the **phosphoroscope**.

This was an instrument that enabled the interval between exposure to the source of light and observation of the resulting effects to be varied at will and accurately measured.

Light emitted has a longer wavelength than the source.



Becquerel's Phosphoroscope

The first steps towards light generating power.

- In the 1840s he found that these photo-chemical reactions could produce an electric current in both liquids and metals.
- He devised an instrument, called an **Actinometer**, that could measure the intensity of a light source by observing the amount of electrical current produced in these substances.
- The connection between light energy and chemical energy was seized upon by many scientists in the following years, and research has led to the development of the **photoelectric cell**.
- During this time, Becquerel was considered the foremost authority on luminescent phenomena and published several important papers on the subject.



An historic
Actinometer



and a more
recent
instrument.

Solar Generation Key dates:

1839: Nineteen-year-old Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell made with two metal electrodes.

1873: Willoughby Smith discovered the photoconductivity of selenium

1876: Adams and Day observed the photovoltaic effect in solid selenium.

1883: Charles Fritts, an American inventor, made the first solar cells made from selenium wafers. They had an efficiency of 1%.

1887: Heinrich Hertz discovered that ultraviolet light altered the lowest voltage capable of causing a spark to jump between two metal electrodes. Electrons ejected from a sodium metal surface were measured as an electric current – the photoelectric effect.

This was dependent not on light intensity, but photon energy. This is based upon the phenomena of the work function of a metal.

1904: Hallwachs discovered that a combination of copper and cuprous oxide was photosensitive.

1904: Einstein published his paper on the photoelectric effect - and this work was rewarded with the Nobel Prize – based upon the *work function*.

1914: The existence of a barrier layer in PV devices was reported.

1916: Millikan provided experimental proof of the photoelectric effect.

1918: Polish scientist Czochralski developed a way to grow single-crystal silicon.

1923: Albert Einstein received the Nobel Prize for his theories explaining the photoelectric effect.

1951: A grown p-n junction enabled the production of a single-crystal cell of germanium.

1954: Chapman, Fuller and Pearson announce a solar cell with 6 % efficiency.

1972: France installs a CdS PV system in a village in Niger to run an educational TV.

1982: Worldwide PV production exceeded 9.3 MW.

2012: China Becomes World's First Nation to Install 3 GW of Utility-Scale Solar Power!



China just secured its position as the world leader in solar power by installing a record 3000 MW of utility-scale solar power.

The nation has constructed 40 new solar plants (with over 1 GW of production capacity) since

December 2012, surpassing Germany as top solar producer in the world. China now operates an astounding 132 utility-scale solar plants.

2014 India:

India has announced plans to build the world's biggest solar-power generating facility on a salt-producing plain in Rajasthan.

The facility, to be located on 20,000 acres (30 square miles) of land owned by Rajasthan's government and a salt-producing firm, would have a capacity of 4,000 megawatts of electricity, and cost \$1.2 billion in the first phase.



Solar panels, covering 750-metre stretch of Sanand branch of Sardar Sarovar canal, are expected to generate some 1.6m units of clean electricity per year and prevent 9m litres of water from evaporating.



India today uses an average of 772,000 GW hours of power annually.



The Gujarat Solar Park in Gujarat, India, is Asia's largest solar power station with an installed capacity of 1,000MW.

Images from:

<http://www.theguardian.com/environment/2014/sep/30/-sp-narendra-modi-india-solar-renewables-energy>

More than one sun in Abu Dhabi?

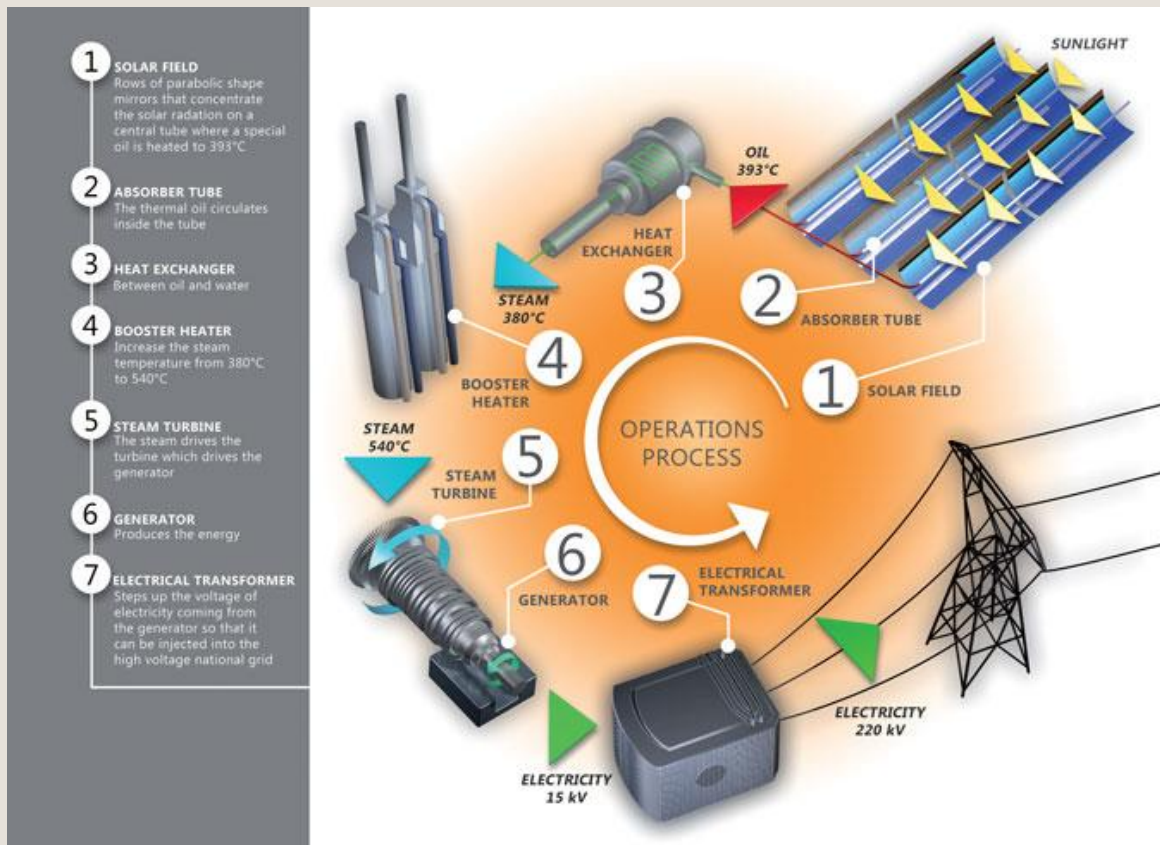
In 2013 Abu Dhabi celebrated the opening of the largest concentrated solar power plant on Earth.

Shams 1, as the plant is called, is a development of 258,048 parabolic trough mirrors that produce enough energy to power 20,000 homes.



Shams 1 is a 100 MW Plant.

It is a modular distributed system of solar collector assemblies (SCAs) connected in parallel via a system of insulated pipes.



The SCAs collect heat via a trough of parabolic mirrors, which focus sunlight onto a line of heat collection elements (HCE), welded in line at the focus of the parabola.

2015 World's largest solar thermal plant goes live, will provide power for 1.1M people



On the left, phase 1 of the Noor Concentrated Solar Power plant is generating energy. On the right, phase 2 will be completed in 2017 and phase 3 in 2018

The new Noor CSP plant uses either lenses or parabolic mirrors to concentrate the sun's light onto a small point where water or another substance is heated.

<http://www.computerworld.com/article/3031659/sustainable-it/worlds-largest-solar-plant-goes-live-will-provide-power-for-11m-people.html>

The heat is used to create steam, which runs a turbine that produces electricity. In the Noor CSP, concave mirrors focus on molten salt, heating it anywhere from 300 degrees to 660 degrees Fahrenheit.



The International Energy Agency estimates that up to 11% of the world's electricity generation in 2050 could come from CSP.

Morocco's goal is to have 42% of its energy come from renewable resources by 2020.

And in the UK

At the start of 2010, cumulative solar PV deployment in the UK was less than 40 MW.

During April 2013, TOTAL solar photovoltaic (PV) demand in the UK broke through the 2.5 GW barrier.



The Solar PV Strategy Group speculates '20 GW by 2020' phrase

The Department of Energy and Climate Change has appeared to have upgraded its 2020 solar forecast again, this time to 13GW.

<http://www.solarpowerportal.co.uk/>

£60M private investment in five UK solar farms a total installed capacity of 80MW

Generate enough electricity to power approximately 18,000 average homes.

Four of the sites have been operational since March 2014 and are located in Dorset (two), Glamorgan, and Norfolk.



The fifth site at Canworthy Water in Cornwall was connected to the grid in December 2014. It has a capacity of 41MW and is the largest solar site in the UK, covering 81ha of farmland.



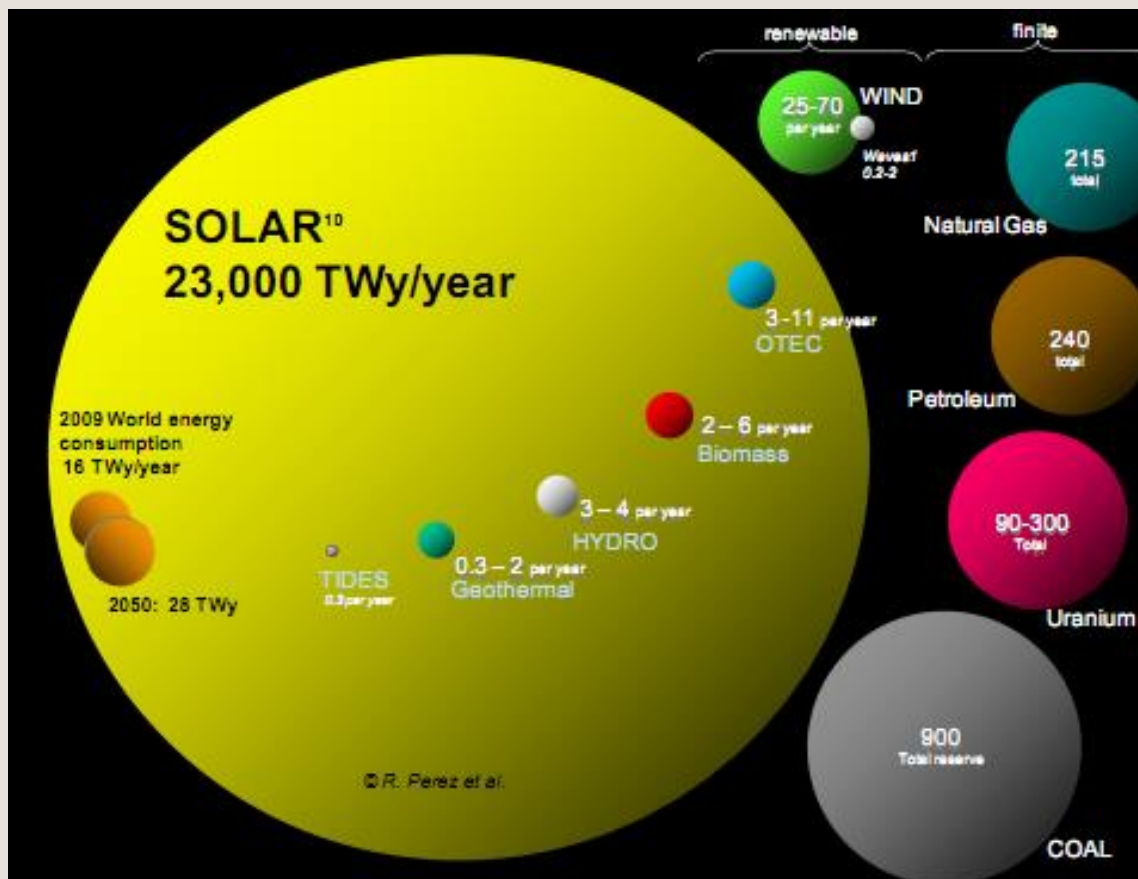
More facts and figures

The annual energy potential from solar energy is 23,000 TWy.

Energy potential from total recoverable reserves of coal is 900 TWy.

For petroleum, it's 240 TWy; and for natural gas, it's 215 TWy.

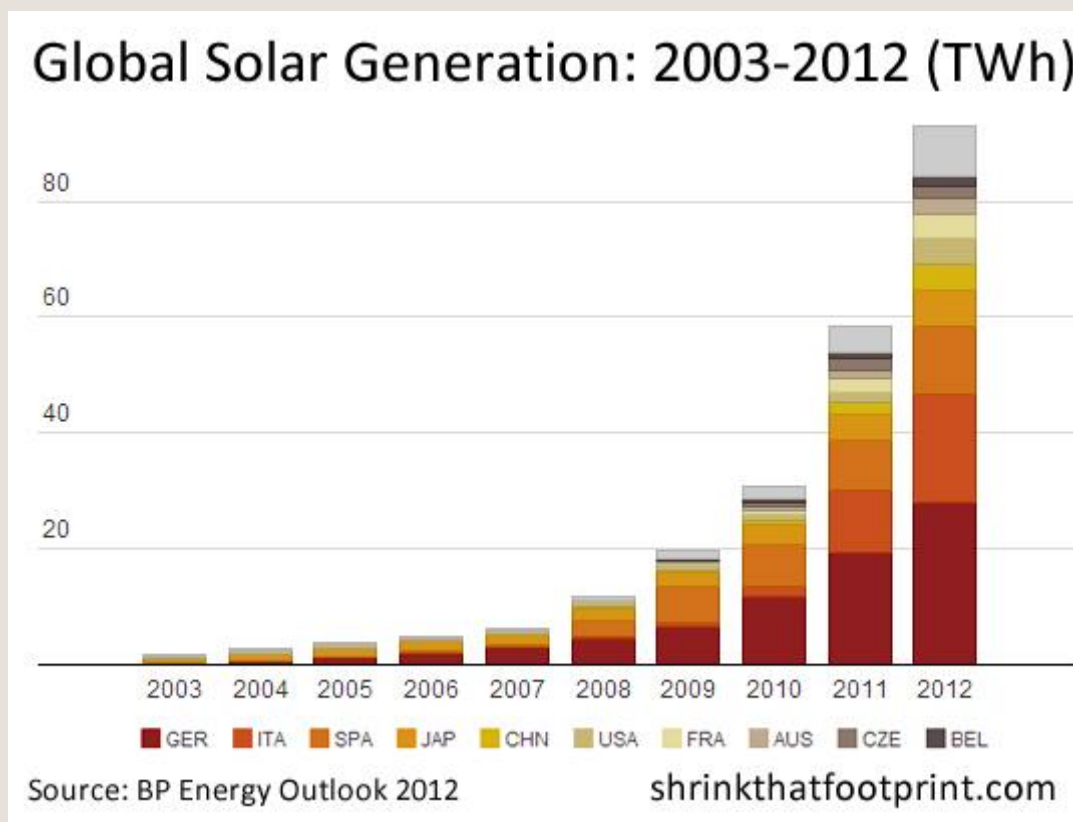
Wind energy's yearly energy potential is 25–70 TWy.



Approximately 66% of installed world solar PV power capacity has been installed in the past 2½ years.

The price of solar PV panels dropped about 100 times over from 1977 to 2012.

Since 2008, the price of solar PV panels has dropped about 80%



SOLAR IMPULSE

2010: The solar aircraft project initiated by Bertrand Piccard, pilot and engineer associated with Andre Borschberg, made its maiden flight.

The plane Solar Impulse, a solar aircraft project designed by Bertrand Piccard, pilot and engineer along with Andre Borschberg, made its maiden in December 2009.

To fly night and day without fuel, powered by solar energy, and to demonstrate that progress is possible using clean energy.

Seven years of studies, simulation, construction and tests to achieve the first solar day-and-night flight in history: 26 hours, 10 minutes and 19 seconds, and 3 world records.

The wingspan of an Airbus A340: 63.40 m

The weight of a family car: 1600 kg

The power of a scooter: four 10 HP engines

Driven by the strength of its four propellers, an output similar to that of a small scooter, the aircraft ran the line of the runway of Dubendorf airport near Zurich (Switzerland).

How far did it fly then?



He flew a distance of
350 meters

At **one metre** above the
ground.

That was just a test flight though.

7th April 2010 the Solar Impulse HB-SIA took off from Payerne (VD) airfield on its maiden flight, lasting 87minutes at up to 1200 meters.

8th July 2010 The Solar Impulse HB-SIA, with André Borschberg at its controls, successfully landed at 09:00, to the cheers of a crowd of supporters who came to celebrate this great milestone.



For more than 26 hours, André Borschberg expertly piloted the plane – it was up in the air for the whole day, then through the entire night, flying solely on solar energy. This flight is the longest and highest in the history of solar aviation!

FLIGHT REPORT

Take-off time: 07/07/2010 - 06:51

Landing time: 08/07/2010 - 09:02

Flight duration: 26 hours 09 min 10 seconds

Maximum speed: 68 knots / 125,9 km/H

Average speed: 20,6 knots / 38,2 km/H

Maximum altitude: 8720 m (above sea-level)

The next important milestones for Solar Impulse will be the crossing the Atlantic and the around the world flight.

<http://www.solarimpulse.com/>

2013 Construction of HB-SIB, the second solar airplane, continues as planned and is scheduled to be fully built by the end of 2013.

2014 Start of flight testing of HB-SIB, and training flights for Bertrand Piccard and André Borschberg.



2015 Attempt to circumnavigate the globe in the northern hemisphere, with 4-5 stopovers along the way. The starting point will be selected from among several candidate cities.

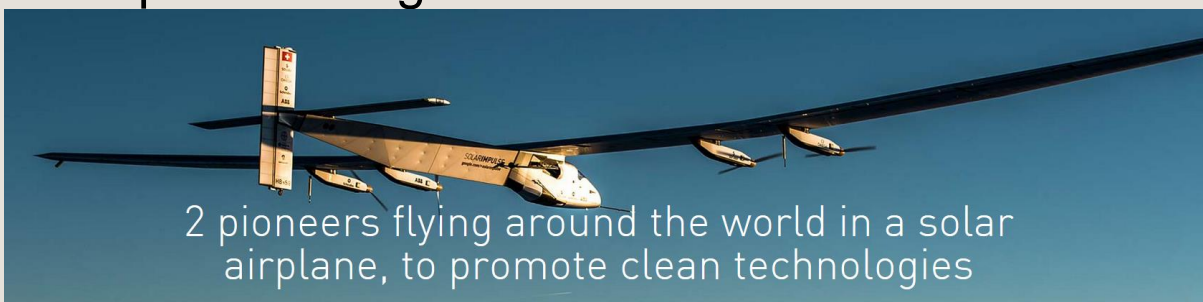
Around The World: crossing oceans and continents



Solar Impulse 2 Non Official Flight Corridor

The Around-the-World Mission Flights will take place over 5 months from the beginning of March to the end of July 2015. Abu Dhabi will be the departing and landing destination.

Abu Dhabi, capital city of the United Arab Emirates, will be the start and finish of the first solar-powered flight around the world.



After the first ever oceanic crossing by a solar airplane and record breaking flight from Japan to Hawaii, the second half of the RTW is delayed to April 2016 due to damaged batteries

World Solar Challenge: Australian electric car race 2015.

A team from Delft University in the Netherlands has won a solar car race in the Australian outback.



The university's Nuon Solar Team was the first to arrive at the finish line in Adelaide. The 3,000km (1,800 mile) race took four days to complete.

Electron Volts and Photon Wavelength

The energy E , frequency ν , and wavelength λ of a photon are related by

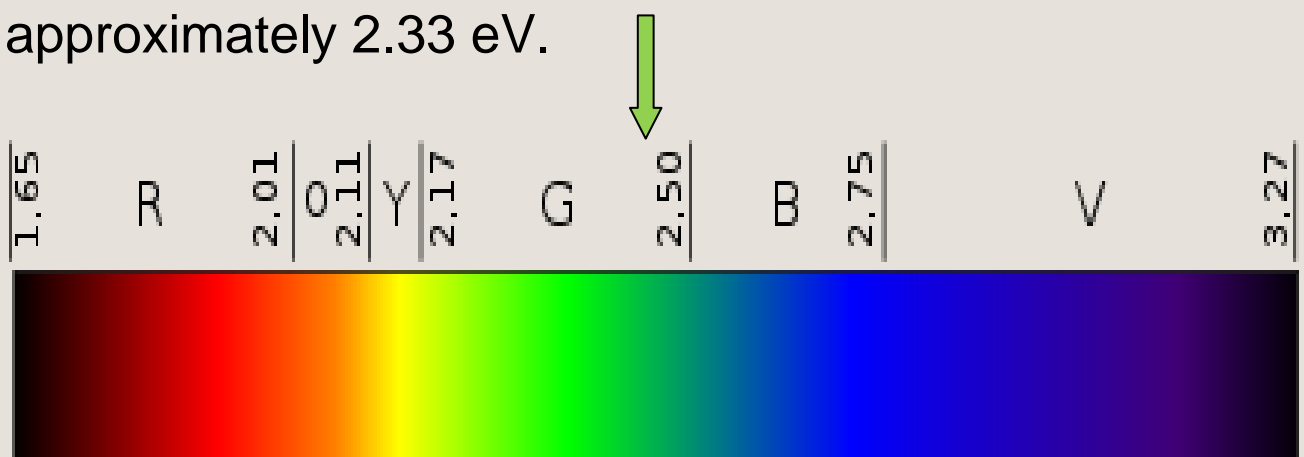
$$E = h\nu = \frac{hc}{\lambda}$$

where h is Planck's constant, c is the speed of light.

This reduces to

$$E = \frac{1240 \text{ eV}}{\lambda \text{ (nm)}}$$

A stream of photons with a wavelength of 532 nm (green light) would have an energy of approximately 2.33 eV.



Do you recall the units and energy released in a solar thermonuclear reaction?

More energy comparisons:

- 200 MeV: The total energy released in nuclear fission of one U-235 atom (on average; depends on the precise break up).
- **17.6 MeV**: The total energy released in the fusion of deuterium and tritium to form He-4 (also on average); this is 0.41 PJ per kilogram of product produced.
- 1 MeV or 1.602×10^{-13} J is about twice the rest mass-energy of an electron.
- 13.6 eV is the energy required to ionise atomic hydrogen.
- 2-3 eV is the energy of a neutrino.
- 1.3 to 2.1 eV is the photon energy of visible light.
- Molecular bond energies are on the order of one eV per molecule.

PHOTOVOLTAIC SOLAR CELLS

The Photovoltaic Effect:

This is NOT the photoelectric effect.

The photovoltaic effect is the conversion of electromagnetic radiation into electric power through absorption by a (semiconducting) material.

- Consider silicon, the most common material upon which solar cells are based.
- In a semiconductor we have to consider tightly bound electrons (valence band) and free electrons (conduction band).
- The conduction band and the valence band are separated by the band gap.
- The energy associated with this gap is

$$E_g = E_c - E_v.$$

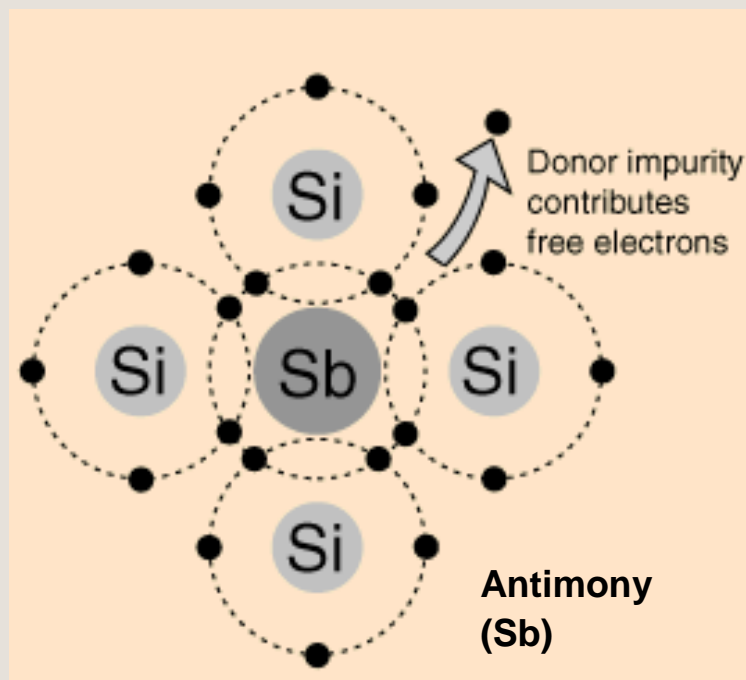
- For crystalline silicon the energy gap
 $E_g = 1.12 \text{ eV}$.
- For amorphous silicon the energy gap
 $E_g = 1.75 \text{ eV}$.
- For silicon (un-doped) there are no electrons in the conduction band.
- It behaves as an insulator, so how do we modify silicon so it can conduct?
- We need to have charge carriers in the conduction band – electrons or holes?
- The process used to do this is known as doping.
- We can dope in two ways.

Doping

Silicon is doped with either Group 5 or group 3 atoms to make what are known as n-type and p-type respectively so we can form a **pn** junction.

n-type - If silicon is doped with antimony, arsenic or phosphorous, which has five electrons in the outer orbit, and silicon has four, then four of the five phosphorous electrons can fill the valence band leaving the single electron to populate the conduction band.

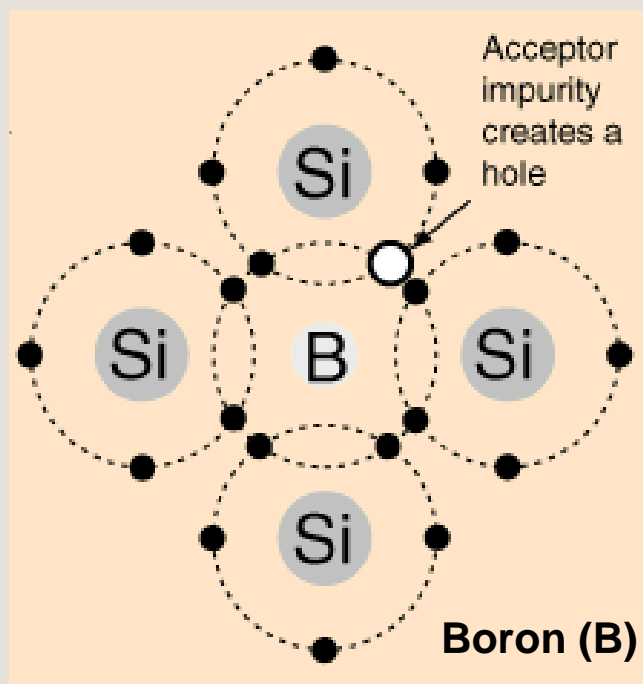
An electron has negative charge and so this doping is known as n-type.



p-type - If silicon is doped with boron, which has three electrons in the outer orbit, and silicon has four.

The three boron electrons cannot fill the valence band completely and so we have an electron void or as we know it a 'hole'.

Holes are positive charge carriers and so doping this way creates p-type silicon.



Photodiodes

What happens when you join n-type and p-type?

The p-layer is the active surface and the n-material is the substrate they form the P-N junction.

Consider the hypothetical situation of physically sticking an n-type and a p-type together.

As we know the n-type has a surplus of electrons and the p-type a surplus of holes. The band gap of each type is also different.

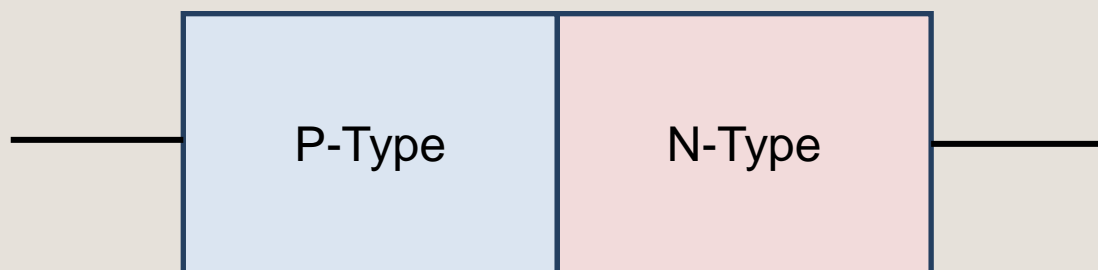
So what happens?



At the instant of contact we get



As soon as the junction is formed, free electrons and holes cross through the junction by the process of diffusion. During this process, electrons cross the junction from the N- region to the P-region.



← Electrons

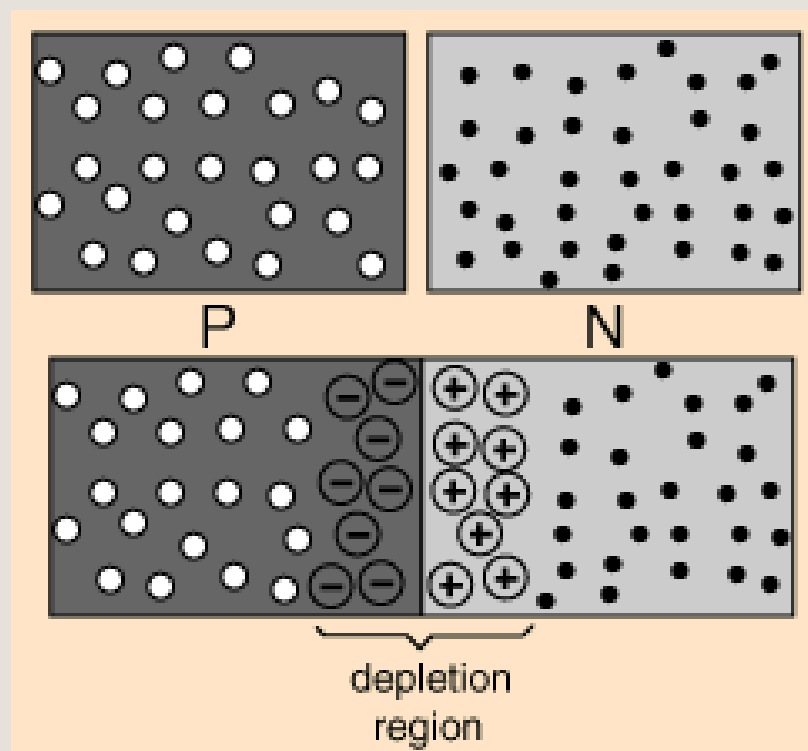
Holes →

Holes cross the junction from the P-region into the N-region

Holes crossing the junction from the P-region into the N-region, recombine with electrons in the N-region very close to the junction.

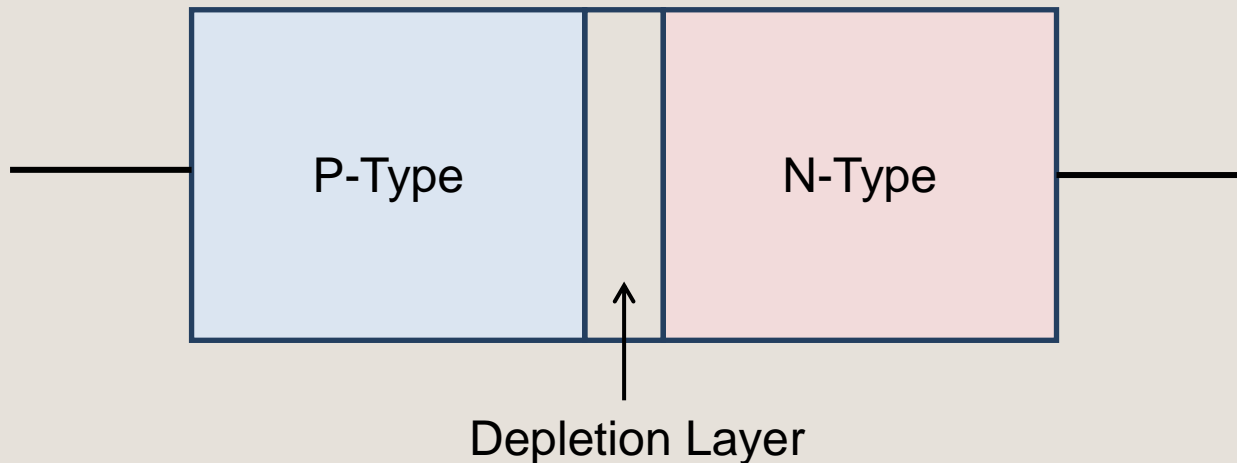
This region when formed does not have any free charge carriers.

This area around the junction is now called the **Depletion Layer**.



<http://hyperphysics.phy-str.gsu.edu/hbase/solids/pnjon.html#c2>

Looking at the depletion region now



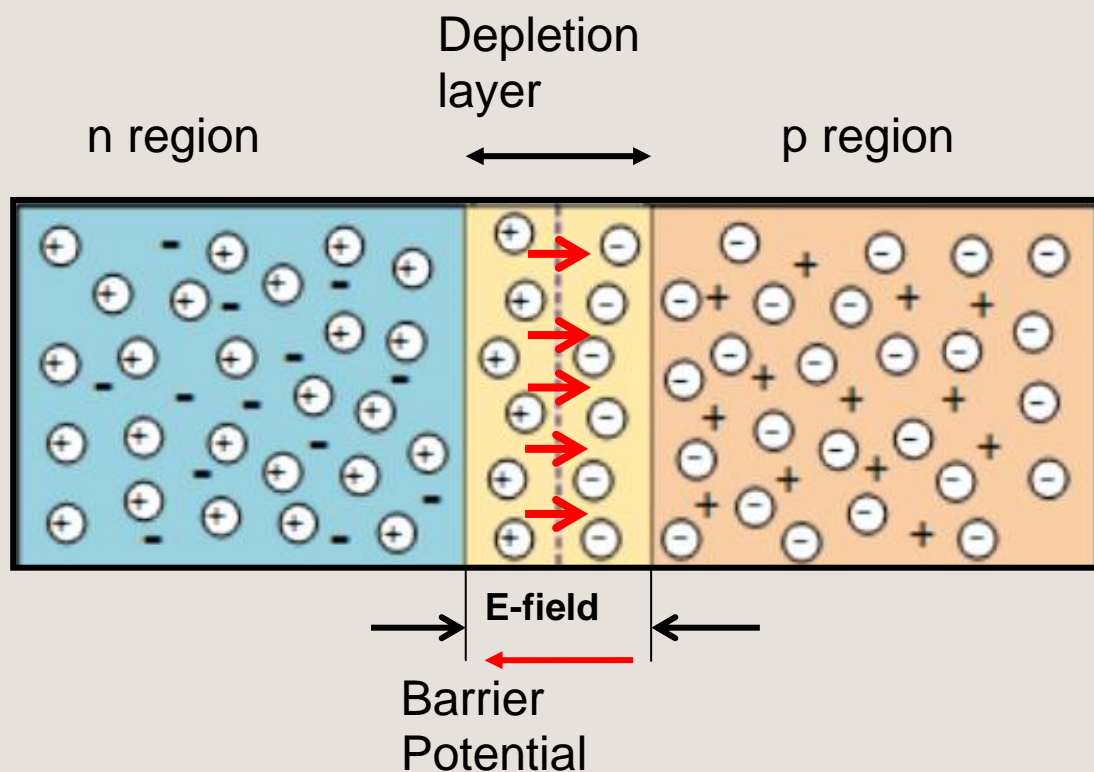
The N-type material has lost electrons and the P-type has lost holes.

This means that the N-type material has become positive with respect to the P-type.

The N-side is at a positive voltage relative to the P-side.

What does this imply?

It means that there now exists an electric field that results from the diffusion process and has created a "built-in potential difference" across the junction – the Barrier Potential.



This electric field created by the diffusion process has created a "built-in potential difference" across the junction with an open-circuit (zero bias) potential of E_0 .

The built in potential can be defined in terms of the number of donor atoms, N_D and N_A

$$E_0 = V_T \ln \left(\frac{N_D N_A}{n_i^2} \right)$$

Where:

E_0 = the zero bias junction voltage

V_T = the thermal voltage of 26mV at room

temperature $V_T = \frac{kT}{q}$

k is Boltzmann's constant $1.380 \times 10^{-23} \text{ J K}^{-1}$

q is the charge on an electron $1.6 \times 10^{-19} \text{ C}$

N_D and N_A are the impurity concentrations

and n_i is the intrinsic concentration.

For silicon the barrier potential is $\sim 0.7 \text{ V}$.

What is the intrinsic concentration n_i ??

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

n_i : intrinsic electron concentration

p_i : intrinsic hole concentration

$$n_i = p_i$$

n_i : intrinsic carrier concentration, which refers to either the intrinsic electron or hole concentration

Commonly accepted values of n_i at $T = 300^\circ\text{K}$

Silicon $1.5 \times 10^{10} \text{ cm}^{-3}$

Gallium arsenide $1.8 \times 10^6 \text{ cm}^{-3}$

Germanium $2.4 \times 10^{13} \text{ cm}^{-3}$

The PN junction - Solar Cell and the Shockley Diode

Named after the transistor co-inventor William Bradford Shockley; one of the first semiconductor devices invented.

The I–V characteristic of an ideal diode in either forward, reverse bias or zero bias are expressed by

$$I_{diode} = I_0 \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

Where:

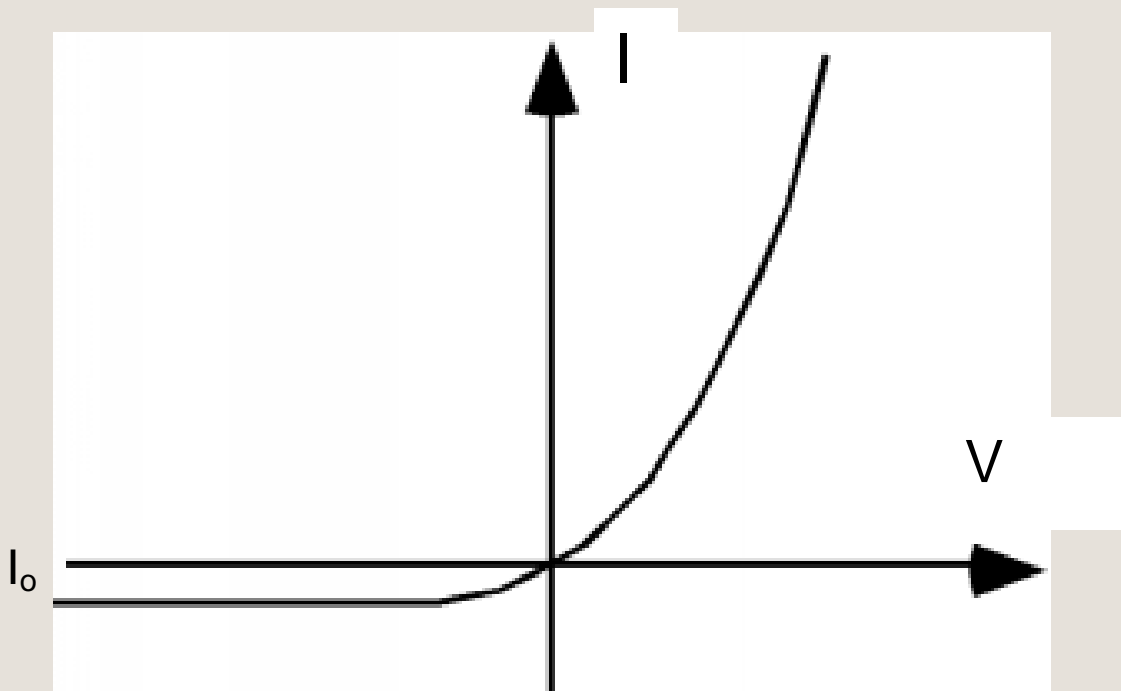
I_{diode} is the diode current

I_0 is the reverse bias saturation current

V is the voltage across the diode

k is Boltzmann's constant $1.380 \times 10^{-23} \text{ J K}^{-1}$

q is the charge on an electron $1.6 \times 10^{-19} \text{ C}$



In the absence of light, the I - V characteristics of a solar cell are also expressed by the Shockley Equation:

$$I_{diode} = I_0 \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

When light is absorbed and photo current generated, I_{photo} , the output current is represented by I – this is simply expressed as the difference between the photocurrent, I_{photo} and the diode current, I_{diode}

$$I = I_{\text{photo}} - I_{\text{diode}}$$

$$I = I_{\text{photo}} - I_0 \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

What is I_{photo} then?

I_{photo} is dependent on:

- the number of photons absorbed by the cell
- the electron charge
- the quantum efficiency
- the photon wavelength
- the surface area

Questions

- 1. What do we mean by the valence band?**
- 2. What do we mean by the conduction band?**
- 3. In a semiconductor what do we mean by band gap energy?**
- 4. For crystalline silicon the band gap is 1.12 eV and for amorphous silicon it is 1.75 eV. What does this imply?**

We have not covered this but I would like you to think about the answers.

- 5. Name some bad thermal conductors?**
- 6. Name some good thermal conductors?**
- 7. How does heat transfer occur in a good thermal conductor and a bad thermal conductor?**

Let us explore I_{photo}

Are you familiar with Photodiodes?

A photodiode is like a very small solar cell – they have different design criteria –eg Si photodiodes are often reverse biased, to change the width of the depletion layer to reduce device capacitance and improve the time response.

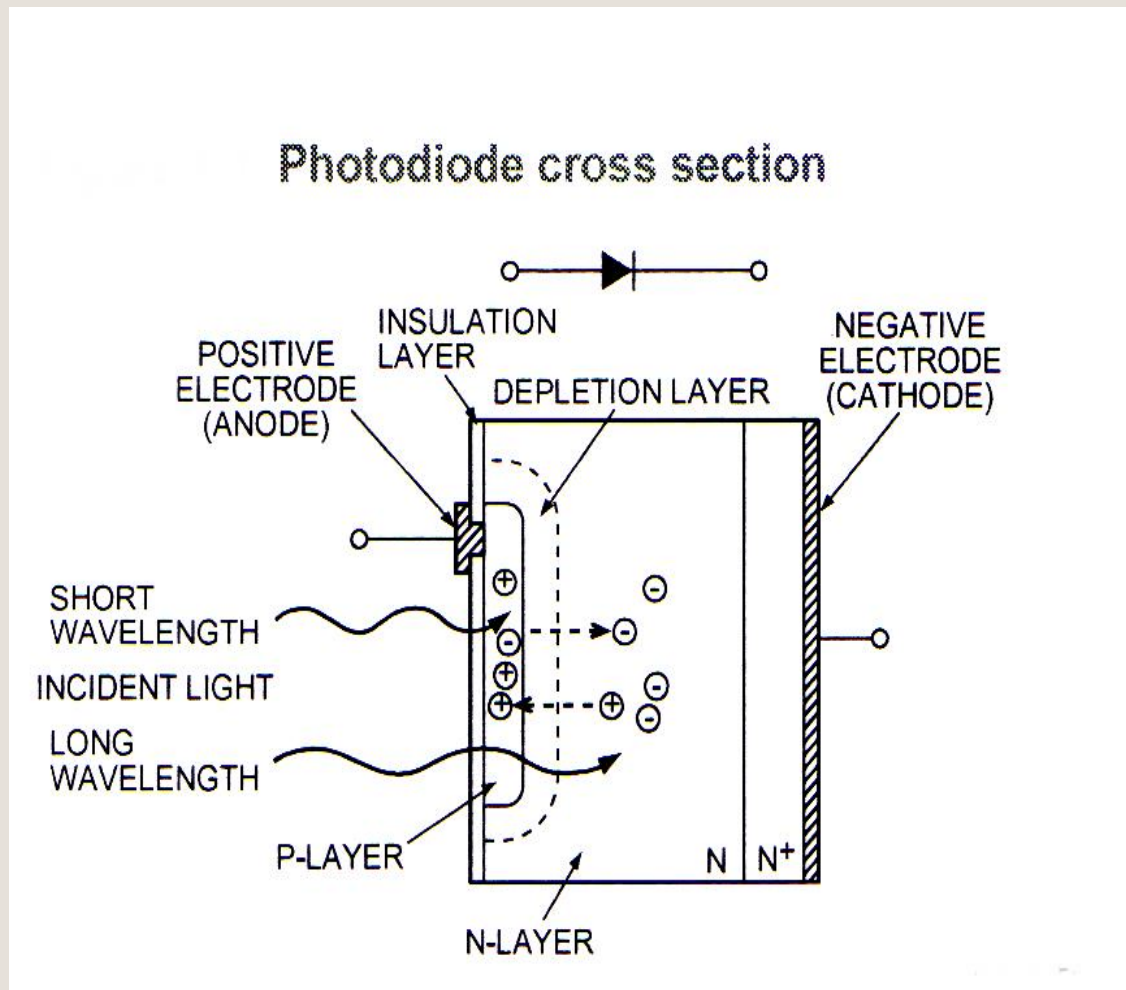


By the reducing the device capacitance the response time of the detector is improved



A photodiode is a **p-n junction** - a junction formed by combining P-type and N-type semiconductors together to form a junction.

Consider a photodiode operating in the **photovoltaic mode** .



When light is incident on the photodiode, electrons within the structure are 'excited'.

The photon energy is given by $E = h\nu$.

h = Plank's constant, ν = frequency

So, what happens when a photon is absorbed?

When a photon is absorbed, an **electron-hole** pair is formed.

How?

When light is incident on the photodiode and is absorbed, electrons within the crystal structure becomes excited or stimulated. What happens depends on the photon energy E .

If the light energy is greater than the band gap energy, E_g , the excited electrons reach the conduction band, leaving holes in their place in the valence band.

We have created an electron-hole pair.

These electron-hole pairs occur throughout the p-layer, depletion layer and n-layer materials.

In the depletion layer the built-in electric field accelerates these **electrons toward the n-layer** and the holes toward the p-layer.

Electron hole pairs formed within the depletion layer maybe '**separated**' by the electric field – a photocurrent is generated.

What about the electron-hole pairs generated in the n-layer?

We shall look at this later.

If an external circuit is connected between the p- and n-layers, electrons will flow away from the n-layer, and holes will flow away from the p-layer toward the opposite respective electrodes.

These electrons and holes generating a current flow in a semiconductor are called the charge carriers.

Do all photons generate a photocurrent?

Not all photons do!.

Silicon is often chosen because its optical band gap permits the absorption of a substantial portion of solar photons via the generation of electron-hole pairs.

The conversion process from incident photon to useful output is a lossy process.

Firstly not all photons will be absorbed due to Fresnel reflection.

Secondly not all photons generate an electron-hole pair – **quantum efficiency**.

Thirdly decay processes in the conduction band to lower level energy states will lose the excess energy by heat generation.

Can this be quantified?

If we first of all assume the incident photon flux consists of N photons that can be absorbed.

Assuming an ideal conversion process from photon to electron-hole pair we can write

$$I_{ph} = qNA$$

Where A is the surface area exposed to light and N is the number of photons incident – if we assume no losses.

At best the though conversion of photons to electrons is around 60 %.

What is the upper limit for voltage generation?

The upper limit on voltage, V , is set by

$$V = E_g / q$$

Where E_g is the band gap energy $E_c - E_v$

The situation is very lossy for crystalline silicon as it is an indirect band gap material.

Amorphous silicon is however a direct band gap material.

Important direct band gap materials like GaAs are more efficient light absorbers.

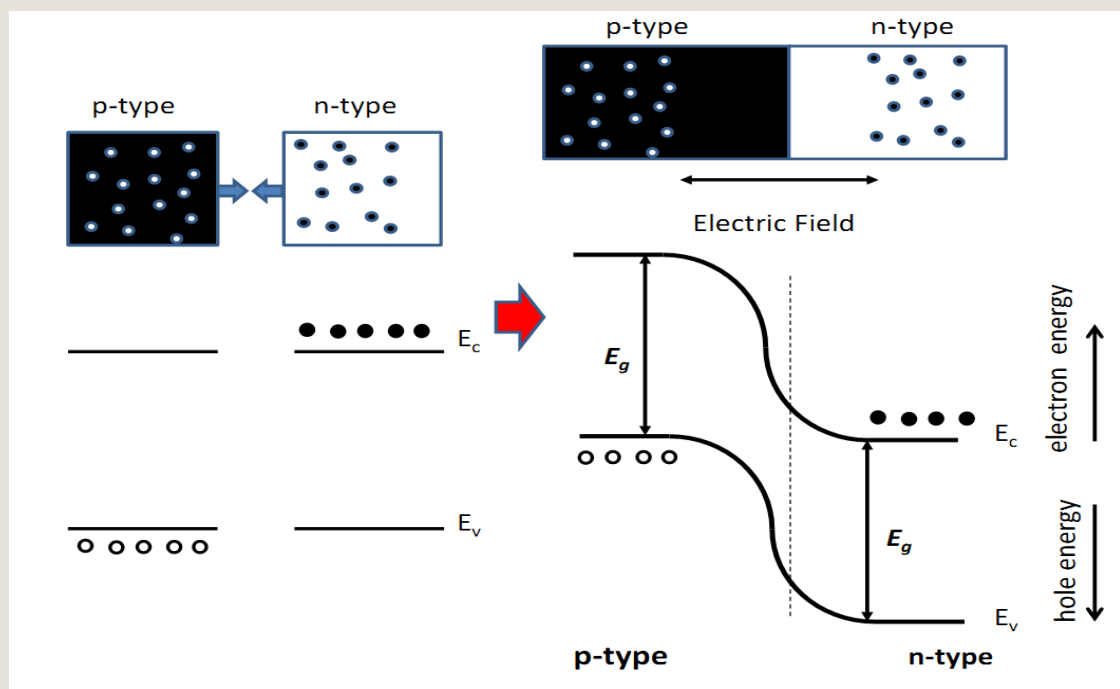
We shall look at this soon too.

First of all, what is the band gap energy.

And then, what are direct and indirect band gaps and why is this so important?

The band gap energy E_g

The band gap energy is the difference between the energy of the conduction band and the valence band:
band: $E_g = E_c - E_v$



The responsivity of the silicon solar cell is limited at both long wavelengths (less energetic) and short wavelengths (more energetic).

The **long wavelength** limit of a photodiode is limited by the band gap energy of the material used.

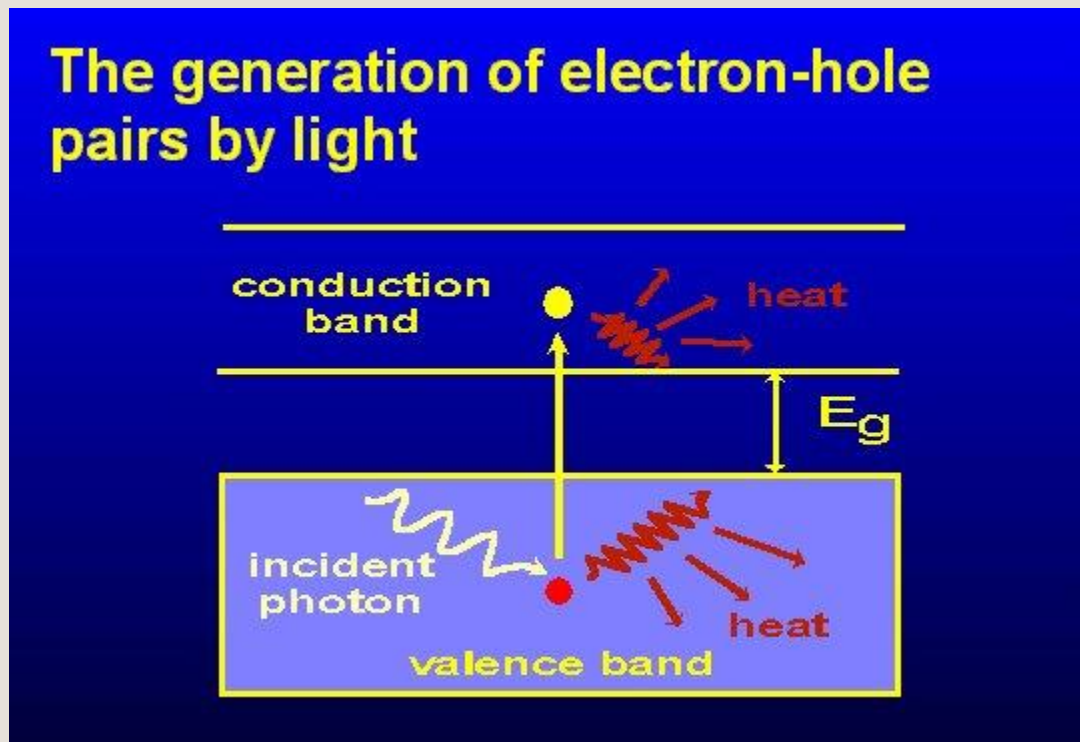
As we know $E_g = hc / \lambda$

	Energy Gap (eV)	λ (nm)	Gap Type
Crystalline Si	1.12	1100	Indirect
Amorphous Si	1.75	700	Direct
GaAs	1.42	875	Direct
InP	1.34	925	Direct

For wavelengths longer than the critical value λ_c , the photon energy is no longer sufficient to excite electrons to the conduction band and the material becomes transparent to those wavelengths.

For crystalline Si the upper limit is 1108 nm.

If this energy is greater than the band gap energy, E_g below, the electrons are excited from the valence band into the conduction band.

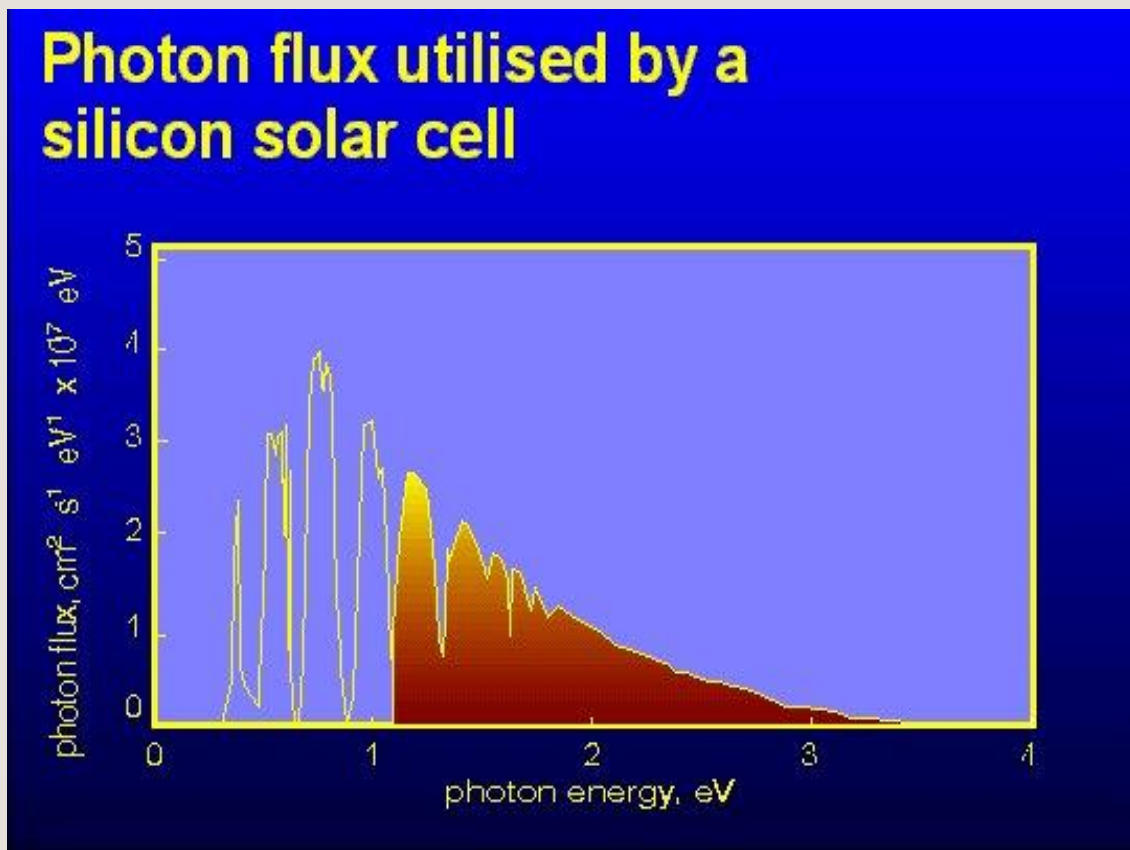


The **short wavelength limit** of a photodiode is attributed to the reduced penetration depth, or absorption length of more the energetic photons.

The carriers generated above the depletion zone are recombined before they can diffuse to the depletion zone.

The short wavelength limit can also be influenced by the protective layers on top of the photodiode, which for short wavelengths can cause significant reflection and absorption losses.

This limits the useful absorption spectrum crystalline silicon.



Note in the above figure, the x-axis is in eV.

Semiconductors - direct and indirect band gaps

The band gap of a semiconductor is always one of two types:

a **direct band gap**

or

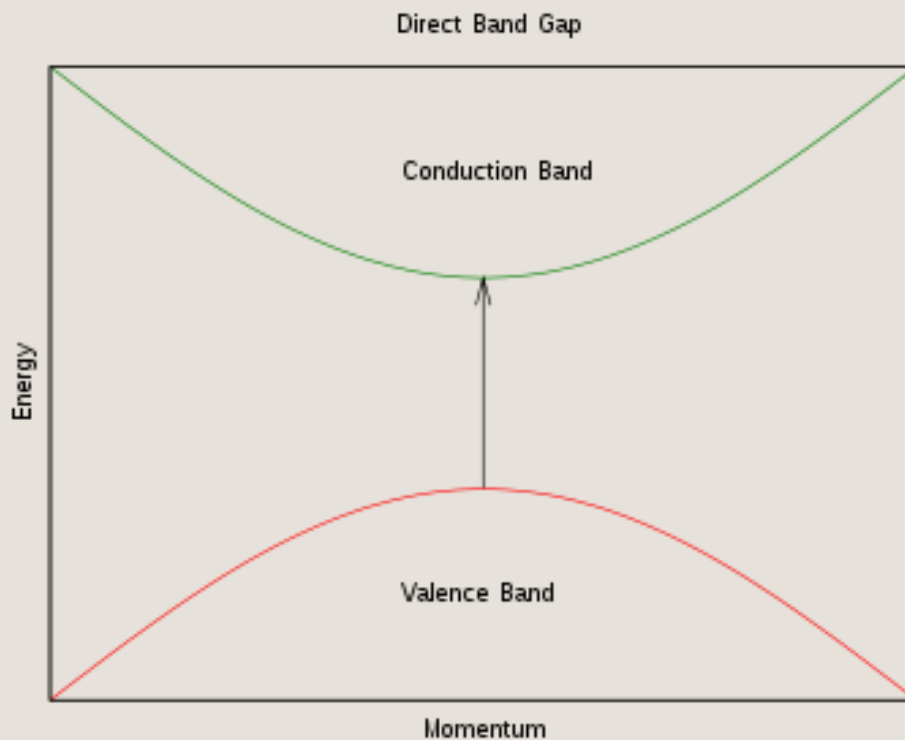
an **indirect band gap**.

The band gap represents the minimum energy difference between the top of the valence band and the bottom of the conduction band,

However, the top of the valence band and the bottom of the conduction band is not always at the same value of the **electron momentum**.

In a **direct band gap semiconductor**, the top of the valence band and the bottom of the conduction band occur at the same value of momentum.

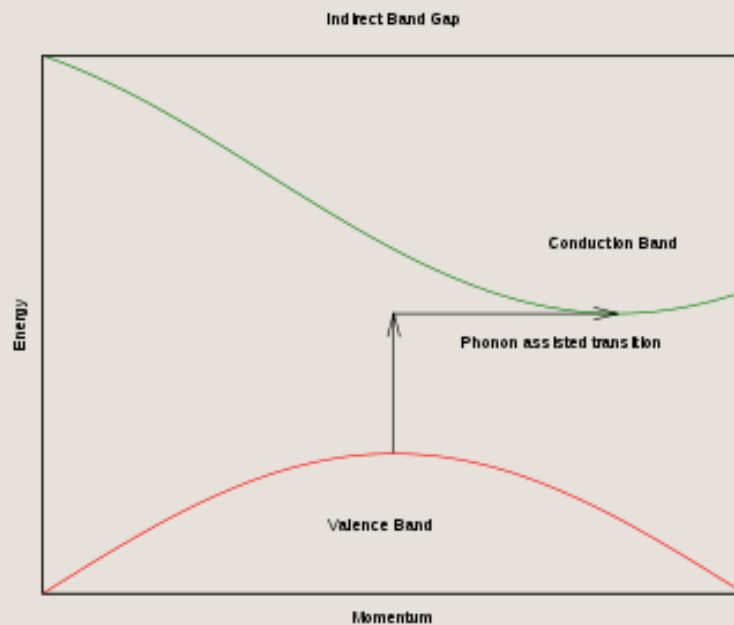
Direct band gap semiconductor



Energy vs. crystal momentum for a semiconductor with a direct band gap

- Depicted is a transition in which a photon excites an electron from the valence band to the conduction band.
- An electron can shift from the highest-energy state in the valence band (red) to the lowest-energy state in the conduction band (green) without a change in momentum.

Indirect band gap semiconductor



Energy vs. crystal momentum for a semiconductor with an indirect band gap

- An electron cannot shift from the highest-energy state in the valence band (red) to the lowest-energy state in the conduction band (green) without a change in momentum.
- Here, almost all of the energy comes from a photon while almost all of the momentum comes from a phonon.
- Phonon = Quantized Lattice Vibration

Solar Cells - so how do we go from photodiode to solar cell?

Light absorbing materials can often be used in *multiple physical configurations* to take advantage of different light absorption and charge separation mechanisms.

Photovoltaic panels are normally made of either single(mono) crystalline or polycrystalline silicon.

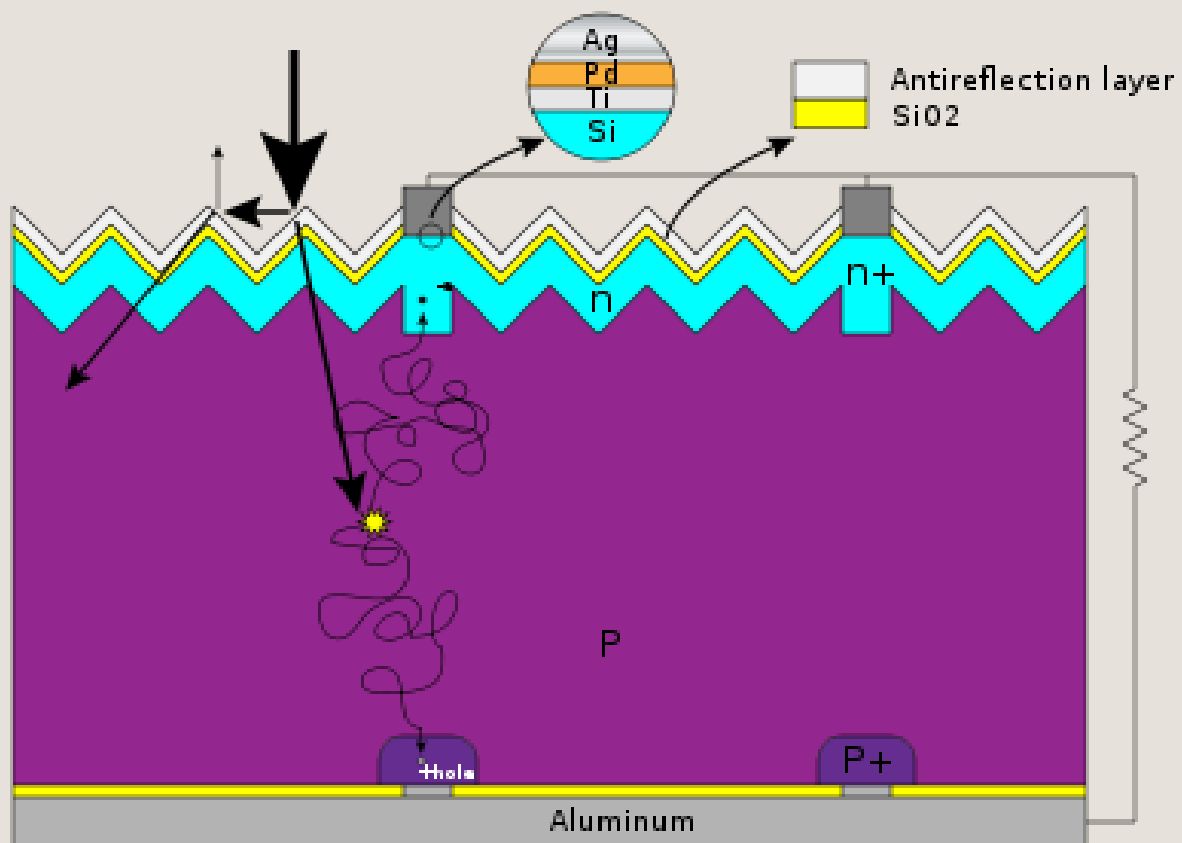
Thin film silicon is also used to extend and enhance PV performance.

Many currently available solar cells are configured as bulk materials that are subsequently cut into wafers and treated in a "top-down" method of synthesis (silicon being the most prevalent bulk material).

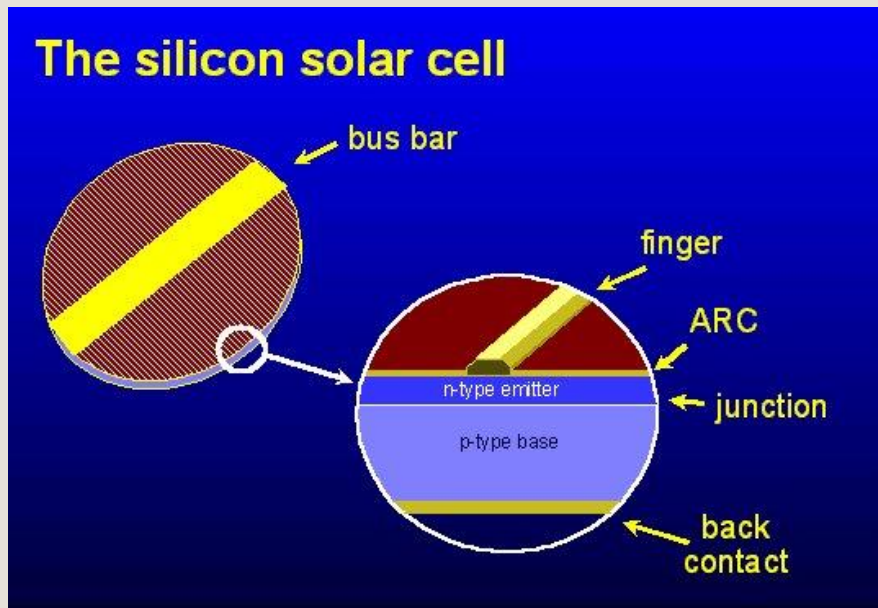
Bulk

Bulk technologies are often referred to as wafer-based manufacturing.

Here, self-supporting wafers between 180 to 240 μm thick are processed and then soldered together to form a solar cell module.



Cross-section of a silicon solar cell



A typical crystalline silicon solar cell.

The electrical current generated in the semiconductor is extracted by contacts at the front and rear of the cell.

The top contact is made in the form of widely-spaced thin metal strips (usually called *fingers*) that supply current to a larger bus bar.

To reduce reflective losses the cell is covered with a thin layer of dielectric material to reduce Fresnel reflection, or the surface is textured.

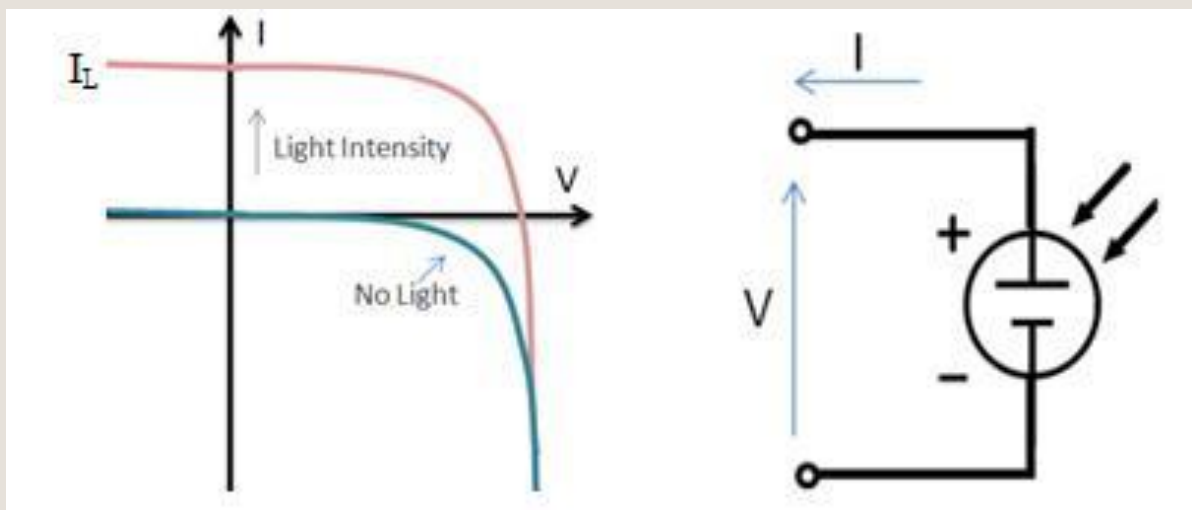
PV Cell Output Power

Recall that the output current is I and is simply expressed as the difference between the photocurrent, I_{photo} and the diode current, I_{diode}

$$I = I_{\text{photo}} - I_{\text{diode}}$$

$$I = I_{\text{photo}} - I_0 \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

This is illustrated below:



The short circuit current is the photo current I_{photo}

Short Circuit Current (I_{sc})

The short circuit current I_{sc} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0.

$$I \text{ (at } V=0) = I_{sc}$$

I_{sc} occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant.

For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.

$$I_{sc} = I_{MAX} = I_l \text{ for forward-bias power quadrant}$$

Open Circuit Voltage (V_{OC})

The open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.

$$V \text{ (at } I=0) = V_{OC}$$

When $I = 0$ the open circuit voltage is:

$$V_{openct} = \frac{kT}{q} \ln \left(\frac{I_{photo}}{I_{diode}} - 1 \right)$$

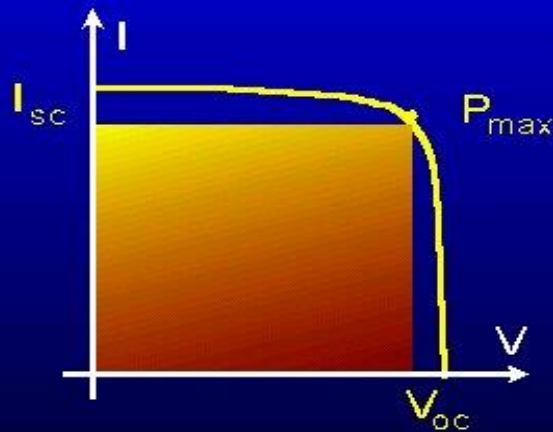
The cell delivers maximum power P_{max} when operating at a point on the characteristic where the product IV is a maximum as shown.

For an **ideal cell** with no losses the maximum power, P_{max} , is given by:

$$P_{max} = I_{SC} \cdot V_{OC}$$

Actual power generated is less than this.

The I-V characteristic of a solar cell with the maximum power point



The efficiency (η) of a solar cell is defined as the power P_{max} supplied by the cell at the maximum power point under standard test conditions, divided by the incident radiation power.

We shall refer back to this when we look at the fill factor for a panel.

An excellent web resource for solar PV may be found here:

<http://pveducation.org/pvcdrom/>

Power Loss

With cell efficiency always low this implies that there are considerable losses to account for.

- (i) Silicon solar cells are indirect band gap materials and so the excitation of phonons will dissipate as heat.
- (ii) There will be reflection losses at the surface.
- (iii) There are 'dead' losses to or 'shady' losses.
- (iv) There will be losses associated with the band gap energy – only photon with sufficient energy can be used for solar conversion.
- (v) Photons with shorter wavelengths (higher energy) have carrier-recombination losses.
- (vi) Impurities also give rise to carrier-recombination losses.

Anything more practical we can do?

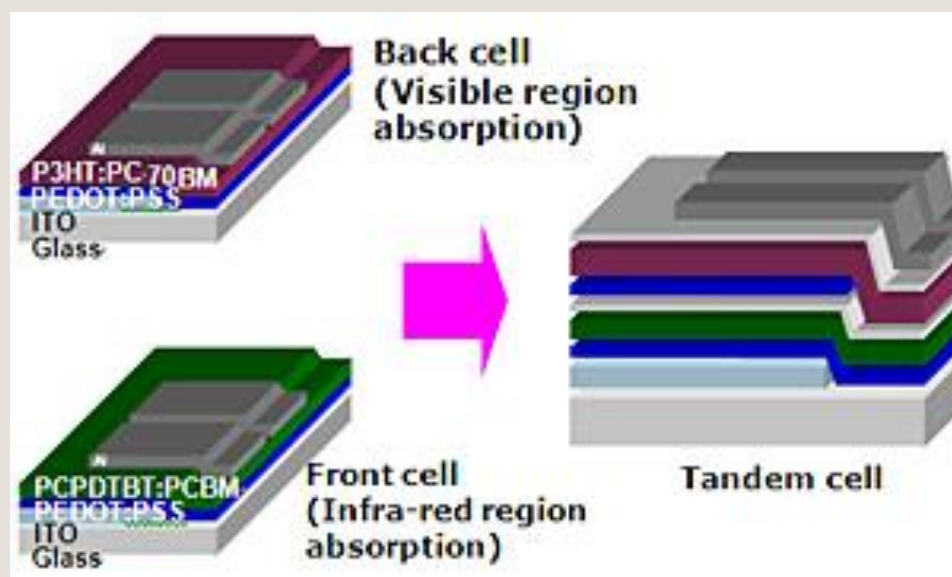
Wavelength Dependent Loss

One solution that has been proposed for (iv) and (v) is known as the tandem cell configuration.

The cell as its name implies consists of two parts:

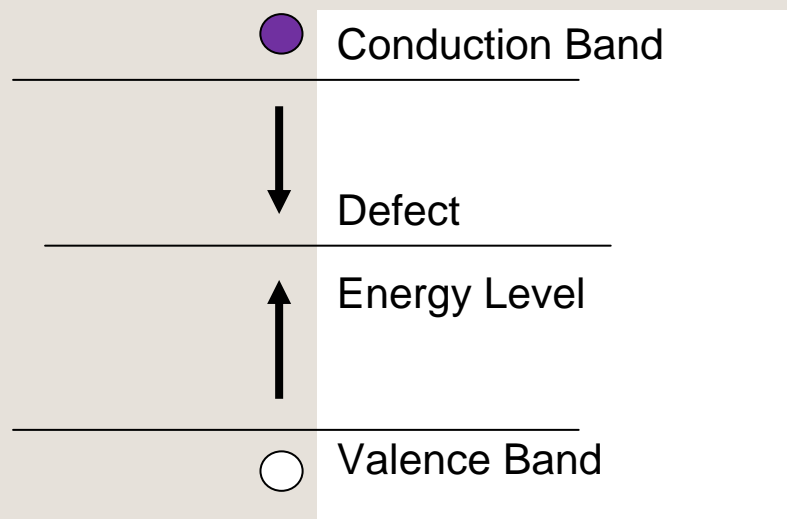
One cell has a high band gap semiconductor to sense the short wave length radiation.

The second cell converts the remaining photo energy.



Recombination

- This can occur at impurity or defect sites within the structure and an electron-hole pair that has been generated is annihilated.
- If the energy level of the defect lies between the conduction band and the valence band then the electron may go via this energy level back to the valence band.



- Where the electrical contacts are made – Ohmic contact – these losses can be significant, and they reduce both current and voltage output.

Reflective Loss

Silicon is not a very efficient absorber of light and so every effort is required to reduce this effect.

The refractive index of silicon is 3.7 and is much greater than for air (1.0) and so this mis-match leads to significant Fresnel reflection losses.

Anti-reflective coatings are used to improve this, but effective anti-reflection coatings are wavelength specific, and we have essentially a broad optical spectrum to capture.

Another method for this is to texture the surface, and combined with anti-reflection coatings the reflective losses can be as low as 1 % or 2 %.

Without coatings or texturing these losses are around 35 %!

Shady Losses

Typical solar cells exhibit losses due to the connector strips on the top of the cell.

The connectors will not enable any useful photon absorption for solar conversion purposes. This part of the solar cell is lossy.

The Stanford Cell design places all electrical contacts at the rear of the cell.

Another option, but will require device modeling to ensure good operation still is to use conducting oxides, such ITO – transparent electrodes.

The effect of Ohmic contacts becoming Schottky contacts will be significant.

Absorption Spectra

As we know the Cut off at long wavelengths occurs for silicon at a wavelength of $1.1\text{ }\mu\text{m}$, where the photon energy is just sufficient to transfer an electron across the silicon band gap.

As this wavelength is approached the probability of photon absorption decreases rapidly with increasing wavelength.

The absorption coefficient also increases with increasing temperature leading to an increase in long wavelength responsivity with temperature.

The penetration depth for 90% absorption can be calculated from the absorption coefficient data and plotted against wavelength.

For wavelengths less than 400 nm, 90% absorption occurs at depths of less than 0.5 μm .

At the wavelength of 1.0 μm a silicon thickness of 1mm would be required for 90 % absorption.

And at 1.1 μm , 5mm is required for 90% absorption.

These widely differing absorption depths result in very different design constraints on solar cells intended for use at opposite ends of the spectrum.

The sensitivity of a photovoltaic device may also be expressed in practical units of amps of photodiode current per watt of incident illumination - A/W.

This parameter, usually known as the responsivity, $R(\lambda)$, is expressed as:

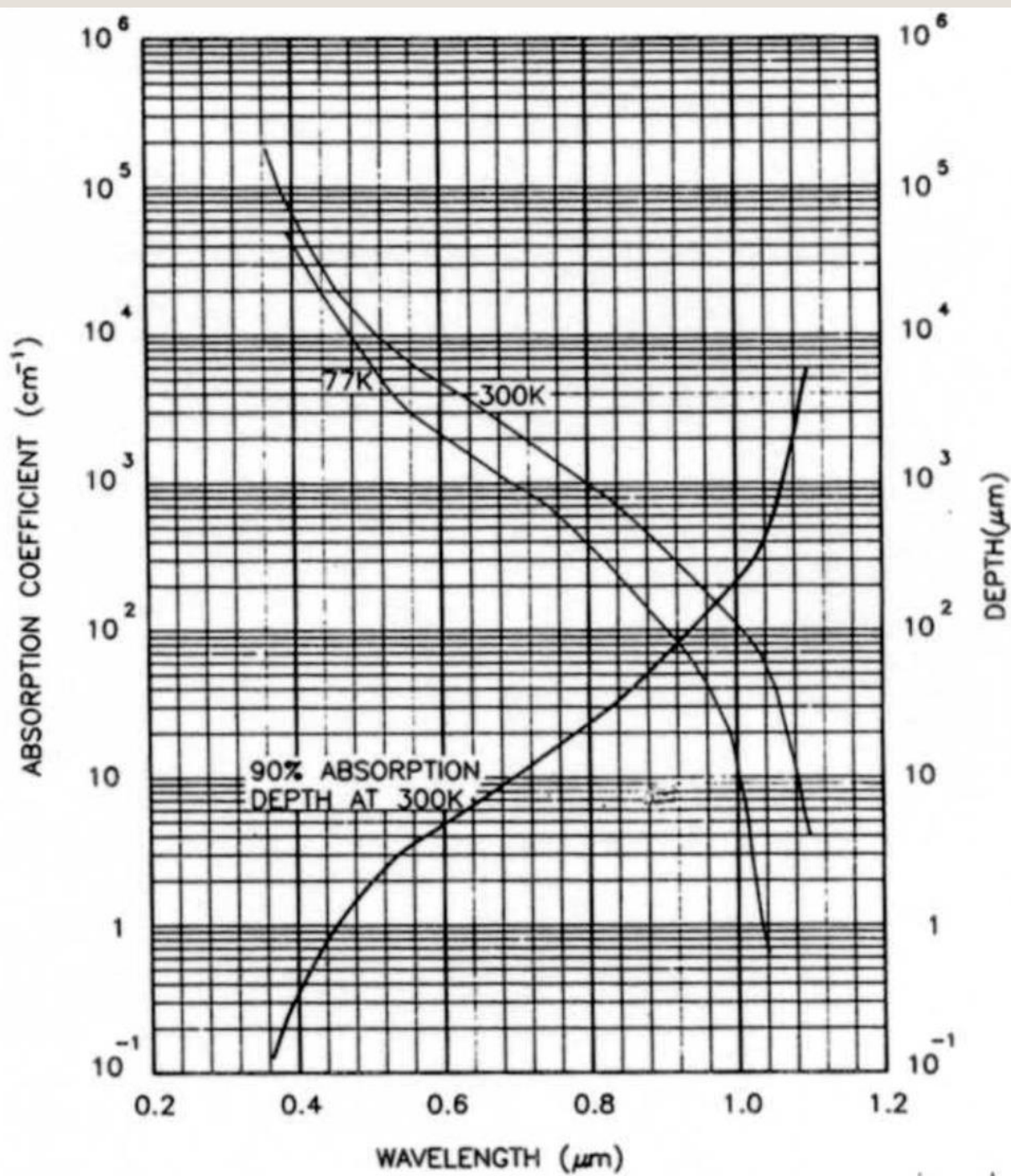
$$R(\lambda) = \frac{\text{Quantun Efficiency (\%)} \cdot \lambda(\text{microns})}{124} (\text{A/W})$$

This relationship leads to a tendency for responsivity to reduce as the wavelength becomes shorter.

For example:

At 900nm, 80% Q.E. represents a responsivity of 0.58 A/W,

At 430nm, the same Q.E. gives only 0.28 A/W.



Ohmic Losses

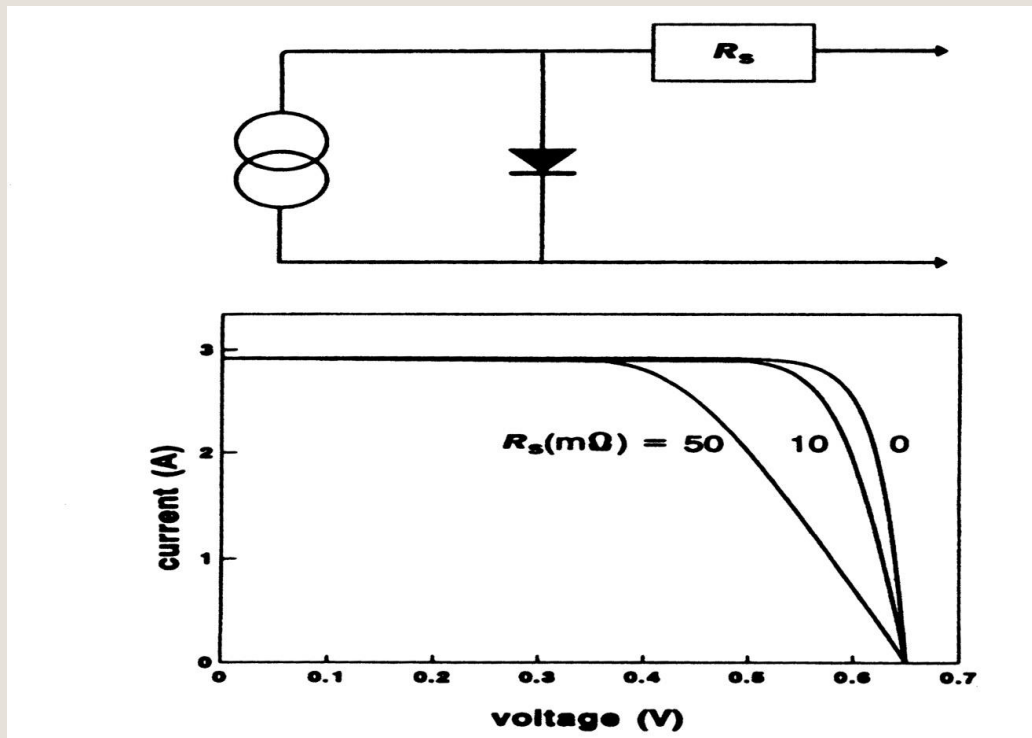
Resistive loss in a solar cell can be accounted for by incorporating a series resistor, R_s , into the equivalent circuit.

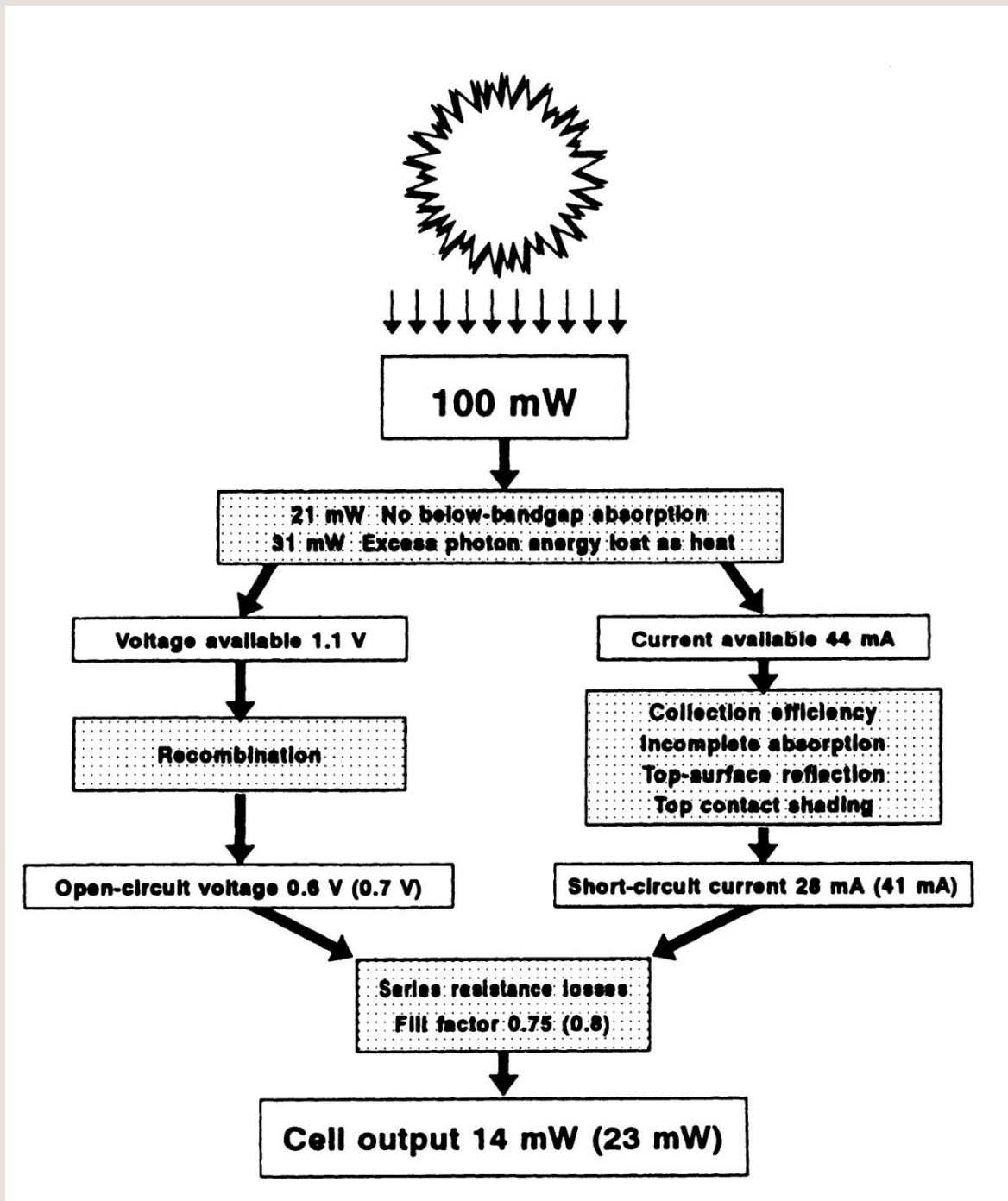
$$I = I_{photo} - I_0 \left[\exp\left(\frac{qV + IR_s}{mkT}\right) - 1 \right]$$

m = non-ideal factor $\cong 1.0$

These can be attributed to crystal defects.

The photo generated current I_{photo} accounts for all **non-ohmic** losses.





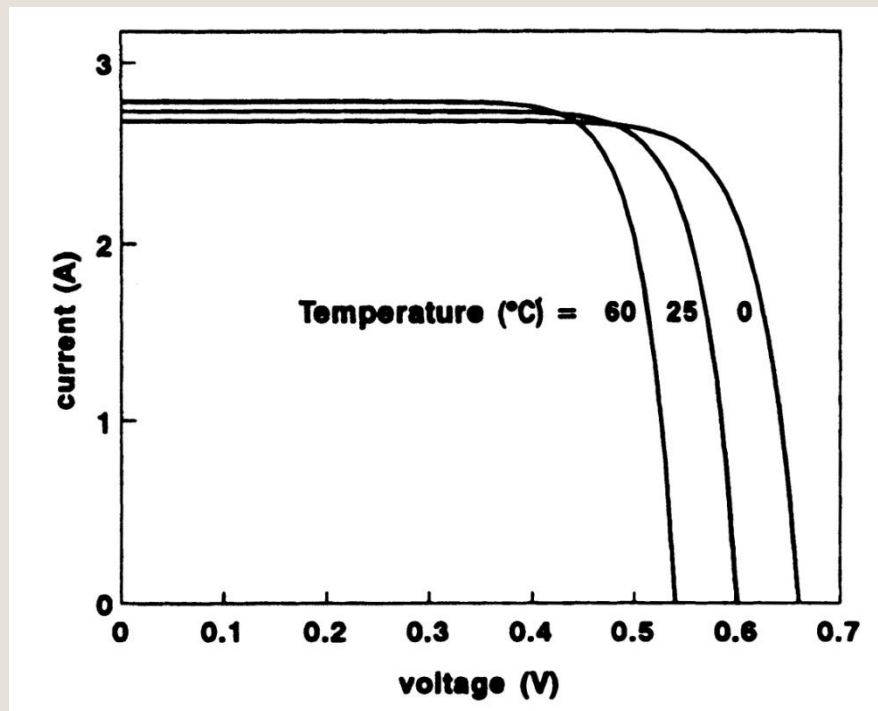
The evolution of the loss processes
in a typical silicon solar cell.

It is useful to understand the effect of the irradiance and ambient temperature on the solar cell and module performance, in order to estimate their I-V curves under various climatic conditions.

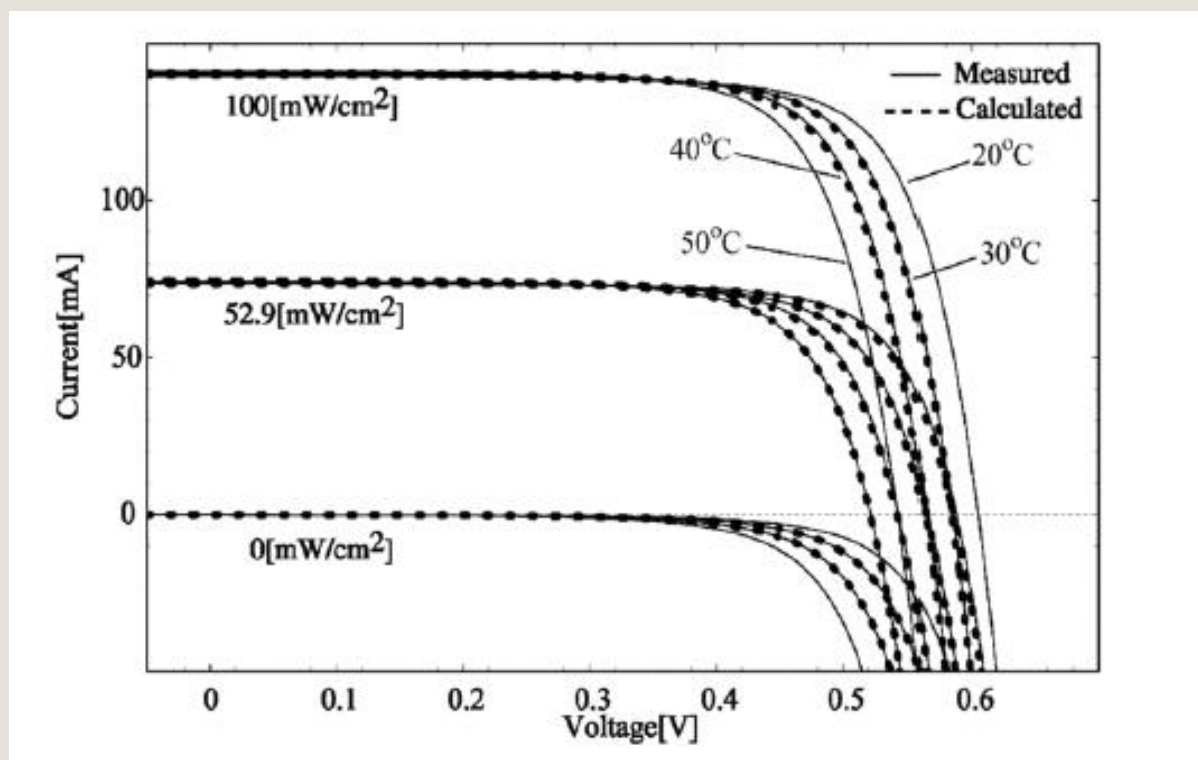
The effect will be different for single-crystalline Si, polycrystalline Si, amorphous Si and a-Si/thin-film crystalline Si tandem cells.

Solar cells are based upon semiconductor materials, so a significant factor affecting device performance is temperature – a significant mobility parameter.

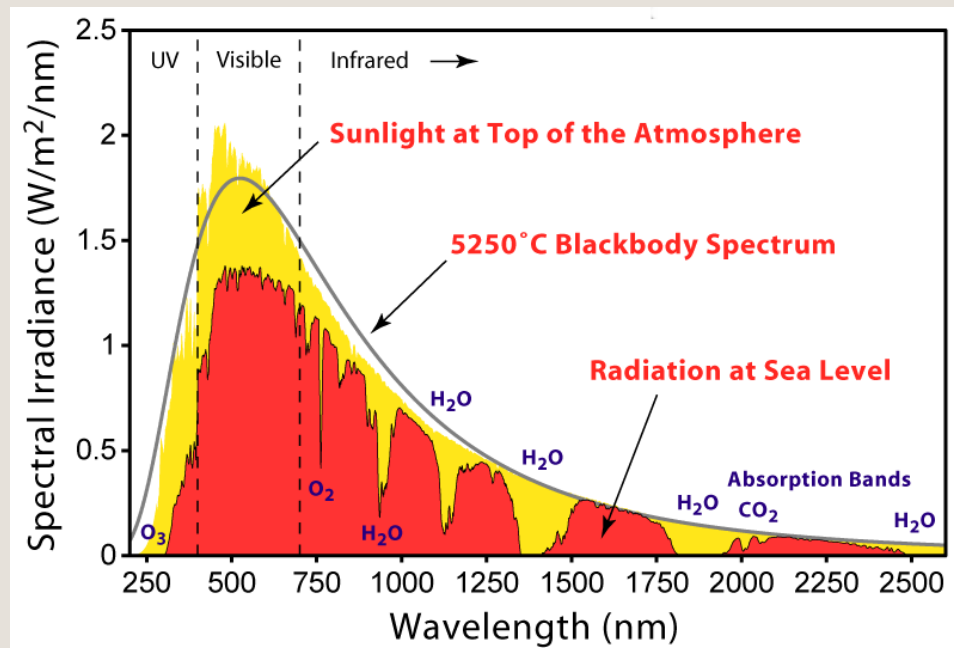
The voltage output reduces significantly with increasing temperature – reducing by around $2.3 \text{ mV} / ^\circ\text{C}$. There is little affect on current generation



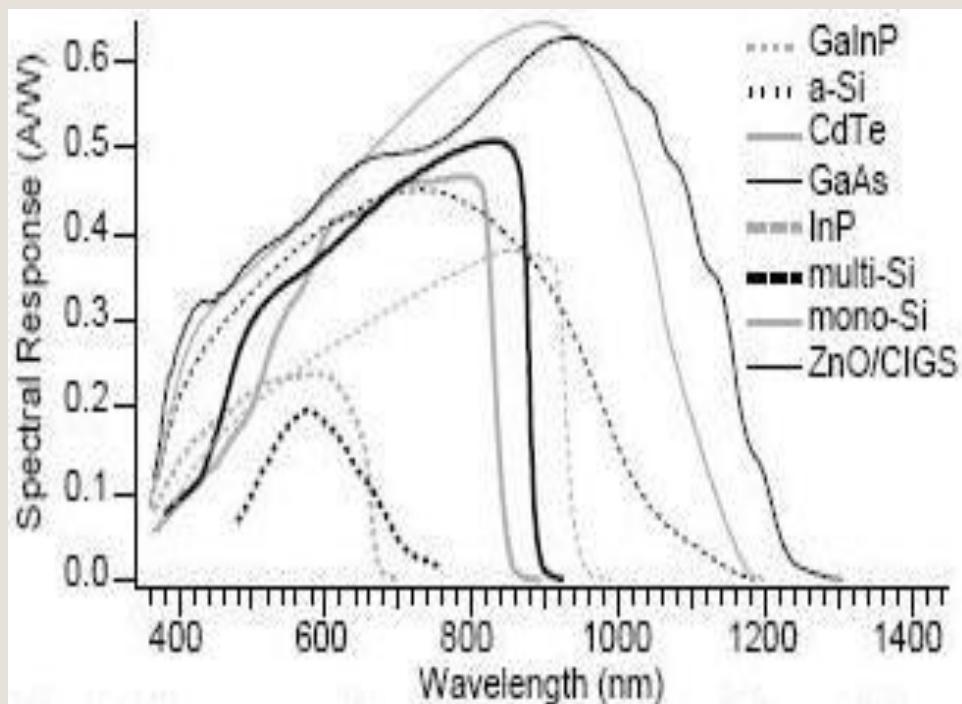
Irradaiance



Solar Cell Spectral Response



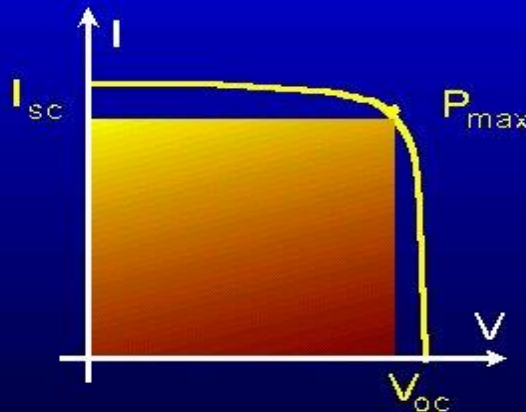
The Sun's Spectrum



The Spectral Response of Solar Cells

Maximum Output Power Theory

The I-V characteristic of a solar cell with the maximum power point



As can be seen above, a solar cell's power output can be characterised by two numbers:

- A maximum Open Circuit Voltage (V_{oc} when $I = 0$).
- A Short Circuit Current (I_{sc} , when $V = 0$).

Remember that power can be computed from

$$P = I.V$$

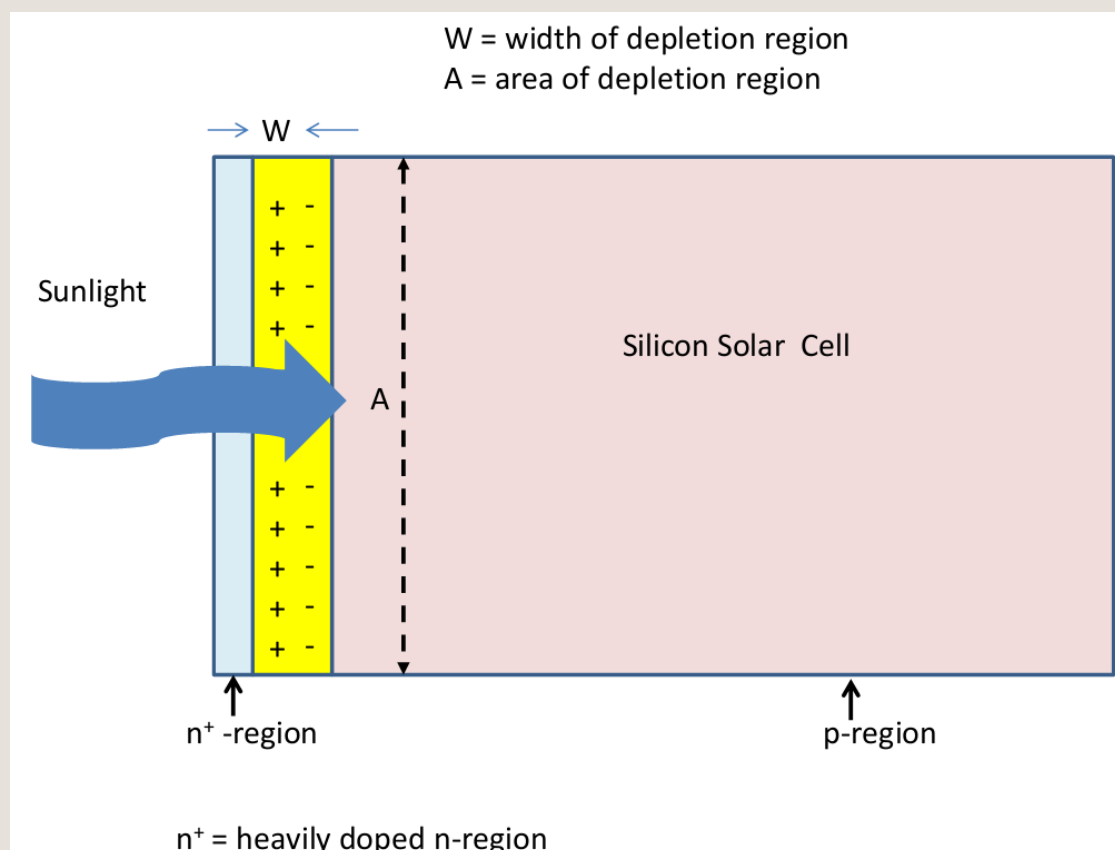
Short Circuit Current (I_{sc})

Solar cell with heavily doped n-region

If we assume the current generation rate within the depletion layer is constant then the current $I_{depletion}$ is given by:

$$I_{depletion} = qGWA$$

Where G = current generation rate



There are also contributions from the n and p regions at the boundary of the depletion layer as carriers diffuse into the depletion region – contributing to the total photo current generated.

The width of these regions is assumed to be the carrier diffusion length L .

This enables the current to be determined from

$$I_{SC} = qAG(L_n + W + L_p)$$

How do we determine the carrier diffusion length?

Without charge carrier mobility the photovoltaic output would not be suitable for energy solutions/.

Carrier diffusion results from charge carrier mobility.

The diffusion length of electrons and holes is given by the following:

$$L_n = \sqrt{D_n \tau_n}$$

$$L_p = \sqrt{D_p \tau_p}$$

Where D is the diffusivity (cm^2/s) and τ is the recombination lifetime (s). We need to also know the carrier mobility, μ , which is the ratio of the carrier drift speed and the applied electric field - and has units $\text{cm}^2.\text{V}^{-1}.\text{s}^{-1}$.

The electron and hole diffusivity and mobility are both related through the Einstein relations to the thermal voltage, $V_T = kT / q \sim 26 \text{ mV}$ at 300 K.

Einstein relations:

$$\frac{D_n}{\mu_n} = \frac{kT}{q} \qquad \frac{D_p}{\mu_p} = \frac{kT}{q}$$

*

See A. Kitai – Principles of Solar Cells, LEDs and Diodes

The mobility μ is given by

$$\mu = \frac{q\tau}{m^*}$$

Where m^* is the **effective mass** of the electron or hole - for electrons or holes in a semiconductor the mass differs from the mass of a free electron - affecting the carrier mobility and the resulting current.

	Electron Mobility μ_n cm/V/s	Hole Mobility μ_p cm/V/s	Effective mass m_n^*/m	Effective mass m_p^*/m
Silicon	1350	480	1.08	0.56

Table: The mobility and effective mass for electrons and holes in silicon.

This means we can now calculate the carrier diffusion lengths for electrons and holes.

The short circuit current I_{SC} corresponds to the short circuit condition when the voltage $V = 0$.

$$I_{SC} = qAG(L_n + W + L_p)$$

q = electron charge C

A = junction area of depletion region cm^2

G = optical generation rate $\text{cm}^{-3} \text{s}^{-1}$

W = width of depletion region cm

L_n and L_p = carrier diffusion length of electrons and holes respectively.

We can now calculate: $P_{MAX} = V_{OC} \cdot I_{SC}$

Example – what is the power output we can predict?

Silicon Solar Cell Power Generation

Consider a silicon pn junction illuminated by sunlight which gives an optical generation, G , of $G = 5 \times 10^{19} \text{ cm}^{-3} \text{ s}^{-1}$ for a depletion region of area of 100 cm^2 and a width W of $3 \mu\text{m}$.

Given, the saturation current, $I_0 = 1 \times 10^{-9}$

and, the carrier lifetime of $\tau_n = \tau_p = 2 \mu\text{s}$ for both electrons and holes

- (i) What is the optical current generated within the depletion layer?

$$I_{\text{depletion}} = qGWA$$

$$I_{\text{depletion}} = 1.6 \times 10^{-19} \times 5 \times 10^{19} \times 1.6 \times 10^{-19} \times 3 \times 10^{-4} \times 100$$

$$\therefore I_{\text{depletion}} = 0.24 \text{ A}$$

- (ii) What is the total optical current generated?

In this case we have $I_{SC} = qAG(L_n + W + L_p)$

From Einstein's relation we have

$$D_n = \mu_n \frac{kT}{q}$$

For silicon the carrier lifetime is $2\mu s$.

We use the following to determine L

$$L_n = \sqrt{D_n \tau_n}$$
$$L_p = \sqrt{D_p \tau_p}$$

This gives $I_{SC} = 10.9 \text{ A}$

- (iii) What is the open circuit voltage for this cell?

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L}{I_0} - 1 \right)$$

We have just calculated I_L and we are given I_0 as

$$I_0 = 1 \times 10^{-9} \text{ A}$$

We know that the thermal voltage at 300 K is ~26 mV.

This gives

$$V_{OC} = 0.6 \text{ V}$$

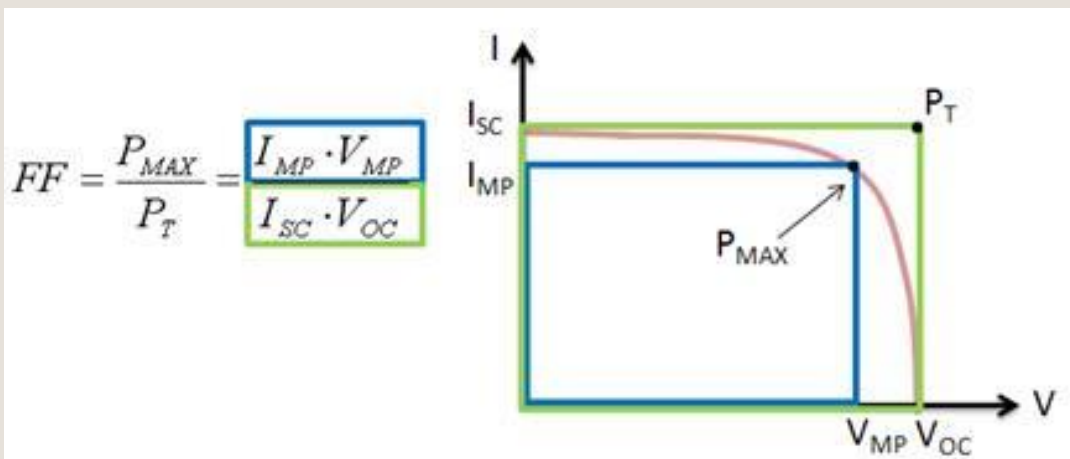
- (iv) Finally what is the power generated?

$$P_{\max} = I_{SC} \times V_{OC} = 10.9 \times 0.6 = 6.5 \text{ W}$$

Or is it?

We are given the solar cell fill factor, $FF = 0.75$.

Fill Factor:



By multiplying the open circuit voltage by the short circuit current and accounting for the fill factor we determine the actual maximum power possible.

$$P_{\max} = FF \times I_{SC} \times V_{OC} = 4.9 \text{ W}$$

$$\therefore P_{\max} = 4.9 \text{ W}$$



SOLAR PANELS



Crystalline Solar Cells

Historically, crystalline silicon (c-Si) has been used as the light-absorbing semiconductor in most solar cells.

As we know it is a relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material.

Nevertheless, it has proved convenient because it abundant and also relatively cheap (11-16%, around half to two-thirds of the theoretical maximum)

There are two types of crystalline silicon used in the PV industry.

- mono-crystalline
- poly-crystalline

Mono-crystalline is a single crystal produced by slicing wafers (up to 150mm diameter and 350 microns thick) from a high-purity single crystal boule. Single crystal means there is a single crystalline orientation, such as $\langle 111 \rangle$.

The second is **multi-crystalline** or **polycrystalline** silicon, made by sawing a cast block of silicon first into bars and then wafers.

The main trend in crystalline silicon cell manufacture is toward single-crystal technology.

For both single - and multi-crystal Si, a semiconductor homojunction is formed by diffusing phosphorus (n-type) into the top surface of the boron doped Si wafer.

Screen-printed contacts are applied to the front and rear of the cell. The front contact pattern is specially designed to allow maximum light exposure of the Si material with minimum electrical (resistive) losses in the cell.

The **most efficient production cells** use mono-crystalline Si with laser grooved, buried grid contacts for maximum light absorption and current collection.

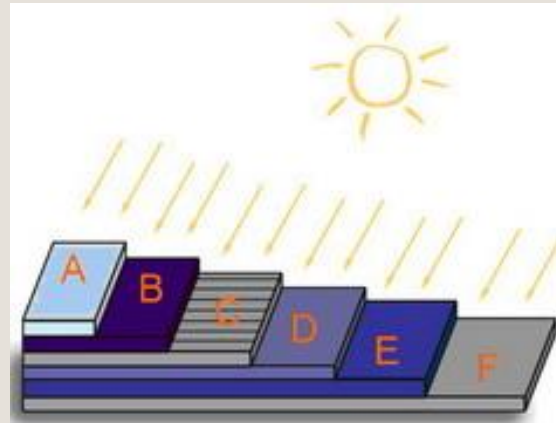
Each crystalline silicon (c-Si) cell generates about 0.5V, so 36 cells can be soldered together in series to produce a module to charge a 12V battery.

The cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be guaranteed for up to 25 years!!

A. Glass Cover Plate:

The cover plate is used to protect the cells from the elements. This should be kept clean in

order to achieve maximum efficiency.



B. Antireflective coating: Silicon is a highly reflective material so an antireflective coating is used to reduce the losses due to reflection. The anti-reflection coating is around 70 nm thick.

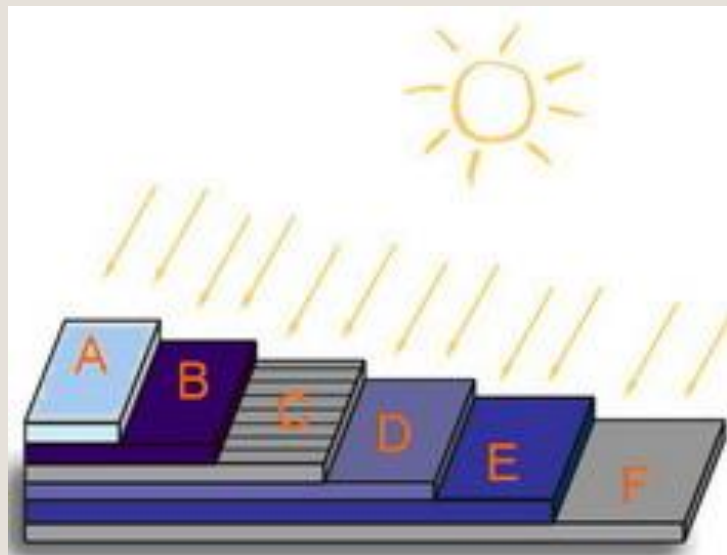
C. Contact Grid: The electricity generated by the silicon needs to be able to flow to the terminals. To help with this a grid of wire is placed on top of the silicon so that the electricity can flow through the low resistance wire instead of the silicon. A grid must be used so that most of the silicon is left exposed to the light.

D. Silicon Layers: N –type layer is formed on the top by diffusing phosphorous to a depth around $0.5\ \mu\text{m}$.

E. This is essentially the P-type substrate of around $300\ \mu\text{m}$ thickness.

F. Bottom

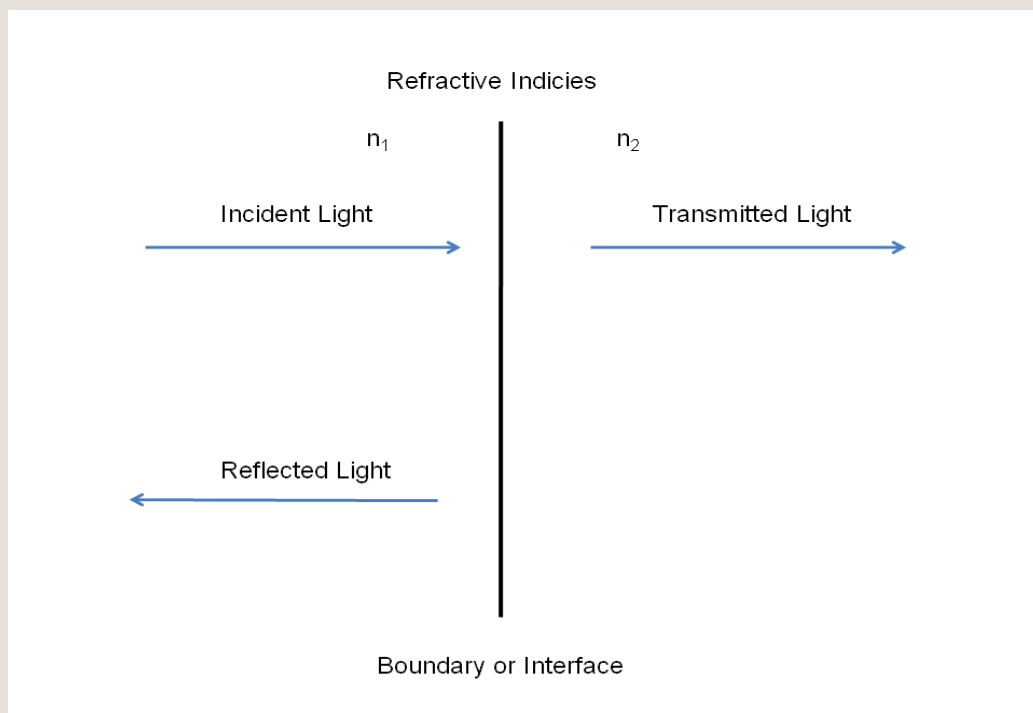
Contact: This layer works the same as the contact grid that is placed above the silicon layers.



It is used to help the electricity flow to the terminals. Since the bottom of the silicon not have to be exposed to the light, the bottom contact can cover the entire surface of the silicon.

Anti-Reflection Layers

Reflections are a fundamental issue in silicon solar technology – due to its high refractive index in the 400-1000 nm spectral range.



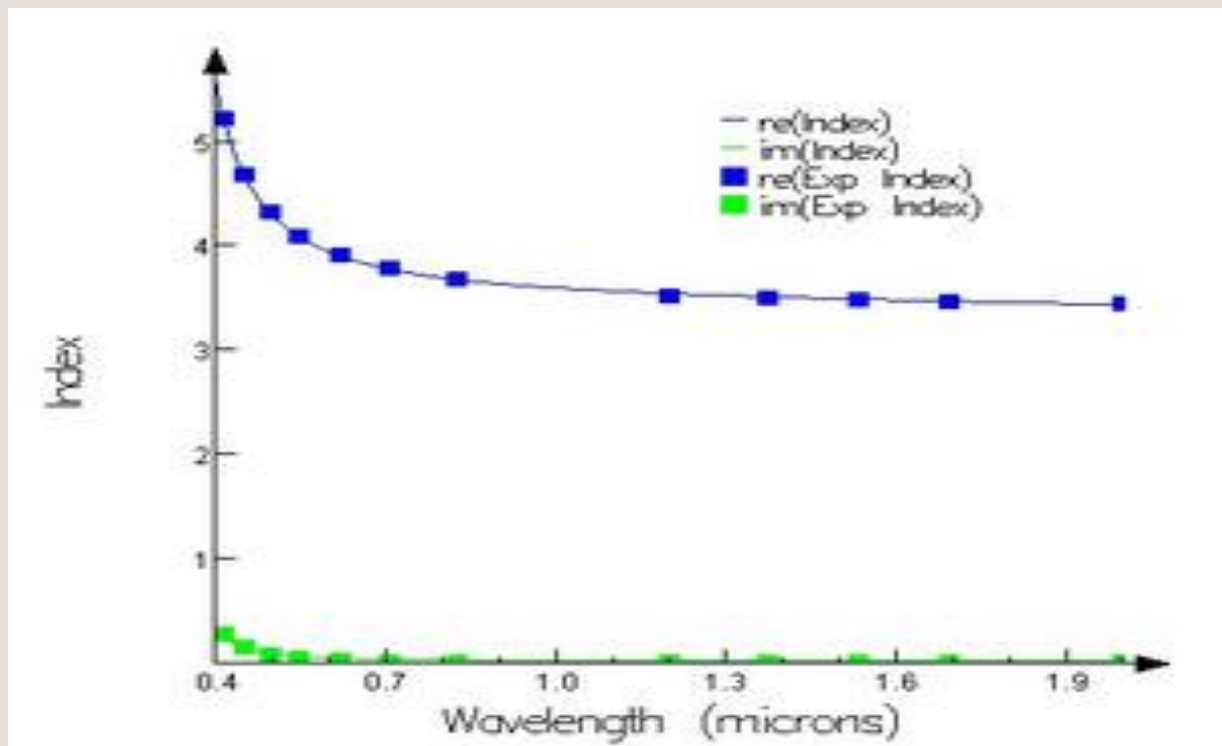
For light at normal incidence we define a reflection coefficient ρ

$$\rho = \frac{n_1 - n_2}{n_1 + n_2}$$

From this we can determine the reflectance, R , defined as the ratio of reflected to incident beam intensity:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

For an air-glass interface, what do we have for R ?



If we take $n = 3.7$ at 600 nm for silicon and $n = 1.0$ for air.

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$
$$R = \left(\frac{3.7 - 1}{3.7 + 1} \right)^2$$
$$R = \left(\frac{7.29}{22.09} \right) = 0.33$$

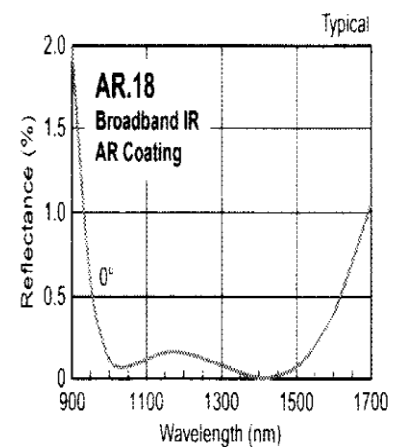
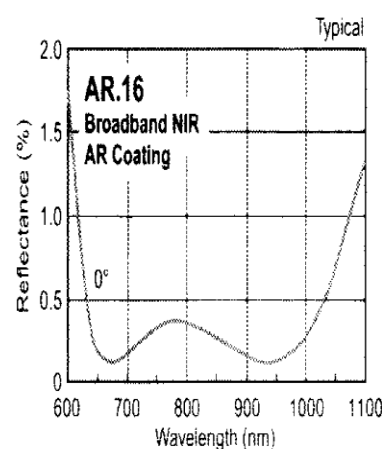
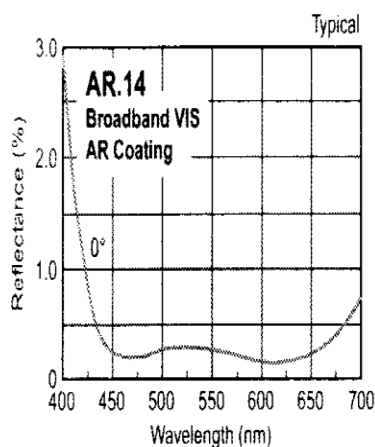
Thus with no consideration for R we would have a reflectivity of around 33 %.

To achieve anti-reflection properties we need to use a multilayer approach as single layer coatings are wavelength specific.

Broad band A/R coatings:

Broadband Multilayer Antireflection Coatings markedly improve the transmission efficiency of solar cell by reducing surface reflections over a wide wavelength range.

Wavelength Range (nm)	Center Wavelength (nm)	Reflectivity per Surface	Angle of Incidence
245–440	320	$R_{avg} < 0.5\%$, $R_{max} < 1.0\%$	0–15°
430–700	530	$R_{avg} < 0.5\%$, $R_{max} < 1.5\%$	0–15°
650–1000	790	$R_{avg} < 0.5\%$, $R_{max} < 1.5\%$	0–15°
1000–1550	1210	$R_{avg} < 0.5\%$, $R_{max} < 1.5\%$	0–15°



Another approach is this.

Find the 'average refractive index of the glass-silicon interface.

Glass: $n_{gl} = 1.5$

Silicon: $n_{Si} = 3.7$

$$n = \sqrt{n_{gl} n_{Si}} = 2.35$$

To obtain anti-reflection across the band we select the wavelength at which the incident light intensity is a maximum; this around $\lambda = 650$ nm.

We need a dielectric film of thickness d , $d = \lambda / n$

Thus, $d = \lambda / n = 650 / 2.35$ nm = 277 nm.

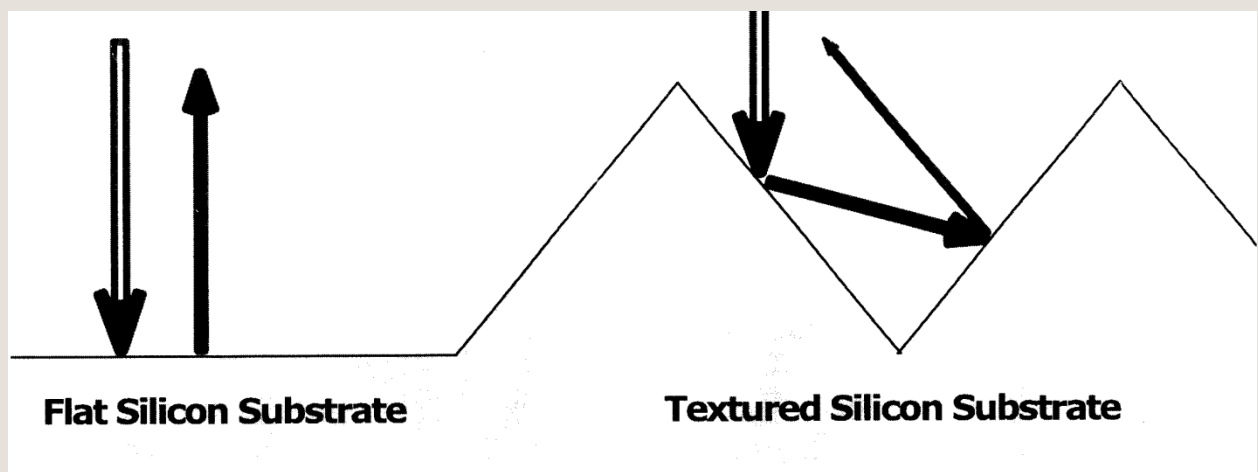
Titanium oxide TiO_2 is used in the solar cell industry. Silicon nitride (Si_3N_4) is also suitable.

Textured Surface:

This technique utilises the crystalline structure of silicon to produce a textured surface.

“Textured” surface - a surface covered with a periodic regular pattern, produced by applying anisotropic etching of silicon.

By choosing crystal orientation of the substrate, asymmetric sectional profile can be obtained, though the profile is limited to saw tooth only.

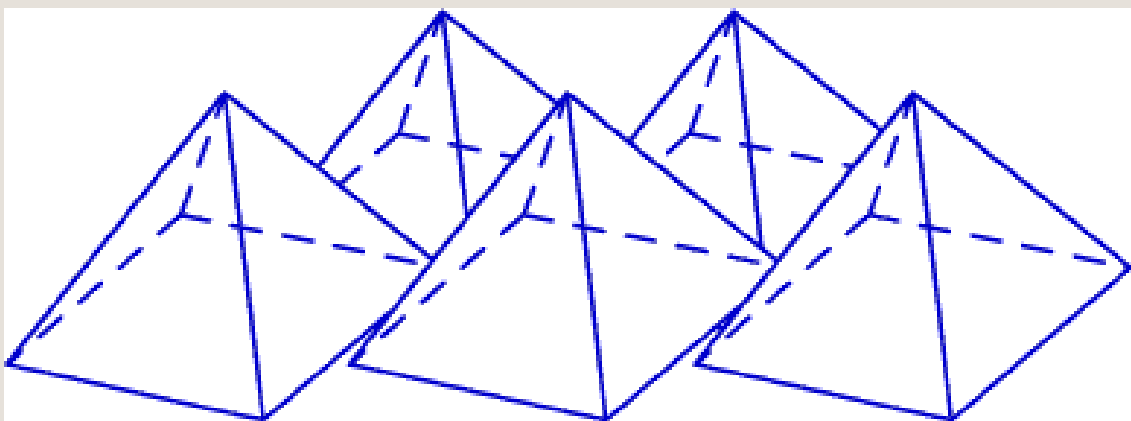


Surface texturing can be accomplished in a number of ways.

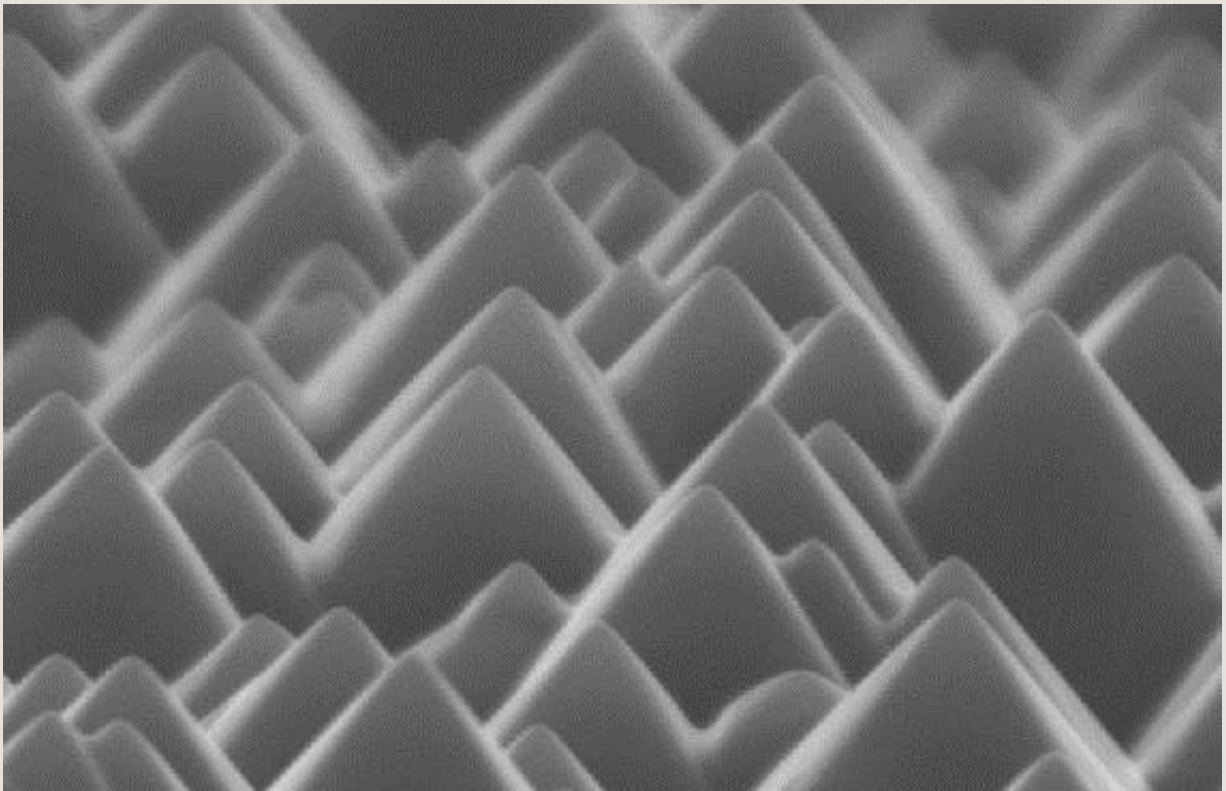
A single crystalline substrate can be textured by etching along the faces of the crystal planes.

The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms.

One such pyramid is depicted below.



An electron microscope photograph of a textured silicon surface is shown in the photograph below.

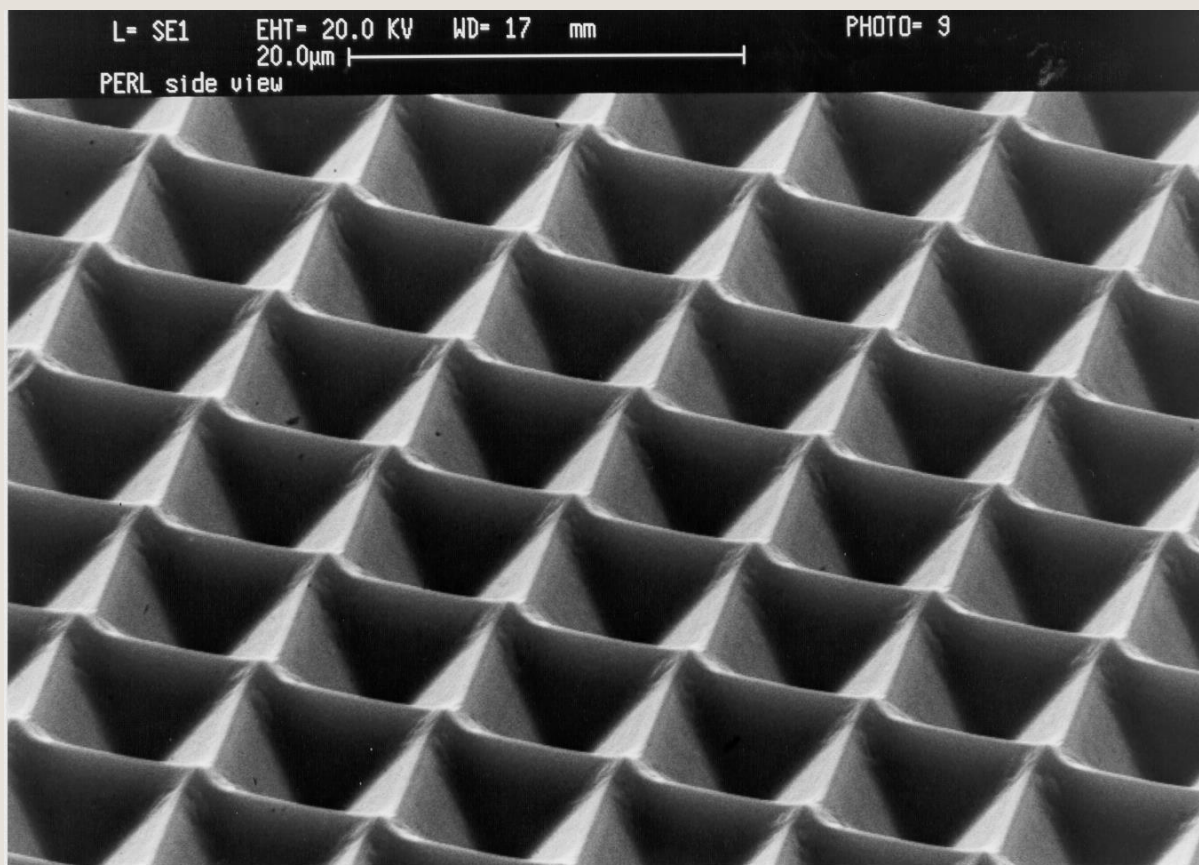


This type of texturing is called "random pyramid" texture, and is commonly used in industry for single crystalline wafers.

Inverted pyramid" texturing

Another type of surface texturing used is known as "inverted pyramid" texturing - the pyramids are etched down into the silicon surface rather than etched pointing upwards from the surface.

A photograph of such a textured surface is below.

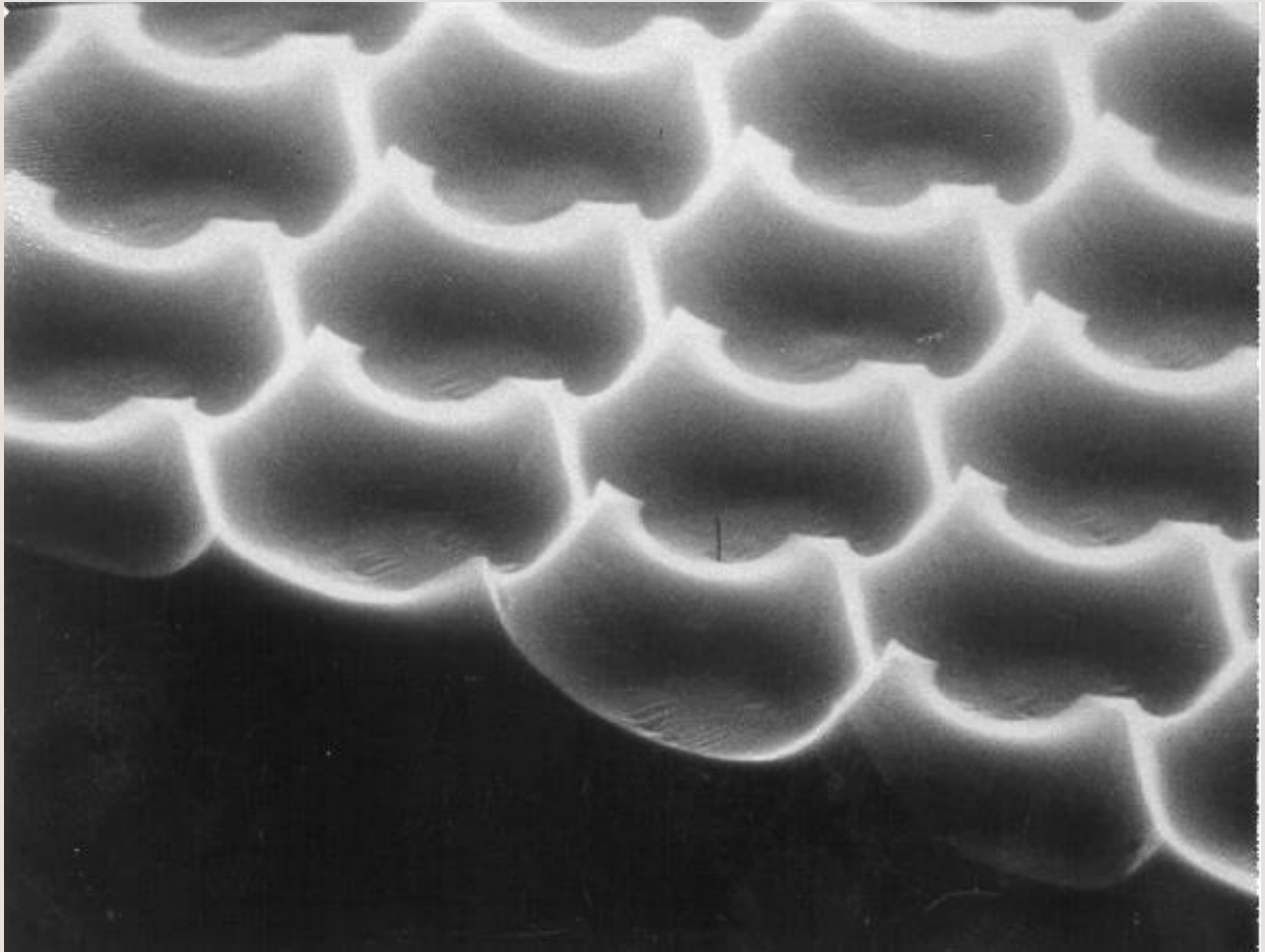


Polycrystalline wafers cannot be textured by using either of the above methods since effective surface morphology can only be achieved when the top surface consists of an exposed $\langle 111 \rangle$ crystal plane.

For multicrystalline wafers, only a small fraction of the surface will have the required orientation of $\langle 111 \rangle$ and consequently these techniques cannot be used in multicrystalline wafers.

However, multicrystalline wafers can be textured using a photolithographic technique as well as mechanically sculpting the front surface using dicing saws or lasers to cut the surface into an appropriate shape.

A micrograph of a photolithographic texturing scheme is shown below.



The reflectivity of silicon (36 %) is reduced to around 12 % when textured.

If a glass cover layer is used then reflectivity is decreased by a further 2% - but there is also a 4 % loss at the air-glass interface.

Contacts

Screen-printed contacts are applied to the front and rear of the cell, with the front contact pattern specially designed to allow maximum light exposure of the Si material with minimum electrical (resistive) losses in the cell.

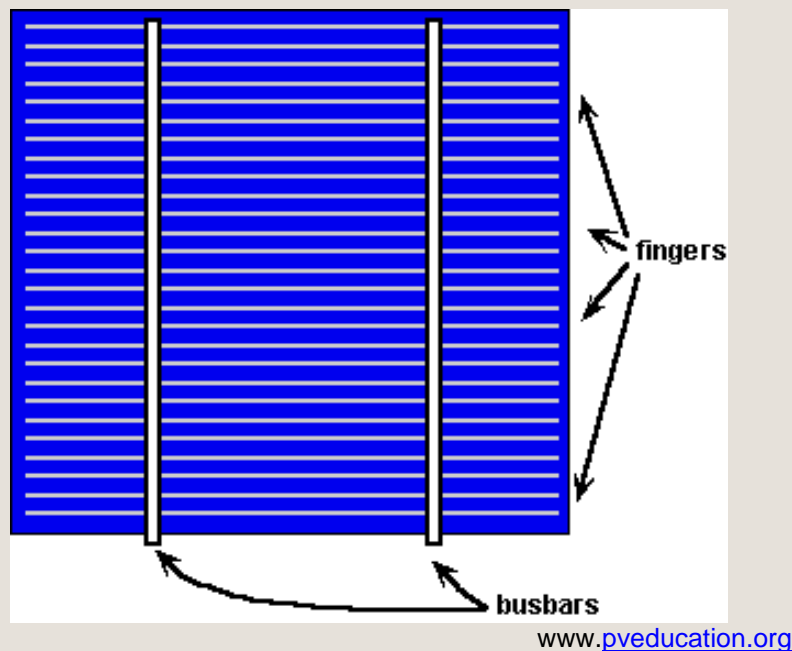
To produce the contacts a conducting paste is forced through the patterned screen mesh. Silver paste is used in this process.

Obviously the screen printed contact will require baking to remove solvents and leave just the conducting 'wires'.

The conducting strips are very fine – around 0.2 mm width and a few mm apart.

Two larger strips around 2 mm wide – bus bars – complete the circuit.

The losses attributed to these connectors can be quite high – shadf losses – and can be up to 10%.



Cells with much higher efficiencies are more demanding of process technology.

Such cells can have their contact width reduced from 200 μm to as low as 10 μm .

Solar cell module fabrication

A photovoltaic module is fabricated by interconnecting ~36 individual cells together.

The number depends on the application etc.

We require:

- (1) A transparent front cover that transmits light above 350 nm or so – to minimise photo degradation – **UV light degrades solar cells!**
- (2) To encapsulate the module in a transparent insulating film – polymer – such as ethylene vinyl acetate around 0.5 mm thick.
- (3) A protective back cover – a polymer such as mylar.

The module is formed by lamination under vacuum at elevated temperatures.



Thin Film Solar Cells

The various thin-film technologies currently being developed reduce the amount (or mass) of light absorbing material required in creating a solar cell.

This can lead to reduced processing costs from that of bulk materials (in the case of silicon thin films) but also tends to reduce *energy conversion efficiency* (an average of 7 to 10% efficiency), although many multi-layer thin films have efficiencies above those of bulk silicon wafers.

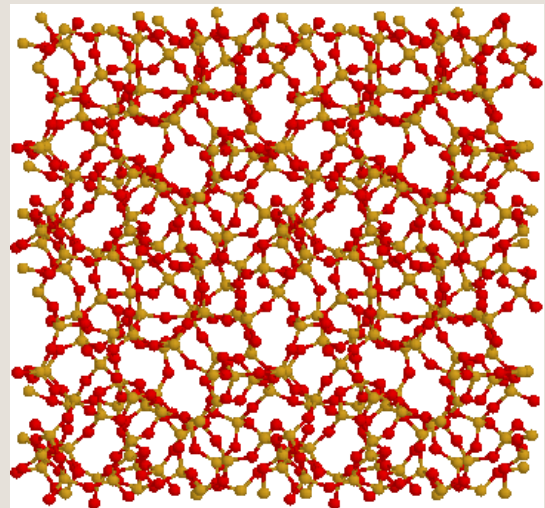
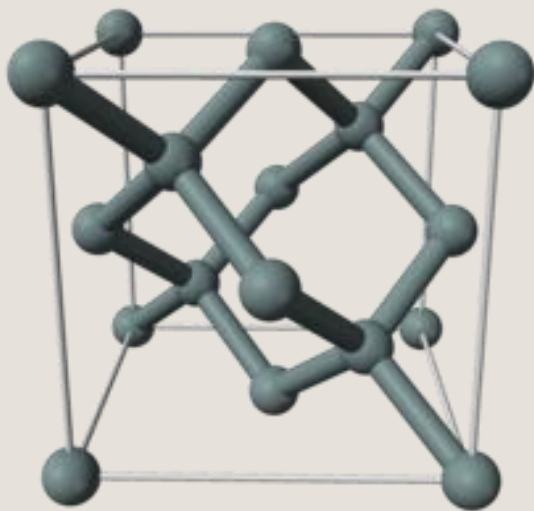
We shall explore:

- (i) Amorphous silicon
- (ii) Polycrystalline silicon
- (iii) Copper Indium Diselenide
- (iv) Gallium Arsenide
- (v) Cadmium Telluride

Amorphous silicon (a-Si)

Non crystalline - amorphous silicon - is most useful in solar cell applications. Its structure, and hence physical properties are very different to single crystal or polycrystalline silicon.

Silicon is a fourfold coordinated atom that is normally tetrahedrally bonded to four neighboring silicon atoms. In crystalline silicon this tetrahedral structure continues over a large range, thus forming a well-ordered crystal lattice.



Single crystal (left) and amorphous silicon (right)

Amorphous Si has advantages and is also much more flexible in finding applications compared to c-Si.

- (i) a-Si layers can be made thinner than c-Si, which may produce savings on silicon material cost.
- (ii) a-Si can be deposited at very low temperatures, e.g., as low as 75 degrees Celsius.
- (iii) a-Si can therefore be deposited on glass and plastics.
- (iv) Deposited a-Si can be doped in a fashion similar to c-Si, to form P-type or N-type layers for devices applications like solar cells.
- (v) a-Si offer lower performance than traditional c-Si solar cells.

- (vi) a-Si's ability to be easily deposited during construction more than makes up for any downsides.
- (vii) Improvements in a-Si growth techniques have made them more attractive for large-area solar cell use as well.
- (viii) Their lower inherent efficiency is made up for, at least partially, by their thinness - higher efficiencies can be reached by stacking several thin-film cells on top of each other, each one tuned to work well at a specific frequency of light – optically thin films can be quite transparent
- (ix) This approach is not applicable to c-Si cells, which are thick as a result of their growth technique and are therefore largely opaque, locking light from reaching other layers in a stack.

You should be familiar with concept of the band gap for optical absorption in silicon and other materials.

Crystalline silicon - the band gap is 1.12 eV .

a-Si the band gap is 1.75 eV.

What does this mean?

Amorphous silicon has a higher band gap (1.75 eV) than crystalline silicon (c-Si) (1.12 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum.

a-Si:H In early studies of amorphous silicon, **a-Si**, it was determined that plasma-deposited amorphous silicon contained a significant percentage of hydrogen atoms within the amorphous silicon structure.

These atoms were discovered to be essential to the improvement of the electronic properties of the material.

The crystal structure can be modified by adding hydrogen to the structure to make amorphous hydrogenated silicon (a-Si:H).

With a-Si:H it is possible to dope with Boron and Phosphorous to make N-type and P-type.

This means a P-N junction can be created.

This cell will have improved absorption characteristics as it is a direct band gap material.

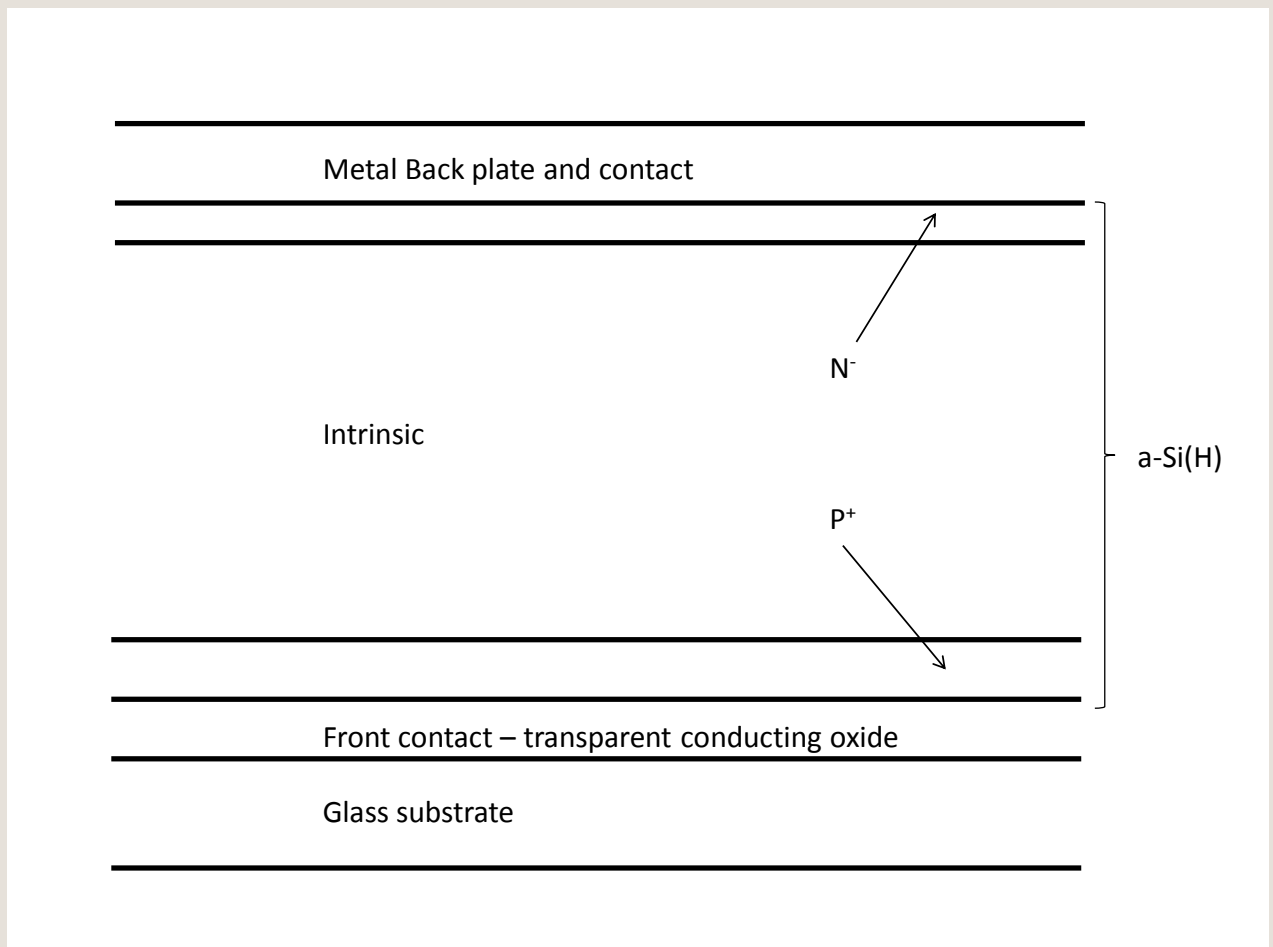
There is a difference though in the physical structure for optimal performance.

The P-N junction becomes a P-I-N junction.

Here this refers to an **intrinsic** layer (region) between the P and N regions.

In this case the intrinsic layer is 'lightly' doped and hence slightly N-type.

The structure that results from this is shown below:



One of the many 'Holy Grails' for solar cell technology – is the need for a highly conductive, optically transparent P-type film.

Indium tin oxide (ITO) is a well known transparent conducting oxide, TCO, however, it is N-type – and this does not work very well.

A major difficulty in fabrication of fully functional transparent oxide-based devices is the low electrical performance of TCOs.

Therefore the development of methods for modification of electrical properties of thin oxide films is of great importance.

Another important issue is integration of different TCOs with standard silicon technology.

Advantages of a-Si:H over c-Si:

Technology is relatively simple and inexpensive for a-Si:H and much less material required for a-Si:H films, lighter weight and less expensive

For a given layer thickness a-Si:H absorbs much more energy than c-Si (about 2.5 times)

The substrate temperature and the hydrogen treatment time can be used to select optical band gaps ranging from 1.8 to 2.1 eV.

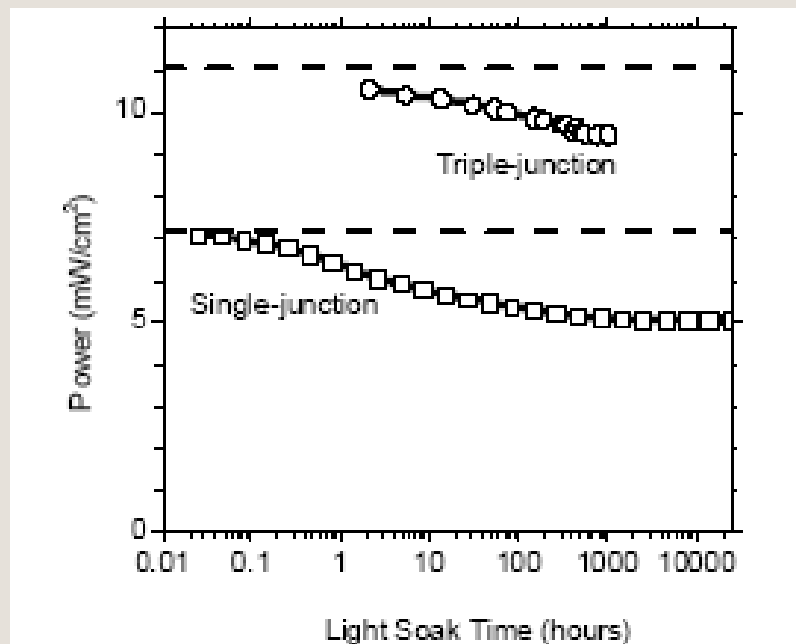
Can be deposited on a wide range of substrates, including flexible, curved, and roll-away types

Overall efficiency is around 10%, still lower than crystalline silicon, but improving.

Staebler-Wronski Effect

There is a significant decline in the efficiency of a-Si:H solar cells during first few hundred hours of illumination

a-Si:H modules reach steady-state after about 1,000 hours of steady illumination.



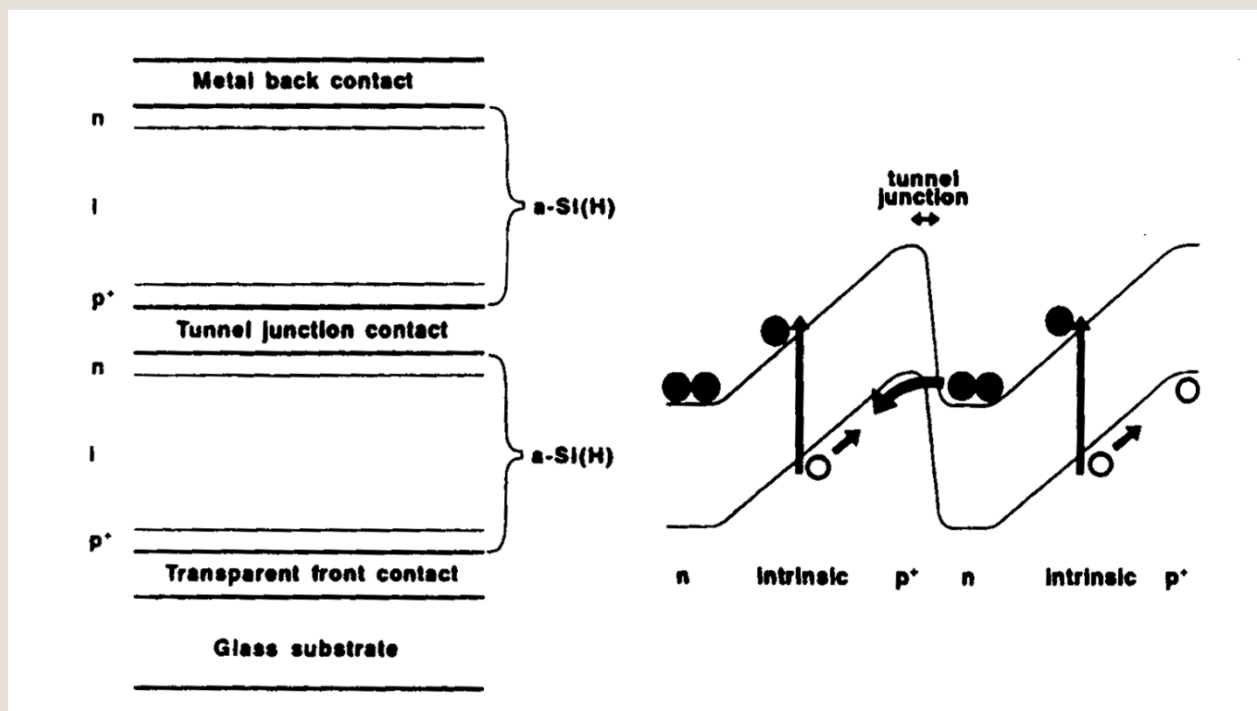
Seasonal variations in conversion efficiency were noticed. For a specific module studied:—Up to 20 deg. C., there is an increase in efficiency with temperature— c-Si has the opposite, where there is a decrease in efficiency with temperature.

Multi-junction Cells

Cell stacking is suited to amorphous cells – No need for lattice matching, as in c-Si – and bandgaps can be readily adjusted by alloying

Multijunction a-Si based cells have higher solar conversion efficiency than single junction cells

Most commercially produced a-Si based cells are multi-junction type



Spectrum Splitting

Top junction has higher band gap than bottom junction, top junction absorbs higher energy photons, and passes by the lower energy photons for the bottom junction to absorb

Semiconductors with wide ranges of band gaps can be created by alloying

By stacking any amount of cells by decreasing band gap, much of the incoming light can be absorbed and converted.

Current State of a-Si

a-Si cells have been made with 15.2% initial efficiency and 13% stable efficiency

Rapid deposition processes are being refined so that high rate, high quality can be achieved

Research into light degradation remedies will provide for cells with efficiencies comparable with c-Si cells

New applications for a-Si cells are being sought such as building-integrated PV, space power, consumer electronics, grid integration, and large scale power generation.

Typically, amorphous silicon thin-film cells use a p-i-n structure.

Polycrystalline Silicon thin films

Thin film polycrystalline cells of tens of microns physical thickness can have 'optical' thicknesses of many times this.

The basis of this is light trapping - light entering the thin film cell will reach the back (or lower) electrode and be reflected – yielding a second pass.

We have seen how texturing reduces the amount of light reflected.

It is possible to texture the front and rear surfaces too.

Light entering this cell configuration can become trapped – the optical thickness can be up to 20 times the physical thickness - complete absorption can be achieved.

p-Si thin films can be grown onto low-cost substrates by liquid phase epitaxy (LPE).

The substrate requires matching of the thermal expansion coefficient of the p-Si thin film – reduces local stresses during device processing.

The as grown films require annealing to modify the crystal structure – a standard thin film technique.

As we have seen diffusion techniques are used to form the n-p junction and top contacts are located on the top surface.

The topology of the substrate surface leads to natural surface texturing and hence light trapping.

An AR coating is also used and efficiency can be up to 16% - but these are small cells.

Copper-Indium diSelenide (CIS)

The materials based on CuInSe_2 that are of interest for photovoltaic applications include several elements from groups I, III and VI in the periodic table.

CIS is an abbreviation for general chalcopyrite films of copper indium selenide (CuInSe_2),

CIS films achieved greater than 19% efficiency.

CIS is a direct band gap semiconductor.

It has the possibly the highest absorption coefficient that has been measure so far.

It can be doped to be P or N type.

And the electronic properties are dependent on the copper / indium levels – can be tuned.

Unlike the conventional silicon based solar cell, which can be modelled as a simple p-n, these cells are best described by a more complex heterojunction model - we shall look at this.

The most stable are heterojunctions with Cadmium Sulphide (CdS).

CIS and CdS are well matched in terms of their lattice parameter – alleviates interface stresses.

Recombination losses are also minimal.

CIS is doped as P since CdS can only be doped as N type.

A consideration is the electrical contacts – Ohmic are preferred, and gold is expensive.

Molybdenum is the preferred low cost **Ohmic** contact.

Optical Absorption

The optical properties of CIS and CdS are important here.

CIS has low band gap energy at around 1 eV – similar to silicon.

CdS has higher band gap energy at around 2.4 eV and so absorbs strongly where the solar radiation is a maximum – green/blue.

The CdS layer is very thin – around 30 nm or so.

In these heterojunction cells the window is typically Zinc Oxide a transparent (semi)conductor.

Metal Back plate and contact

Copper Indium diselenide - P-type 2-3 μm

Cadmium Sulphide - N-type 300 nm

Front contact – transparent conducting oxide

Glass substrate

CIS-Cds Heterojunction Solar Cell

When gallium is substituted for some of the indium in CIS, the material is referred to as CIGS, or copper indium/gallium diselenide.

The band gap increases with increasing gallium content.

The band gap of CIGS should be > 1.1 eV to compliment the absorption window of ZnO.

The effect is to increase the available power by around 50 % ! similar to that for crystalline silicon.

This is a solid mixture of CuInSe_2 and CuGaSe_2 , often abbreviated by the chemical formula $\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$.

The best efficiency of a thin-film solar cell as of March 2008 was 19.9% with CIGS absorber layer.

Higher efficiencies (around 30%) can be obtained by using optics to optimising light collection.

This is known as solar concentration or 'more than one sun'

The use of gallium increases the optical band gap of the CIGS layer as compared to pure CIS.

This increases the open-circuit voltage, but decreases the short circuit current.

The atomic ratio for Ga in the >19% efficient CIGS solar cells is ~7%.

CIGS solar cells with higher Ga amounts have lower efficiency.

Gallium arsenide

A triple-junction cell, for example, may consist of the semiconductors: GaAs, Ge, and GaInP₂.

Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain colour, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum.

The semiconductors are carefully chosen to absorb nearly the entire solar spectrum, thus generating electricity from as much of the solar energy as possible.

GaAs based multijunction devices are the most efficient solar cells to date, reaching a record high of 40.7% efficiency under "500-sun" solar concentration and laboratory conditions.

Tandem solar cells based on monolithic, series connected, gallium indium phosphide (GaInP), gallium arsenide GaAs, and germanium Ge pn junctions, are seeing demand rapidly rise.

Triple-junction GaAs solar cells were also being used as the power source of the Dutch four-time World Solar Challenge winners Nuna in 2005 and 2007, and also by the Dutch solar cars Solutra (2005) and Twente One (2007).

The Dutch Radboud University of Nijmegen set the record for thin film solar cell efficiency using a single junction GaAs to 25.8% in August 2008 using only 4 μm thick GaAs layer which can be transferred from a wafer base to glass or plastic film.

Cadmium telluride (CdTe)

A cadmium telluride solar cell is a solar cell based on cadmium telluride, an efficient light-absorbing material for thin-film cells.

Compared to other thin-film materials, CdTe is easier to deposit and more suitable for large-scale production.

There has been much discussion of the toxicity of CdTe-based solar cells.

The perception of the toxicity of CdTe is based on the toxicity of elemental cadmium, a heavy metal that is a cumulative poison.

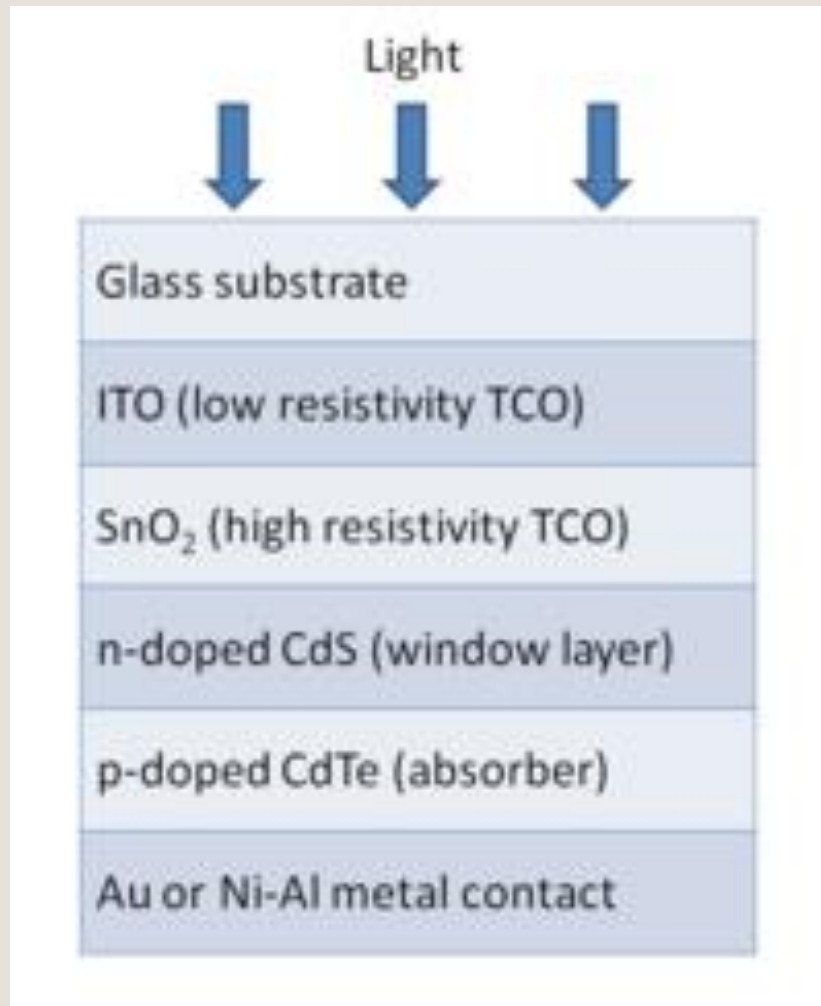
CdTe was originally limited by a far too significant number of defects sites at a level between the conduction band and the valence band – as we saw this leads to recombination losses.

Film growth and post-deposition process technology has improved this situation.

It is now possible to have high quality and hence efficient thin film cells.

The opportunity to increase current has been almost fully exploited, but more difficult challenges associated with junction quality, with properties of CdTe and with contacting have not been as successful.

However, until recently the number of active scientists working on CdTe PV has been low.



CdTe has the optimal band gap for single-junction devices, it may be expected that efficiencies close to exceeding 20% should be achievable in practical CdTe cells.

Other issues include the supply of Tellurium:

Tellurium (Te) is an element not currently used for many applications.

Only a small amount, estimated to be about 800 metric tons per year, is available.

One Gigawatt (GW) of CdTe PV modules would require about 93 metric tons (at current efficiencies and thicknesses), so this seems like a limiting factor.