EEE337 Semiconductor Electronics
EEE348 Electronics and Devices
(Solar Cells)

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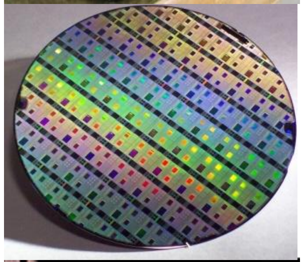
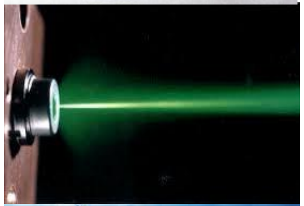
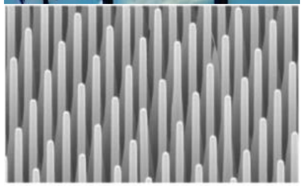
Light detection

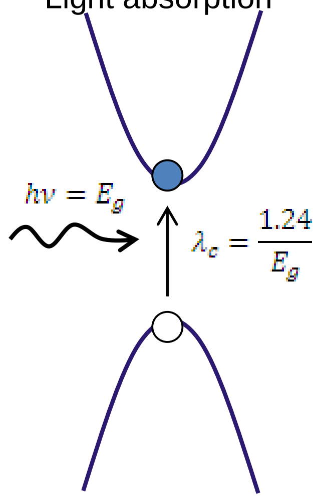






In the absorption process the longest wavelength that can be absorbed is given by λ_c.

$$\lambda_c = \frac{1.24}{E_g(eV)}\,\mu m$$

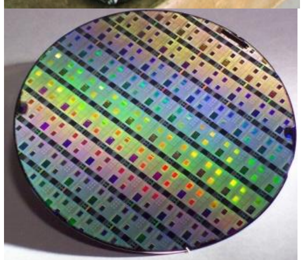
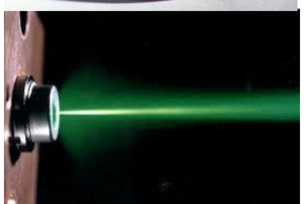
The material is transparent at wavelengths > λ_c, since the photon energy is smaller than the band gap. Therefore different semiconductors are chosen for different wavelength detections. In practice the availability of lattice matched substrates Si, Ge, GaAs, InP, InAs, GaSb and InSb determines the choice of semiconductor used. Substrates for II-VI are much smaller in size and costly, consequently they are not as widely used as III-V and Si.

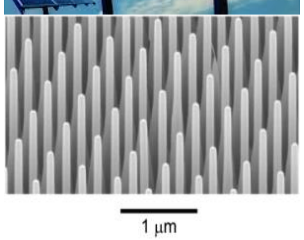


Material	Si*	GaAs*	GaSb	InAs	InSb	CdTe	CdZnTe
Size	2" diameter					10mm×10mm	
Doping	undoped						Zn-doped
Orientation	(100)					(110)	
Price (US$)	39.95	59	450	475	495	399	459

What is the largest Si and GaAs substrates available commercially?

Light detection

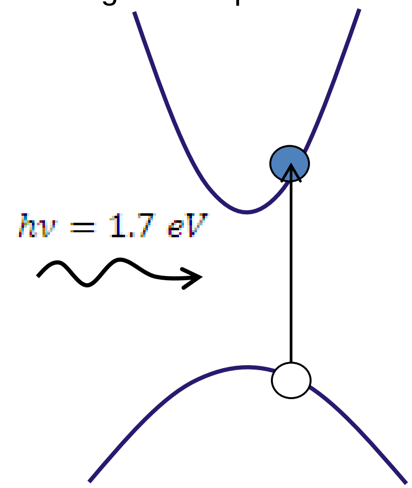


Conservation of energy and momentum is necessary. The momentum can be easily satisfied in direct bandgap materials such as GaAs as illustrated above.

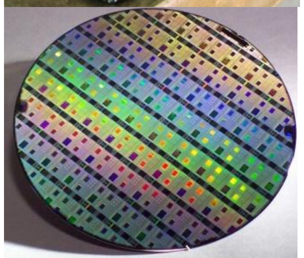
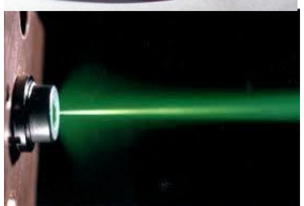
Consider a 2.84 eV photon being absorbed in GaAs which has a bandgap E_g = 1.41 eV. How many electron-hole pair will be generated?

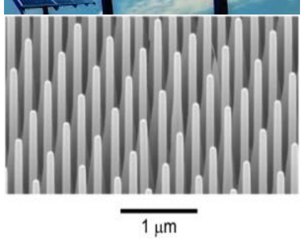
Consider a 1.7 eV photon being absorbed in GaAs which has a bandgap E_g = 1.41 eV. What happens to the energy difference of 0.29 eV?

Light absorption

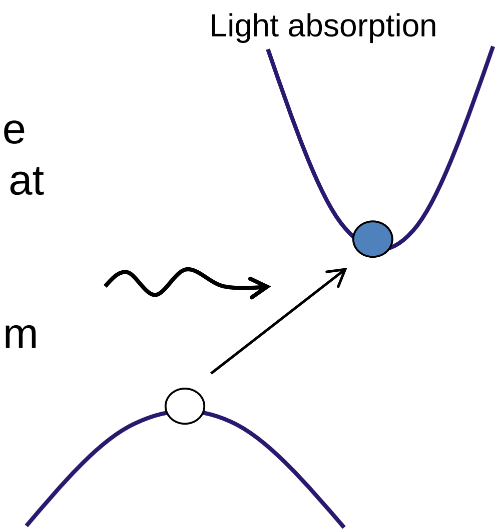


Light detection

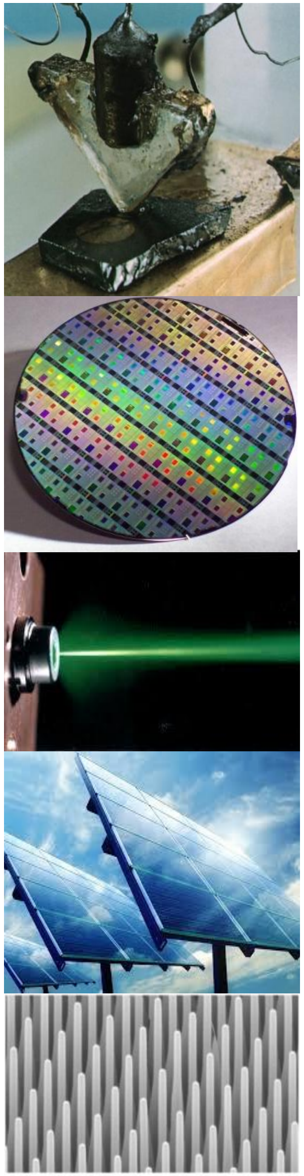


How is momentum conserved in indirect bandgap materials such as Si? Note that the wavevector difference between an electron at the top of the valence band and one at the bottom of the conduction band is given by $0.85\times2\pi/a \sim 10^{10}\ \mathrm{m}^{-1}$. Find out the momentum of a photon with an energy of 1.17 eV.



A phonon is a quantum of lattice vibrational energy.

Absorption coefficient

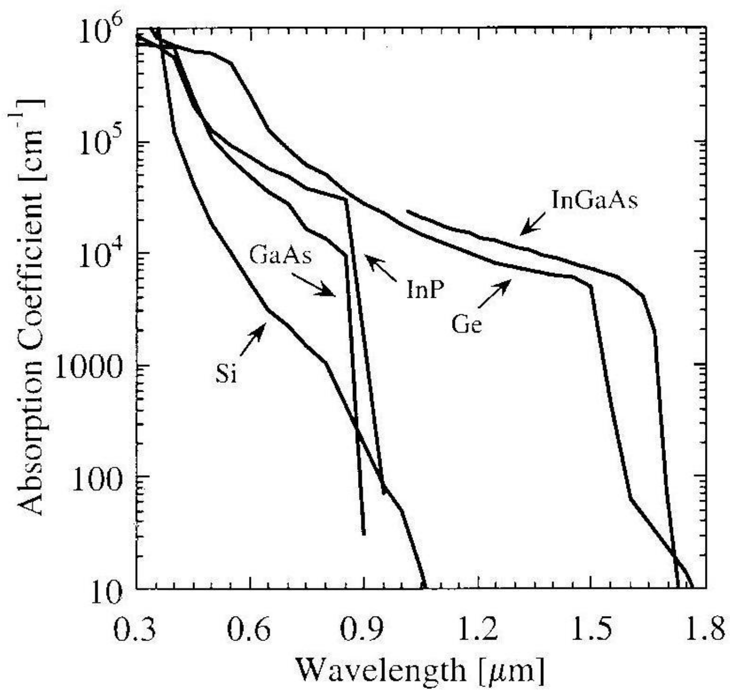


1 µm

The intensity of light travelling through a semiconductor is given by

$$I = I_o \exp(-\alpha x)$$

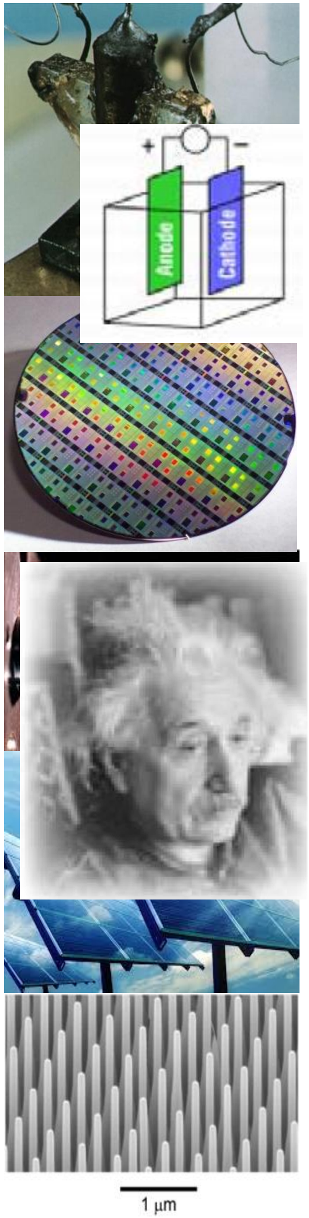
where x is the position, I_0 is the intensity at x = 0 and is the optical absorption coefficient.



Handbook of Optical Constants of Solids, edited by Edward D. Palik, (1985), Academic Press NY.

The absorption coefficient in a direct bandgap material (GaAs, InP, InGaAs) is much stronger than that in an indirect bandgap material (Si, Ge).

Solar timeline



1839	French scientist Edmond Becquerel discovers photovoltaic effect while experimenting with electrolytic cell
1876	William Grylls Adams and Richard Evans Day discover Selenium produces electricity (solid material can generate electricity without heat or moving parts)
1883	Charles Fritts described the first solar cells made from Selenium
1891	Clarence Kemp patented the first commercial solar water heater.
1905	Albert Einstein published the photoelectric effect
1916	Robert Millikan provide proof of photoelectric effect
1918	Jan Czochralski develop a method to grow single crystal silicon

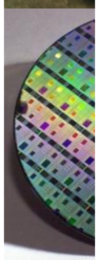
See https://www.youtube.com/watch?v=AMgQ1-HdElM for wafer production

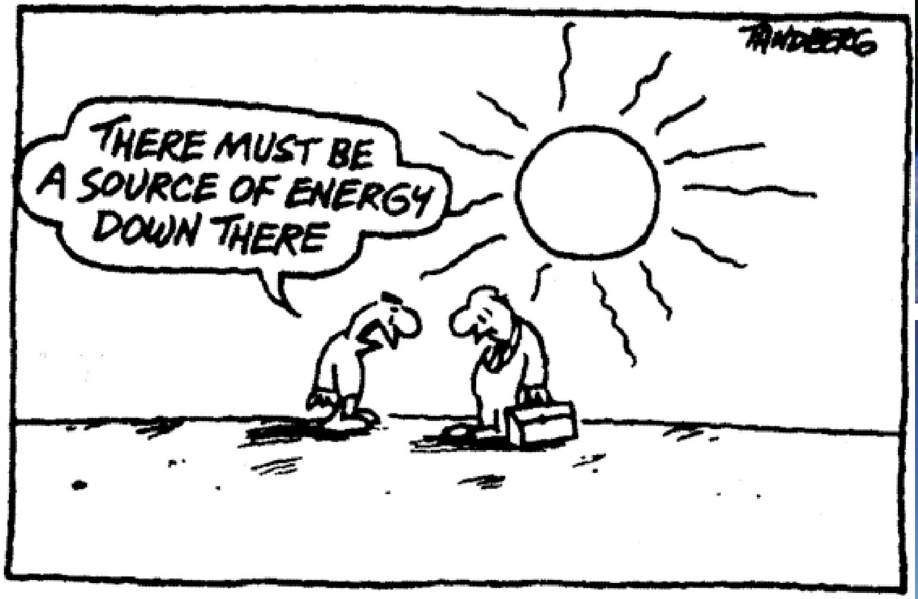
Solar timeline

1954	Daryl Chapin, Calvin Fuller and Gerald Pearson develop the Si PV at Bell Labs, 11% efficiency.
1959	Hoffman Electronics achieves 10% efficient commercial solar cells (use grid contacts)
1976	RCA Laboratories fabricated the first amorphous Si PV cells
1980	University of Delawarre, the first thin film solar cell > 10%, using copper sulphide/cadmium sulfide.
1985	Si solar cells breaks the 20% efficiency barrier
1994	NREL-InGaP-GaAs solar cells exceeds 30%
2014	World record 46% using 4 junction cell

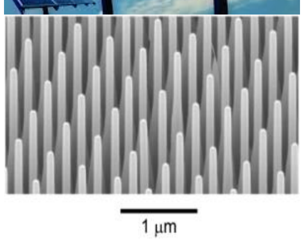
Adapted from https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

Solar Cell





Cartoon Credit: "Solar Cartoon." Michael Shellenberger. The Breakthrough Institute. 2011. With permission from Roy Tandberg.

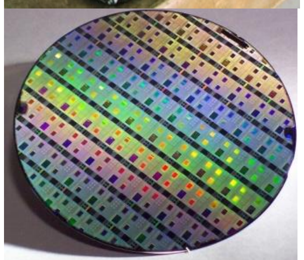


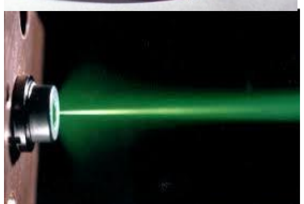
Used in special locations such as space

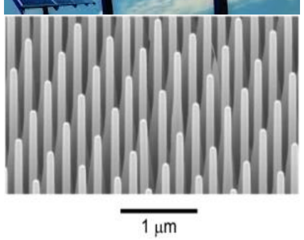
Used in lamp post

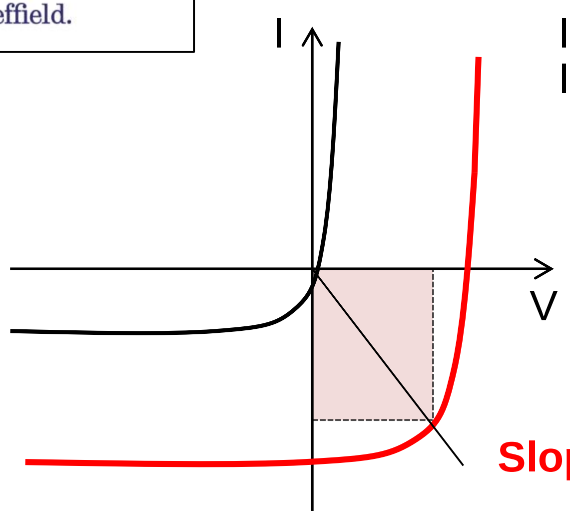
An increasingly important source of renewable energy (home as well as solar farm).

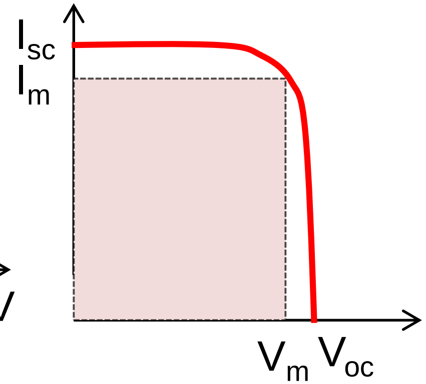
Solar Cell









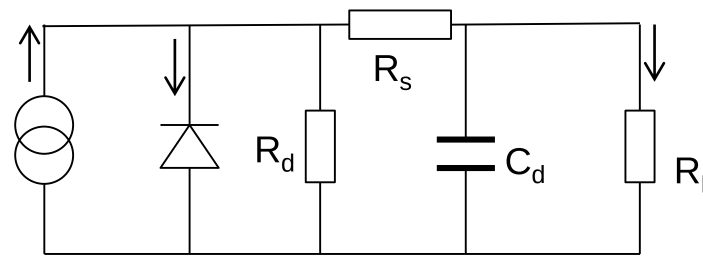


I_{sc} = short circuit current
V_{oc} = open circuit voltage
$P_m = I_m V_m$ = maximum output power

In the dark, the ideal I-V of a diode is given

$$I_d = I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Saturation current



Photodiode equivalent circuit

$$I_s = qAN_cN_v\left[\frac{1}{N_A}\sqrt{\frac{D_e}{\tau_e}} + \frac{1}{N_D}\sqrt{\frac{D_h}{\tau_h}}\right]\exp\left(-\frac{E_g}{kT}\right)$$

$$n_i^{\,2} = N_cN_v\exp\left(-\frac{E_g}{kT}\right)$$

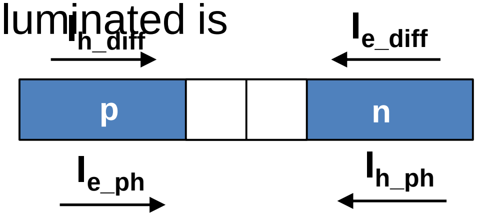
$$I_s = qAn_i^{\,2}\left[\frac{1}{N_A}\sqrt{\frac{D_e}{\tau_e}} + \frac{1}{N_D}\sqrt{\frac{D_h}{\tau_h}}\right]$$

I_s decreases exponentially with increasing E_g or decreasing T. Minimising I_s is important to maximise V_{OC}.

Solar Cell

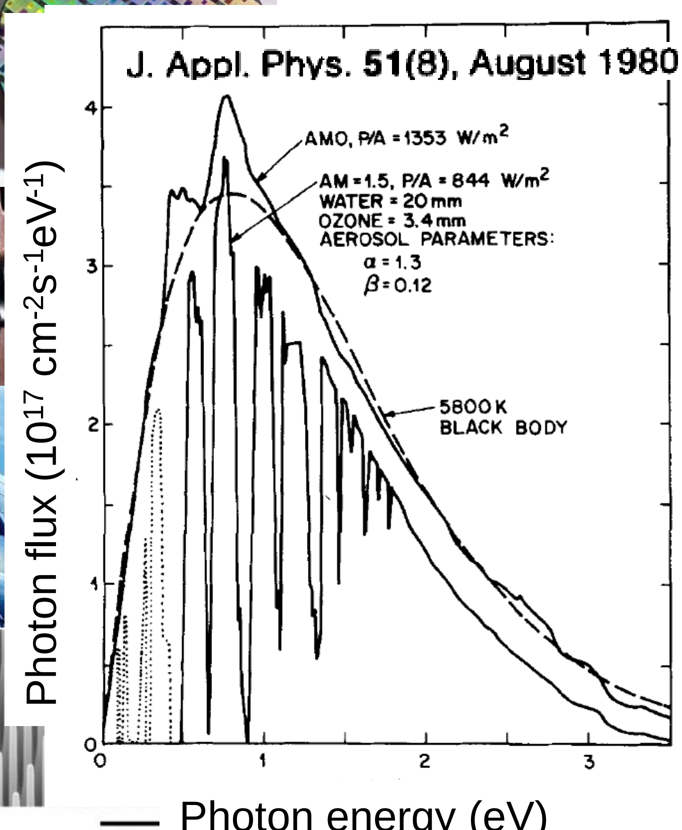
Under illumination, photons absorbed produced electrons and holes which flow in the opposite direction to carrier diffusion process that produces I_d. Therefore the total current when the diode is illuminated is

$$I_{tot} = I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_{ph}$$



The output power at the load resistor is $\mathbf{I_{tot} \times R_L}$.
We need to keep I_s low and produce large I_{ph}.

$$\lambda_c = \frac{1.24}{E_g(eV)}\,\mu m$$



The cutoff wavelength is longer if E_g is smaller.
The photocurrent can be obtained from integrating the photon flux for photon energies above E_g. Therefore the photocurrent is higher for smaller band gap because more photons, across a wider wavelength range, are absorbed. I_{ph} is higher for materials with smaller bandgap but this doesn't mean small E_g is ideal for solar cell.

When a photon with energy higher than E_g the excess energy is lost as heat energy. Therefore not all the solar energy is converted into electrical current.

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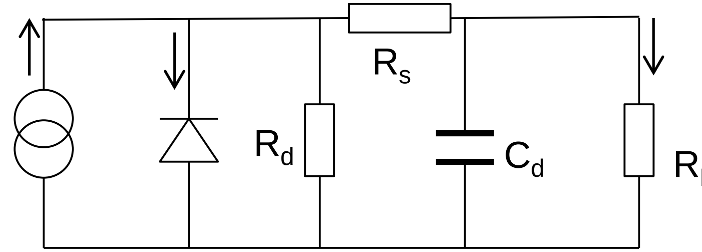
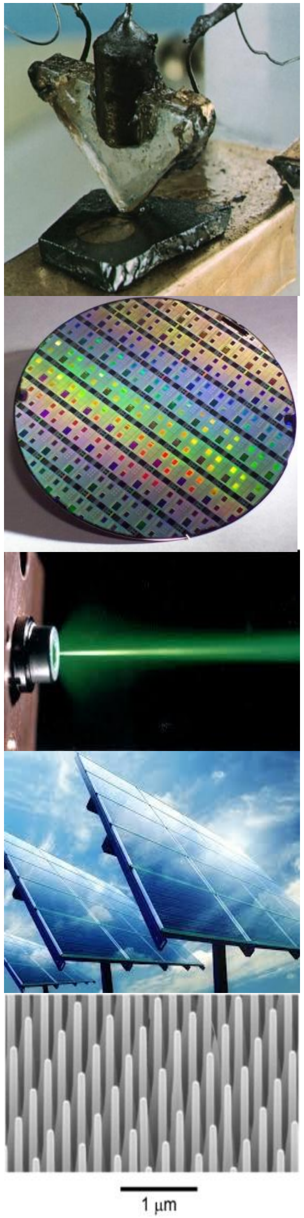
Solar Cell



Photodiode equivalent circuit



$$I_{tot} = I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_{ph}$$

To derive V_{oc}, we remove R_L, so that I_{tot} = 0. $I_s\left[1 - \exp\left(\frac{qV_{OC}}{kT}\right)\right] + I_{ph} = 0$

$$V_{OC} = \frac{kT}{q}\ln\left(1 + \frac{I_{ph}}{I_s}\right)$$

If the diode is short circuited, we have $I_d = 0, I_{tot} = I_{ph}$

$$I_{SC} = I_{ph}$$

To maximise the output power, we need to maximise I_{ph} and minimise I_s.

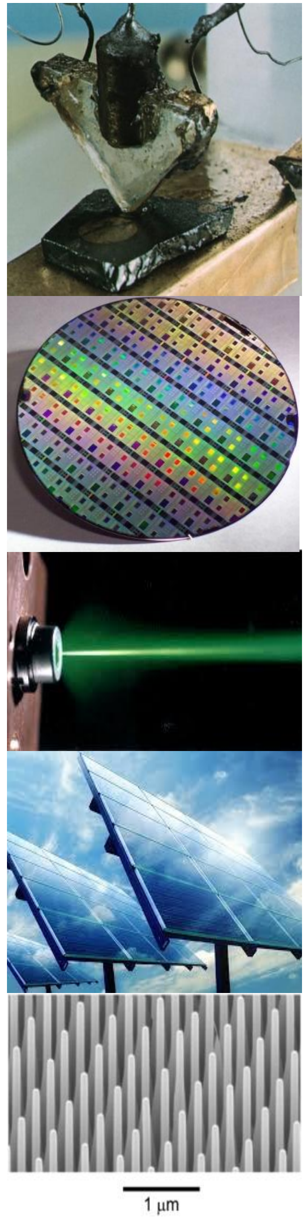
How do we reduce I_s?

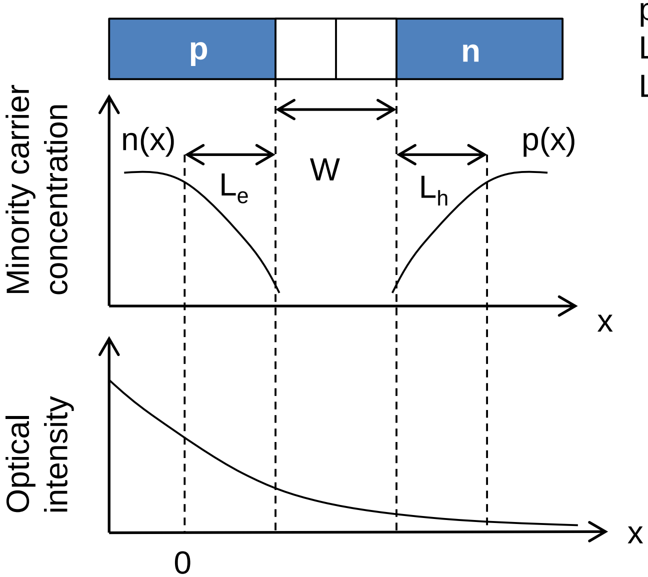
$$I_s = qAN_cN_v\left[\frac{1}{N_A}\sqrt{\frac{D_e}{\tau_e}} + \frac{1}{N_D}\sqrt{\frac{D_h}{\tau_h}}\right]\exp\left(-\frac{E_g}{kT}\right)$$

I_s drops with temperature. So solar cell works well in cooler climate.

Large E_g also reduces I_s.

Photocurrent in a p-i-n diode





n(x) = minority electron conc.
p(x)=minority hole conc.
L_e =minority electron diffusion length
L_h =minority hole diffusion length

The photocurrent in each region is given by

$$I_p = qA\int_0^{L_e} G(x)dx$$

$$I_i = qA\int_{L_e}^{L_e+W} G(x)dx$$

$$I_n = qA\int_{L_e+W}^{L_e+W+L_h} G(x)dx$$

For simplicity, assuming that the optical generation rate, G(x) = G, we have

$$\boxed{I_{ph} = qA\int_0^{L_e+W+L_h} G(x)dx = qAG\left(L_e + W + L_h\right)}$$

Here we have also assumed that all carriers generated within the minority carrier diffusion lengths will diffuse to the depletion width without recombination.

Clearly, to maximise the photocurrent in solar cells, we need large values for the minority carrier diffusion lengths and the depletion width.

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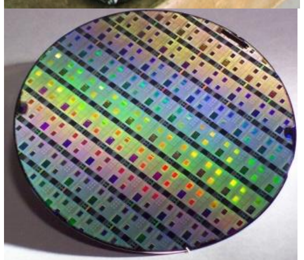
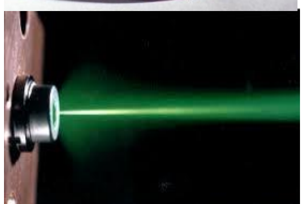
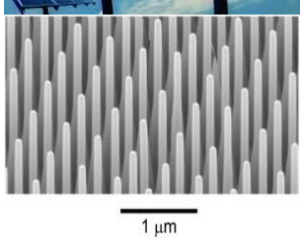
Photocurrent







How do we increase the minority carrier diffusion lengths?

Recall that the minority carrier diffusion length is the average distance that a carrier can move, from its point of generation, before recombination.

$$L_{e(h)} = \sqrt{D_{e(h)}\tau_{e(h)}} \qquad D_{e(h)} = \frac{kT}{q}\mu_{e(h)}$$

Diffusion constant   Carrier lifetime

From a previous lecture, we learnt that “some missing atoms, faults in atom stacking and presence of impurity atom will all introduce disturbance to the perfect periodicity that give rise to the band structure. These defects introduce energy levels in the energy gap.”. These defects act as traps that reduce the amount of free carriers generated via light absorption. Therefore we can increase diffusion length by reducing the defect density via careful crystal growth optimisation.

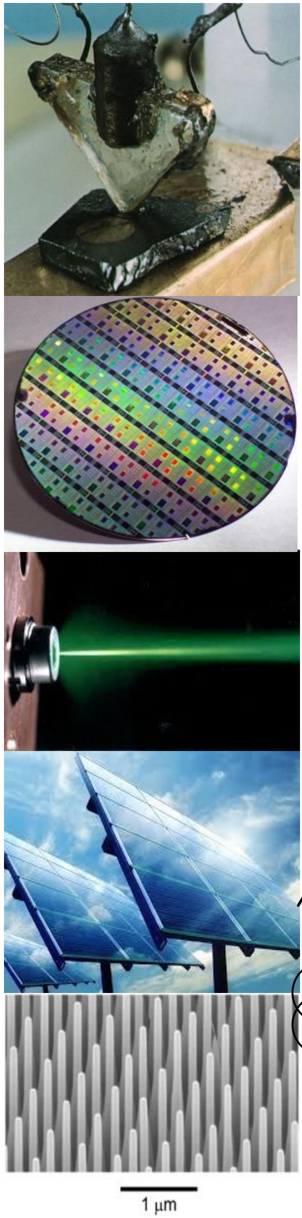
How do we increase the depletion width?

From pn diode theory (chap. 3 Sze, chap. 6, Pulfrey)

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_{bi}} \qquad W = \sqrt{\frac{2\varepsilon_s}{qN_D}V_{bi}} \quad for \quad N_A >> N_D \qquad V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Reducing the doping N_D, in a pn diode is the best approach.

Solar cell optimisation



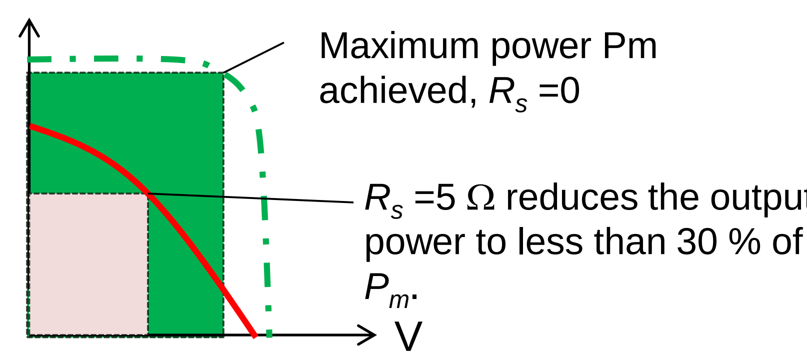
Note the presence of series resistance, R_s. What is its effect on the solar cell performance? Including R_s in the ideal diode current equation gives

$$I_{tot} = I_s\left[1 - \exp\left(\frac{q(V - I_{tot}R_s)}{kT}\right)\right] + I_{ph}$$

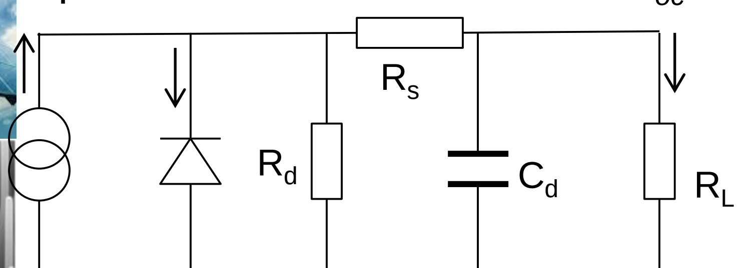
Re-arranging the equation gives

$$\ln\left(\frac{I_{tot} + I_{ph}}{I_s}\right) = \frac{q(V - I_{tot}R_s)}{kT}$$

Effect of R_s on output power



It is therefore important to R_s by using highly doped contact layer and low resistivity ohmic contact. Typically for Si, R_s < 1 Ω can be achieved. Another factor that can reduce the output power is recombination within the depletion region (due to presence of defects). This leads to reduced output power due to smaller value of V_{oc}.



Photodiode equivalent circuit

Solar cell optimisation

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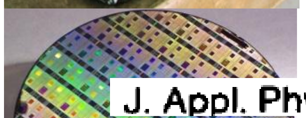
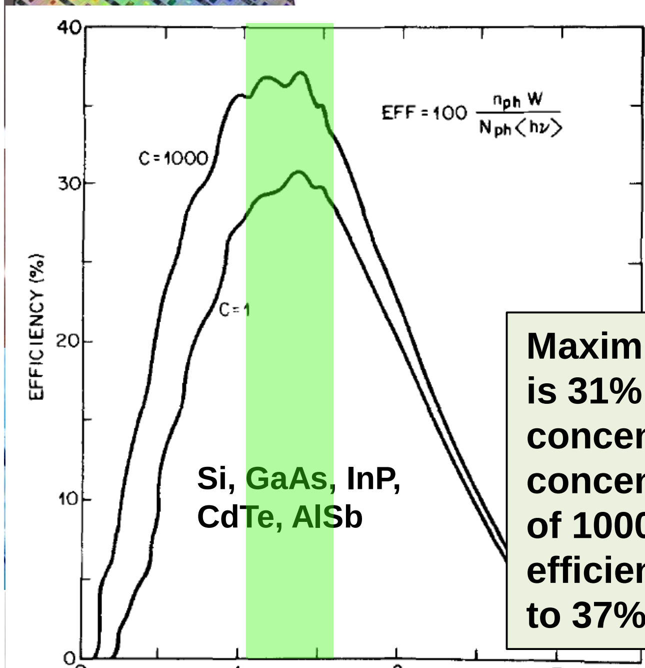
The conversion efficiency is given by $\frac{I_m V_m}{P_{opt}} \times 100$

P_{opt} is the incident optical power

The fill factor is $F_{fill} = \frac{I_m V_m}{I_{SC} V_{OC}}$



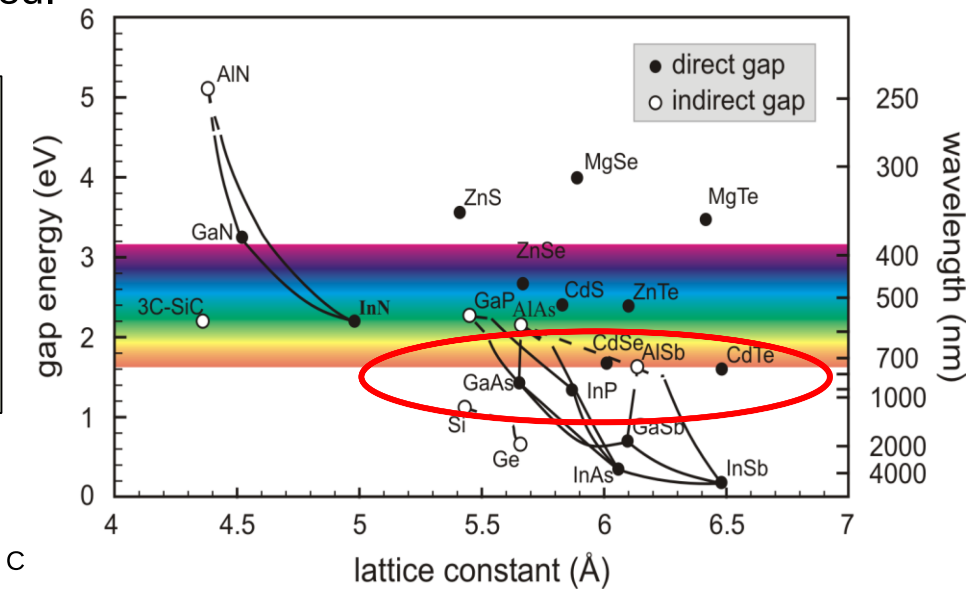
J. Appl. Phys. 51(8), August 1980

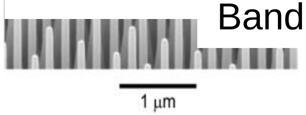


Bandgap energy (eV)

Maximum efficiency is 31% without concentrator. With a concentration factor of 1000 the efficiency increases to 37%

Consider a single junction solar cell with a bandgap E_g. Photons with energies < E_g will not be absorbed. As noted earlier, excess energy from photons with energies > E_g will be dissipated as heat. In addition to these some carriers are lost through recombination process. These three intrinsic losses limits the conversion efficiency of the solar cell. Using E_g = 1.35 eV, a maximum efficiency of 31% can be obtained.





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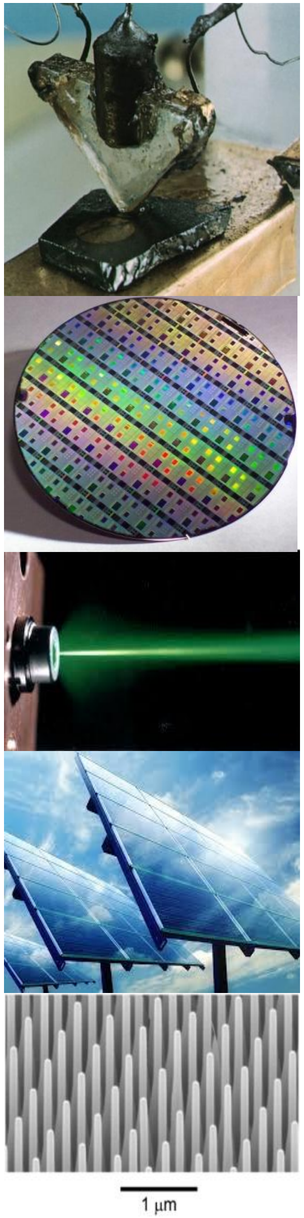
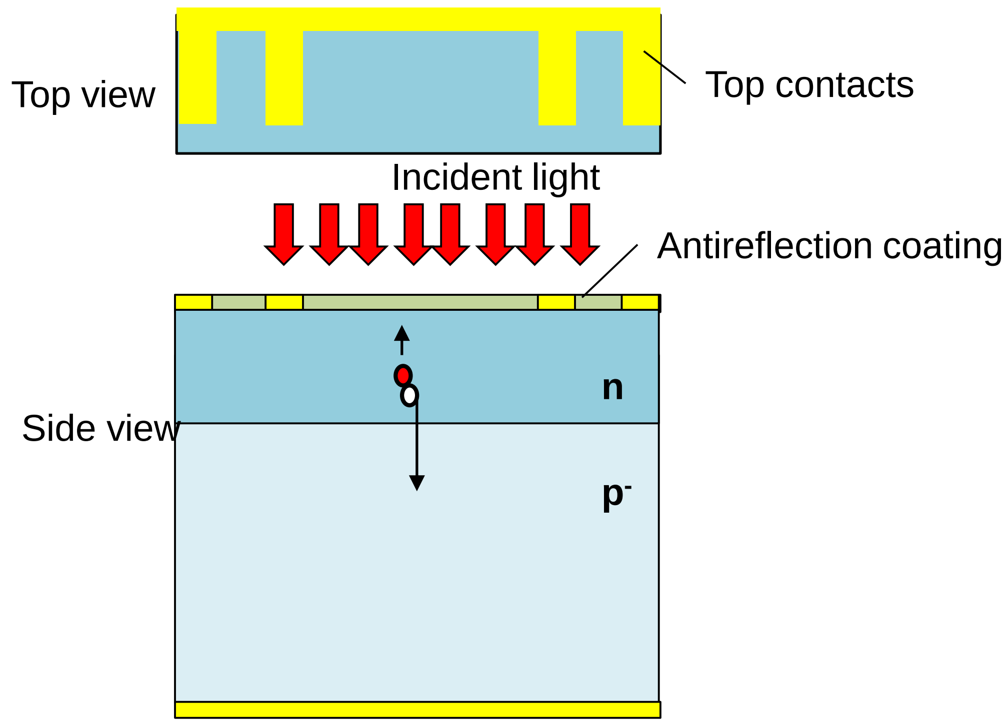
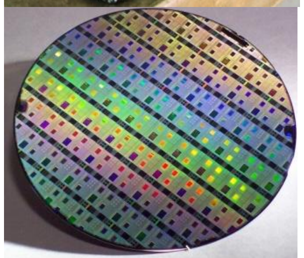
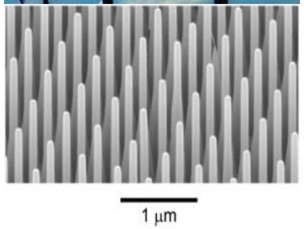
Solar cell optimisation





Solar cell optimisation

We can see that we need to maximise I_m and V_m. Can you summarise the basic strategies to achieve this?

Minimise reflected light at the air/semiconductor interface since ~31% of light is reflected.

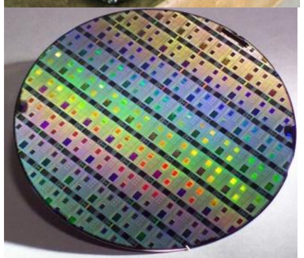
Maximise light absorption using a thick absorption region.

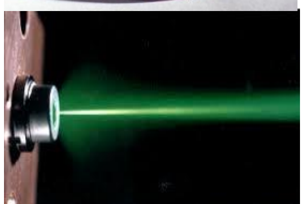
Reduce carrier recombination near the surface which has high density of dangling bonds.

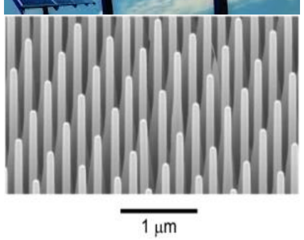
Maximise generated photocurrent using materials with long minority carrier diffusion lengths.

Minimise the dark current using low defect materials. (large bandgap or low temperature also helps)

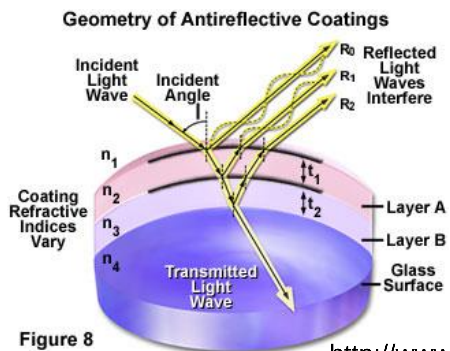
Solar cell optimisation







Minimise reflected light at the air/semiconductor interface since ~31% of light is reflected.



http://www.olympusmicro.com/primer/anatomy/objectives.html

Majority of light that is perpendicular to the antireflection coating is transmitted.

Changing the refractive index and thickness can provide an effective anti-reflection coating.

A single layer AR coating can be designed based on

$$\boxed{nt = \frac{\lambda}{4}}$$

Maximise light absorption using a thick absorption region.

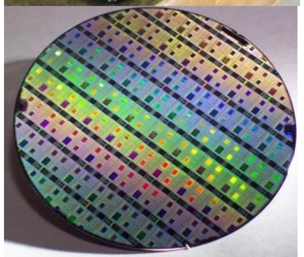
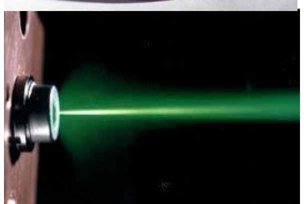
Remember that light intensity in a semiconductor is described by

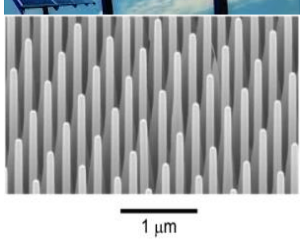
$$I = I_o \exp(-\alpha x)$$

To absorb 99% of light, we have $0.01 = \exp(-\alpha x)$

$$x = -\frac{1}{\alpha}\ln(0.01)$$

Solar cell optimisation



Reduce carrier recombination near the surface which has high density of surface states.

Thermal oxidation at ~1000 ^oC, can produce SiO_2 that act as passivate the Si surface. SiO_2/Si with trap low trap density can be routinely produced. Use of hydrogen atom to passivate Si is also shown to be very effective. There are many other methods of passivating Si, that are well studied. Without efficient surface passivation, Si based solar cell may not reach the its high efficiency.

Maximise generated photocurrent using materials with long minority carrier diffusion lengths.

Si can be grown with very low defect density. The minority electron diffusion length is > 100 µm Si with p-type doping below 10^{17} cm^{-3}.

The recombination current can be expressed as

Minimise the dark current using low defect materials (large effective recombination time τ_{eff}), reduced recombination current. (large bandgap or low temperature also helps)

The recombination current which reduces V_{OC}, can be expressed as

$$I_{rec} = \frac{qn_i AW}{\tau_{eff}}\left[\exp\left(\frac{qV}{2kT}\right)-1\right]$$

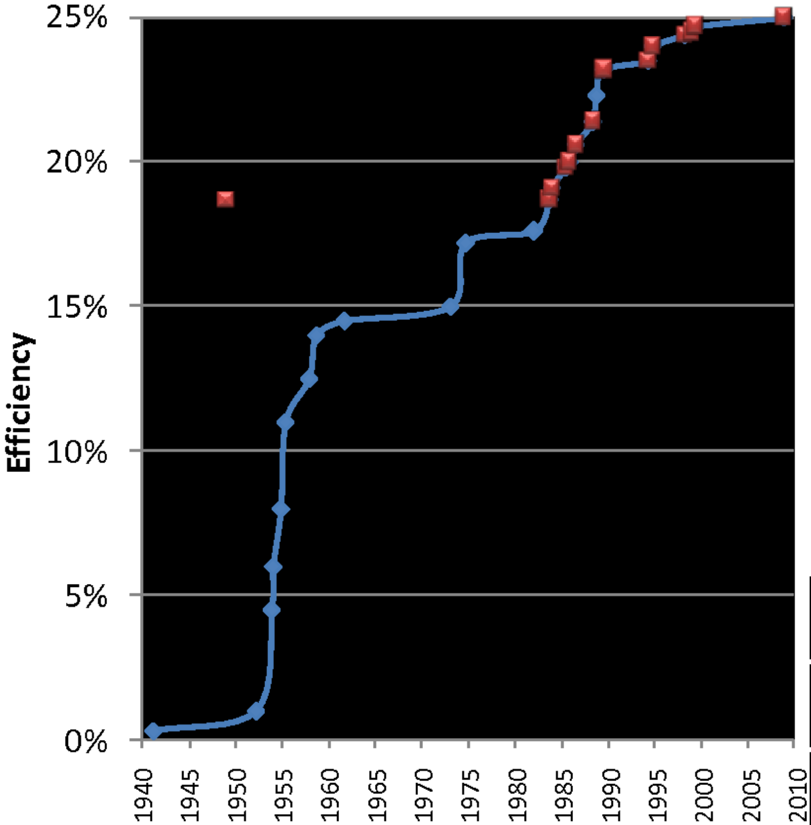
Minimise series resistance.

How efficiency is Si solar cell?

UNSW THE UNIVERSITY OF NEW SOUTH WALES NSi NewSouth Innovations

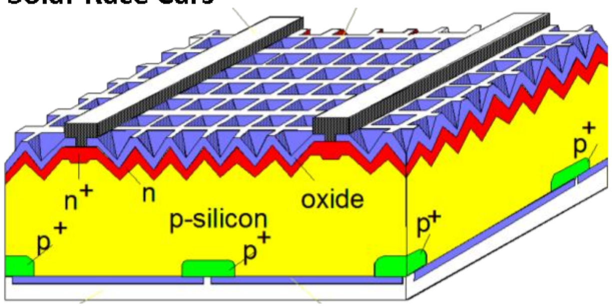
PERL cell

Passivated Emitter & Rear Locally-diffused cell



UNSW's World Record Breaking Solar Cell

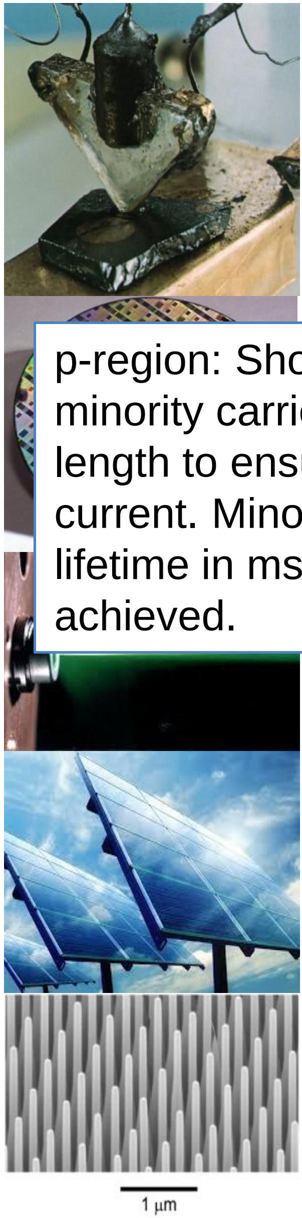
- World's Highest Performing Silicon Solar Cell
- Uses float zone wafers, high quality mono
- Used for specialist applications such as;
  - Mobile phones
  - Laptops
  - Solar Race Cars

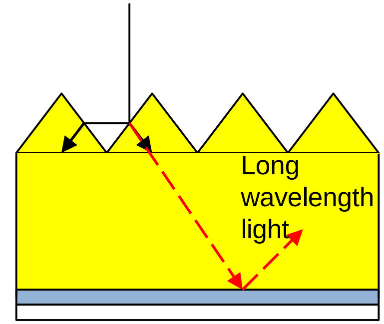


Use add-on technology to reduce the costs with little performance loss

Anti-Reflection Coating (08_2281)	Good surface passivation & low reflection
Plating (08_2283)	Improved performance with good aspect ratios & reduce the costs, by using non-precious metals
Patterned Etching of Dielectrics (05_1910, 07_2081, 08_2191, 09_5341)	Reduce the number of steps & reduce costs

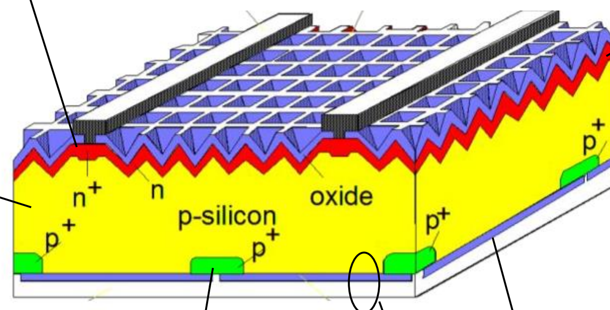
PERL solar cell





N+ regions: Highly doped to minimise series resistance

p-region: Should have long minority carrier diffusion length to ensure high output current. Minority carrier lifetime in ms is routinely achieved.



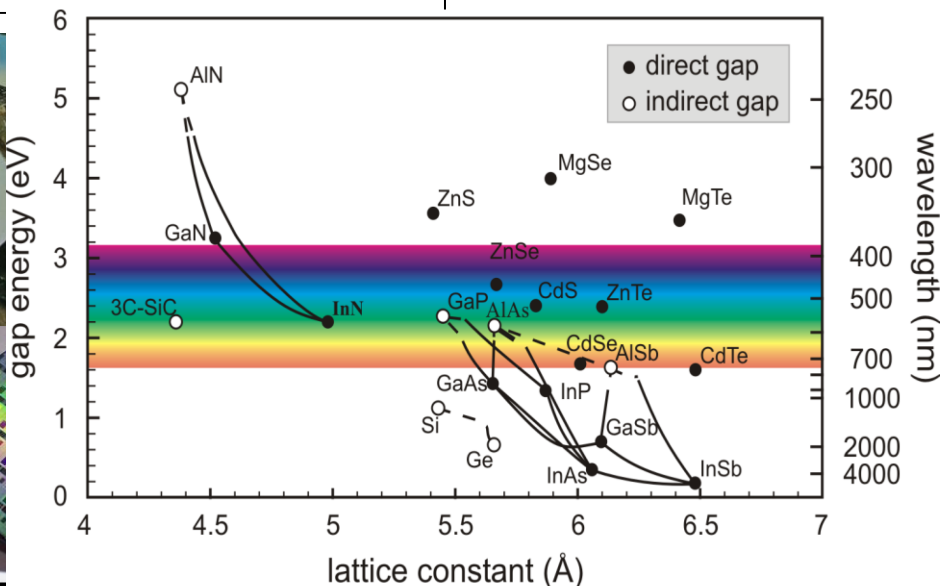
Inverted pyramid : Sunlight incident on a side slope is partially transmitted into the cell and partially reflected to the other slope, increasing the probability of light being absorbed.

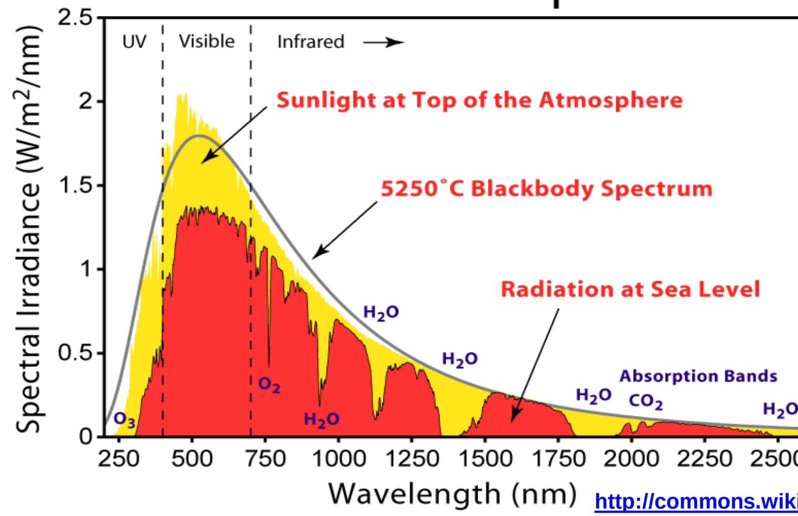
Oxide layer: Designed to minimise reflection of incident sunlight. It also passivates the surface to minimise surface recombination.

P+ regions: Minority carriers are collected and is highly doped to minimise series resistance. Metal-semiconductor area (defined by the small Boron diffused p+ region) is small to minimise surface recombination loss.

Si-Oxide-Aluminium: Act as mirror to reflect light (particularly at long wavelengths) back into the cell.

Materials for Solar cell





http://commons.wikimedia.org/wiki/File:Solar_Spectrum.png

Material	
Si	• Covers 0.4-1.0 μm detection. • Although the absorption coefficient is not the highest, the material is high quality and low cost making them the preferred detector for visible wavelengths **solar cell**.
Ge	• Indirect bandgap material with lower absorption coefficient than InGaAs. • Covers up to 1.8μm • Used in **multi-junction solar cell with GaAs and InGaP**.
$In_{0.53}Ga_{0.47}As$ (lattice match to InP)	• The preferred choice for optical communication at 1300 and 1550nm. • Used for night vision camera.
$In_{0.53}Ga_{0.47}As_yP_{1-y}$	• Can be grown to be lattice matched to InP and InGaAs (for device engineering). • Bandgap can be adjusted Eg = 1.35 - 0.72y + 0.12y^2.
GaAs	• Bandgap is 1.42 eV, has a lattice constant that is close to Ge • Used as a material for a **multijunction solar cell.**
InGaP	• Can be grown lattice matched to GaAs to form multijunction solar cell

1 μm

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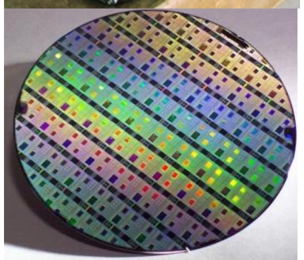
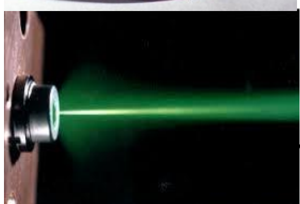
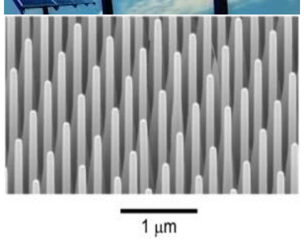
Multi-junction (tandem) solar cell







Theoretical calculation suggests that the maximum efficiency can be achieved using multijunction (tandem) solar cell. An example of prediction is shown below.

J. Phys. D: Appl. Phys., 13 (1980) 839–46

Table 1. The optimal set of bandgaps E_{gi} for tandem structures with n stacked cells in unconcentrated sunlight.

n	η (%)	E_{g1} (eV)	E_{g2} (eV)	E_{g3} (eV)	E_{g4} (eV)
1	30	1·3	—	—	—
2	42	1·9	1·0	—	—
3	49	2·3	1·4	0·8	—
4	53	2·6	1·8	1·2	0·8

What are the suitable material combinations?

Two junction solar cell

E_{g1}: $Ga_{0.51}In_{0.49}P$ (1.86 eV) or $Al_{0.3}Ga_{0.8}As$ (1.8 eV) lattice matched to GaAs
E_{g2}: GaAs (1.42 eV)

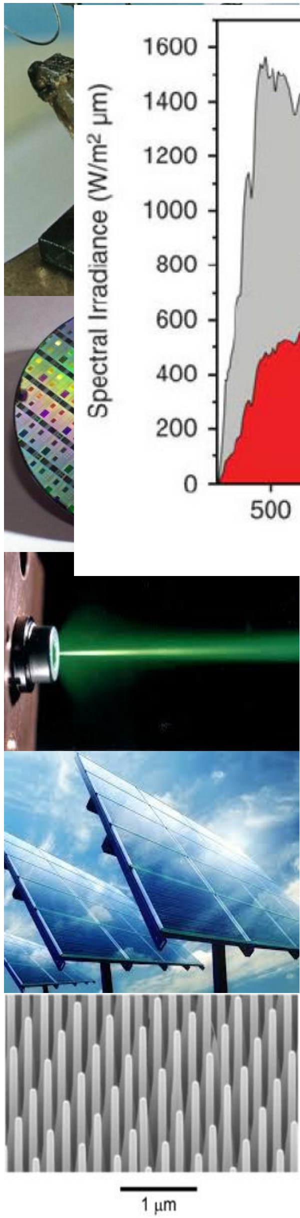
Three junction solar cell

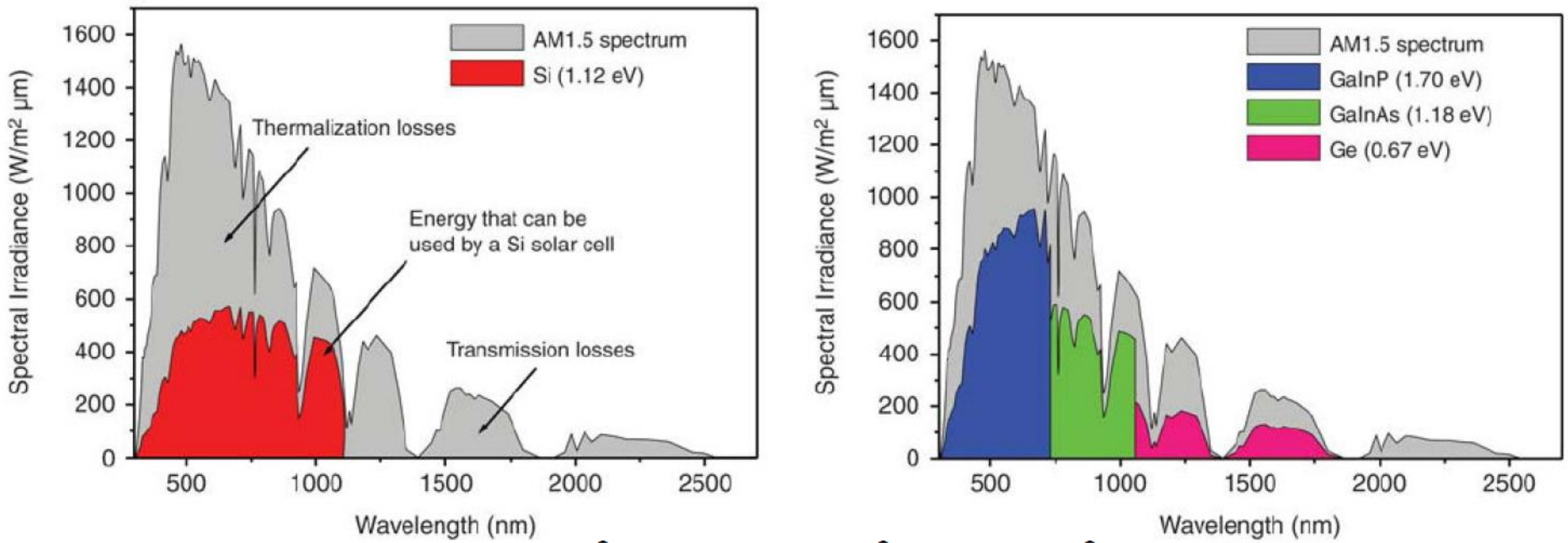
E_{g1}: $Ga_{0.51}In_{0.49}P$ (1.86 eV) or $Al_{0.3}Ga_{0.8}As$ (1.8 eV)
E_{g1} : GaAs (1.42 eV)
E_{g2}: Ge (0.8 eV)

Table 1. Some physical properties of important semiconductor materials

Type of material	*Material*	*Width of energy gap electron volts*		*Carrier mobility at 300°K (cm^2/volt-sec)*		*Crystal-structure type*	*Lattice constant (angstrom units)*	*Melting point (°c)*	*Vapor pressure at melting point (atmospheres)*
		At 300°K	*At 0°K*	*Electrons*	*Holes*				
Element	C (diamond)	5.47	5.51	1,800	1,600	Diamond	3.56679	4027	10^{-9}
	Ge	0.803	0.89	3,900	1,900	Diamond	5.65748	937	
	Si	1.12	1.16	1,500	600	Diamond	5.43086	1420	10^{-6}
	a-Sn		–0.08			Diamond	6.4892		
$A^{IV}B^{IV}$compound	a-SiC	3	3.1	400	50	Zinc blende	4.358	3100	
$A^{III}B^{V}$	AlSb	1.63	1.75	200	420	Zinc blende	6.1355	1050	<0.02
compound	BP	6				Zinc blende	4.538	>1300	>24
	GaN	3.5				Wurtzite	3.186 (*a*=axis)	>1700	>200
							5.176 (*c*=axis)		
	GaSb	0.67	0.80	4,000	1,400	Zinc blende	6.0955	706	$<4\times10^{-4}$
	GaAs	1.43	1.52	8,500	400	Zinc blende	5.6534	1239	1
	GaP	2.24	2.40	110	75	Zinc blende	5.4505	1467	35
	InSb	0.16	0.26	78,000	750	Zinc blende	6.4788	525	$<10^{-5}$
	InAs	0.33	0.46	33,000	460	Zinc blende	6.0585	943	0.33
	InP	1.29	1.34	4,600	150	Zinc blende	5.8688	1060	25
$A^{II}B^{VI}$	CdS	2.42	2.56	300	50	Wurtzite	4.16 (*a*=axis)	1750	
compound							6.756 (*c*=axis)		
	CdSe	1.7	1.85	800		Zinc blende	6.05	1258	
	ZnO	3.2		200		Cubic	4.58	1975	
	ZnS	3.6	3.7	165		Wurtzite	3.82 (*a*=axis)	1700	
							6.26 (*c*=axis)		
	PbS	0.41	0.34	600	700	Cubic	5.935	1103	
compound	PbTe	0.32	0.24	6,000	4,000	Cubic	6.460	917	

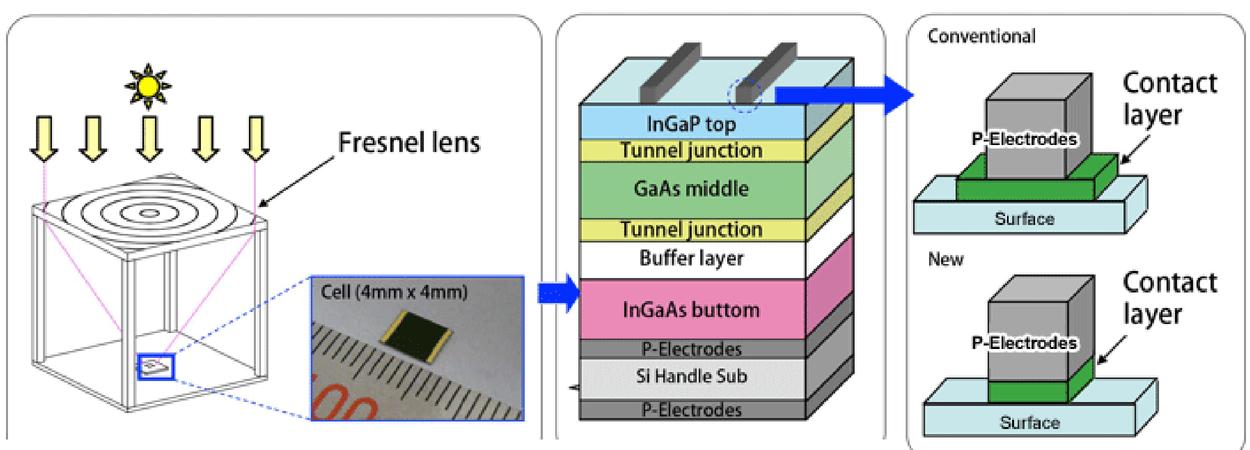
Multi-junction (tandem) solar cell





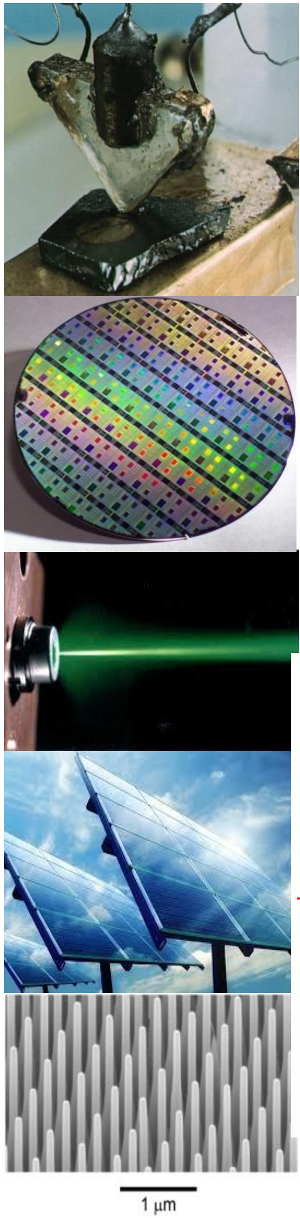
(a) Si solar cells; (b) $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$

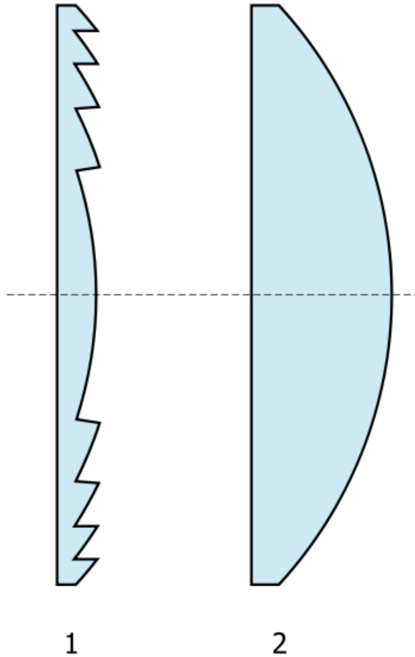
■ Concentrator solar cell system ■ Structure of a triple-junction compound solar cell ■ Comparison with a conventional structure

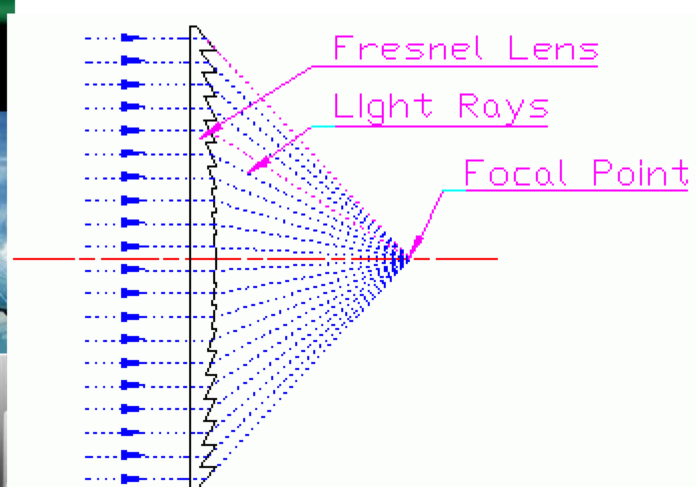


http://sharp-world.com/corporate/news/130614.html

Fresnel lens







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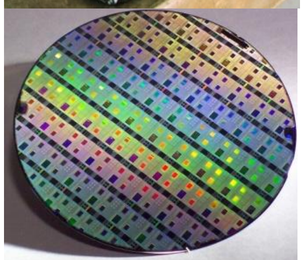
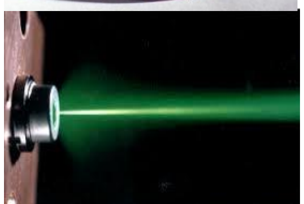
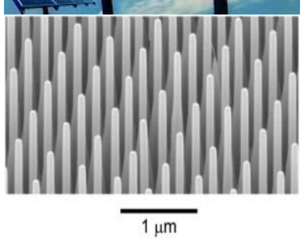
Tunnel junction

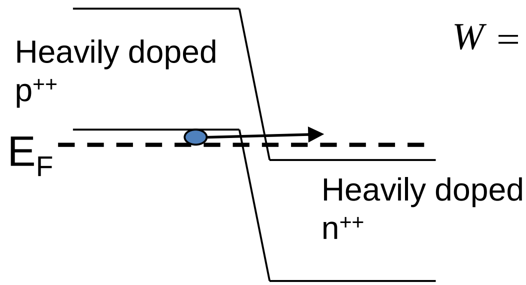






Recall that in a pn diode the depletion width is given by

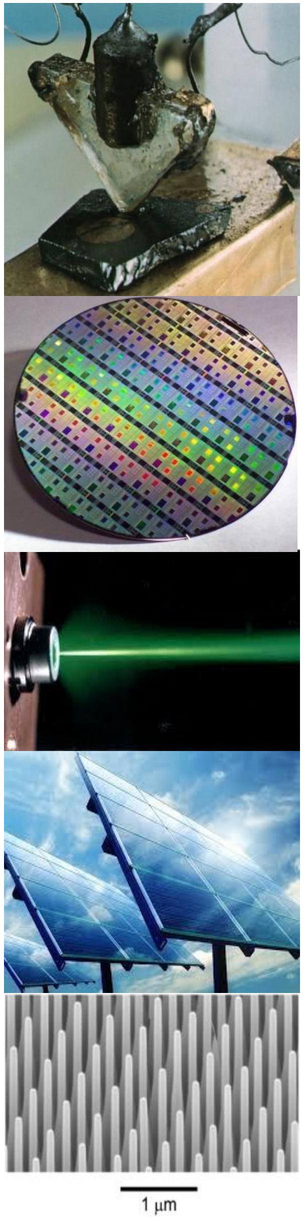
$$W = \sqrt{\frac{2\varepsilon_s}{qN_D} V_{bi}} \qquad for \quad N_A = N_D \qquad V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$



For very heavily doped junction, *W* is small and V_{bi} is large. The Fermi Levels are in the conduction and valence bands on the n-side and p-side respectively.
Electrons can easily tunnel through the depletion width and hence this is called a tunnel junction.

A very highly doped pn diode is inserted to provide low electrical resistance and low optical loss (i.e low loss of optically generated carriers) between the cells.

The bandgap is reduced from the top to the bottom. For example the junctions, from top to bottom, are InGaP, InGaAs and Ge with bandgaps of 1.7, 1.2 and 0.65 eV respectively. Very highly doped pn junctions are inserted between each junction. These pn junctions are designed such that carriers can tunnel through the different bandgap junctions. The current from each junction should be the same as the junctions are connected in series. The triple junction can be designed to achieve high absorption efficiency from UV to 1.9 µm and achieves much higher efficiency than Si
Other combinations for example InGaP/GaAs/Ge and InGaP/GaAs/InGaAs have also been used.



Some of the best reported results

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904–3: 2008, ASTM G-173-03 global).

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test centre[e] (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[f]	82.8	Sandia (3/99)[g]	UNSW PERL [18]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[g]	FhG-ISE [19]
Si (thin film transfer)	19.1 ± 0.4	3.983 (ap)	0.650	37.8[h]	77.6	FhG-ISE (2/11)	ISFH (43-μm thick) [20]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492[i]	29.7[i]	72.1	FhG-ISE (8/07)[g]	CSG Solar (1–2 μm on glass; 20 cells) [21]
III-V cells							
GaAs (thin film)	28.3 ± 0.8	0.9944 (ap)	1.107	29.47[j]	86.7	NREL (8/11)	Alta devices [3]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[g]	RTI, Ge substrate [22]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial [23]
Thin film chalcogenide							
CIGS (cell)	19.6 ± 0.6[k]	0.996 (ap)	0.713	34.8[l]	79.2	NREL (4/09)	NREL, CIGS on glass [24]
CIGS (submodule)	17.4 ± 0.5	15.993 (da)	0.6815[i]	33.84[i]	75.5	FhG-ISE (10/11)	Solibro, four serial cells [4]
CdTe (cell)	16.7 ± 0.5[k]	1.032 (ap)	0.845	26.1	75.5	NREL (9/01)[g]	NREL, mesa on glass [25]
Amorphous/nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3[m]	1.036 (ap)	0.886	16.75[f]	67.0	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [26]
Si (nanocrystalline)	10.1 ± 0.2[n]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [27]
Photochemical							
Dye sensitised	11.0 ± 0.3[o]	1.007 (da)	0.714	21.93[h]	70.3	AIST (9/11)	Sharp [5]
Dye sensitised (submodule)	9.9 ±0.4[o]	17.11 (ap)	0.719[i]	19.4[i,l]	71.4	AIST (8/10)	Sony, eight parallel cells [28]
Organic							
Organic thin film	10.0 ± 0.3[o]	1.021 (ap)	0.899	16.75[j]	66.1	AIST (10/11)	Mitsubishi Chemical [6]
Organic (submodule)	4.2 ± 0.2[o]	294.5 (da)	0.714	12.26[j]	47.7	AIST (9/11)	Sumitomo Chemical (10 series cells) [7]
Multijunction devices							
GaInP/GaInAs/Ge	34.1 ± 1.2	30.17 (t)	2.691	14.7[j]	86.0	FhG-ISE (9/09)	AZUR (monolithic) [8]
a-Si/nc-Si/nc-Si (thin film)	12.4 ± 0.7[p]	1.050 (ap)	1.936	8.96[h]	71.5	NREL (3/11)	United Solar [29]
a-Si/nc-Si (thin film cell)	12.3 ± 0.3[q]	0.962(ap)	1.365	12.93[j]	69.4	AIST (7/11)	Kaneka [9]
a-Si/nc-Si (thin film submodule)[j]	11.7 ± 0.4[n,r]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka [30]

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
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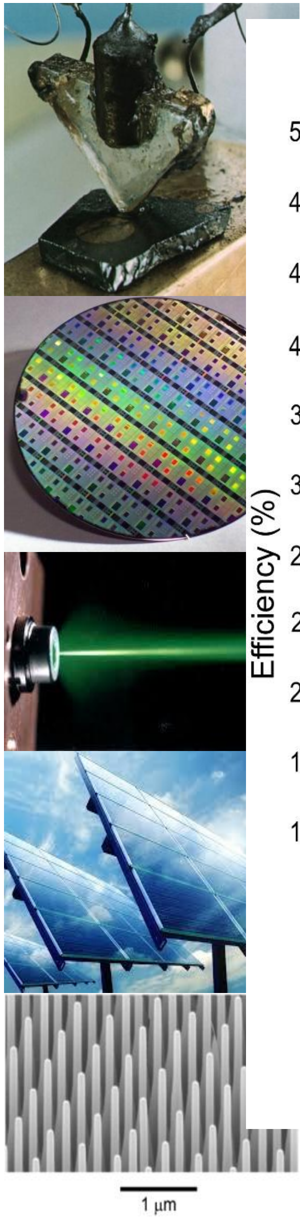
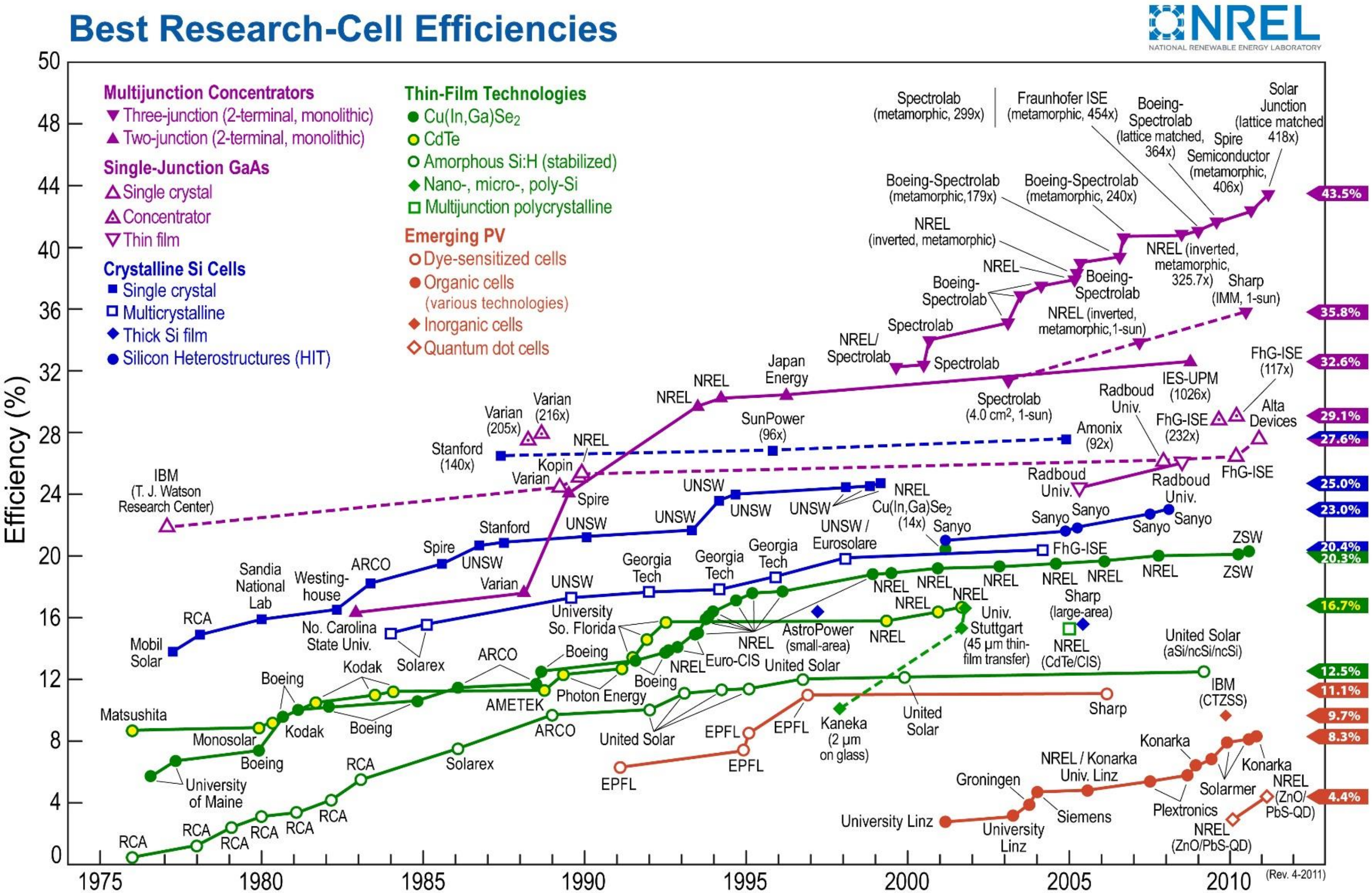
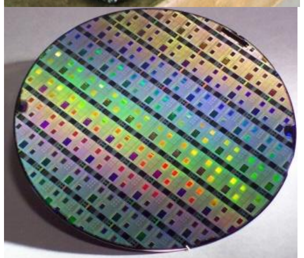
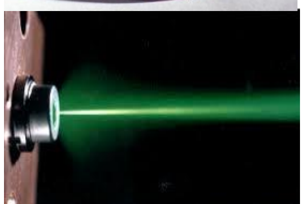
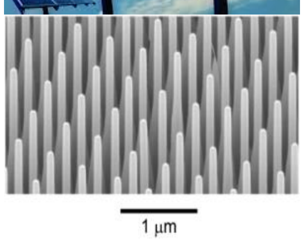
Solar cell continues to improve

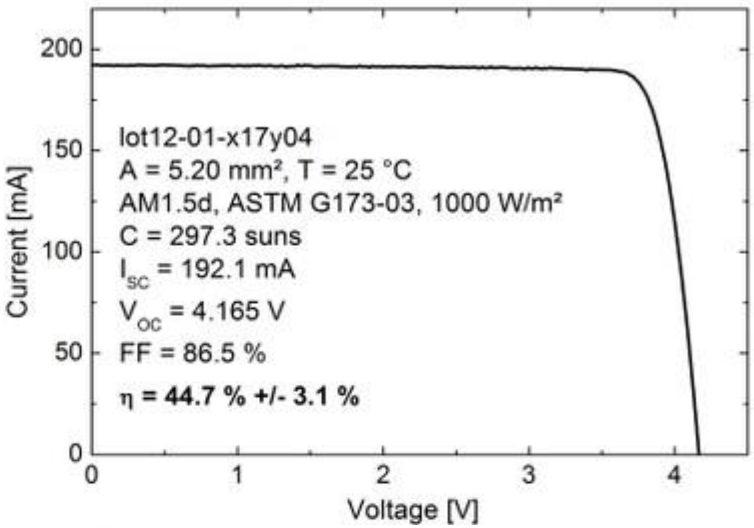


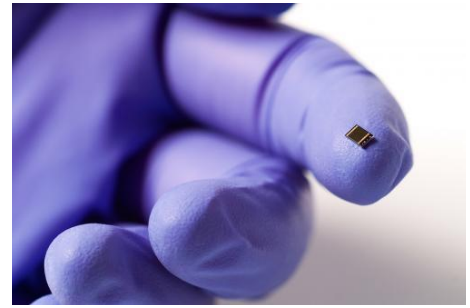


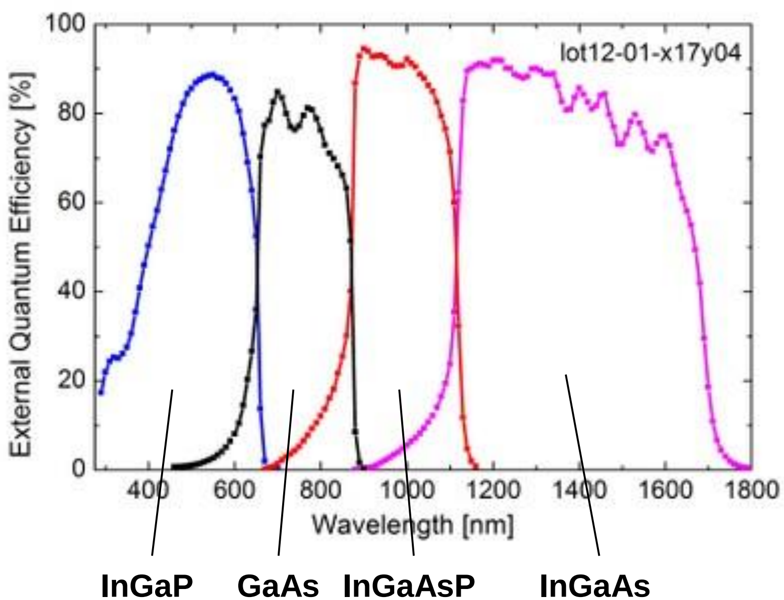
Solar cell with 44.7% efficiency (Sept 2013)

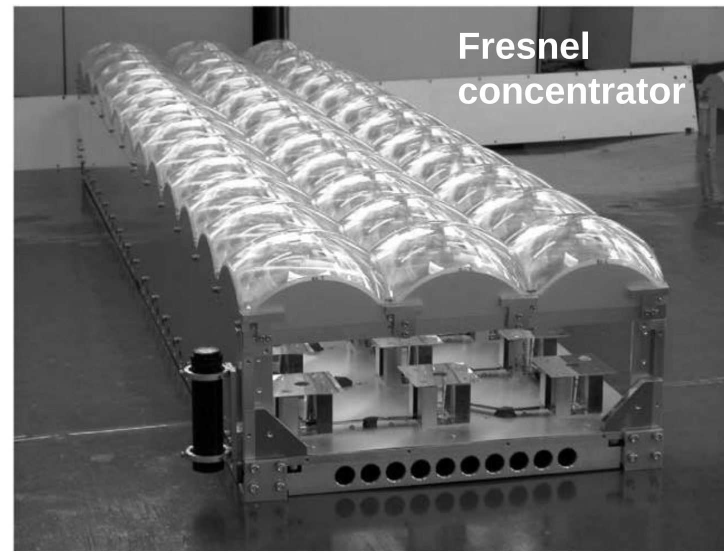










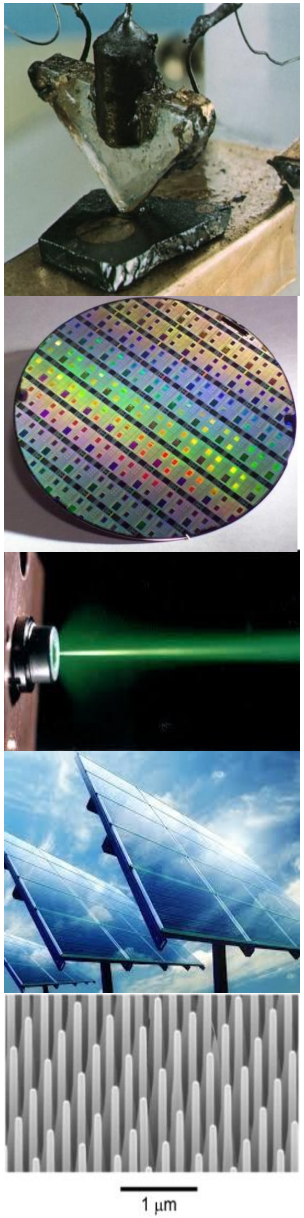


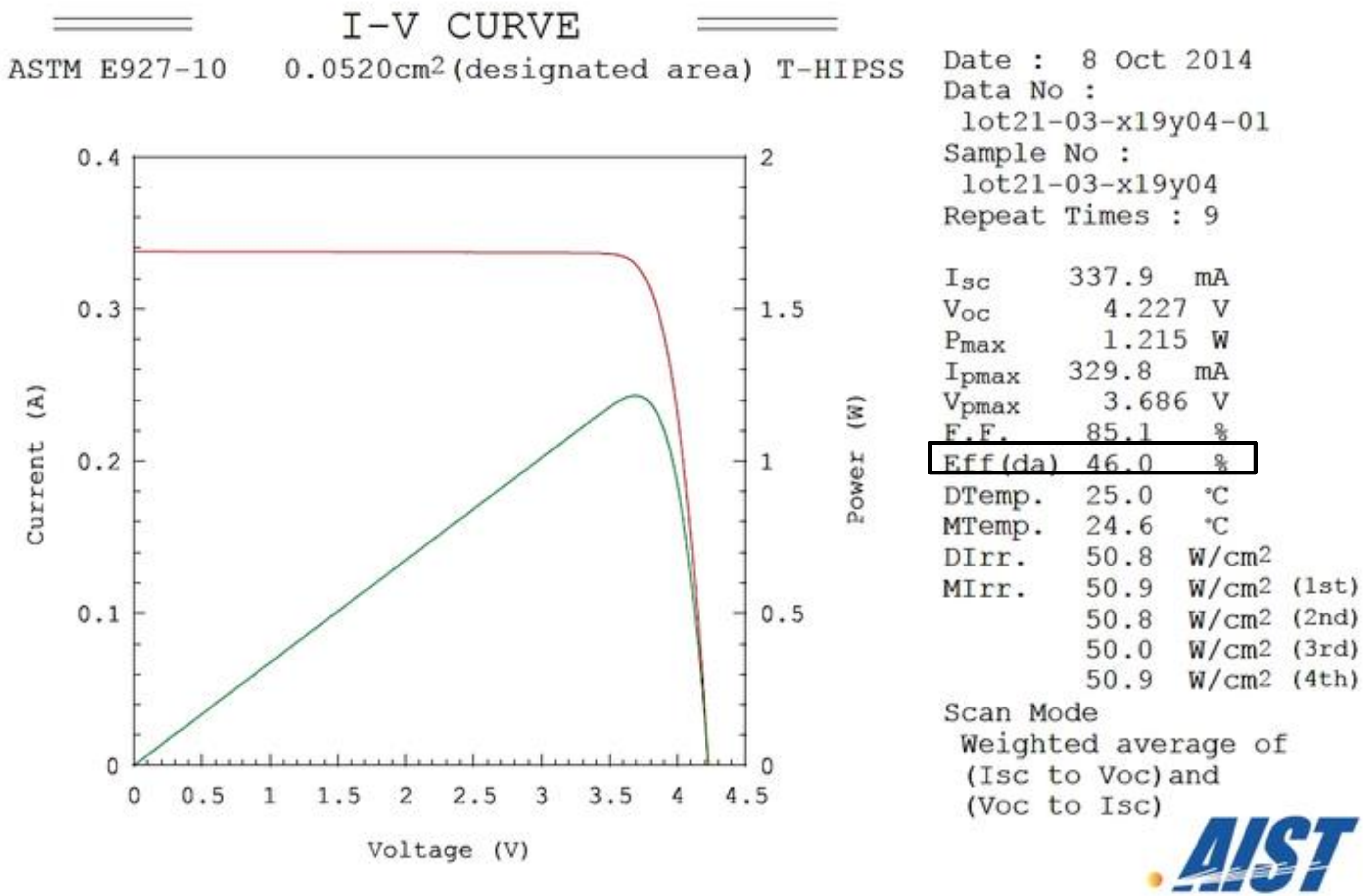


Solar Energy Materials & Solar Cells 90 (2006) 3068–3077

http://www.ise.fraunhofer.de/en/press-and-media/press-releases/presseinformationen-2013/world-record-solar-cell-with-44.7-efficiency

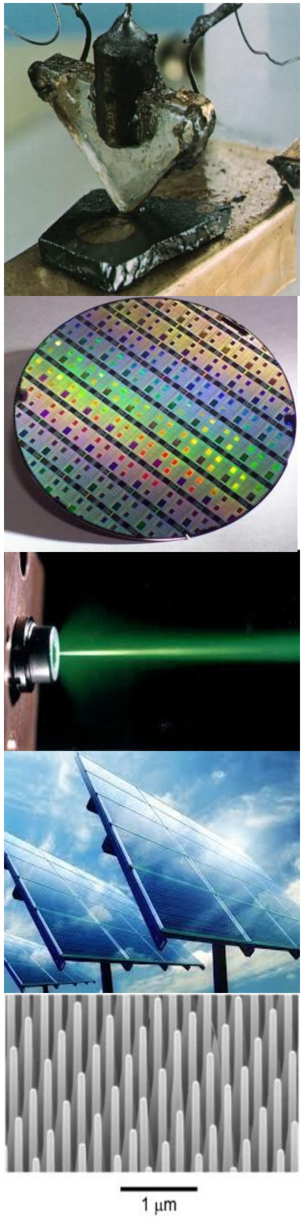
46% efficiency





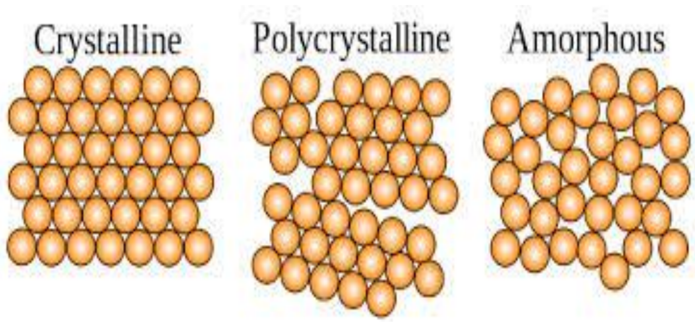
http://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2014/new-world-record-for-solar-cell-efficiency-at-46-percent

Thin Film Solar Cell



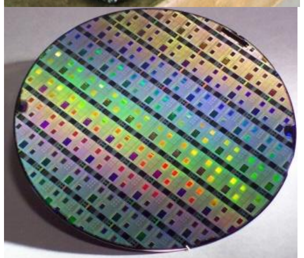
Although high efficiency can be achieved using crystalline semiconductors, the cost of manufacturing large solar panel is still high. Thin Film semiconductors are attractive options.

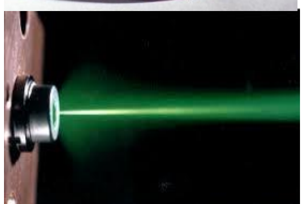
Although Si is considered the most affordable semiconductor, the cost of fabricating large area Si solar cell is high for mass market exploitation. In contrast Amorphous Si thin film, which can be deposited a variety of low cost substrate (such as glass, metal and plastic), is significantly lower cost and versatile. For instance amorphous Si can be deposited on plastic to fabricate flexible solar cell.

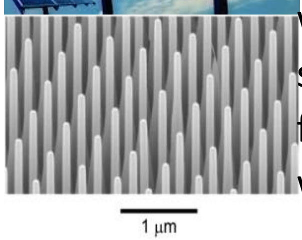


Silane (SiH_4) is used in a plasma chemical vapour deposition system to deposit the amorphous Si on the substrate of choice. Unlike the perfect lattice in crystalline Si, amorphous Si has a short range order as illustrated below.

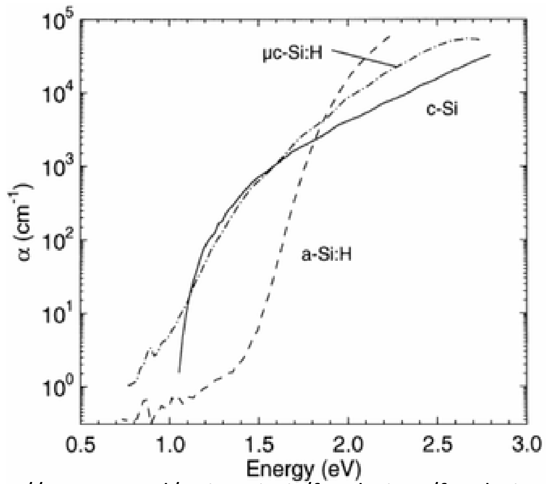
Thin Film Solar Cell

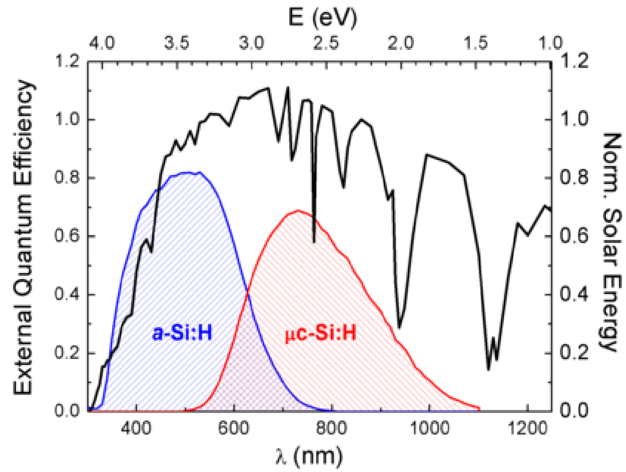






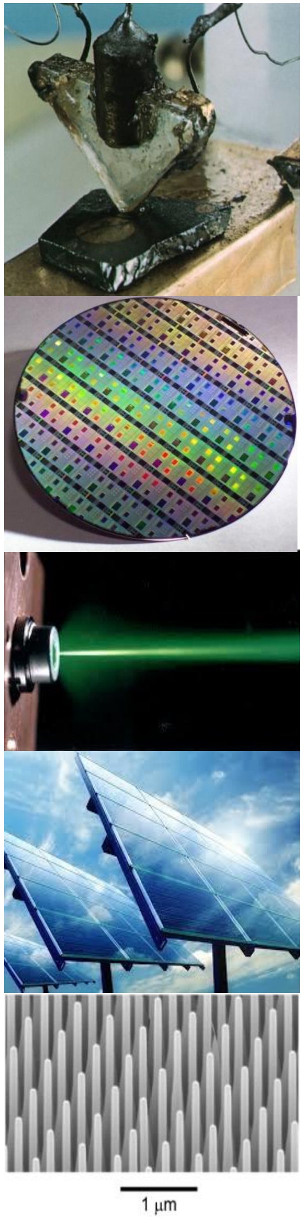
The lack of long range order leads to low mobility but the optical absorption coefficient (within the visible wavelengths) in amorphous Si is actually higher than crystalline Si as shown in figure 2. The k-selection rule which applies to perfect crystal is not applicable in amorphous Si. Hence a reasonably thin layer (~μm) of amorphous Si is sufficient to absorb solar energy.





(http://www.tue.nl/universiteit/faculteiten/faculteit-tn/onderzoek/onderzoekscluster-plasmas-en-straling/newplasma-and-materials-processing-pmp/research/research-topics/microcrystalline-silicon-for-thin-film-solar-cells/)

The bandgap of amorphous Si is around 1.7 eV. The conversion efficiency achieved is around 9.3%. An additional micro-crystalline Si (there are small regions with crystalline Si within the amorphous material) with a band gap of ~1 eV can be used to form a tandem solar cell that increases the efficiency to ~14 %. The wavelengths covered are shown in figure 3. The shorter wavelengths are absorbed by amorphous Si while the longer wavelengths are absorbed by the micro-crystalline Si.



Thin Film Solar Cell

In addition to amorphous Si thin film, the copper-indium-gallium-diselenide, $CuIn_xGa_{1-x}Se_2$ (CIGS) is an important thin film for solar cell. The bandgap of CIGS can be varied from 1 eV ($CuInSe_2$) to 1.7 eV($CuGaSe_2$). CIGS solar cell can achieve ~20% efficiency. CdTe with a bandgap of 1.5 eV is also an important thin film technology.