Photovoltaic Systems Engineering

Solar Cells

Solar Electricity

Solar-thermally generated electricity: Lowest cost solar electric source.

Complex collectors to gather solar radiation to produce temperatures high enough to drive steam turbines to produce electric power.

For example, a turbine fed from parabolic trough collectors might take steam at 750 K and eject heat into atmosphere at 300 K will have a ideal thermal (Carnot) efficiency of about 60%. Realistic overall conversion (system) efficiency of about 35% is feasible.

Photovoltaic energy:

The direct conversion of sun light to electricity.

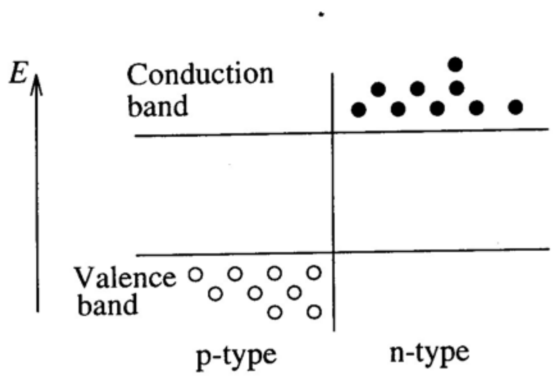
The efficiency (the ratio of the maximum power output and the incident radiation flux) of the best single-junction silicon solar cells has now reached 24% in laboratory test conditions. The best silicon commercially available PV modules have an efficiency of over 19%.

Semiconductor Junction

Consider two pieces of a given semiconductor, one doped with donor atoms and the other with acceptor atoms. Suppose that each piece has a plane face and imagine bringing them together at their plane faces. This forms a *pn-junction.* In practice the junction is manufactured from a single piece of host crystal by varying the doping in different parts of it as the crystal is grown. This produces a transition region between the *p-part* and *n-part* that is typically about 1 μm in width.

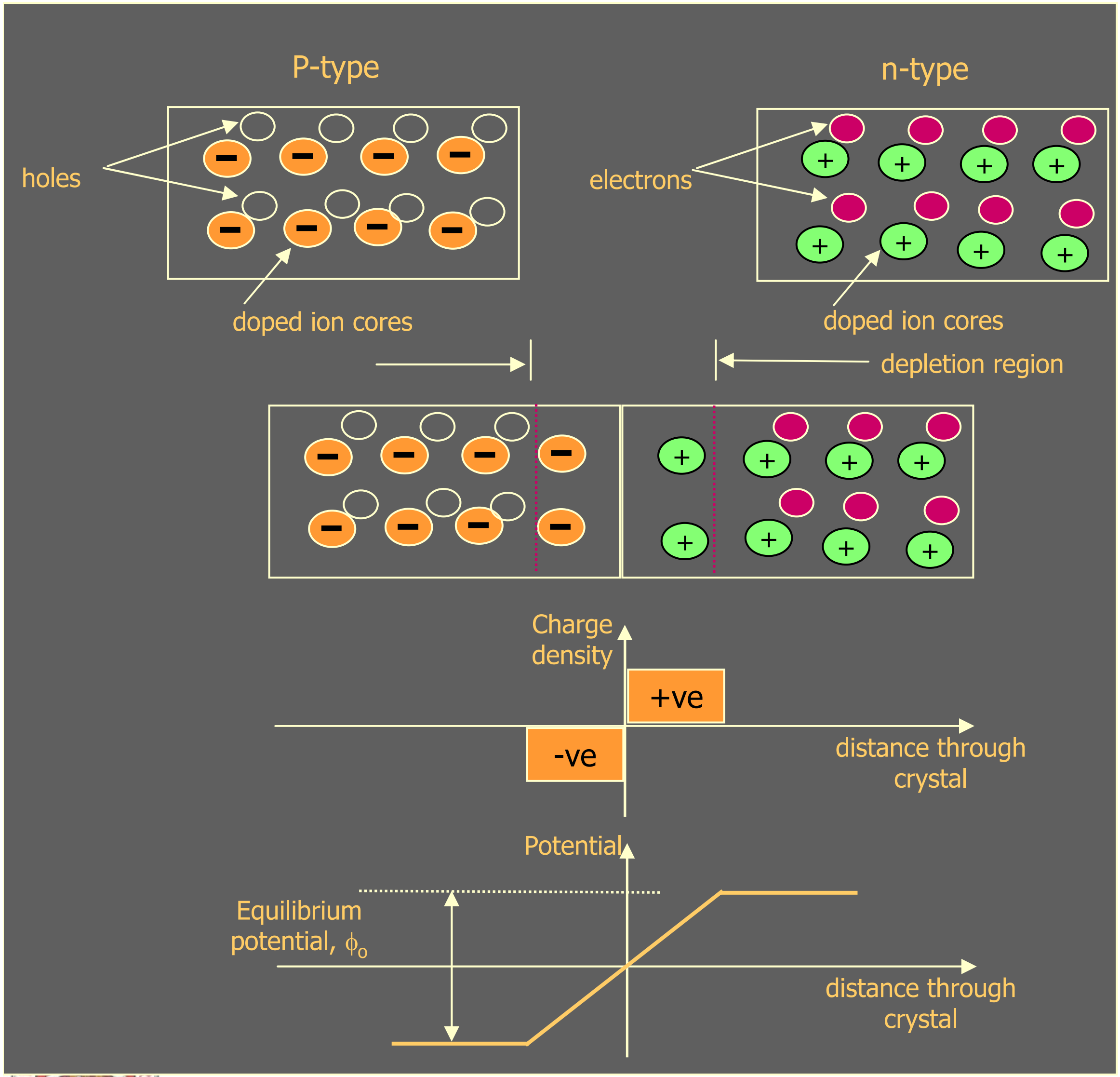
p-type material - excess holes in the valance band compared with n-type material

n-type material - excess electrons in the conduction band compared with the p-type material



After the contact is made, it is energetically favorable for some of the excess electrons in the conduction band of the n-type material to cross to the p-type material and annihilate some of the holes there. Consequently, a net negative charge is built up in the p-type material and a net positive charge in the n-type material. Thus an electrostatic potential is set up, and this eventually stop the flow of further electrons across the junction.

pn -Junction



In trying to neutralize charges

Free electrons in n-type diffuse across junction to p-type and free holes in p-type diffuse to n-type; electrons and holes close to junction recombine.

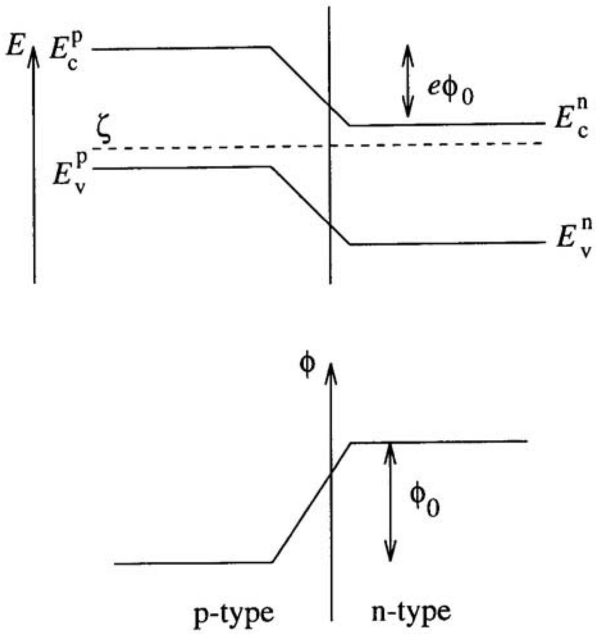
A depletion region (free of mobile charge carriers) develops on either side of the junction with fixed -ve ions on p-side and fixed +ve ions on the n-side. These residue charges prevent further diffusion so that recombination between holes and electrons is inhibited.

A potential difference develops across the junction with equilibrium potential, ϕ_o and depletion region has high resistivity due immobile charge carriers

Now some extra energy is required for the charges to move across the barrier.

Pn-junction

ϕ is the electrostatic potential



Suppose that heat is applied to the junction, so that extra electron-hole pairs are created by thermal excitation, the electric field drives the electrons towards the n-type material and the holes towards the p-type material. So if the two sides of the crystal are joined to an external circuit, the effect of the heat is to drive a current through the crystal from n-type side to the p-type side, and round the circuit.

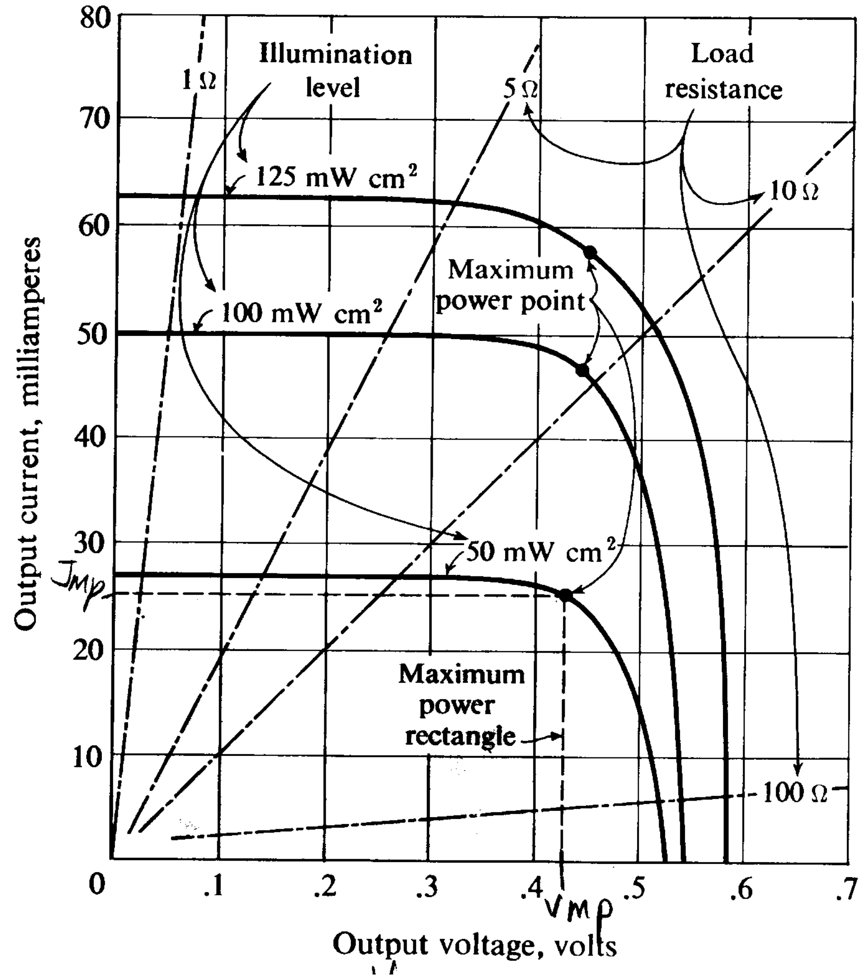
A current is also generated if light is shone on the junction, so that the absorbed photons create electron-hole pairs. This is the photovoltaic effect - the basis of *solar cell*.

If current is driven through the junction by an external source, like a battery, electrons and holes recombine in the junction region producing photons - the *light emitting diode*.

If two faces of the crystal, perpendicular to the junction plane, are polished flat and made parallel to each other, the device operates as a *semiconductor laser*.

Solar Cell Performance

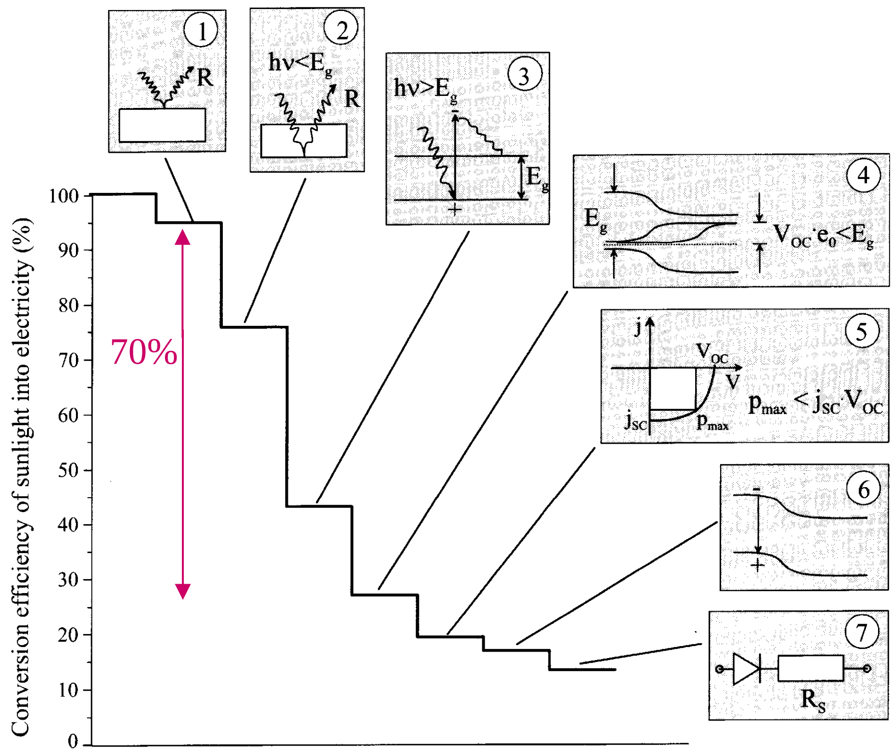
Typical voltage-current plot



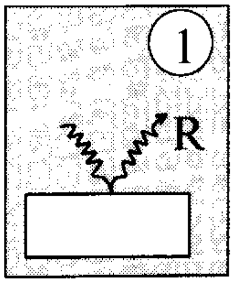
Solar Cell Performance Losses

Conversion efficiency:

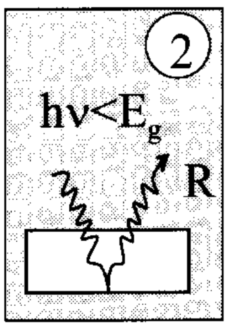
It is defined as the ratio of the electrical power produced to the incident solar power (typically at 1 kW/m²). The figure illustrates the many physical and technological loss mechanisms that result in a low conversion efficiency.



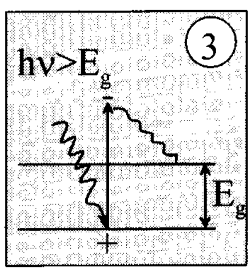
Solar Cell Performance Losses



The reflection losses at the top surface of the cell can be eliminated by putting antireflection coating composed of a thin optically transparent dielectric layer on the top surface of the cell.

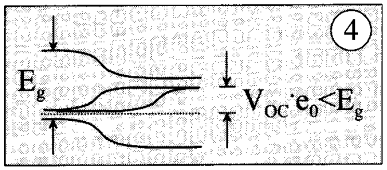


There is a minimum energy level (and thus the maximum wavelength) of photons that can cause the creation of a hole-electron pair. For silicon, the maximum wavelength is 1.15μm. Radiation at higher wavelengths does not produce hole-electron pairs but heats the cell.

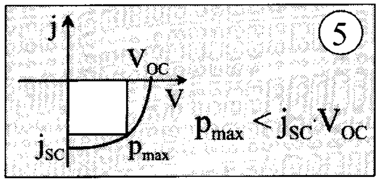


Each photon causes the creation of a single-ole pair, and the energy of photons in excess of that required to create hole-electron pairs is also converted into heat.

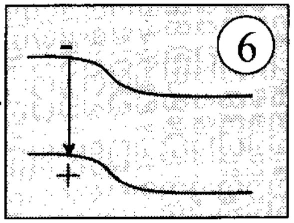
Solar Cell Performance Losses



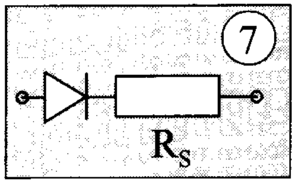
The open circuit voltage is physically limited to values less than the bandgap voltage.



Since I-V curve is not perfectly rectangular, only 80% of the maximum power is achieved.



Recombination losses due to photogenerated carriers not reaching the electrical contacts gives raise to a loss.



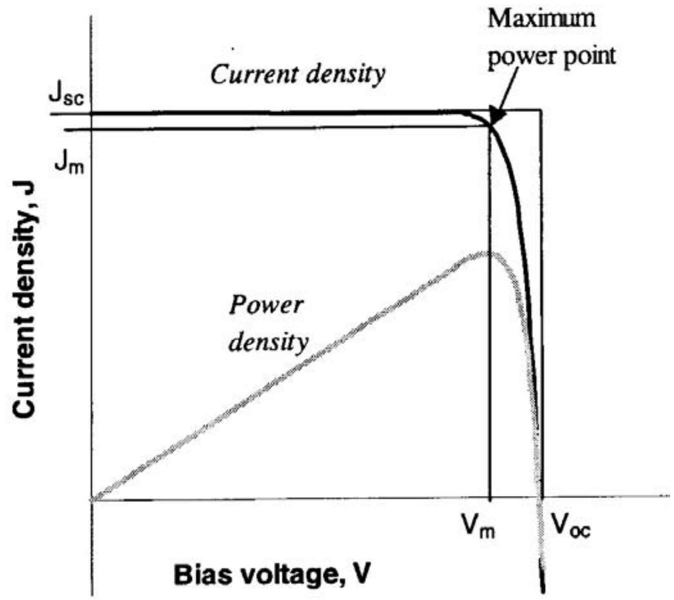
The electrical series resistance in the cell itself, its contacts and in the external circuitry lead, contributes to the loss.

Efficiency

The *cell power density* is given by

$$P = JV$$

P reaches maximum at the cell's operating point *or maximum power point (MPP).*



The *fill factor* is defined as

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}}$$

Efficiency

The efficiency η of the cell is the power density delivered at the operating point as a fraction of the incident light power density, P_s

$$\eta = \frac{J_m V_m}{P_s} = \frac{J_{oc} V_{oc} FF}{P_s}$$

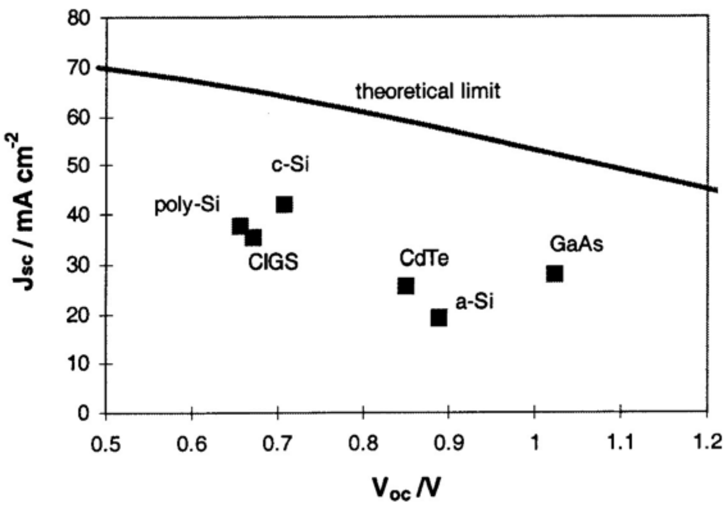
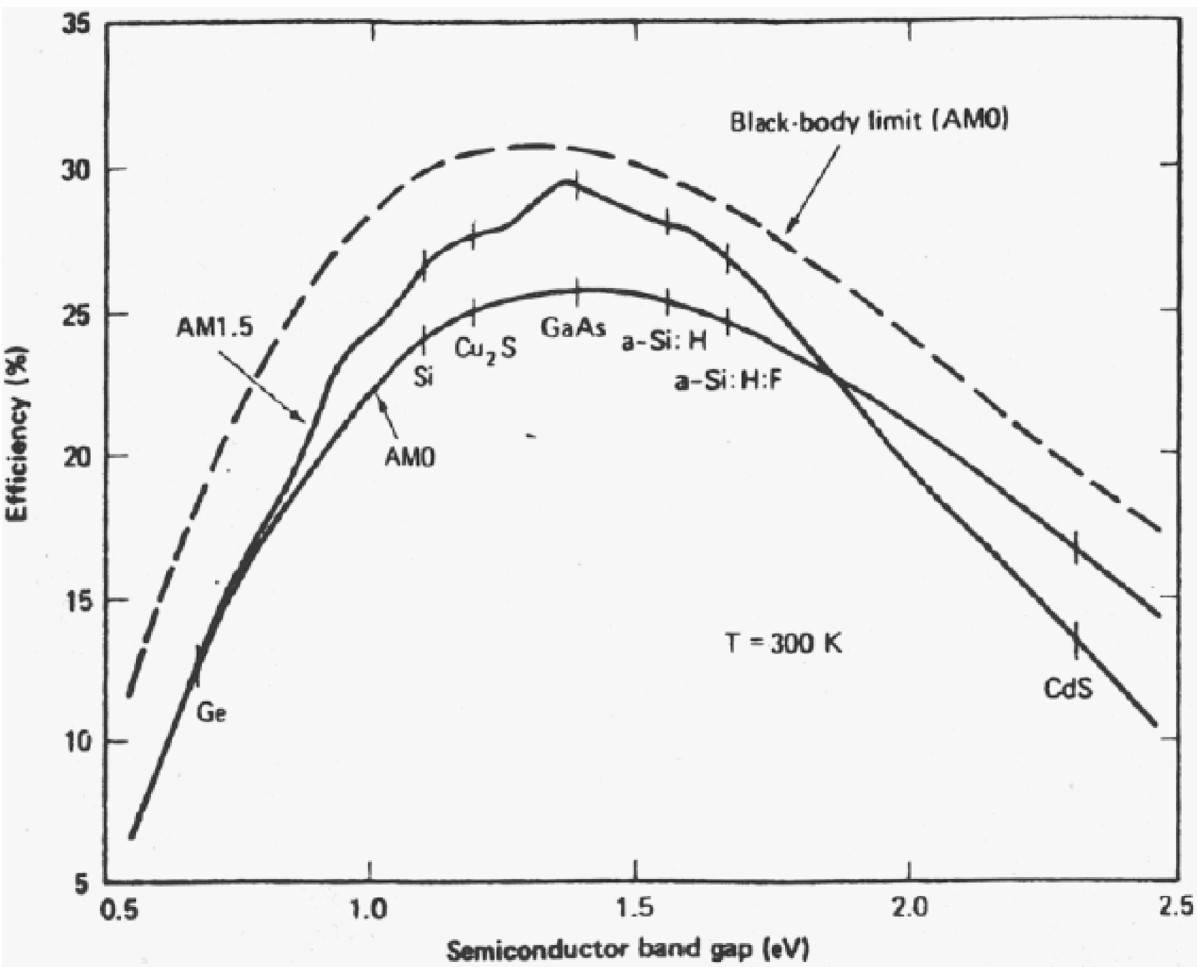


Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

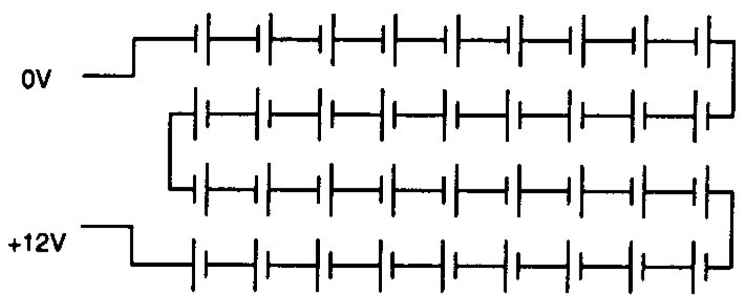
Cell Type	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
crystalline Si	4.0	0.706	42.2	82.8	24.7
crystalline GaAs	3.9	1.022	28.2	87.1	25.1
poly-Si	1.1	0.654	38.1	79.5	19.8
a-Si	1.0	0.887	19.4	74.1	12.7
$CuInGaSe_2$	1.0	0.669	35.7	77.0	18.4
CdTe	1.1	0.848	25.9	74.5	16.4

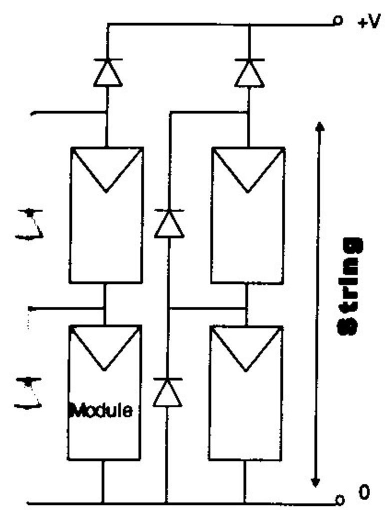
Power Conversion Efficiency Limits



PV Module

The solar cell is the basic building block of solar photovoltaics. When charged by the sun, this basic unit generates a dc photovoltage of 0.5 to 1.0V and, in short circuit, a photocurrent of some tens of mA/cm^2. Since the voltage is too small for most applications, to produce a useful voltage, the cells are connected in series into *modules,* typically containing about 28 to 36 cells in series to generate a dc output of 12 V. To avoid the complete loss of power when one of the cells in the series fails, a blocking diode is integrated into the module. Modules within arrays are similarly protected to form a photovoltaic generator that is designed to generate power at a certain current and a voltage which is a multiple of 12 V.





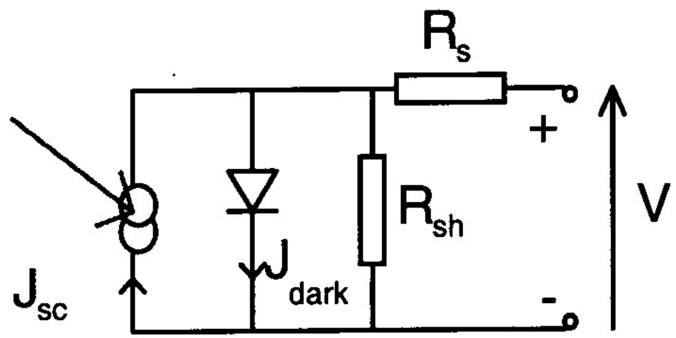
Parasitic Resistances

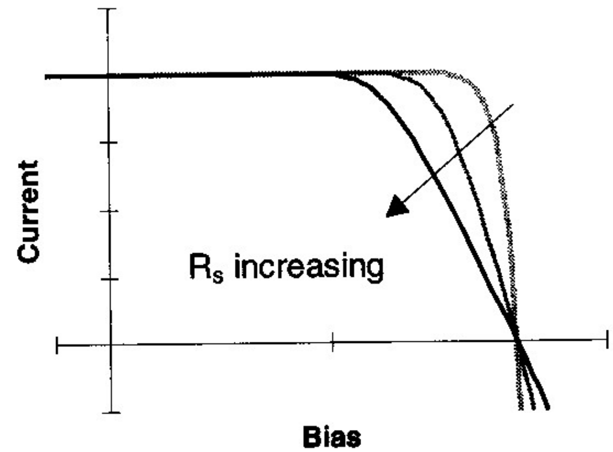
Real cells: Resistance of the contacts and leakage currents around the sides of the device

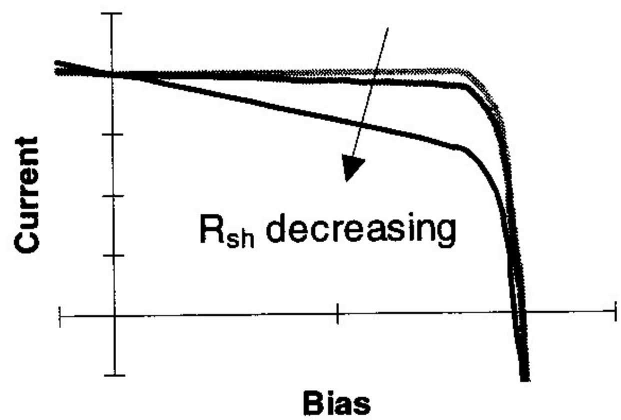
Series resistance: it arises from the resistance of the cell material to current flow, particularly through the front surface to the contacts and from resistive contacts. It is a particular problem at high current densities, i.e. under concentrated light.

Shunt resistance: It arises from the leakage of the current through the cell around the edges of the device and between contacts of different polarity. It is a problem with poorly rectifying devices.

Parasitic Resistances

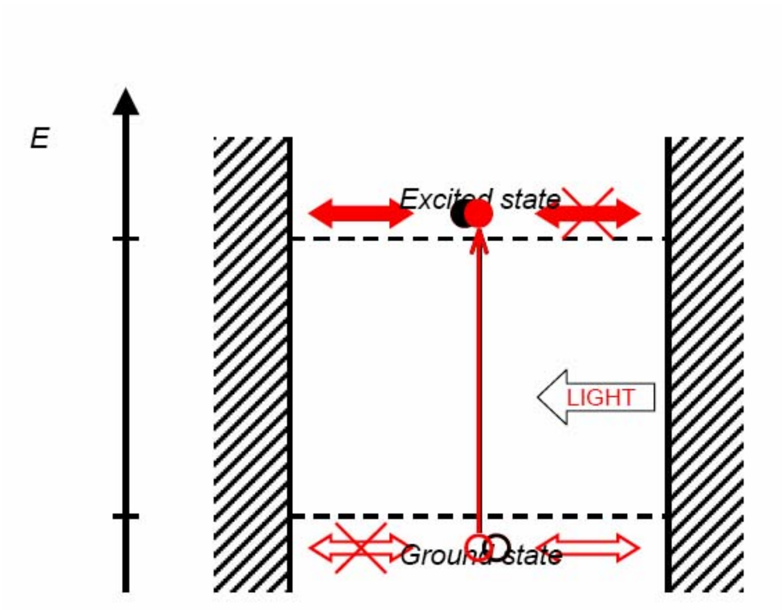






The effect of resistances is to reduce the area of the maximum power rectangle compared to J_{sc} x V_{oc}.

Solar Cells and Photovoltaics



Light harvesting
Charge Separation
Selective Charge Transport

Consider a two band system: the ground state is initially full and the excited state empty

Band gap, E_g : The bands are separated by a band gap.

Photons with energy $E < E_g$ can not promote an electron to the excited state. Photons with $E \geq E_g$ can raise the electron but any excess energy is quickly lost as heat as the carriers relax to the band edges.

Source: Keld West, Riso National Laboratory, Denmark

Solar Cell - Definitions

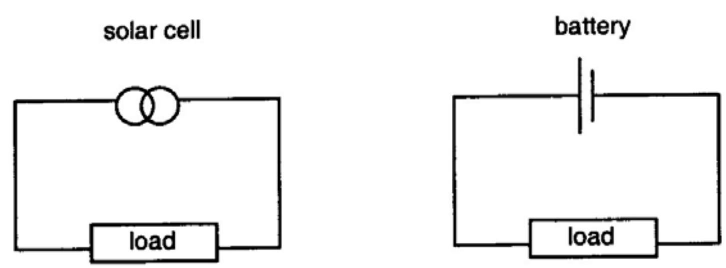
Open circuit voltage V_{oc}: When light hits a solar cell, it develops a voltage, analogous to the e.m.f. of a battery in a circuit. The voltage developed when the terminals are isolated (infinite load resistance) is called the open circuit voltage.

Short circuit current I_{sc}: The current drawn when the terminals are connected together is the short circuit current.

For any intermediate load resistance R_L the cell develops a voltage V between 0 and V_{oc} and delivers a current I such that $V = IR_L$, and *$I(V)$ is determined by the Current-voltage characteristic* of the cell under that illumination.

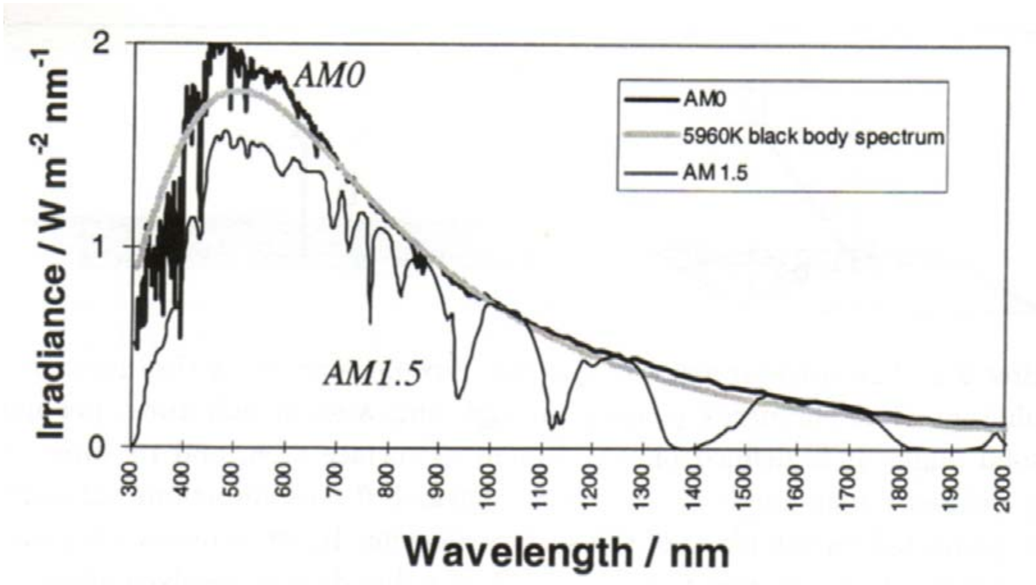
Both I and V are determined by the illumination as well as the load.

The current is approximately proportional to the illumination area, the *short circuit current density, J_{sc}* is a useful quantity for comparison.



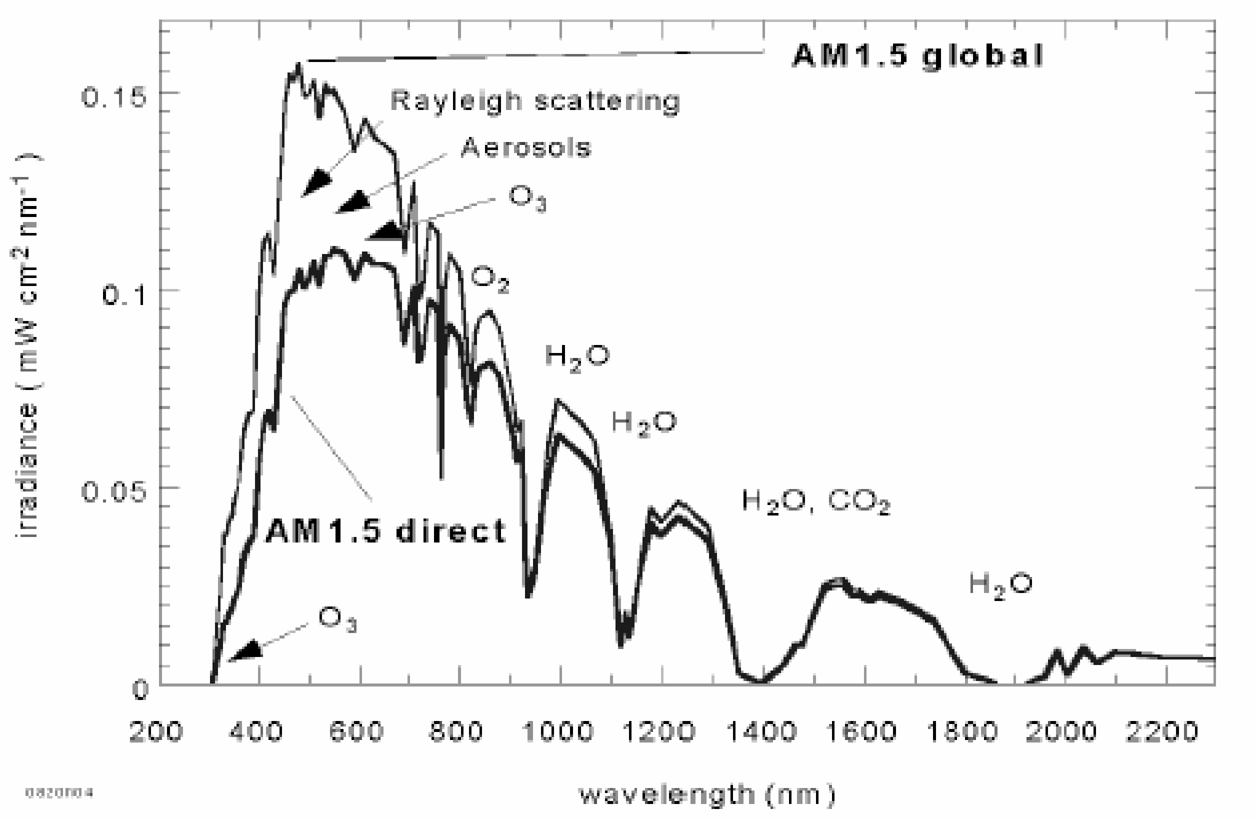
Solar Irradiance

Solar irradiance: The amount of radiant energy received from the Sun per unit area per unit time. It is a function of wavelength at a point outside the Earth's atmosphere. Solar irradiance is greatest at wavelengths, 300-800 nm.



The extraterrestrial spectrum resembles the spectrum of a *black body* radiation at 5760 K. The black body emits photons with a distribution of energies determined by it's surface temperature.

Solar Radiation Spectrum



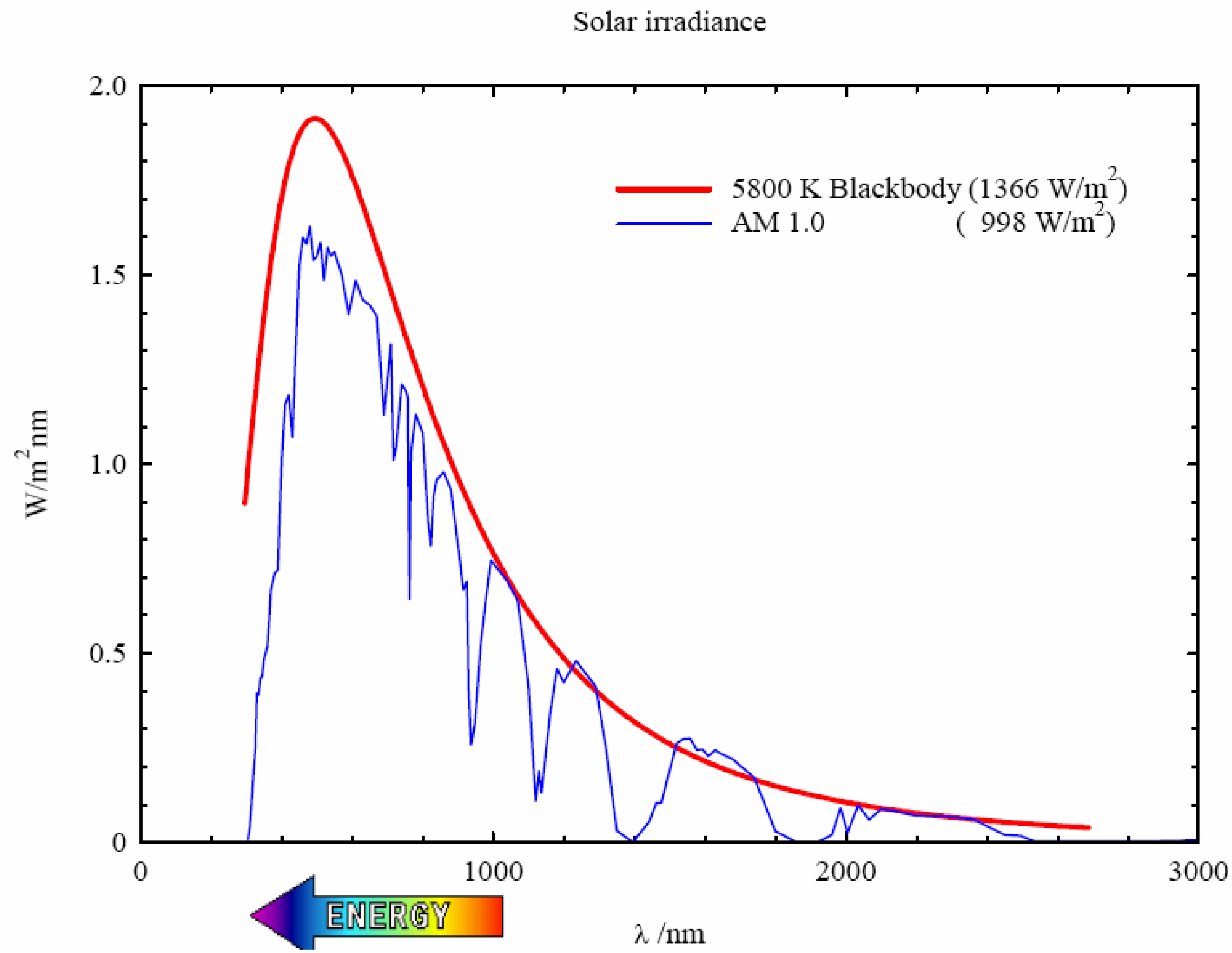
The global spectrum comprises the direct plus the diffused light.

AM 1.5d Spectrum Energy Distribution

(eV) :	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.24	1.18	1.13	1.08	1.03	0.99	0.95	0.69	0.62	0.5
(nm):	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1800	2000	2500
300	0	0.7	2.9	7.6	14	21	28	35	42	48	54	59	64	67	70	74	77	79	81	84	86	96	96	100
350		0	2.2	6.9	14	21	28	35	41	47	53	58	63	66	69	73	77	78	80	83	85	95	96	99
400			0	4.7	11	18	25	33	39	45	51	56	61	64	67	71	74	76	78	81	83	93	93	97
450				0	6.7	14	21	28	34	40	46	51	56	59	62	66	70	71	73	76	78	88	89	92
500					0	7.0	14	21	28	34	39	44	50	52	56	60	63	64	67	69	72	81	82	86
550						0	7.1	14	21	27	32	37	42	45	49	53	56	57	60	62	65	74	75	79
600							0	7.1	14	20	25	30	35	38	42	46	49	50	52	55	58	67	68	72
650								0	6.5	13	18	23	28	31	35	39	42	43	45	48	51	60	61	65
700									0	6.1	12	17	22	25	28	32	35	37	39	42	44	54	54	58
750										0	5.6	11	16	19	22	26	29	30	33	35	38	48	48	52
800											0	5.1	10	13	16	20	24	25	27	30	32	42	43	46
850												0	5.1	8.0	11	15	19	20	22	25	27	37	37	41
900													0	2.9	6.3	10	13	15	17	20	22	32	32	36
950														0	3.3	7.3	11	12	14	17	19	29	29	33
1000															0	3.9	7.2	8.4	11	13	16	26	26	30
1050																0	3.2	4.5	6.8	9.5	12	22	22	26
1100																	0	1.2	3.5	6.2	8.7	18	19	23
1150																		0	2.3	5.0	7.5	17	18	21
1200																			0	2.7	5.2	15	15	19
1250																				0	2.5	12	13	16
1300																					0	10	10	14
1800																						0	0.5	4.3
2000																							0	3.8
2500																								0

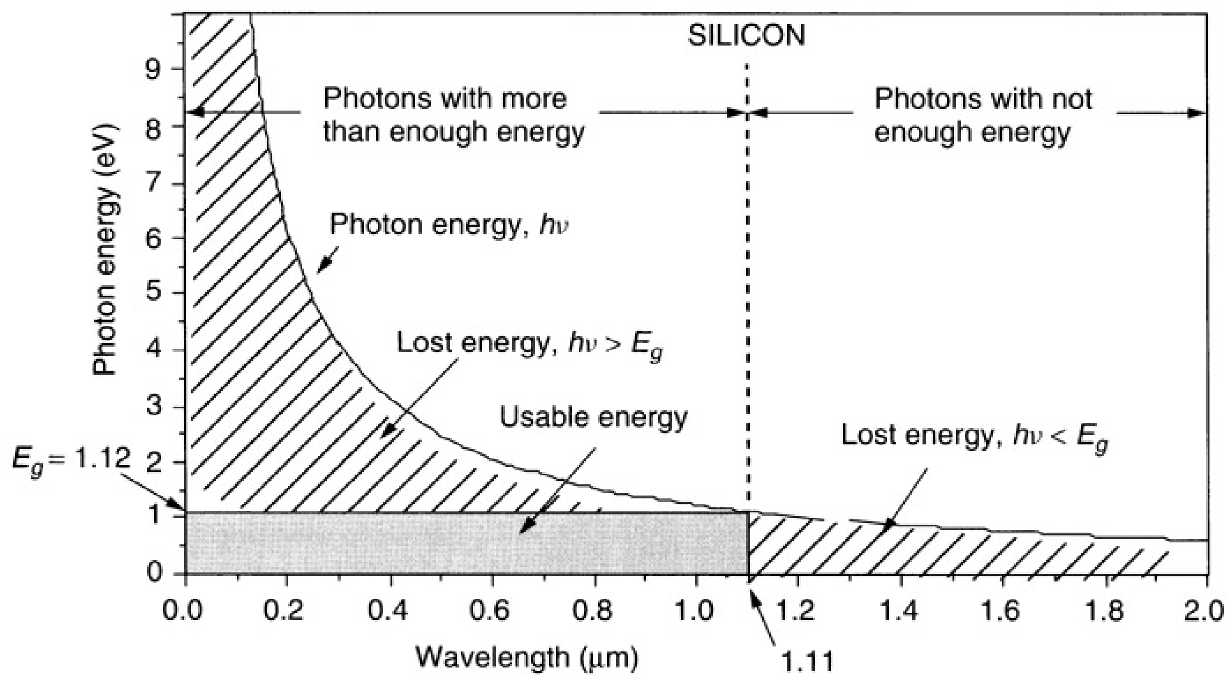
Silicon solar cells with a bandgap of 1.13ev can maximally absorb 77% of the terrestrial solar energy.

Solar Spectrum



Source: Keld West, Riso National Laboratory, Denmark

The Solar Spectrum



Photons with wavelengths above 1.11 μm do not have 1.12 eV needed to excite the electron, and this energy is lost. Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted as well

Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

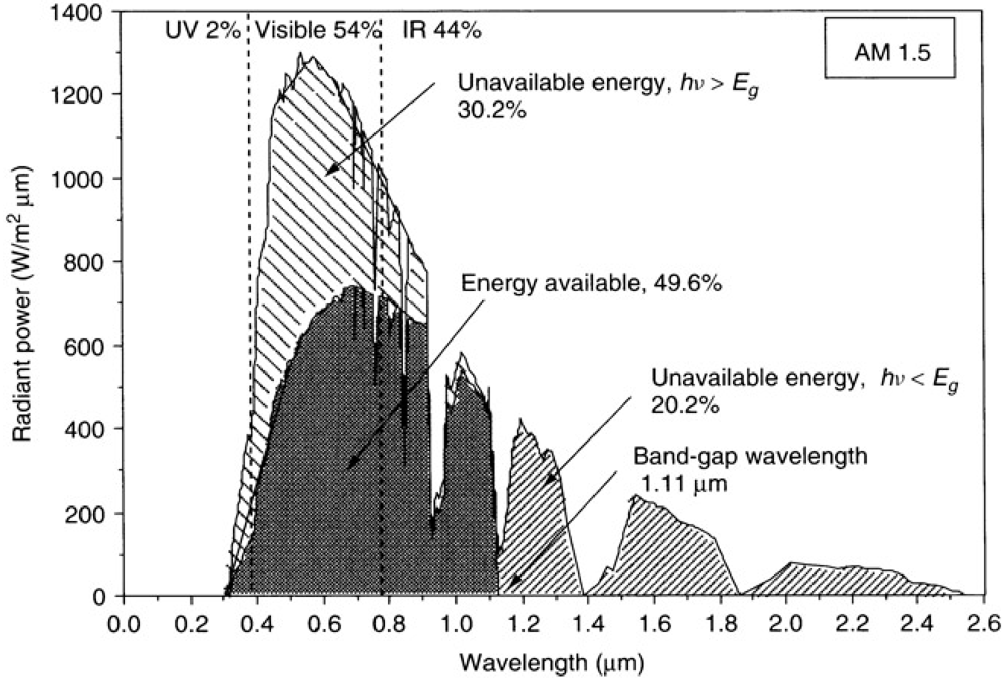
Band Gaps

The band gap of a semiconductor, measured in electron volts [eV], is the difference between the valence band and the conduction band potentials. Each type of semiconductor has a unique band gap, most of which fall in the range 1.0 to 2.6 eV.

Semiconductor	Band Gap [eV]
Silicon	1.1
Gallium Arsenide	1.34
Copper Indium Delenide	1.0
Germanium	0.72
Indium antimonide	0.18
Cadium Sulfide	2.45
Zinc Oxide	3.3

The point to note here is that a photovoltaic material can only capture those photons which have an energy greater than or equal to the band gap of that material. Silicon, for example, will be transparent to photons with an energy of less than 1.1 eV.

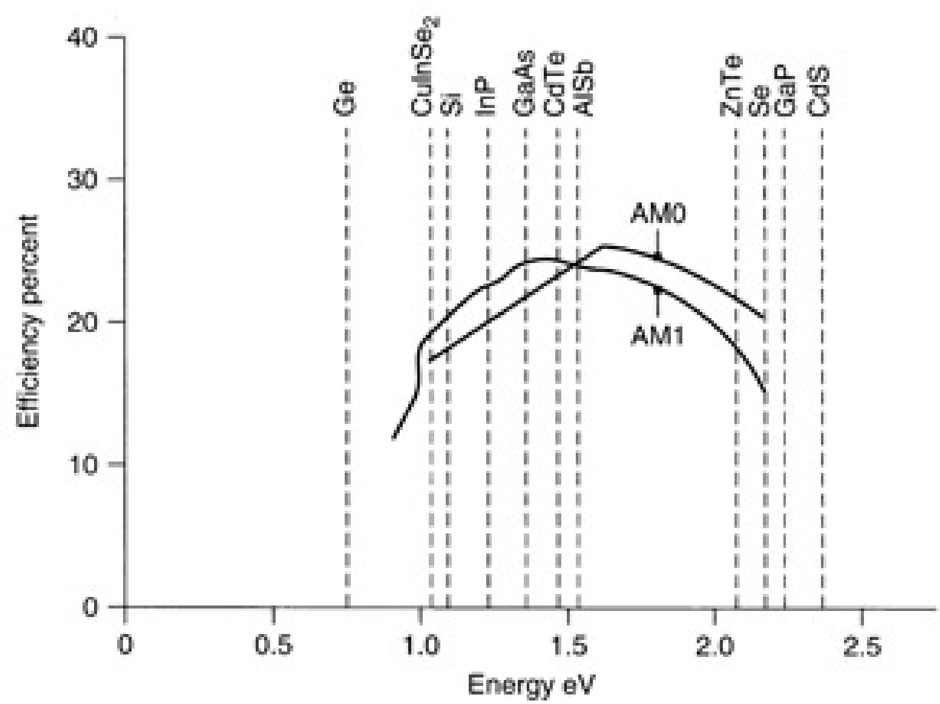
Photovoltaic Efficiency



Solar spectrum at AM 1.5. Photons with wavelengths longer than 1.11 μm do not have enough energy to excite electrons (20.2% of the incoming solar energy); those with shorter wavelengths can not use all their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell. With a smaller band gap, more solar photons have the energy needed to excite electrons resulting in creating the charges that will enable current to flow (more current with less voltage). However, more photons have surplus energy above the threshold needed to create hole-electron pairs, which waste their potential. A high band gap means that fewer electrons have energy to create the current carrying electrons and holes, which limits the current that can be generated. However, high band gap gives those charges a higher voltage with less left over surplus energy (less current and higher voltage) .

Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

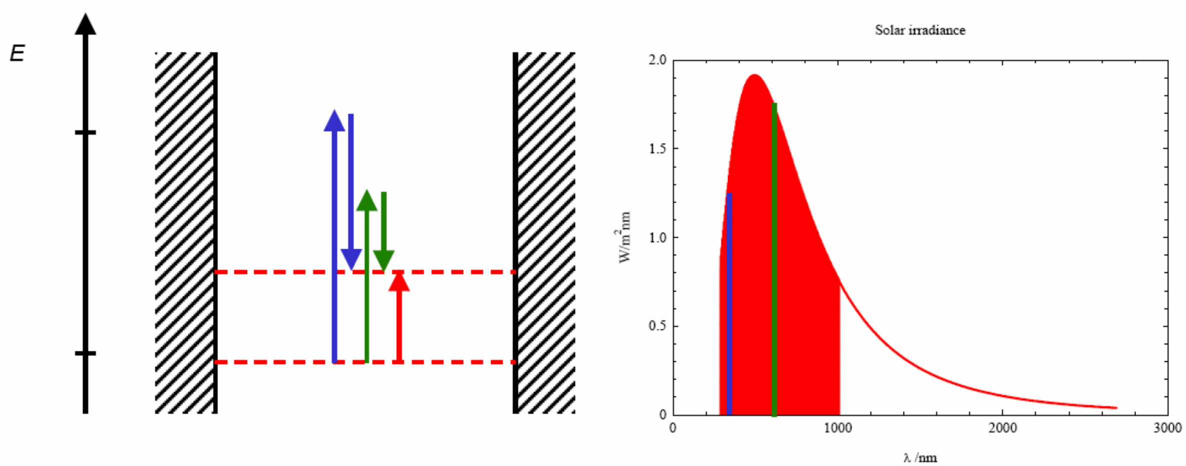
Band Gap- Efficiency



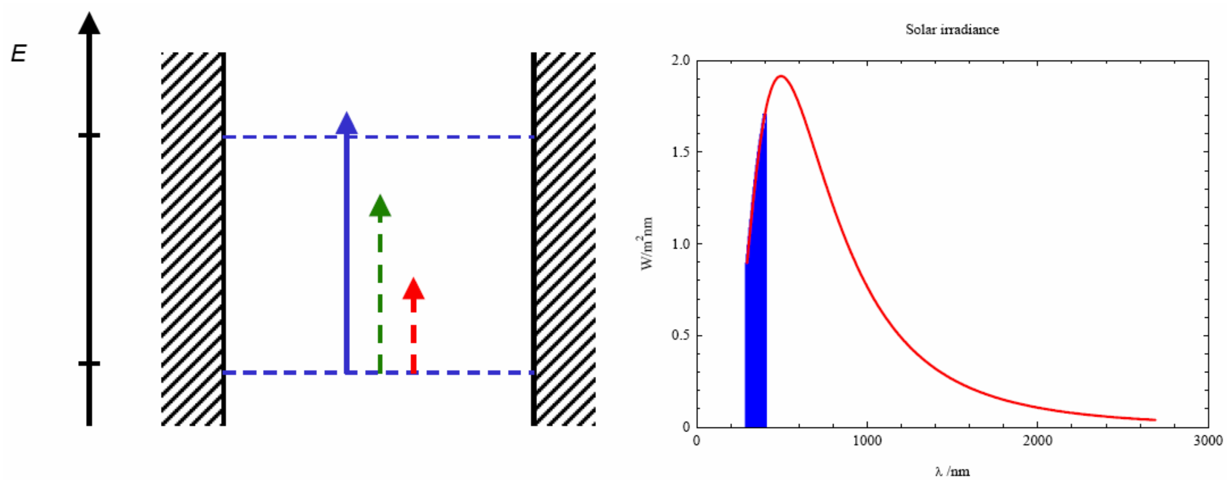
The drop in theoretical efficiency include: only about half to two-thirds of the full band gap voltage across the terminals of the solar cell; recombination of holes and electrons before they can contribute to current flow; internal resistance within the cell, which dissipates power; Photons that are not absorbed in the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.

Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

Efficiency Limitations



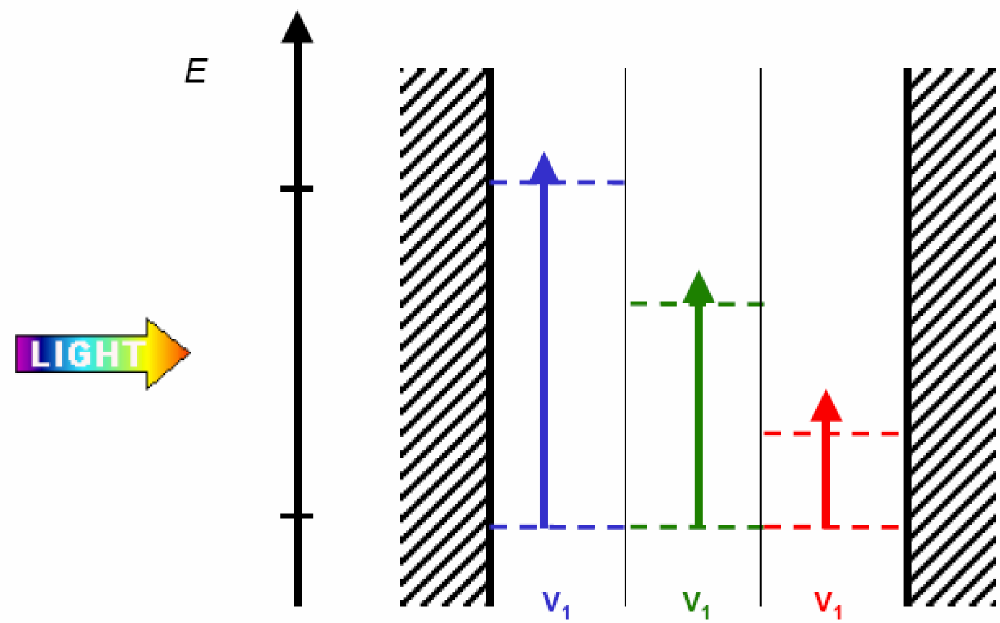
High current – low voltage



Low current – high voltage

Source: Keld West, Riso National Laboratory, Denmark

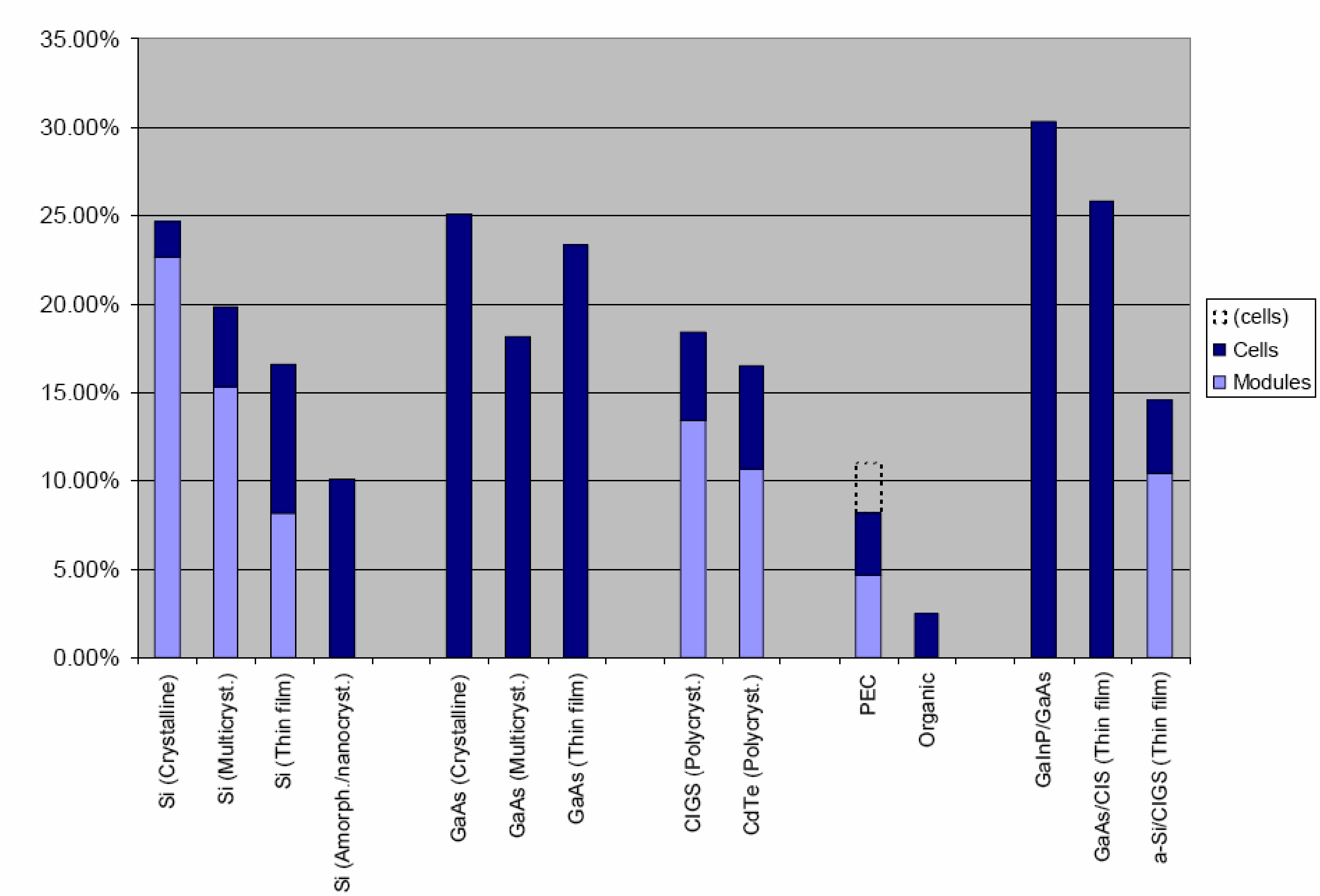
Multi-gap Devices



Efficiencies up to 0.63 may be realised with multi-gap devices, P. Würfel, *Physica E* **14** 18 (2002).

Source: Keld West, Riso National Laboratory, Denmark

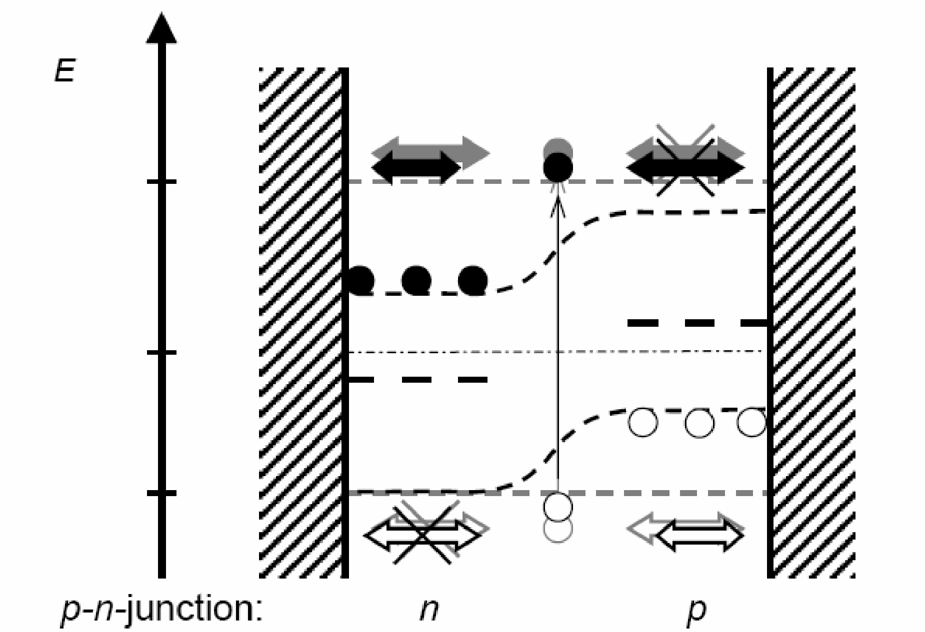
PV Efficiency



Source: Keld West, Riso National Laboratory, Denmark

1st Generation PV

Made from single or poly crystalline silicon



Mature technology

Typical efficiency: 10-15%

Life time: >20 years

40% of the cost is due to Si cost

Improved designs:

Buried contacts

Better Si-feedstock (float Zone Si)

Cheaper Si-feedstock (ribbon Si)

Efficiency >20%

Life time >25 years

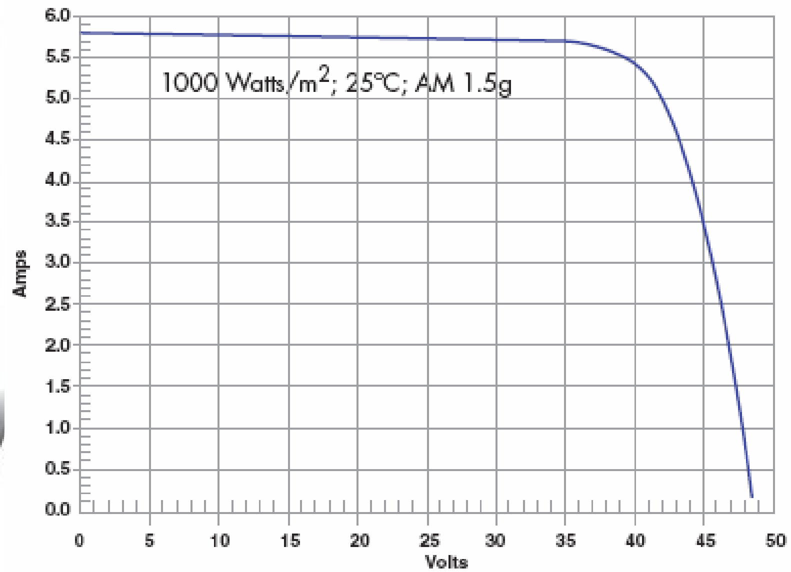
Source: Keld West, Riso National Laboratory, Denmark

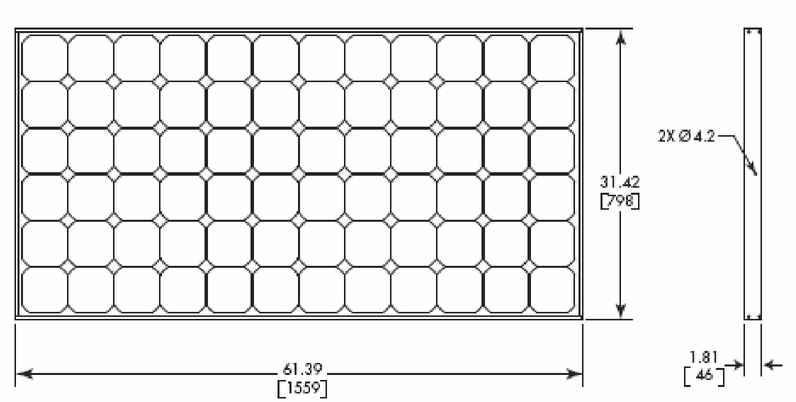
Sustainable Energy Science and Engineering Center

1st Generation Solar Panels

http://www.sunpowercorp.com/solarpanels/

Unique all-back-contact solar cells with conversion efficiency up to 21.5%





SPR-215-BLK
RESIDENTIAL PV MODULE

ELECTRICAL CHARACTERISTICS AT STANDARD TEST CONDITIONS (STC)
STC is defined as: irradiance of 1000W/m^2, spectrum AM 1.5g and cell temperature of 25°C

Peak Power[1,2]	P_{max}	215W
Rated Voltage	V_{mp}	39.8V
Rated Current	I_{mp}	5.40A
Open Circuit Voltage	V_{oc}	48.3V
Short Circuit Current	I_{sc}	5.80A
Series Fuse Rating		15A
Maximum System Voltage		600V (UL)
		1000V (IEC)
Temperature Co-efficients	Power	-0.38%/°C
	Voltage	-136.8mV/°C
	Current	2.3mA/°C
Module Efficiency		17.3%
Peak Power per Unit Area		16W/sq.ft. ; 173W/m^2
PTC Rating		197.6W

PVUsa Test Conditions (PTC) Rating

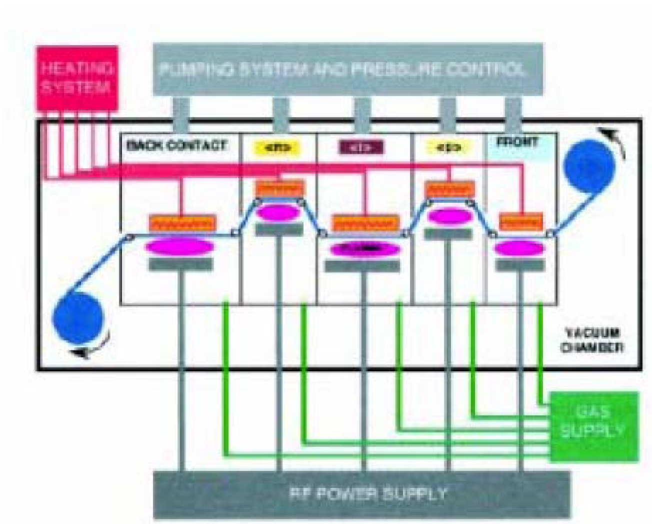
1st Generation Solar Panels

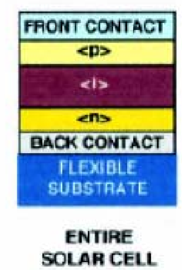
4 kW system at a base cost of $9.50 per AC watt

	California:		New Jersey:	
Total System Cost	$38,000		Total System Cost	$38,000
Rebate ($2.50 per Watt x 4000 Watts)	-$10,000		Rebate ($4.35 per Watt x 4000 Watts)	-$17,400
Net Cost	$28,000		Net Cost	$20,600
Federal Tax Credit	-$2,000		Federal Tax Credit	-$2,000
Net System Cost	$26,000		Net System Cost	$18,600
Net Savings 32%			Net Savings 51%	

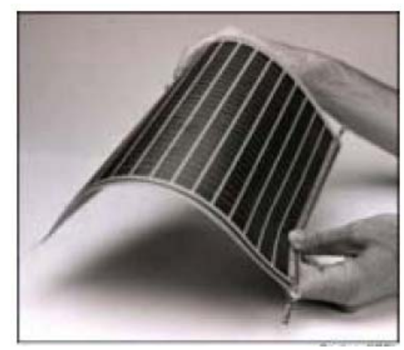
2nd Generation PV

Thin Film Technology: Thin films of active material is deposited onto a supporting substrate.





- Flexible substrate
- Small amount of material
- Low deposition rates
- Lower efficiencies



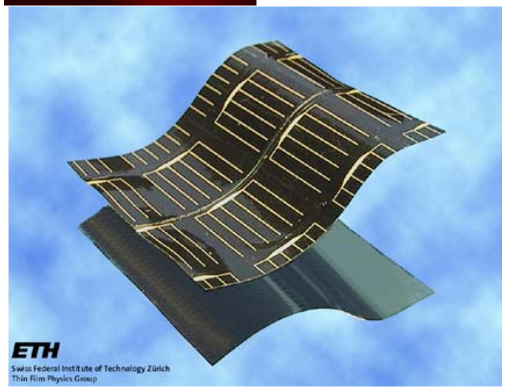
Amorphous Silicon: a-Si:H; Microcrystalline Silicon: μc-SiH

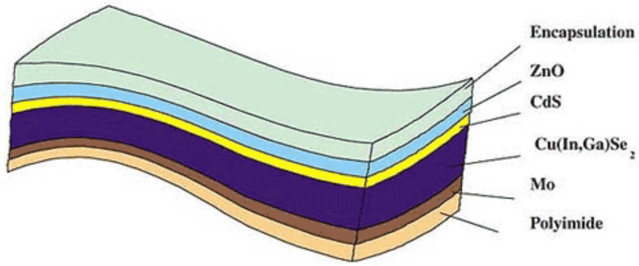
Copper indium gallium diselenide : CIGS

Cadmium telluride: CdTe

Source: Keld West, Riso National Laboratory, Denmark

2nd Generation PV

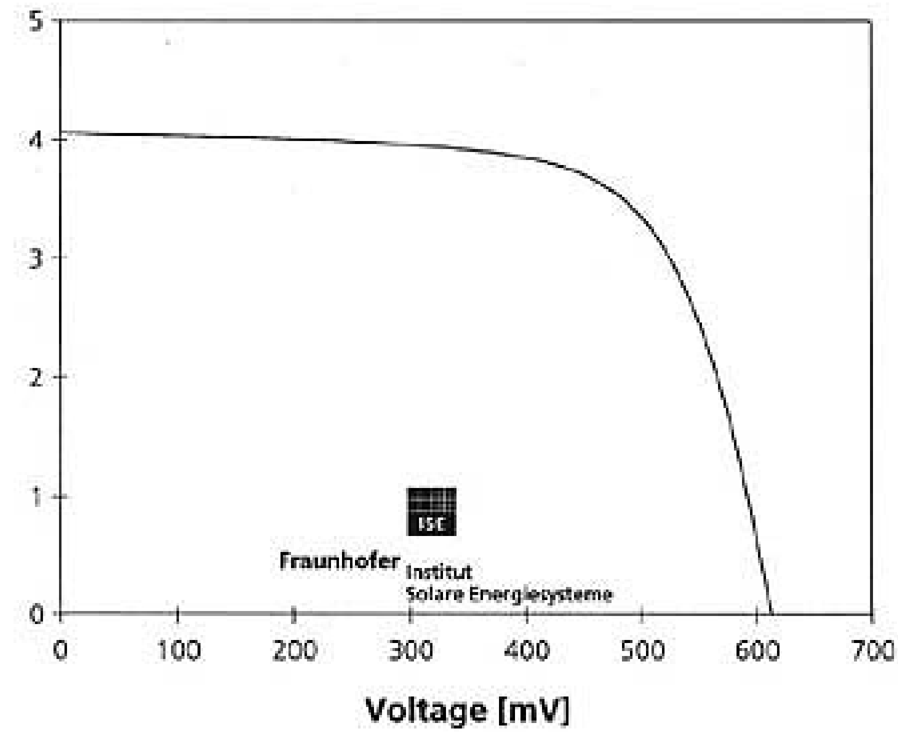




The total thickness of the solar cell including polymer substrate is less than 25 micron. A thin layer of $Cu(In,Ga)Se_2$ (also called CIGS) compound semiconductor is used for the absorption of solar light and generation of electrical current.

Thin film solar cell on Plastic (polyimide) foil - ETH

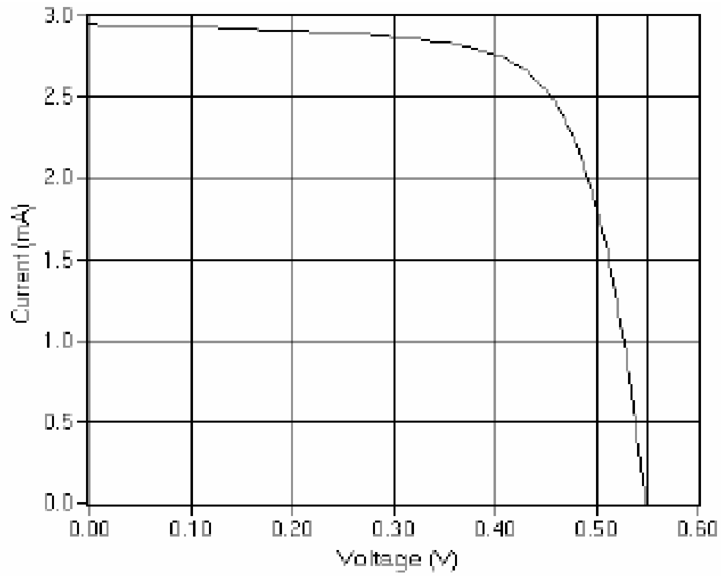
14.1% efficiency



V_{oc}	=	612.7 mV
I_{sc}	=	4.072 mA
J_{sc}	=	30.62 mA/cm²
V_{max}	=	479.2 mV
I_{max}	=	3.550 mA
P_{max}	=	1.702 mW
FF	=	68.2 %
ETA	=	**12.8 %**

2nd Generation PV

Voc (V)	0.548
Isc (mA)	2.946
Jsc (mA/cm2)	35.07
FF	0.71
Pmax (mW)	1.147
Imax (mA)	2.606
Vmax (V)	0.440
Eff (%)	13.7
Area (cm2)	0.084
N series cells	1
Irradiance (mW/cm2)	100.0



CIGS solar cell fabricated on glass substrate

CIGS Solar cell with a screen printed top contact

Voc (V)	0.489
Isc (mA)	38.104
Jsc (mA/cm2)	40.11
FF	0.63
Pmax (mW)	11.696
Imax (mA)	33.420
Vmax (V)	0.350
Eff (%)	12.3
Area (cm2)	0.950
N series cells	1
Irradiance (mW/cm2)	100.0

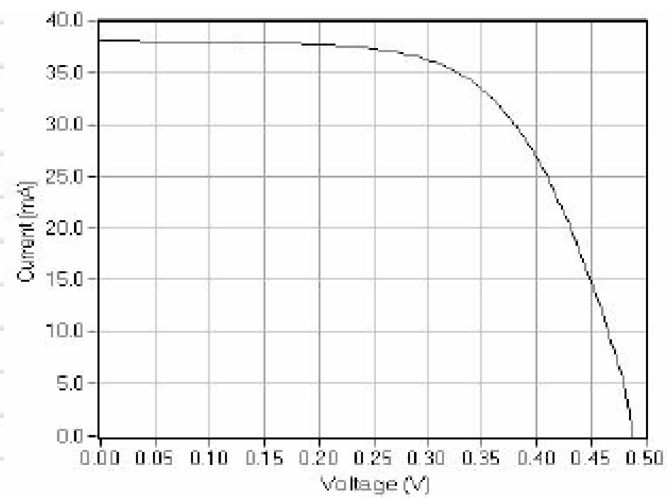
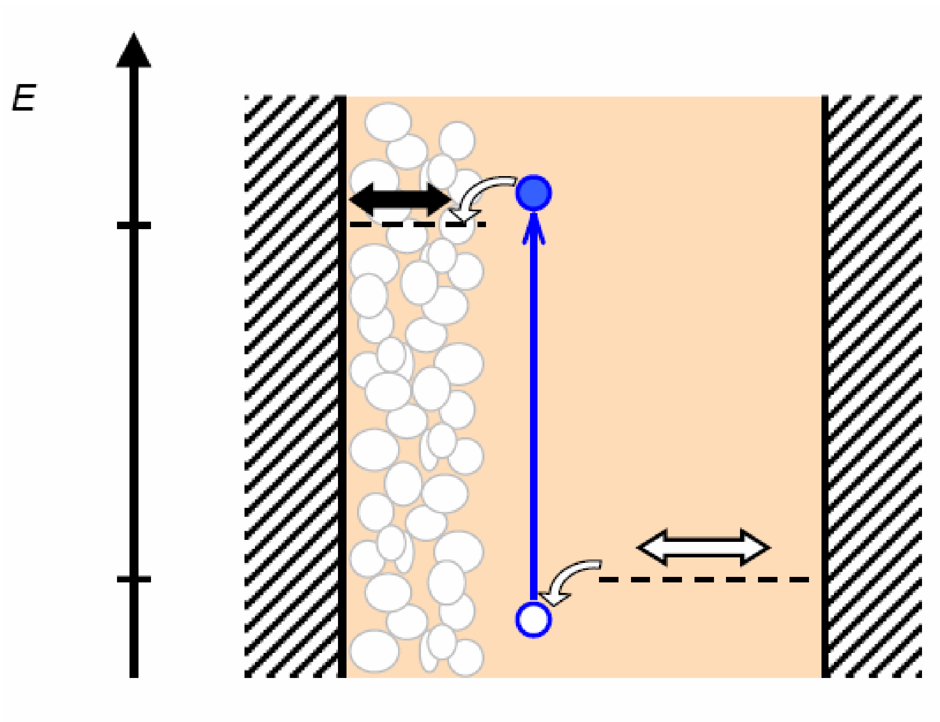


Photo Electro Chemical Solar cell



Low cost Materials

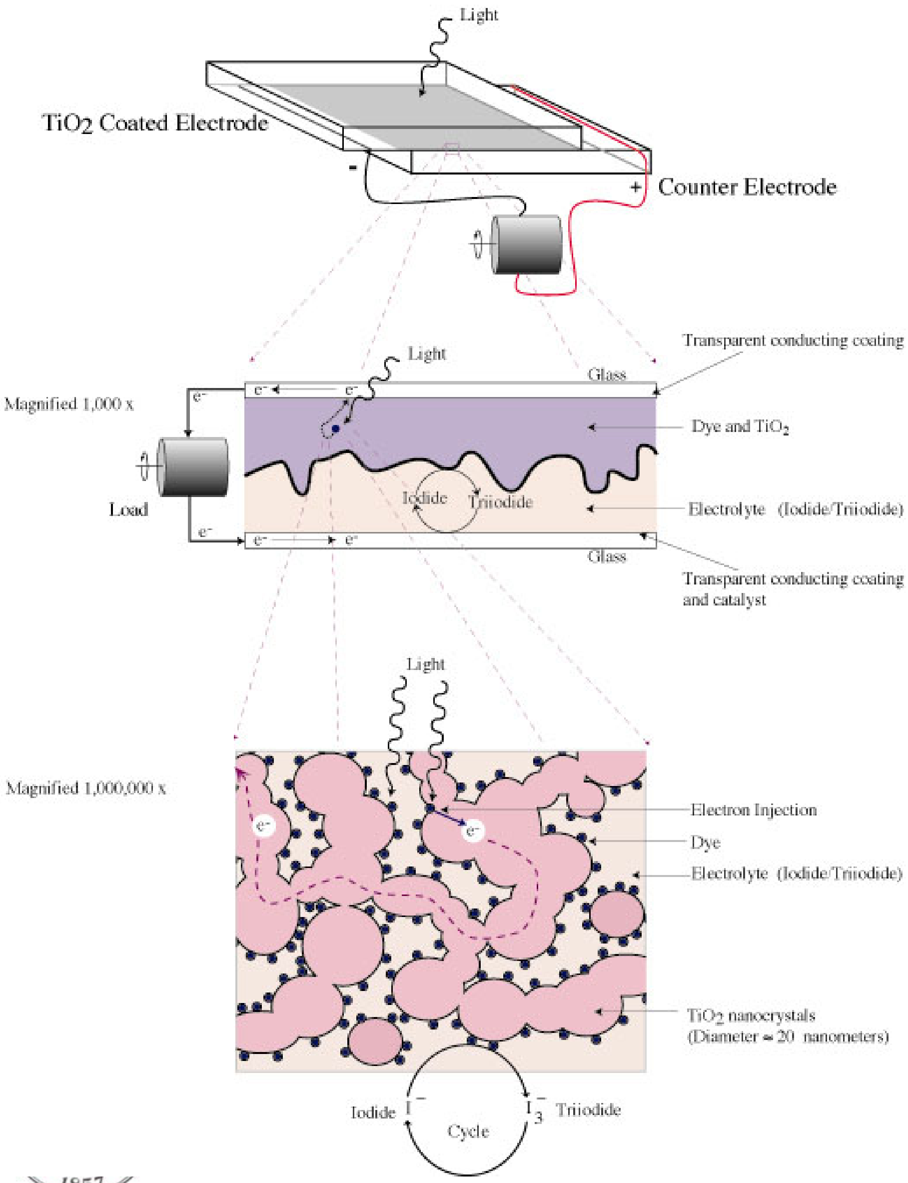
Cell efficiency: 10% (modules: 5%)

Well suited for building integration

Long term stability not yet proven

Source: Keld West, Riso National Laboratory, Denmark

Graetzel Cell

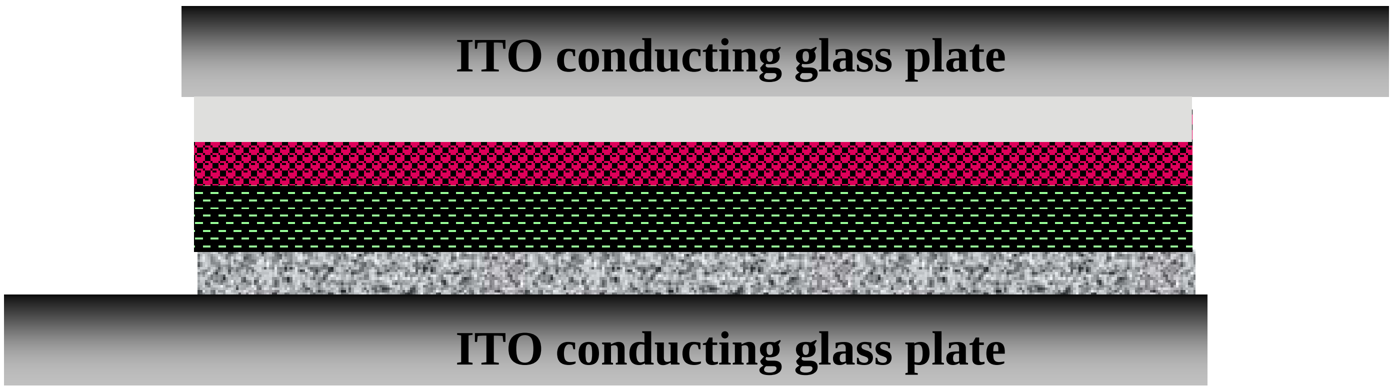


To fabricate the new cell, a titanium dioxide film that is coated on a conductive glass plate is dipped into a solution of a dye (for example blackberry, raspberry, or pomegranate juice). A single layer of dye molecules self assembles on each titanium dioxide particle and absorbs sunlight. To complete the device, a drop of liquid electrolyte containing iodide (similar to medicinal iodide) is placed on the film to enter the pores of the film. A counter electrode, made of conductive glass that has been coated with a catalytic layer, is then placed on top, and the two glass plates are clipped together using binder clips.

As the glass sandwich is illuminated, light excites electrons within the dye, and they are transferred into the film. These electrons are quickly replaced by the iodide in the electrolyte solution. The titanium dioxide serves the same role as the silver halide grain in color photography except that the electrons from the dye produce electricity rather than forming an image. The oxidized iodide becomes iodine or triiodide, and travels to the counter electrode to obtain an electron after it has flowed through the electrical load. The cycle is completed and electricity is generated. This operation mimics natural photosynthesis in which the electron acceptor is ultimately carbon dioxide, water is the electron donor, and the organic molecule chlorophyll absorbs the light.

Source: http://www.solideas.com/solrcell/news97.html

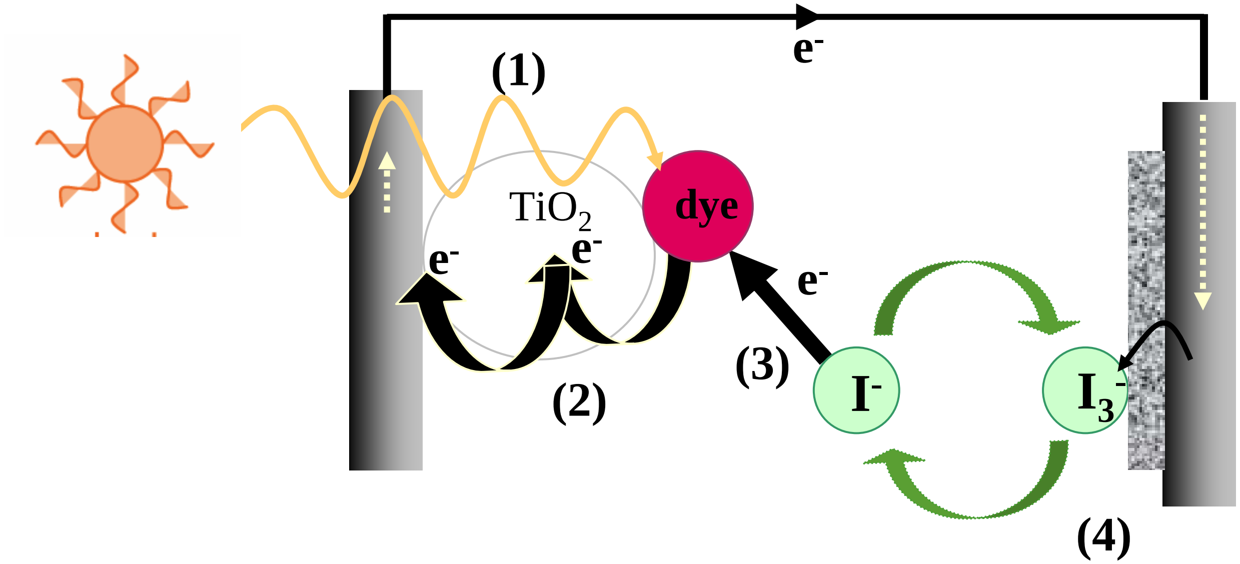
Graetzel Cell



- TiO_2 Layer
- Dye adsorbed onto TiO_2 particles
- Iodide Electrolyte
- Graphite layer

Source: http://www.lboro.ac.uk/departments/cm/business/Gratzel.html

Graetzel Cell



1) Sunlight energy (photoelectric effect) strike dye molecules, exciting electrons

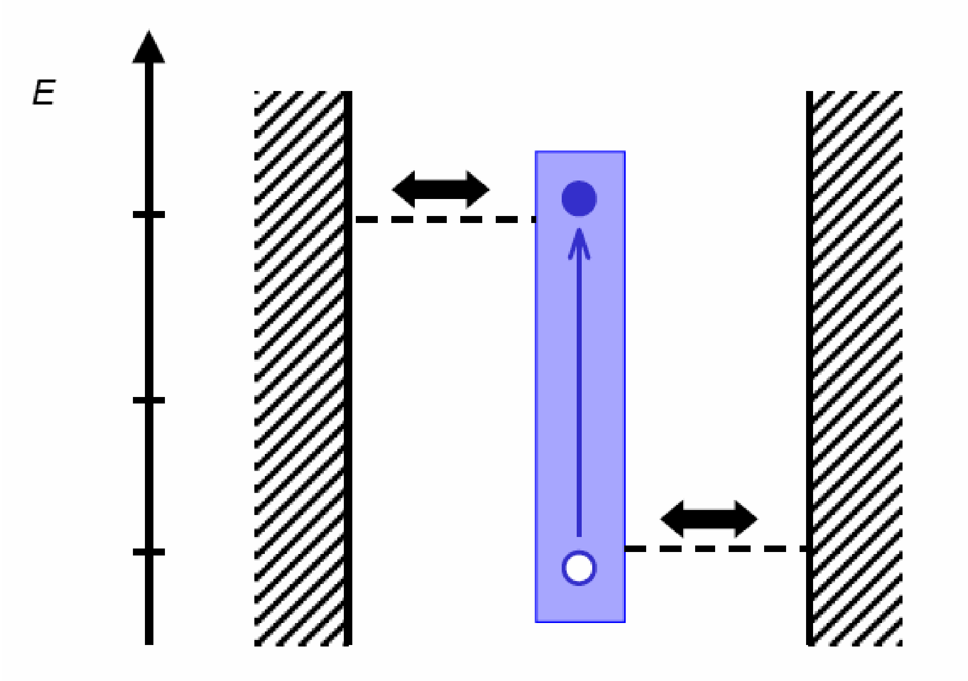
2) The excited electrons move through the conduction band of TiO_2 up to the conducting plate. Flow of electricity is initiated.

3) The dye is regenerated by the Iodide molecule giving up one of its electrons to form triiodide (oxidation occurs).

4) The triiodide molecule is reduced back to iodide by an electron at graphite conducting plate.

Source: http://www.lboro.ac.uk/departments/cm/business/Gratzel.html

Organic/Polymer Solar Cell



Relatively low efficiencies realized- 5%

Facile product integration

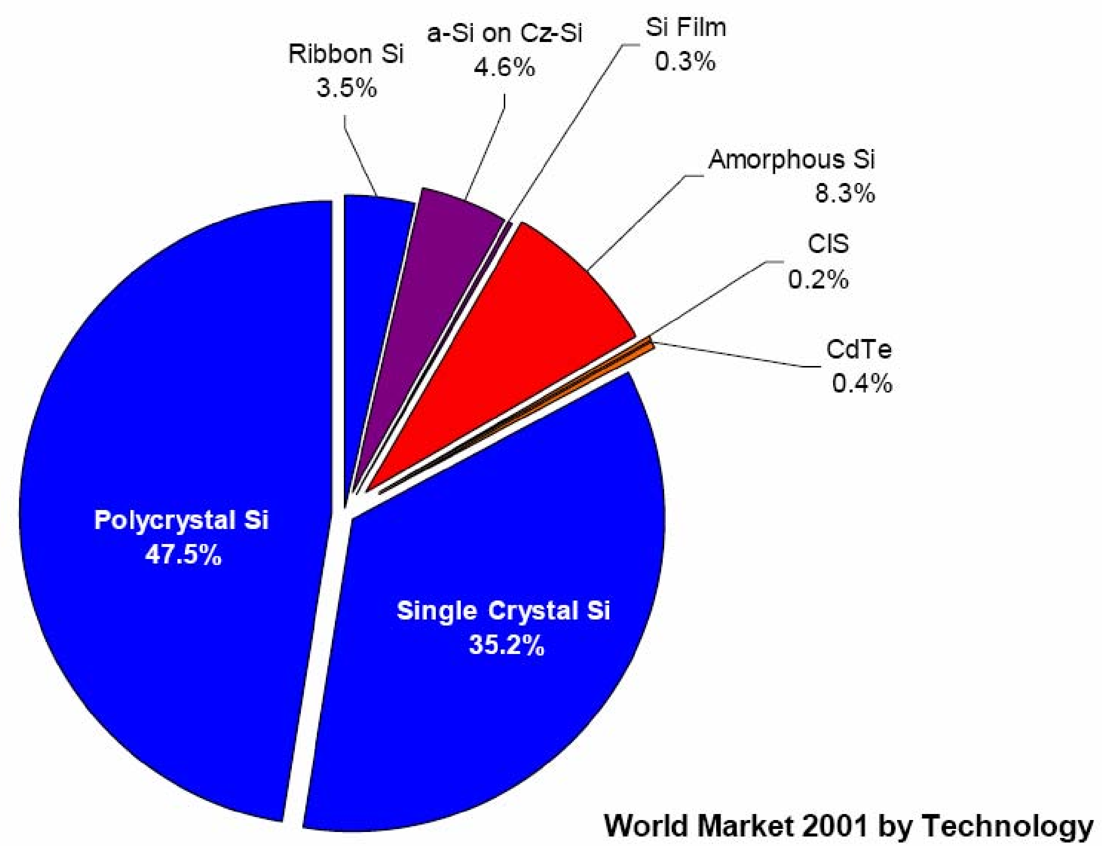
Potential for very low cost production

Potential for realization of advanced light harvesting techniques

Longevity is yet proven

Source: Keld West, Riso National Laboratory, Denmark

PV Markets



Source: Keld West, Riso National Laboratory, Denmark