



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%.



Power Requirements

- Lighting and electrical appliances
- Refrigeration and air-conditioning (includes space heating)
- Hot water





Approaches

Direct conversion of solar radiation into electricity - photovoltaics and dye sensitized and organic solar cells

Concentrating solar power - produce high grade heat for the production of electricity and use in other processes

Energy storage using hydrogen as energy carrier.



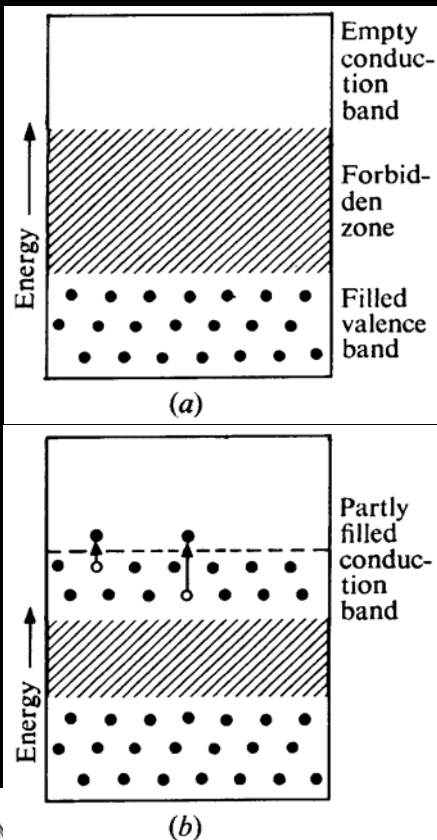
Semiconductors

1. Materials, both compounds and elements, can be classified according to how well they conduct electricity. There are materials such as metals which conduct electricity well and those which conduct electricity poorly, called insulators. There are a few materials which fall in between. They conduct electricity a little bit. These materials are called semiconductors.
2. With the development of quantum theory and the band theory description of the (electrical) properties of elements, it became possible to understand what differentiated conductors, insulators and semiconductors in a comprehensive and testable theory.
3. The Pauli Exclusion Principle applied to electrons bound to an atom defines a series of distinct energy shells which electrons can fill. These shells are filled from the lowest energy level upwards. The Periodic Table arises with each element adding a proton and the filling of each shell taking one 'period' of the table.
4. The semiconducting elements form a loose band on the table; not quite metals and not quite insulators. Compounds formed from various crystalline and amorphous mixtures are also semiconducting.
5. On top of which, the electrical characteristics of semiconductors can be changed by introducing traces of other elements in minute proportions. This is called doping and is how n-type and p-type semiconductors are constructed.
6. By applying voltages and bias currents, semiconductors can function as switches forming the basis of transistors and by applying light radiation, semiconductors can function as photovoltaic devices.



Solar Cells- Energy bands

In crystals, each original discrete atomic energy level spreads out into *bands* of closely spaced levels. These bands are separated by *energy gaps* that are forbidden to the electrons. This band structure is important in determining the properties of electrons in crystals. The band structure of a material has profound effect on its physical properties such as electrical conductivity and its optical properties. A solid is classified as an insulator or a semiconductor based on largely according to how good conductor it is.



The energies of the electrons are restricted to energetically separated ‘energy bands’ : the lower lying so-called valance band and energetically higher lying conduction band. The two bands are energetically separated by a band gap. Under the condition of thermal equilibrium the valance band of a pure semiconductor is practically fully occupied by immobile electrons sitting between neighboring semiconductor atoms and the conduction band is empty. Under these conditions no electrons can move about freely in the solid and the semiconductor behaves like an insulator.

When a photon is absorbed in the semiconductor, thereby transferring energy to a bound immobile electron in the valance band which is then excited across the band gap into the conduction band, where it is free to move about the solid. The photon must carry more energy than required to transfer the electron across the gap. The electron that has been excited to the conduction band leaves a place in the valance band that is now not occupied by an electron. Such an empty energy state of a negatively charged electron behaves like a positively charged particle- a so-called *hole*. These charge carrying holes are also comparatively free to move about the semiconductor solid.

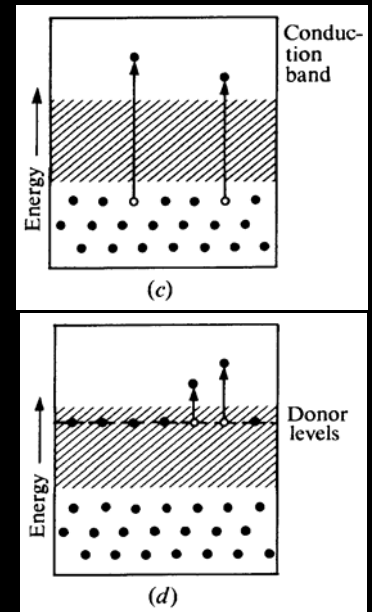
Electron-Hole pair

There is an attractive force between the negatively charged electron in the conduction band and the positively charged hole in the valence band resulting in a locally confined electron-hole pair. The attractive force creating this pair has to be overcome and the electron-hole pair split spatially in order to produce a **useful electric current**. If left alone, the excited electron will eventually recombine either with the original hole of the electron-hole pair or any other hole within reach to produce a photon or waste heat. It is therefore essential (in a solar cell application) to separate the charges in the photogenerated electron hole-pairs as soon as possible and to collect the charge at the external electrodes before they combine.

Recombination process between electrons and holes occur with high probability at distributed crystal sites. Surfaces represent areas of crystal imperfections and they can be avoided by depositing suitable coatings on the surface.

To manipulate electrical conductivity of a semiconductor is done by introducing well-controlled small amounts of **dopant atoms**. For example, the electrical conductivity in silicon can be significantly increased by replacing every one-millionth silicon atom by a phosphorus or a boron atom. The phosphorus atom has one electron more than the silicon atom. This leads to the fact that we have **more freely mobile electrons than holes in the semiconductor, which is then said to be *n-doped***.

In contrast, the boron atom has one less electron than the silicon atom. The boron atom easily **binds an electron from the valence band and produces a hole there, leading to *p-type* conduction**. This p- and n-type conduction forms the basis of all semiconductors.





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. It might seem therefore, that the thing to do is use a very low band gap material, but the strength of the electric field created by the conjunction of n-type and p-type material is also dependent upon the band gap. One has to make a tradeoff between photon energy and field strength.

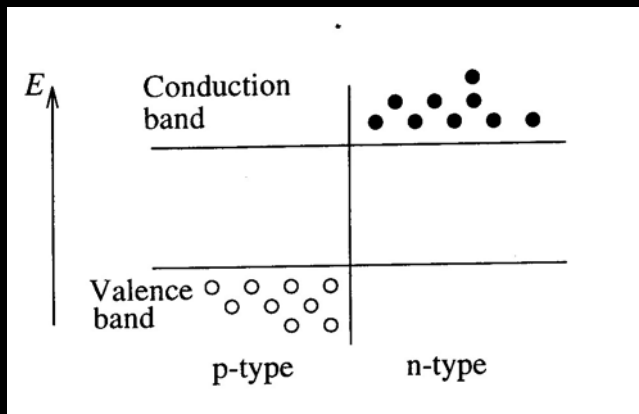


Semiconductor Junction

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 $1\ \mu\text{m}$ in width.

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

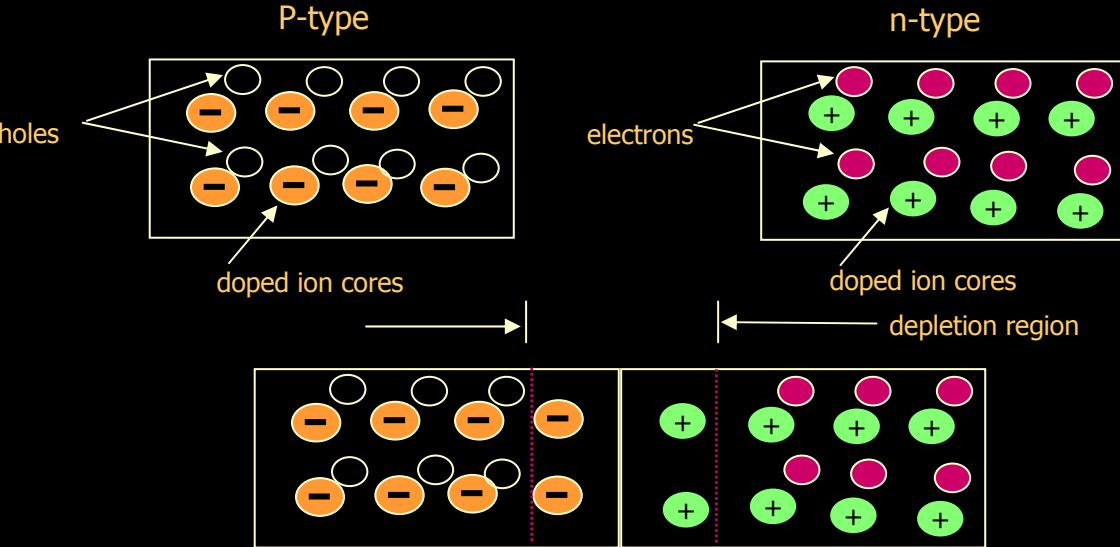
n-type material - excess electrons in the conduction band compared with the p-type material



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.



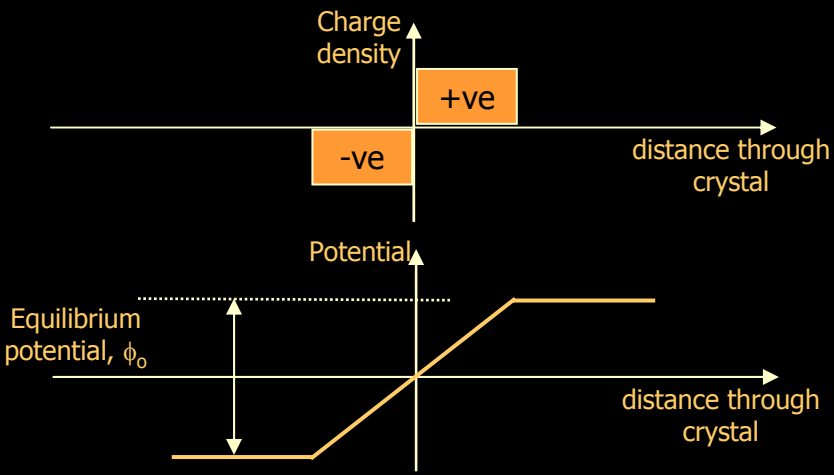
pn -Junction



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.



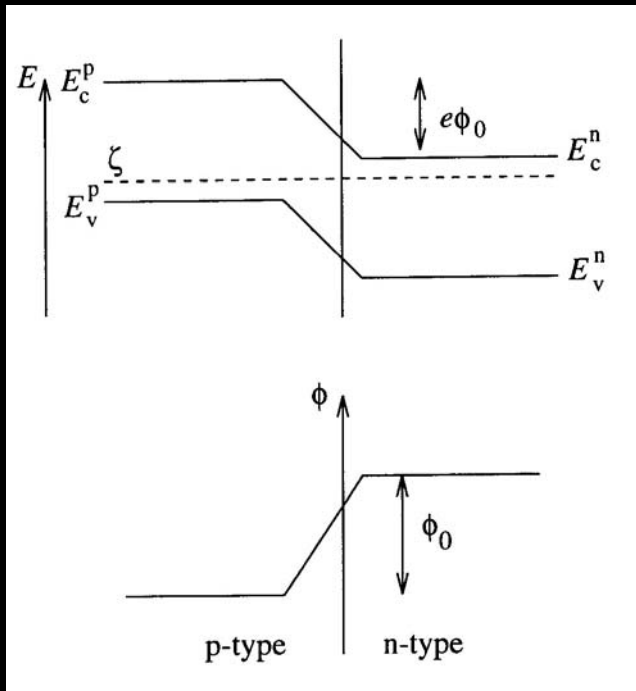
A potential difference develops across the junction with equilibrium potential, ϕ_0 and depletion region has high resistivity due immobile charge carriers

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*.

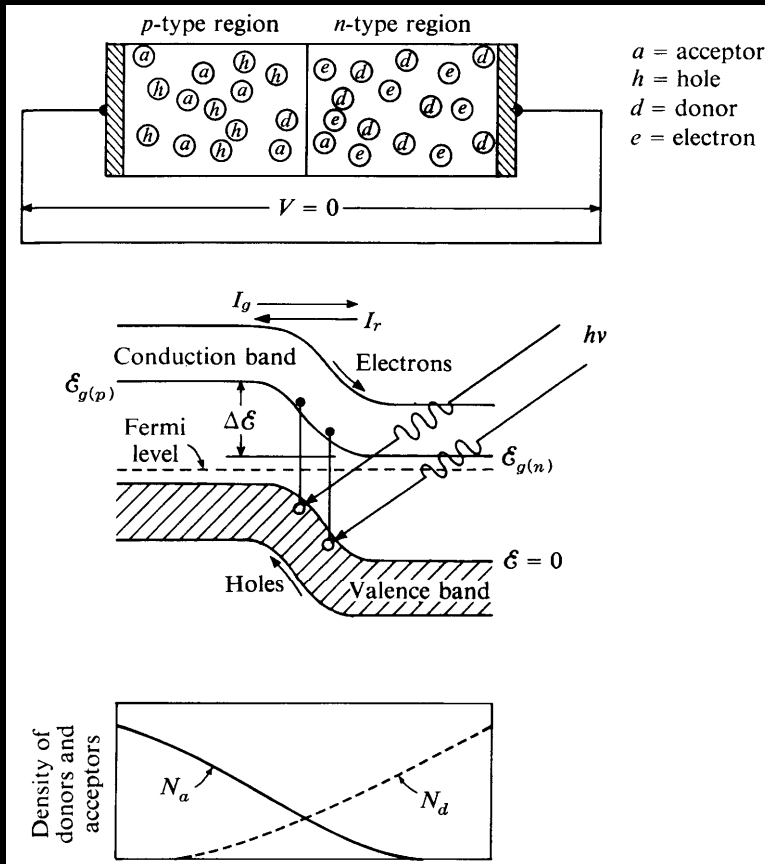
If current is driven through the junction by an external source, like a battery, electrons and holes recombine in the junction region producing photons - the *light emitting diode*.

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*.



Pn Junction

The *p-n junction*: The photoconversion device that has attained the highest efficiency is the *p-n junction*.



I_r : Recombination current for electrons

I_g : Thermally generated current

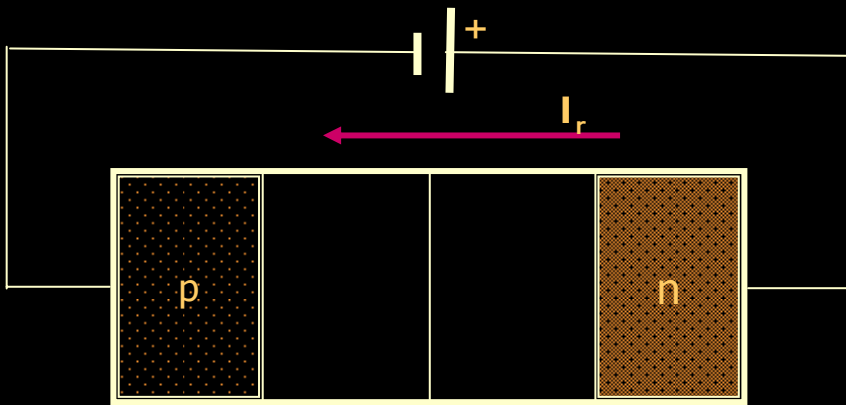
$$I_g \propto n_p \approx A_1 e^{\frac{[-(\mathcal{E}_{g(p)} - \mathcal{E}_f)]}{kT}}$$

$$n_n \approx A_1 e^{\frac{[-(\mathcal{E}_{g(n)} - \mathcal{E}_f)]}{kT}}$$

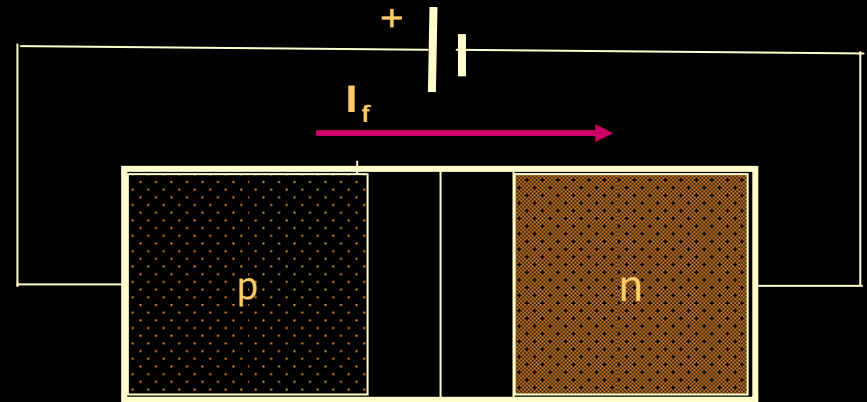
Where n_p and n_n are the number of thermally excited electrons in the *p-type* and *n-type* region correspondingly, \mathcal{E}_f is the Fermi energy (the energy at which the probability of a state being filled is exactly one-half and also corresponds to the thermodynamic free electron energy, k is Boltzmann's constant ($=1.38048 \times 10^{-23}$ joule/°K) and T is temperature.



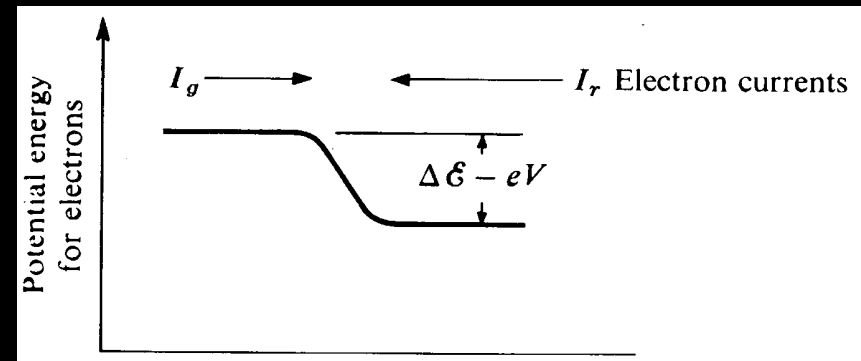
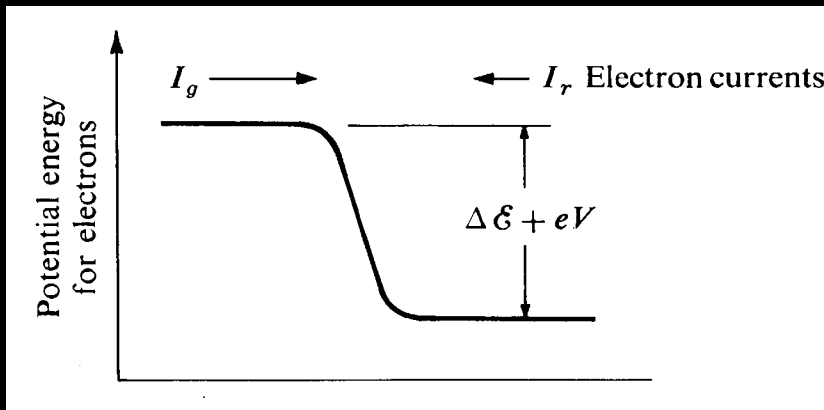
Diode Current



Reverse biased



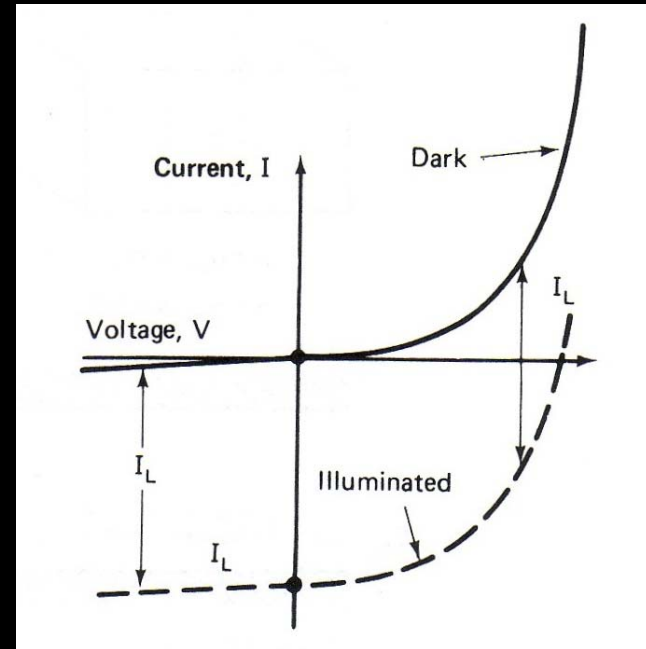
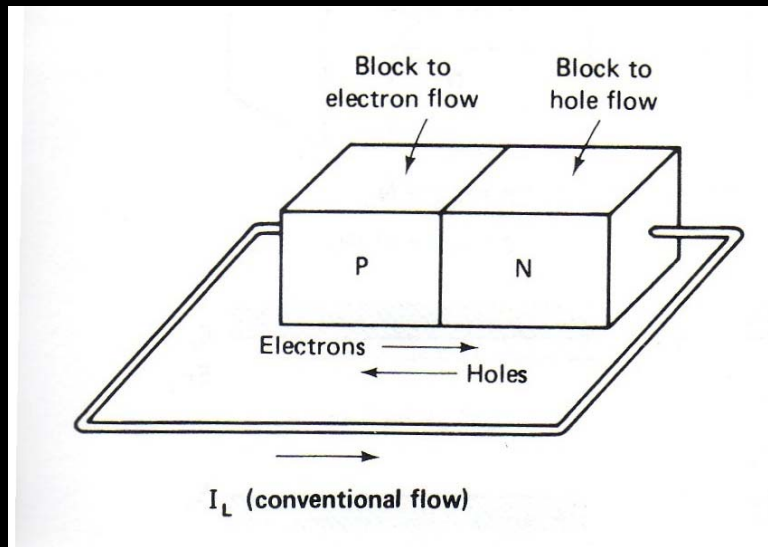
Forward biased





Pn-Junction Diode

The solar cell is the basic building block of solar photovoltaics. The cell can be considered as a two terminal device which conducts like a diode in the dark and generates a photovoltage when charged by the sun.



When the junction is illuminated, a net current flow takes place in an external lead connecting the p-type and n-type regions.

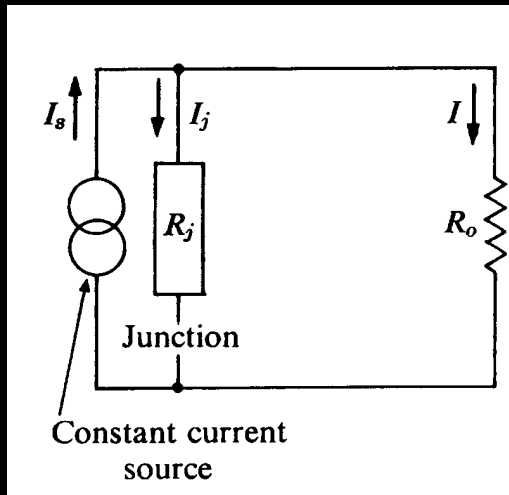
The light generated current is superimposed upon the normal rectifying current-voltage characteristics of the diode. The power can be extracted from the device in a region shown in the fourth quadrant.

Solar cell

The simplified equivalent circuit of an illuminated p - n junction

Application of Kirchhoff's law:

The illuminated light causes a current I to flow in the load.



$$I = I_s - I_j$$

$$I = I_s - I_o \left\{ e^{\frac{eV}{kT}} - 1 \right\}$$

Where I_j is the total current due to electron and hole flow across the junction, I_o is the dark current and V is the voltage across the junction. Using current densities instead of currents, we have

$$J = J_s - J_j$$

$$J = J_s - J_o \left\{ e^{\frac{eV}{kT}} - 1 \right\}$$

Where J is the current density that flows through the load.

Solar cell

The maximum voltage that we could measure on the cell would occur under open circuit conditions, $J = 0$, which is

$$V_{oc} = \frac{kT}{e} \ln \left(\frac{J}{J_o} + 1 \right)$$

The power output of the device

$$P = JV = \left(J_s - J_o \left\{ e^{\frac{eV}{kT}} - 1 \right\} \right) V$$

The voltage that produce maximum power density, we take the derivative of the above expression with respect V and setting it to zero will yield

$$e^{\frac{eV_{mp}}{kT} \left(1 + \frac{eV_{mp}}{kT} \right)} = 1 + \frac{J}{J_o} = e^{\frac{eV_{mp}}{kT}}$$



Solar cell

Substituting the expression for J in the previous equation, we will obtain the following

$$J_{mp} = \frac{\frac{eV_{mp}}{kT} J_s}{1 + \frac{eV_{mp}}{kT}} \left[1 + \frac{J_o}{J_s} \right]$$

The maximum power density is simply $P_{max} = J_{mp} V_{mp}$

The power density input to the junction is $N_{ph} \epsilon_{av}$

Where N_{ph} is the total number of photons in the solar spectrum and ϵ_{av} is the average energy of each of the photons. The dark current density J_o is generally five or more orders of magnitude smaller than the short circuit current density J_s . We may then approximate the *maximum efficiency* of the converter as

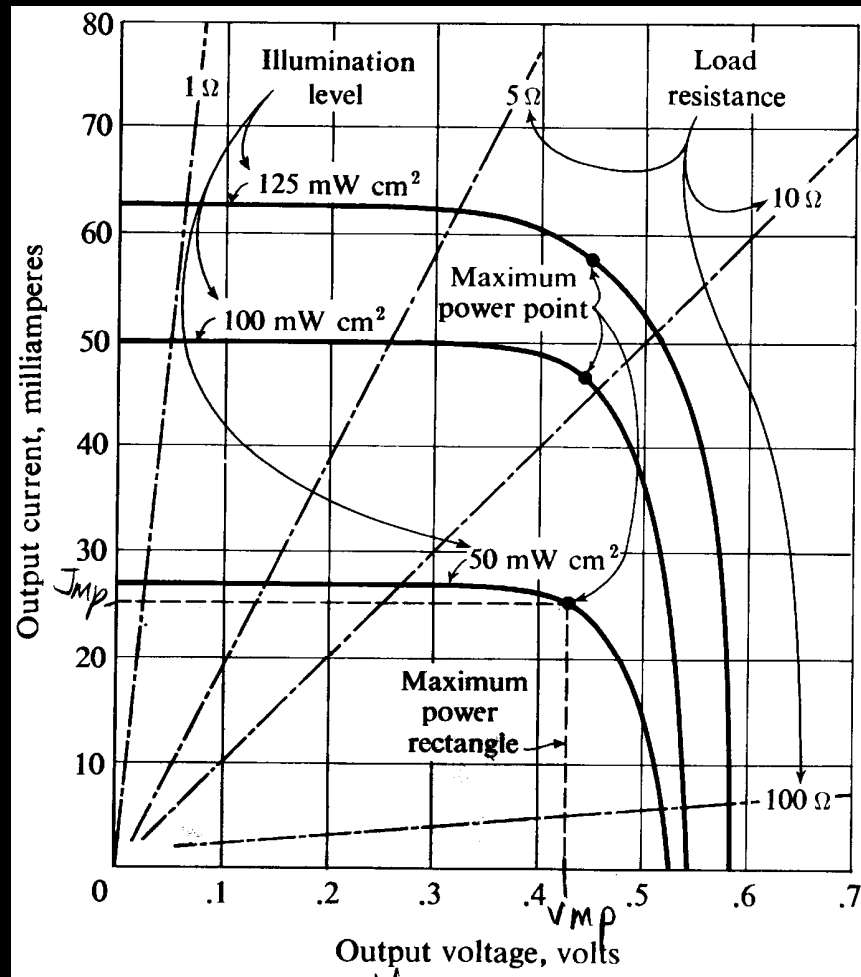
$$\eta_{max} \approx \frac{\frac{eV_{mp}}{kT} V_{mp} J_s}{\left(1 + \frac{eV_{mp}}{kT} \right) N_{ph} \epsilon_{av}}$$





Solar Cell Performance

Typical voltage-current plot

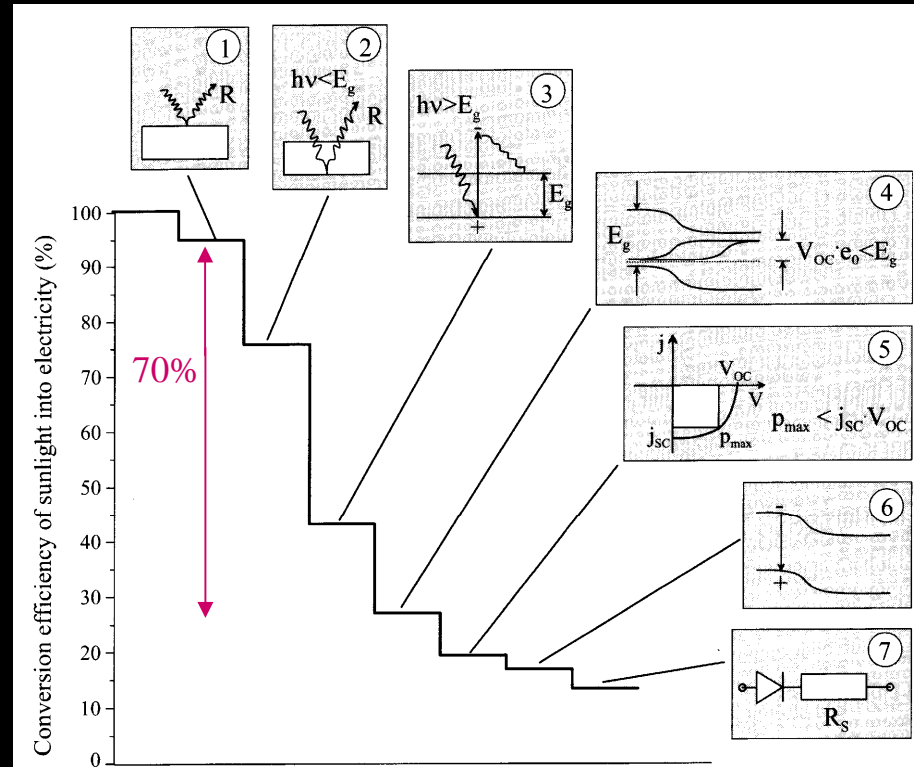




Solar Cell Performance Losses

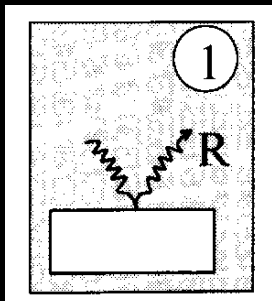
Conversion efficiency:

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.

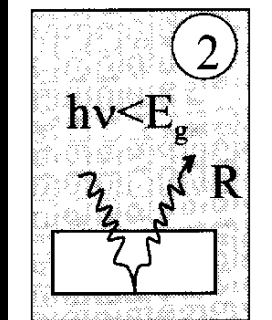




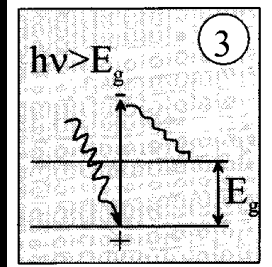
Solar Cell Performance Losses



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.

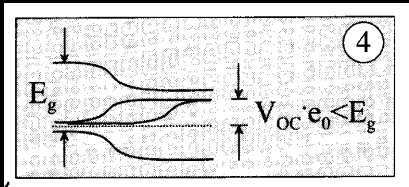


There is a minimum energy level (and thus the maximum wavelength) of photons that can cause the creation of a hole-electron pair. For silicon, the maximum wavelength is $1.15\mu\text{m}$. Radiation at higher wavelengths does not produce hole-electron pairs but heats the cell.

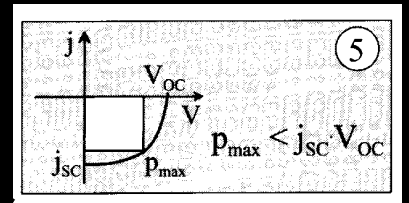


Each photon causes the creation of a single-hole pair, and the energy of photons in excess of that required to create hole-electron pairs is also converted into heat.

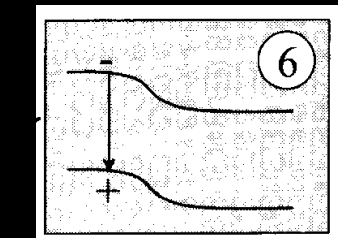
Solar Cell Performance Losses



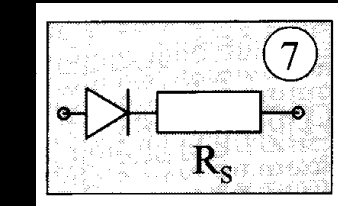
The open circuit voltage is physically limited to values less than the bandgap voltage.



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.



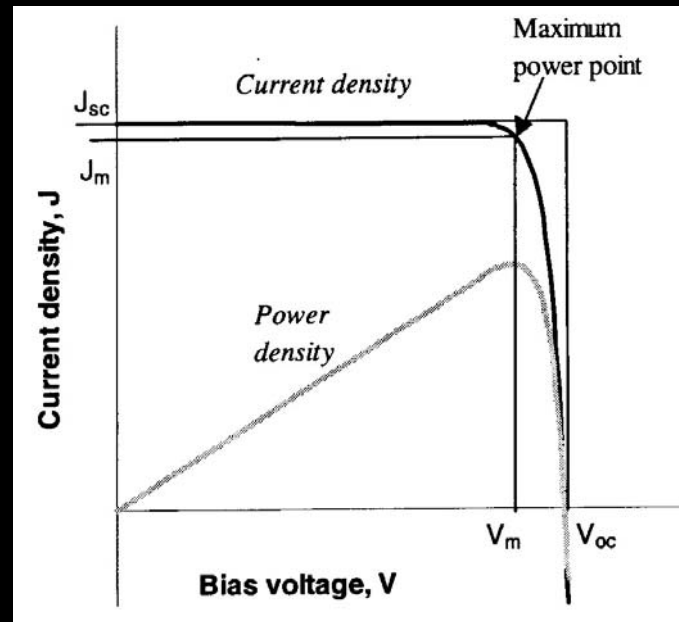
The electrical series resistance in the cell itself, its contacts and in the external circuitry lead, contributes to the loss.

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

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

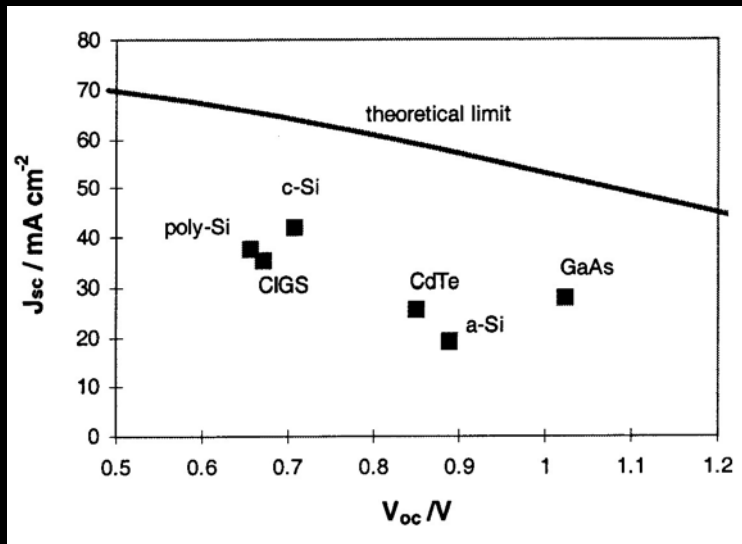
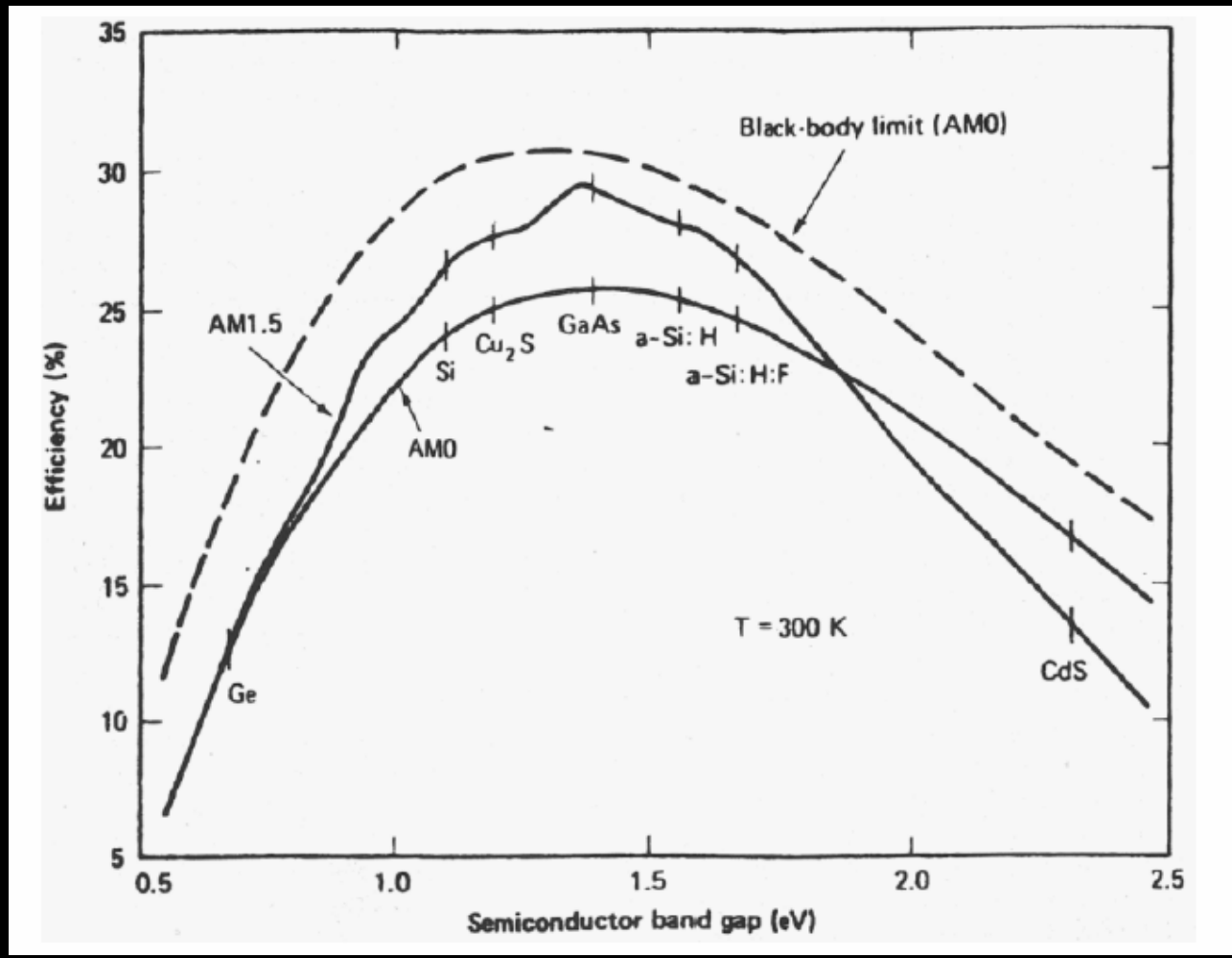


Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

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



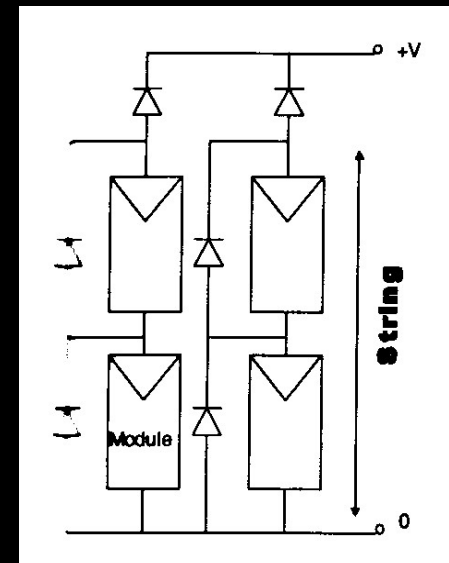
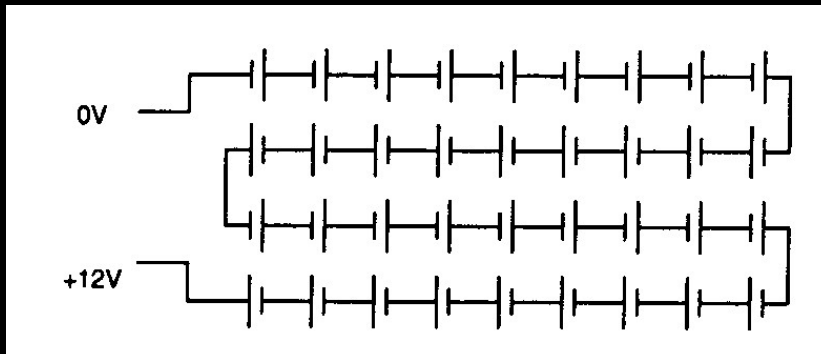
Power Conversion Efficiency Limits





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.

The diode equation becomes

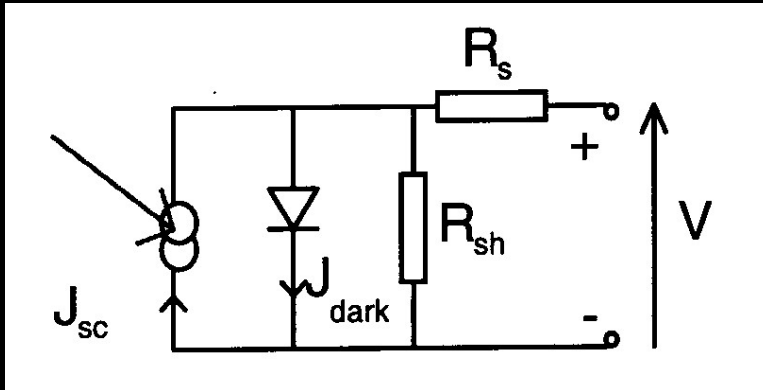
$$J = J_{sc} - J_0 \left(e^{q \left(\frac{V + JAR_s}{kT} \right)} - 1 \right) - \frac{V + JAR_s}{R_{sh}}$$

Where A is the cell area

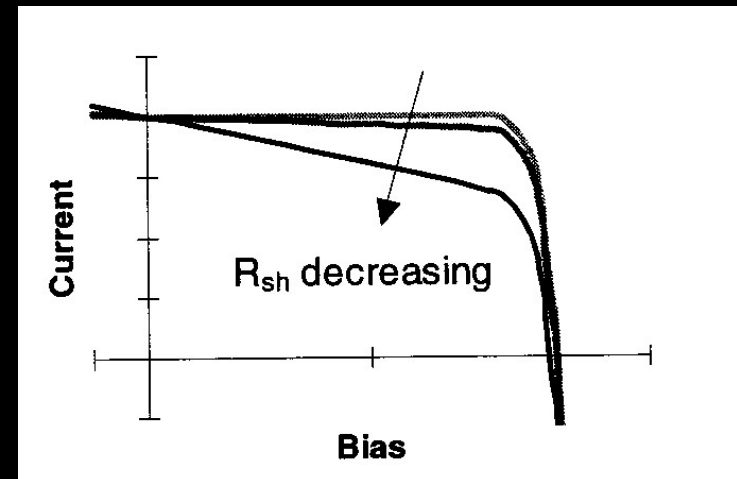
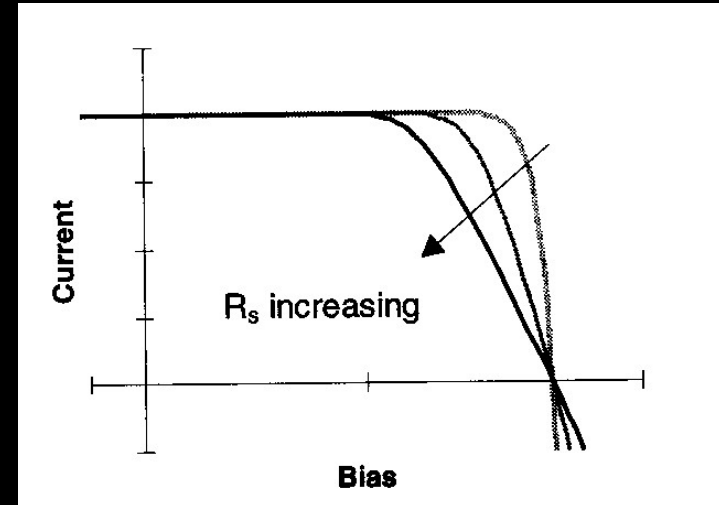




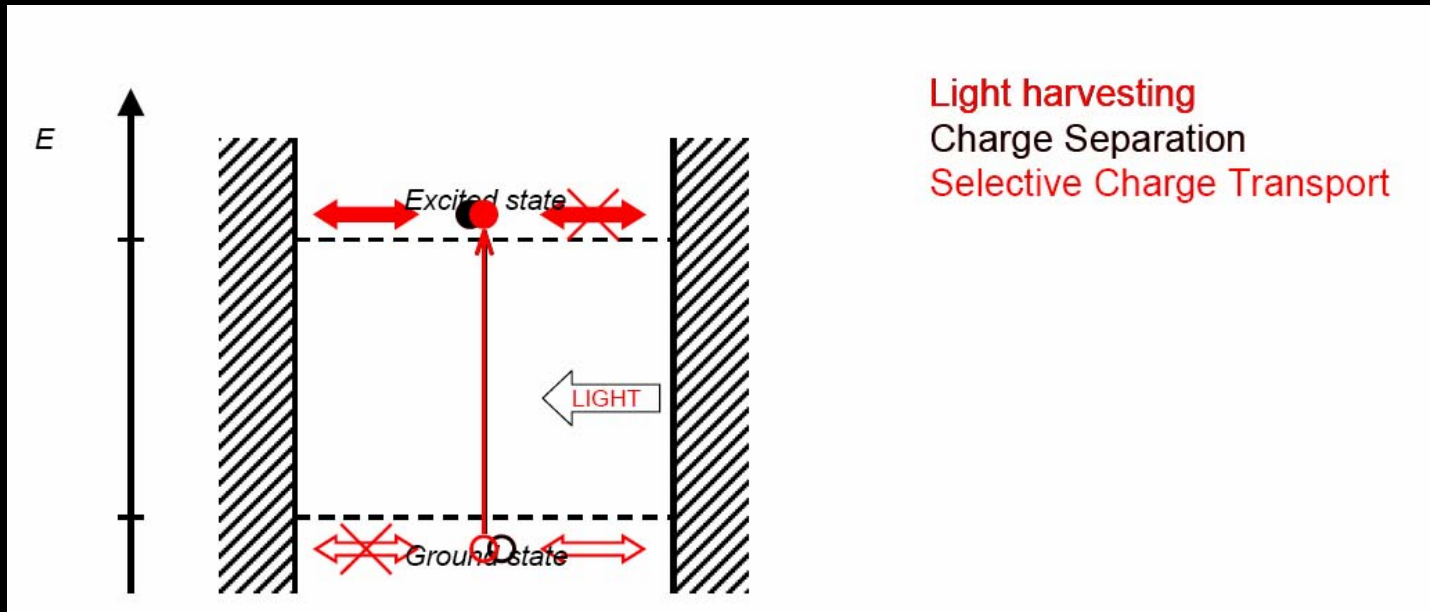
Parasitic Resistances



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



Solar Cells and Photovoltaics



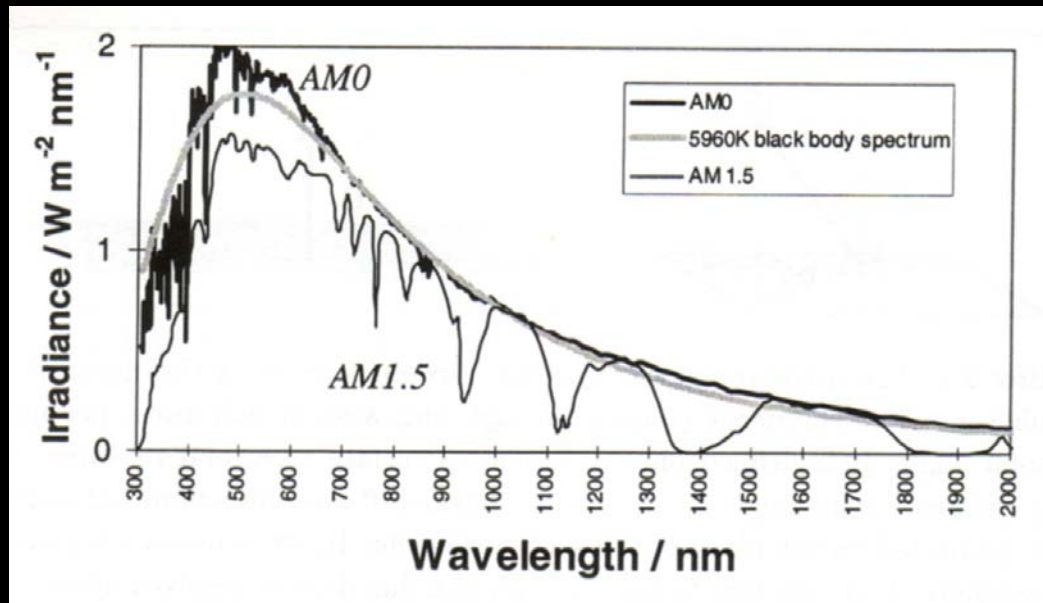
Consider a two band system: the ground state is initially full and the excited state empty
Band gap, E_g : The bands are separated by a band gap.

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.



Solar Irradiance

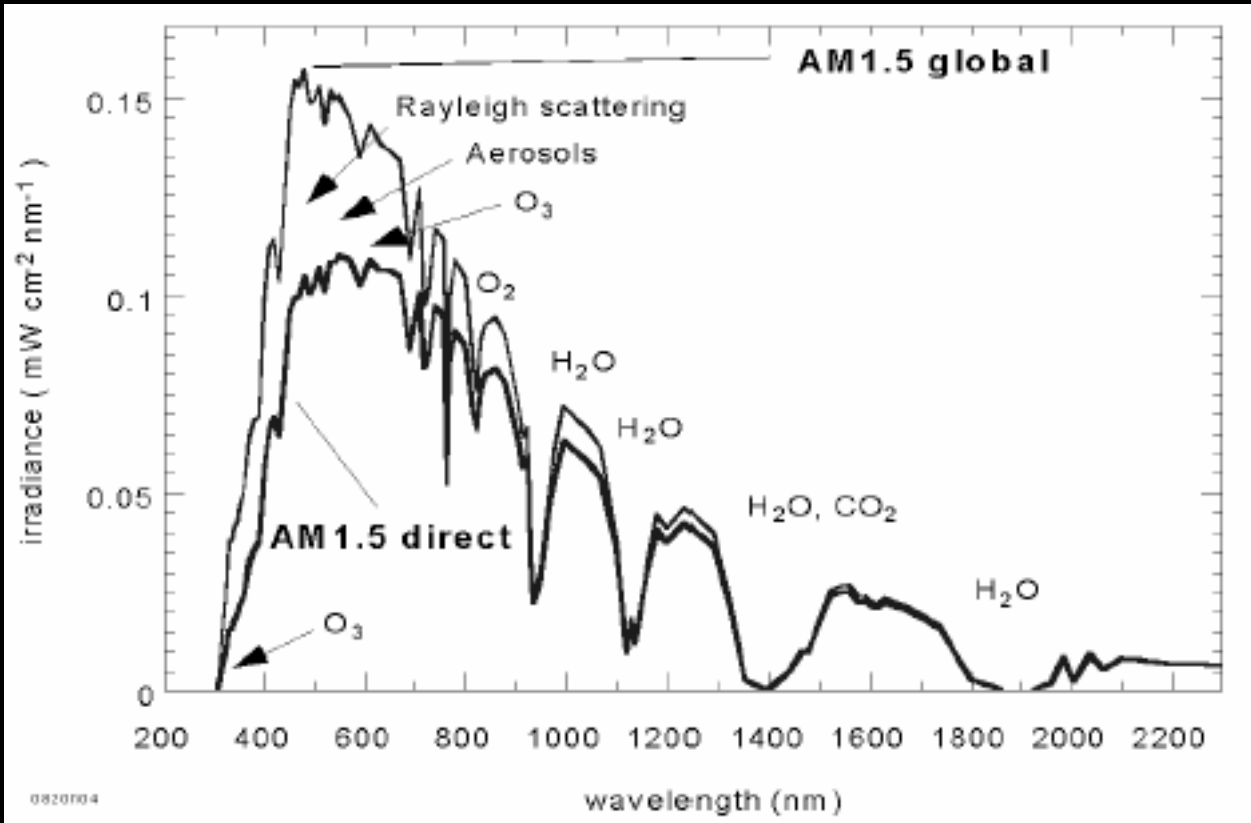
Solar irradiance: The amount of radiant energy received from the Sun per unit area per unit time. It is a function of wavelength at a point outside the Earth's atmosphere. Solar irradiance is greatest at wavelengths, 300-800 nm.



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 its surface temperature.



Solar Radiation Spectrum



The global spectrum comprises the direct plus the diffused light.



AM 1.5d Spectrum Energy Distribution

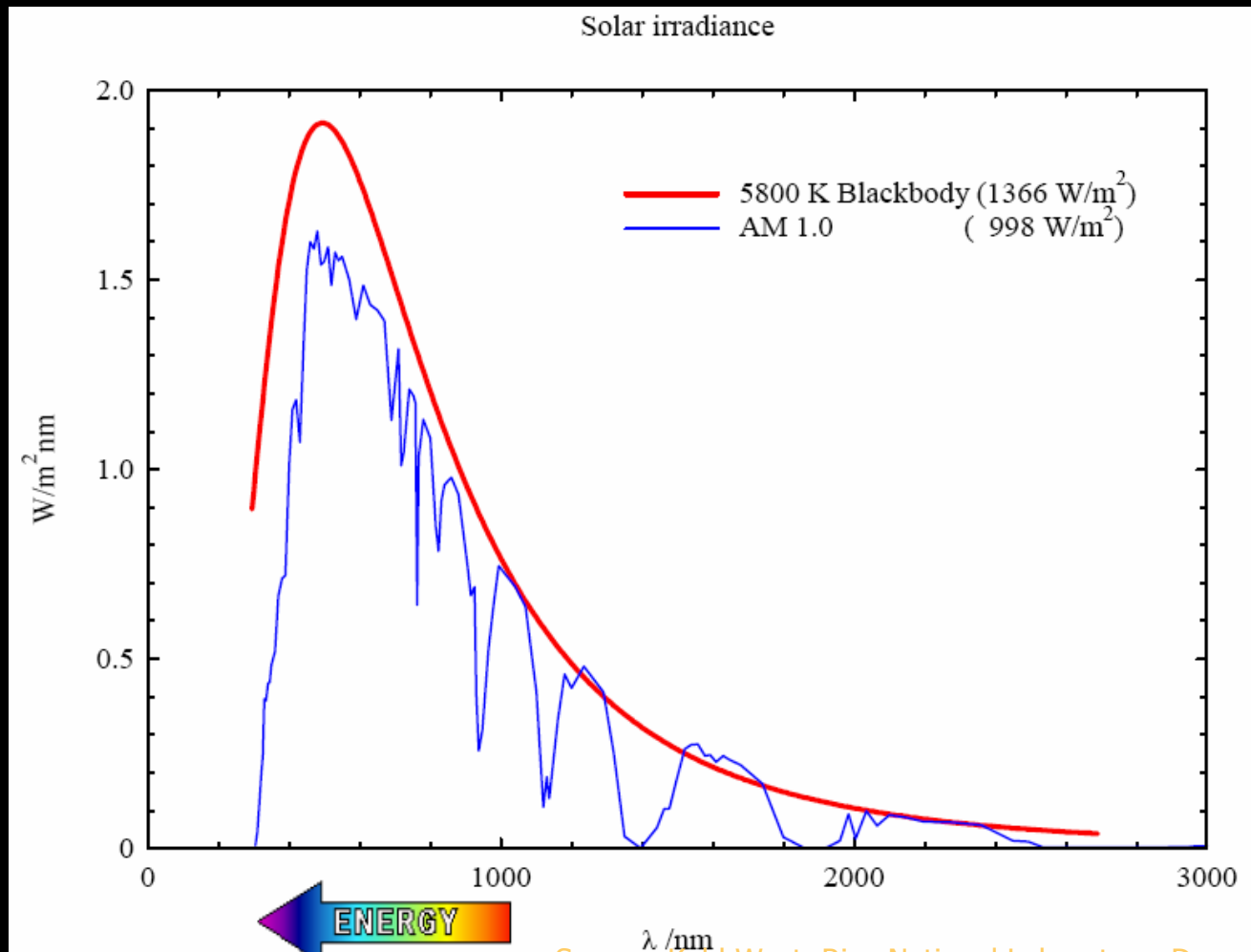
(eV):	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.24	1.18	1.13	1.08	1.03	0.99	0.95	0.69	0.62	0.5
(nm):	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1800	2000	2500
300	0	0.7	2.9	7.6	14	21	28	35	42	48	54	59	64	67	70	74	77	79	81	84	86	96	96	100
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

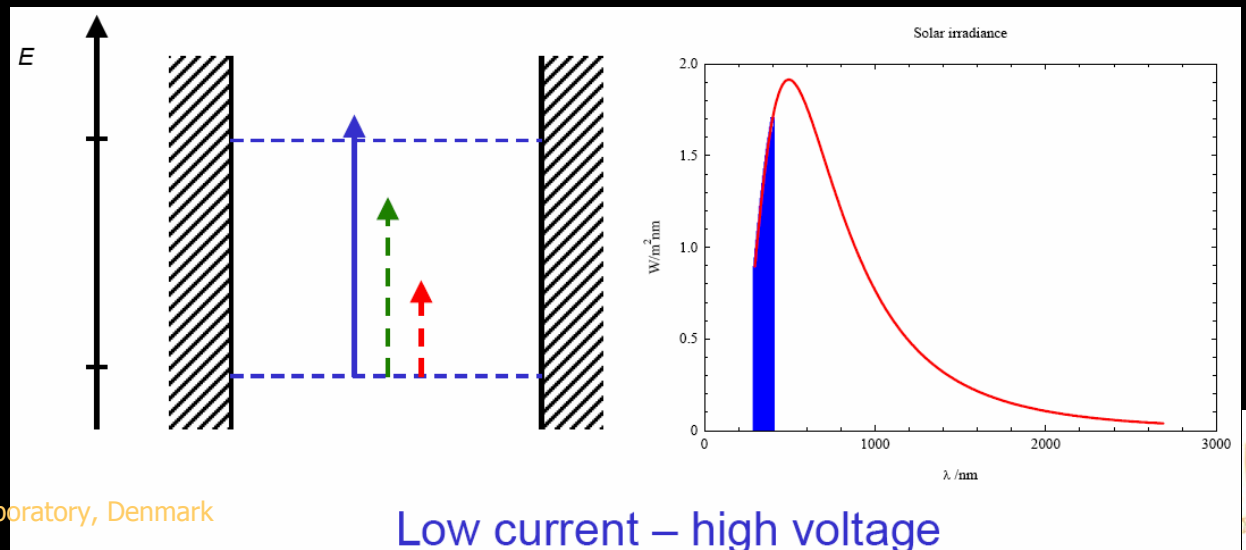
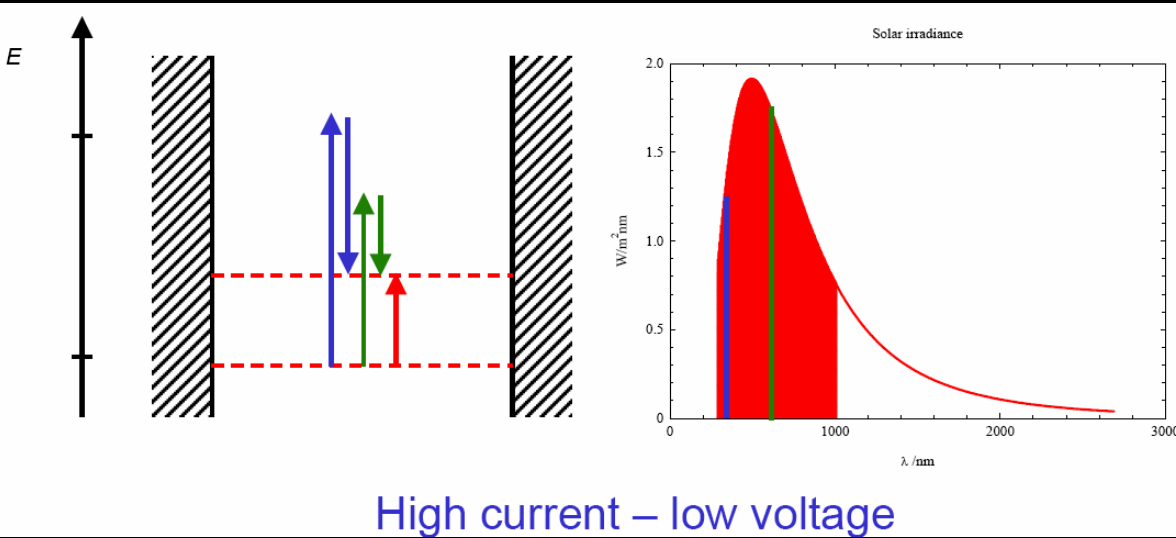


Source: Kjeld West, Riso National Laboratory, Denmark



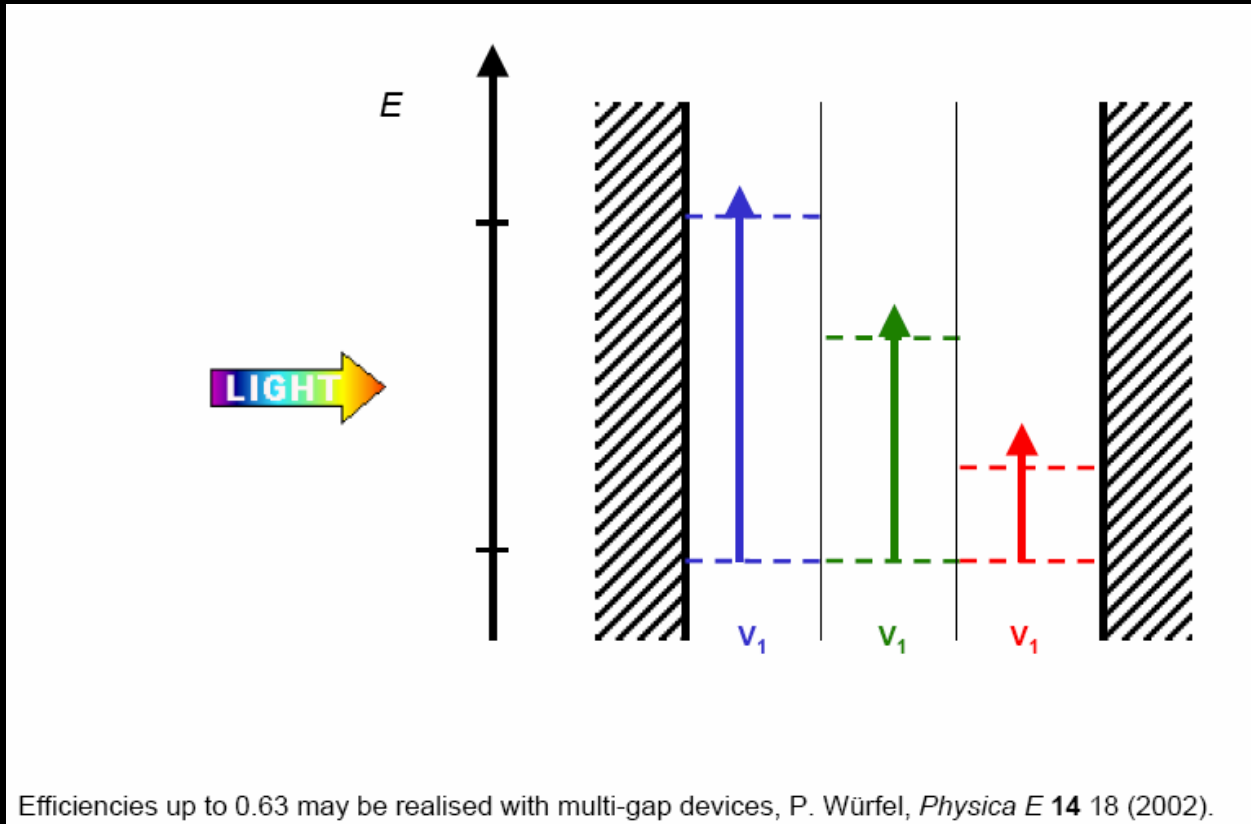


Efficiency Limitations



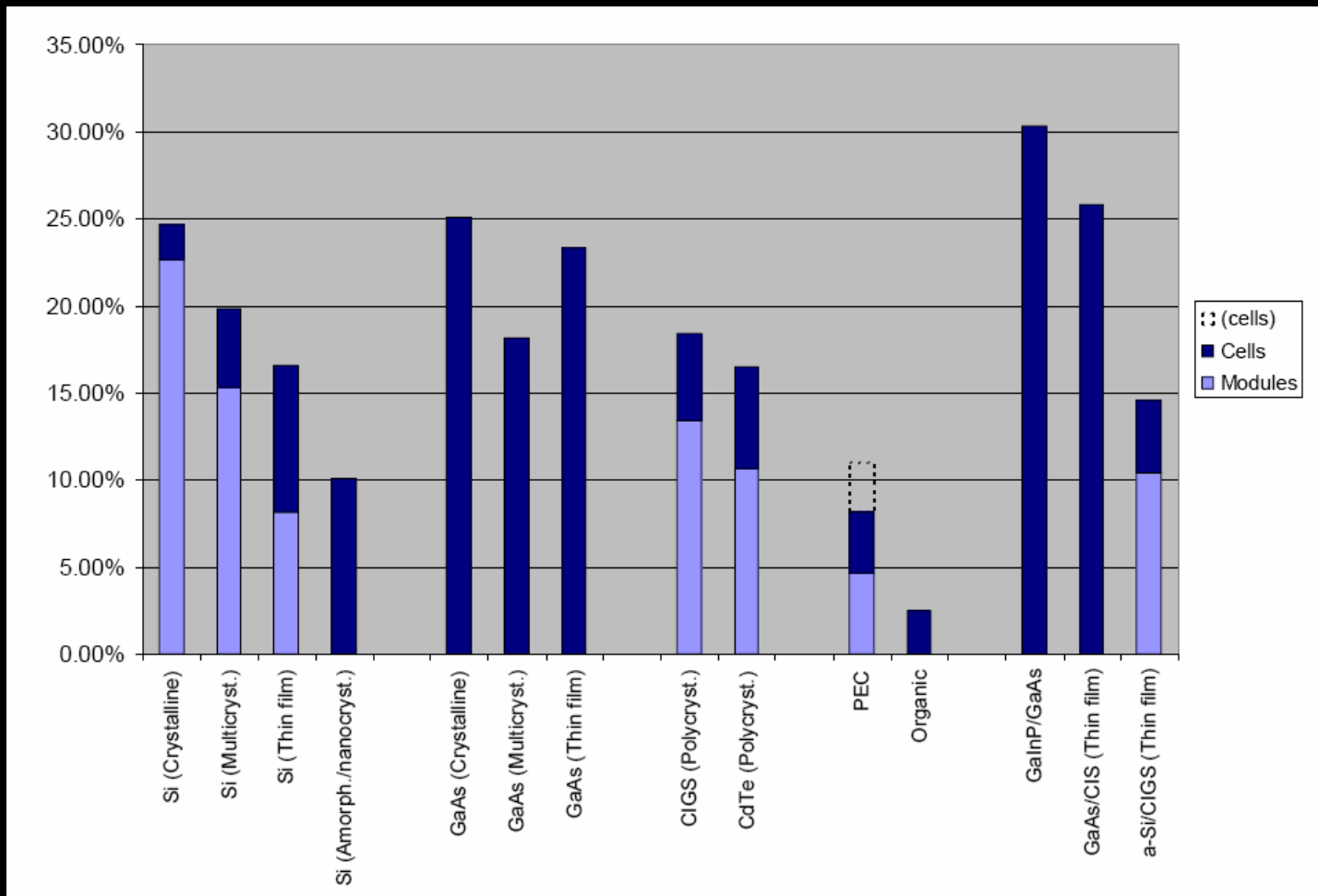


Multi-gap Devices





PV Efficiency



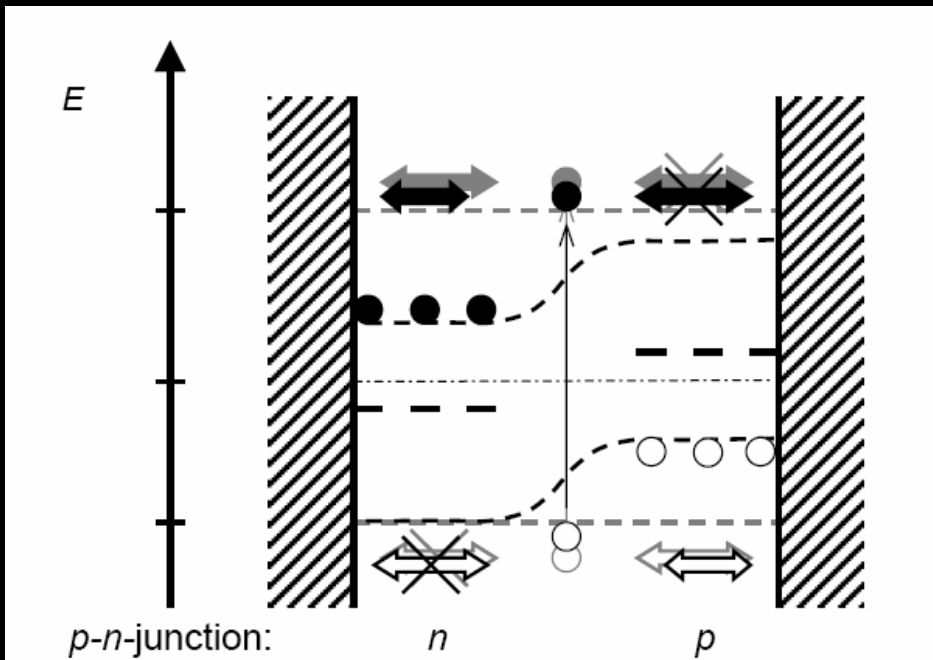
Source: Keld West, Riso National Laboratory, Denmark





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)

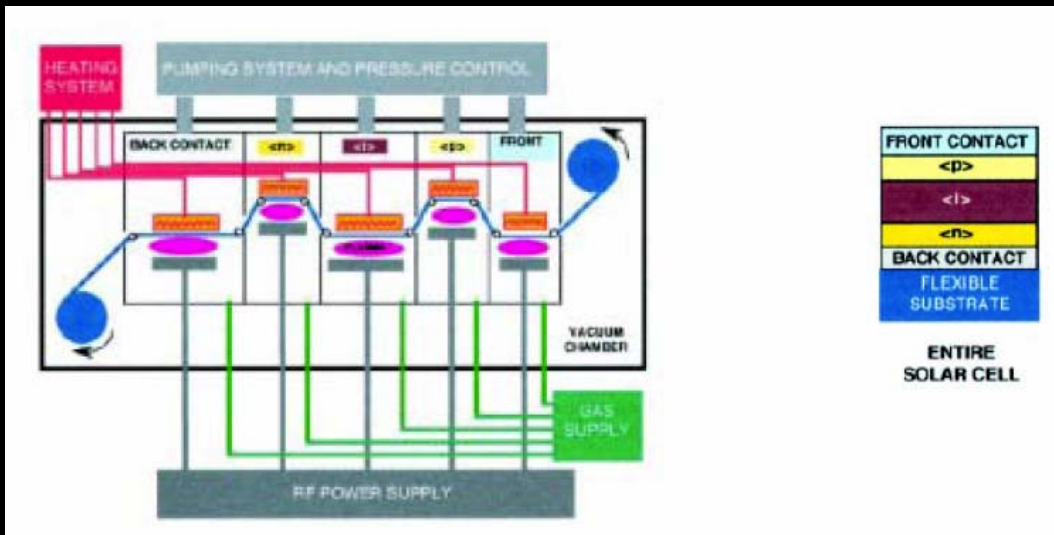
Efficiency >20%

Life time >25 years



2nd Generation PV

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

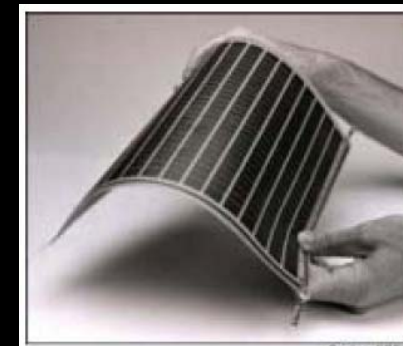


Flexible substrate

Small amount of material

Low deposition rates

Lower efficiencies



Amorphous Silicon: a-Si:H; Microcrystalline Silicon: $\mu\text{c-SiH}$

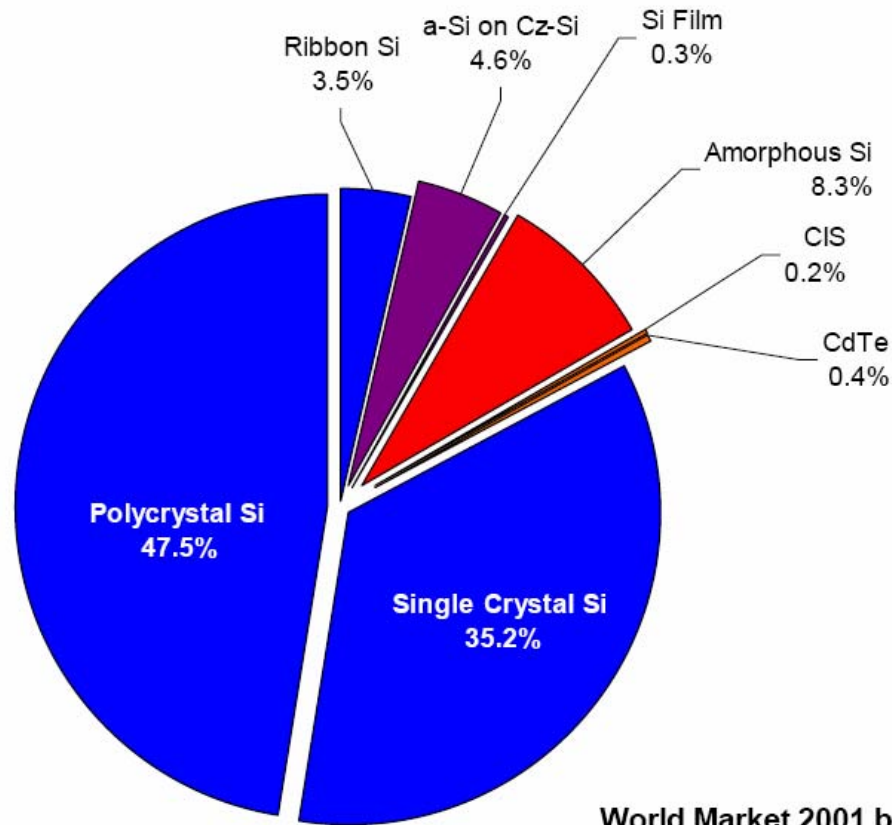
Copper indium gallium diselenide : CIGS

Cadmium telluride: CdTe





PV Markets

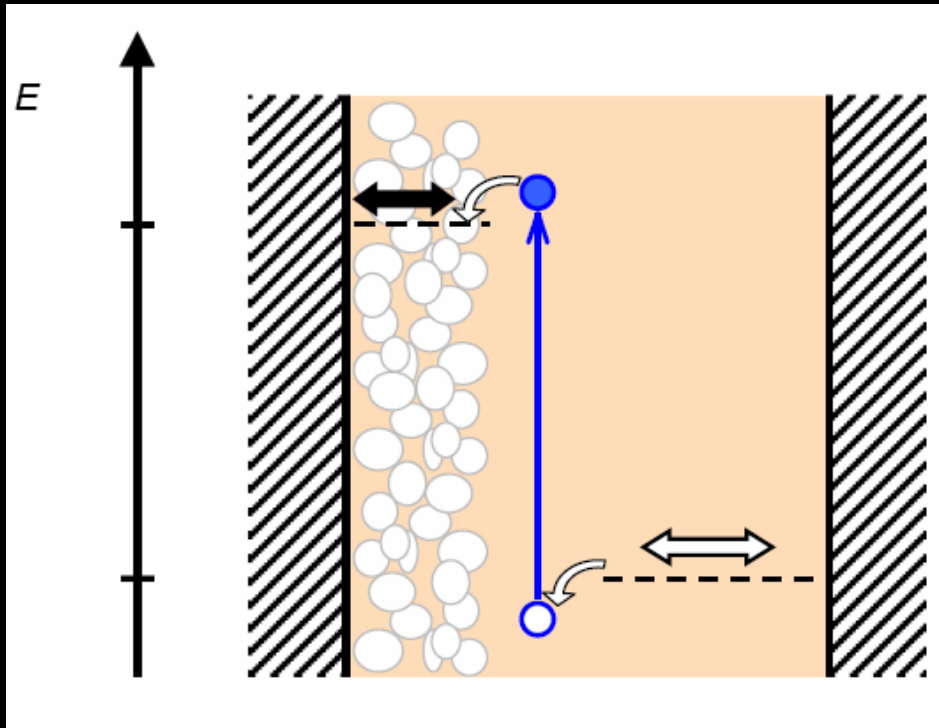


World Market 2001 by Technology





Photo Electro Chemical Solar cell



Low cost Materials

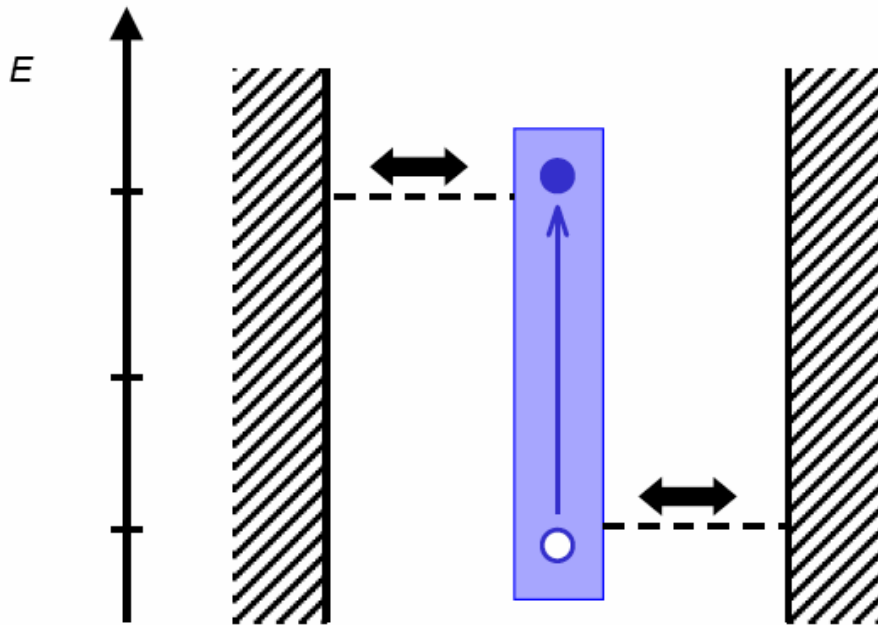
Cell efficiency: 10% (modules: 5%)

Well suited for building integration

Long term stability not yet proven



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

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.

