FUNDAMENTAL PROPERTIES OF SOLAR CELLS

January 31, 2012
The University of Toledo, Department of Physics and Astronomy
SSARE, PVIC

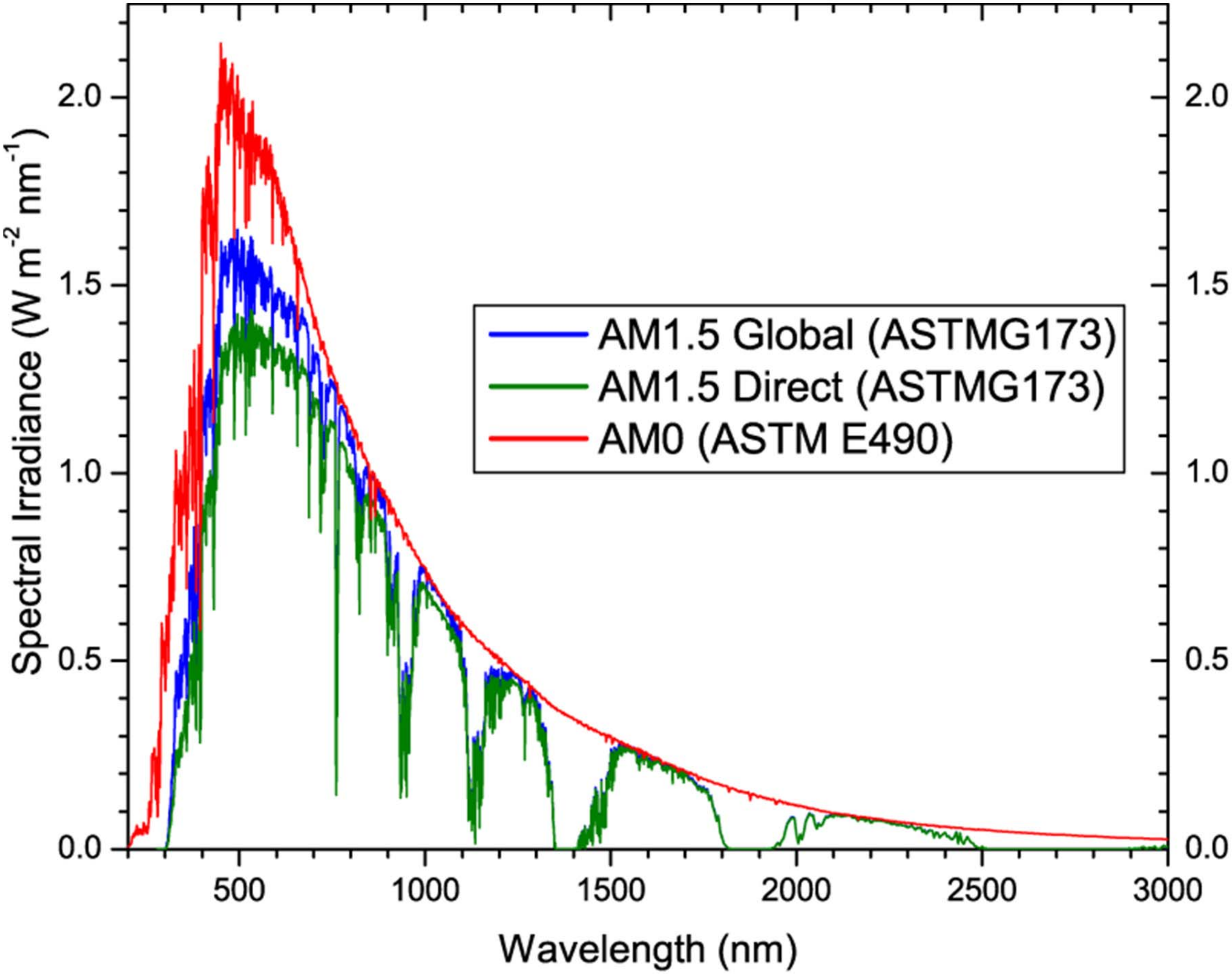
Principles and Varieties of Solar Energy (PHYS 4400)
and
Fundamentals of Solar Cells (PHYS 6980)

On today’ s menu

- photovoltaic effect
- fundamental solar cell properties
- diode equation
- dark current
- light current
- Efficiency
- J_{SC}
- V_{OC}
- internal and external QE
- maximum power point

Quiz #2 next Tuesday, Feb. 7th

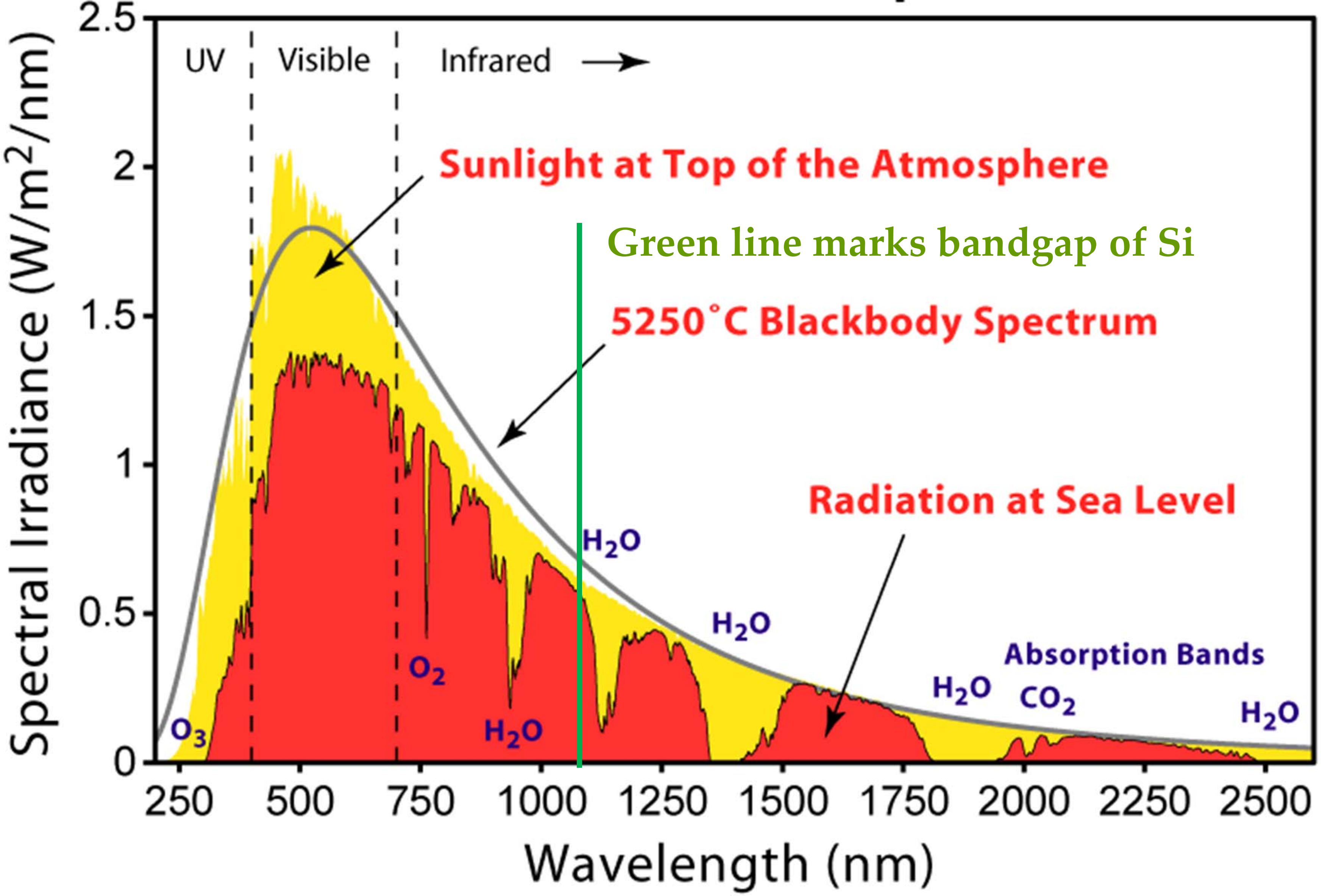
Solar spectra at Earth



http://pvcdrom.pveducation.org/APPEND/Am1_5.htm

.... energizing Ohio for the 21st Century

Solar Radiation Spectrum



Green line marks bandgap of Si

Image created by Robert A. Rohde / Global Warming Art

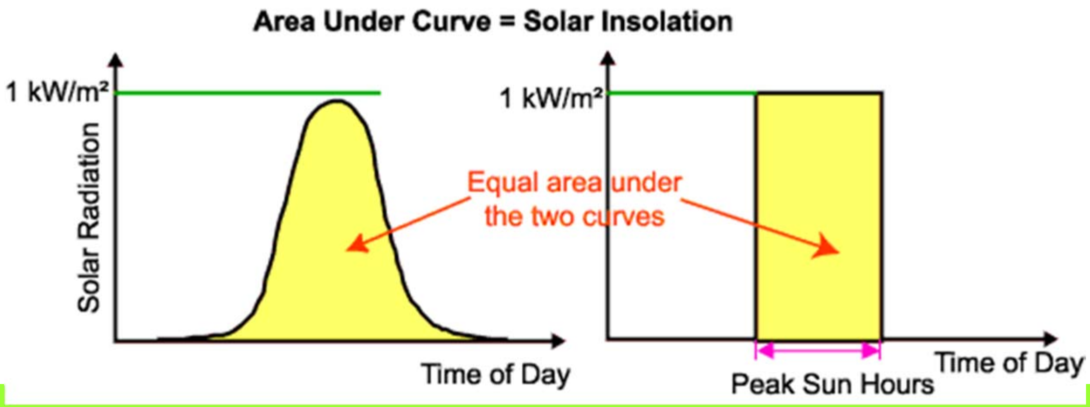
Average Solar Insolation

Average Solar Radiation

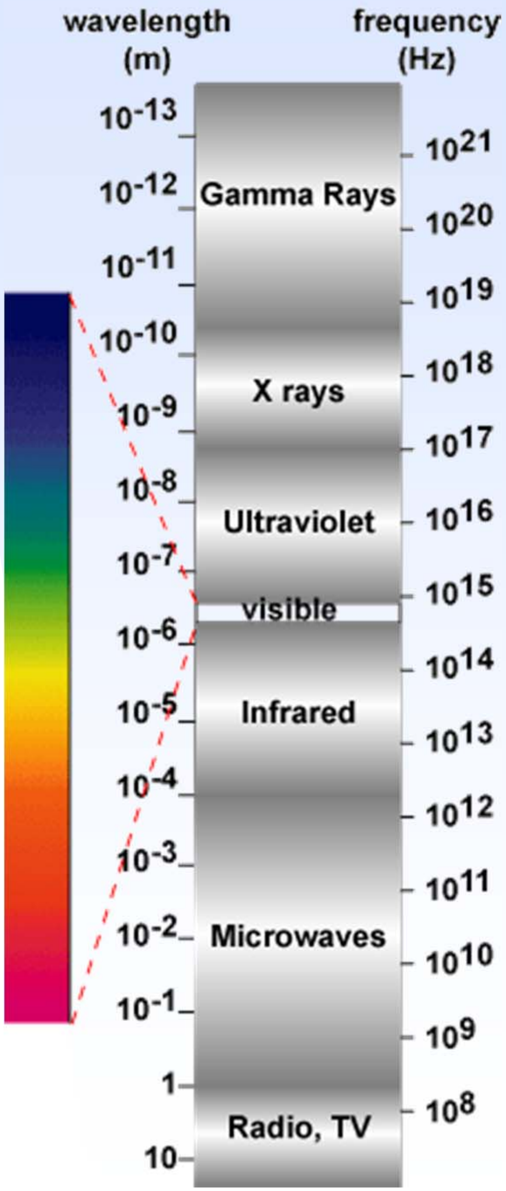
Average daily solar radiation at a location in a given month: this data may be presented either as measured on the horizontal or measured with the measuring surface perpendicular to the solar radiation (corresponding to a PV system which tracks the sun). The angular dependence to account for the tilt of the module must also be incorporated.

Peak Sun Hours

The average daily solar **insolation** in units of kWh/m^2 per day is sometimes referred to as "peak sun hours". The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours. Since the peak solar radiation is 1 kW/m^2, the number of peak sun hours is numerically identical to the average daily solar insolation. For example, a location that receives 8 kWh/m^2 per day can be said to have received 8 hours of sun per day at 1 kW/m^2. Being able to calculate the peak sun hours is useful because PV modules are often rated at an input rating of 1kW/m^2.



Properties of light



Energy of a photon: $E = \frac{hc}{\lambda}$

Convenient relation: $E = \frac{1.24}{\lambda(\mu m)}$

1 eV = 1.602 x 10^{-19} J

Definition of photon flux: $\Phi = \frac{\#\, of\ photons}{\sec m^2}$

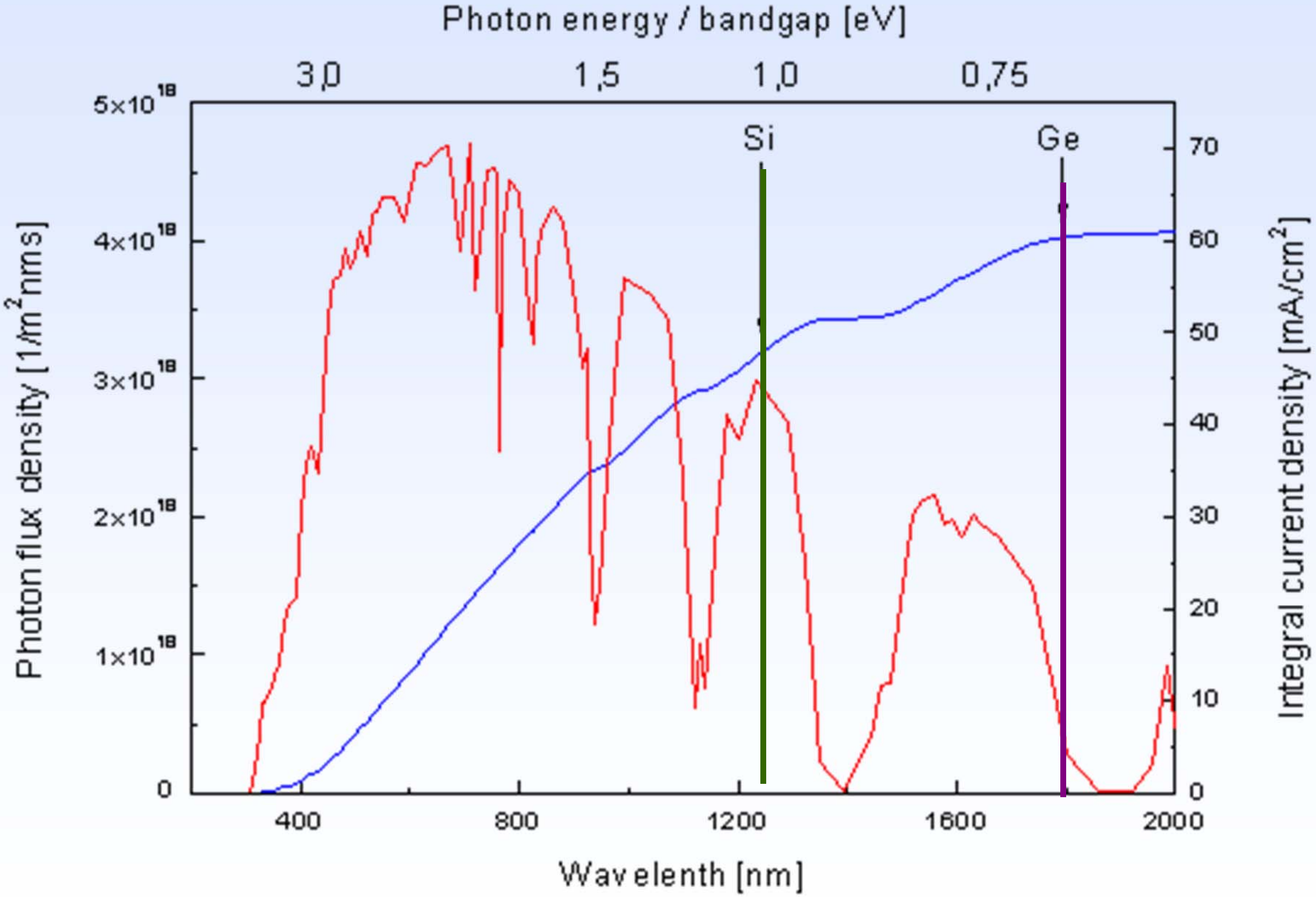
Spectral irradiance:

$$F = \left(\frac{W}{m^2 \mu m}\right) = q\Phi \frac{1.24}{\lambda^2 (\mu m)} = q\Phi \frac{E^2(eV)}{1.24}$$

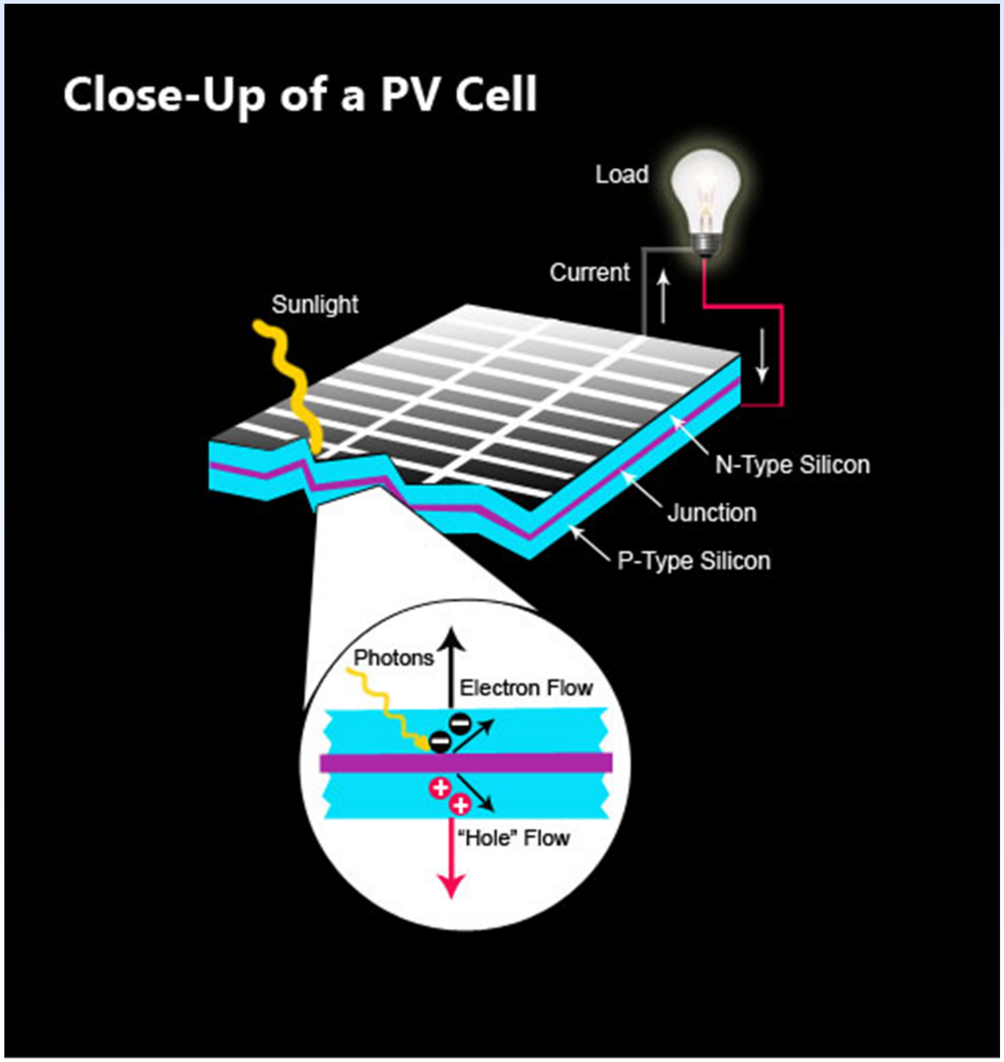
F is the spectral irradiance in $Wm^{-2}\mu m^{-1}$; Φ is the photon flux in # photons $m^{-2}sec^{-1}$; E and λ are the energy and wavelength of the photon in eV and μm respectively; and q, h and c are constants.

An excellent resource:
http://www.pveducation.org

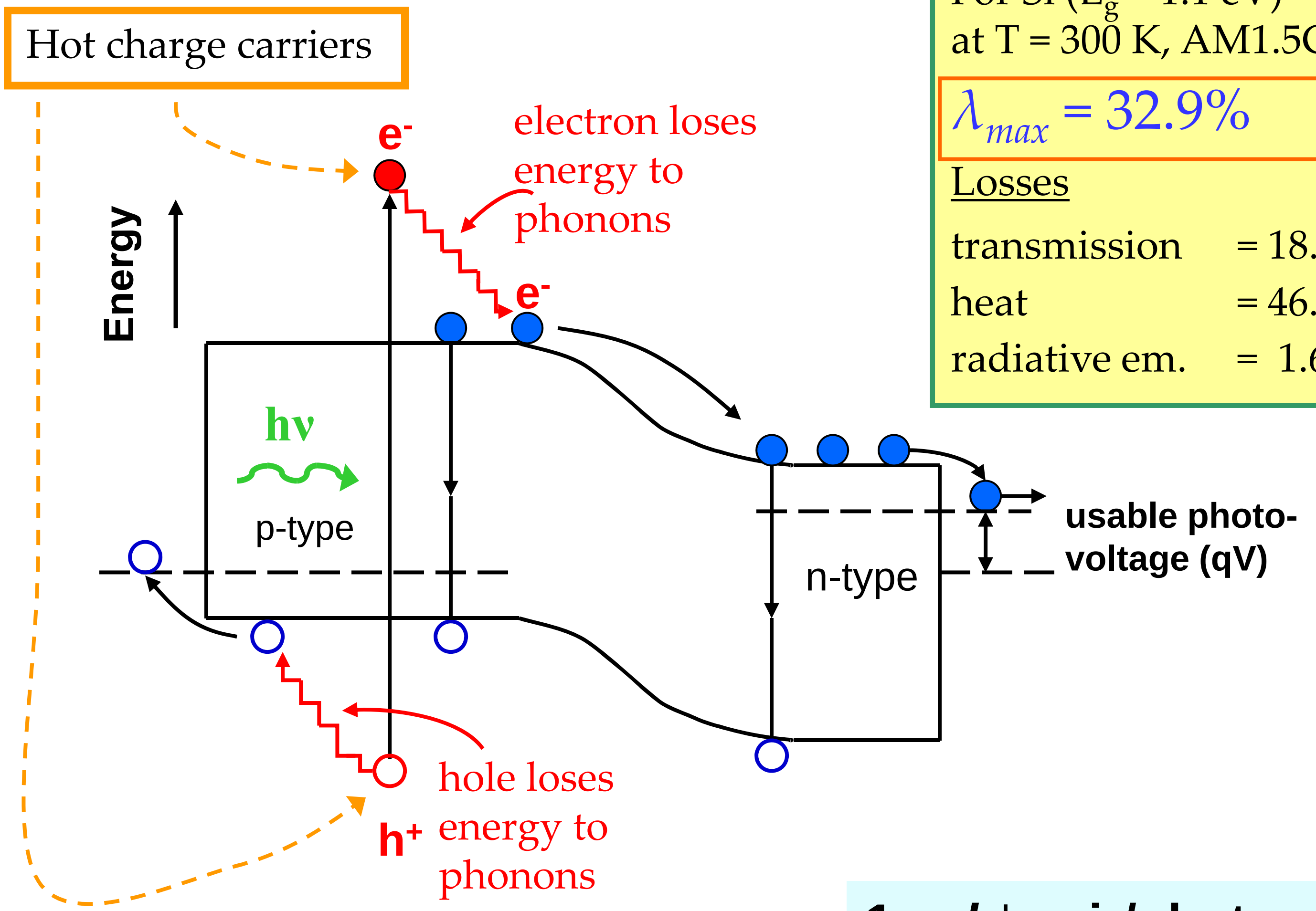
Integrating the Solar Spectrum



Simple solar cell structure



Conventional p-n junction photovoltaic cell



Hot charge carriers

e^-

electron loses energy to phonons

e^-

Energy

hν

p-type

n-type

usable photo-voltage (qV)

hole loses energy to phonons

h^+

For Si (E_g = 1.1 eV)
at T = 300 K, AM1.5G

$\lambda_{max} = 32.9\%$

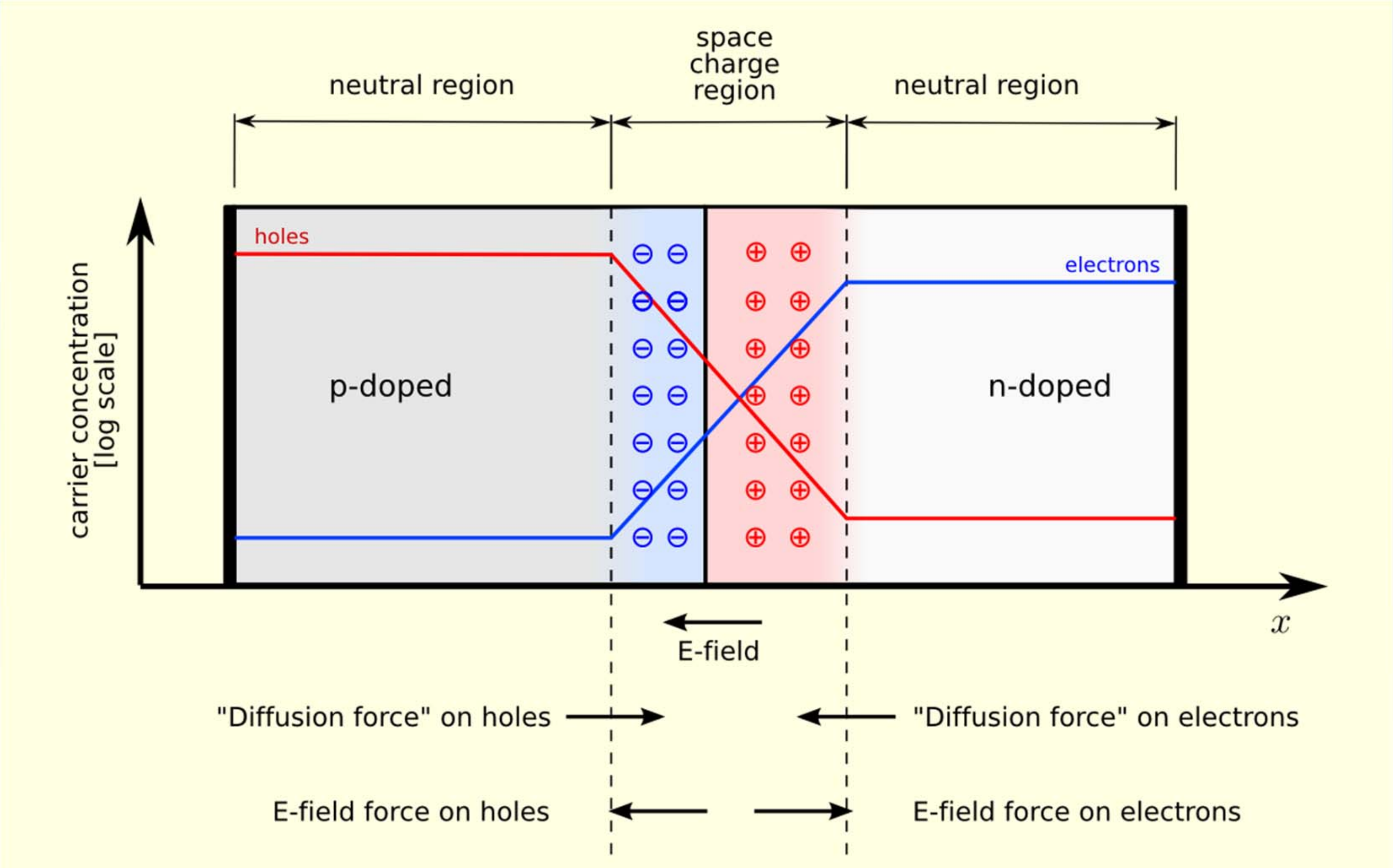
Losses

transmission	= 18.7%
heat	= 46.8%
radiative em.	= 1.6%

1 e^--h^+ pair/photon

Photovoltaic effect

The photovoltaic effect is the creation of a voltage (or a corresponding electric current) in a material upon exposure to light.



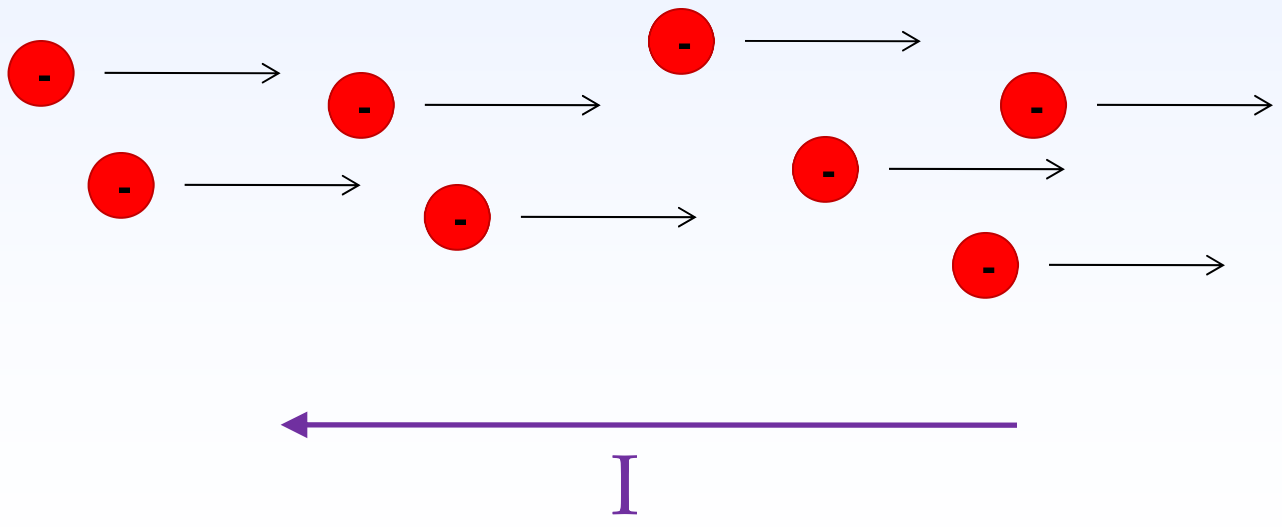
http://en.wikipedia.org/wiki/P-n_junction

Electric current flow

Conventional Electric Current

Although it is electrons which are the mobile charge carriers which are responsible for electric current in conductors such as wires, it has long been the convention to take the direction of electric current as if it were the positive charges which are moving.

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elecur.html#c3

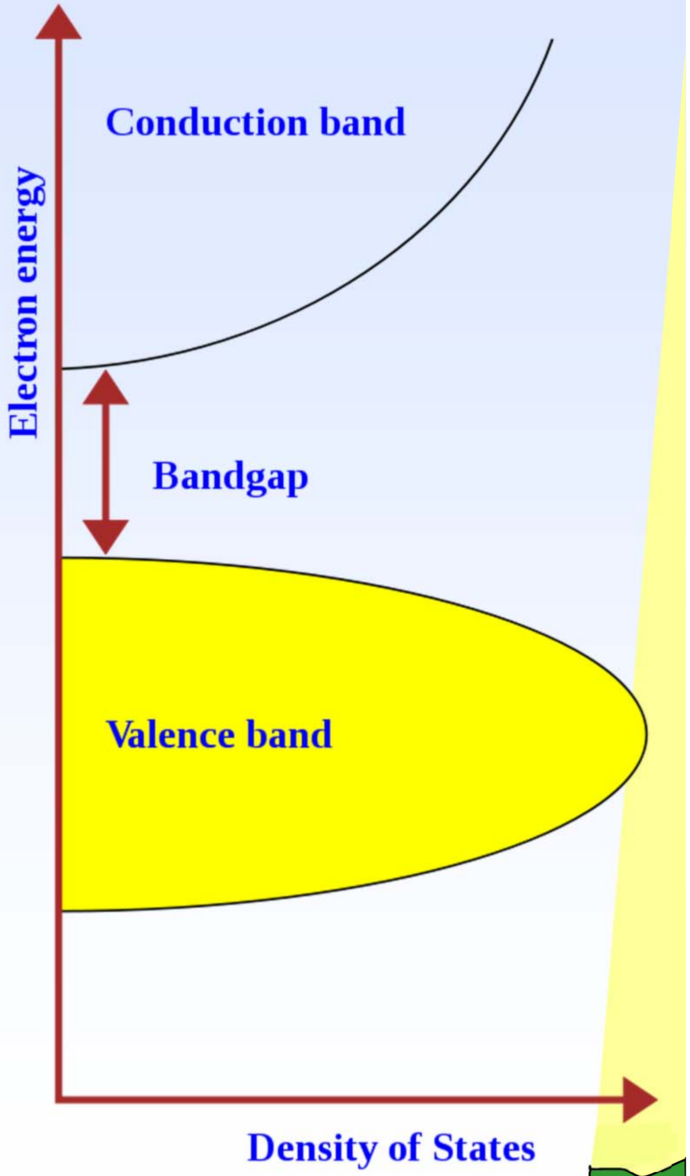


Semiconductors

A semiconductor has electrical conductivity due to electron flow (as opposed to ionic conductivity) intermediate in magnitude between that of a conductor and an insulator.

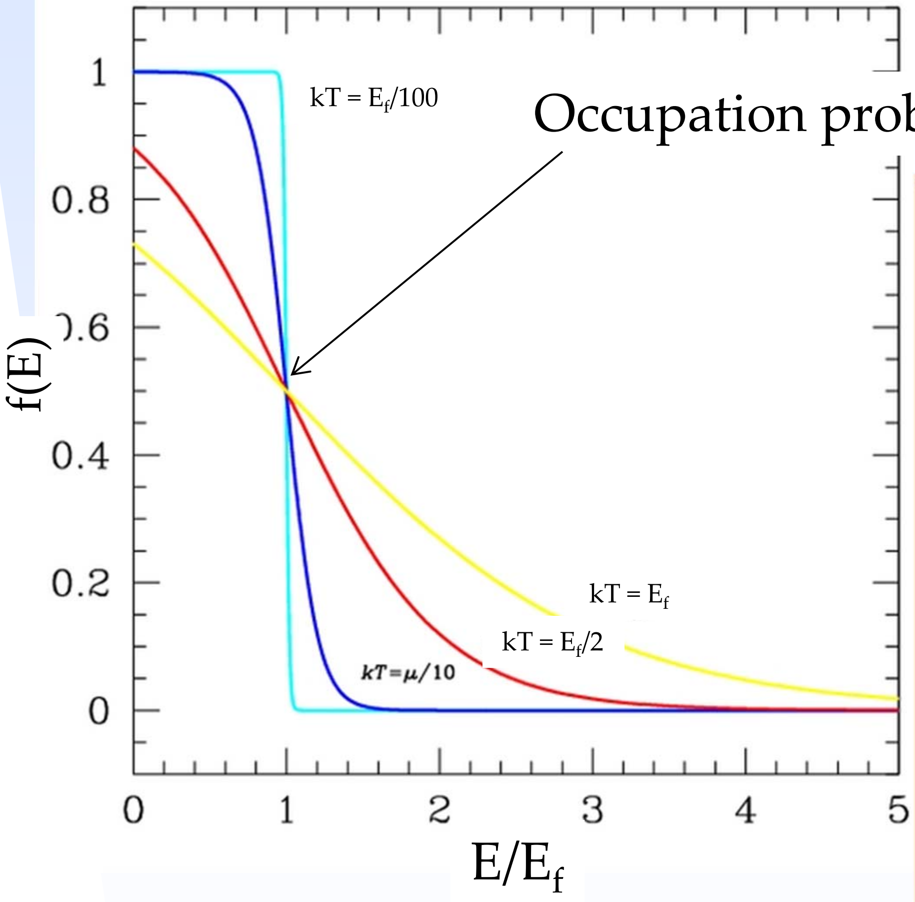
Semiconducting materials are the foundation of modern electronics, and are used in transistors, solar cells, many kinds of diodes including the light-emitting diode, and digital and analog integrated circuits.

Semiconductor PV cells directly convert light energy into electrical energy. In metals, current is carried by the flow of electrons. In semiconductors, current is often schematized as being carried either by the flow of electrons or by the flow of positively charged "holes" in the electron structure of the material (in both cases only electron movements are actually involved).

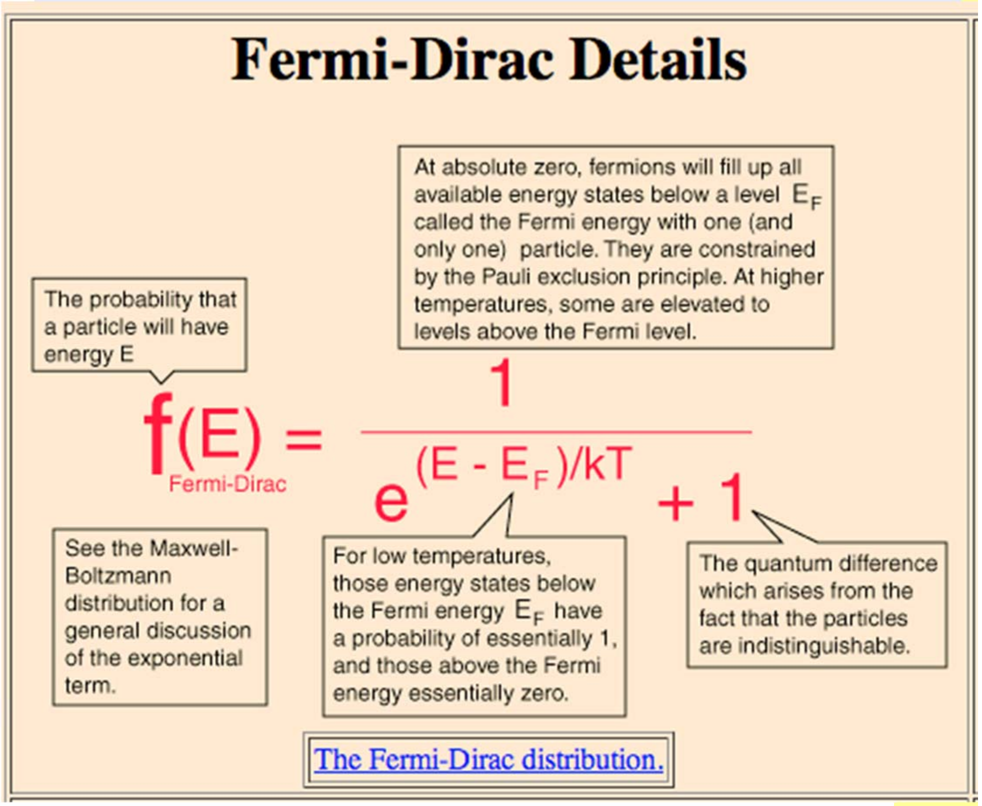


http://en.wikipedia.org/wiki/Semiconductor

Fermi-Dirac statistics



Occupation probability at E_f is 1/2



Fermi-Dirac Details

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

The probability that a particle will have energy E

$$f(E)_{\text{Fermi-Dirac}} = \frac{1}{e^{(E - E_F)/kT} + 1}$$

See the Maxwell-Boltzmann distribution for a general discussion of the exponential term.

For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

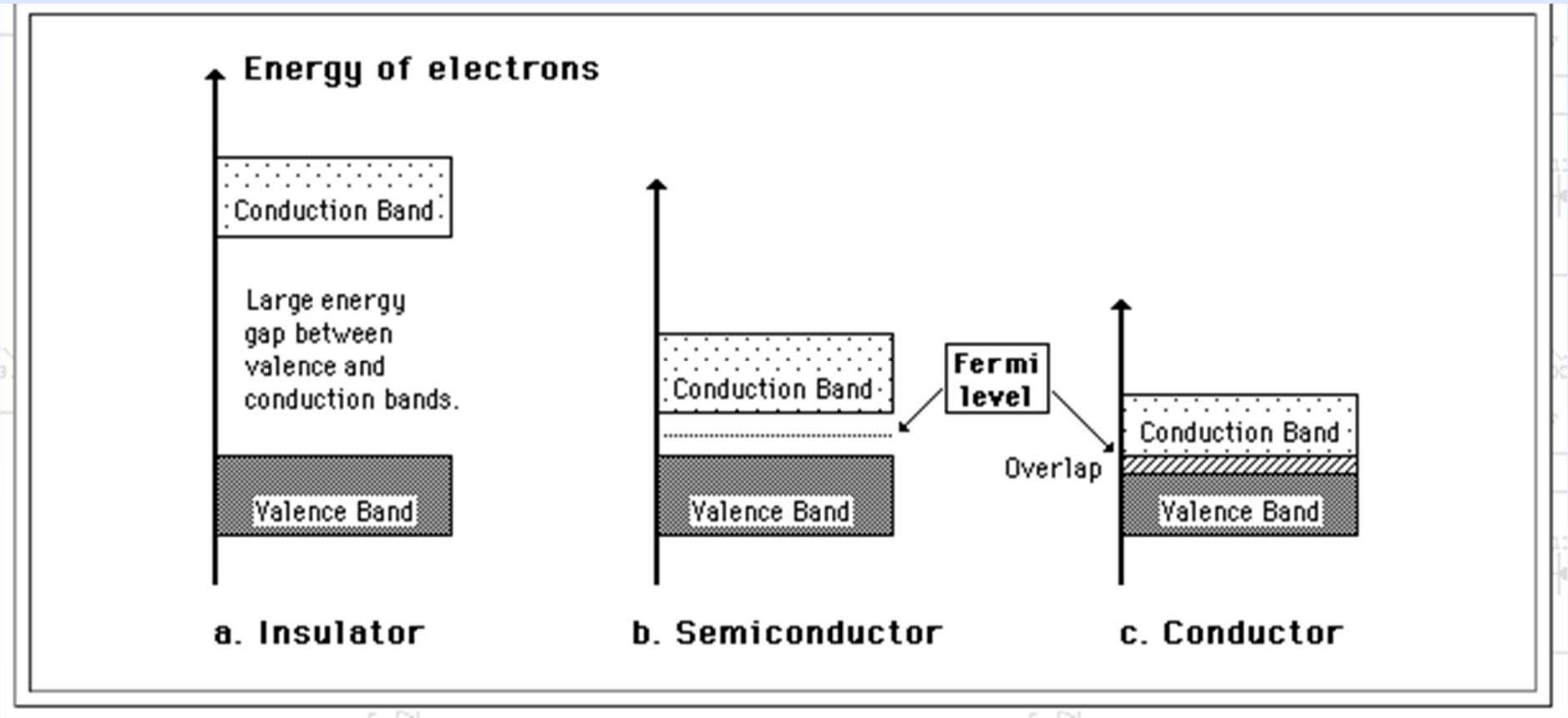
The quantum difference which arises from the fact that the particles are indistinguishable.

The Fermi-Dirac distribution.

kT ~ 26 meV at 300 K

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/disfd.html

Insulators, semiconductors, and conductors



http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/energy_gap/energy_gap.html

The **Fermi level** is the energy, also called the chemical potential (μ) that appears in the electrons' Fermi-Dirac distribution function. A state at the Fermi level has a 50% chance of being occupied by an electron.

$$\bar{n}_i = \frac{1}{e^{(\varepsilon_i - \mu)/kT} + 1}$$

http://en.wikipedia.org/wiki/Fermi_level

The Diode Equation

Ideal Diodes

The diode equation gives an expression for the current through a diode as a function of voltage. The *Ideal Diode Law*:

$$I = I_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$

where:
I = the net current flowing through the diode;
I_0 = "dark saturation current", the diode leakage current density in the absence of light;
V = applied voltage across the terminals of the diode;
q = absolute value of electron charge;
k = Boltzmann's constant; and
T = absolute temperature (K).

The "dark saturation current" (I_0) is an extremely important parameter which differentiates one diode from another. I_0 is a measure of the recombination in a device. A diode with a larger recombination will have a larger I_0.

Note that:
I_0 increases as T increases; and
I_0 decreases as material quality increases.
At 300K, kT/q = 25.85 mV, the "thermal voltage".

IV Curve

The IV curve of a solar cell is the superposition of the IV curve in the dark with the light-generated current.[1] Illumination shifts the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L$$

where I_L = light generated current.

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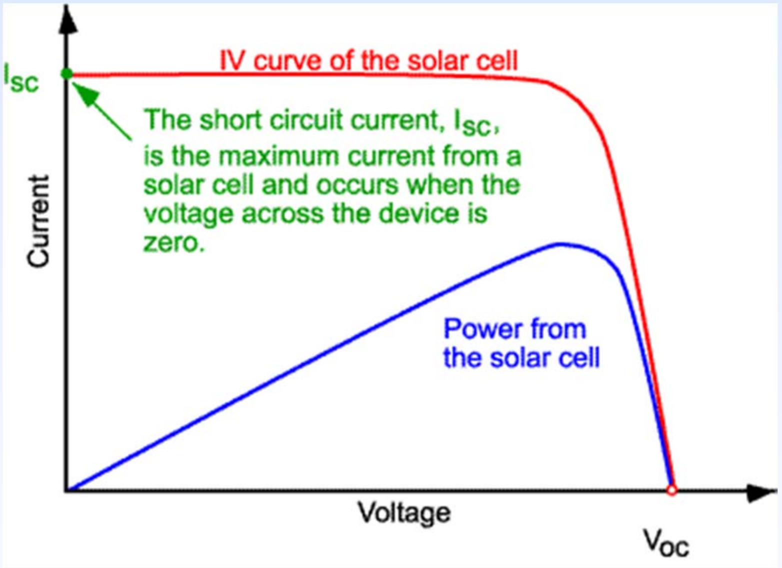
1. Lindholm, F. A., J. G. Fossum, and E. L. Burgess, "Application of the superposition principle to solar-cell analysis", *IEEE Transactions on Electron Devices*, vol. 26, no. 3, pp. 165–171, 1979.

Short circuit photocurrent

The short-circuit current (I_{SC}) is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the IV curve below.



I_{SC} is due to the generation and collection of light-generated carriers. For an ideal PV cell with moderate resistive loss, I_{SC} and the light-generated current are identical (I_{SC} is the largest current which may be drawn from the solar cell).

PV EDUCATION.ORG

Short circuit photocurrent (I_{SC})

The short-circuit current depends on a number of factors which are described below:

the area of the solar cell. To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in mA/cm^2) rather than the short-circuit current;

the number of photons (i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity as discussed in Effect of Light Intensity;

the spectrum of the incident light. For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum;

the optical properties (absorption and reflection) of the solar cell (discussed in Optical Losses); and

the collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

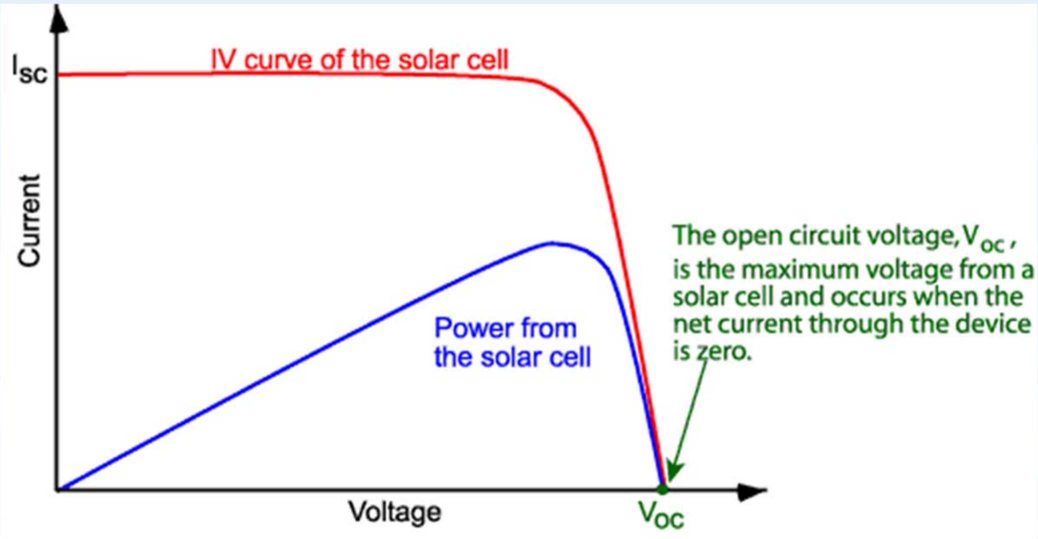
When comparing solar cells of the same material type, the most critical material parameter is the diffusion length and surface passivation. In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current can be approximated as:

$$J_{SC} = qG\left(L_n + L_p\right)$$

where G is the generation rate, and L_n and L_p are the e^- and h^+ diffusion lengths respectively. The above equation indicates that J_{SC} depends strongly on generation rate and the diffusion length.

Open circuit photovoltage (V_{OC})

The open-circuit voltage, V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the IV curve below.



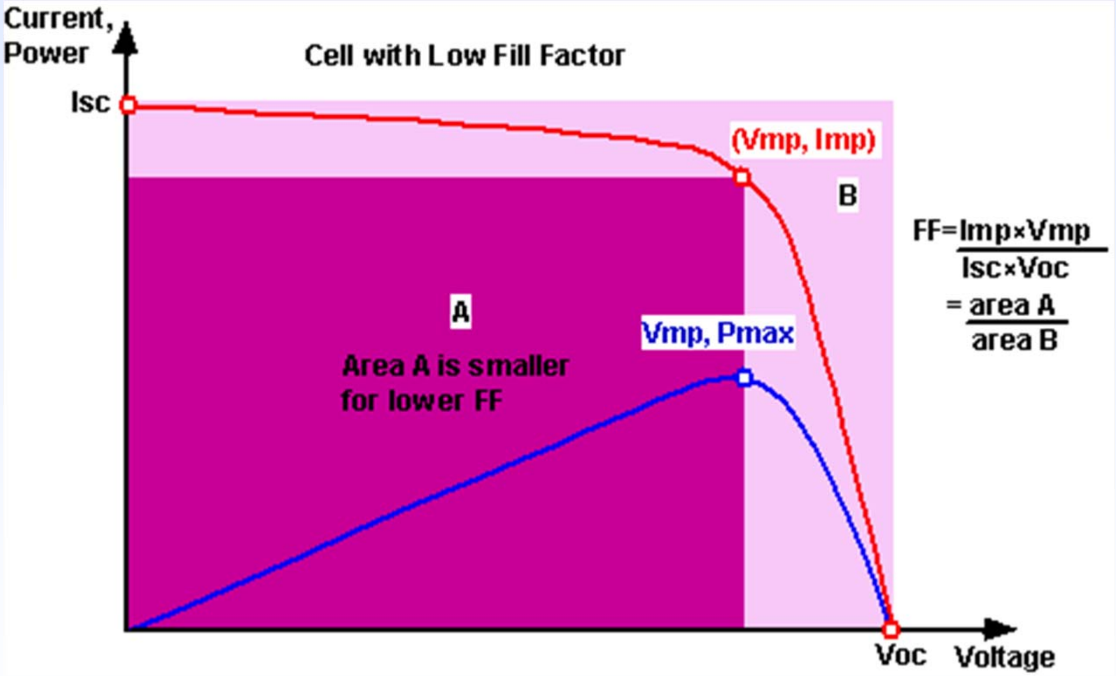
The open circuit voltage, V_{OC}, is the maximum voltage from a solar cell and occurs when the net current through the device is zero.

An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_o} + 1\right)$$

Solar cell fill factor (FF)

At both of the operating points corresponding to I_{SC} and V_{OC}, the power from the solar cell is zero. The "fill factor“ (FF) is the parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below:



Graph of cell output current (red line) and power (blue line) as function of voltage. Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}). Click on the graph to see how the curve changes for a cell with low FF.

Solar cell efficiency

The efficiency of a solar cell (sometimes known as the power conversion efficiency, or PCE, and also often abbreviated η) represents the ratio where the output electrical power at the maximum power point on the IV curve is divided by the incident light power – typically using a standard AM1.5G simulated solar spectrum.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{\max} = V_{OC} I_{SC} FF \qquad \eta = \frac{V_{OC} I_{SC} FF}{P_{inc}}$$

where V_{oc} is the open-circuit voltage;
where I_{sc} is the short-circuit current; and
where FF is the fill factor
where η is the efficiency.

In a 10 x 10 cm^2 cell the input power is 100 mW/cm^2 x 100 cm^2 = 10 W.

External and internal quantum efficiency

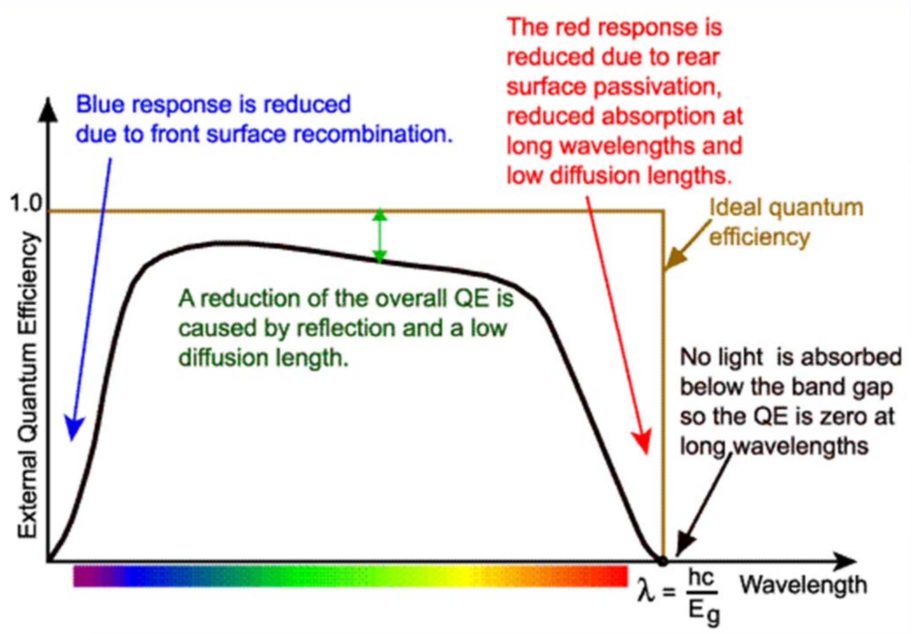
Internal and external quantum efficiency are functions of wavelength, i.e., EQE(⌊) and QE(⌊):

External quantum efficiency (EQE):

$$EQE(\lambda) = \frac{\text{Electrons collected as photocurrent, per second}}{\text{Photons } \textit{incident}\text{, per second}}$$

Internal quantum efficiency (QE):

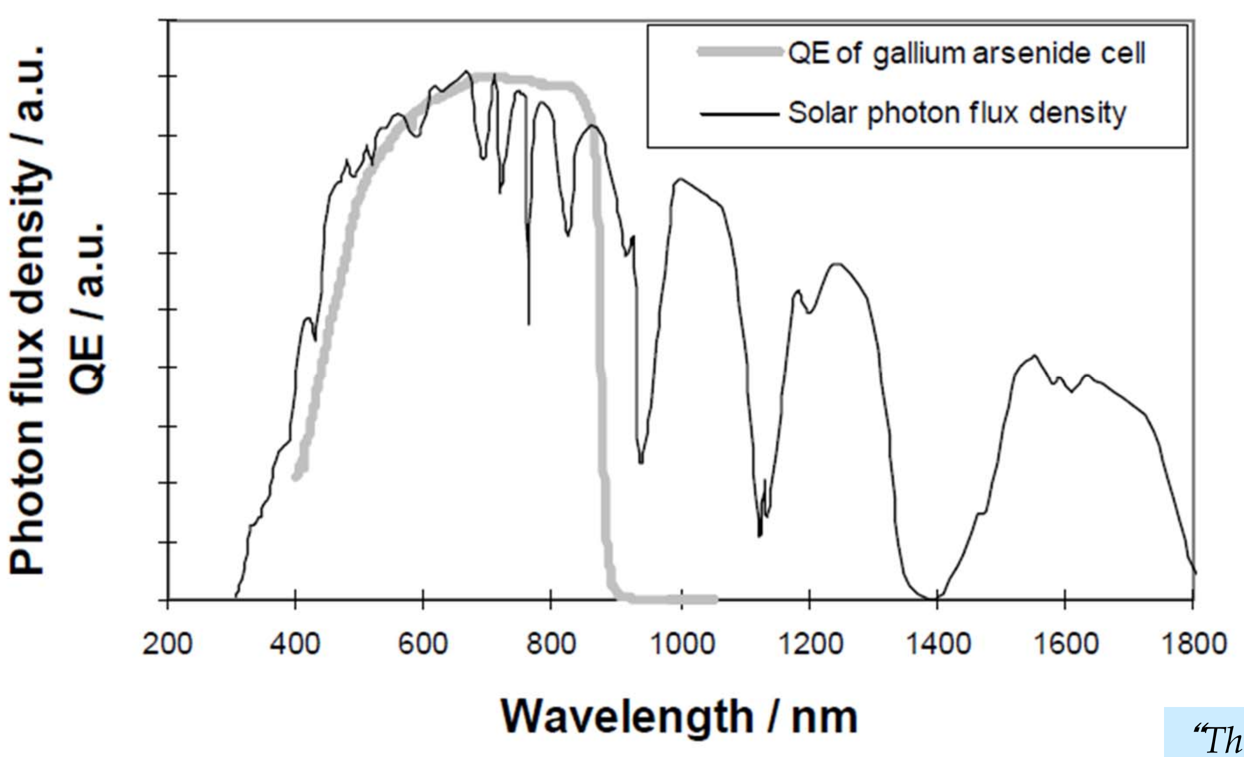
$$QE(\lambda) = \frac{\text{Electrons collected as photocurrent, per second}}{\text{Photons } \textit{absorbed}\text{, per second}}$$



Relationship between QE and J_{sc}

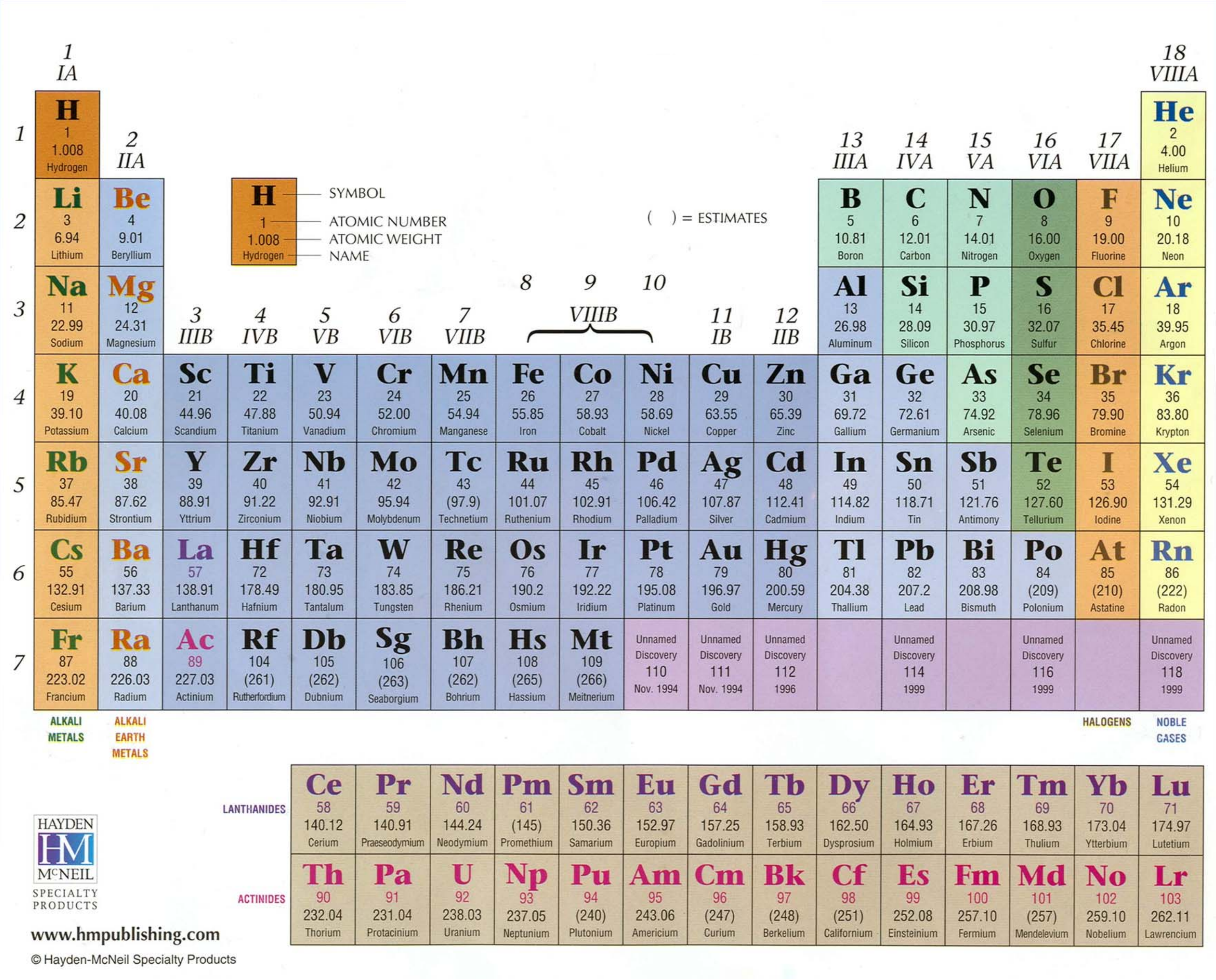
$$J_{SC} = q\int b_s(E)QE(E)dE$$

where $b_s(E)$ is the incident spectral photon flux density, i.e. the number of photons in the energy range E to $E + dE$ which are incident on unit area in unit time, and q is the electronic charge. *QE* depends upon the absorption coefficient of the solar cell materials, the efficiency of charge separation, and the efficiency of charge collection in the device; but it does not depend on the incident spectrum.



"The Physics of Solar Cells", J. Nelson

Bonding in Materials *and* The periodic table



	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	H 1 1.008 Hydrogen																	He 2 4.00 Helium
2	Li 3 6.94 Lithium	Be 4 9.01 Beryllium											B 5 10.81 Boron	C 6 12.01 Carbon	N 7 14.01 Nitrogen	O 8 16.00 Oxygen	F 9 19.00 Fluorine	Ne 10 20.18 Neon
3	Na 11 22.99 Sodium	Mg 12 24.31 Magnesium											Al 13 26.98 Aluminum	Si 14 28.09 Silicon	P 15 30.97 Phosphorus	S 16 32.07 Sulfur	Cl 17 35.45 Chlorine	Ar 18 39.95 Argon
4	K 19 39.10 Potassium	Ca 20 40.08 Calcium	Sc 21 44.96 Scandium	Ti 22 47.88 Titanium	V 23 50.94 Vanadium	Cr 24 52.00 Chromium	Mn 25 54.94 Manganese	Fe 26 55.85 Iron	Co 27 58.93 Cobalt	Ni 28 58.69 Nickel	Cu 29 63.55 Copper	Zn 30 65.39 Zinc	Ga 31 69.72 Gallium	Ge 32 72.61 Germanium	As 33 74.92 Arsenic	Se 34 78.96 Selenium	Br 35 79.90 Bromine	Kr 36 83.80 Krypton
5	Rb 37 85.47 Rubidium	Sr 38 87.62 Strontium	Y 39 88.91 Yttrium	Zr 40 91.22 Zirconium	Nb 41 92.91 Niobium	Mo 42 95.94 Molybdenum	Tc 43 (97.9) Technetium	Ru 44 101.07 Ruthenium	Rh 45 102.91 Rhodium	Pd 46 106.42 Palladium	Ag 47 107.87 Silver	Cd 48 112.41 Cadmium	In 49 114.82 Indium	Sn 50 118.71 Tin	Sb 51 121.76 Antimony	Te 52 127.60 Tellurium	I 53 126.90 Iodine	Xe 54 131.29 Xenon
6	Cs 55 132.91 Cesium	Ba 56 137.33 Barium	La 57 138.91 Lanthanum	Hf 72 178.49 Hafnium	Ta 73 180.95 Tantalum	W 74 183.85 Tungsten	Re 75 186.21 Rhenium	Os 76 190.2 Osmium	Ir 77 192.22 Iridium	Pt 78 195.08 Platinum	Au 79 196.97 Gold	Hg 80 200.59 Mercury	Tl 81 204.38 Thallium	Pb 82 207.2 Lead	Bi 83 208.98 Bismuth	Po 84 (209) Polonium	At 85 (210) Astatine	Rn 86 (222) Radon
7	Fr 87 223.02 Francium	Ra 88 226.03 Radium	Ac 89 227.03 Actinium	Rf 104 (261) Rutherfordium	Db 105 (262) Dubnium	Sg 106 (263) Seaborgium	Bh 107 (262) Bohrium	Hs 108 (265) Hassium	Mt 109 (266) Meitnerium	Unnamed Discovery 110 Nov. 1994	Unnamed Discovery 111 Nov. 1994	Unnamed Discovery 112 1996		Unnamed Discovery 114 1999		Unnamed Discovery 116 1999		Unnamed Discovery 118 1999
	ALKALI METALS	ALKALI EARTH METALS															HALOGENS	NOBLE GASES

LANTHANIDES	Ce 58 140.12 Cerium	Pr 59 140.91 Praseodymium	Nd 60 144.24 Neodymium	Pm 61 (145) Promethium	Sm 62 150.36 Samarium	Eu 63 152.97 Europium	Gd 64 157.25 Gadolinium	Tb 65 158.93 Terbium	Dy 66 162.50 Dysprosium	Ho 67 164.93 Holmium	Er 68 167.26 Erbium	Tm 69 168.93 Thulium	Yb 70 173.04 Ytterbium	Lu 71 174.97 Lutetium
ACTINIDES	Th 90 232.04 Thorium	Pa 91 231.04 Protacinium	U 92 238.03 Uranium	Np 93 237.05 Neptunium	Pu 94 (240) Plutonium	Am 95 243.06 Americium	Cm 96 (247) Curium	Bk 97 (248) Berkelium	Cf 98 (251) Californium	Es 99 252.08 Einsteinium	Fm 100 257.10 Fermium	Md 101 (257) Mendelevium	No 102 259.10 Nobelium	Lr 103 262.11 Lawrencium

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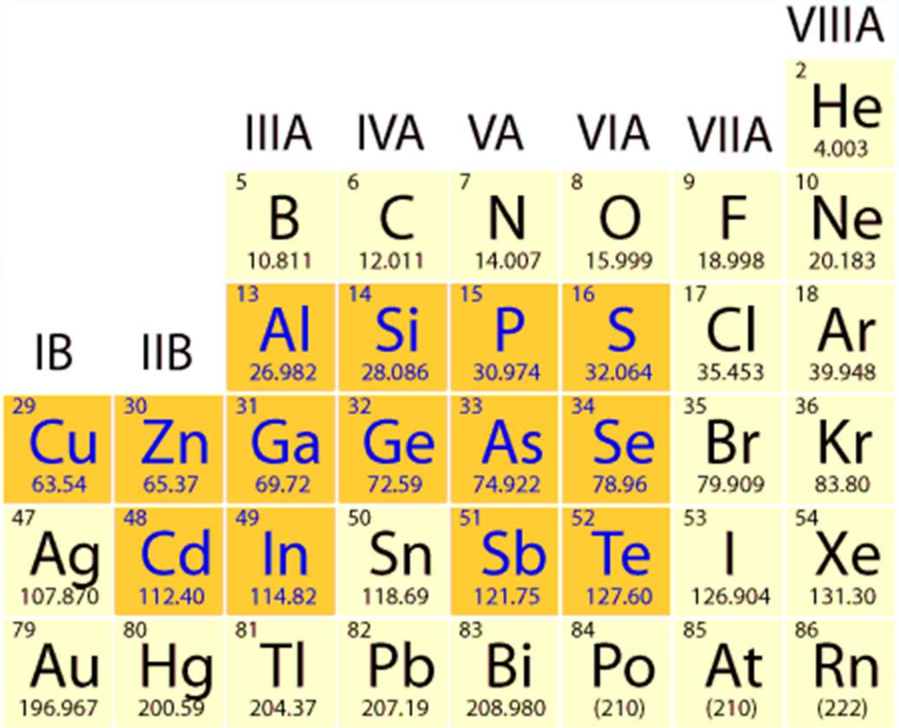
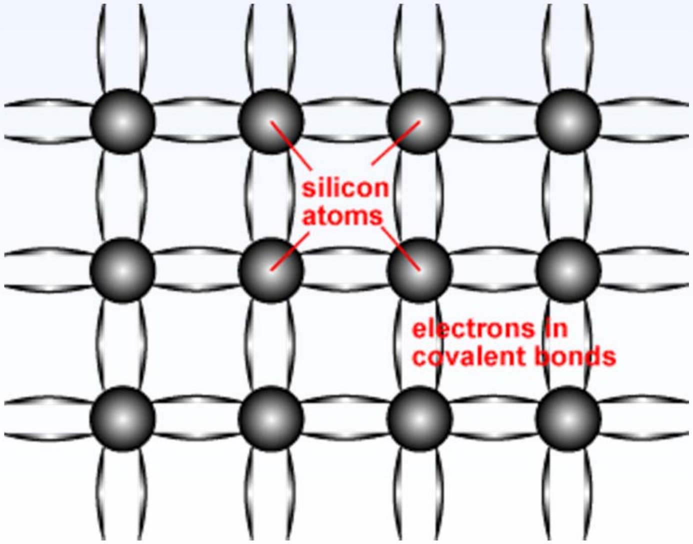
Common elemental components of semiconductors



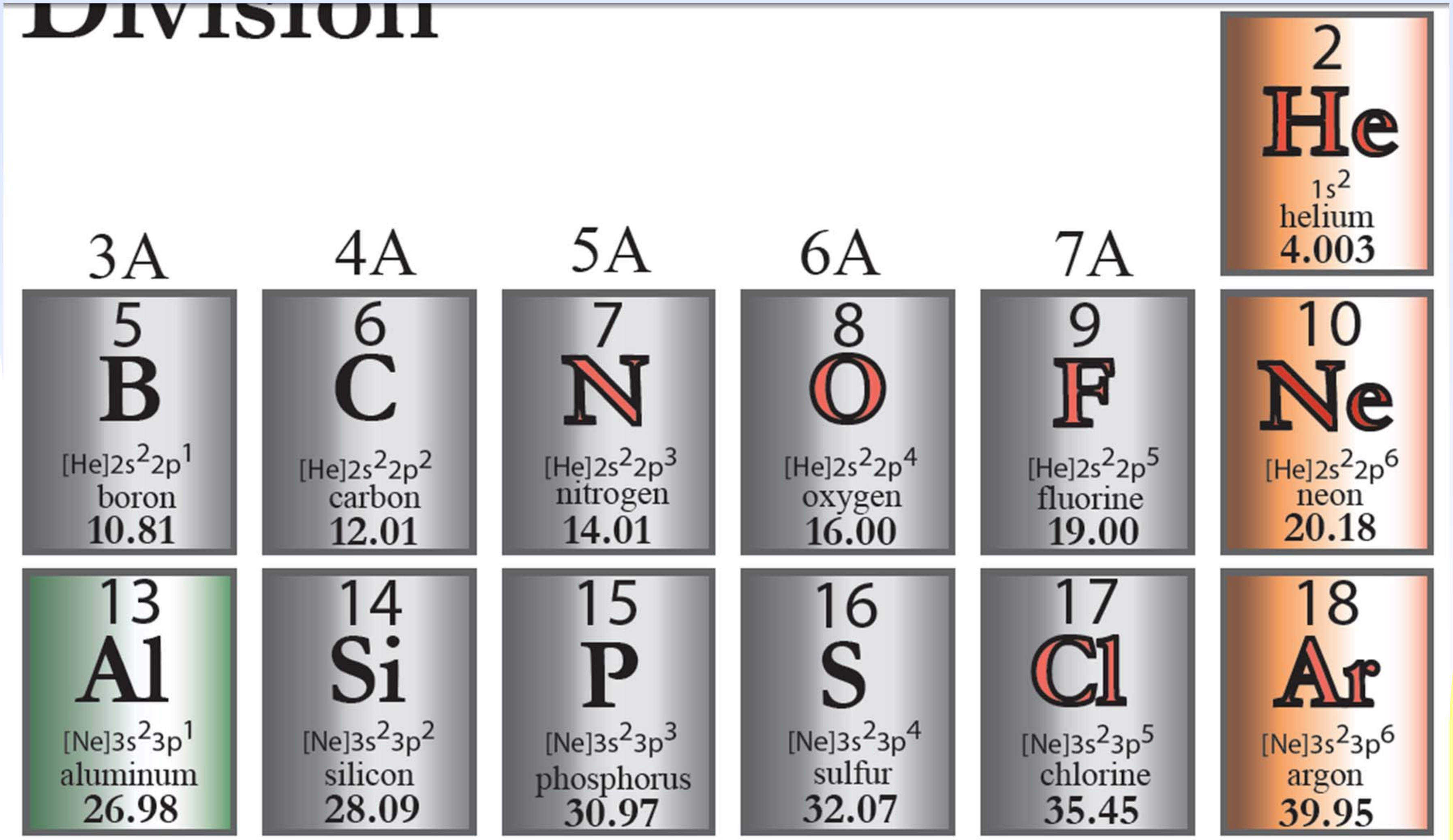
IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

Silicon (a semiconductor)

Silicon is a semiconductor with individual atoms bonded together in a regular, periodic structure to form an arrangement whereby each atom is surrounded by 8 electrons. Each atom consists of a nucleus made up of a core of protons (positively charged particles) and neutrons (particles having no charge) surrounded by electrons. The number of electrons and protons is equal, such that the atom is overall electrically neutral. The electrons occupy certain energy levels, based on the number of electrons in the atom, which is different for each element in the periodic table. The structure of a semiconductor is shown in the figure below.



Electron configuration of the elements

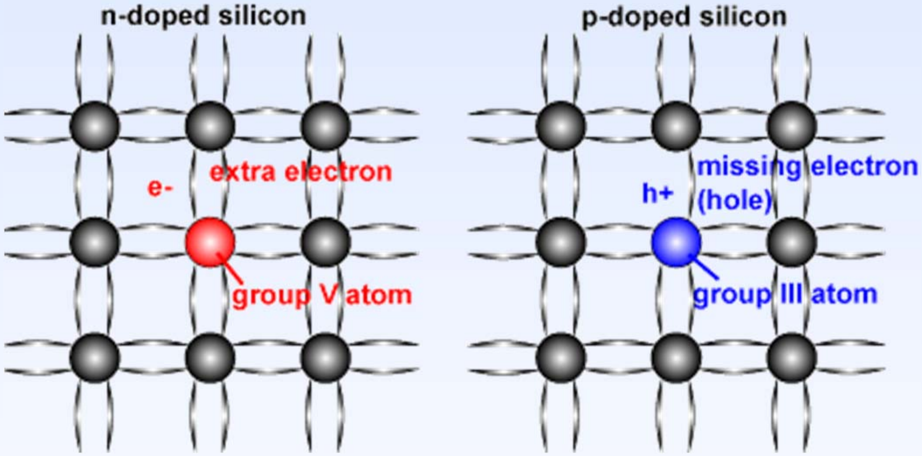


3A	4A	5A	6A	7A	
					2 He $1s^2$ helium 4.003
5 B $[He]2s^22p^1$ boron 10.81	6 C $[He]2s^22p^2$ carbon 12.01	7 N $[He]2s^22p^3$ nitrogen 14.01	8 O $[He]2s^22p^4$ oxygen 16.00	9 F $[He]2s^22p^5$ fluorine 19.00	10 Ne $[He]2s^22p^6$ neon 20.18
13 Al $[Ne]3s^23p^1$ aluminum 26.98	14 Si $[Ne]3s^23p^2$ silicon 28.09	15 P $[Ne]3s^23p^3$ phosphorus 30.97	16 S $[Ne]3s^23p^4$ sulfur 32.07	17 Cl $[Ne]3s^23p^5$ chlorine 35.45	18 Ar $[Ne]3s^23p^6$ argon 39.95

http://www.sciencegeek.net/tables/LosAlamosperiodictableColor.pdf

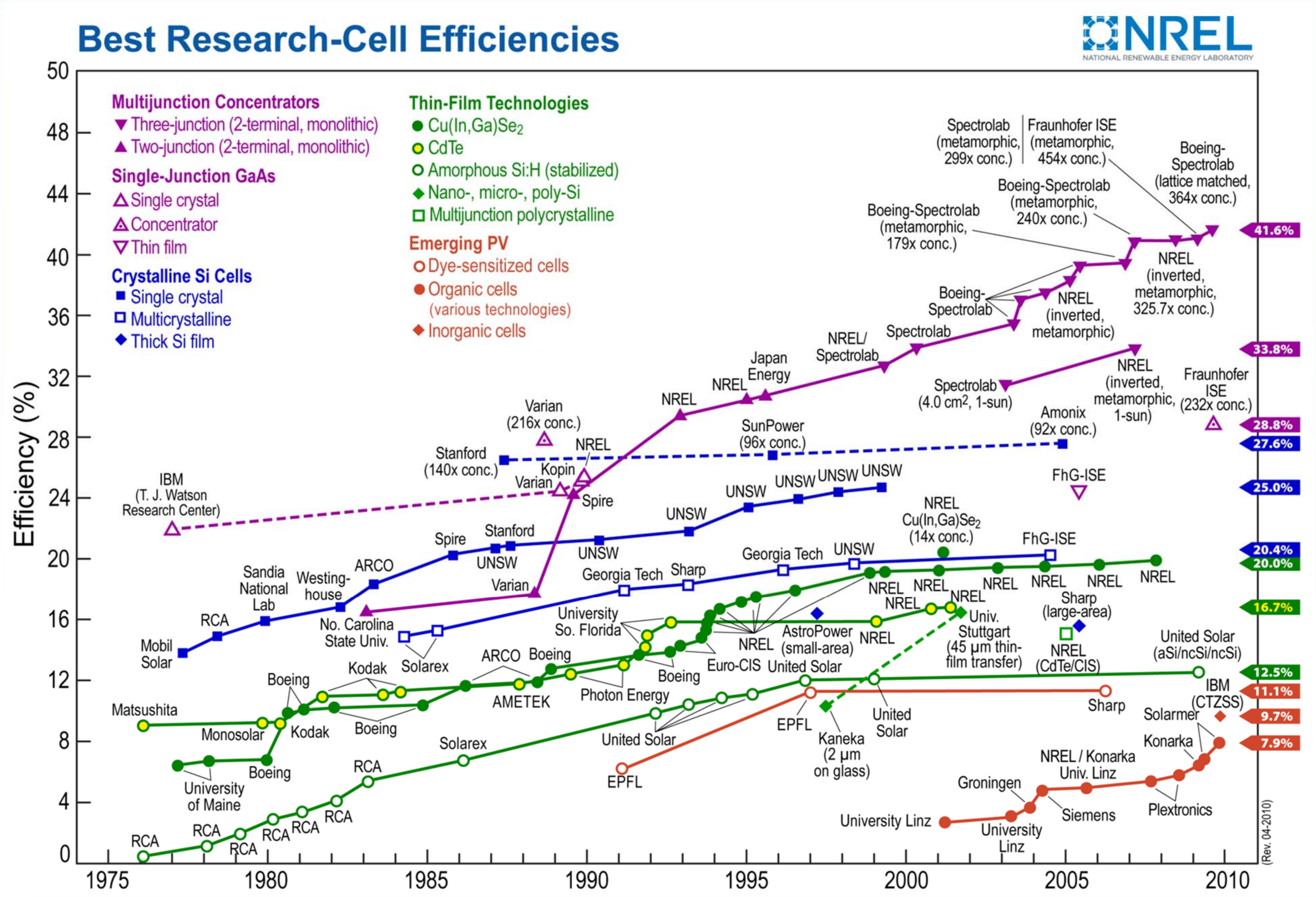
Intrinsic, p-type, and n-type semiconductors

“Doping” in a silicon crystal lattice with other atoms enables one to shift the balance of free electrons and holes. Choose an atom with an extra valence electron to produce "*n*-type" semiconductor material (this adds a free electron to the conduction band. Choose an atom with one too few valence electrons to produce “*p*-type" semiconductor material (this results in acceptance of an electron from the valence band, adding a free hole to the valence band. In *p*-type material, the number of electrons trapped in bonds is higher, increasing the number of holes. In an n- or p-type doped material, there is always more of one type of carrier than the other and the type of carrier with the higher concentration is called a "majority carrier", while the lower concentration carrier is called a "minority carrier."



	P-type (positive)	**N-type (negative)**
Dopant	Group III (e.g. Boron)	Group V (e.g. Phosphorous)
Bonds	Missing Electrons (Holes)	Excess Electrons
Majority Carriers	Holes	Electrons
Minority Carriers	Electrons	Holes

Trends in solar cell efficiencies

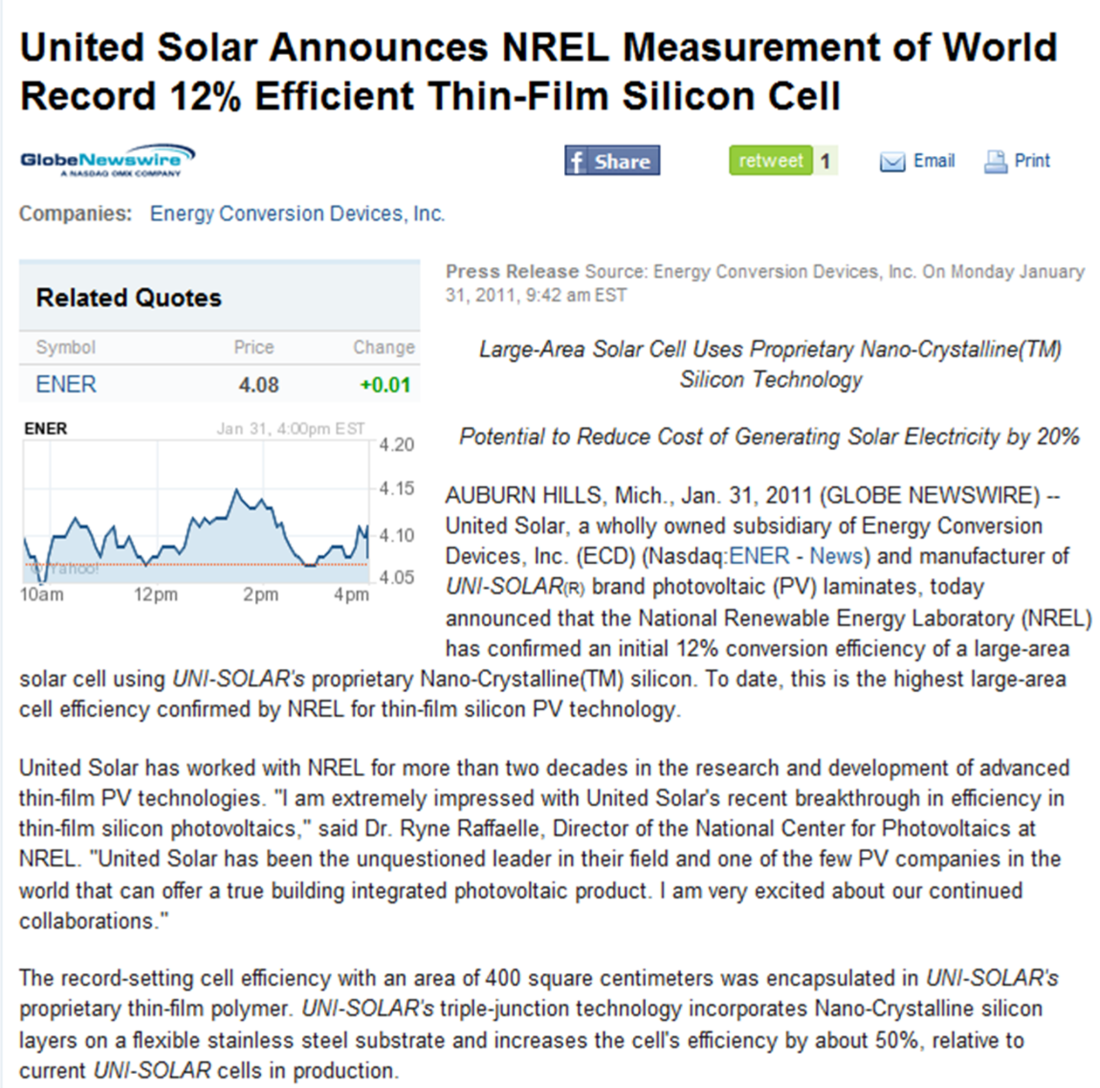


Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).

.... energizing Ohio for the 21st Century

Xunlight

2nd gen.: thin film Si



United Solar Announces NREL Measurement of World Record 12% Efficient Thin-Film Silicon Cell

GlobeNewswire

Companies: Energy Conversion Devices, Inc.

Related Quotes

Symbol	Price	Change
ENER	4.08	+0.01

Press Release Source: Energy Conversion Devices, Inc. On Monday January 31, 2011, 9:42 am EST

Large-Area Solar Cell Uses Proprietary Nano-Crystalline(TM) Silicon Technology

Potential to Reduce Cost of Generating Solar Electricity by 20%

AUBURN HILLS, Mich., Jan. 31, 2011 (GLOBE NEWSWIRE) -- United Solar, a wholly owned subsidiary of Energy Conversion Devices, Inc. (ECD) (Nasdaq:ENER - News) and manufacturer of *UNI-SOLAR*(R) brand photovoltaic (PV) laminates, today announced that the National Renewable Energy Laboratory (NREL) has confirmed an initial 12% conversion efficiency of a large-area solar cell using *UNI-SOLAR's* proprietary Nano-Crystalline(TM) silicon. To date, this is the highest large-area cell efficiency confirmed by NREL for thin-film silicon PV technology.

United Solar has worked with NREL for more than two decades in the research and development of advanced thin-film PV technologies. "I am extremely impressed with United Solar's recent breakthrough in efficiency in thin-film silicon photovoltaics," said Dr. Ryne Raffaelle, Director of the National Center for Photovoltaics at NREL. "United Solar has been the unquestioned leader in their field and one of the few PV companies in the world that can offer a true building integrated photovoltaic product. I am very excited about our continued collaborations."

The record-setting cell efficiency with an area of 400 square centimeters was encapsulated in *UNI-SOLAR's* proprietary thin-film polymer. *UNI-SOLAR's* triple-junction technology incorporates Nano-Crystalline silicon layers on a flexible stainless steel substrate and increases the cell's efficiency by about 50%, relative to current *UNI-SOLAR* cells in production.