FUNDAMENTAL PROPERTIES OF

SOLAR CELLS

February 1, 2011
The University of Toledo, Department of Physics and Astronomy
SSARE, PVIC

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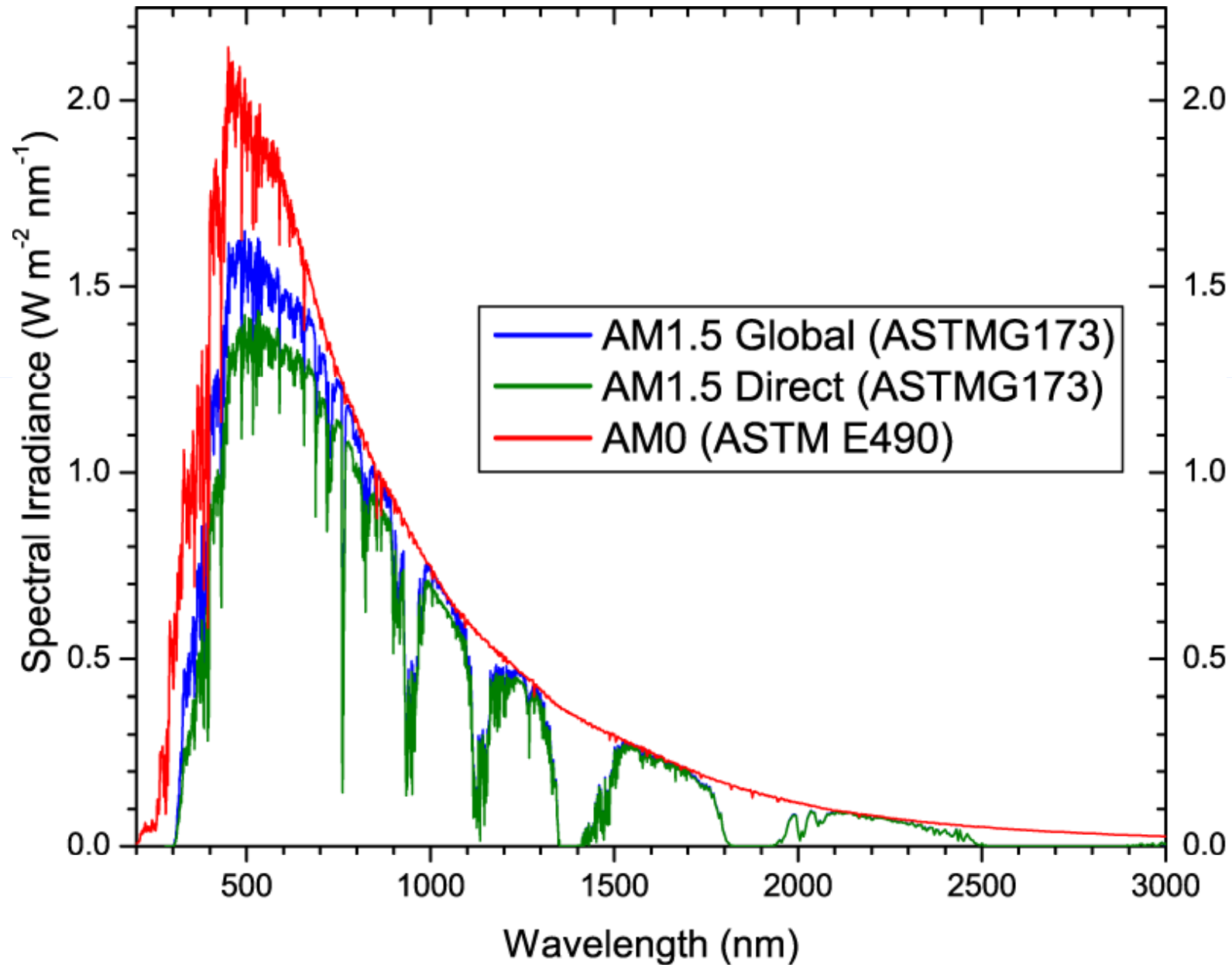and
Fundamentals of Solar Cells (PHYS 6980)

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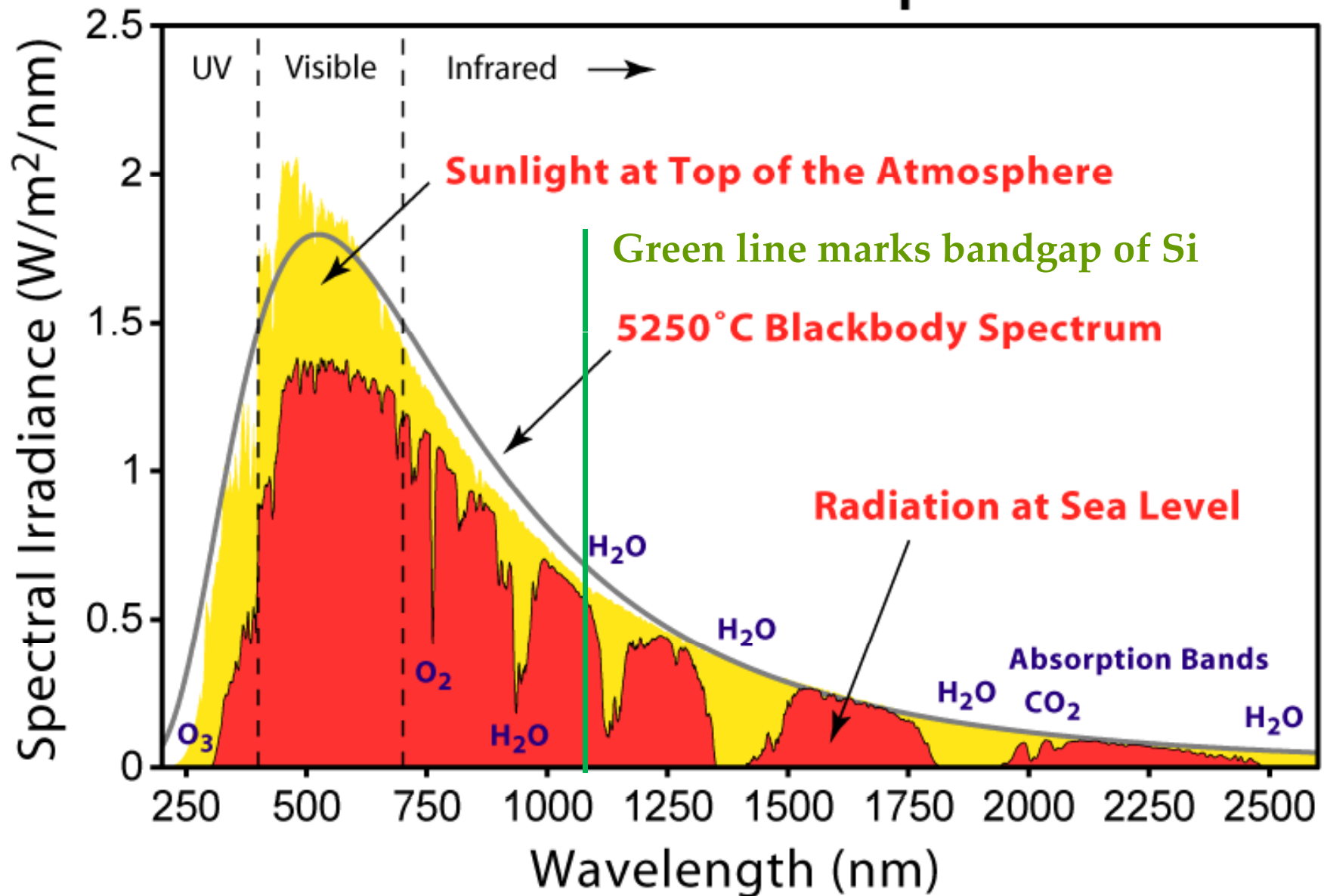- internal and external QE
- maximum power point

Quiz #2 next Tuesday, Feb. 8th

Solar spectra at Earth

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Solar Radiation Spectrum

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## 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.

Area Under Curve = Solar Insolation
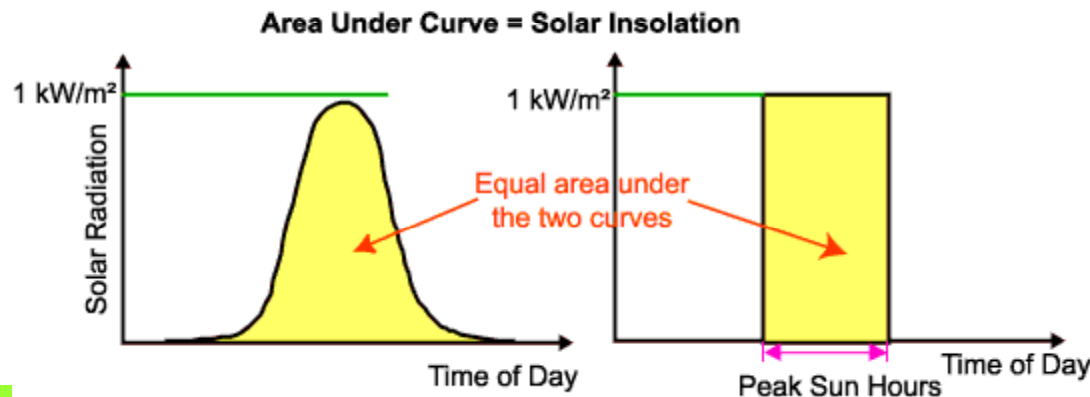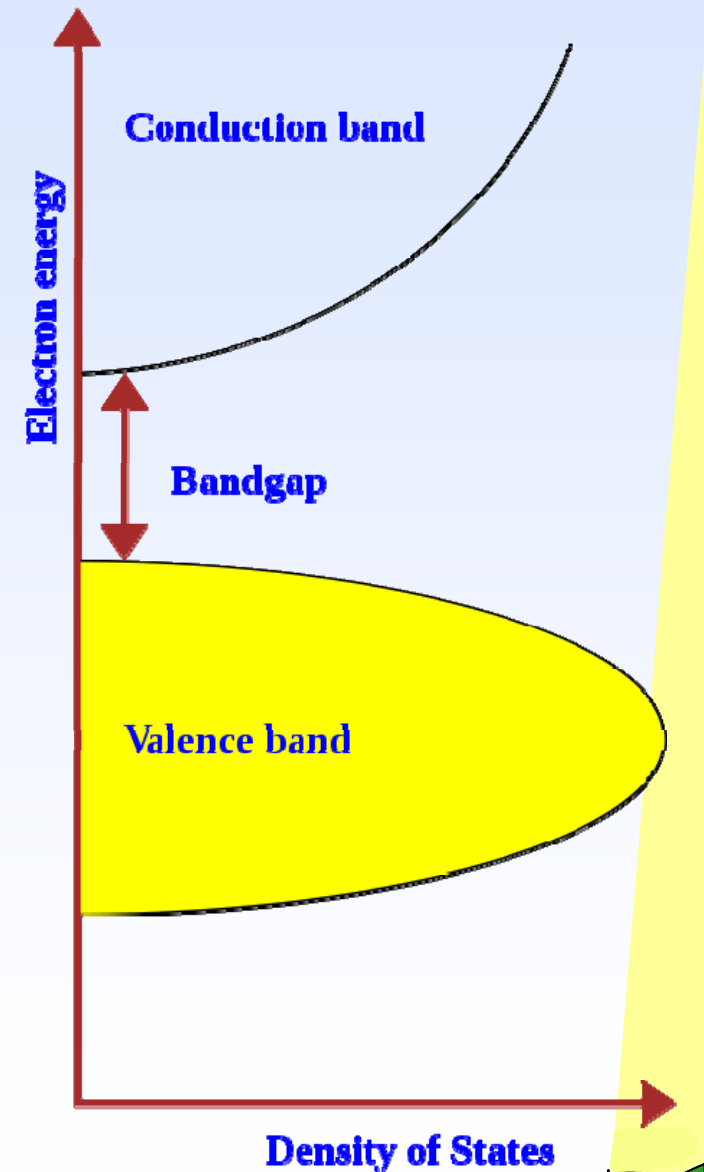
Integrating the Solar Spectrum
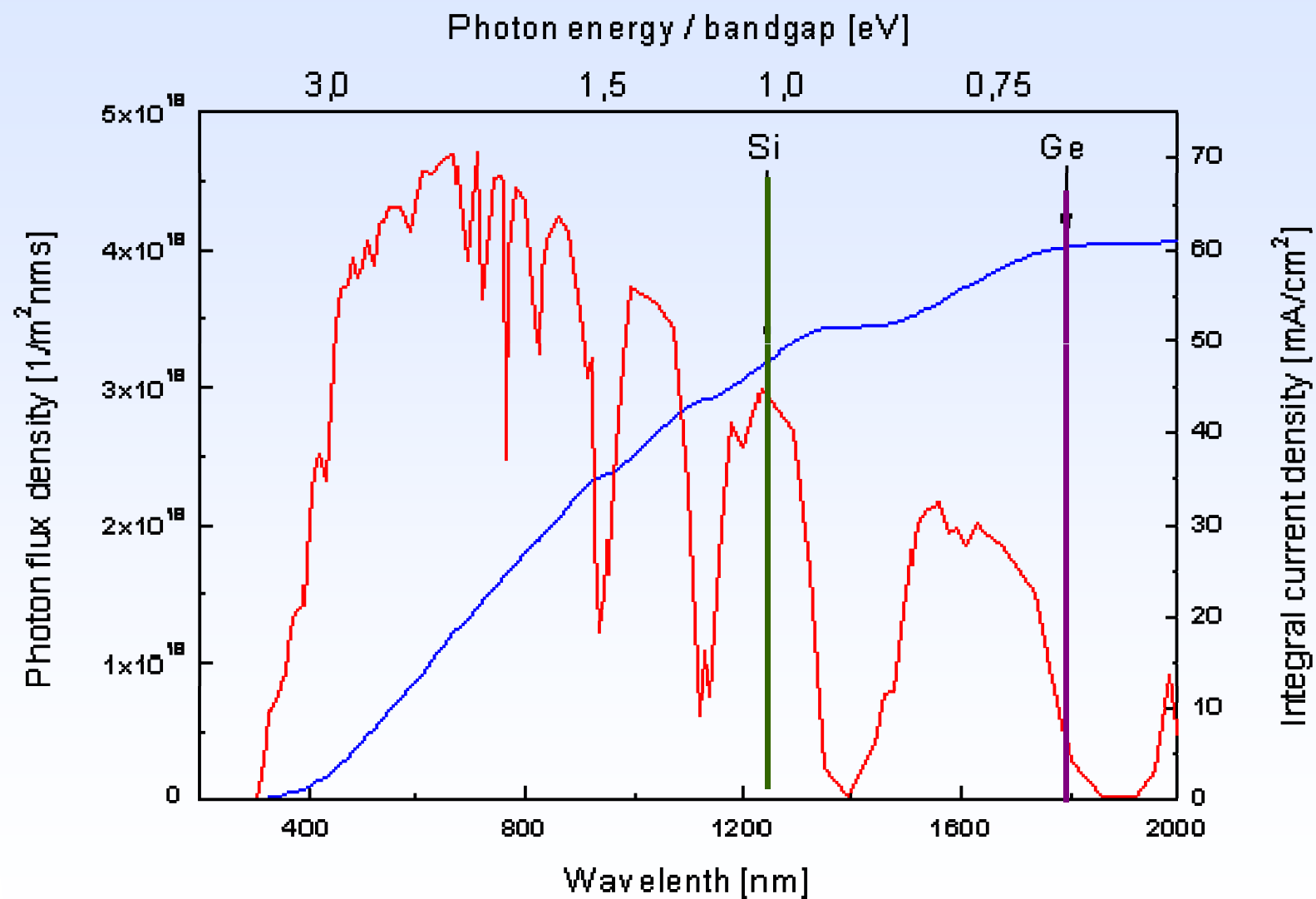
Semiconductors

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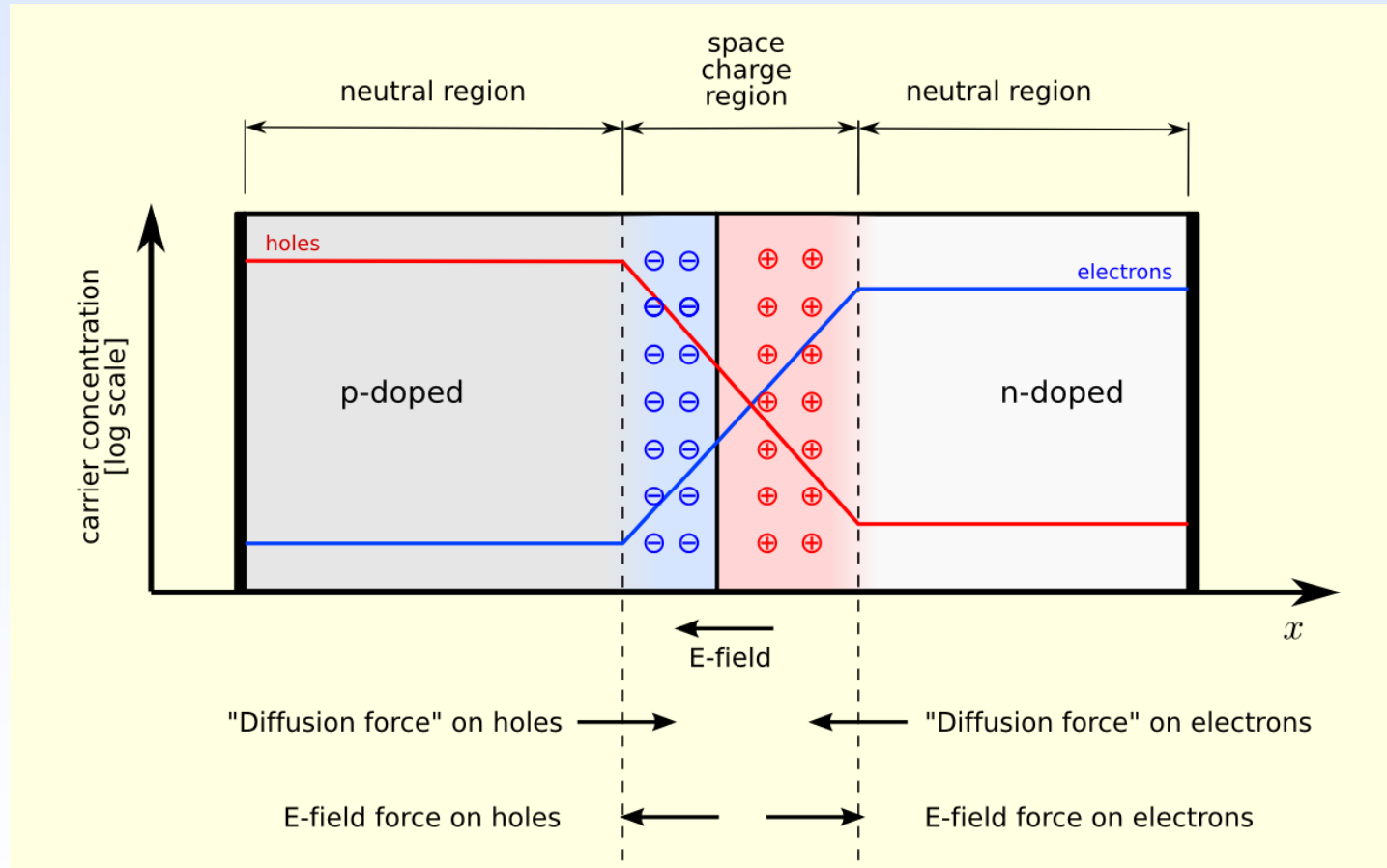
Semiconducting materials are the foundation of modern electronics, and are used in transistors, solar cells, many kinds of diodes including the light-emitting diode, and digital and analog integrated circuits.

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).

Electron energy

Conduction band

Bandgap

Valence band

Density of States

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

Photovoltaic effect

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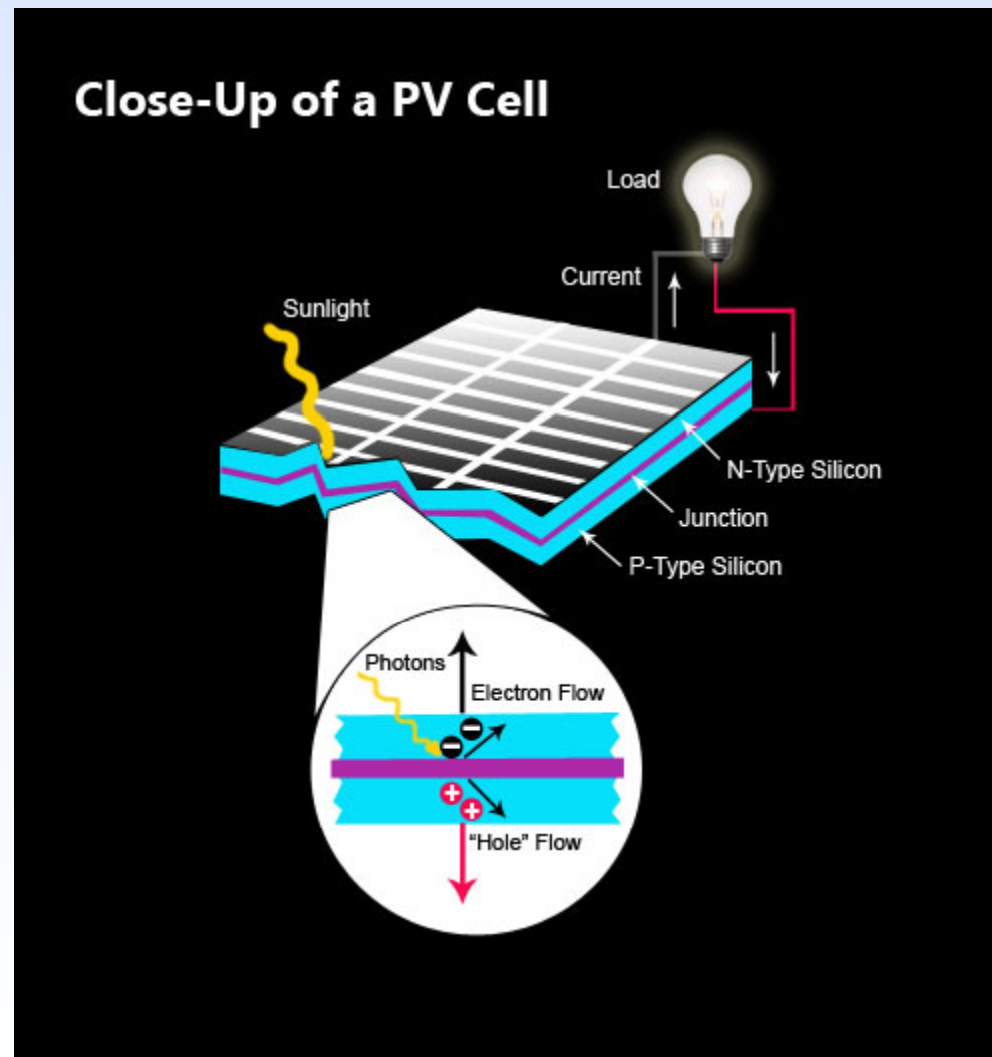
Electric current flow

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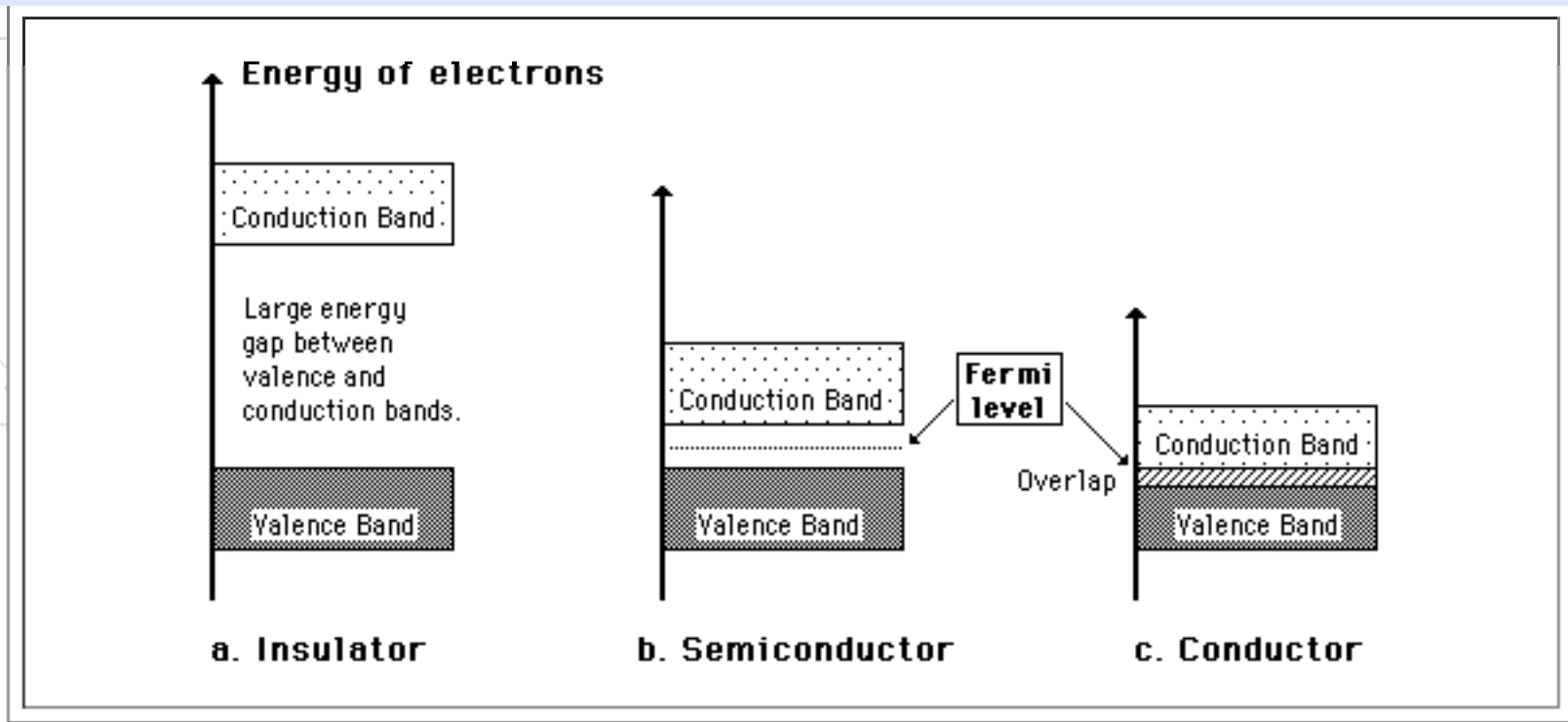
http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elecur.html#c3

I
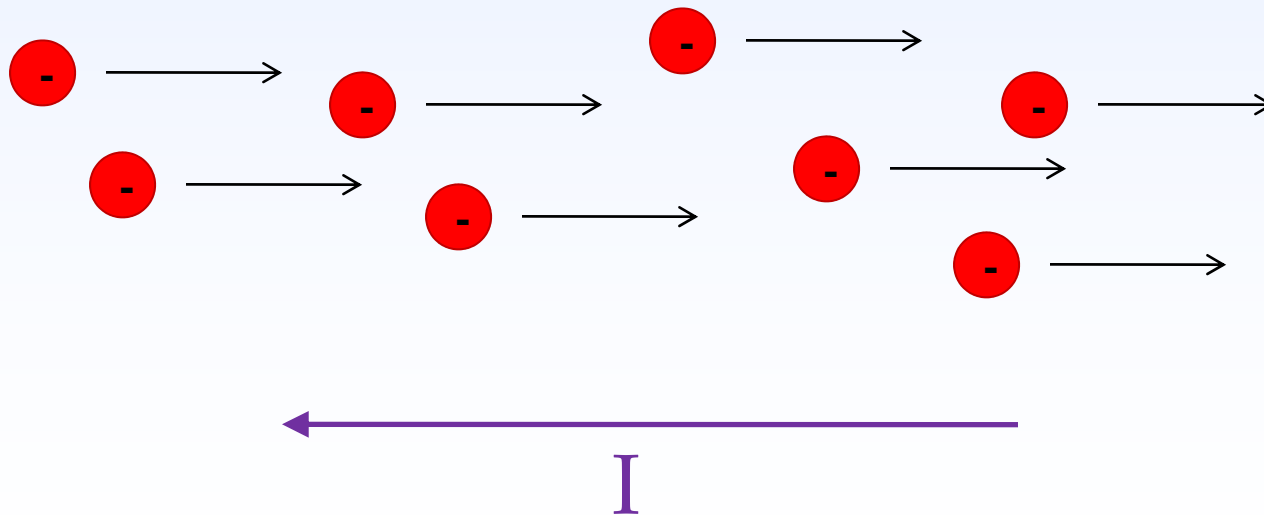
Simple solar cell structure

Close-Up of a PV Cell

Insulators, semiconductors, and conductors

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.

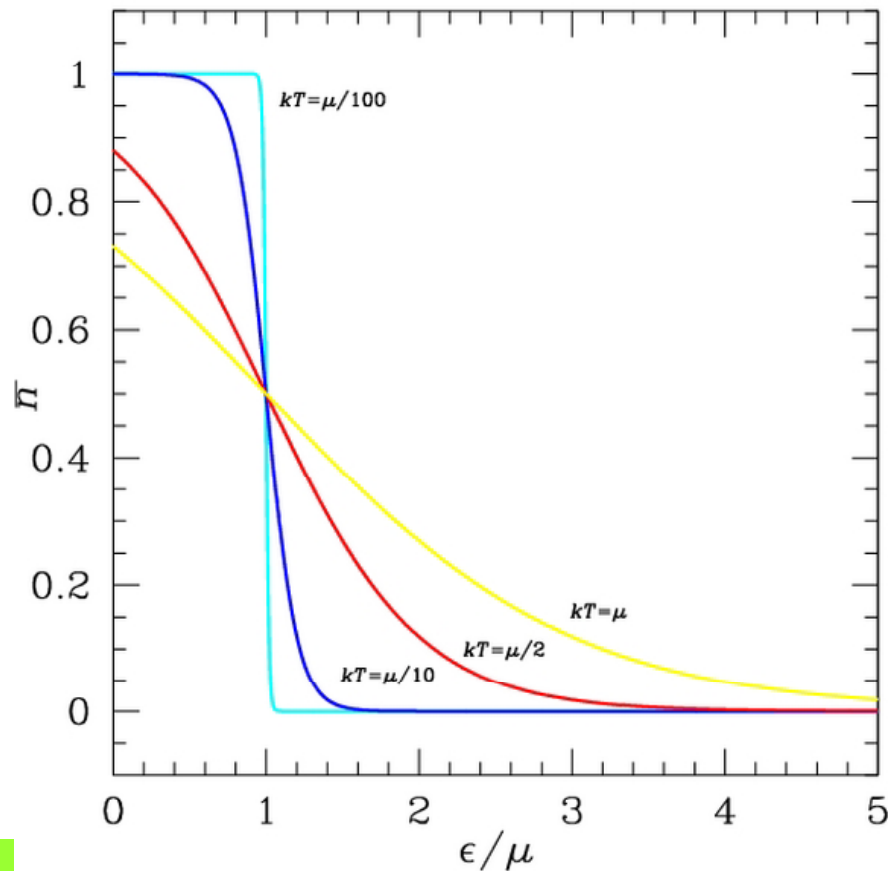$$\overline{n}_i = \frac{1}{e^{(\varepsilon_i - \mu)/kT} + 1}$$

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Fermi-Dirac statistics

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

where k is Boltzmann's constant, T is the absolute temperature, ε_i is the energy of the single-particle state i, and μ is the chemical potential. At $T = 0$, the chemical potential is equal to the Fermi energy. For the case of electrons in a semiconductor, is also called the 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".

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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:

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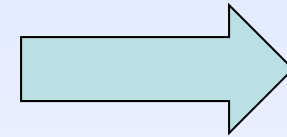
where I_L = light generated current.

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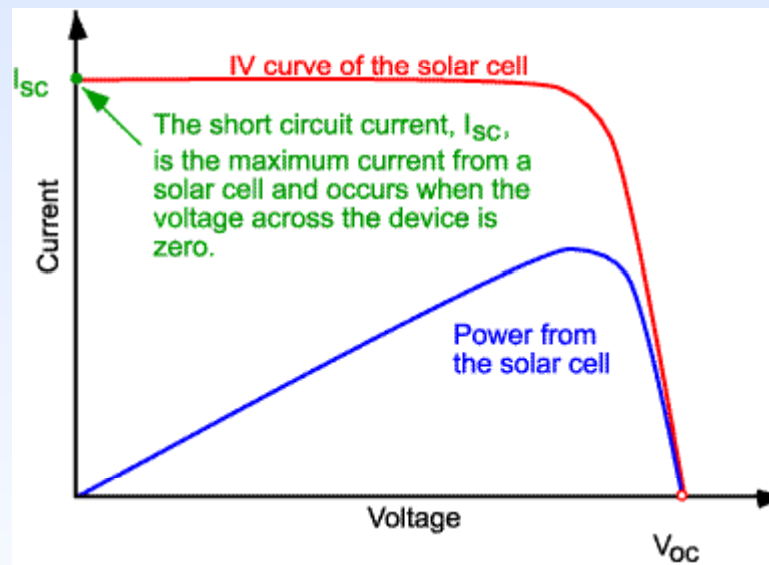
I_{SC} is due to the generation and collection of light-generated carriers. For an ideal PV cell with moderate resistive loss, I_{SC} and the light-generated current are identical (I_{SC} is the largest current which may be drawn from the solar cell).

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:

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

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.

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.
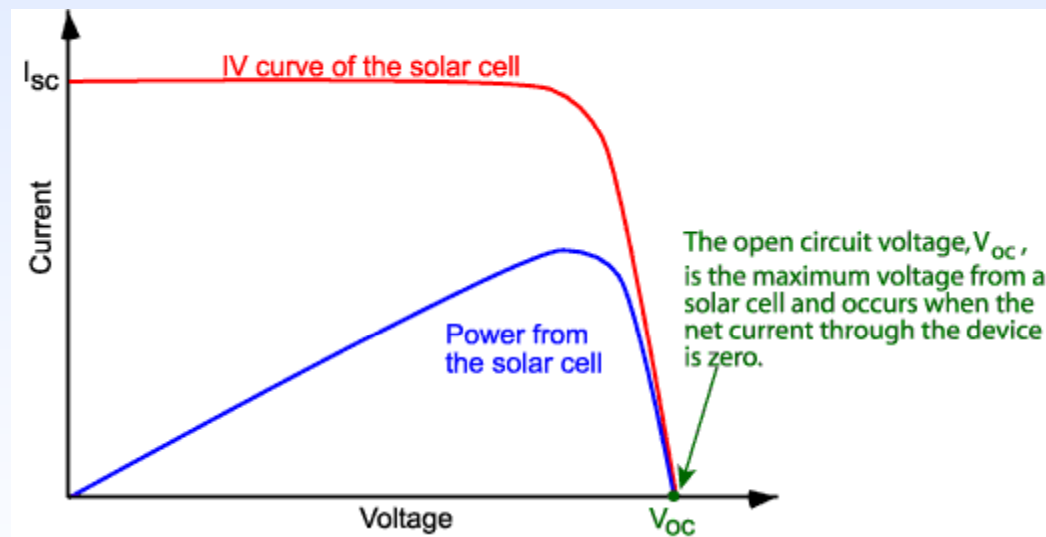

An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

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

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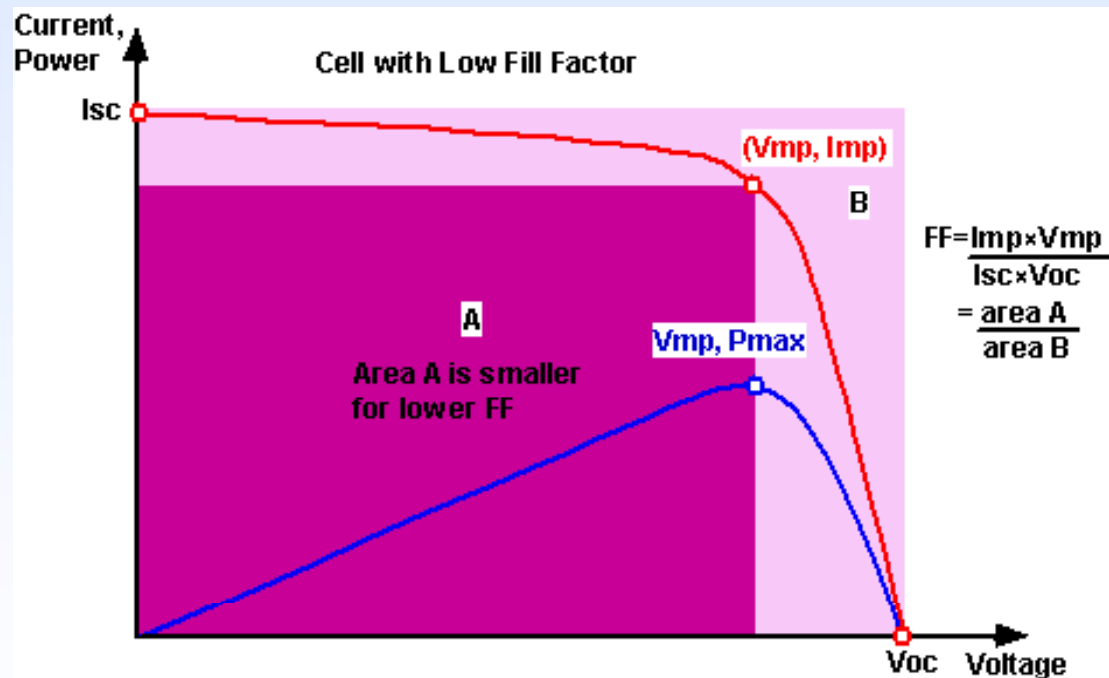
Graph of cell output current (red line) and power (blue line) as function of voltage. Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}). Click on the graph to see how the curve changes for a cell with low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

$$P_{max} = V_{OC} I_{SC} FF$$

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

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.
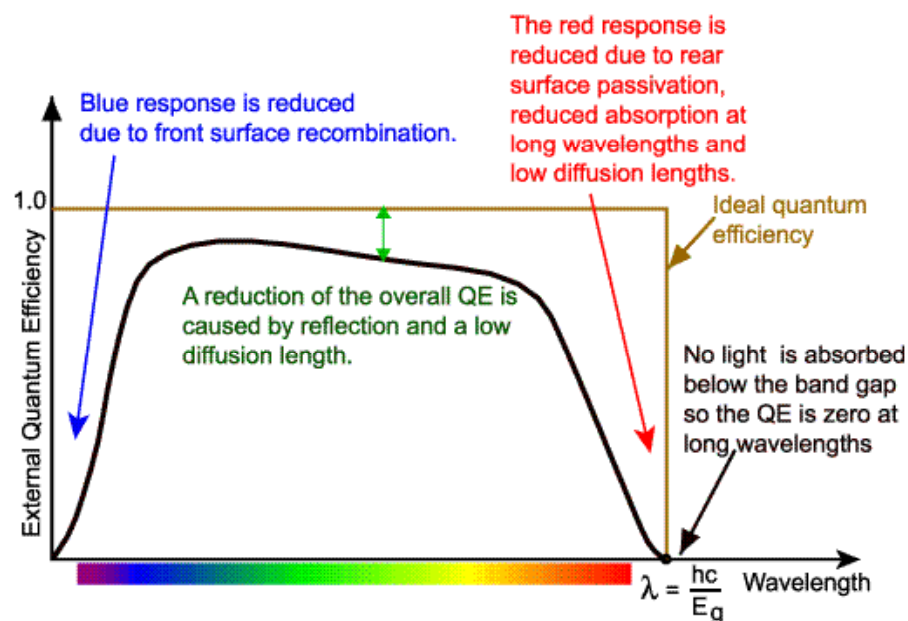
External and internal quantum efficiency

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

External quantum efficiency (EQE):

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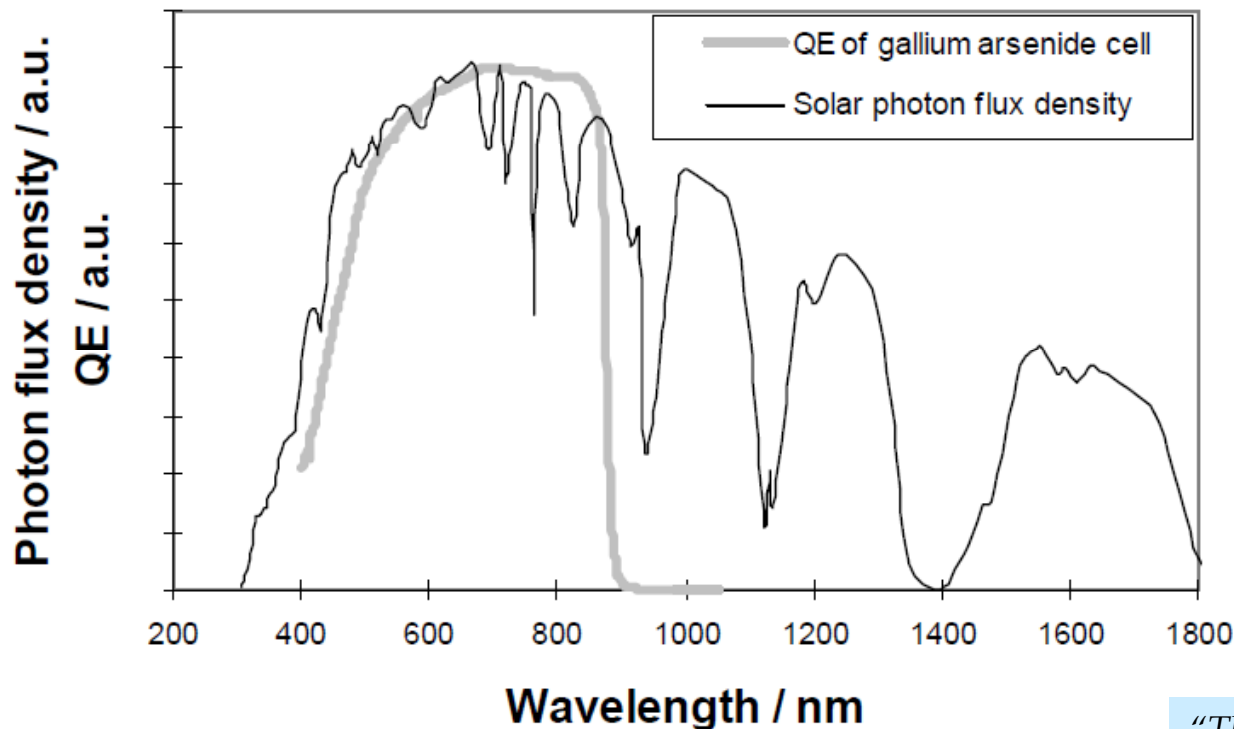
Internal quantum efficiency (QE):

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

Blue response is reduced due to front surface recombination.

The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.

A reduction of the overall QE is caused by reflection and a low diffusion length.

Ideal quantum efficiency

No light is absorbed below the band gap so the QE is zero at long wavelengths

$\lambda = \dfrac{hc}{E_g}$ Wavelength

External Quantum Efficiency

1.0

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

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

The periodic table

Common elemental components of semiconductors

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.
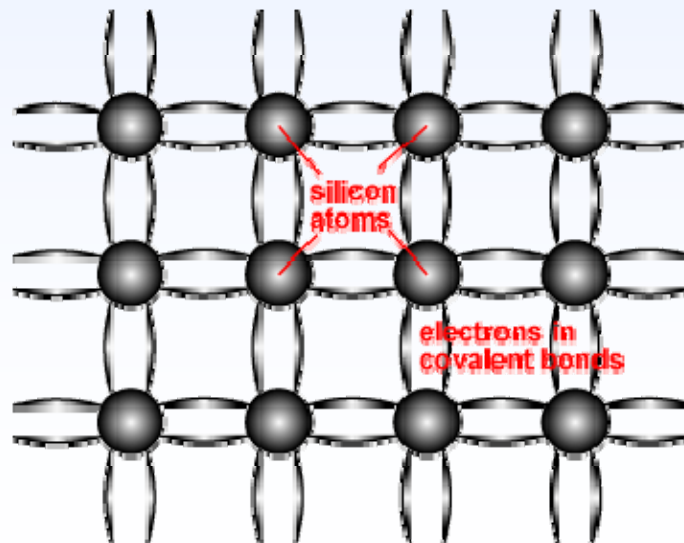
Electron configuration of the elements

Division

2 **He** $1s^2$ helium 4.003

3A	4A	5A	6A	7A	
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."
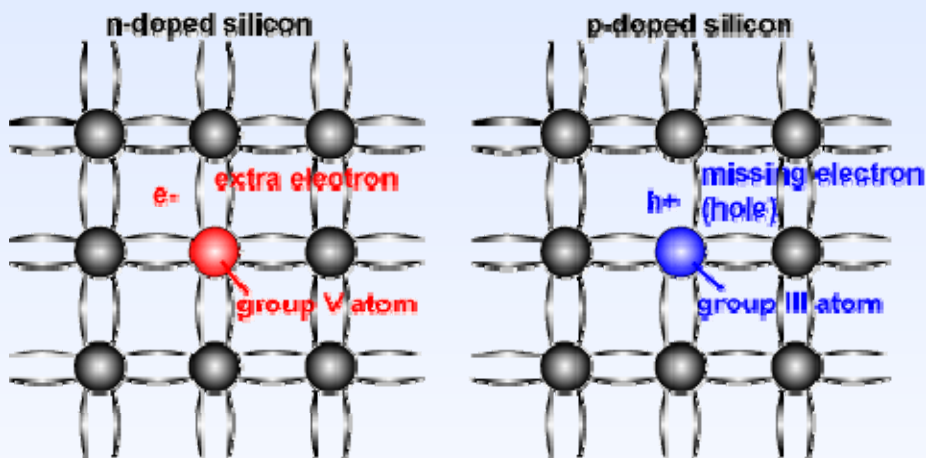
	P-type (positive)	N-type (negative)
Dopant	Group III (e.g. Boron)	Group V (e.g. Phosphorous)
Bonds	Missing Electrons (Holes)	Excess Electrons
Majority Carriers	Holes	Electrons
Minority Carriers	Electrons	Holes

Properties of light
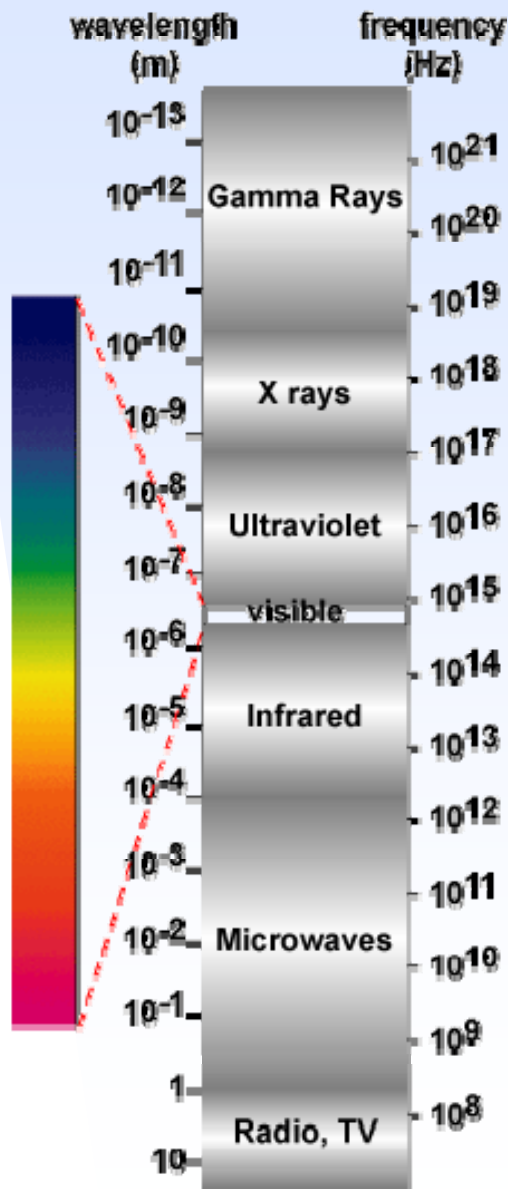
Energy of a photon: $\quad E = \dfrac{hc}{\lambda}$

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

$1\ eV = 1.602 \times 10^{-19}\ J$

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

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

Electromagnetic spectrum (left figure)

wavelength (m) / frequency (Hz)

wavelength (m)	band	frequency (Hz)
10^{-13}		
10^{-12}	Gamma Rays	10^{21}
10^{-11}		10^{20}
10^{-10}		10^{19}
10^{-9}	X rays	10^{18}
10^{-8}		10^{17}
10^{-7}	Ultraviolet	10^{16}
10^{-6}	visible	10^{15}
10^{-5}	Infrared	10^{14}
10^{-4}		10^{13}
10^{-3}		10^{12}
10^{-2}	Microwaves	10^{11}
10^{-1}		10^{10}
1	Radio, TV	10^{9}
10		10^{8}

Conventional p-n junction photovoltaic cell

Hot charge carriers

e⁻

electron loses
energy to
phonons

Energy

e⁻

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

η_{max} = 32.9%

Losses

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

hν

p-type

n-type

usable photo-
voltage (qV)

hole loses
h⁺ energy to
phonons

1 e⁻-h⁺ pair/photon
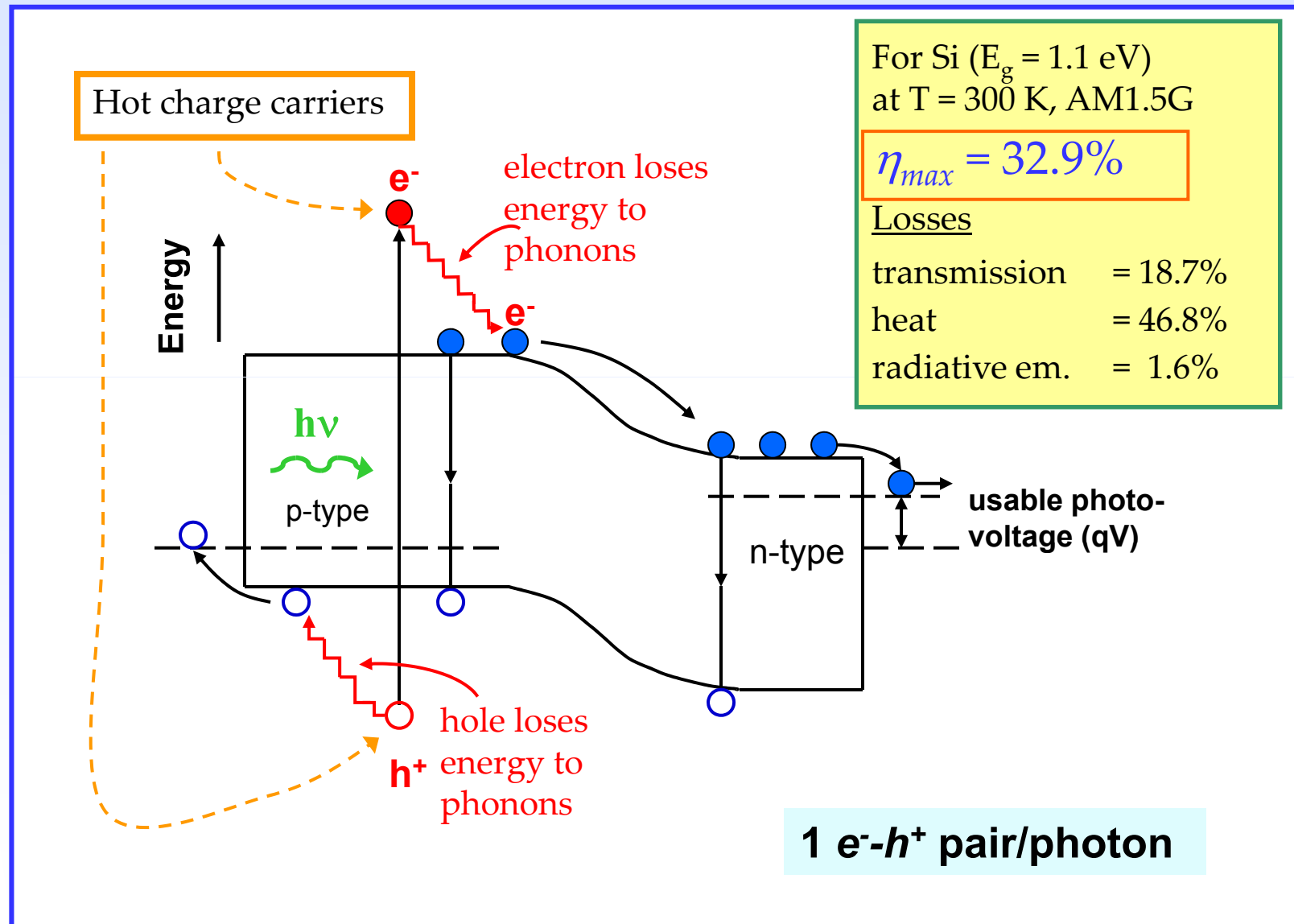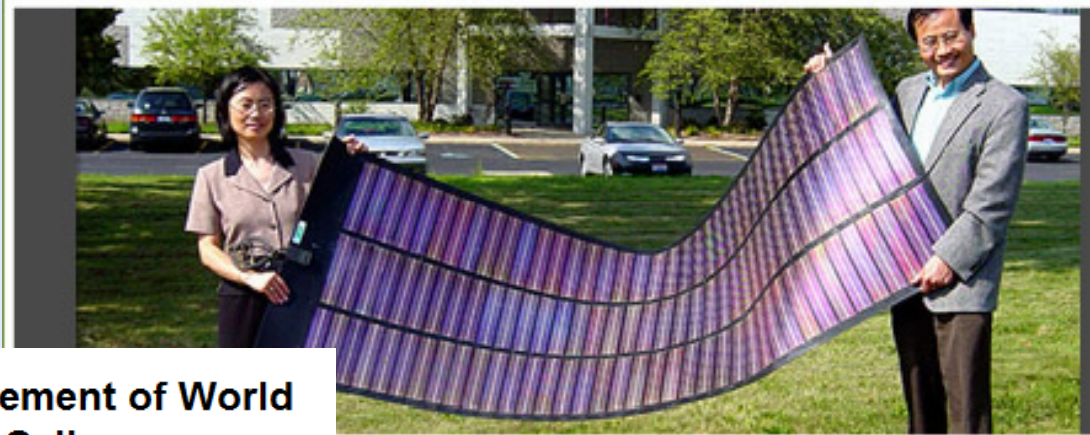
Trends in solar cell efficiencies
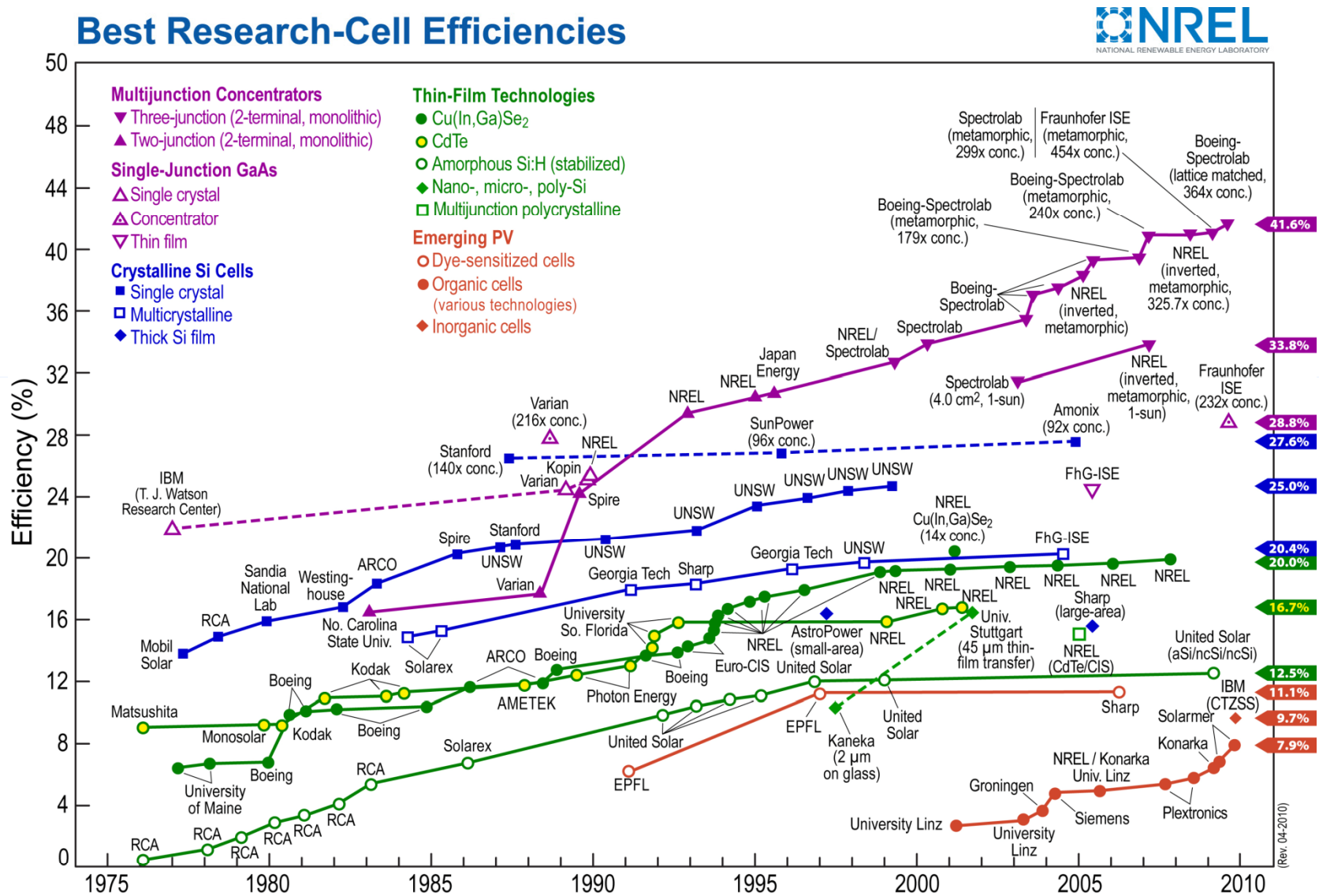
Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).

Xunlight

2nd gen.: thin film Si

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

GlobeNewswire
A NASDAQ OMX COMPANY

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Companies: Energy Conversion Devices, Inc.

Related Quotes

Symbol	Price	Change
ENER	4.08	+0.01

ENER   Jan 31, 4:00pm EST

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.

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