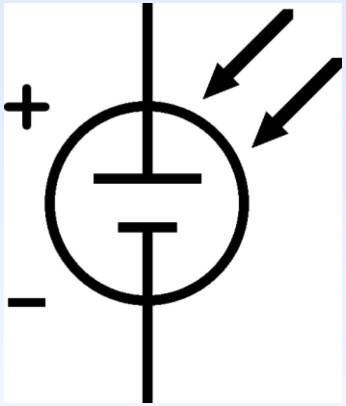
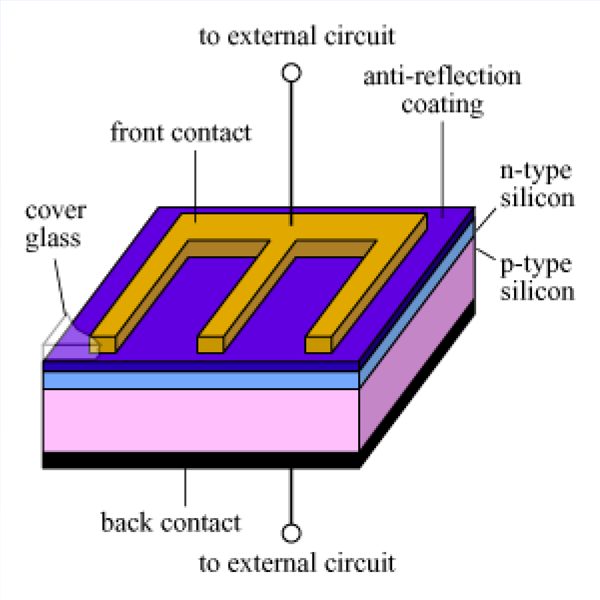
Introduction to Photovoltaics





PHYS 4400, Principles and Varieties of Solar Energy

Instructor: Randy J. Ellingson
The University of Toledo

February 24, 2015

Only solar energy…

"Of all the possible sources of energy we understand today, only solar energy has the potential to supply <u>all</u> of Earth's energy needs."

-- Steve Martin, 3M, Saint Paul, MN

But first, we need to make PV energy cheaper, more efficient, easier to produce and install, etc.

Photovoltaic effect

The *photovoltaic effect* refers to the generation of an electromotive potential by a condensed matter "device" under illumination.

When illuminated, the device is able to do electrical work; i.e., it can drive a current at a voltage such that power is delivered to an external "load" such as a light bulb or motor.

$P = IV = I^2R$ (remember that $V = IR$, which is Ohm's Law).

"Condensed matter" indicates liquid or solid; typical photovoltaic solar cells are all-solid-state, based on layers of semiconductors and metals.

Solar Radiation Spectrum

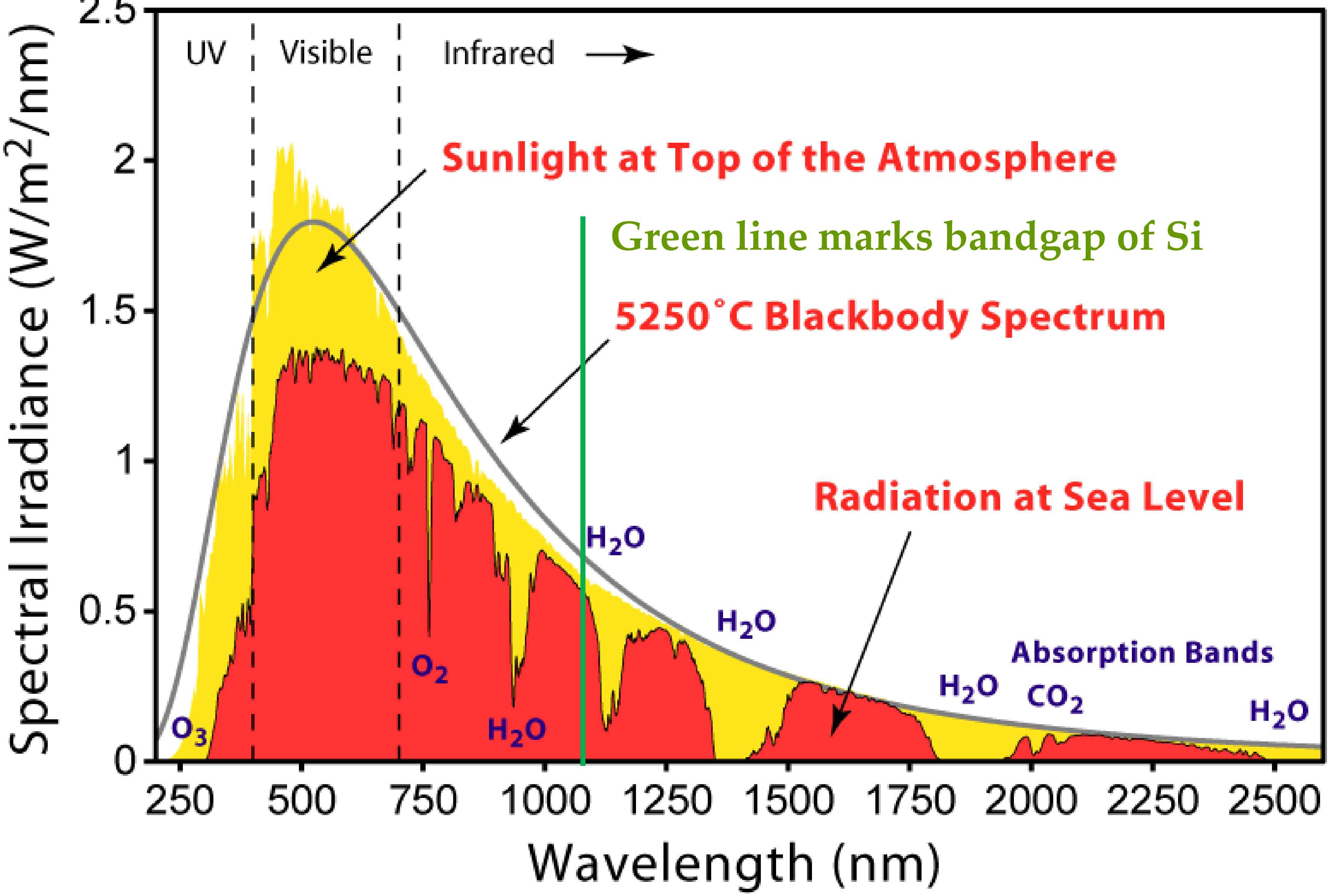
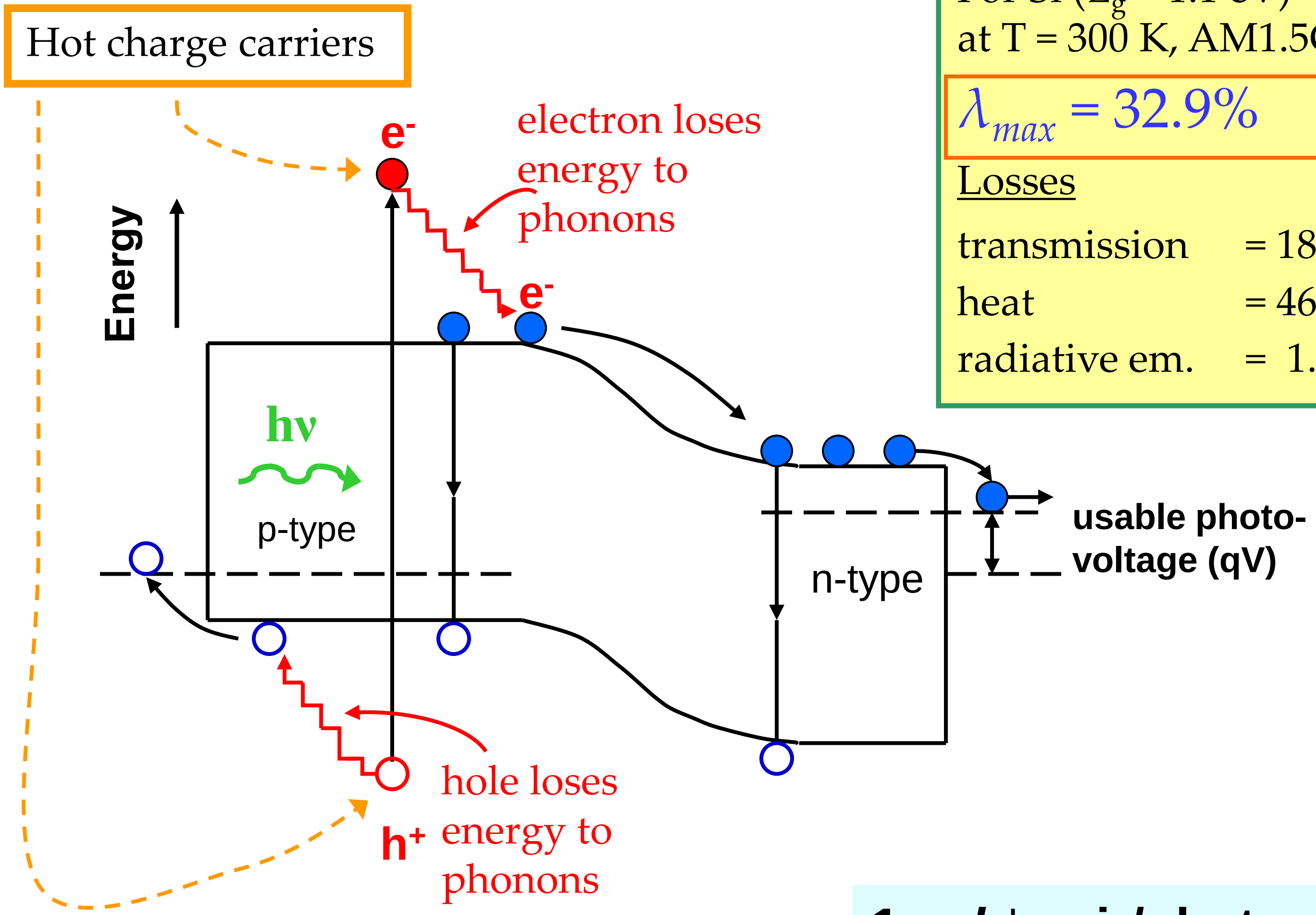


Image created by Robert A. Rohde / Global Warming Art

Conventional p-n junction photovoltaic cell



Hot charge carriers

electron loses energy to phonons

hole loses energy to phonons

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

$\lambda_{max} = 32.9\%$

<u>Losses</u>

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

1 e^{-}-h^{+} pair/photon

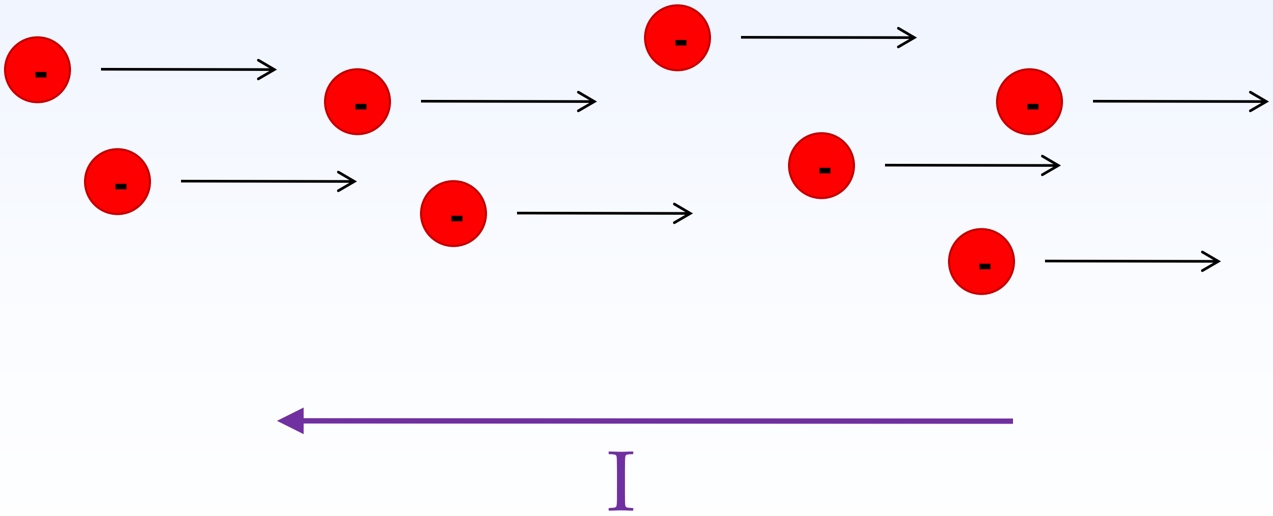
PV concepts (partial list)

- photovoltaic effect
- p-n junction
- light absorption
- diode equation
- dark current
- light current
- short circuit current density (J_{SC})
- open circuit voltage (V_{OC})
- efficiency
- quantum efficiency (internal and external)
- maximum power point
- calculation of photocurrent density from quantum efficiency (QE)

Electric current flow

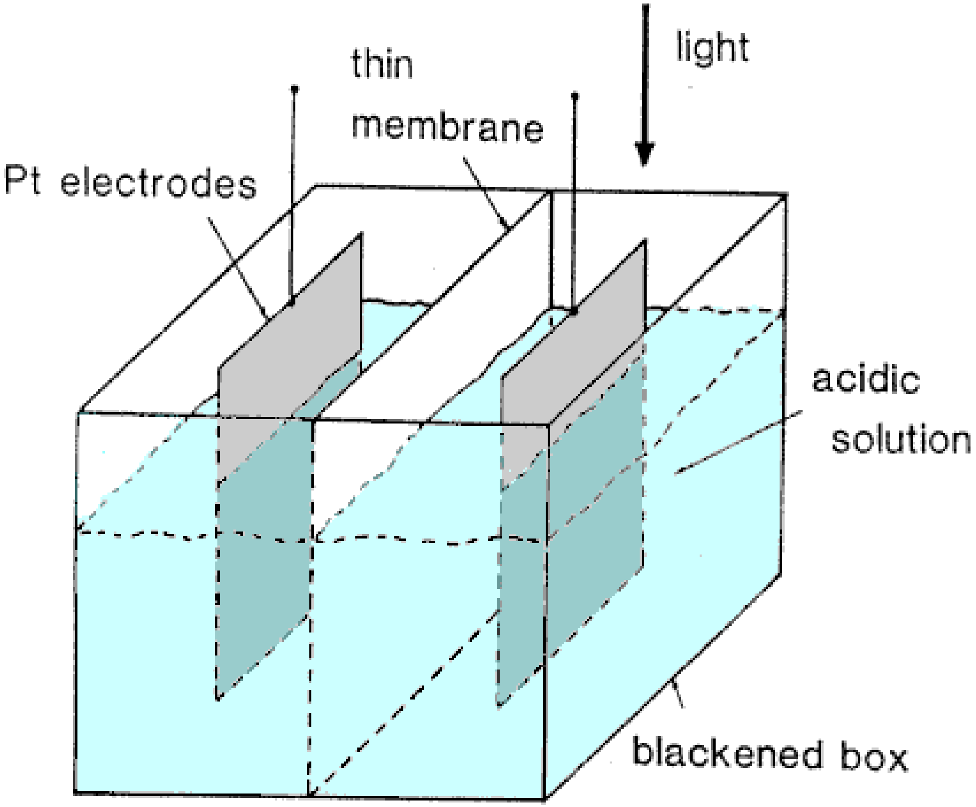
Conventional Electric Current

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.



Early "Photovoltaics"

Edmond Becquerel appears to have been the first to demonstrate the photovoltaic effect [5], [6]. Working in his father's laboratory as a nineteen year old, he generated electricity by illuminating an electrode with different types of light, including sunlight (see the figure below). Best results were obtained with blue or ultraviolet light and when electrodes were coated with light sensitive material such as AgCl or AgBr. Although he usually used platinum electrodes, he also observed some response with silver electrodes. He subsequently found a use for the photovoltaic effect by developing an "actinograph" which was used to record the temperature of heated bodies by measuring the emitted light intensity.

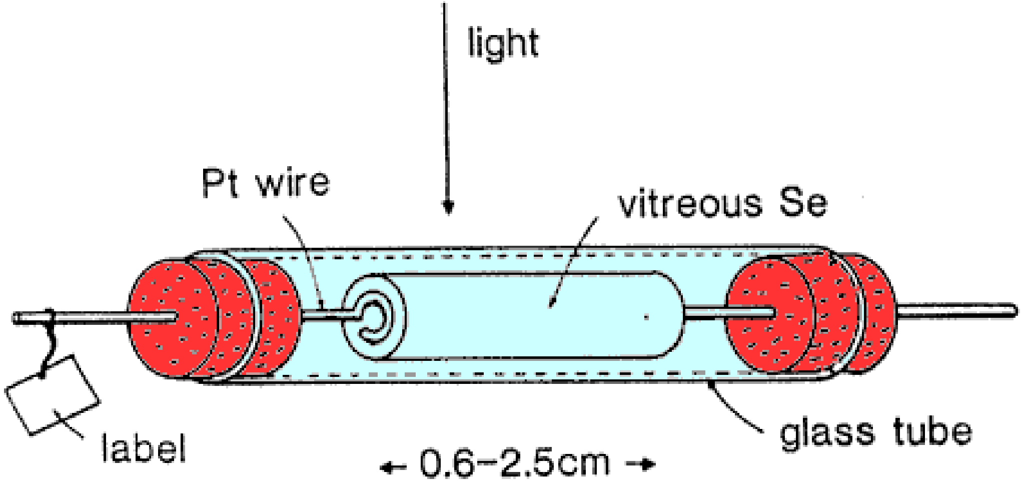


1839

Diagram of apparatus described by Becquerel (1839)

Early "Photovoltaics", cont.

The next significant photovoltaic development arose from the interest in the photoconductive effect in selenium. While investigating this effect, Adams and Day (1877) [7] noted an anomaly they thought could be explained by the generation of internal voltages. They investigated this anomaly more carefully using samples as shown below. Heated platinum contacts were pushed into opposite ends of small cylinders of vitreous selenium. The objective of one experiment conducted by Adams and Day upon such specimens was to see 'whether it would be possible to start a current in the selenium merely by the action of light'.

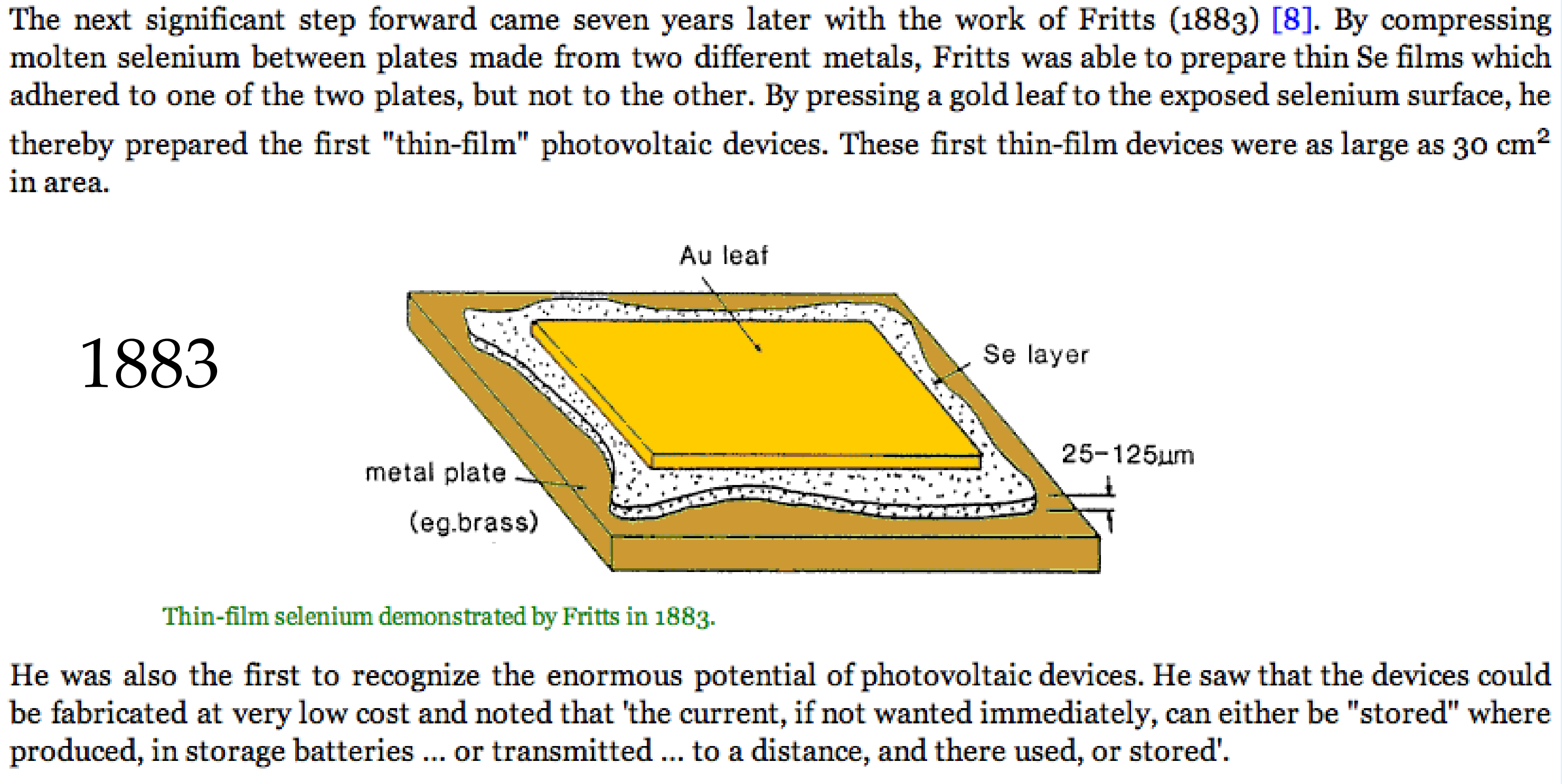


1876

Sample geometry used by Adams and Day (1876) for the investigation of the photoelectric effects in selenium.

The result was positive! This was the first demonstration of the photovoltaic effect in an all solid-state system. Adams and Day attributed the photogenerated currents to light induced crystallization of the outer layers of the selenium bar. Several decades were to pass before the development of physics allowed more insight into this process.

Early “Photovoltaics”, cont.



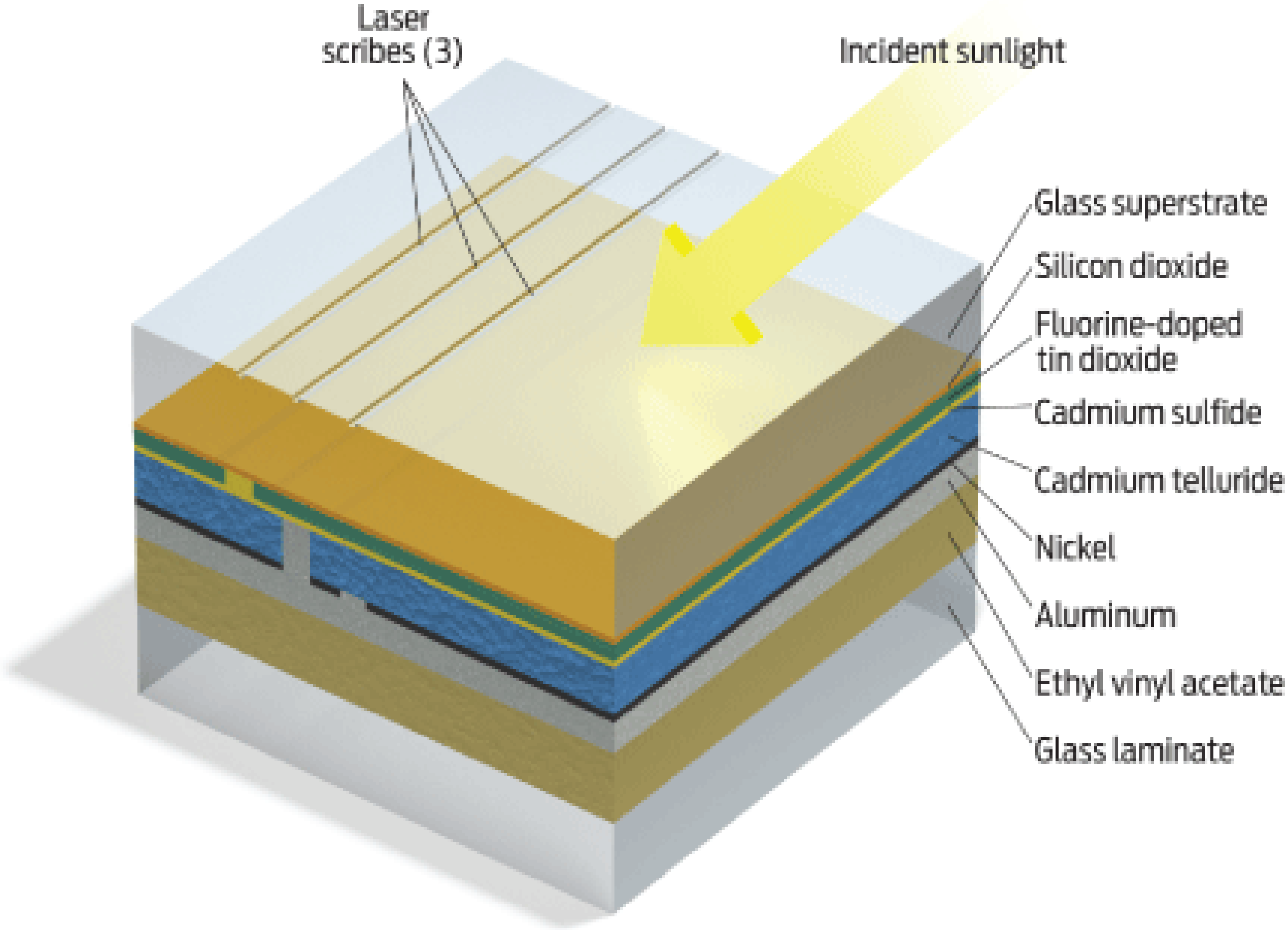
The next significant step forward came seven years later with the work of Fritts (1883) [8]. By compressing molten selenium between plates made from two different metals, Fritts was able to prepare thin Se films which adhered to one of the two plates, but not to the other. By pressing a gold leaf to the exposed selenium surface, he thereby prepared the first "thin-film" photovoltaic devices. These first thin-film devices were as large as 30 cm^2 in area.

1883

Thin-film selenium demonstrated by Fritts in 1883.

He was also the first to recognize the enormous potential of photovoltaic devices. He saw that the devices could be fabricated at very low cost and noted that 'the current, if not wanted immediately, can either be "stored" where produced, in storage batteries ... or transmitted ... to a distance, and there used, or stored'.

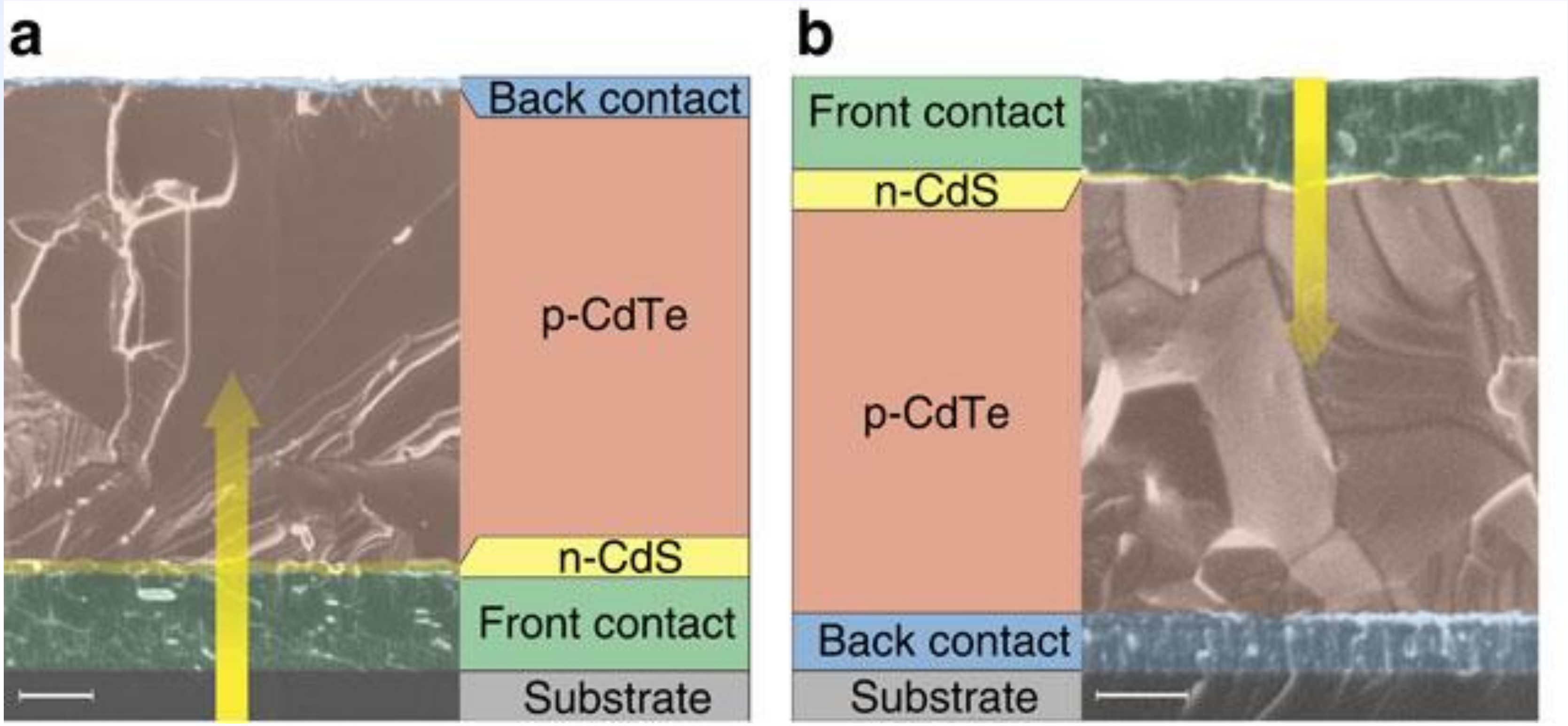
A simple solar cell design



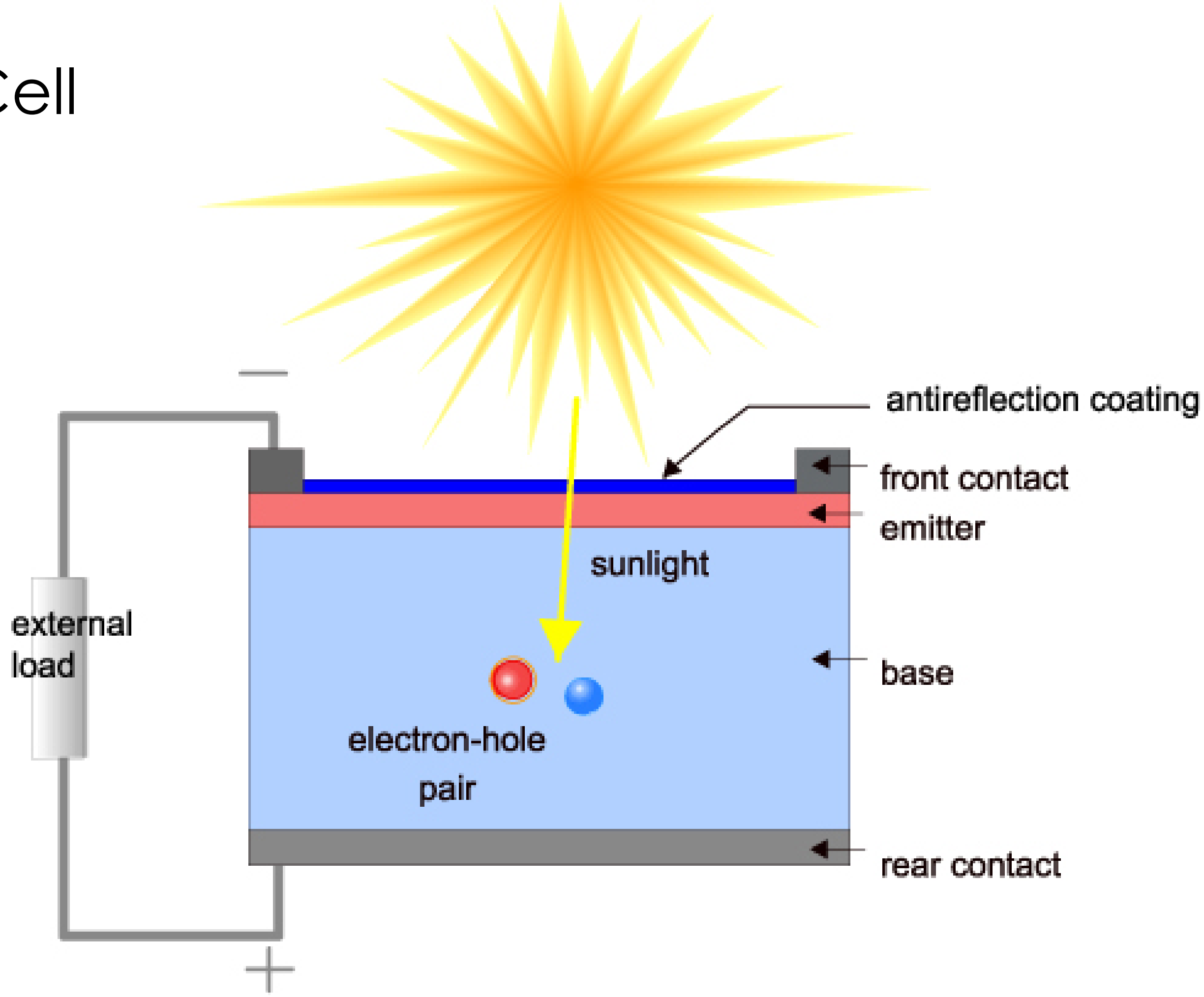
CdTe on flexible substrates

Doping of polycrystalline CdTe for high-efficiency solar cells on flexible metal foil

doi:10.1038/ncomms3306



Basic Solar Cell



Cross section of a solar cell.

The basic steps in the operation of a solar cell are:

- the generation of light-generated carriers;
- the collection of the light-generated carries to generate a current;
- the generation of a large voltage across the solar cell; and
- the dissipation of power in the load and in parasitic resistances.

PVEDUCATION.ORG

The ideal 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 = 25.8 mV, the "thermal voltage".

pveducation.org

I-V Curve

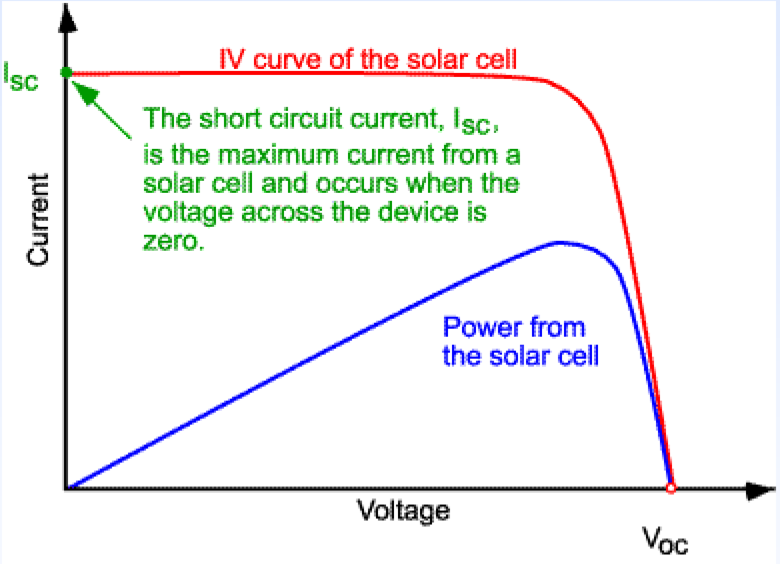
The IV curve of a solar cell is the superposition of the IV curve in the dark with the light-generated current. Illumination shifts the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode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

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

where I_L = light generated current.

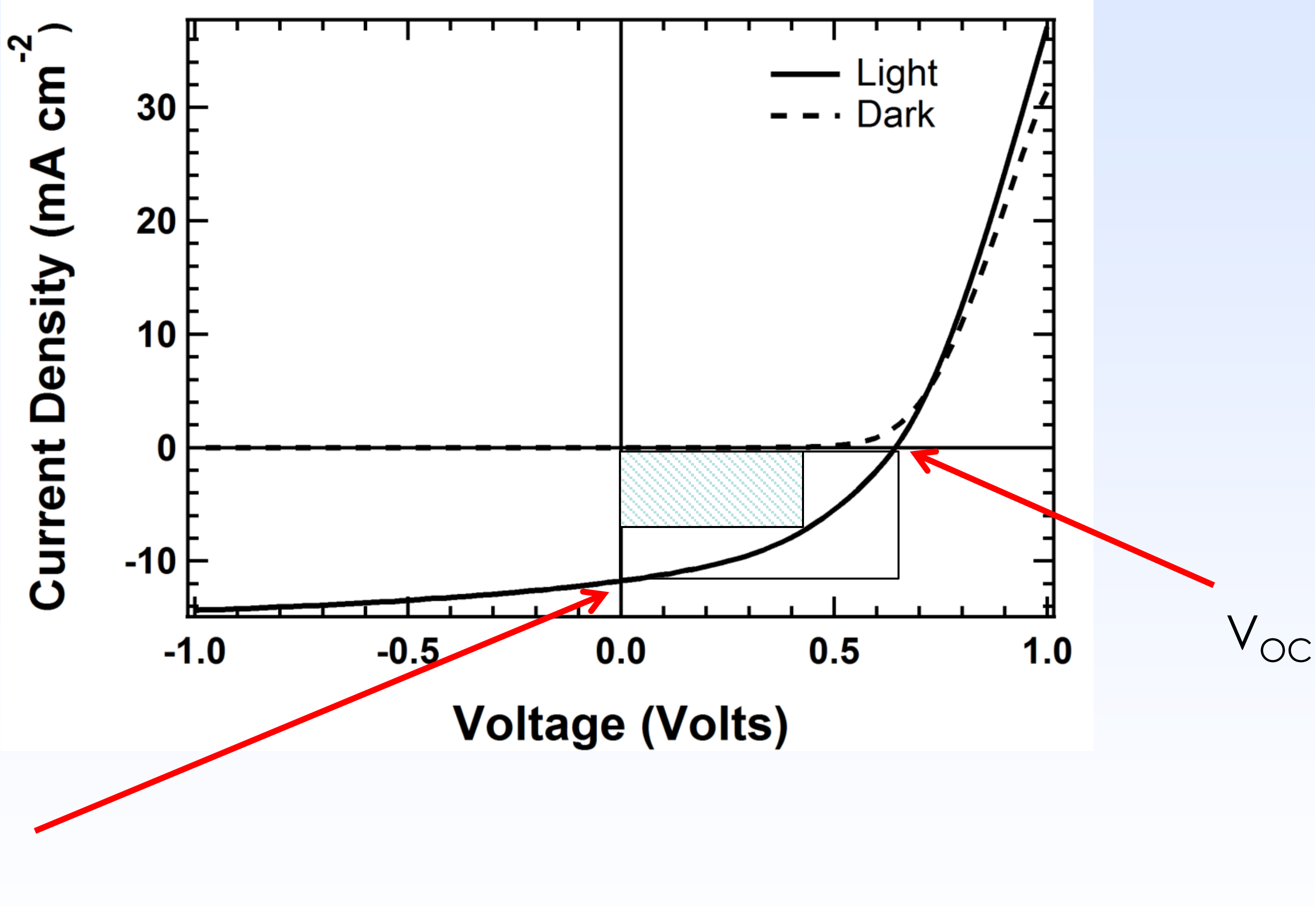
Short circuit photocurrent

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.



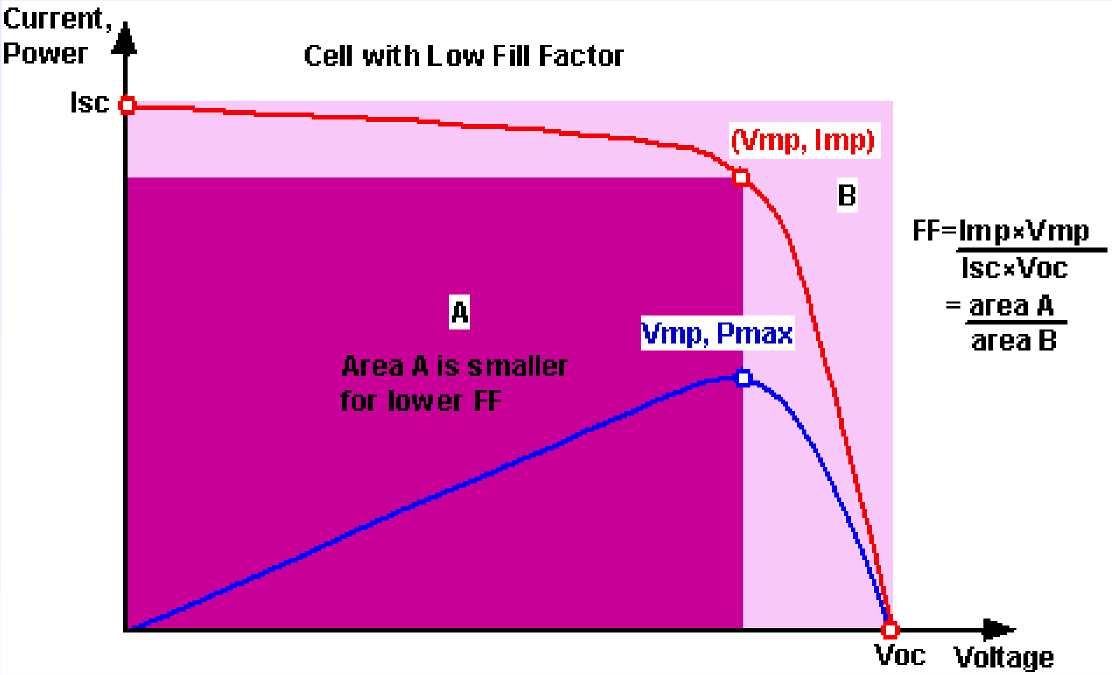
I_{SC} is due to the generation and collection of light-generated carriers. For an ideal PV cell with moderate resistive loss, I_{SC} and the light-generated current are identical (I_{SC} is the largest current which may be drawn from the solar cell).

The current-voltage curve



K. Bhandari et al, UT

Fill factor


Current,
Power
Cell with Low Fill Factor
Isc
(Vmp, Imp)
B
FF=Imp×Vmp
Isc×Voc
= area A
area B
A
Area A is smaller
for lower FF
Vmp, Pmax
Voc
Voltage

Current vs. current density

- Under AM1.5G standard illumination, the intensity of the light is 1,000 W m^{-2}.

- Therefore, a solar cell with dimensions 1 cm x 1 cm = (0.01 m)^{2} = 1 x 10^{-4} m^{2} receives less total light than a cell with dimensions 10 cm x 10 cm = 1 x 10^{2} m^{2}.

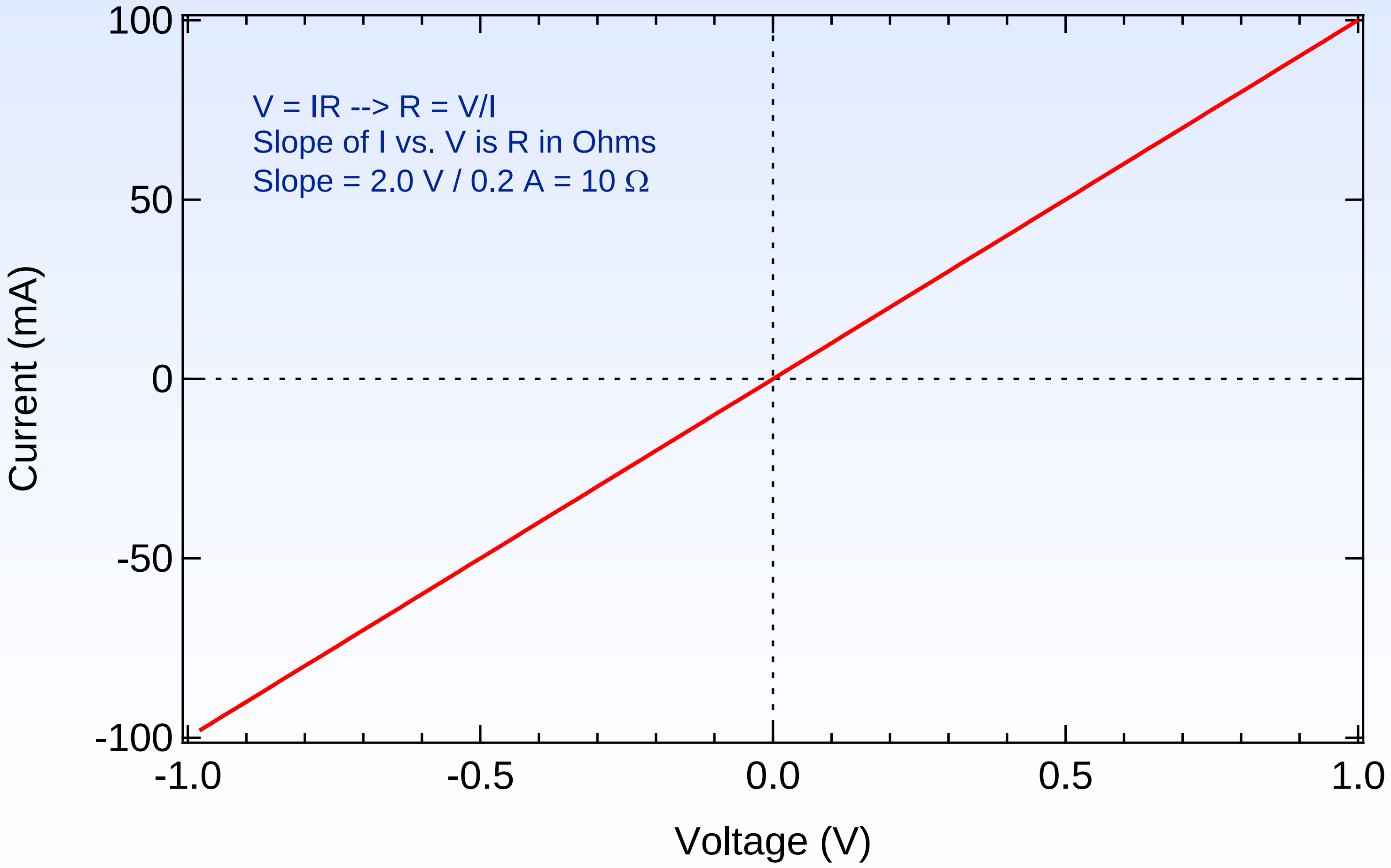
- Therefore, when measuring the current produced by a solar cell, if other parameters are held constant then the current depends linearly on the area.

- When comparing the performance of two solar cells, it is common to normalize the current by dividing by the illuminated cell area. In this way, the current density values are compared.

- Current is expressed as Amps (or milliAmps, mA); current density is expressed as mA cm^{-2}.

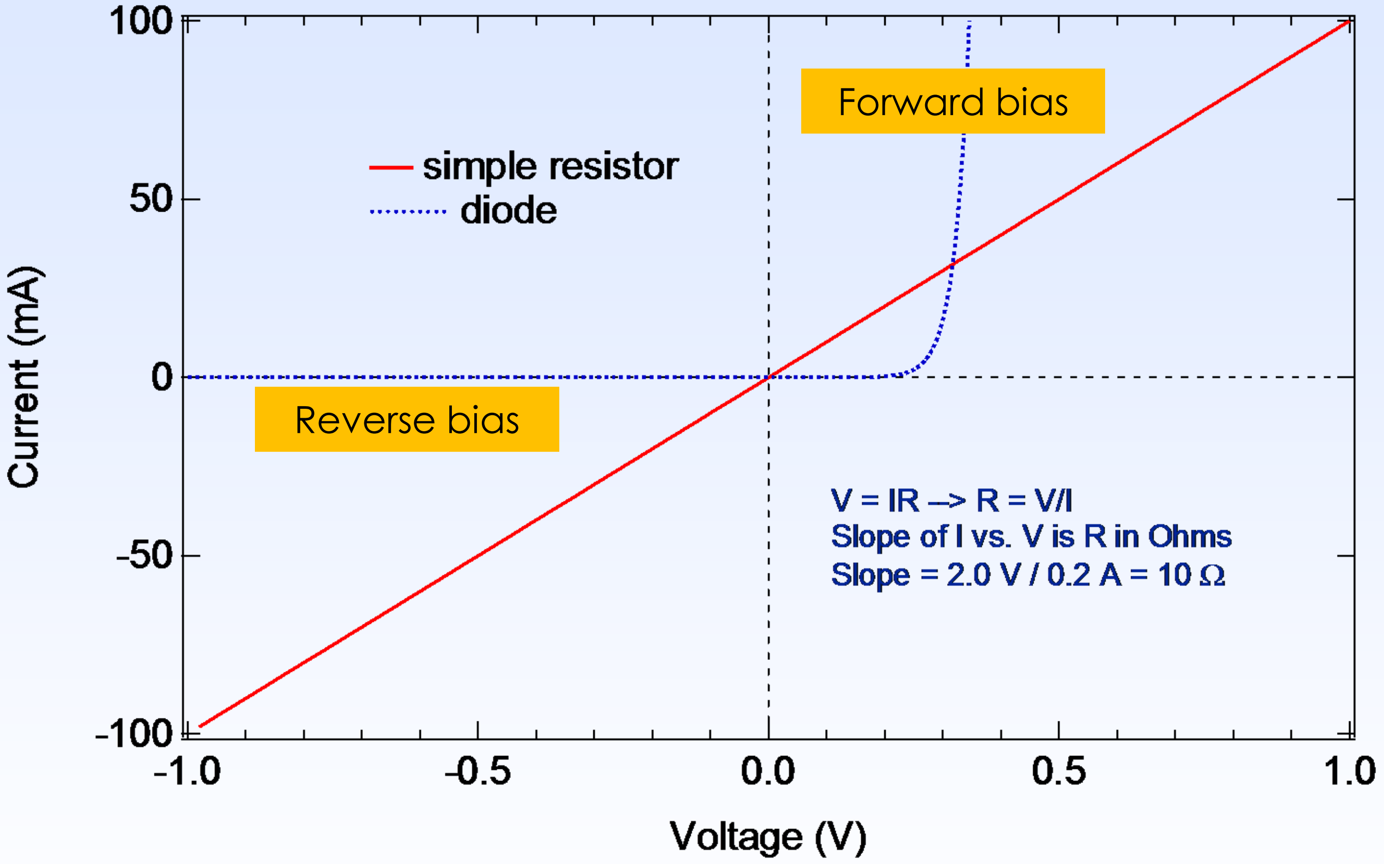
Current in a diode (PV "device", or PV "cell")

A typical solar cell behaves as a diode and consists of a p-n junction fabricated out of crystalline semiconductor materials. Diodes enable electrical current to flow easily in one direction, but not in the other. Consider a simple resistor:



Current in a diode (PV "device", or PV "cell")

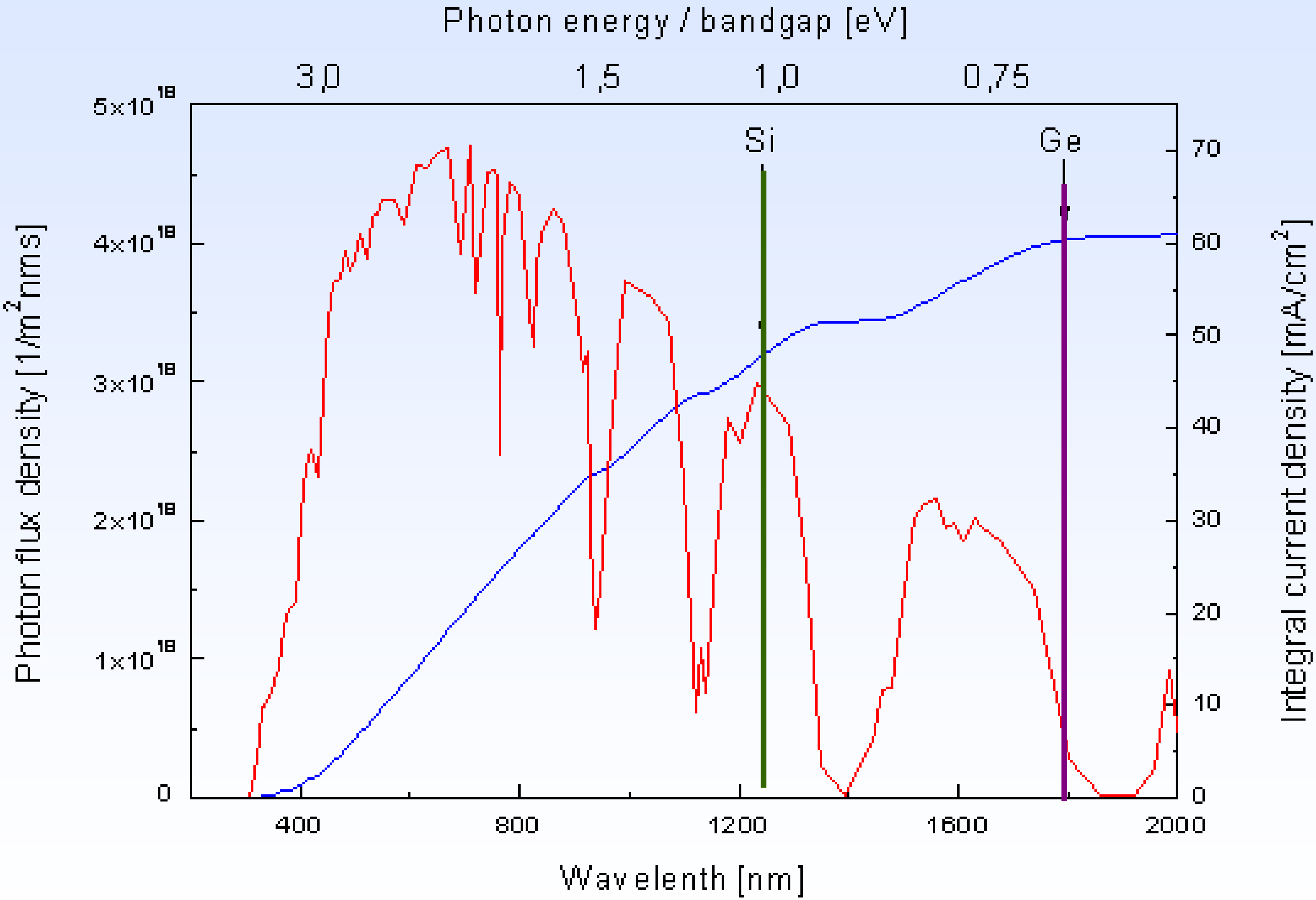
Now compare the I vs. V behavior of a simple resistor with a diode:



Note that the diode "rectifies" the current, so that in forward bias the diode can pass current, but in reverse bias it does not (to a point, known as the breakdown voltage). One key to forming a p-n junction that works as a diode is to control the doping of the semiconductor materials on either side of the junction.

See also: http://en.wikipedia.org/wiki/Diode

Integrating the Solar Spectrum



External and internal quantum efficiency

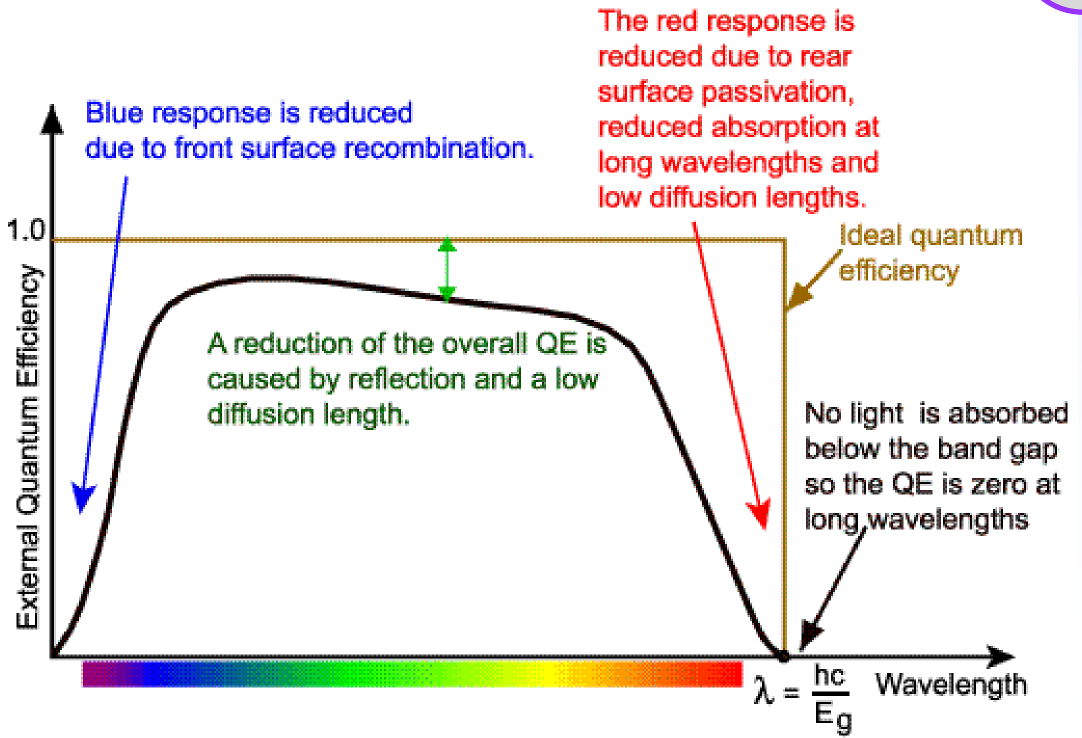
Internal and external quantum efficiency are functions of wavelength, i.e., EQE(λ) and IQE(λ):

External quantum efficiency (EQE):

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

Internal quantum efficiency (IQE):

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



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

Blue response is reduced due to front surface recombination.

Ideal quantum efficiency

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

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

“Integrating” the Solar Spectrum – photocurrent density

Consider light absorption in a solar cell, and determine the maximum possible photocurrent it can generate, per unit area, for given incident spectrum (power per unit area, vs. wavelength) of light.

Convert **photons s^{-1} cm^{-2}** to **electrons s^{-1} cm^{-2}:**

Rule: 1 electron is generated for each photon absorbed by the solar cell’s “active” layer(s)

Convert **electrons s^{-1} cm^{-2}** to current density **(mA cm^{-2}):**

What is an electrical current? What is the definition of 1 Amp?

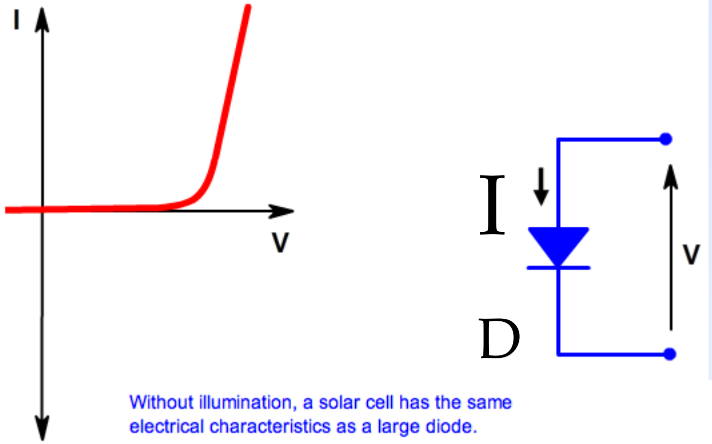
How can we calculate a current density from the absorbed photon flux per unit area?

1 A = 1 C s^{-1}

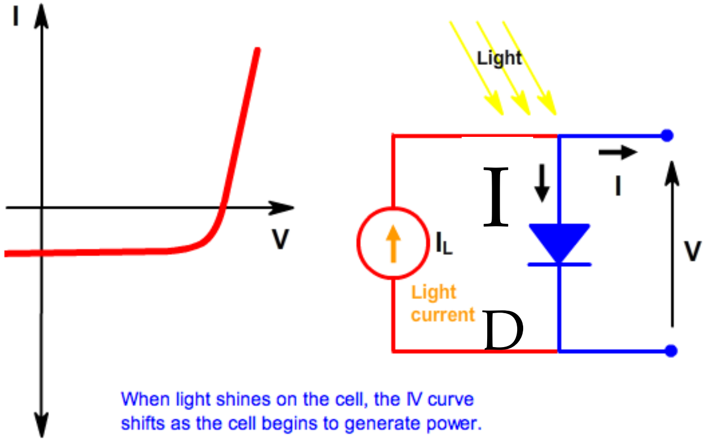
Charge on 1 electron is -1.602×10^{-19} C/electron.

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

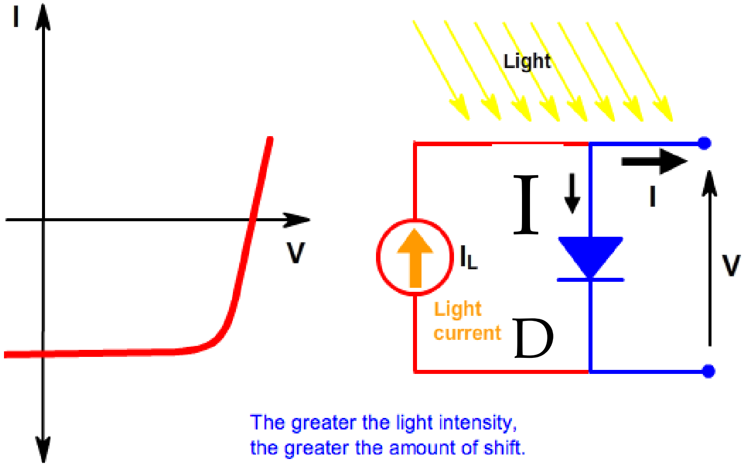
PVEDUCATION.ORG



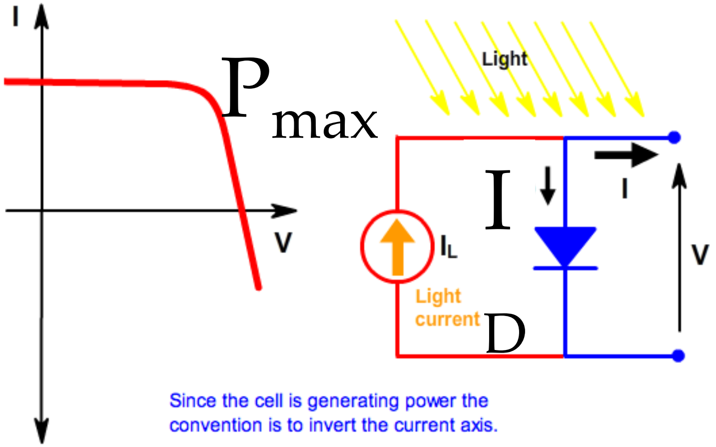
Without illumination, a solar cell has the same electrical characteristics as a large diode.



When light shines on the cell, the IV curve shifts as the cell begins to generate power.



The greater the light intensity, the greater the amount of shift.



Since the cell is generating power the convention is to invert the current axis.

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

More general equivalent circuit