Lecture 5

Photovoltaic Devices

Solar Cells

ECE 325

OPTOELECTRONICS

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Ahmed Farghal, Ph.D.

Electronics and Electrical Communications Engineering Department
Menoufia University

Photovoltaic Devices: Solar Cells

An experimental solar cell aircraft called Helios flying over the coast of Hawaii (Courtesy of NASA Dryden Research Centre)

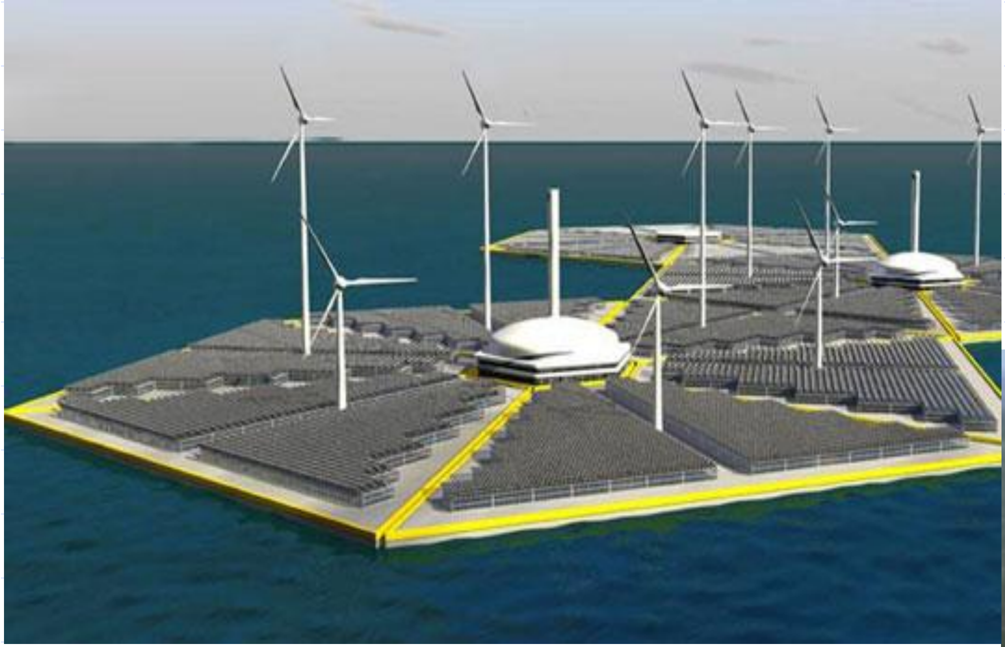
Solar cell inventors at Bell Labs (left to right): Gerald Pearson, Daryl Chapin, and Calvin Fuller. They are checking a Si solar cell sample for the amount of voltage produced (1954). © Nokia Corporation.

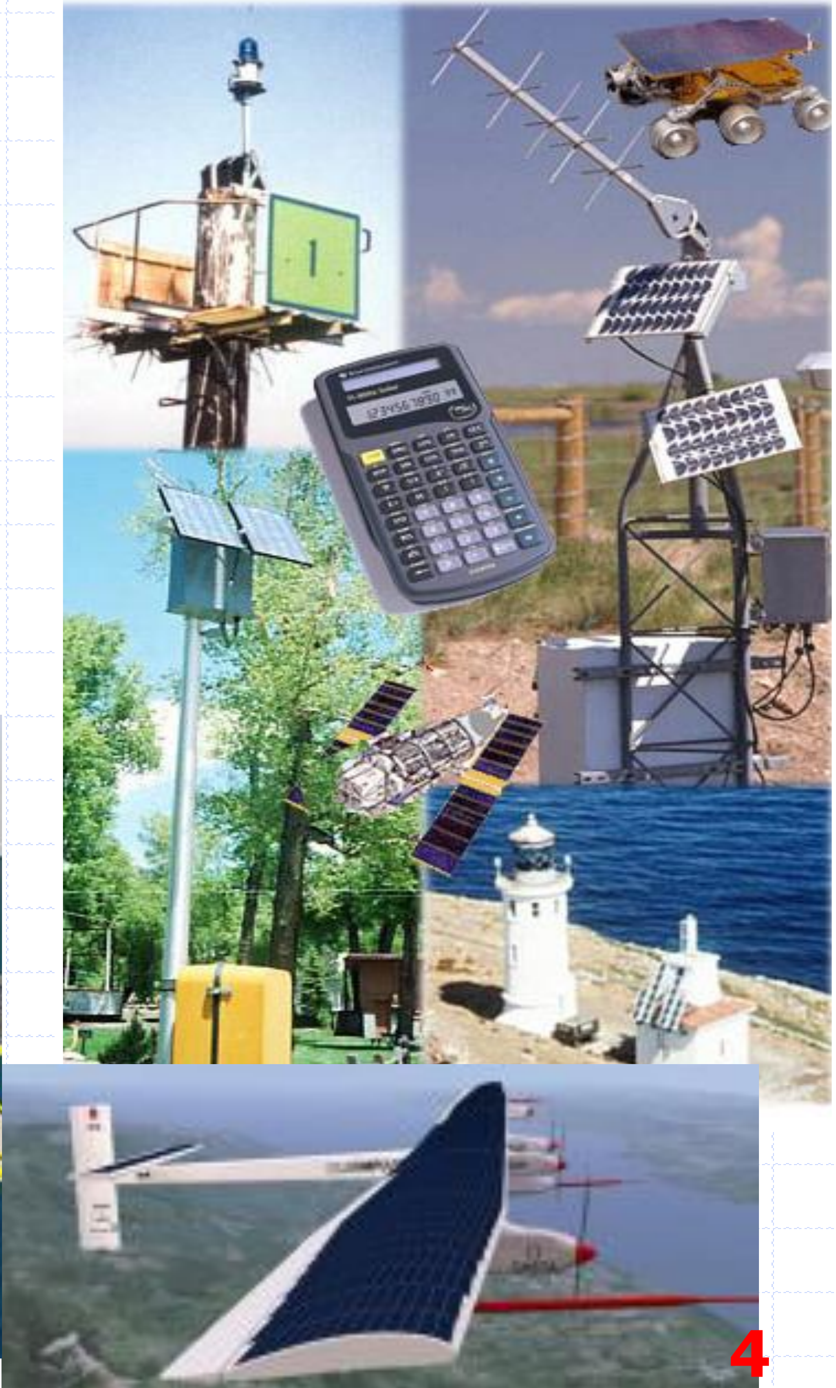
Honda's two seated Dream car is powered by photovoltaics. The Honda Dream was first to finish 3,010 km in four days in the 1996 World Solar Challenge. (Courtesy of Photovoltaics Special Research Centre, University of New South Wales, Sydney, Australia)

Why Photovoltaic?

- The amount of solar energy that strikes earth in a period of a few days is greater than the amount of fuel burnt over the entire course of human history.
- With regard to the required land area, it has been estimated that PV cells with a sunlight-to-electricity conversion efficiency of $\eta = 15\%$ would need to cover just 0.25% of the global pastoral area to meet all of the world's primary energy requirements.
- Environmentally-friendly renewable energy source with no CO_2 emissions.
- Do not produce noise and they are totally silent.
- Reliable and have long life time.

Applications





Applications

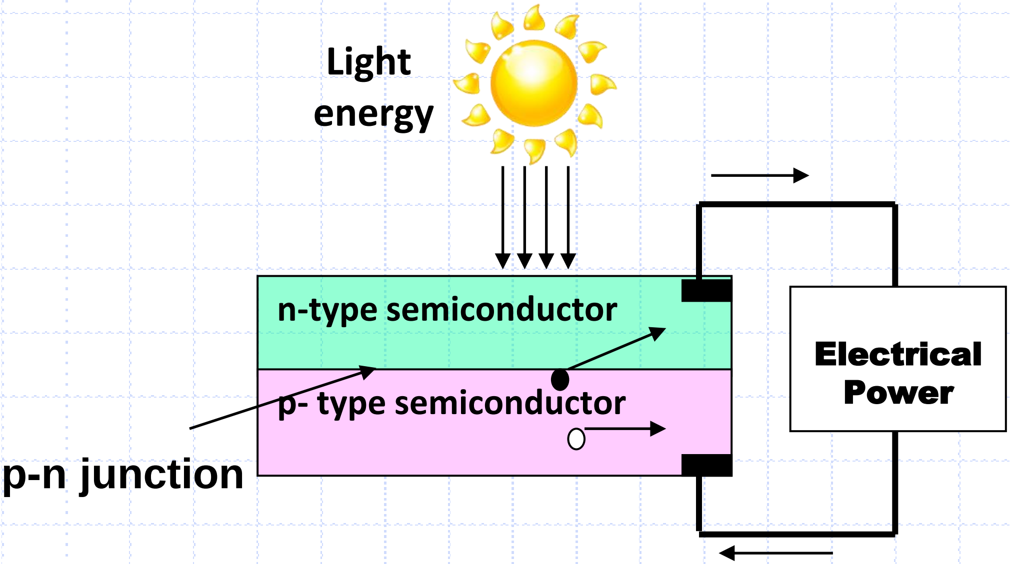
- Powering water pumps, control and measurement devices or cathodic protection equipment for oil and gas lines.
- Domestic power supply for people who do not have access to mains electricity.
- Ocean navigation aids: Number of lighthouses and most buoys are powered by solar cells
- Telecommunication systems: radio repeater stations on mountain tops, or telephone boxes in the country can often be solar powered.
- Electric power generation in space: To providing electrical power to satellites in an orbit around the Earth

1950s	First modern solar cells
1960s	Solar cells become main source of electric power for satellites
1970s	First remote industrial applications on the ground
1980s	Solar cells used in rural electrification and water pumping. First grid connected systems
1990s	Major expansion in building-integrated systems

Photovoltaic Devices: Solar Cells

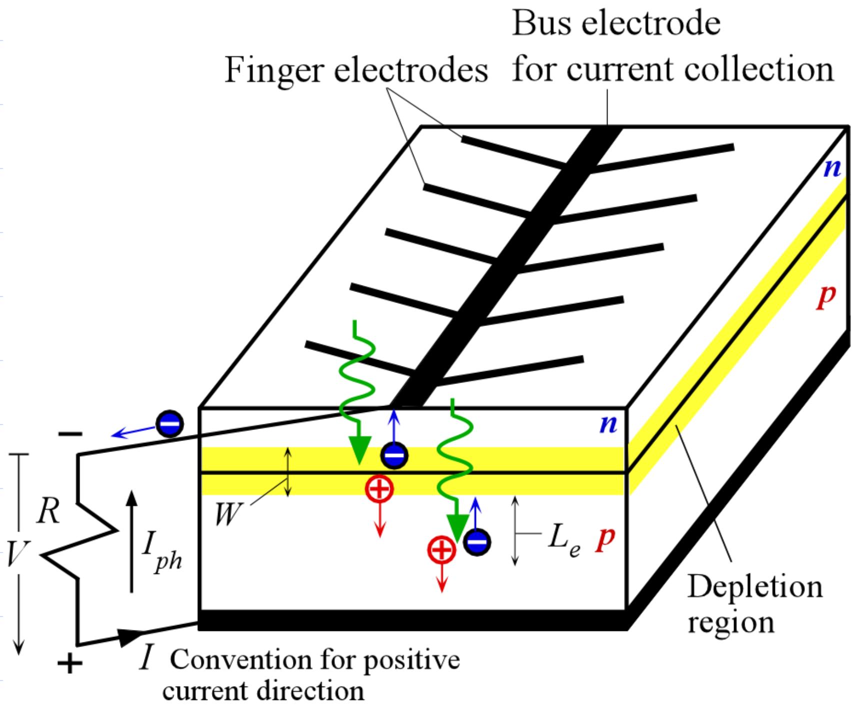
- A **photovoltaic device** (or a **solar cell**) converts the incident solar radiation energy into electrical energy.
  - Incident photons are absorbed to photogenerate charge carriers, which then pass through an external load to do electrical work.

- Photovoltaic devices may be:
  1. metal–semiconductor Schottky junctions,
  2. *pn* junctions, or
  3. *pin* devices.



- Most solar cells use **crystalline silicon** because silicon-based semiconductor fabrication is now a mature technology that enables cost-effective devices to be manufactured.

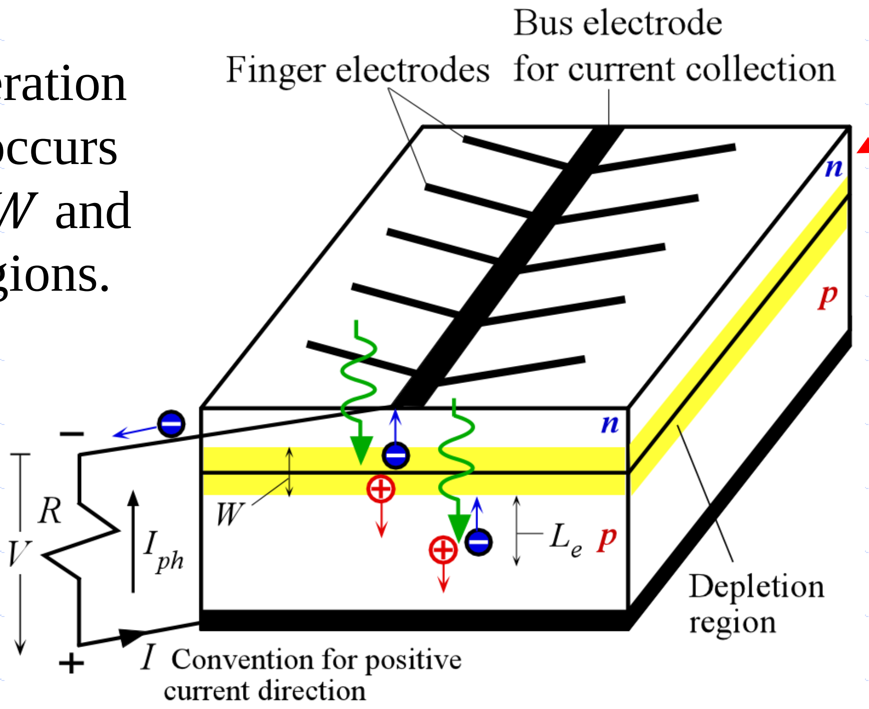
Crystalline Si *pn* Junction Solar Cell



- Have a thin *n*-type semiconductor layer on a thick *p*-type substrate.
- The **finger electrodes** attached to the *n*-side:
  - must allow the light to enter the device
  - at the same time must result in a small series resistance.
- **Thin antireflection (AR)** coatings on the surface (one or two layers) are used to prevent excess reflection of the bare semiconductor–air interface and improve efficiency

Crystalline Si *pn* Junction Solar Cell

Photogeneration of EHPs occurs mainly in W and p-side regions.

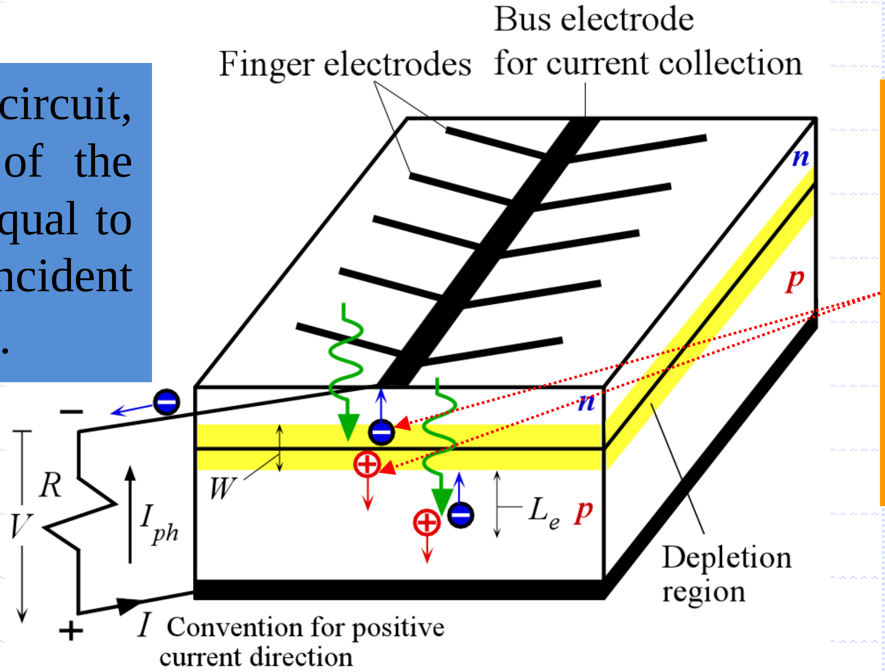


very narrow to allow most of the photons to be absorbed within the depletion region (W) and within the neutral p-side.

- In Si, the electron diffusion length L_e is longer than the hole diffusion length L_h, which is the reason for having the p-layer as the main photon absorbing layer.
- EHP photogeneration then occurs in a volume defined by W and L_e in the p-side.
- The built-in Field, E_o in the depletion region drives EHPs to their respective electrode.

Crystalline Si *pn* Junction Solar Cell

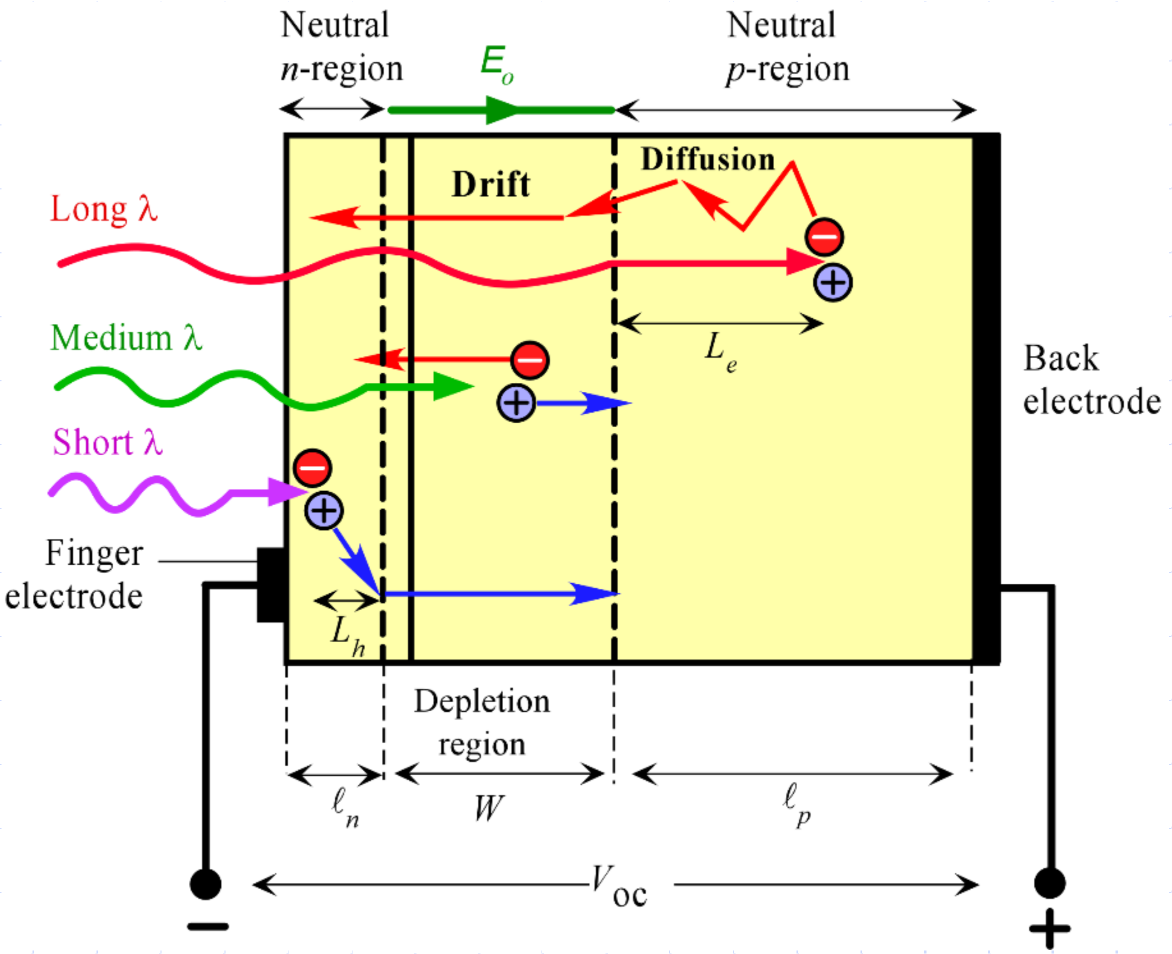
If the load is a short circuit, then the magnitude of the external current I is equal to I_{ph} generated by the incident radiation ($I_{SC} = -I_{\mathrm{ph}}$).



Without the internal field E_o , it is not possible to drift apart the photogenerated EHPs and hence cause a current flow in the external circuit.

- The electrons drift toward the n-side and holes toward the p-side, generating I_{ph}.
- The excess electrons reach the neutral n-side, then drift around the external circuit, do work, and reach the p-side to recombine with the excess holes on this side.
  - As a result, there will be a continuous external photocurrent during illumination.

Photovoltaic Device Principles



The basic principle of operation of the solar cell (exaggerated features to highlight principles). The built-in field change upon illumination.

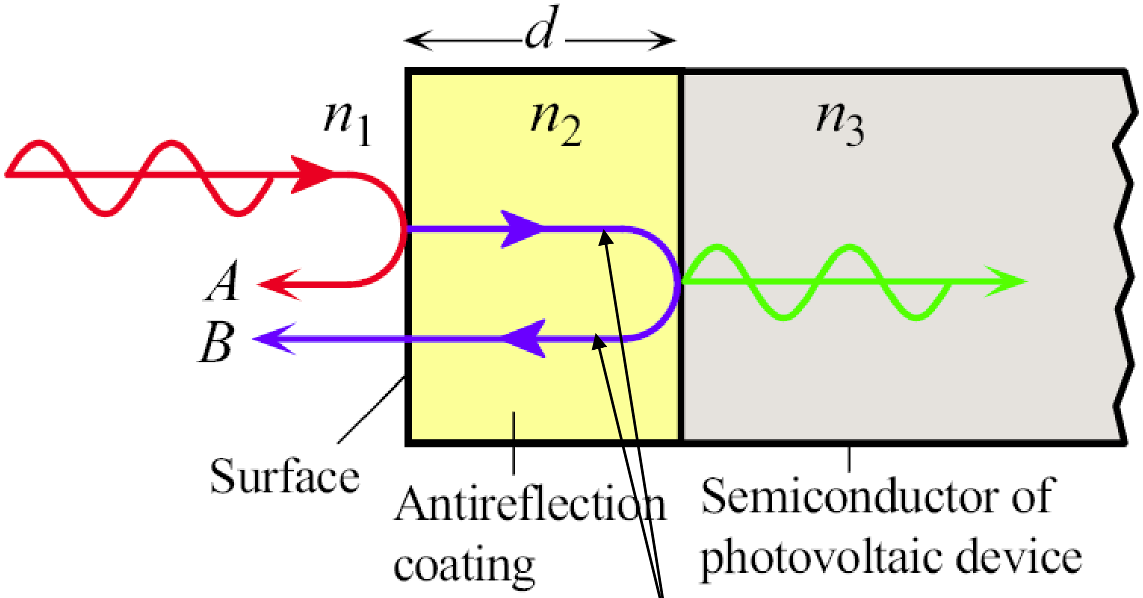
AR Coatings on Solar Cells

When light is incident on the surface of a semiconductor it becomes partially reflected. The refractive index of Si is about 3.5 at wavelengths around 700 - 800 nm. Thus the reflectance with n_1(air) = 1 and n_2(Si) ≈ 3.5 is

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = \left(\frac{1-3.5}{1+3.5}\right)^2 = 0.309$$

30% of the light is reflected and is not available for conversion to electrical energy

AR Coatings on Solar Cells



Phase change = $(n_2k)(2d)$

$k = 2\pi/\lambda$ in free space

Illustration of how an antireflection coating reduces the reflected light intensity.

Coat the surface of the semiconductor device with a thin layer of a dielectric material such as Si_3N_4 (silicon nitride) that has an intermediate refractive index. In this case n_1(air) = 1, n_2(coating) ≈ 1.9 and n_3(Si) = 3.5

AR Coatings on Solar Cells

Destructive interference requires

$$\text{Phase change} = (n_2k)(2d) = m(\pi)$$

$m = 1,3,5\ldots$**odd integer**

$$\left(\frac{2\pi n_2}{\lambda}\right)2d = m\pi$$

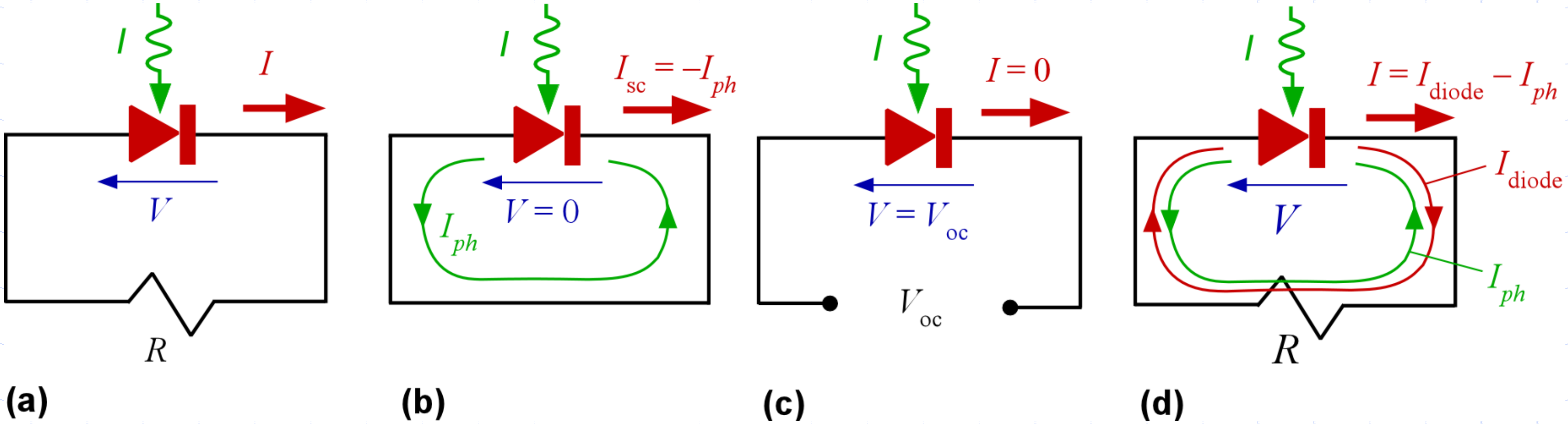
or

$$d = m\left(\frac{\lambda}{4n_2}\right)$$

Thus, the thickness of the coating must be multiples of the quarter wavelength in the coating and depends on the wavelength

To obtain a good degree of destructive interference between waves *A* and *B*, the two amplitudes must be comparable. We need $n_2 = \sqrt{(n_1n_3)}$

I–V Characteristics of a Typical Si Solar Cell



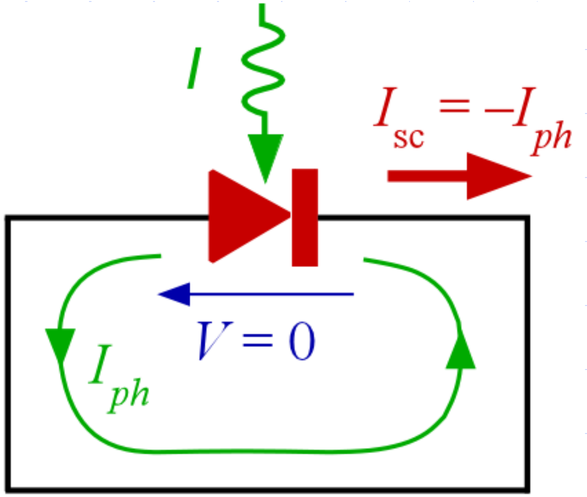
(a) The positive I and V convention.

(b) The short circuit behavior of an illuminated *pn* junction . $I_{SC} = -I_{ph}$ (an important solar cell quantity)

(c) If the solar cell is in open circuit, there is no external current ($I = 0$) but there is a voltage, called the open circuit voltage, V_{oc}, across the device. This voltage corresponds to the point where the illuminated $I - V$ characteristic cuts the V-axis.

(d) The solar cell driving an external load *R*. There is a voltage *V* and current *I* in the circuit.

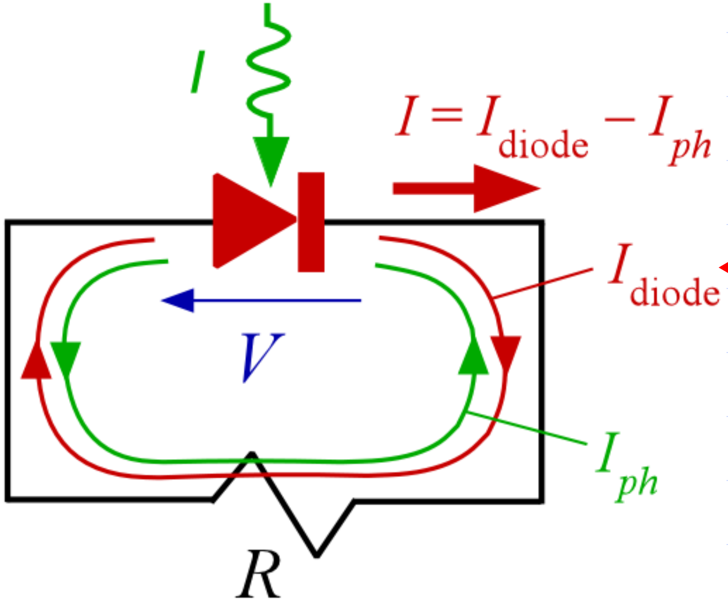
I–V Characteristics of a Typical Si Solar Cell



$$I_{ph} = KI$$

Device dependent constant

Light intensity



$$I_{\text{diode}} = I_o\left[\exp\left(\frac{eV}{\eta k_B T}\right) - 1\right]$$

I–V Characteristics of a Typical Si Solar Cell

- Dark $I - V$

$$I_{\text{diode}} = I_o\left[\exp\left(\frac{eV}{\eta k_B T}\right) - 1\right]$$

usual forward biased *pn* junction diode equation

where I_o is the reverse saturation current and η is the ideality factor: 1 - 2

- Under illumination, the I–V dark characteristics are shifted down by an amount $= I_{\text{ph}}$.

$$I = -I_{\text{ph}} + I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

- The photocurrent I_{ph} is proportional to the photogeneration rate and hence to the incident light intensity I, i.e.,

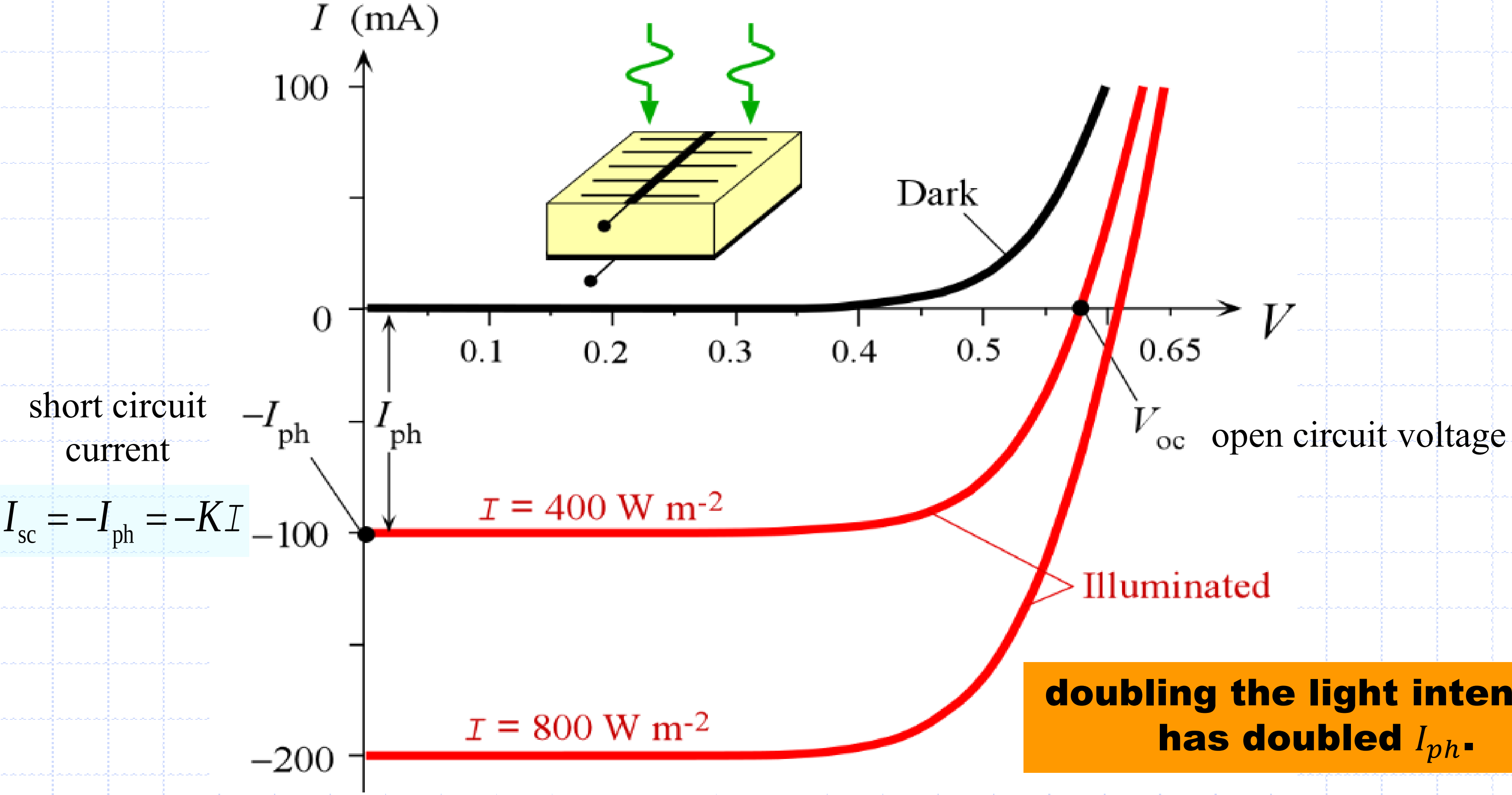
$$I_{\text{ph}} = K I$$

Photocurrent generated by light

Light intensity

Constant that depends on the particular device

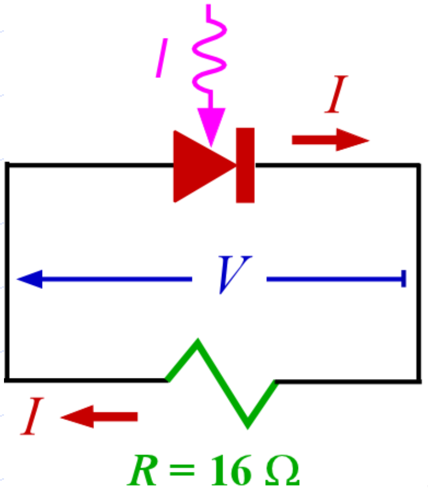
I–V Characteristics of a Typical Si Solar Cell



doubling the light intensity has doubled I_{ph}.

Typical I–V characteristics of a Si solar cell. Photovoltaic operation is always in the negative current region. *I-V* characteristics in the dark and under illumination at intensities corresponding to 400 and 800 W m^{-2}

Operating Current and Voltage

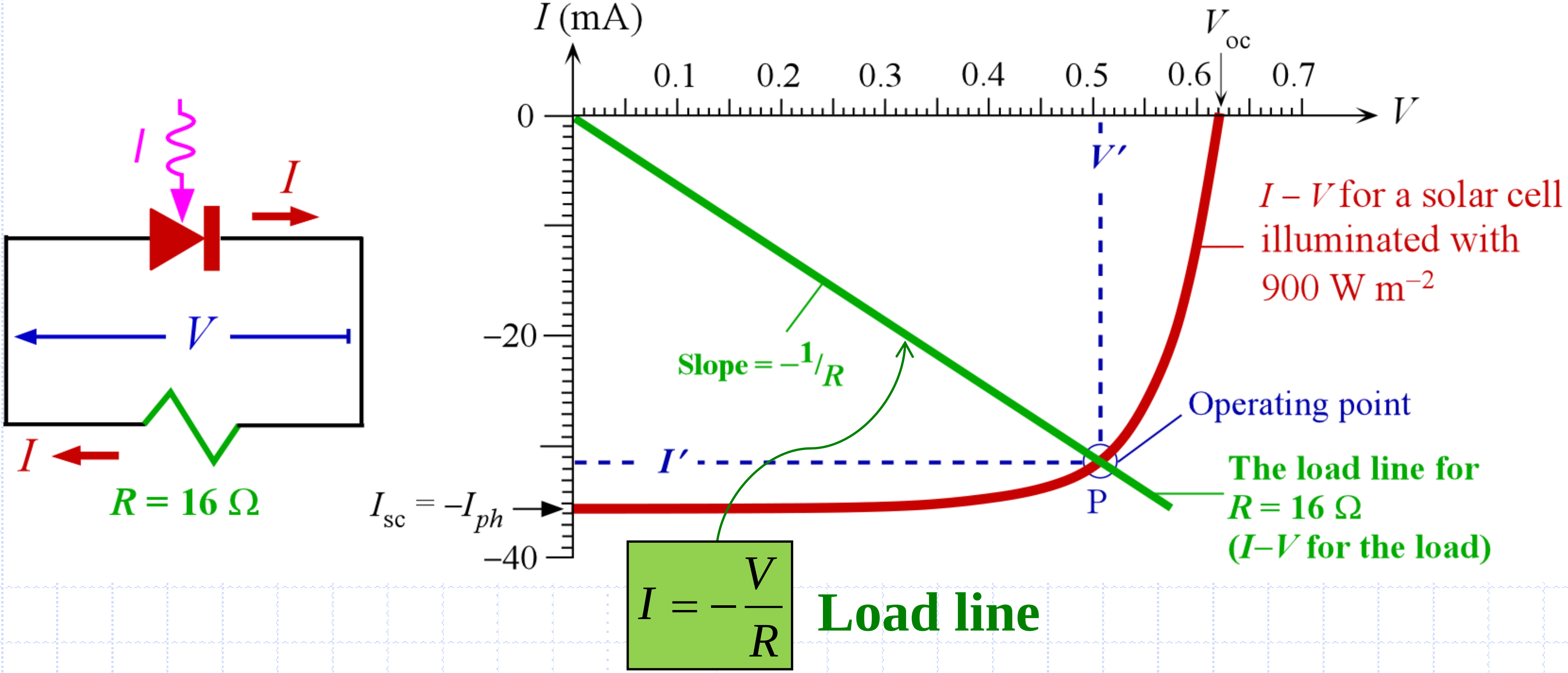


- Consider a solar cell connected to a resistive load, *R*.
  - *R* maintains the same voltage as the solar cell
  - *R* carries the same current as the solar cell
  - However the current through *R* travels in the opposite direction of conventional current.
  - The current in this circuit passes from low to high potential

$$I = -V/R$$

- The actual current and voltage in the circuit must satisfy both the solar cell I-V curve and that of the load.

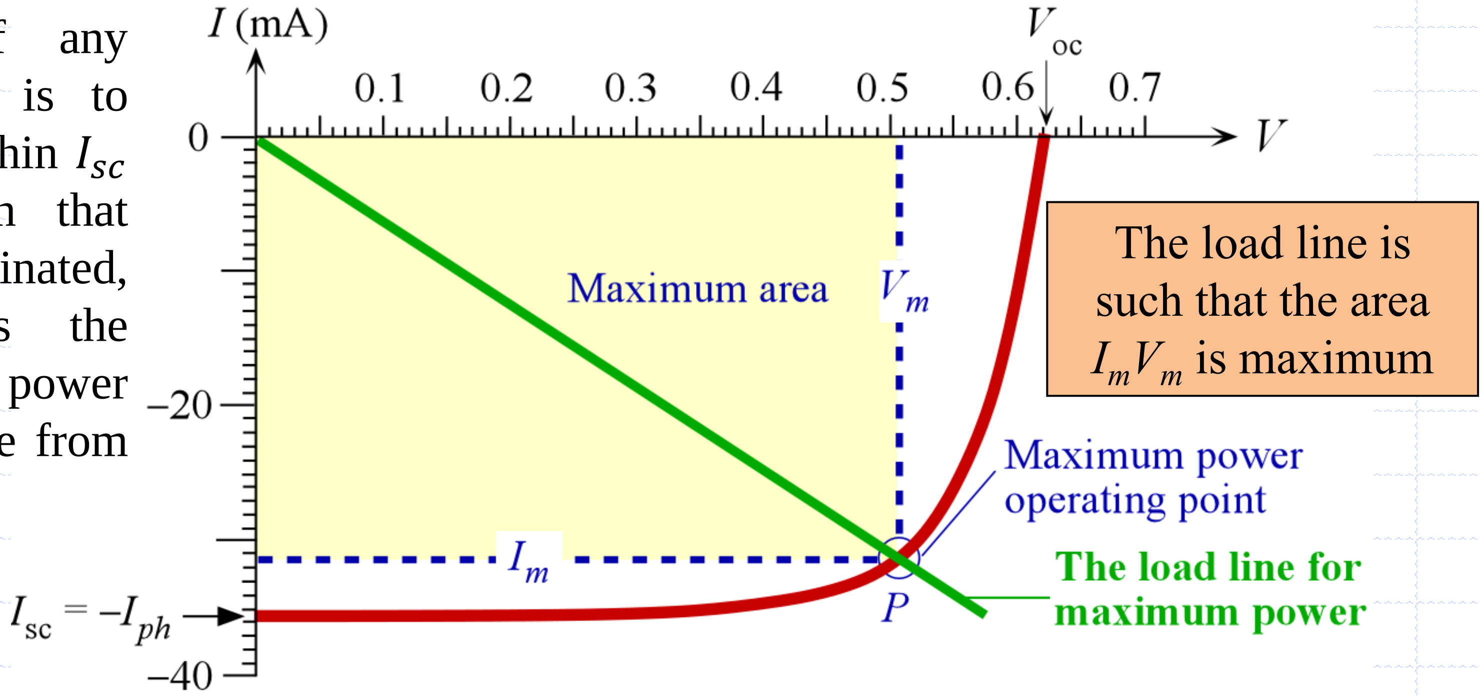
Operating Current and Voltage



- A graphical solution is presented here
  - Construct a “load line” with the slope = - $1/R$.
  - The load line intercepts the solar cell I-V curve at point ‘P’ where the load and the solar cell have the same voltage V' and current I'.
  - Point ‘P’ satisfies both governing conditions and represents the operating point of the circuit.
  - The power delivered to the load is $P_{\text{out}} = I'V'$.

Fill Factor (FF)

- The goal of any circuit design is to optimize R within I_{sc} and V_{oc} such that when illuminated, one generates the maximum power output available from the load.



- The fill factor (FF), which is a figure of merit for the solar cell, is defined as

$$\text{Fill Factor} = \text{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}$$

- The FF is a measure of the closeness of the solar cell I–V curve to the rectangular shape (the ideal shape).
- It is clearly advantageous to have FF as close to unity as possible, but the exponential pn junction properties prevent this.

EXAMPLE: Solar cell driving a load

Consider the solar cell driving a 16-Ω resistive load as in Figure 5.42 (b). Suppose that the cell has an area of 1 cm × 1 cm and is illuminated with light of intensity 900 W m^{-2} as in the figure. What are the current and voltage in the circuit? What is the power delivered to the load? What is the efficiency of the solar cell in this circuit? If you assume it is operating close to the maximum deliverable power, what is the FF?

Solution

The *I*-*V* characteristic of the load is the load line described by, $I = -V / R$ with $R = 16$ Ω. This line is drawn in Figure 5.42 (b) with a slope 1/(16 Ω). It cuts the *I*-*V* characteristics of the solar cell at $I' \approx -$ 31.5 mA and $V' \approx$ 0.505 V which are the current and voltage in the photovoltaic circuit of Figure 5.42 (b). In fact, V'/I' gives – 16 Ω as expected. The power delivered to the load is

$$P_{out} = |I'V'| = (31.5\times10^{-3}\text{ A})(0.505\text{ V}) = \mathbf{0.0159\ W} \text{ or } \mathbf{15.9\ mW}$$

This is not necessarily the maximum power available from the solar cell.

The input sun-light power is

$$P_{in} = (\text{Light Intensity})(\text{Surface Area}) = (900\text{ W m}^{-2})(0.01\text{ m})^2$$
$$= \mathbf{0.090\ W}$$

EXAMPLE: Solar cell driving a load

Solution (continued)

The efficiency is

$$\text{Efficiency} = 100 \times (P_{out} / P_{in}) = 100\ (15.9\ \text{mW} / 90\ \text{mW})$$

$$= \mathbf{17.7\%}$$

This will increase if the load is adjusted to extract the maximum power from the solar cell but the increase will be small as the rectangular area $I'V'$ in Figure 5.42 in it is already close to the maximum. Assuming that $|I'V'|$ is roughly the maximum power available (maximum area for the rectangle $I'V'$), then $I_m \approx I' \approx -$ 31.5 mA and $V_m \approx V' \approx 0.505$ V. For the solar cell in Figure 5.42 (b), $I_{sc} = -$ 35.5 mA and V_{oc} = 0.62 V. Then,

$$FF = I_m V_m / I_{sc} V_{oc} \approx (-31.5\ \text{mA})(0.505\ \text{V}) / (-35.5\ \text{mA})(0.62\ \text{V})$$

$$= \mathbf{0.72}\ \text{or}\ \mathbf{72\%}$$

EXAMPLE: Open circuit voltage and short circuit current

A solar cell under an illumination of 500 W m^{-2} has a short circuit current I_{sc} of –16 mA and an open circuit output voltage V_{oc}, of 0.50 V. What are the short circuit current and open circuit voltages when the light intensity is doubled? Assume $\eta = 1$.

Solution

The general I-V characteristics under illumination is given by

$$I = -I_{ph} + I_o[\exp(eV/\eta k_B T) - 1]$$

The short circuit current corresponds to the photocurrent so that, from $I_{ph} = KI$, at double the intensity the photocurrent is

$$\boxed{I_{ph2} = \left(\frac{I_2}{I_1}\right) I_{ph1}} = (16 \text{ mA})(1000/500) = 32 \text{ mA}$$

Setting $I = 0$ for open circuit we can obtain the open circuit voltage V_{oc},

$$I = -I_{ph} + I_o[\exp(eV_{oc}/\eta k_B T) - 1] = 0$$

Assuming that $V_{oc} >> \eta k_B T/e$, rearranging the above equation we can find V_{oc}

$$\boxed{V_{oc} = \frac{\eta k_B T}{e} \ln\left(\frac{I_{ph}}{I_o}\right)}$$

Open circuit output voltage

EXAMPLE: Open circuit voltage and short circuit current

Solution (continued)

Since the photocurrent, I_{ph}, depends on the light intensity I via, $I_{ph} = KI$. At a given temperature, then the change in V_{oc} is

$$V_{\mathrm{oc2}} - V_{\mathrm{oc1}} = \frac{\eta k_B T}{e} \ln\left(\frac{I_{ph2}}{I_{ph1}}\right) = \frac{\eta k_B T}{e} \ln\left(\frac{I_2}{I_1}\right)$$

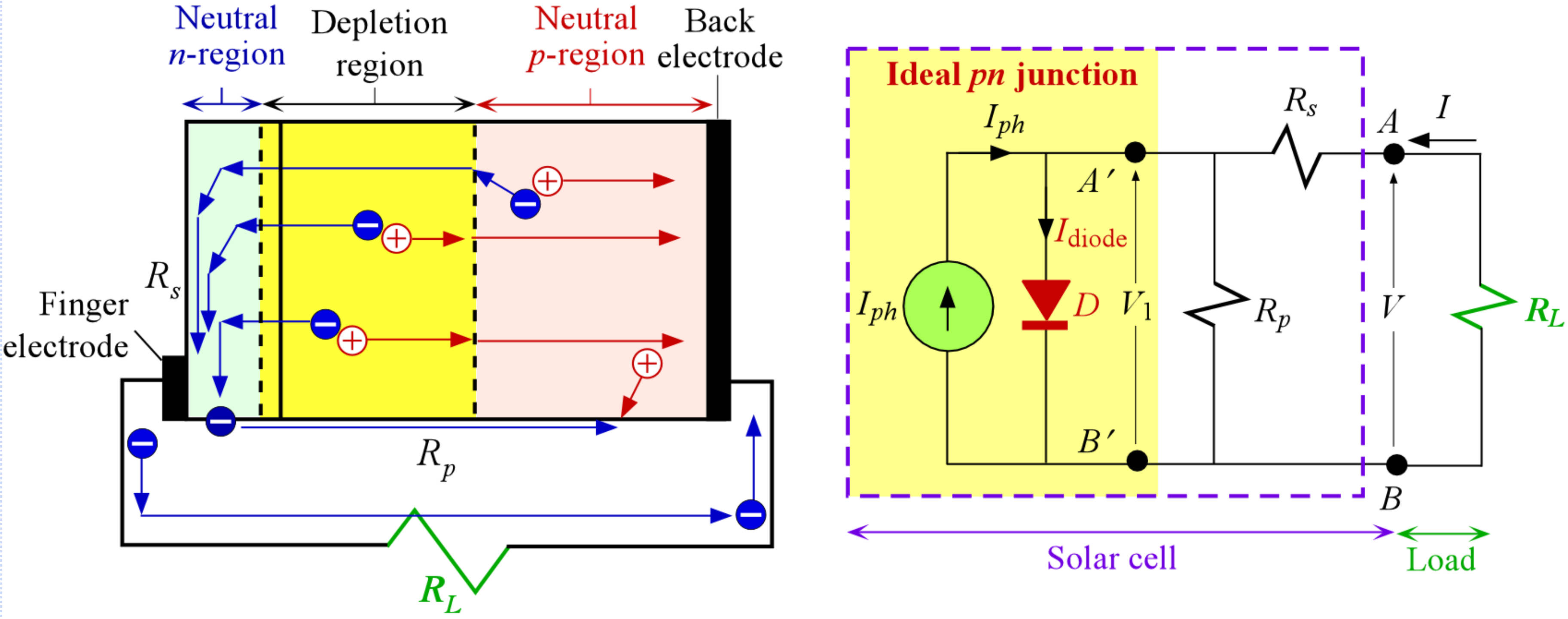
Assuming $\eta = 1$, the new open circuit voltage is

$$V_{\mathrm{oc2}} = V_{\mathrm{oc1}} + \frac{\eta k_B T}{e} \ln\left(\frac{I_2}{I_1}\right)$$

= 0.50 V + (1)(0.0259 V)ln(2) ≈ **0.52 V**

NOTE: This is a ~4% increase in V_{oc} compared with the 100% increase in illumination and the short circuit current.

Equivalent Circuit



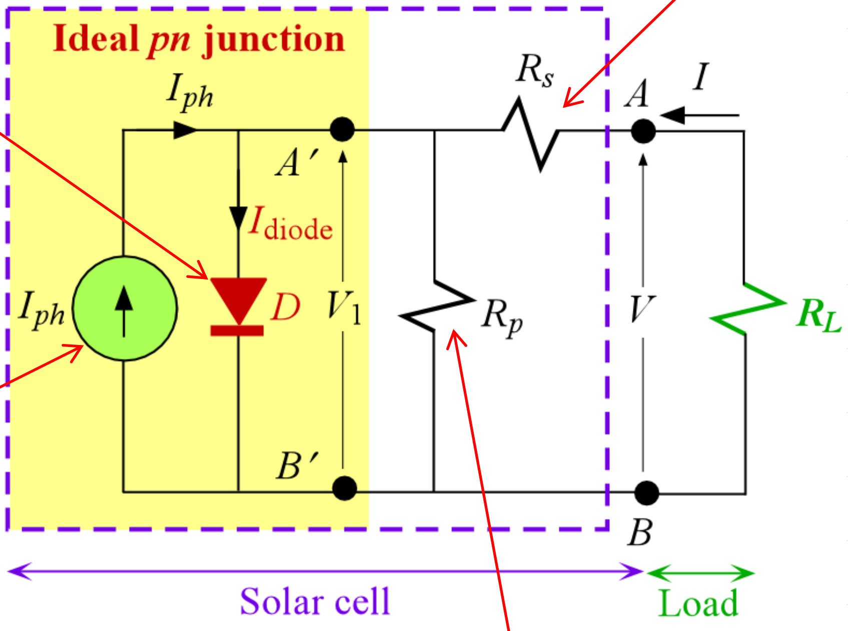
LEFT: Series and shunt resistances and various fates of photegenerated EHPs. RIGHT: A simple equivalent circuit diagram for a solar cell. The current I into A, and V across A and B, follow the convention for positive current and voltage. A' and B' represent the ideal diode terminals.

Equivalent Circuit

Ideal diode current

$$I_{\text{diode}} = I_o\left[\exp\left(\frac{eV}{\eta k_B T}\right) - 1\right]$$

Series resistance



$$I_{ph} = KI$$

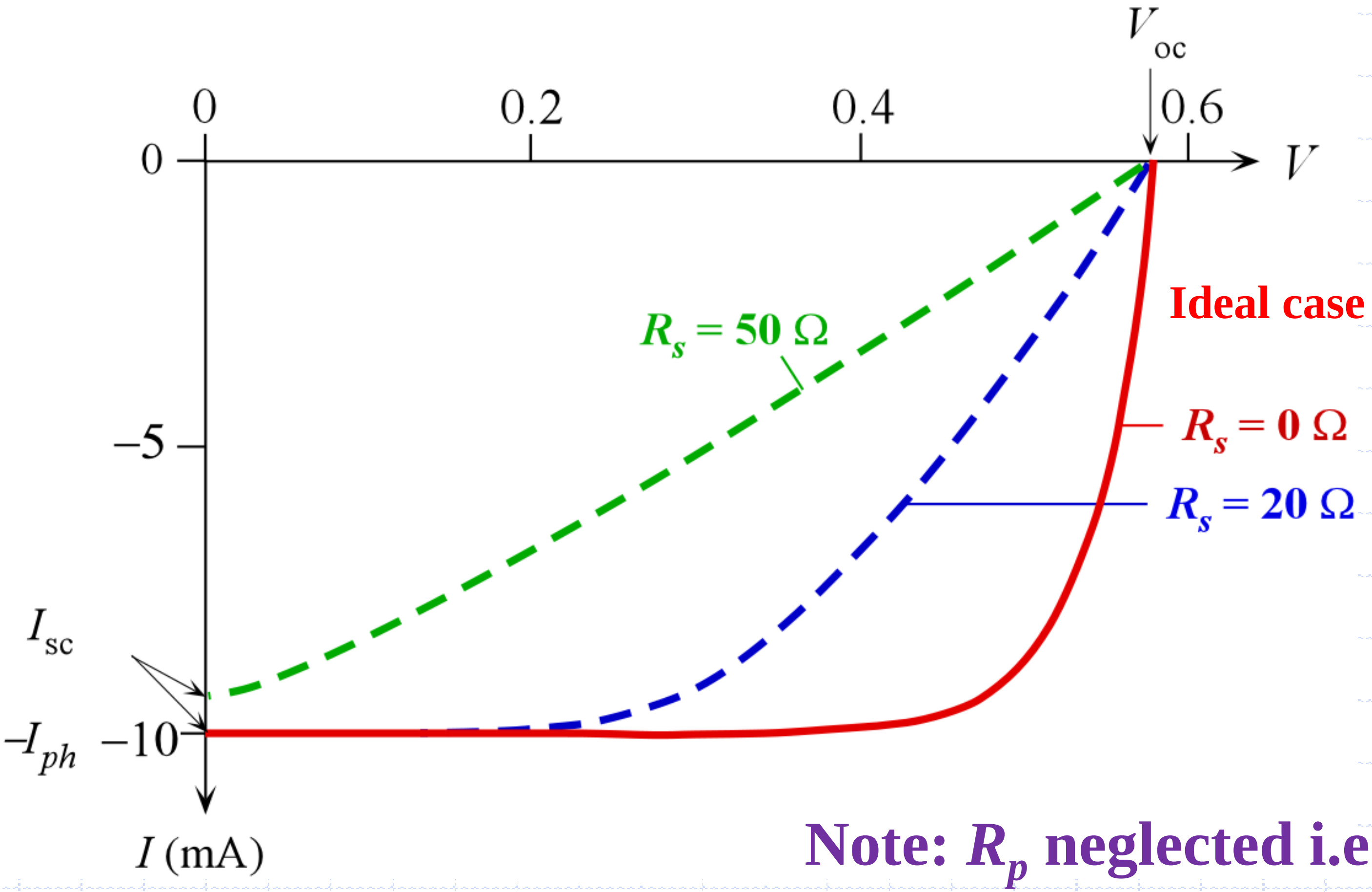
Current generator

Shunt or parallel resistance

External solar cell terminals are *A* and *B*

A′ and *B* ′ are the internal terminals for the **ideal diode**.

The Effect of Series Resistance

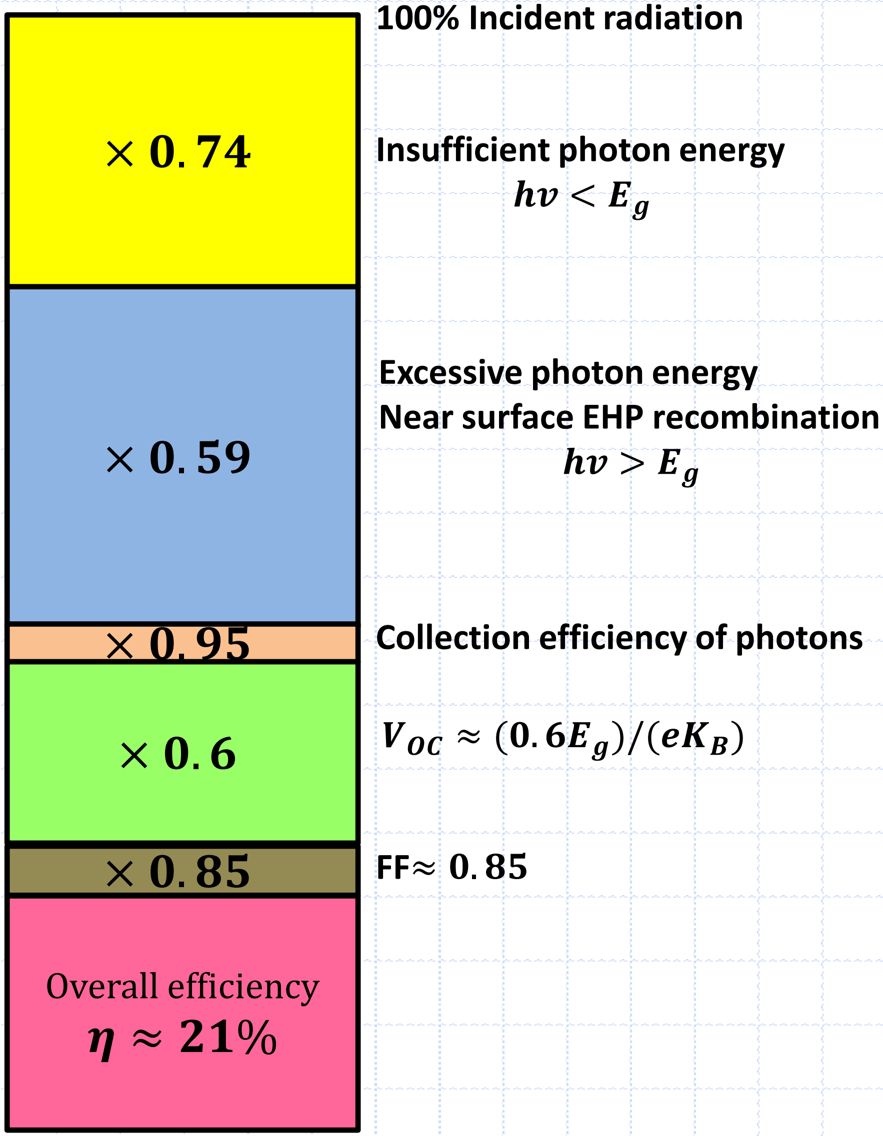


Note: R_p neglected i.e. $R_p = \infty$

The effect of series resistance R_s on the I-V characteristics. This example is a Si pn junction solar cell with $\eta = 1.5$ and $I_o = 3\times10^{-6}$ mA. The light intensity is such that it generates $I_{ph} = 10$ mA.

Solar Cell Materials, Devices, And Efficiencies

- Most solar cells are Si-based due to the vast infrastructure and inexpensive fabrication schemes available
- The figure presented shows how various aspects of a silicon solar cell effect its efficiency
- Note: some 25% of all the incident energy is wasted because of photons having insufficient energy to generate EHPs
- Of the 75% of light absorbed, only 60% of the is effectively utilized due to near surface absorption in the n-region
- etc. etc. etc.



100% Incident radiation

$\times 0.74$ — **Insufficient photon energy** $h\nu < E_g$

$\times 0.59$ — **Excessive photon energy**, **Near surface EHP recombination** $h\nu > E_g$

$\times 0.95$ — **Collection efficiency of photons**

$\times 0.6$ — $V_{OC} \approx (0.6E_g)/(eK_B)$

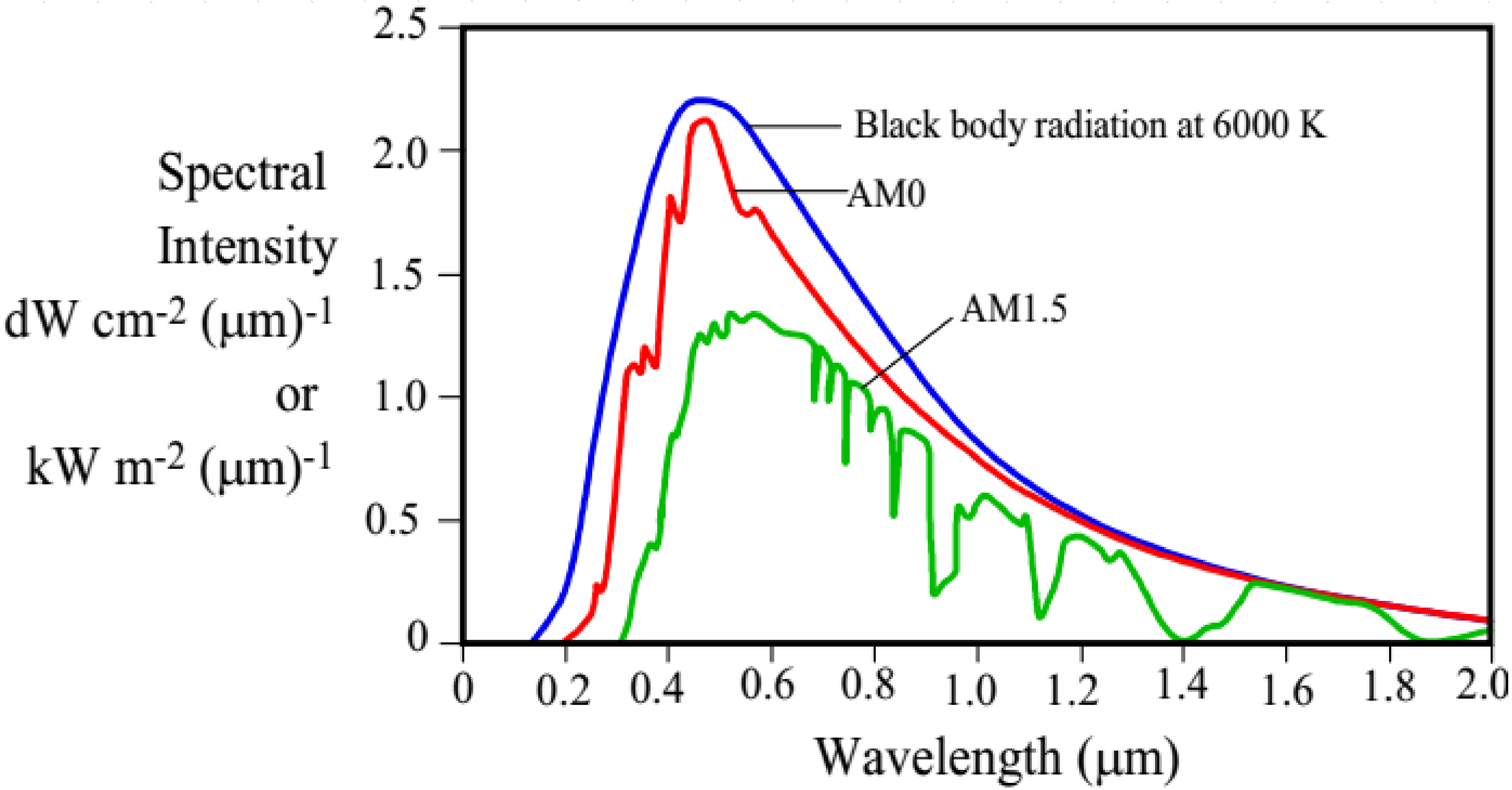
$\times 0.85$ — **FF**≈ 0.85

Overall efficiency $\eta \approx 21\%$

High Efficiency Solar Cells

- Solar cell efficiency: the maximum output power from the device per unit incident radiation power under well-defined conditions.
- The Sun's spectrum is different at different heights from Earth due to absorption and scattering effects in the atmosphere, which depend on the wavelength.
  - For terrestrial use, one common standard condition for solar cell comparisons is the so-called global AM1.5 solar spectrum that represents the radiation arriving on Earth's surface with an integrated intensity (over all wavelengths) of 1000 W m^{-2}; and the test temperature is 25°C.
- AM1.5 means Air-Mass1.5. In general, the number m in AMm represents $m = \sec\theta$, where θ is the Zenith angle between the shortest path the sun rays can take and the actual path to the solar cell.

Solar Energy Spectrum



The spectrum of the solar energy represented as spectral intensity (I_λ) vs wavelength above the earth's atmosphere (AM0 radiation) and at the earth's surface (AM1.5 radiation). Black body radiation at 6000 K is shown for comparison

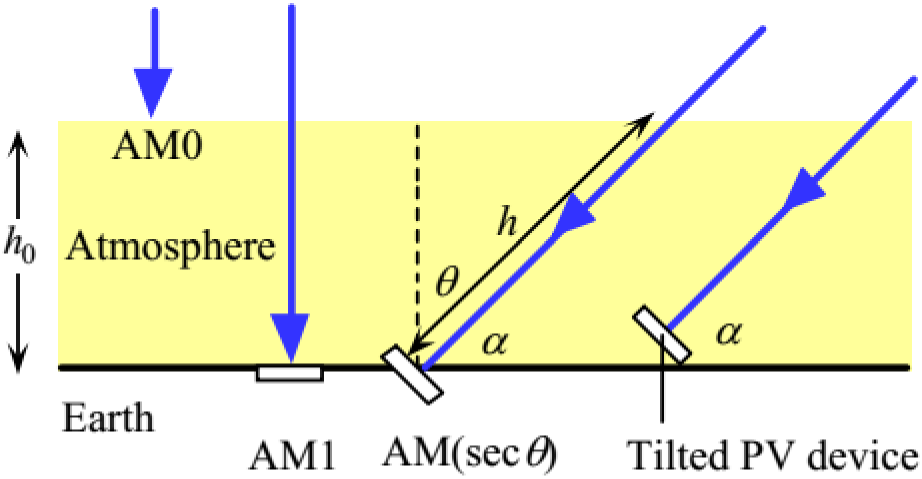
(After H.J. Möller, Semiconductors for Solar Cells, Artech House Press, Boston, 1993, p.10)

Solar Energy Spectrum

- The integrated intensity above the earths atmosphere, gives the total power flow through a unit area perpendicular to the direction of the sun. This quantity is called the solar constant (air-mass zero) or AM0 radiation and is approximately 1.367 kW/m^2
- Actual intensity on the earth's surface depends on absorption and scattering in the atmosphere. The effects of water vapor (clouds) in the air provide a general value of solar intensity at the surface that is approximately 70% of AM0. The received spectrum is called Air Mass 1 (AM1)
- AMm: the ratio of actual radiation path to shortest possible path through an atmosphere. So for light entering an atmosphere at angle θ

$$m = h/h_o = (h_o \sec\theta)/h_o$$

$$\Rightarrow m = \sec\theta$$



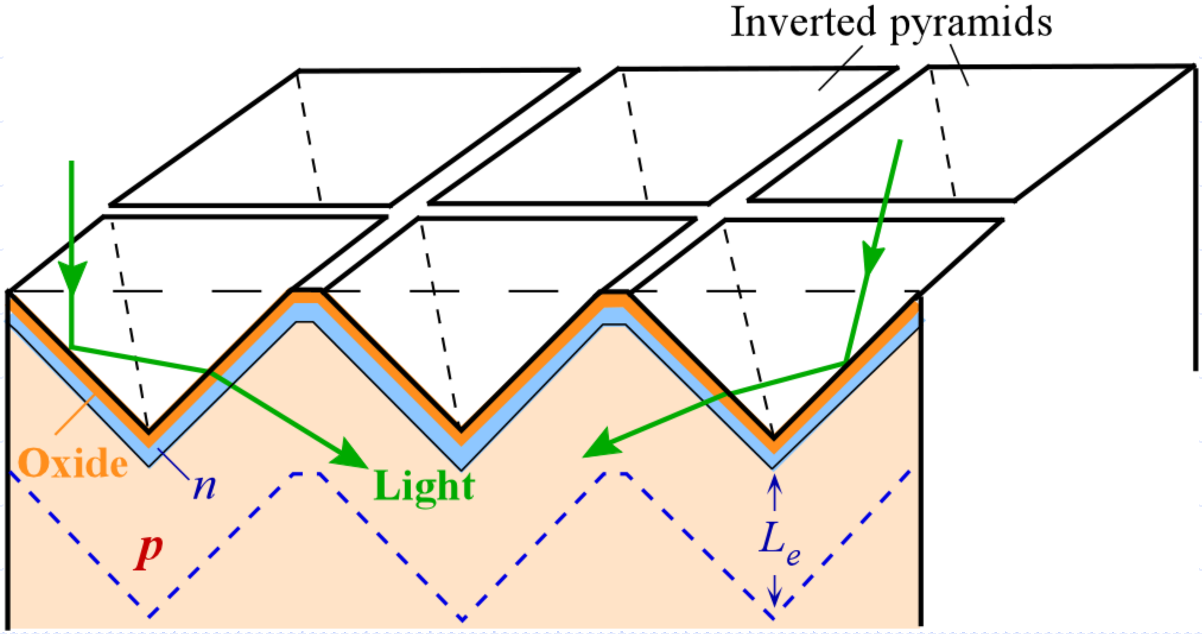
Solar Cell Efficiencies

Characteristics of a few selected classes of solar cells, and reported efficiencies under global AM1.5 solar spectrum (1000 W/m^2) at 25°C.

Semiconductor	V_{oc} V	$\lvert J_{sc}\rvert$ mA cm^{-2}	FF %	Efficiency %	E_g eV
Si, single crystal (PERL)	0.707	42.7	82.8	25.0	1.11
Si, polycrystalline	0.664	38.0	80.9	20.4	1.11
Amorphous Si:H (pin)	0.886	16.75	67.0	10.1	~1.7
GaAs, single crystal	1.030	29.8	86.0	26.4	1.42
GaAs, thin film	1.107	29.6	84.1	27.6	1.42
InP, single crystal	0.878	29.5	85.4	22.1	1.35
GaInP/GaAs Tandem	2.488	14.22	85.6	30.3	1.95/1.42
GaInP/GaAs/Ge Tandem	2.622	14.37	85.0	32.0	1.95/1.42/0.66

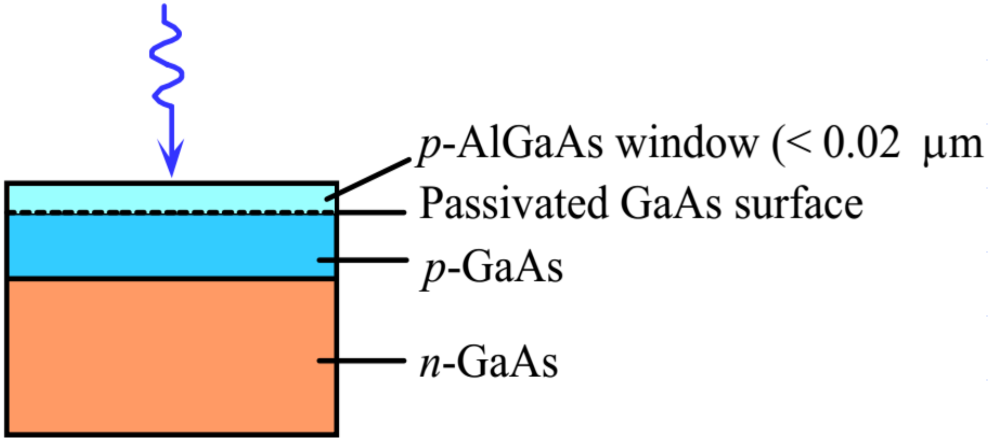
- Typical Si-based solar cell efficiencies range from about 18% for polycrystalline to 22–25% in high efficiency single crystal devices that have special structures to absorb as many of the incident photons as possible.

Inverted pyramid textured surface

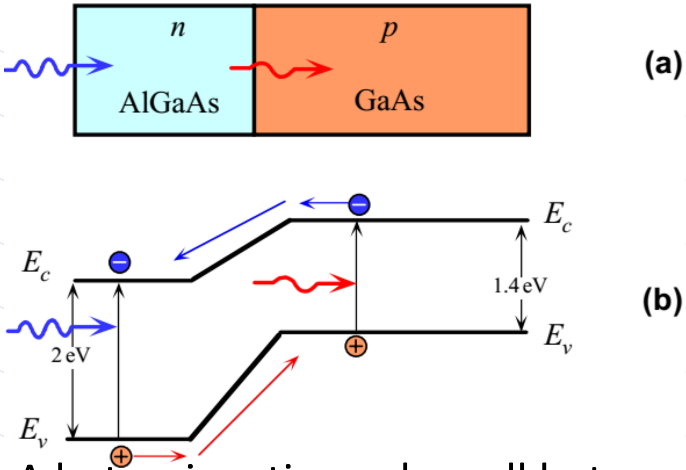


- The reflection of light from the solar cell surface must be minimized to increase the device efficiency.
- Inverted pyramid textured surface substantially:
  - Reduces reflections from surface
  - Increases path length for absorption and improves EHP and collection efficiencies

III-V Materials for Thermal Photovoltaics



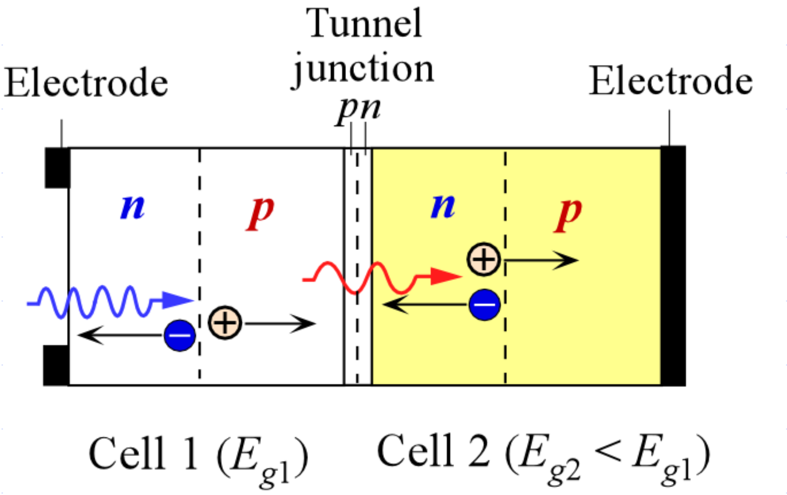
AlGaAs window layer on GaAs passivates the surface states and thereby increases the low wavelength photogeneration efficiency



A heterojunction solar cell between two different bandgap semiconductors (GaAs and AlGaAs)

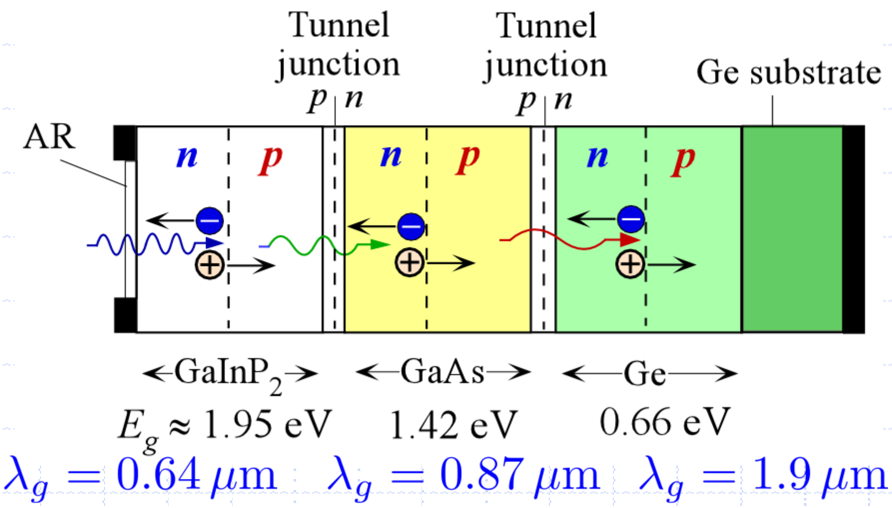
- Heterojunction devices used to overcome surface recombination limitations and improve efficiencies to as much as 24%
- Wider bandgaps provide longer wavelength absorbtion
  - AlGaAs absorb $h\nu > 2$ eV
  - GaAs absorb 1.4 eV $< h\nu <$ 2 eV
- In more advanced cell designs, the composition of Al is graded slowly from the surface allowing the device to absorb the broad spectrum between 1.4 and 2.0 eV more evenly.

Tandem or Multijunction Solar Cells



- Research over the years has led to the development of high efficiency heterostructure tandem solar cells, which are also called multijunction solar cells.
- Multijunction solar cells essentially use two or more cells in tandem, or in cascade, to increase the absorbed photons from the incident light.
- The first cell is made from a wider bandgap material and only absorbs photons with $h\nu > E_{g1}$. The second cell absorbs photons that pass the first cell and have $h\nu > E_{g2}$.

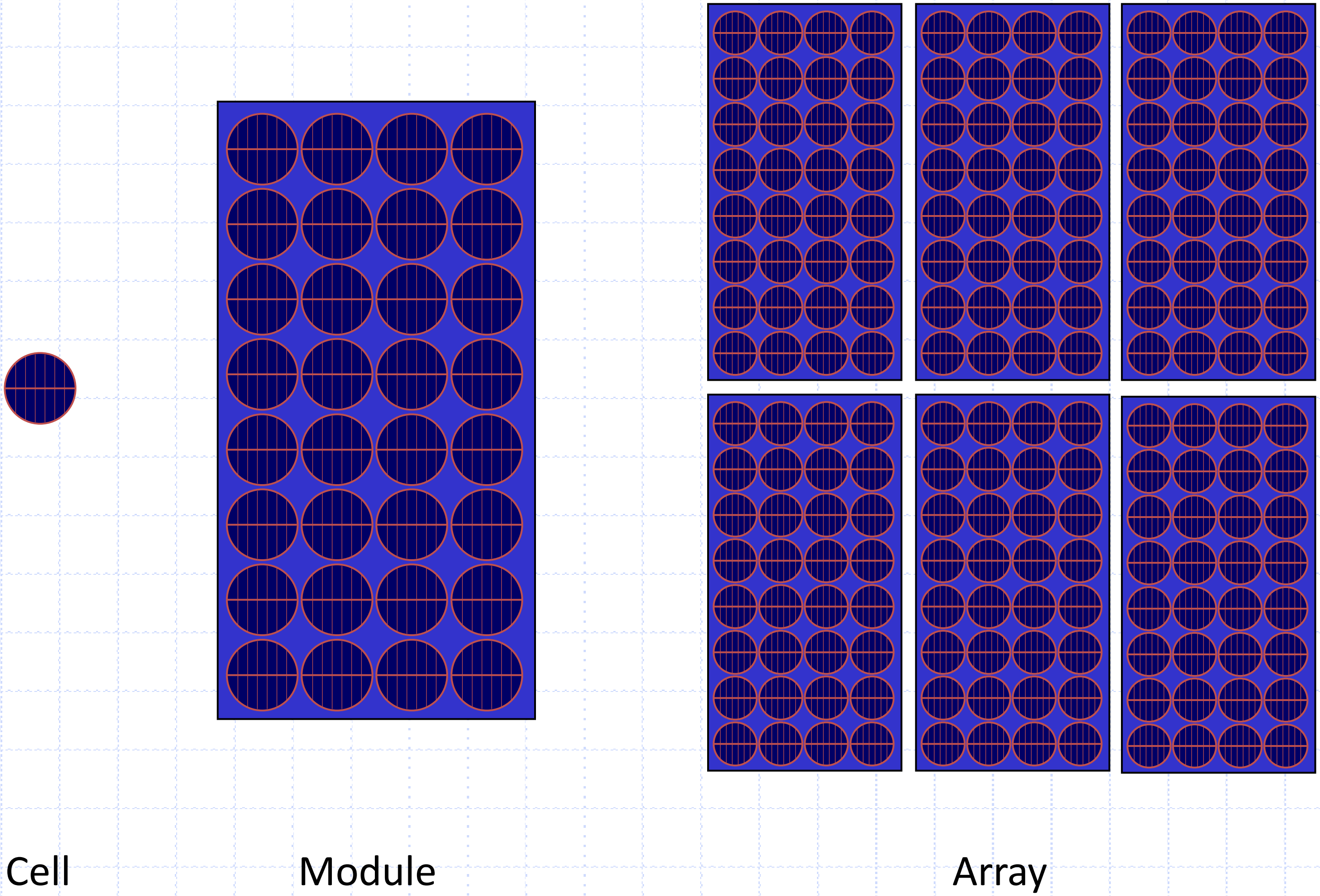
Tandem or Multijunction Solar Cells

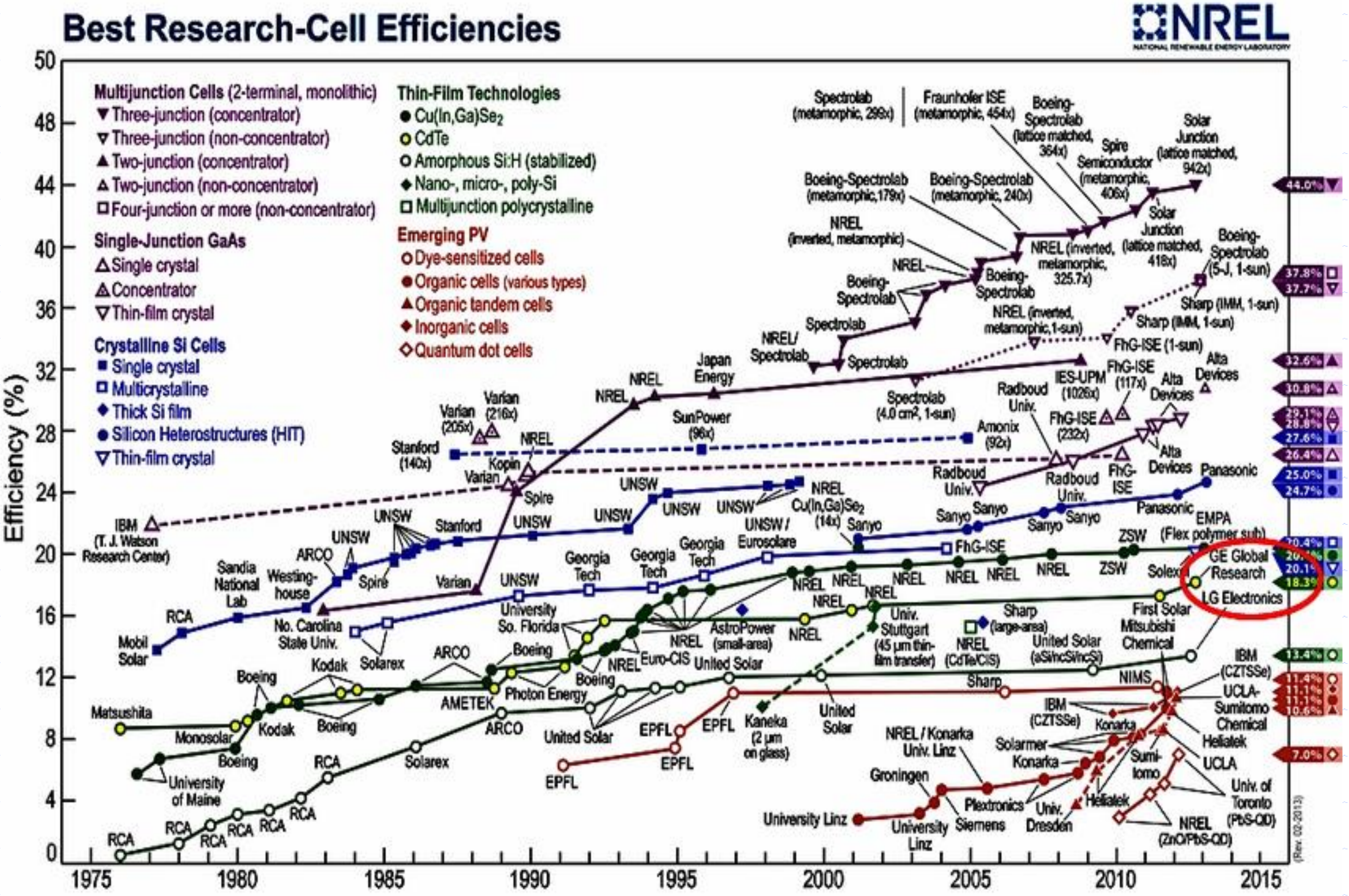


- Better efficiencies are achieved by using a three junction solar cell.
- The layers are all grown on a *Ge* substrate and each cell is an *np* junction.
- There are two very thin *pn* tunnel junctions that connect the cells in tandem to allow the drifting carriers tunnel through (pass through).
- The three cells have a wide spectral range and are able to capture a very high percentage of the solar radiation.

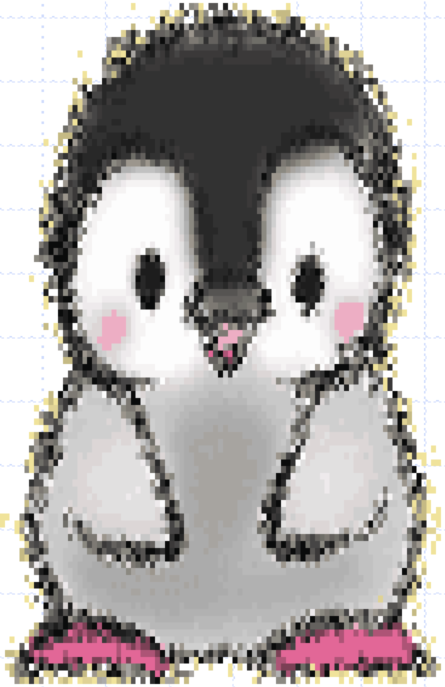
Semiconductor	V_{oc} V	$\lvert J_{sc} \rvert$ mA cm^{-2}	**FF** %	**Efficiency** %	E_g eV
GaInP/GaAs Tandem	**2.488**	**14.22**	**85.6**	**30.3**	**1.95/1.42**
GaInP/GaAs/Ge Tandem	**2.622**	**14.37**	**85.0**	**32.0**	**1.95/1.42/0.66**

Photovoltaic power Photovoltaic cells: Arrays




Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
50
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Multijunction Cells (2-terminal, monolithic)
▼ Three-junction (concentrator)
▽ Three-junction (non-concentrator)
▲ Two-junction (concentrator)
△ Two-junction (non-concentrator)
□ Four-junction or more (non-concentrator)
Single-Junction GaAs
△ Single crystal
△ Concentrator
▽ Thin-film crystal
Crystalline Si Cells
■ Single crystal
□ Multicrystalline
◆ Thick Si film
● Silicon Heterostructures (HIT)
▽ Thin-film crystal
Thin-Film Technologies
● Cu(In,Ga)Se2
○ CdTe
○ Amorphous Si:H (stabilized)
◆ Nano-, micro-, poly-Si
□ Multijunction polycrystalline
Emerging PV
○ Dye-sensitized cells
● Organic cells (various types)
▲ Organic tandem cells
◆ Inorganic cells
◇ Quantum dot cells
Spectrolab (metamorphic, 299x)
Fraunhofer ISE (metamorphic, 454x)
Boeing-Spectrolab (lattice matched, 364x)
Solar Junction (lattice matched, 942x)
Spire Semiconductor (metamorphic, 406x)
Boeing-Spectrolab (metamorphic, 179x)
Boeing-Spectrolab (metamorphic, 240x)
NREL (inverted, metamorphic)
Solar Junction (lattice matched, 418x)
NREL (inverted, metamorphic, 325.7x)
Boeing-Spectrolab (5-J, 1-sun)
NREL
Boeing-Spectrolab
Boeing-Spectrolab
Sharp (IMM, 1-sun)
Sharp (IMM, 1-sun)
NREL (inverted, metamorphic, 1-sun)
FhG-ISE (1-sun)
Spectrolab
NREL/ Spectrolab
Spectrolab
Japan Energy
NREL
NREL
Spectrolab (4.0 cm², 1-sun)
Radboud Univ.
IES-UPM (1026x)
FhG-ISE (117x)
Alta Devices
Alta Devices
Varian (205x)
Varian (216x)
SunPower (96x)
Amonix (92x)
FhG-ISE (232x)
Stanford (140x)
NREL
Kopin
Varian
Spire
Radboud Univ.
Radboud Univ.
FhG-ISE
Alta Devices
Panasonic
IBM (T. J. Watson Research Center)
UNSW
UNSW
UNSW
UNSW
UNSW
UNSW
Stanford
NREL Cu(In,Ga)Se2 (14x)
Sanyo
Sanyo
Sanyo
Sanyo
Sanyo
Panasonic
EMPA (Flex polymer sub)
UNSW / Eurosolare
ZSW
ZSW
Sandia National Lab
ARCO
Westing-house
Spire
Varian
UNSW
Georgia Tech
Georgia Tech
Georgia Tech
FhG-ISE
GE Global Research
LG Electronics
Solexel
RCA
Mobil Solar
No. Carolina State Univ.
University So. Florida
NREL
NREL
NREL
NREL
NREL
NREL
NREL
NREL
AstroPower (small-area)
Univ. Stuttgart (45 μm thin-film transfer)
NREL (CdTe/CIS)
Sharp (large-area)
United Solar (aSi/ncSi/ncSi)
First Solar
Mitsubishi Chemical
Kodak
Solarex
ARCO
Boeing
NREL
Euro-CIS
United Solar
Boeing
Boeing
AMETEK
Photon Energy
Sharp
NIMS
IBM (CZTSSe)
UCLA-Sumitomo Chemical
Heliatek
Matsushita
Monosolar
Kodak
Boeing
ARCO
United Solar
EPFL
EPFL
Kaneka (2 μm on glass)
United Solar
IBM (CZTSSe)
Konarka
Solarmer
Konarka
NREL / Konarka Univ. Linz
Sumi-tomo
UCLA
Boeing
RCA
Solarex
EPFL
Groningen
Plextronics
Univ. Dresden
Heliatek
Univ. of Toronto (PbS-QD)
University of Maine
RCA
RCA
RCA
RCA
RCA
RCA
University Linz
University Linz
Siemens
NREL (ZnO/PbS-QD)
44.0%
37.8%
37.7%
32.6%
30.8%
29.1%
28.8%
27.6%
26.4%
25.0%
24.7%
20.4%
20.1%
18.3%
13.4%
11.4%
11.1%
11.1%
10.6%
7.0%
(Rev. 02-2013)

Thank you



Have a nice day.