Solar Cells

History

- 1839: French physicist **Alexandre-Edmond Becquerel** (father of radioactivity pioneer Henri Becquerel) discovers some metals are photoelectric: they produce electricity when exposed to light.
- 1873: English engineer **Willoughby Smith** discovers that selenium is a particularly effective photoconductor (it's later used by Chester Carlson in his invention of the photocopier).
- 1905: German-born physicist **Albert Einstein** figures out the physics of the photoelectric effect, a discovery that eventually earns him a Nobel Prize.
- 1916: American physicist **Robert Millikan** proves Einstein's theory experimentally.
- 1940: **Russell Ohl** of Bell Labs accidentally discovers that a doped junction semiconductor will produce an electric current when exposed to light.
- 1954: Bell Labs researchers **Daryl Chapin**, **Calvin Fuller**, and **Gerald Pearson** make the first practical photovoltaic silicon solar cell, which is about 6 percent efficient (a later version manages 11 percent). They announce their invention—initially called the "solar battery"—on April 25.

History

- 1958: Vanguard, Explorer, and Sputnik space satellites begin using solar cells.
- 1962: 3600 of the Bell solar batteries are used to power Telstar, the pioneering telecommunications satellite.
- 1997: US Federal government announces its Million Solar Roofs initiative—to construct a million solar-powered roofs by 2010.
- 2002: NASA launches its Pathfinder Plus solar plane.
- 2009: Scientists discover that perovskite crystals have great potential as third-generation photovoltaic materials.
- 2014: A collaboration between German and French scientists produces a new record of 46 percent efficiency for a four-junction solar cell.
- 2020: Solar cells are predicted to achieve grid parity (solar-generated electricity you make yourself will be as cheap as power you buy from the grid).

Applications of Solar Cells

- Renewable energy
- Can be powered for remote locations
- It's free, limitless, and environmentally friendly…






What is a solar cell?

- A structure that converts solar energy directly to DC electric energy.
  - It supplies a voltage and a current to a resistive load (light, battery, motor).
- It is like a battery because it supplies DC power.
- It is different from a battery in the sense that the voltage supplied by the cell changes with changes in the resistance of the load.

Basic Physics of Solar Cells

- Silicon (Si) is from group 4 of the period table. When many Si atoms are in close proximity, the energy states form bands of forbidden energy states.
- One of these bands is called the band gap(Eg) and the absorption of light in Si is a strong function of Eg.

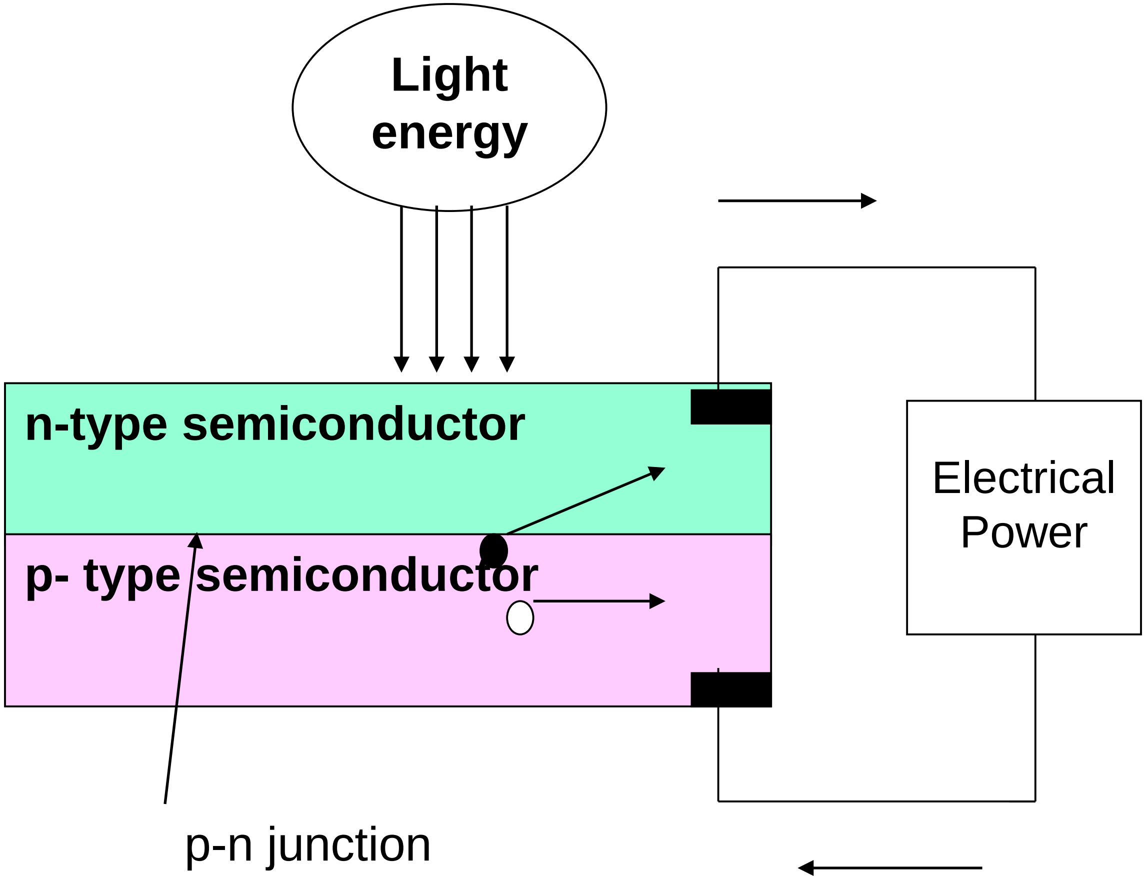
Basic Physics of Solar Cells

- Si is covalently bonded: It shares electrons.
  - When a Si atom is replaced with a group 3 (Al, B) it forms a positive particle called a hole that can move around the crystal through diffusion or drift (electric field).
  - When a Si atom is replaced with a group 5 (As, P) it forms an electron that can move around the crystal.
  - By selectively doping the Si Crystal when can change the resistivity and which type of carrier transfers charge (carries current). Because we can selectively dope a Si crystal it is called a semiconductor.

Photovoltaic effect

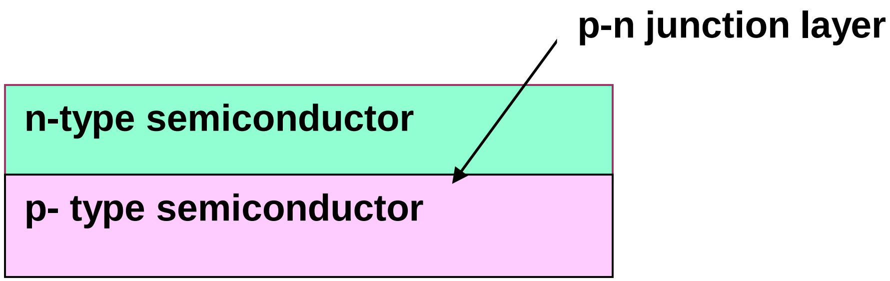
Definition:

The generation of voltage across the PN junction in a semiconductor due to the absorption of light radiation is called photovoltaic effect. The Devices based on this effect is called photovoltaic device.



Basics of solar cells

- If *two differently* contaminated semiconductor *layers* are combined, then a so-called *p-n-junction results* on the boundary of the layers.

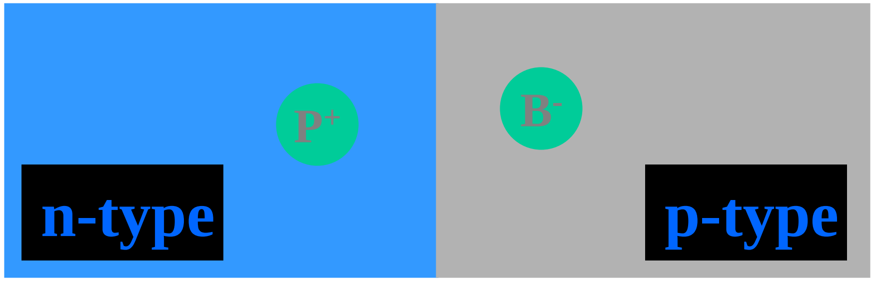


- By doping *trivalent* element, we get p-type semiconductor. (with excess amount of hole)

- By doping *pentavalent* element, we get n-type semiconductor (with excess amount of electron)

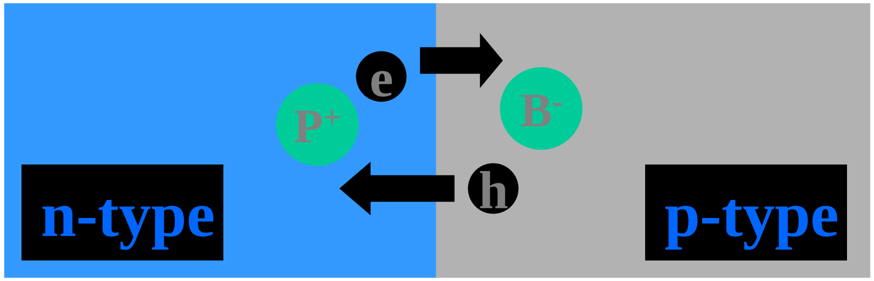
Physics of Solar Cells

- Semiconductor material can be p-type (hole carriers) or n-type (electron carriers)



- N-type has impurities with an extra electron (phosphorus)
- P-type has impurities with one fewer electron (boron)
- Put them together: p-n junction
- A solar cell is a very large p-n junction (or diode)

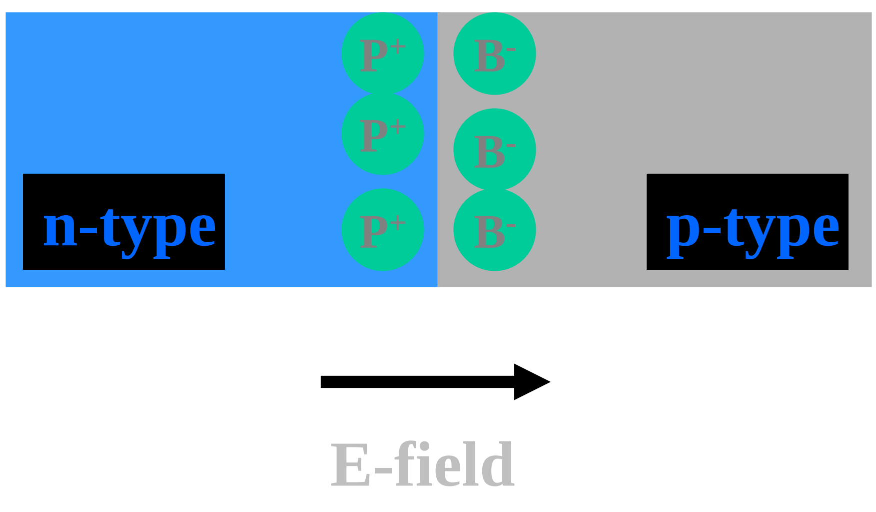
Basic Physics of Solar Cells



- The holes from the p-type side diffuse to the n-type side.
- The electrons diffuse to the p-type side.
- This leaves behind charged ions (missing electrons or holes).

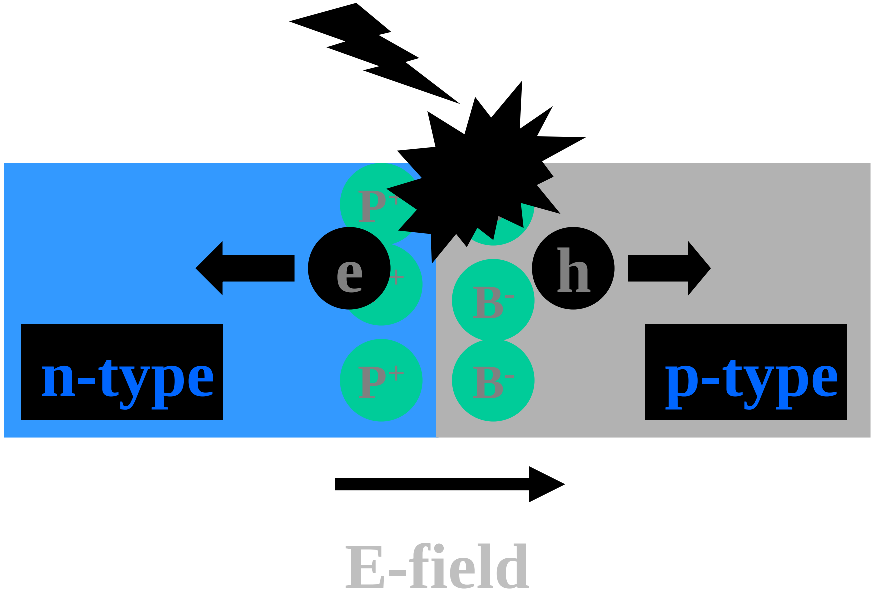
Built-In Electric Field

- The charged atoms (ions) create an electric field.
- This electric field makes it easy for current to flow in one direction, but hard to flow in the opposite direction.



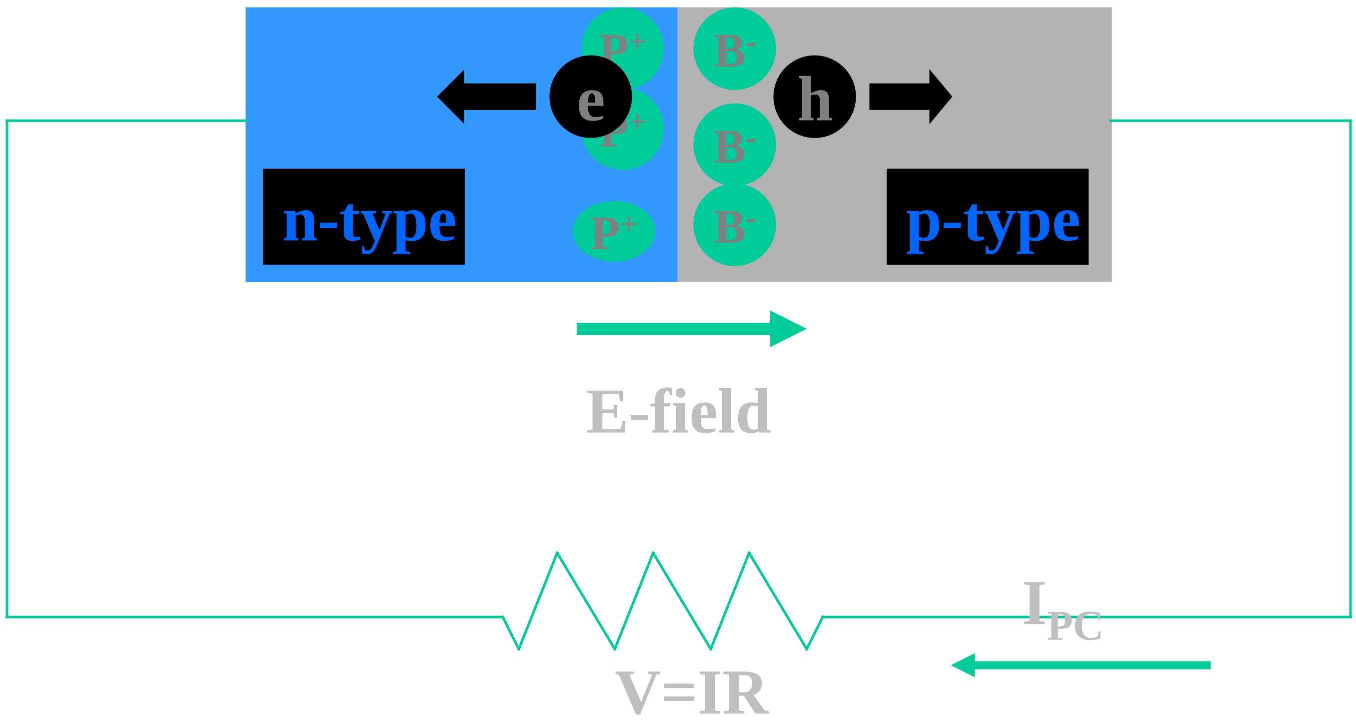
Generating Charges From The Sun

- Light breaks silicon bonds and creates “free” electrons and holes “missing electrons”
- Holes are positive charges
- Built-in field separates electrons and holes



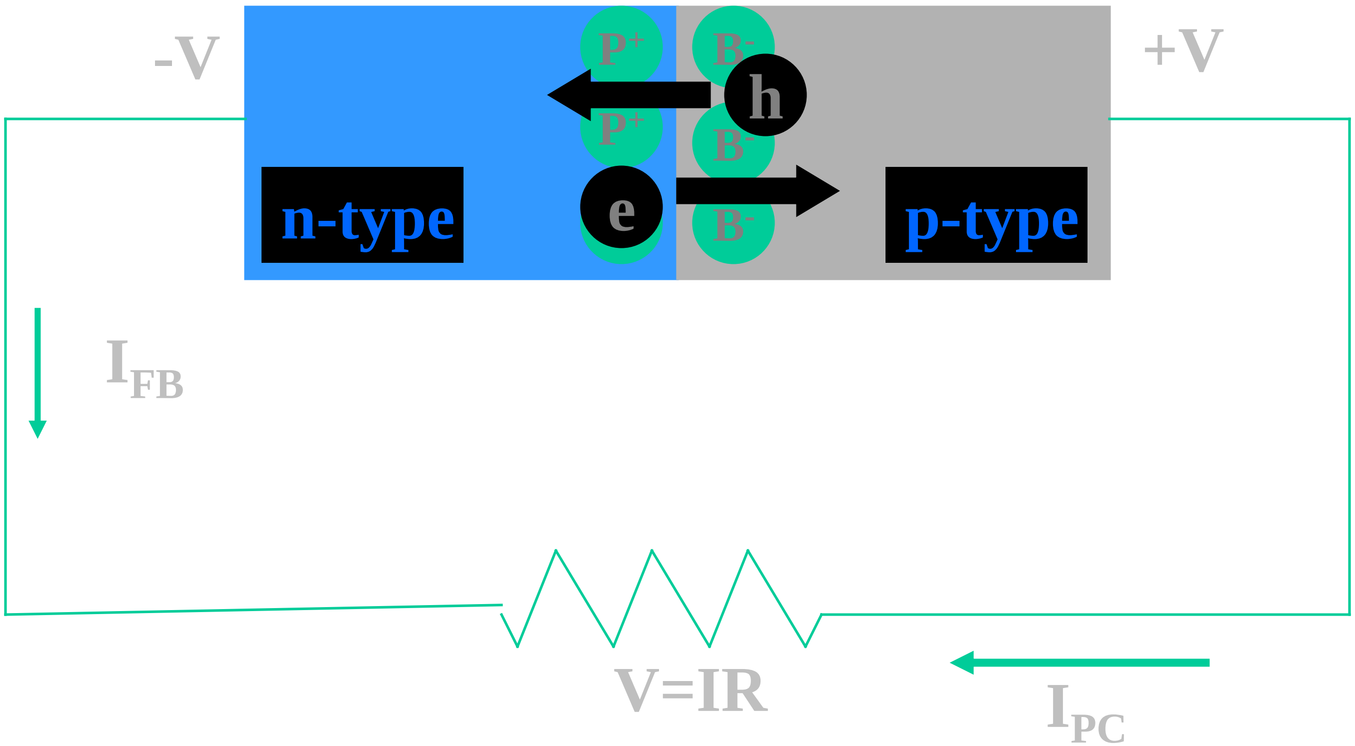
Generating Charges From The Sun

- Connect diode to a circuit
- Photocurrent goes through resistor
- Causes a voltage drop



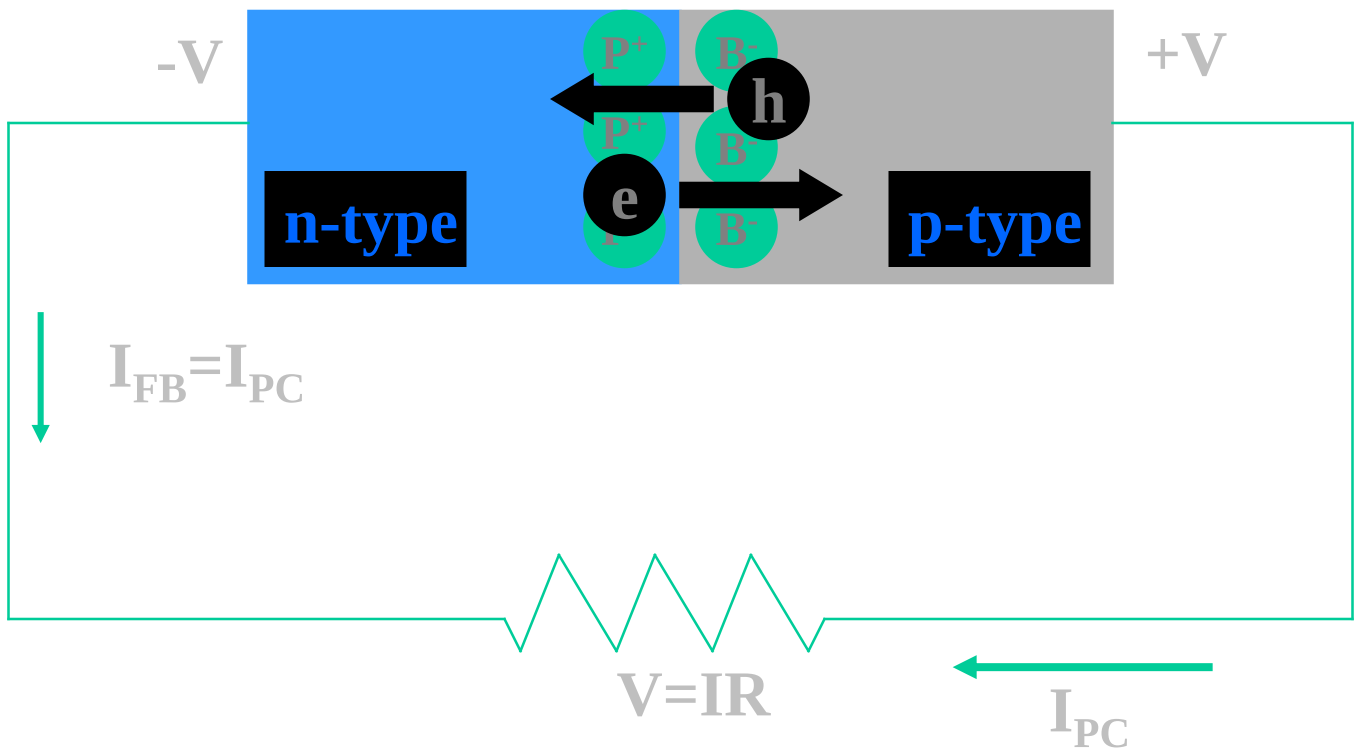
Generating Charges From The Sun

- Forward biases the diode
- Causes a current in opposite direction



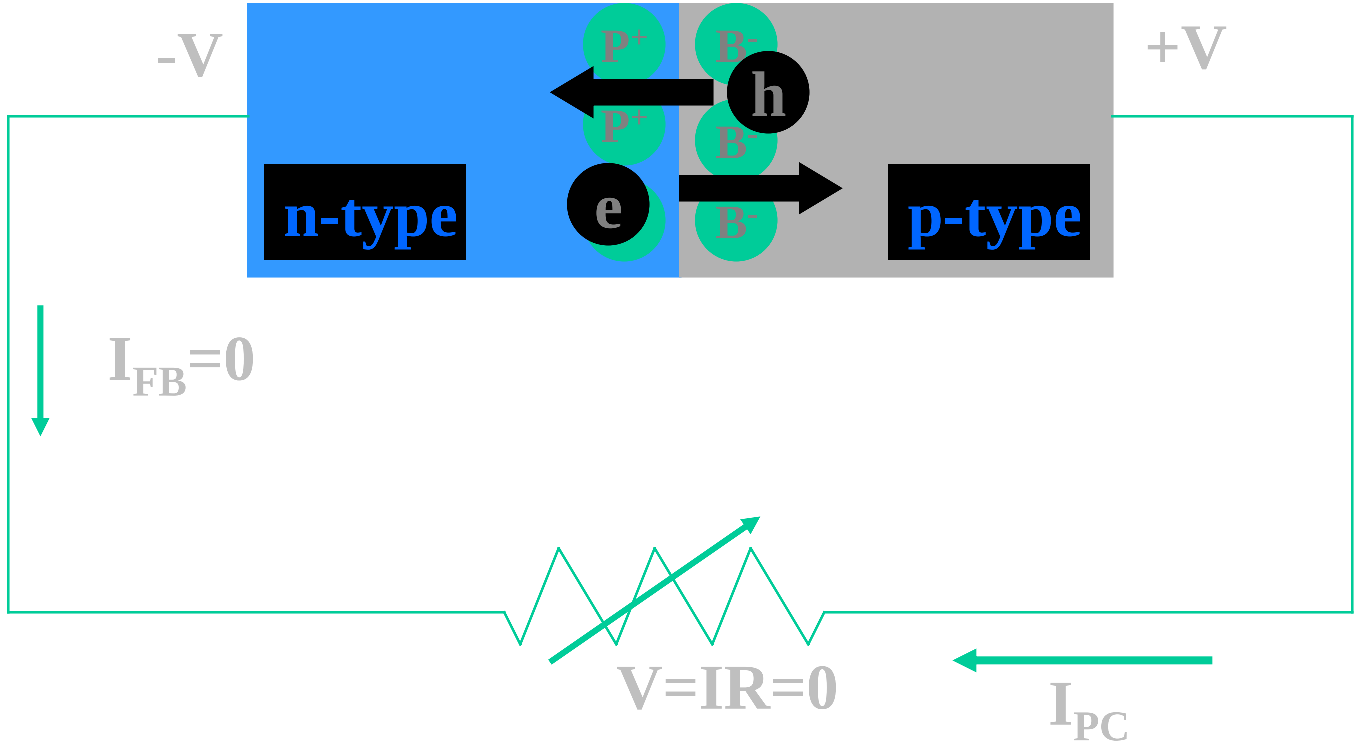
Generating Charges From The Sun

- If R is very large, V is very large
- If V is very large, $I_{FB} = I_{PC}$
- I=0
- Open Circuit condition



Generating Charges From The Sun

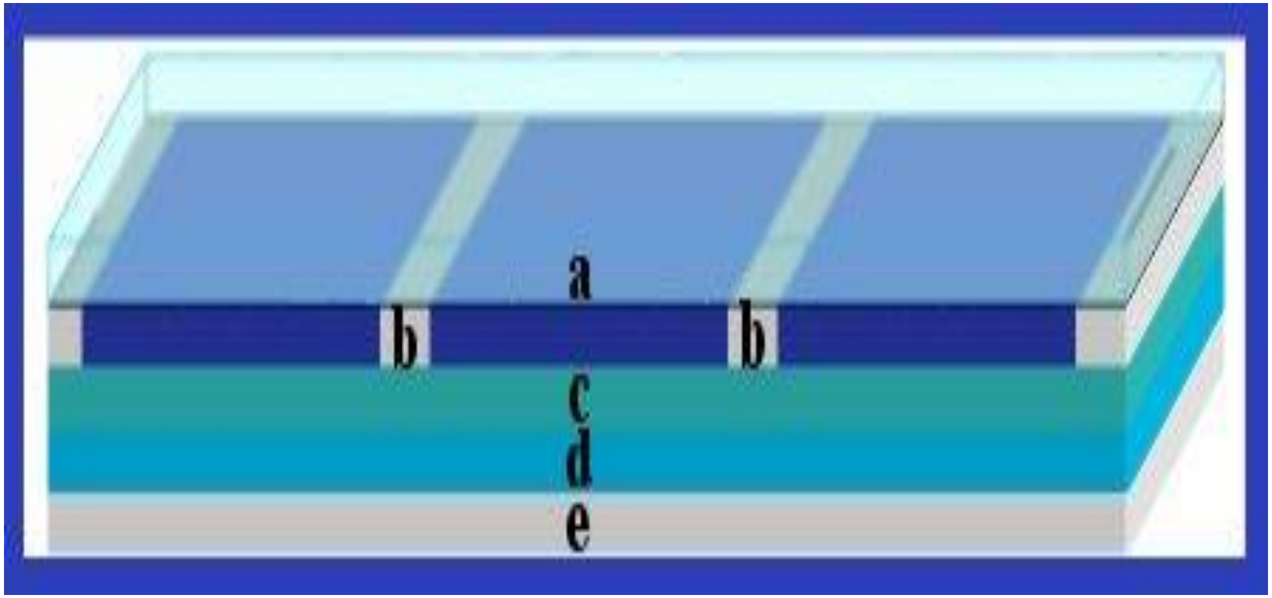
- If R is very small, V is very small
- If V = 0, $I_{FB} = 0$
- $I = I_{PC}$
- Short Circuit condition



Construction of Solar cells

- They are constructed by layering special materials called semiconductors into thin, flat sandwiches.
- These are linked by electrical wires and arranged on a panel of a stiff, non-conducting material such as glass. The panel itself is called a **module.**
- Modules are then interconnected, in series or parallel, or both, to create an **array** with the desired peak DC voltage and current.

http://www.specmat.com/Overview%20of%20Solar%20Cells.htm



a. Encapsulate

b. Contact Grid

c. Antireflective Coating

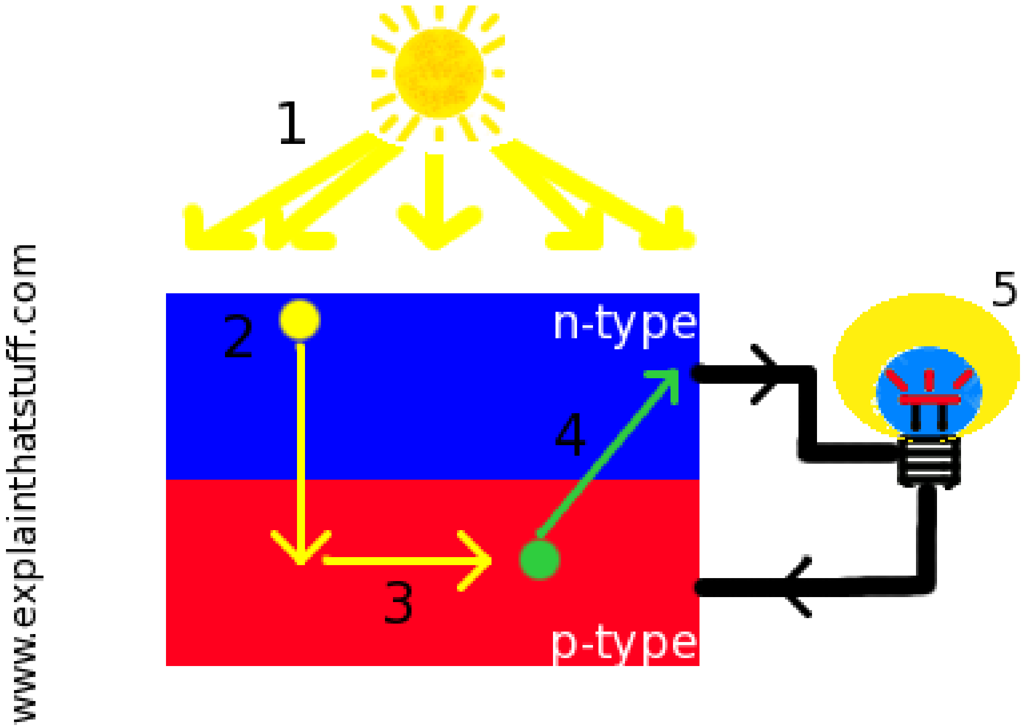
d. N-type Silicon

e. P-type Silicon

f. Back Contact

How Solar cells work

- Function 1: Photogeneration of charge carriers (electrons and holes) in a light-absorbing material
- Function 2: Separation of the charge carriers to a conductive medium such as a metal contact or a wire in order to transmit the electricity
  - ✓
  - ✓



1. A solar cell is a sandwich of n-type silicon (blue) and p-type silicon (red).
2. When sunlight shines on the cell, photons (light particles) bombard the upper surface.
3. The photons (yellow dot) carry their energy down through the cell.
4. The photons give up their energy to electrons (green dot) in the lower, p-type layer.
5. The electrons use this energy to jump across the barrier into the upper, n-type layer and escape out into the circuit.
6. Flowing around the circuit, the electrons make the lamp light up.

http://www.explainthatstuff.com/solarcells.html

Solar Cell Properties

- Open circuit voltage (V_{OC})
- Short circuit current (I_{SC})
- Maximum power
- Efficiency

Factors affecting Solar Cell Performance

- Light intensity (type of light)
- Light wavelength (color of light)
- Angle of incident light
- Surface condition of solar cells (cleanness)
- Temperature on solar cells

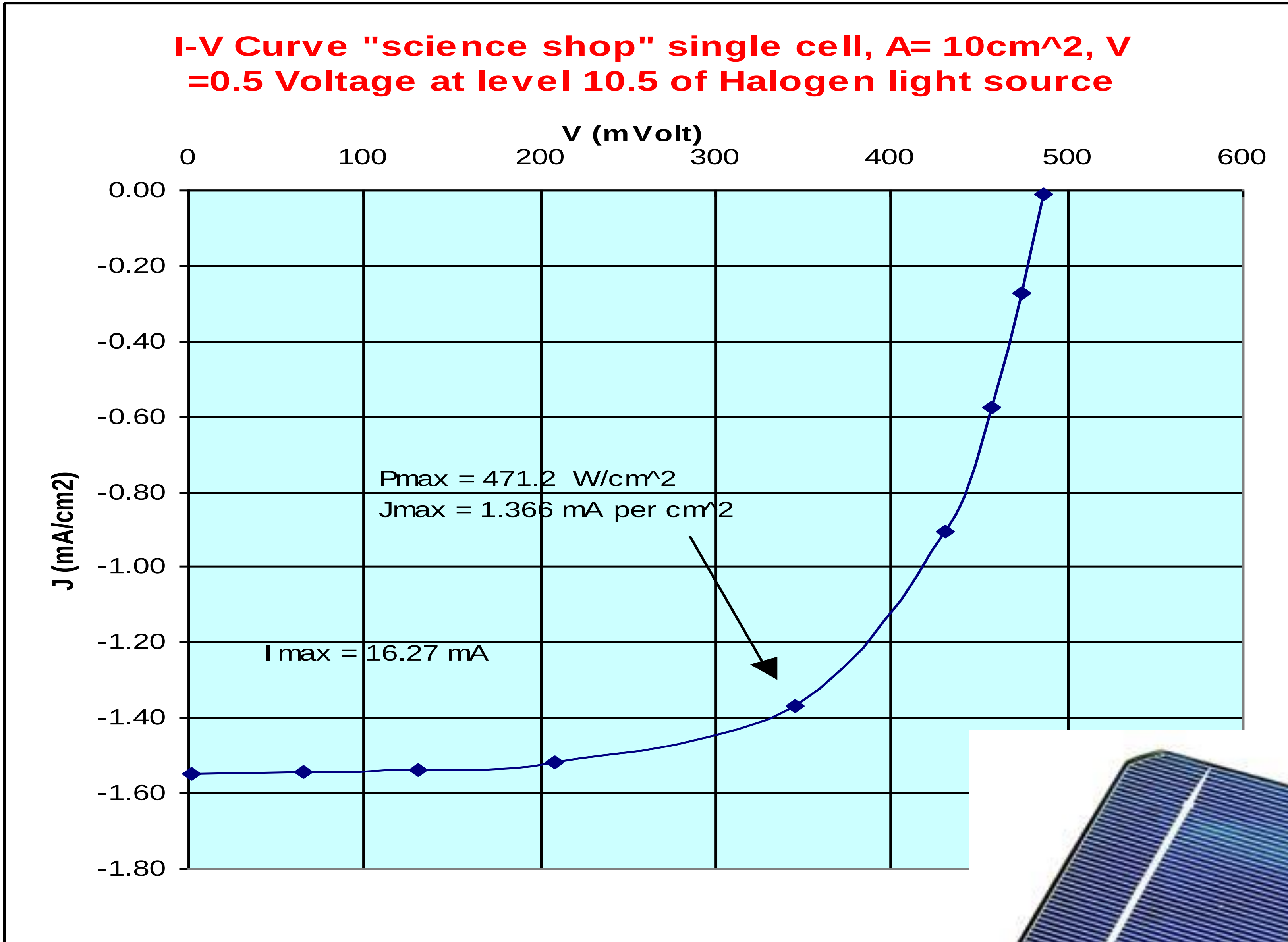
Peak Power Point (Maximum Power)

- A solar cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a *short circuit*) to a very high value (an *open circuit*) one can determine the maximum-power point, the point that maximizes V×I, that is, the load for which the cell can deliver maximum electrical power at that level of irradiation.
- Dynamically adjust the load so the maximum power is *always* transferred, regardless of the variation in lighting.

Efficiency

- A solar cell's *energy conversion efficiency* (η, "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of P_m, divided by the input light *irradiance* under "standard" test conditions (E, in W/m²) and the *surface area* of the solar cell (A_c in m²).

$$\eta = \frac{P_m}{E \times A_c}$$


I-V Curve "science shop" single cell, A= 10cm^2, V =0.5 Voltage at level 10.5 of Halogen light source
V (mVolt)
0
100
200
300
400
500
600
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
J (mA/cm2)
Pmax = 471.2 W/cm^2
Jmax = 1.366 mA per cm^2
I max = 16.27 mA

Solar Cell Process Flow

- Start with n-type silicon wafers
- Cleaning the wafers

  Sulfuric: peroxide - removes organics

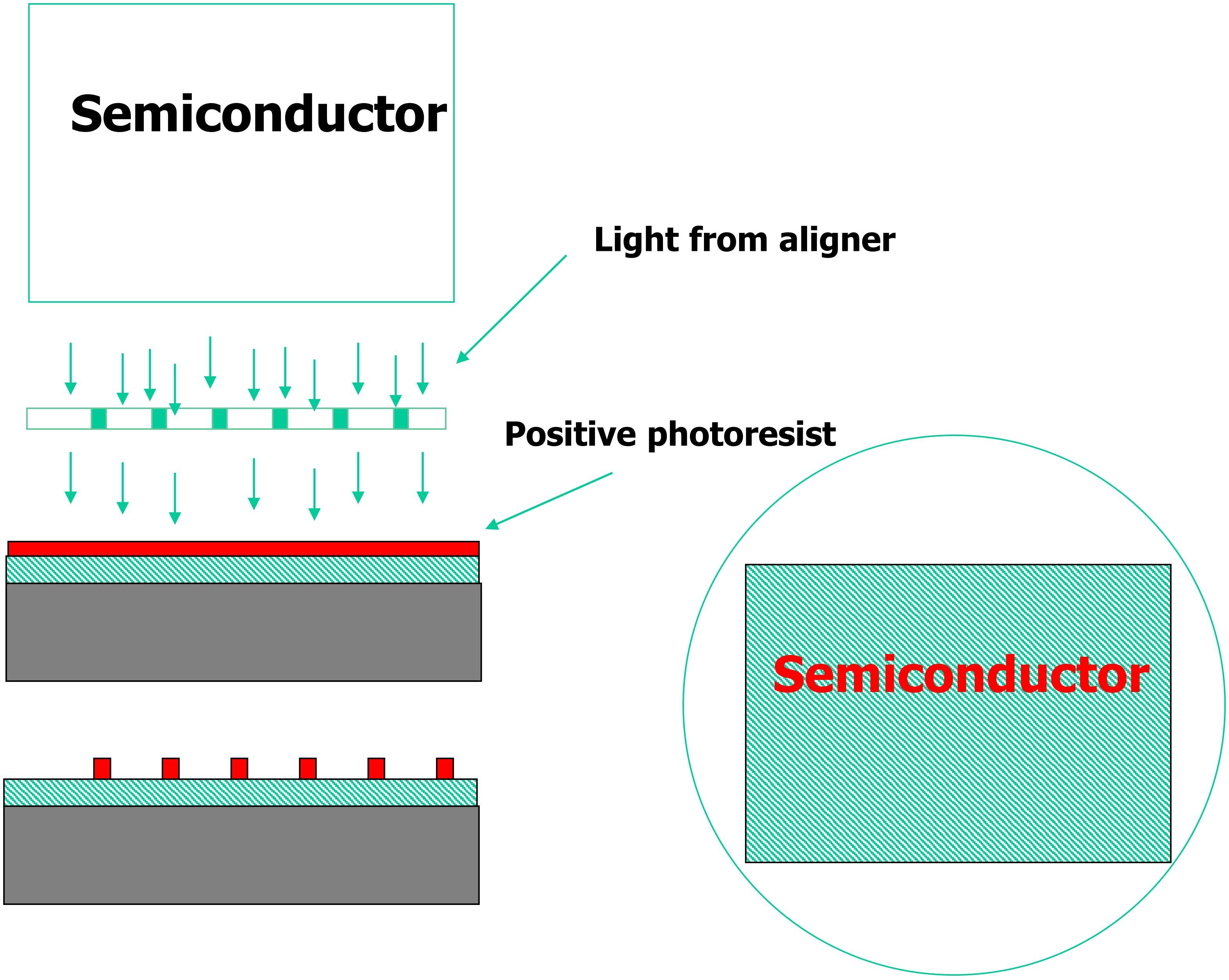
  Buffered Hydrofluoric acid - removes residual oxide

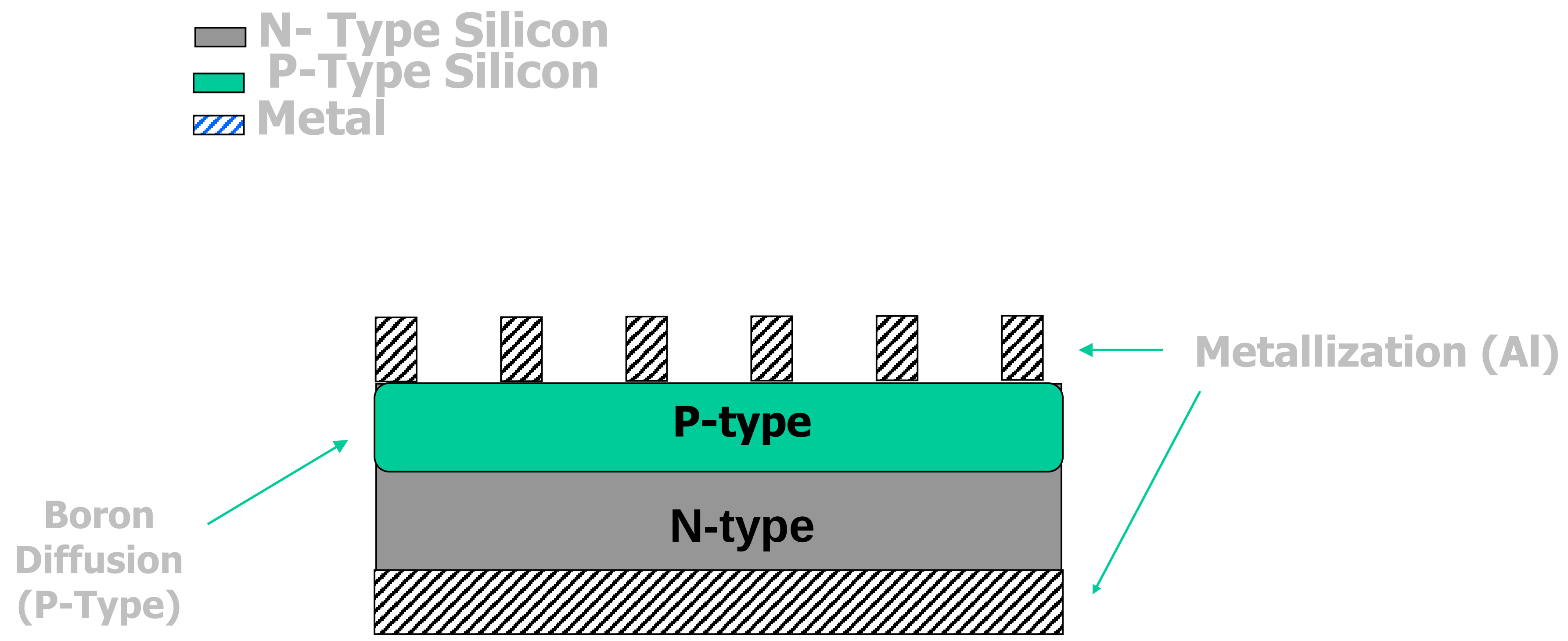
  HCl: peroxide - removes heavy metals
- Spin on dopant: a liquid source of boron (p-type impurity)
- Anneal: $1000^{o}C$ furnace step drives B into wafer (forming diode).

Solar Cell Process Flow

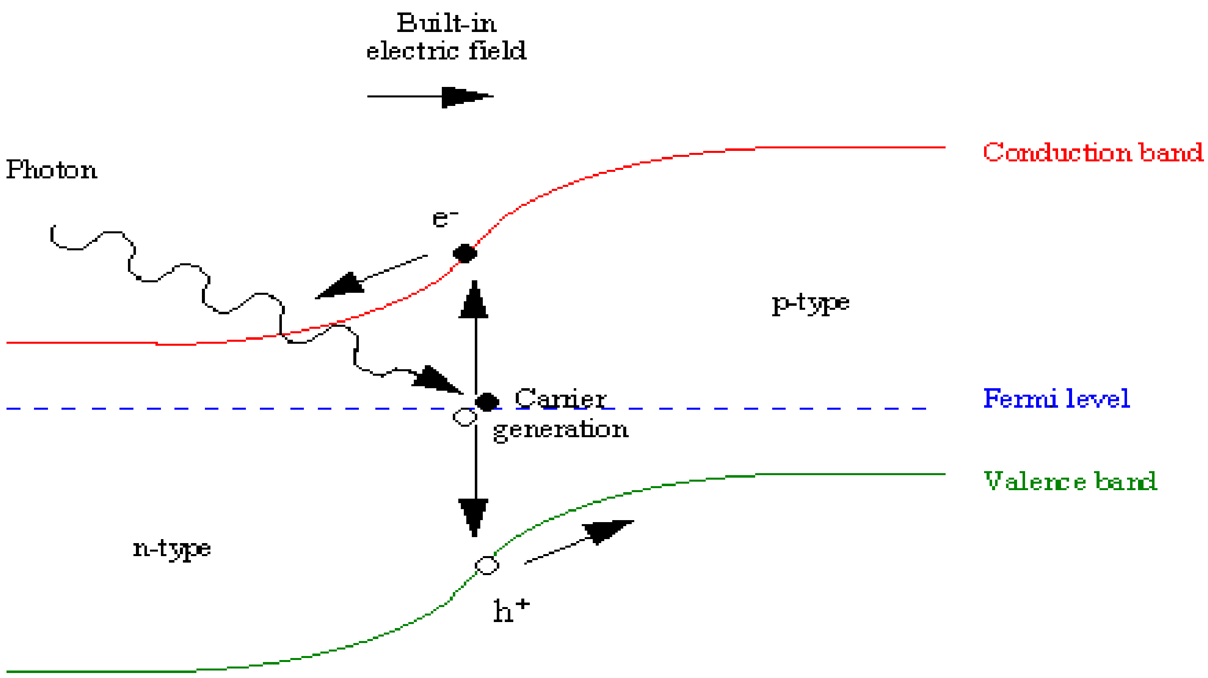
- **Metallization:** Aluminum deposited on the front and backside of the wafer.
- **Patterning:** Resist is spun on the front and back sides of the wafer and exposed using a mask and UV light. The exposed resist is removed during developing.
- **Metal Etch:** The pattern from the mask is transferred to the metal using a wet metal etch. The remaining photoresist is then removed.
- **Metal Anneal:** The wafer is annealed at 400C to improve the conductivity of the metal.

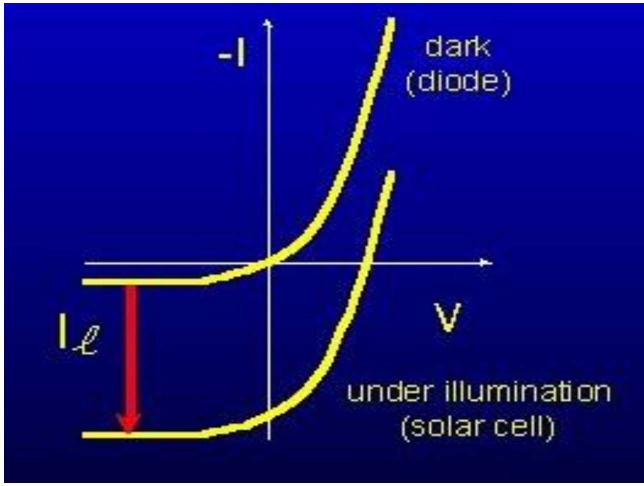
MASK LEVEL 1


Semiconductor
Light from aligner
Positive photoresist
Semiconductor


N- Type Silicon
P-Type Silicon
Metal
Metallization (Al)
P-type
N-type
Boron
Diffusion
(P-Type)

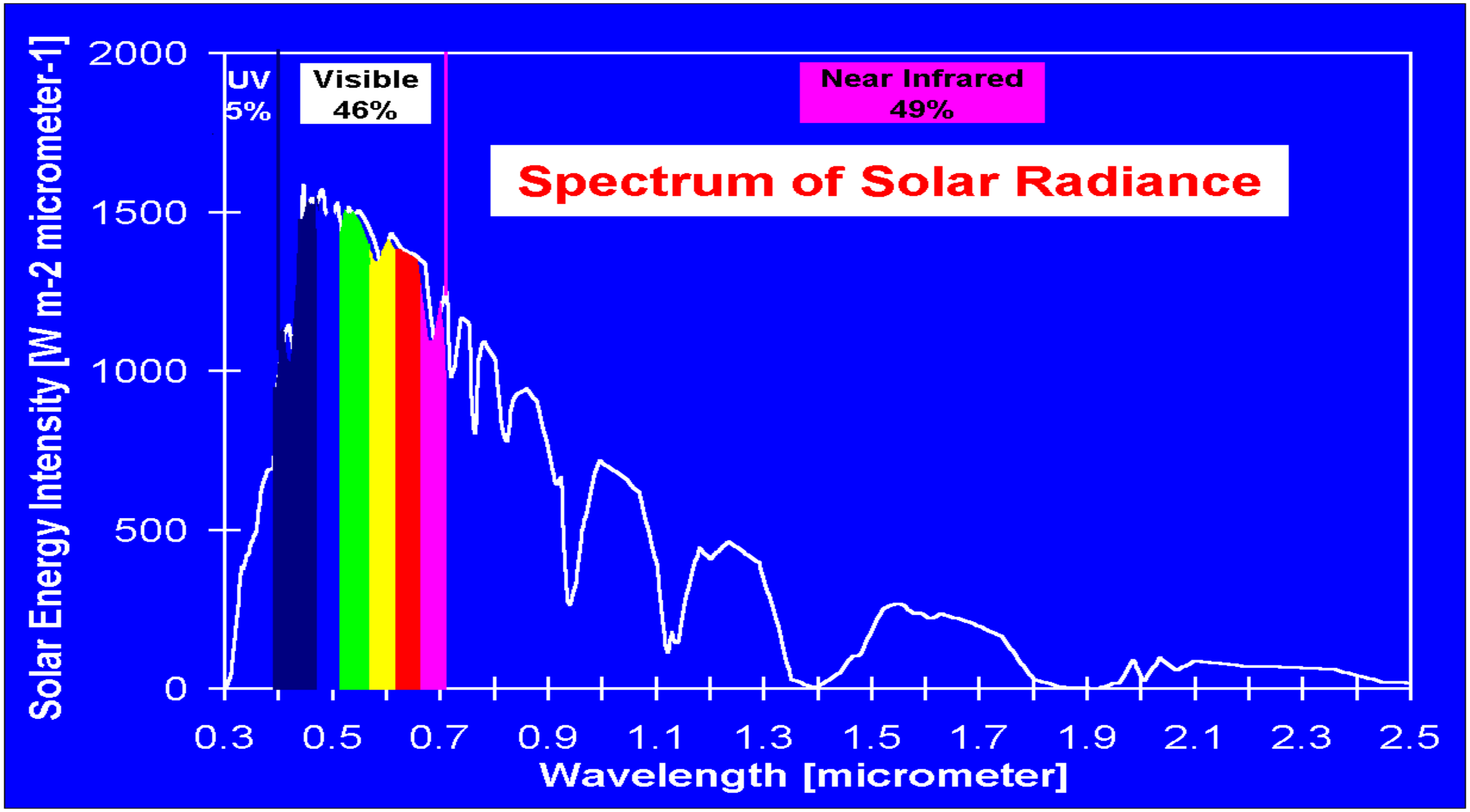
Solar Cell Principle





- Operating diode in fourth quadrant generates power

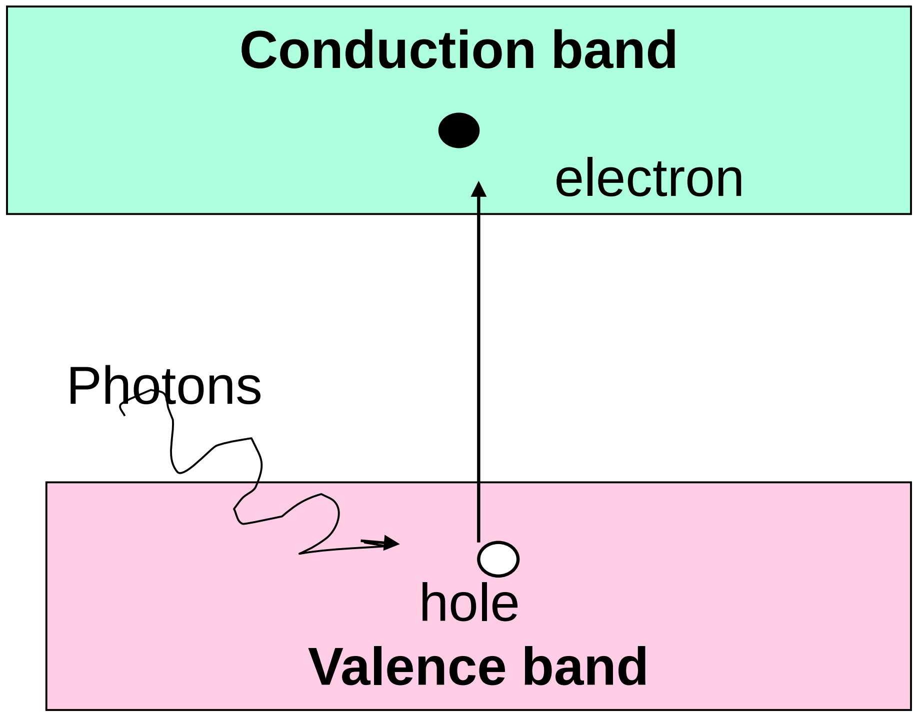
Solar Energy Spectrum

- 

- Power reaching earth 1.37 KW/m^2

Electron Hole Formation

- Photovoltaic energy conversion relies on the number of *photons striking the earth*. (photon is a flux of light particles)
- On a clear day, about *4.4 x 10^{17} photons* strike a square centimeter of the Earth's surface every second.
- Only some of these photons - those with *energy in excess of the band gap* - can be converted into electricity by the solar cell.
- When such photon enters the semiconductor, it may be absorbed and *promote an electron* from the valence band to the conduction band.



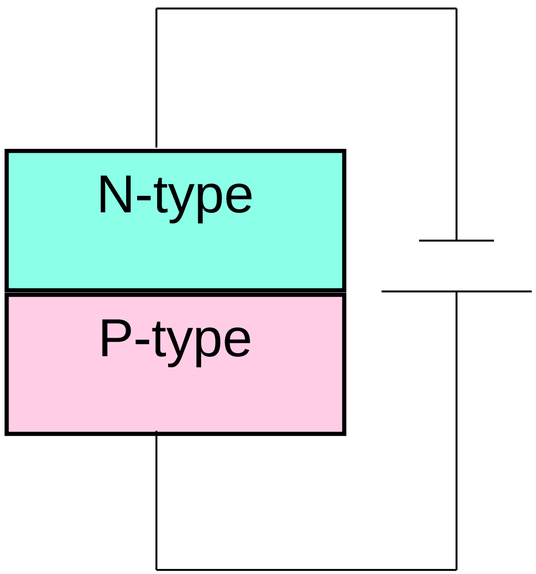
- Therefore, a *vacant is created* in the valence band and it is called hole.
- Now, the electron in the conduction band and hole in valence band *combine together* and forms *electron-hole pairs*.

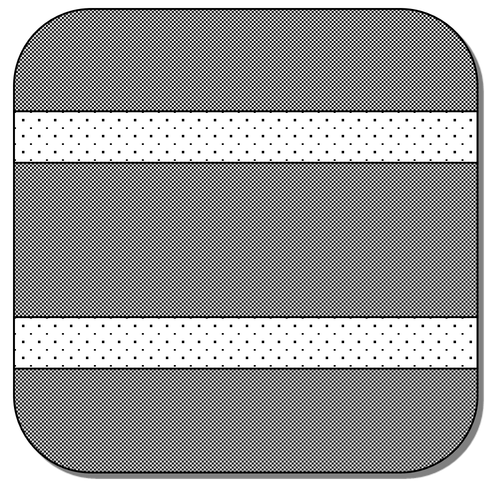
A solar panel (or) Solar array

Single solar cell

- The single solar cell constitute the *n-type* layer *sandwiched* with p-type layer.
- The most *commonly* known *solar cell* is configured as a large-area p-n junction made from *silicon wafer*.
- A *single cell* can produce only very *tiny* amounts of *electricity*
- It can be used only to light up a small light bulb or power a calculator.
- Single photovoltaic cells are used in many small electronic appliances such as watches and calculators

Single Solar cell

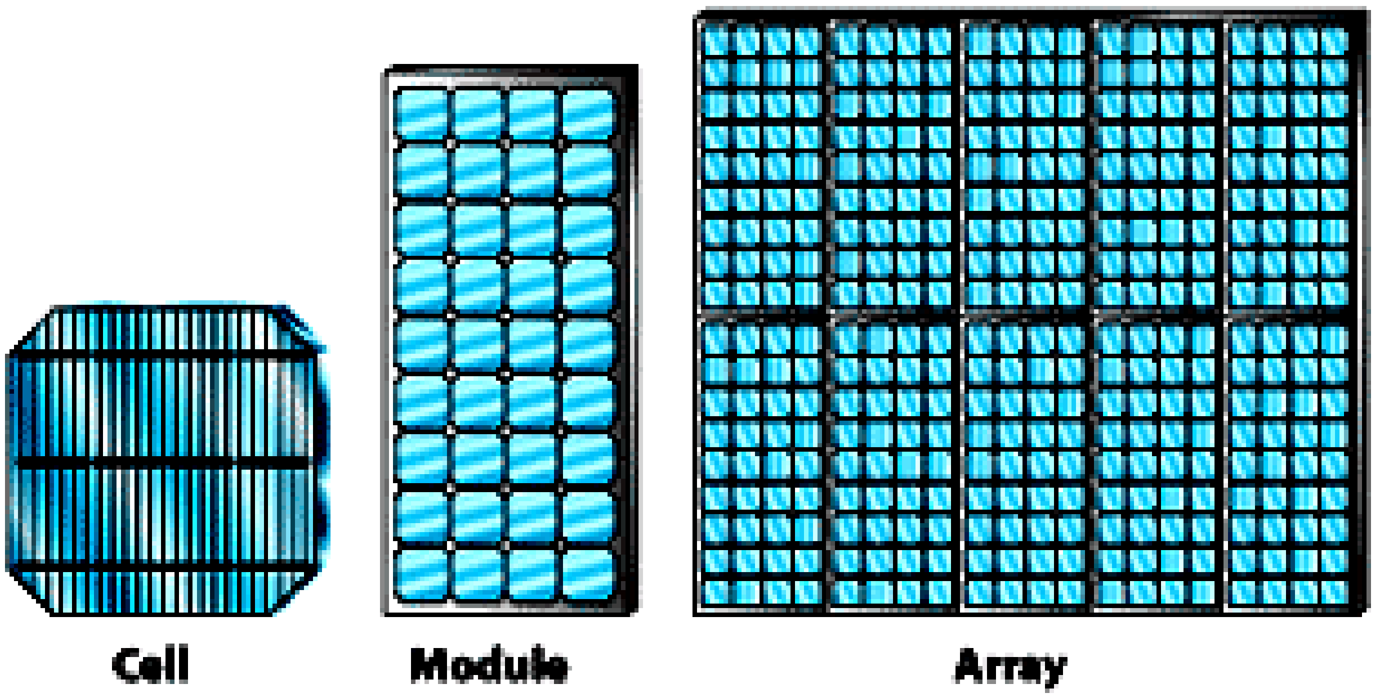




Solar panel (or) solar array (or) Solar module

The solar panel (or) solar array is the interconnection of number of solar module to get efficient power.

- A solar module consists of number of interconnected solar cells.
- These interconnected cells embedded between two glass plate to protect from the bad whether.
- Since absorption area of module is high, more energy can be produced.


Cell
Module
Array

Types of Solar cell

Based on the types of crystal used, soar cells can be classified as,

1. Monocrystalline silicon cells
2. Polycrystalline silicon cells
3. Amorphous silicon cells

1. The Monocrystalline silicon cell is produced from *pure silicon (single crystal).* Since the Monocrystalline silicon is pure and defect free, the efficiency of cell will be higher.

2. In polycrystalline solar cell, *liquid silicon* is used as raw material and polycrystalline silicon was obtained followed by *solidification process*. The materials contain various crystalline sizes. Hence, the efficiency of this type of cell is less than Monocrystalline cell.

Amorphous Silicon

Amorphous silicon is obtained by *depositing silicon film on the substrate like glass plate.*

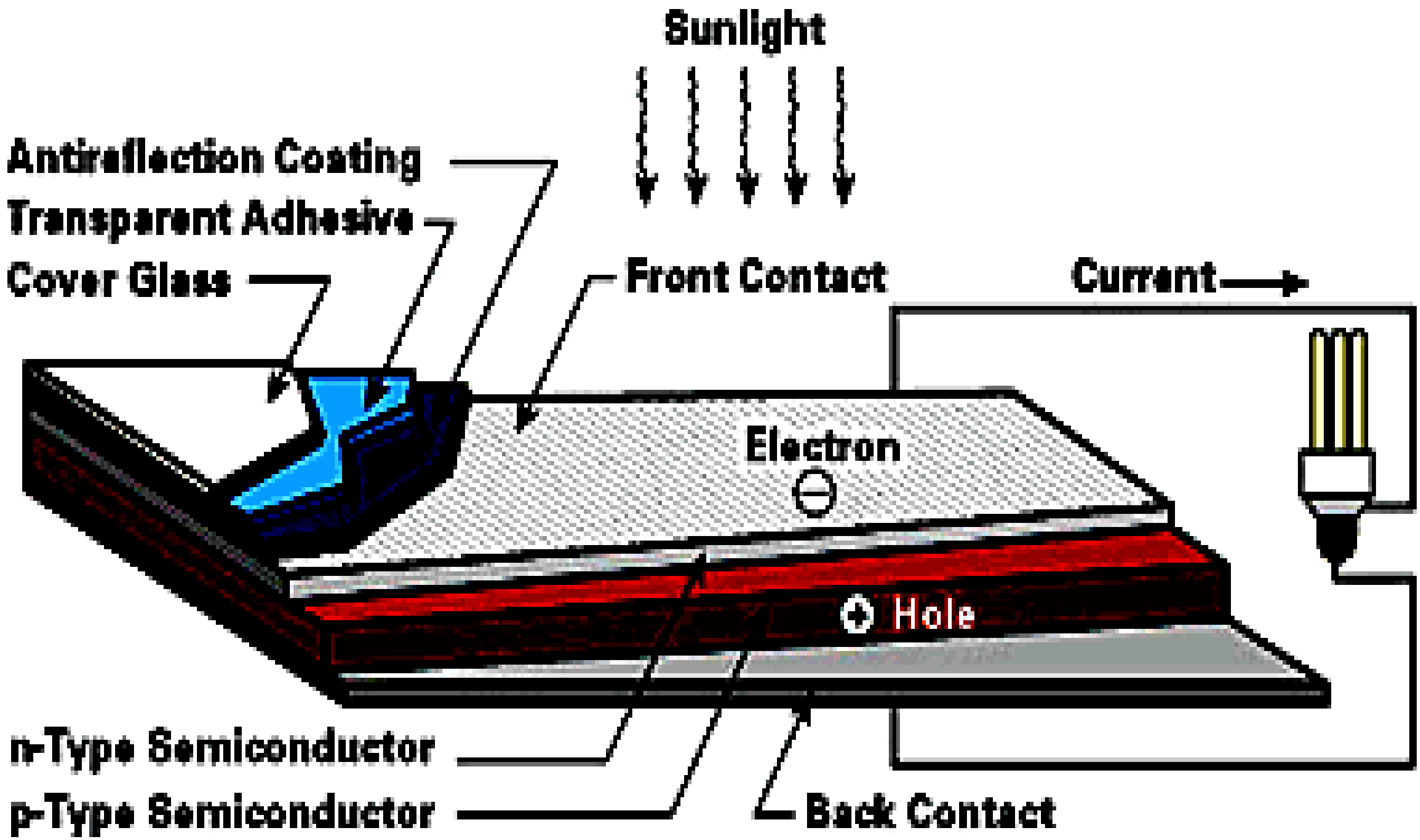
- The layer thickness amounts to less than 1µm – the thickness of a human hair for comparison is 50-100 µm.

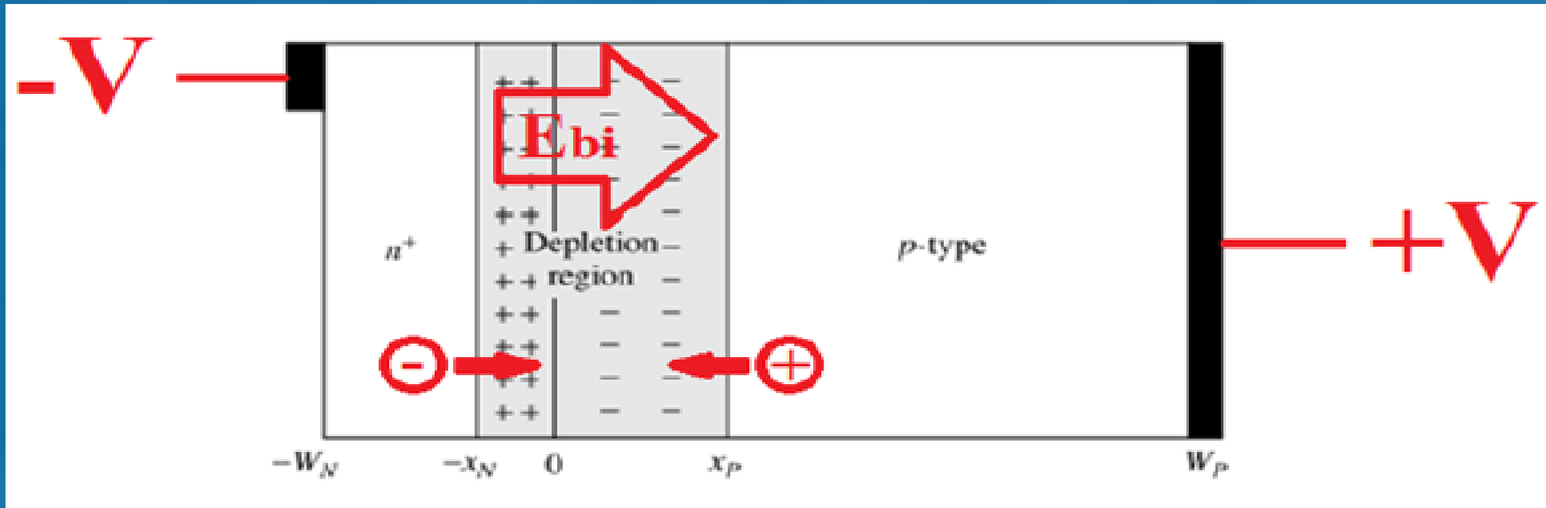
- The efficiency of amorphous cells is much lower than that of the other two cell types.

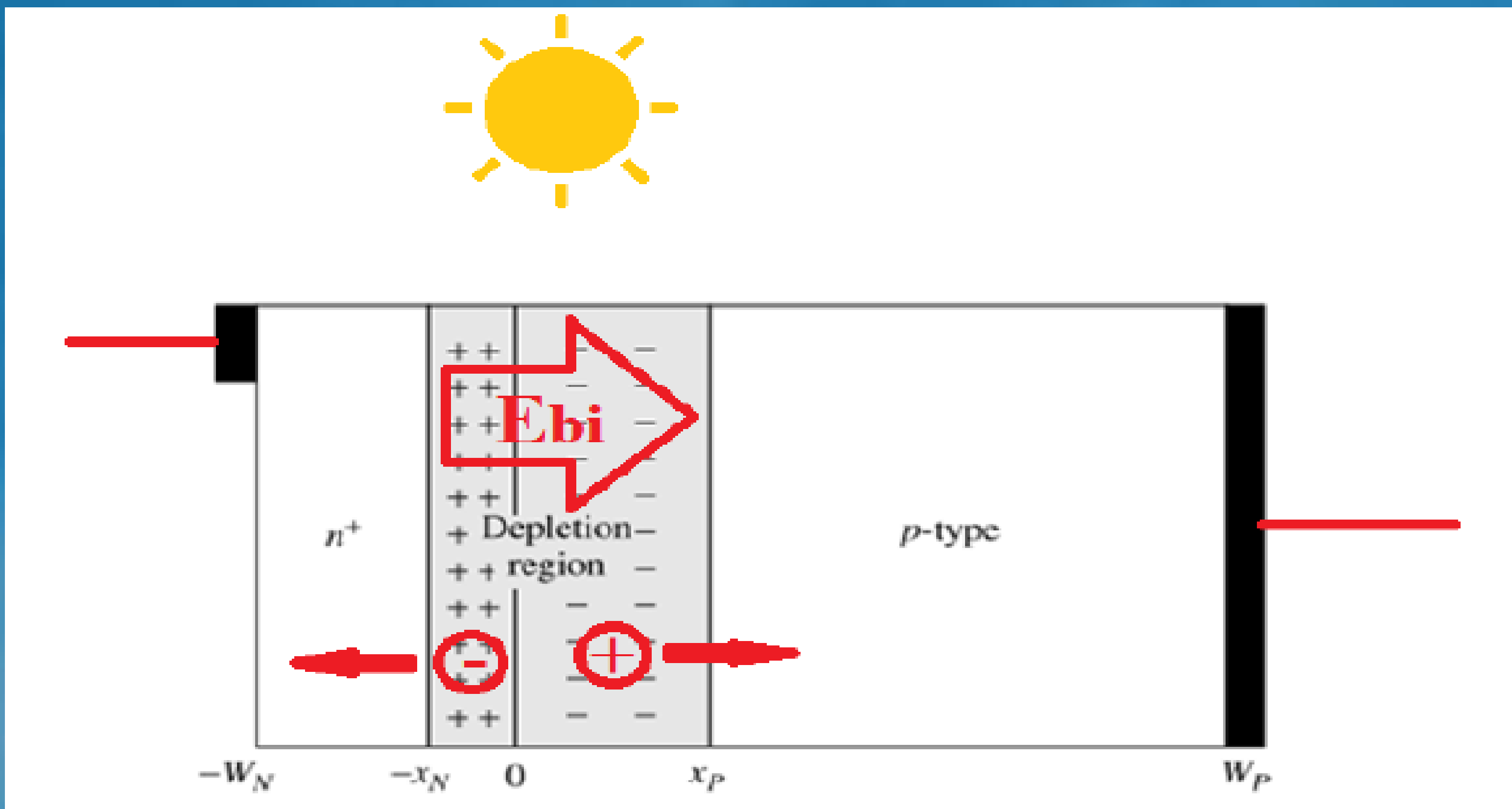
- As a result, they are used mainly in low power equipment, such as watches and pocket calculators, or as facade elements.

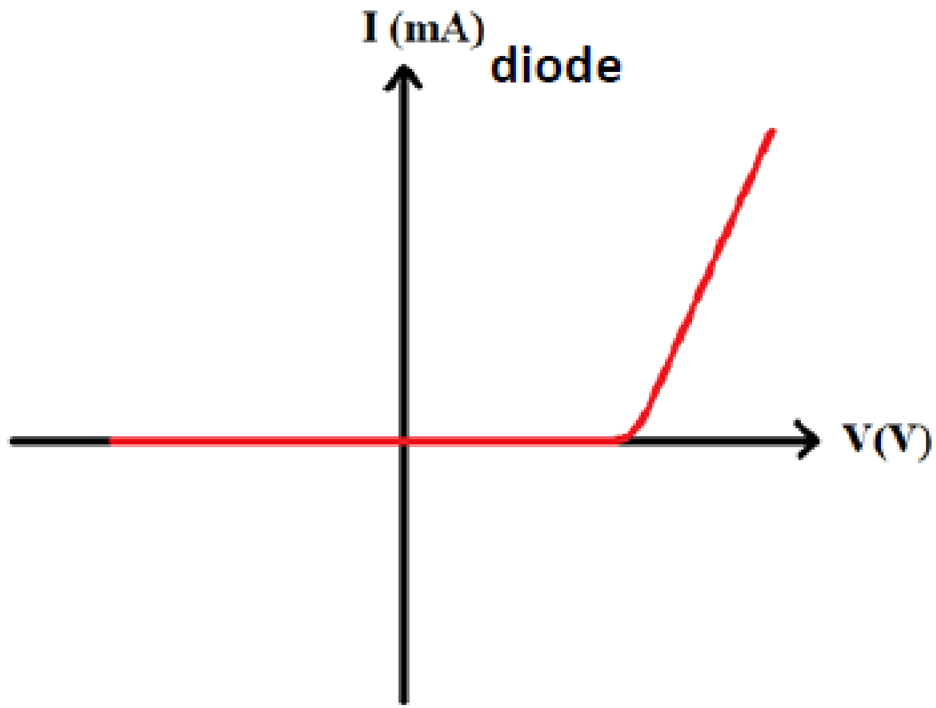
Comparison of Types of solar cell

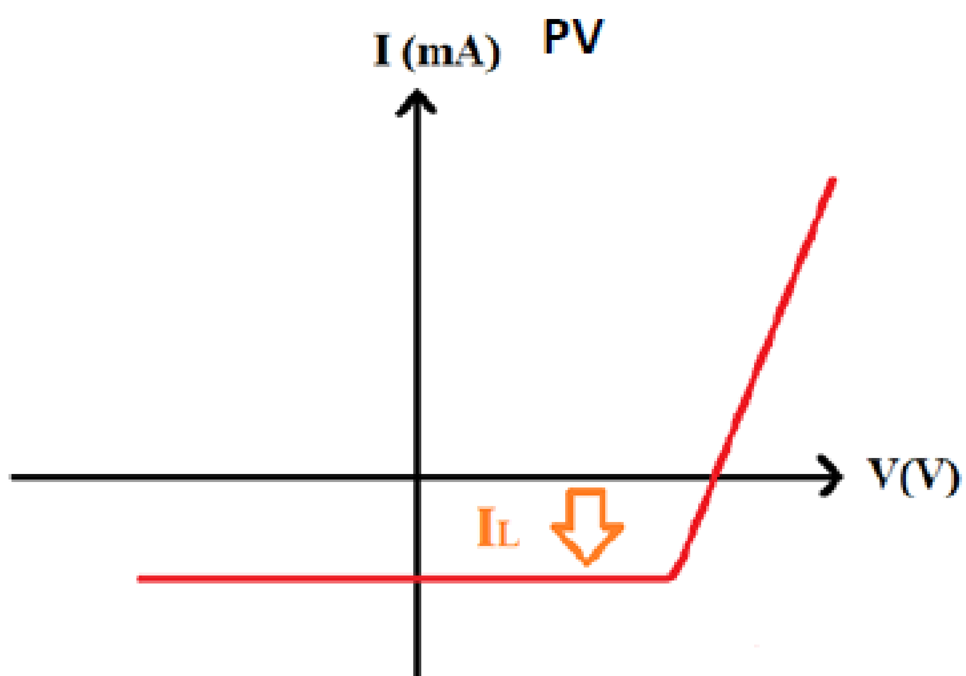
Material	Efficiency (%)
Monocrystalline silicon	14-17
Polycrystalline silicon	13-15
Amorphous silicon	5-7

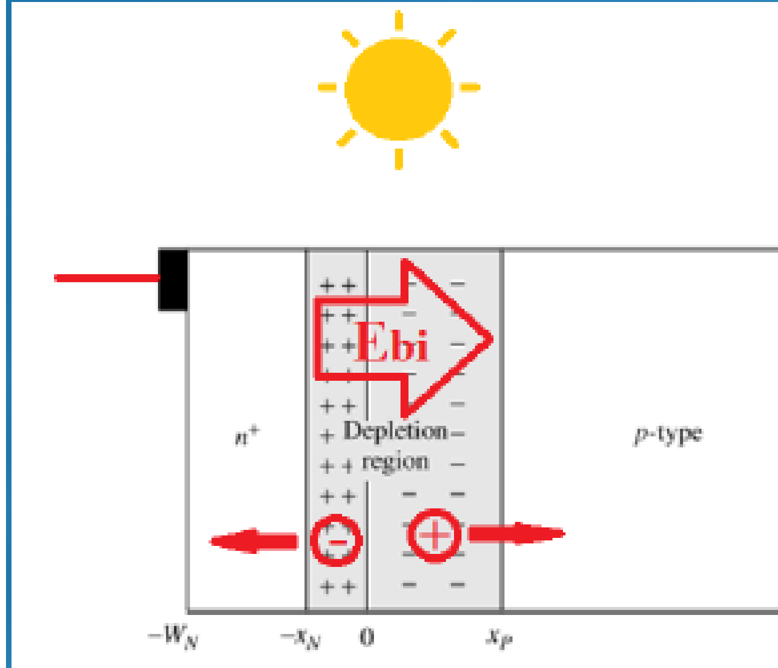

Sunlight
Antireflection Coating
Transparent Adhesive
Cover Glass
Front Contact
Current
Electron
Hole
n-Type Semiconductor
p-Type Semiconductor
Back Contact

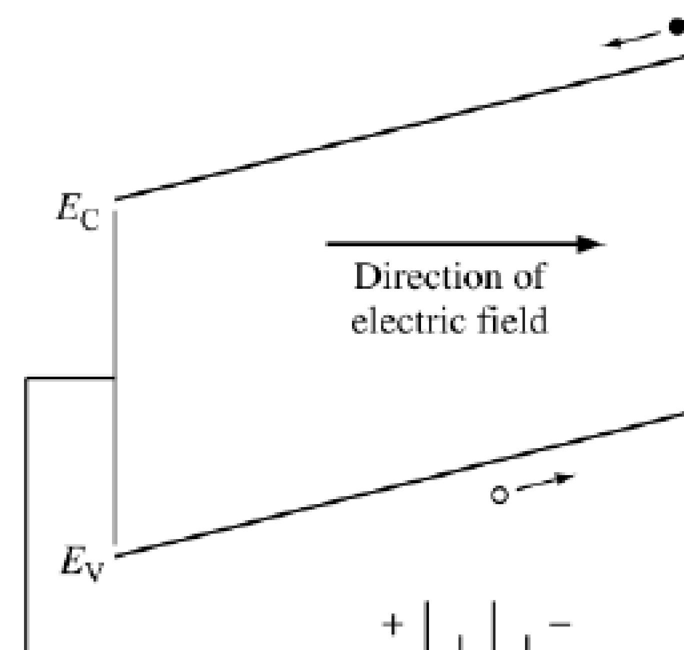

-V
+V
Ebi
n+
Depletion region
p-type
−W_N
−x_N
0
x_P
W_P

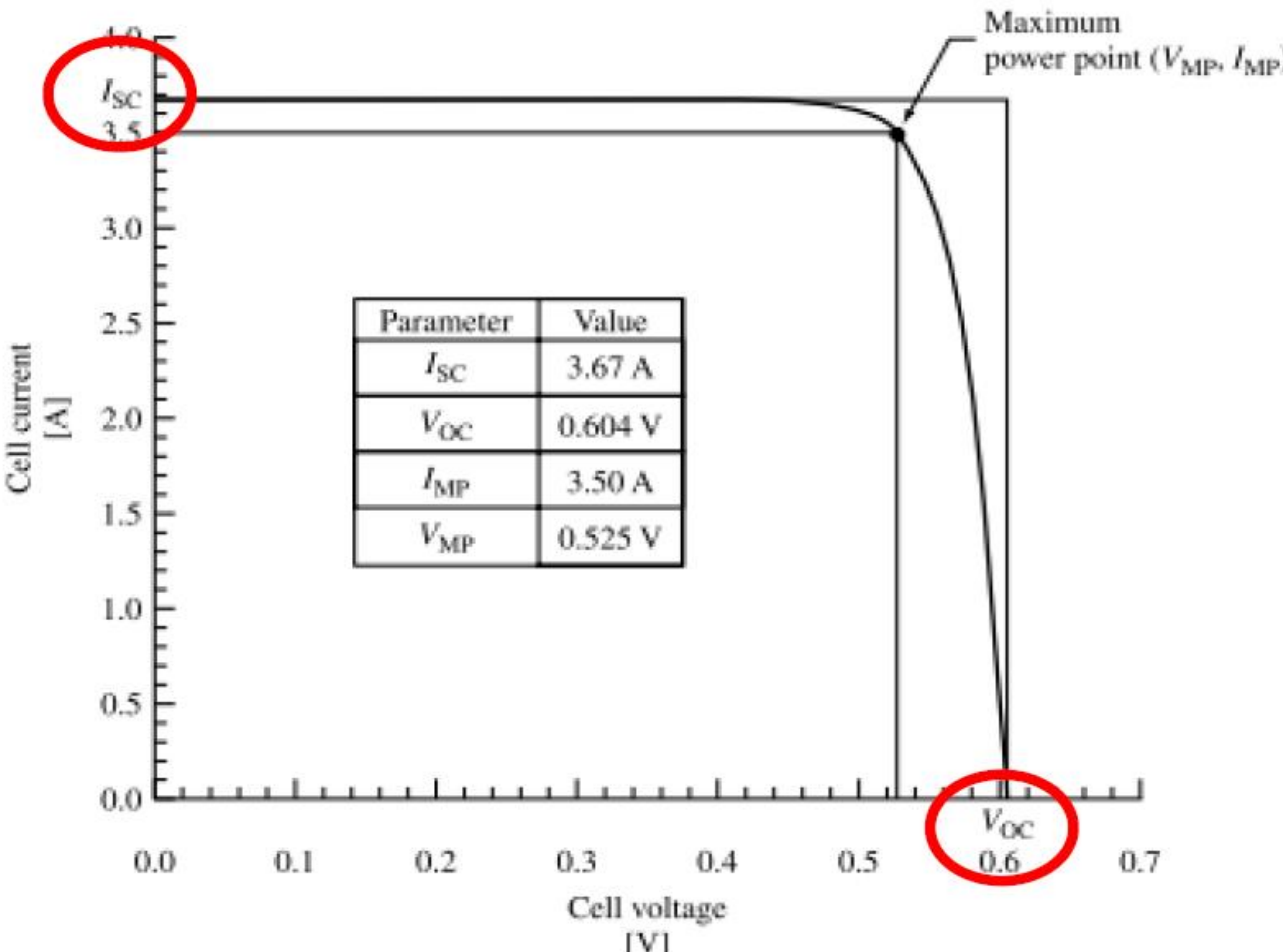

Ebi
n+
Depletion region
p-type
−W_N
−x_N
0
x_P
W_P


I (mA)
diode
V(V)


I (mA)
PV
V(V)
IL


Ebi
Depletion region
n+
p-type
−WN
−xN
0
xP

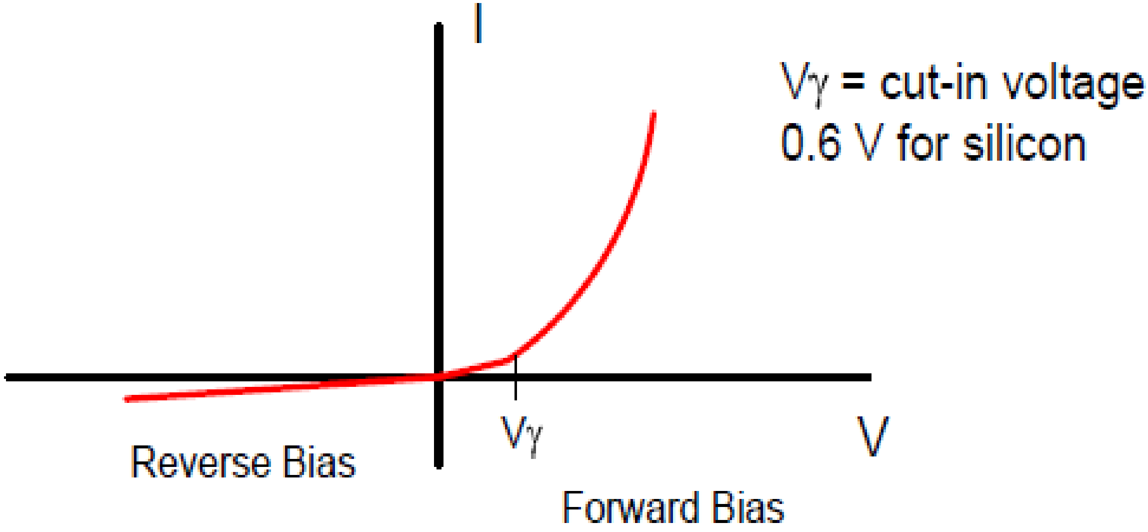

EC
Direction of electric field
EV


Maximum
power point (V_{MP}, I_{MP})
I_{SC}
Cell current
[A]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Parameter | Value
I_{SC} | 3.67 A
V_{OC} | 0.604 V
I_{MP} | 3.50 A
V_{MP} | 0.525 V
V_{OC}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Cell voltage
[V]

PN Junction-Diode Operation

PN Junction Characteristic

Junction conducts when forward biased



$$I = I_s(e^{V/V_T} - 1)$$

V_T = Voltage-equivalent of Temperature = 0.026 V at room temperature

I_s = saturation current depends on junction area and doping

- There are two currents in a solar cell

1. Current due to reverse biased junction (I_S) (Diode Current)
2. Current due to photovoltaic effect (I_L) [Also called reverse current]
3. The two currents are in opposite directions

$$I = I_s(e^{V/V_T} - 1)$$

$$I = I_s(e^{V/V_T} - 1) - I_L$$

$$V_{OC} = V_T \ln\left(\frac{I_L}{I_S} + 1\right)$$

$$I_{SC} = I_L$$

“OC” : Open Circuit

“SC” : Short Circuit

$$I = I_s(e^{V/V_T} - 1) - I_L$$

$$P = IV = I_S V\left(e^{V/V_T} - 1\right) - I_L V$$

$$V_{\max} = V_T \ln\left(\frac{I_L/I_S + 1}{V_{\max}/V_T + 1}\right)$$

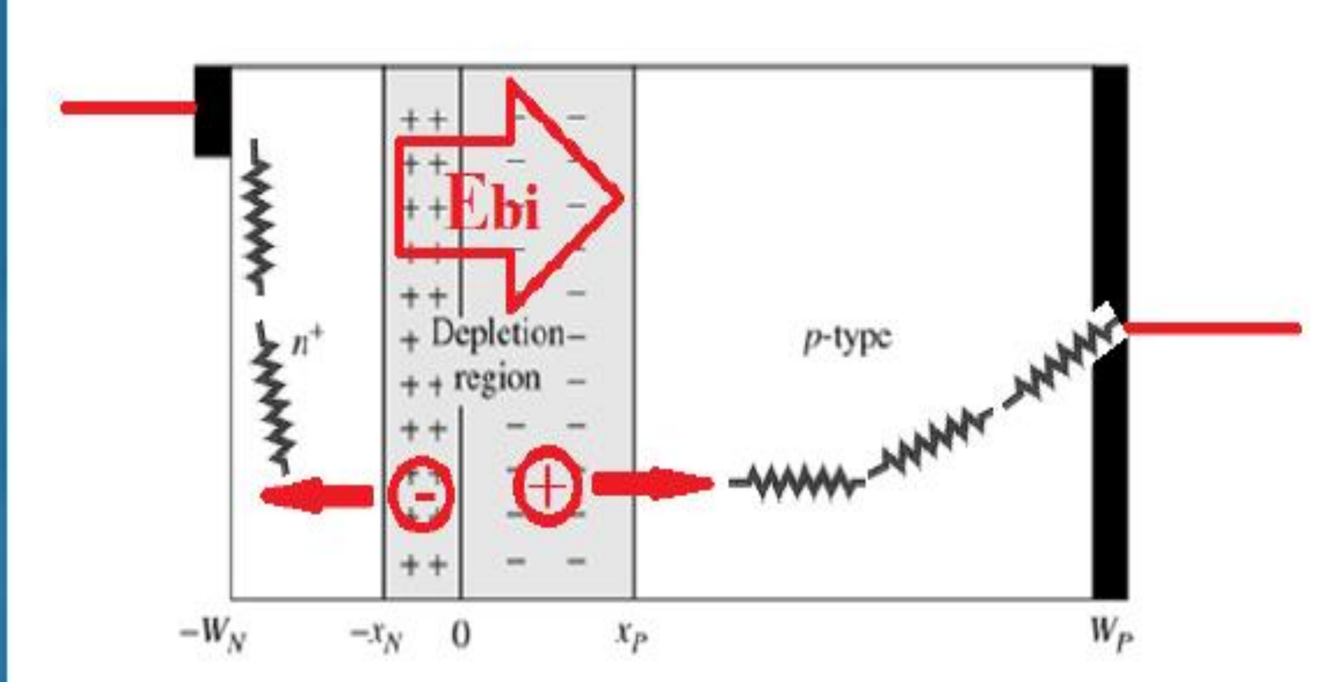
$$I_{\max} = I_S \frac{V_{\max}}{V_T} e^{V_{\max}/V_T}$$

$V_T = kT/e$

$$P_{\max} = I_{\max} V_{\max}$$

$$\eta \equiv \frac{P_{\max}}{P_{in}}$$

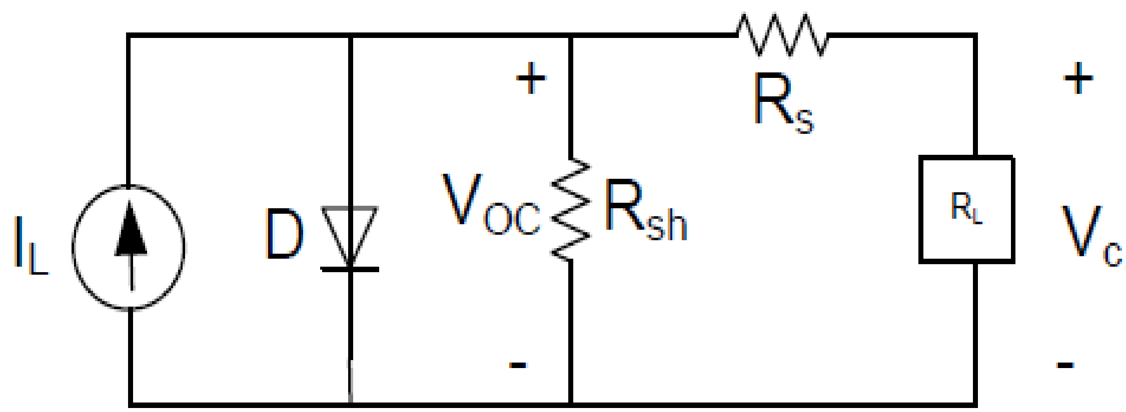
$$FF \equiv \frac{P_{\max}}{I_{sc} V_{oc}}$$



$$I = I_s\left(e^{V/V_T} - 1\right) - I_L \rightarrow I = I_S\left(e^{(V - IR_s)/V_T} - 1\right) - I_L$$

Rs : Series Resistance

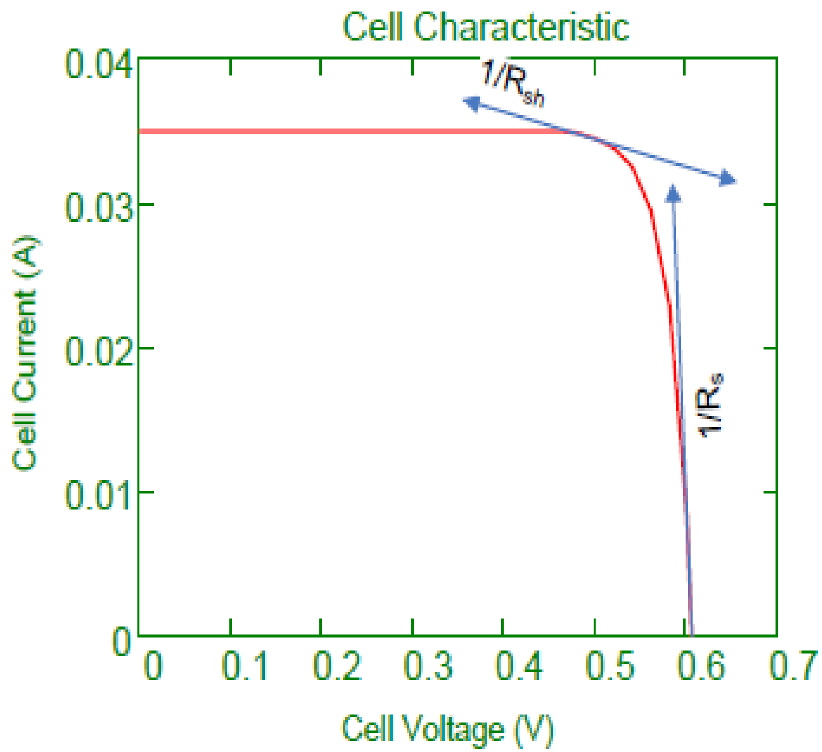
Circuit Model of Solar Cell



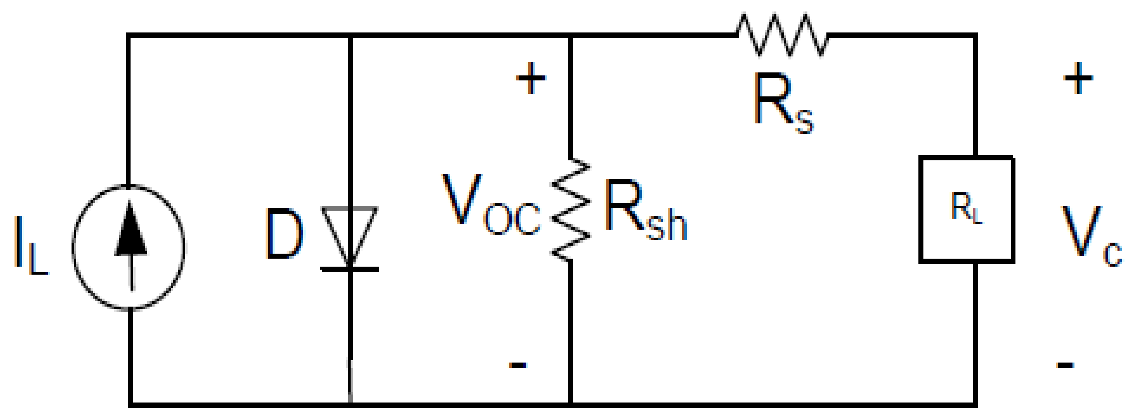
R_s slope of characteristic near V_{oc}

R_{sh} slope of characteristic near I_{sc}

Values determined by cell construction



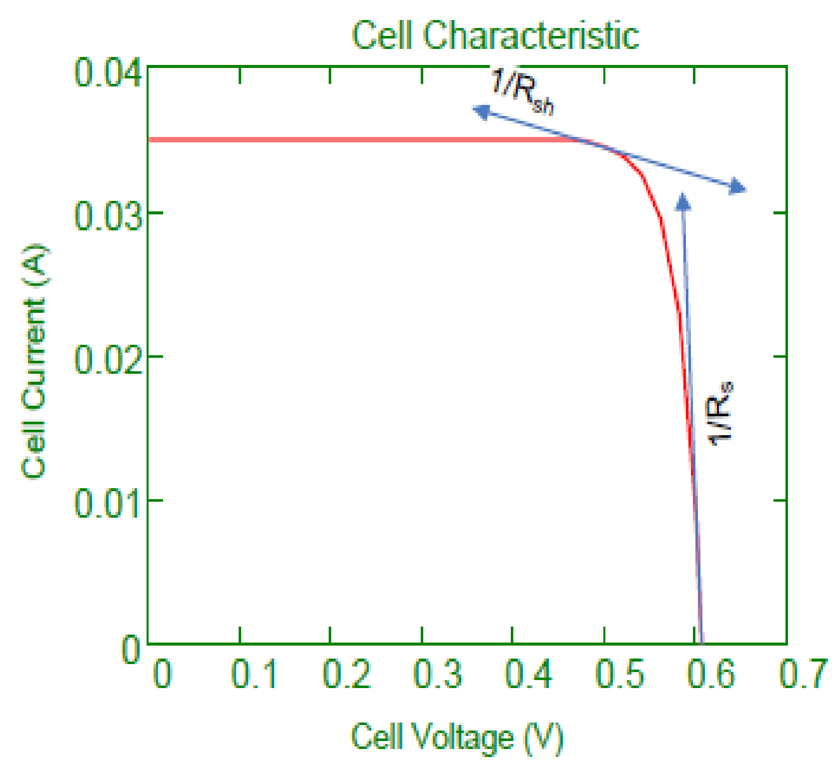
Circuit Model of Solar Cell



Total current, $I = I_L - I_D - I_{SH}$

$V_C = V_{OC} + IR_S$
$I_{SH} = V_{OC} / R_S$
$I_D = I_S(\exp(V/V_T - 1)$

When I=0, the voltage which
we get at the output (V_C) is open circuit voltage
Neglecting, shunt resistance, we get,
$V_{OC} = V_T \ln(I_L / I_S + 1)$
At short circuit, $V_C = 0$, $I_{SC} = I$



Open Circuit Voltage/Short Circuit Current

Open circuit means $R=\infty$ and $I_C=0$, so open circuit voltage is

$$V_{OC} = V_T \ln\left(1+\frac{I_L}{I_s}\right) \approx V_T \ln\left(\frac{I_L}{I_s}\right)$$

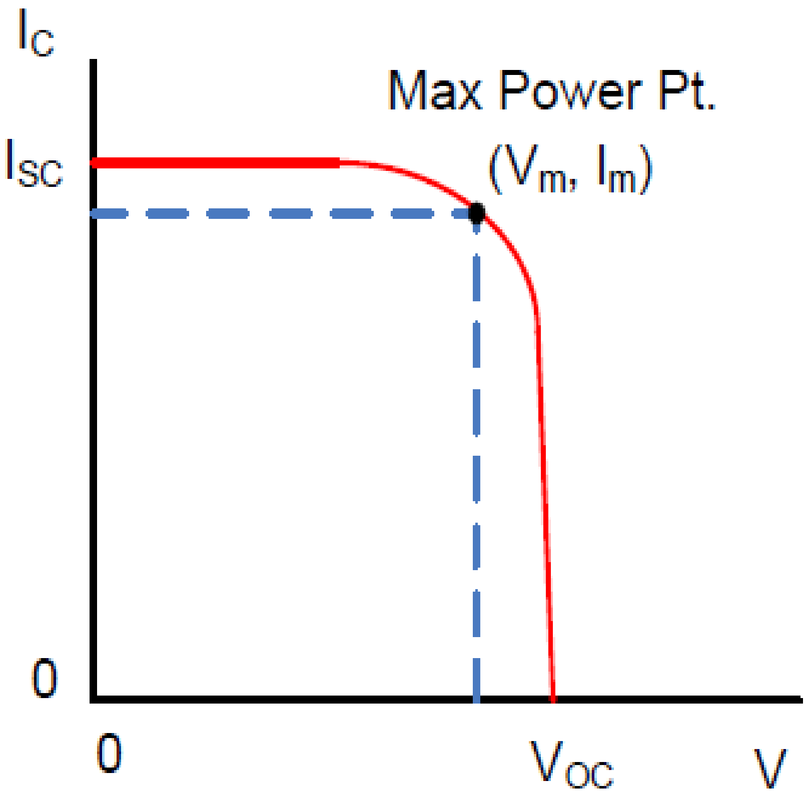
$V_T = 0.026$ V at room temperature
I_s = saturation current
I_L = reverse current

Short circuit means $R=0$ so $V=0$ and short circuit current, $I_{SC} = I_L$.

Cell power output given by

$$P_C = I_C V = I_C^2 R$$

Photocell Characteristic Curve



Fill Factor = FF

P_m = Maximum cell power

$$P_M = I_M V_M$$

$$FF = \frac{P_m}{I_{SC} V_{OC}}$$

0.7 <FF<0.85 Typical FF range

Cell Efficiency $$\eta_C = \frac{P_C}{P_I}$$

P_I = incident solar power

Quantum Efficiency (Q.E.)

Definition : $$\frac{\textit{number of photon}-\textit{generated carrie}}{\textit{number of photon}}$$

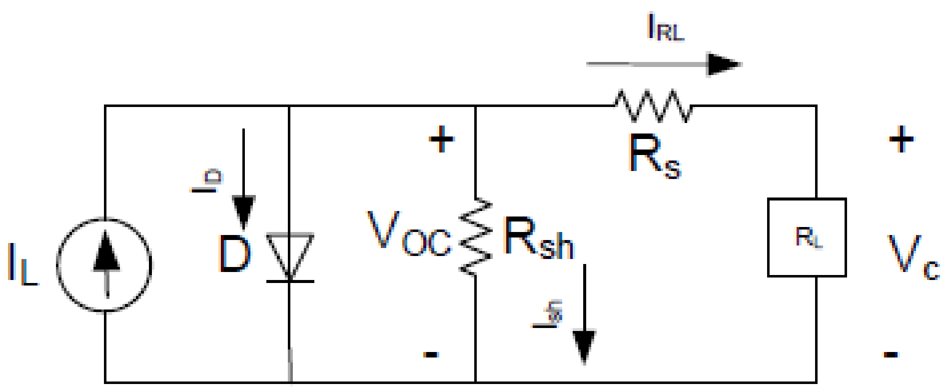
External Quantum Efficiency (E.Q.E.) :

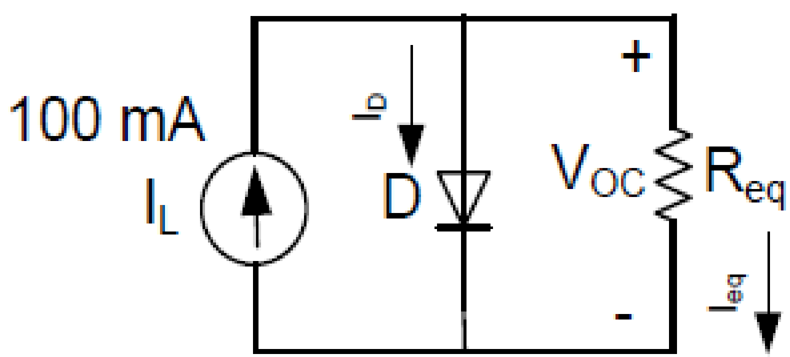
$$\frac{\textit{number of photon}-\textit{generated carrier}}{\textit{number of photon } \color{red}{\textit{from outside}}}$$

External Quantum Efficiency (E.Q.E.) :

$$\frac{\textit{number of photon}-\textit{generated carrier}}{\textit{number of photon } \color{red}{\textit{from inside}}}$$

Solar Cell Circuit Model





Example: Find the power delivered to a 30 ohm res
by the solar cell with a light current of 100 mA and m
parameters of R_s=1.176 Ω and R_{sh} of 11.875
the cell load voltage for this load resistance.

$I_L := 100 \cdot mA$ $\qquad V_{OC} := 0.71 \cdot volt$

$R_{sh} := 11.875 \cdot \Omega$ $\qquad R_s := 1.176 \cdot \Omega$ $\qquad$ R

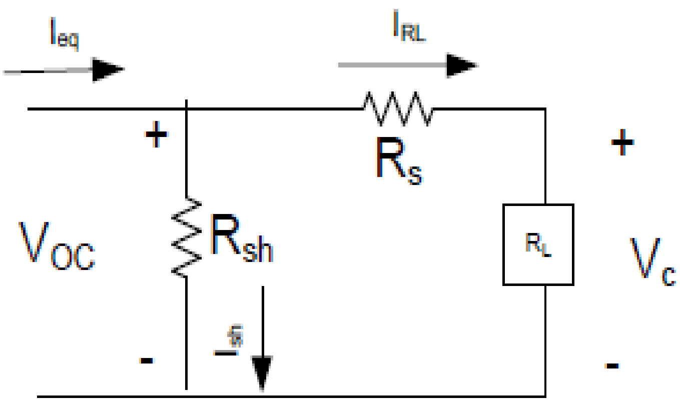
By KCL $\qquad I_L - I_D - I_{eq} = 0$

$$R_{eq} := \frac{(R_s + R_L) \cdot R_{sh}}{(R_s + R_L) + R_{sh}} \qquad R_{eq} = 8.599$$

Parallel circuit so..... $\qquad I_{eq} := \frac{V_{OC}}{R_{eq}}$

$I_D := I_L - I_{eq}$ $\qquad I_D = 17.4\ mA$

Solar Cell Model Example -Continued



Use Current Divider rule to find I_{RL}

$$I_{RL} := I_{eq} \cdot \frac{R_{sh}}{R_{sh} + R_L + R_s} \qquad I_{RL} = 22.77mA$$

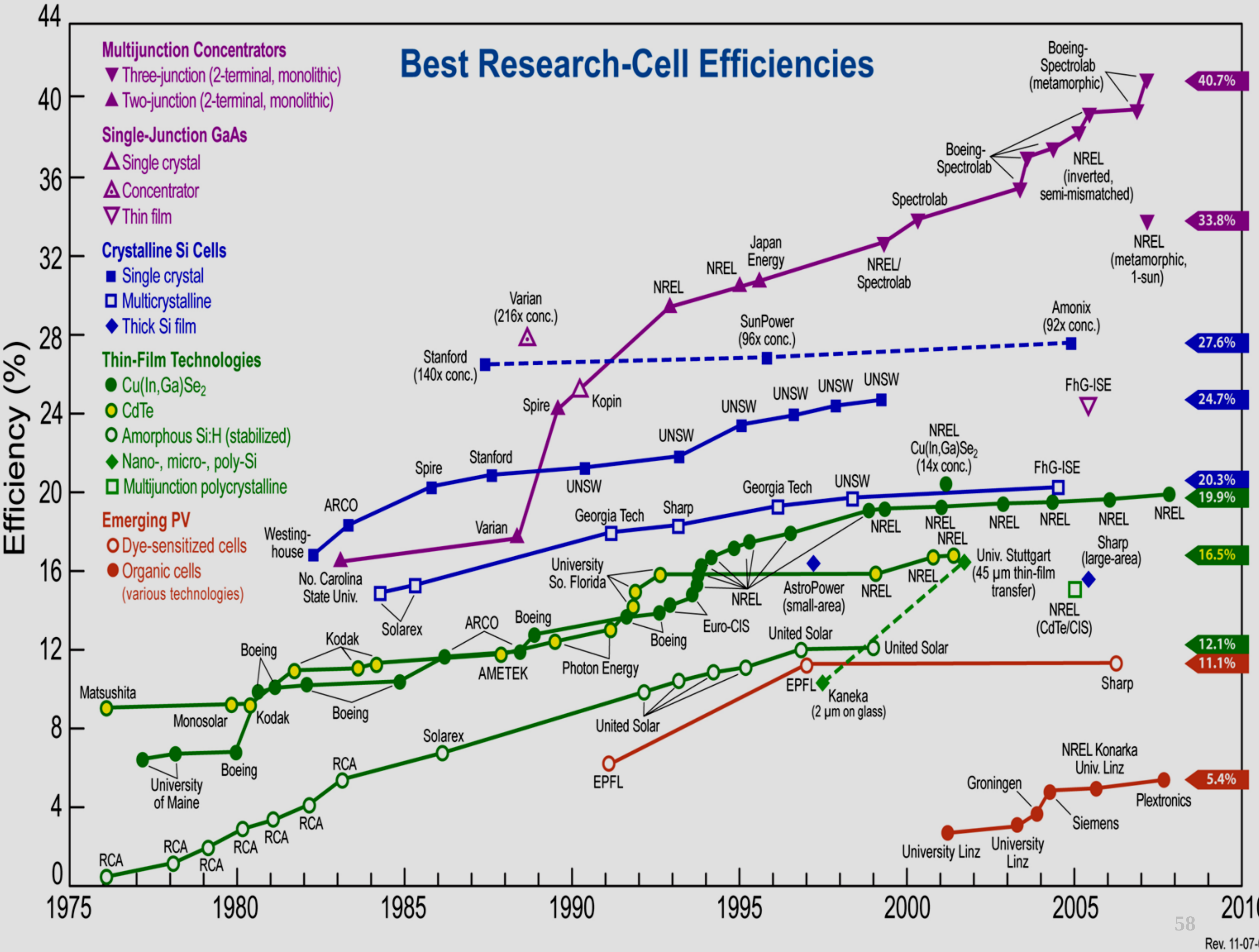
$$P_L := I_{RL}^{\,2} \cdot R_L \qquad P_L = 15.6mW$$

Find V_C from KVL $\qquad V_C := V_{OC} - I_{RL} \cdot R_s$

$$V_C = 0.683V$$

Solar Cell Efficiency

- AM1.5 Solar Intensity (Incident power density) 1000 W/m^2 or 100 mW/cm^2
  - Losses
    - Photon Energy -47% of photons have eV<1.1, 30% goes to heat
    - Voltage factor – ratio of energy given to energy required to produce electron 0.65
    - Recombination – electron/holes that recombine 10%
    - Reflection – reduced to 4%
    - Overall Efficiency $\eta_c = (0.47)(0.65)(.90)(.96)=.26$
      - 26% Maximum efficiency using current technologies


Best Research-Cell Efficiencies
Efficiency (%)
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se_2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
Boeing-Spectrolab (metamorphic)
40.7%
Boeing-Spectrolab
NREL (inverted, semi-mismatched)
Spectrolab
33.8%
NREL (metamorphic, 1-sun)
Japan Energy
NREL
NREL/Spectrolab
Varian (216x conc.)
SunPower (96x conc.)
Amonix (92x conc.)
27.6%
Stanford (140x conc.)
Spire
Kopin
FhG-ISE
24.7%
UNSW
NREL Cu(In,Ga)Se_2 (14x conc.)
Stanford
Georgia Tech
Sharp
20.3%
19.9%
ARCO
Westing-house
Varian
No. Carolina State Univ.
Solarex
University So. Florida
Euro-CIS
AstroPower (small-area)
Univ. Stuttgart (45 µm thin-film transfer)
Sharp (large-area)
16.5%
NREL (CdTe/CIS)
ARCO
Boeing
AMETEK
Photon Energy
Kodak
United Solar
12.1%
11.1%
EPFL
Kaneka (2 µm on glass)
Matsushita
Monosolar
Kodak
Boeing
University of Maine
Solarex
RCA
EPFL
NREL Konarka Univ. Linz
Groningen
Plextronics
Siemens
5.4%
University Linz
University Linz
0
4
8
12
16
20
24
28
32
36
40
44
1975
1980
1985
1990
1995
2000
2005
Rev. 11-07-

Uses of Solar Cells

- Renewable power
- Power for remote locations

Advantages of Solar Cells

- Consumes no fuel
- No pollution
- Wide power-handling capabilities
- High power-to-weight ratio

DISADVANTAGES

- The main disadvantage of solar cell is the initial cost. Most types of solar cell require large areas of land to achieve average efficiency.
- Air pollution and weather can also have a large effect on the efficiency of the cells.
- The silicon used is also very expensive and the solar cells can only ever generate electricity during the daytime.

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THANK YOU
for listening!