BRAE 470 Solar Photovoltaic System Engineering

Photovoltaic Energy Conversion

September 28, 2015

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Outline

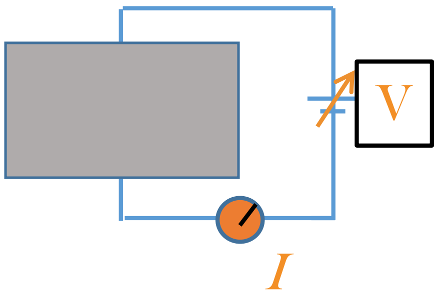
Monday, September 28

1. Semiconductors – especially silicon
2. Electrons (and photons) in semiconductors
3. Basic components of a solar cell
4. Power generation from a solar cell
5. Equivalent circuit of a solar cell

Wednesday, September 30

1. How solar cells are fabricated
2. Why (and how) cells are made into modules
3. How modules are fabricated
4. Types of crystalline photovoltaic modules
5. Module Specs

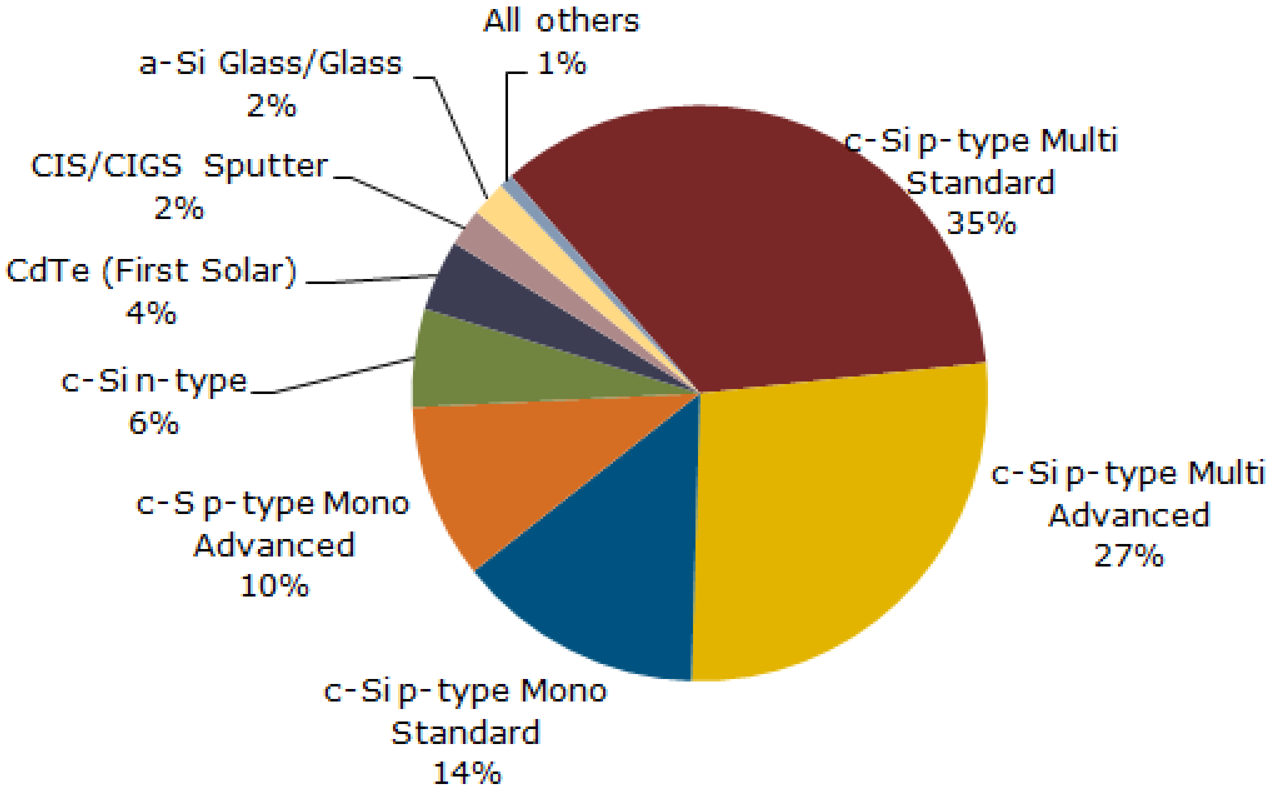
What is a Semiconductor?



- Low resistivity => "conductor" — e.g. metals
- High resistivity => "insulator" — e.g. diamond, window glass

- Intermediate resistivity => "semiconductor"
  - conductivity lies between that of conductors and insulators
  - examples
    - * silicon
    - gallium arsenide
    - cadmium telluride
    - copper indium gallium diselenide (CIGS)

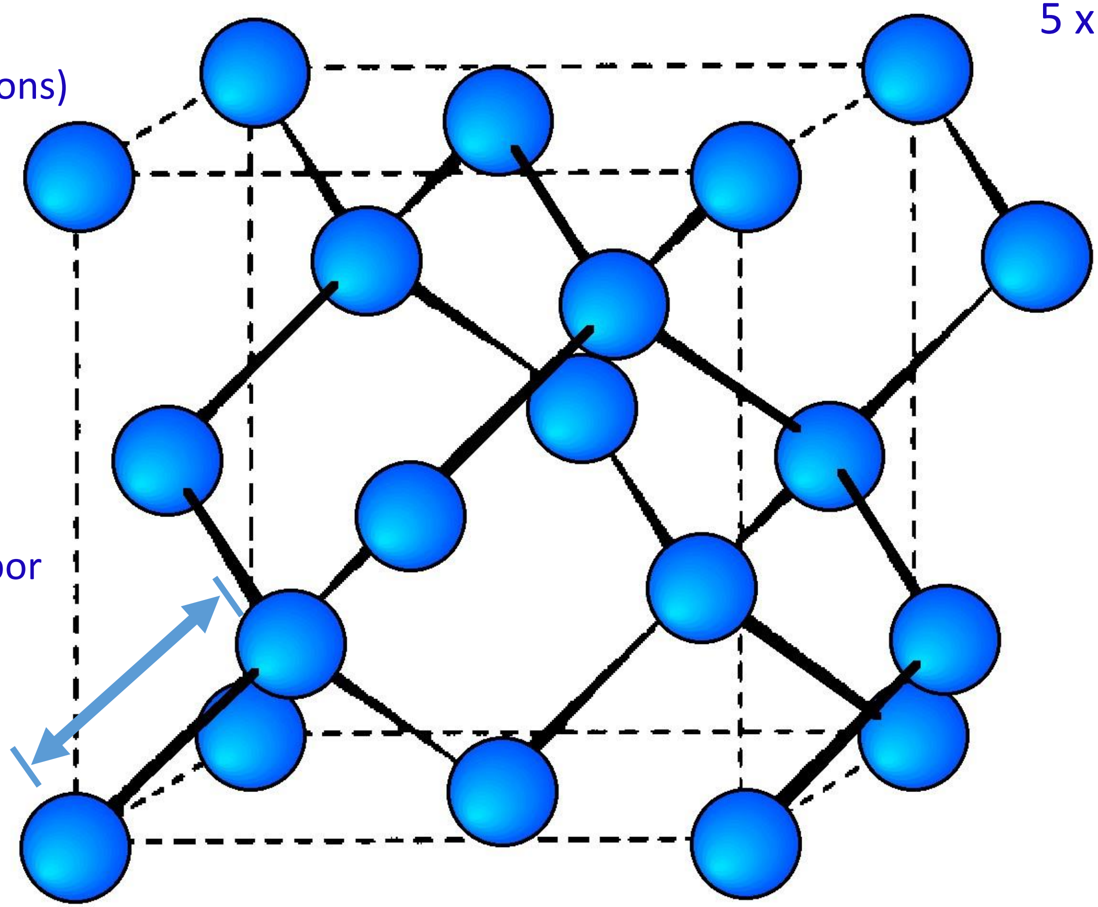
PV module market share by technology 2014
(Solarbuzz.com)



Silicon crystal structure – bond model

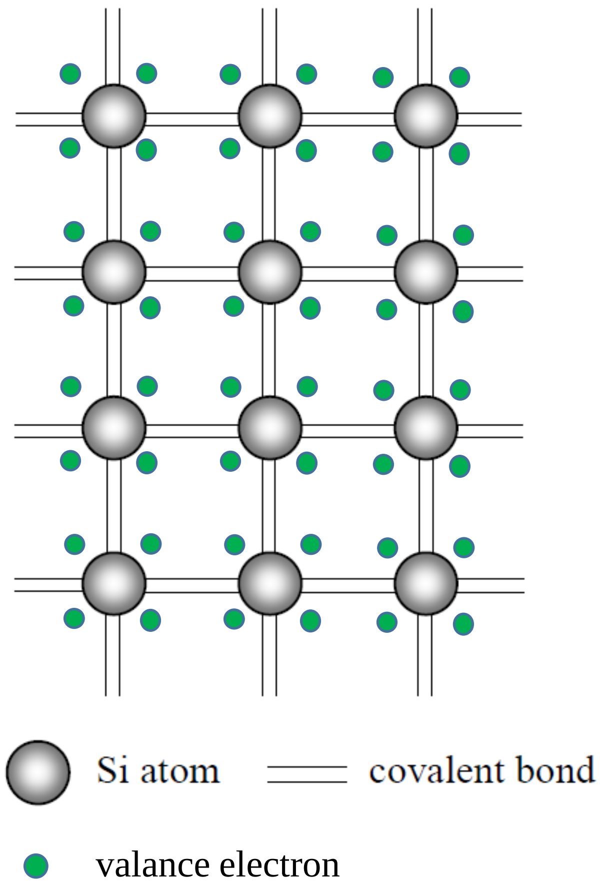
Silicon atomic density:
5×10^{22} atoms/cm^3

Silicon atom core:
nucleus (+14 protons)
and 10 core
electrons



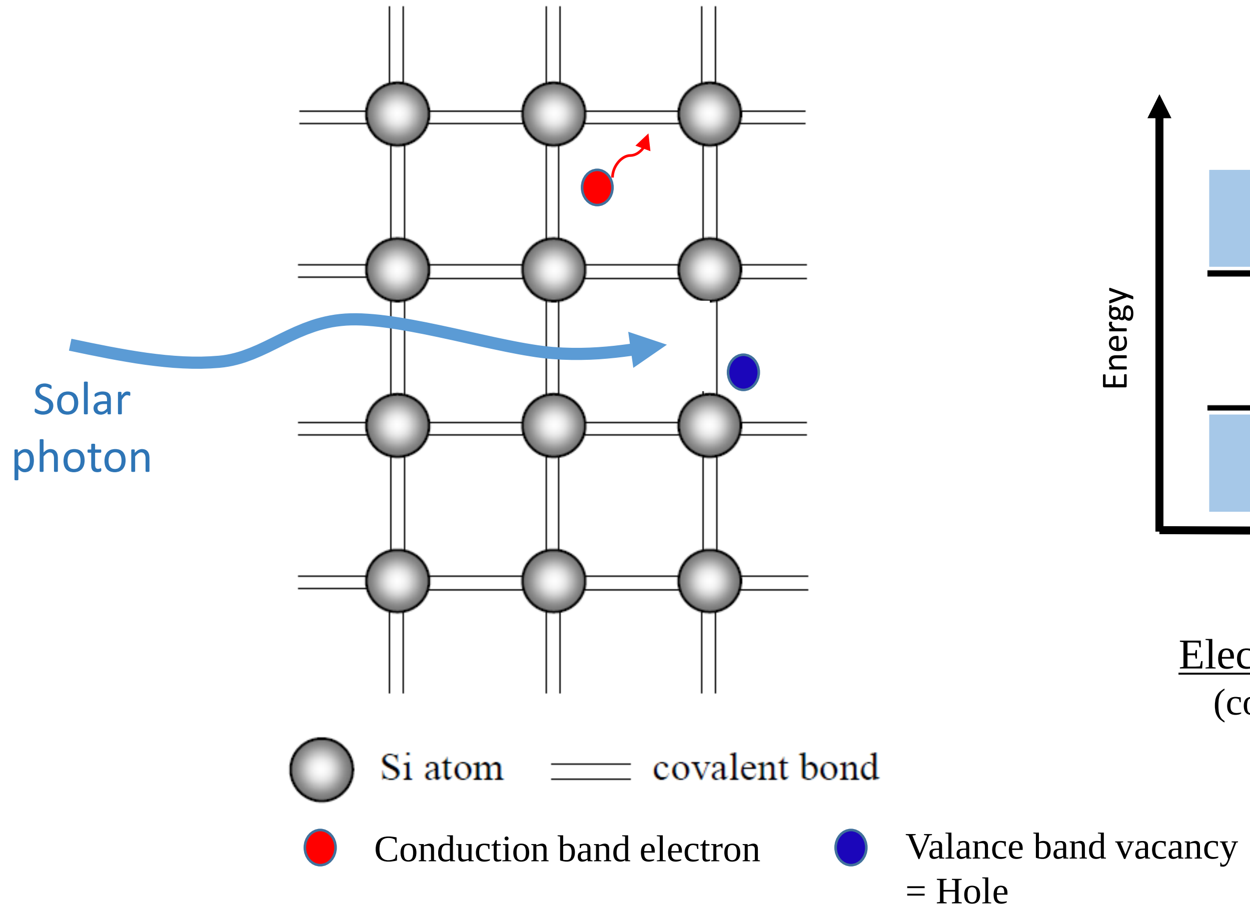
nearest-neighbor
distance:
0.235 nm

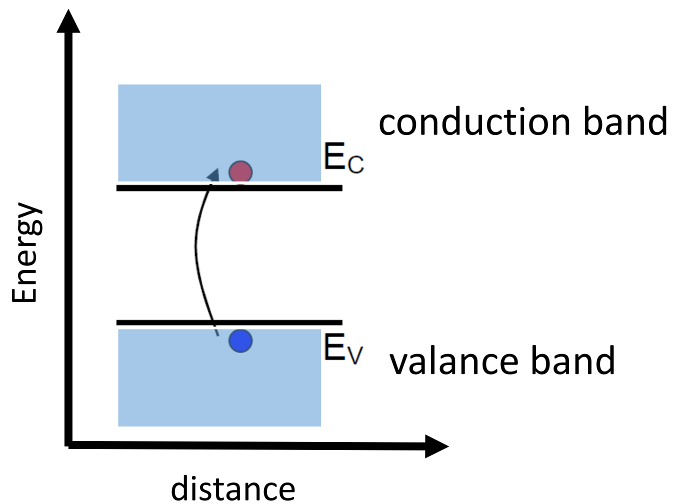
Silicon - simplified bond model



In pure silicon, each atom’s 4 valence electrons are “shared” another atom. This sharing forms a covalent bonds – strong bonds that require significant energy to break

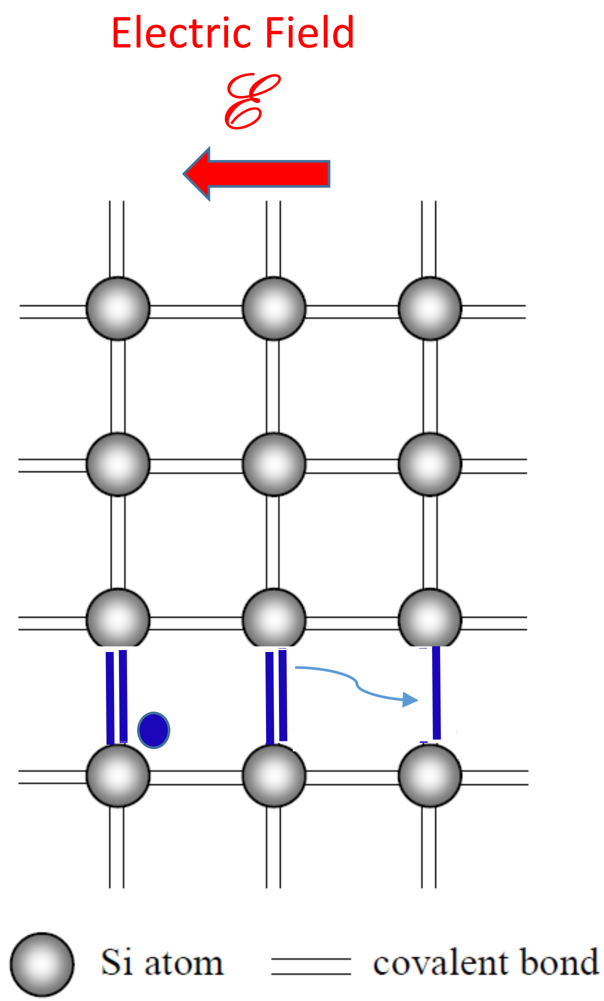
What happens when light is absorbed?
- a bond is broken





Electron Band Model
(covered in EE 306)

What is with this hole stuff?



Valance band electrons can move into a valance band vacancy – but they move differently than conduction band electron and have to be treated separately

valance electrons
(and conduction electrons)

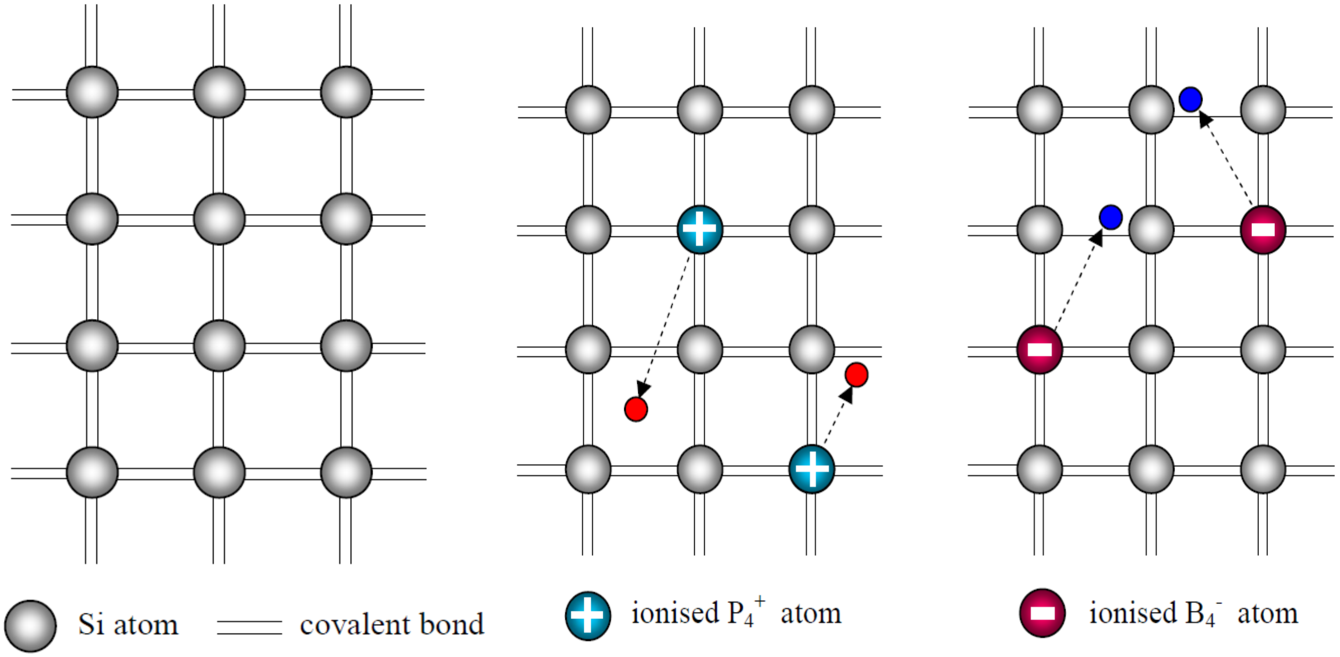
holes

Valance band vacancy
= Hole

Doping a semiconductor

Phosphorous
5 valance electrons

Boron
3 valance electrons



n-type

p-type

Doping typically at 10^{16} atoms/cm^3

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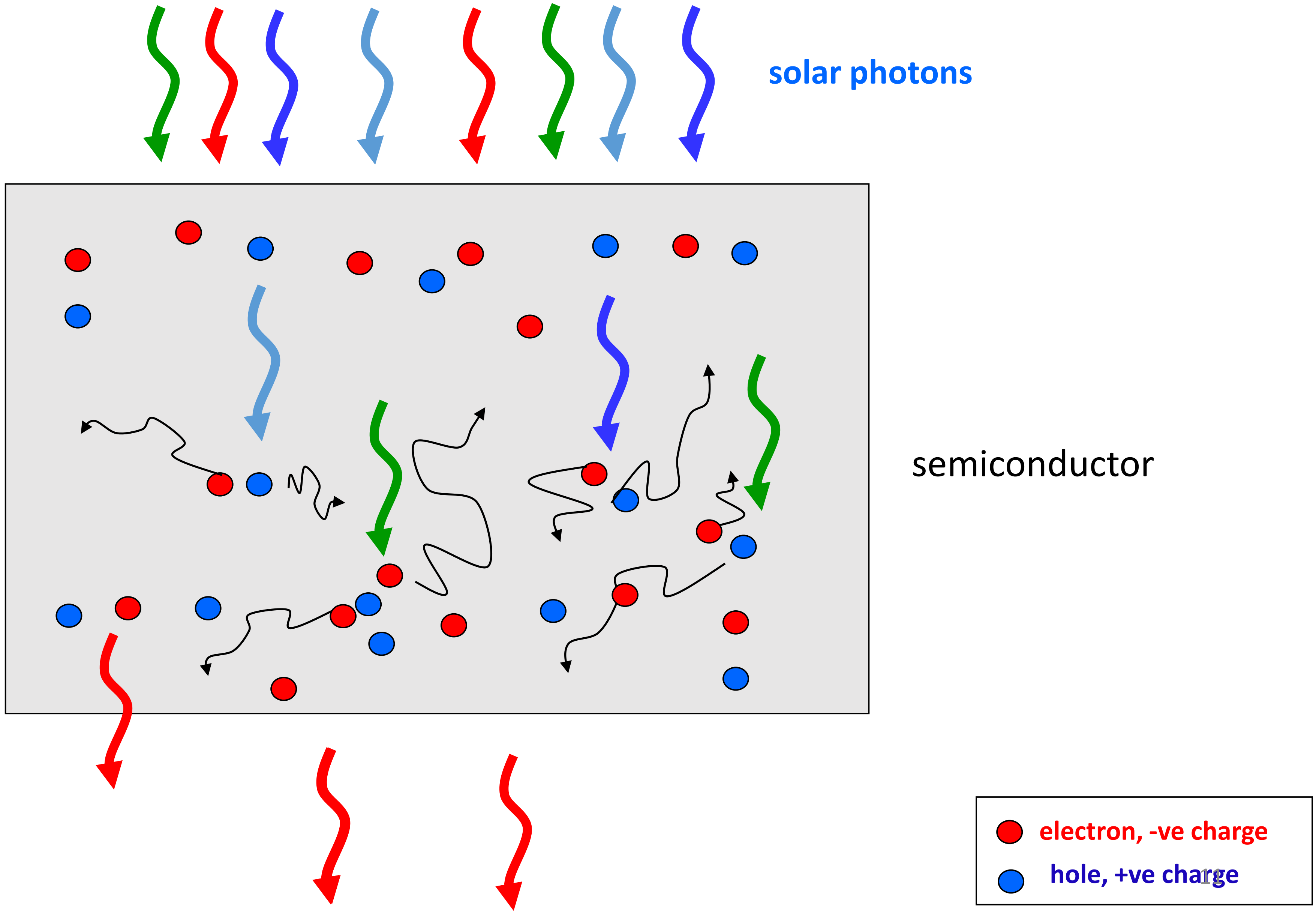
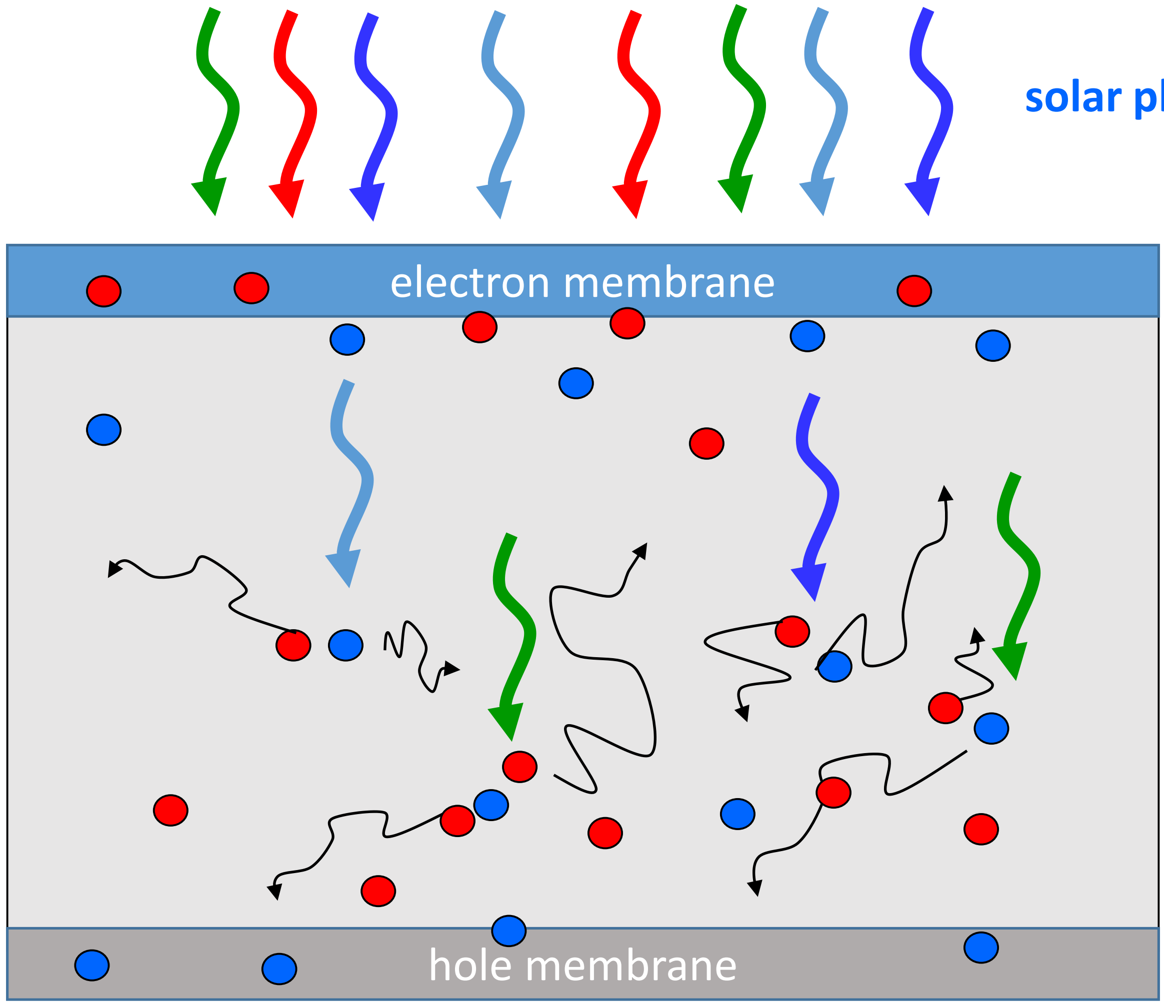
Photo-generated electron and hole pairs diffuse randomly



Need selective electron and hole “membranes” to create a voltage and drive a current



solar photons

a “pn” junction makes a good selective membrane

semiconductor

a “back surface field” makes an ok selective membrane

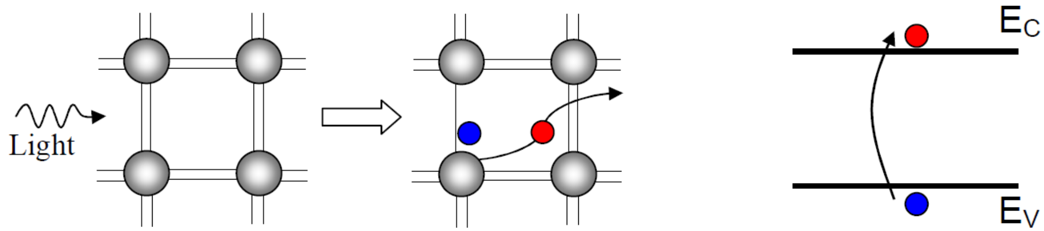
electron, -ve charge

hole, +ve charge

Generation and recombination

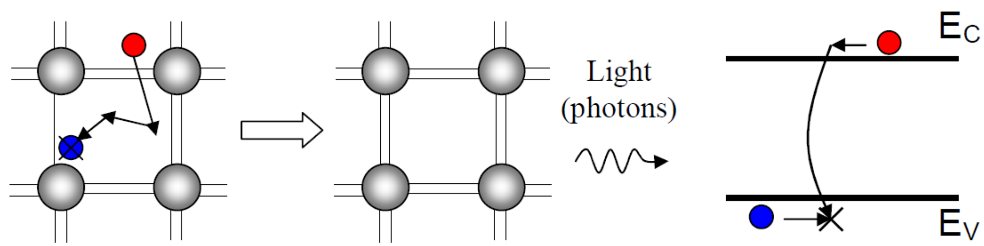
(a)

Generation



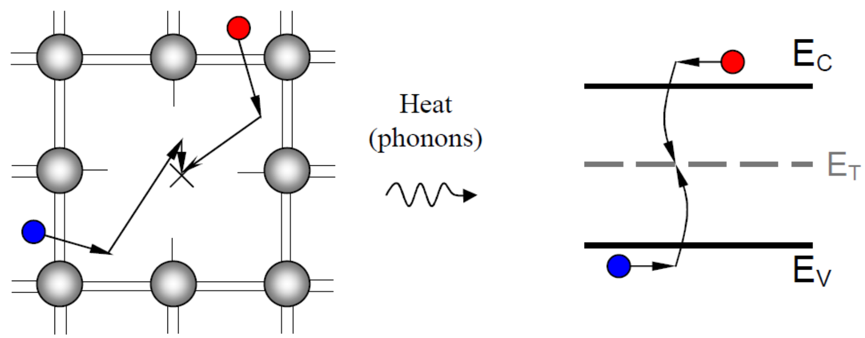
(b)

Radiative recombination



(c)

Non-radiative recombination at defects such as impurities,
crystal structure defect
grain boundaries, etc.



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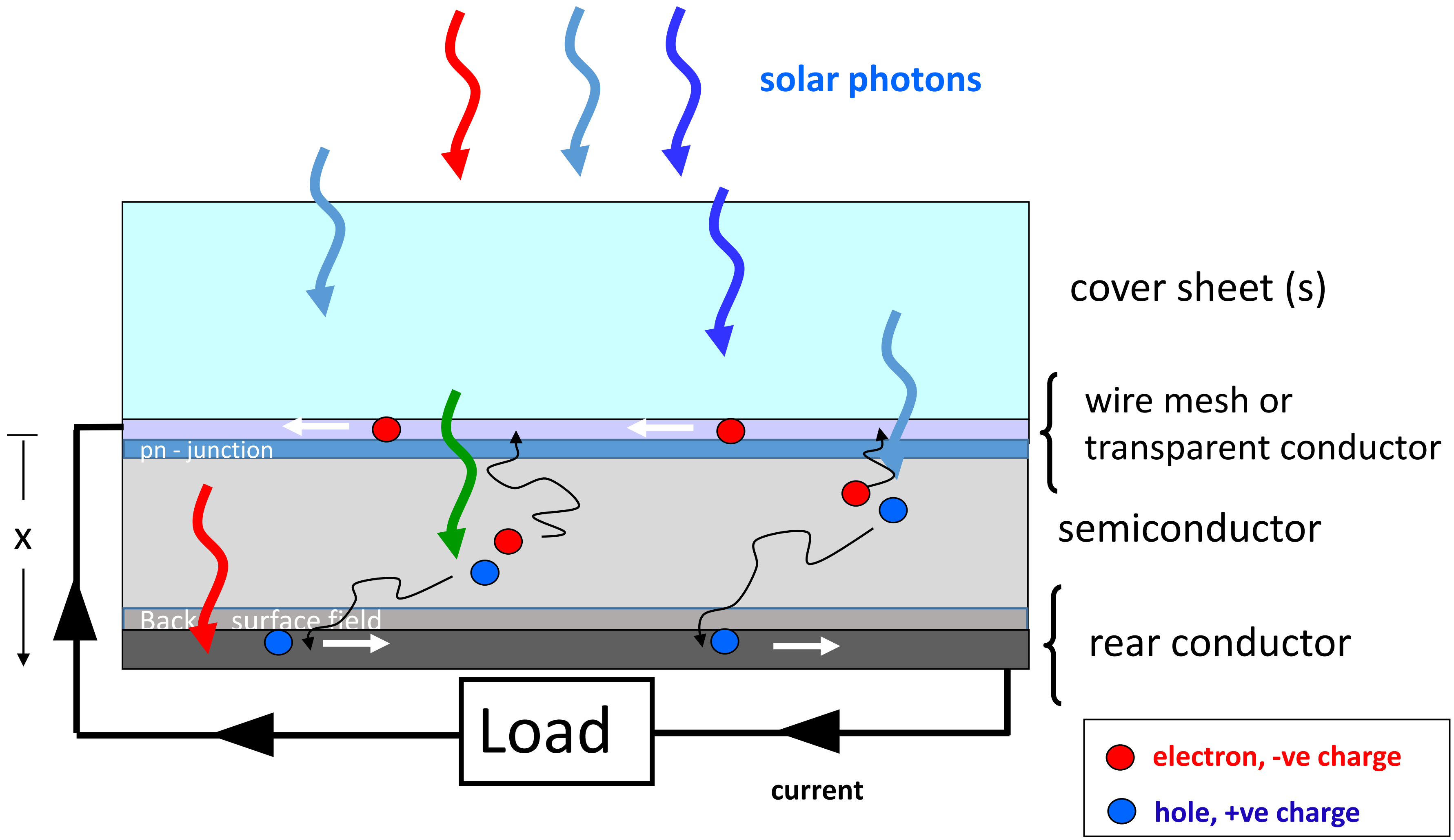
Photovoltaic Cell - electric current from photons

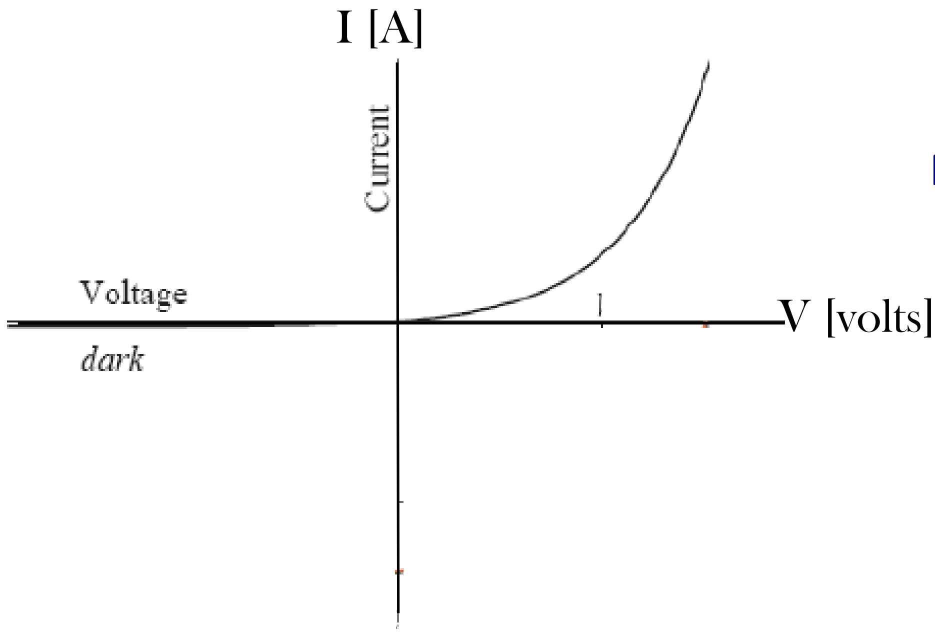


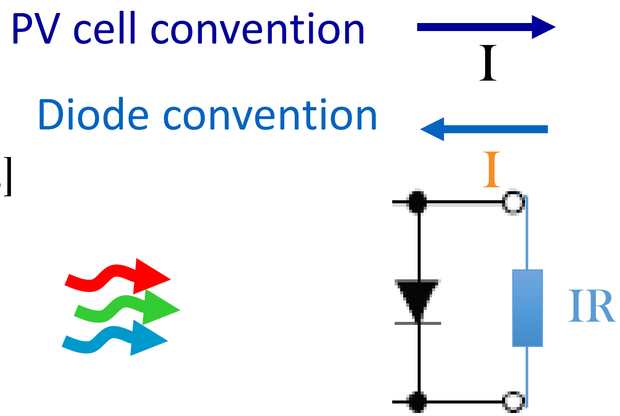
In words:

- A photovoltaic cell is a large area diode with
  - an "emitter" that acts as an electron (or hole) membrane
  - a large volume of "base" material that absorbs photons, converting photon energy to electron & hole energy.

  - These electrons and holes defuse and separate when they pass through the membranes,
  - creating a current source, depending on the amount fo light absorbed in the base, that can drive power out of the diode.

PV cell current-voltage (I-V) – starts with a diode





$$\eta = \frac{P_{\max}}{P_{solar}} = \frac{V_{\max} I_{\max}}{P_{solar}} = FF \frac{V_{oc} I_{sc}}{P_{solar}}$$

where $FF \equiv \dfrac{V_{\max} I_{\max}}{V_{oc} I_{sc}}$ is the 'fill-factor'

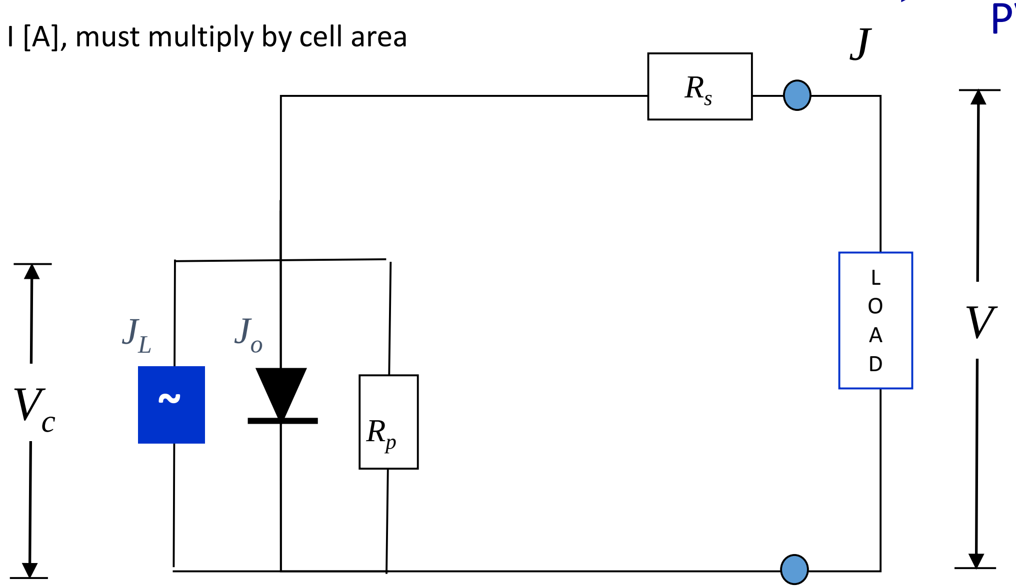
@ 1000 W/m^2
spectrum = AM1.5

Standard equivalent circuit model of PV cell

Note:
Equation is for a unit area of semiconductor
J units = [A/cm²]
R units = [Ω-cm²]
To get total current, I [A], must multiply by cell area

Diode convention

PV cell convention



$$V = V_c - JR_s$$

Series resistance

$$\pm \quad J = J_L - J_0\left(\exp\left[\frac{qV_c}{nkT}\right] - 1\right) - \frac{V_c}{R_p}$$

Light induced current

Saturation current

Diode ideality factor

Shunt resistance

Shockley diode equation

Using the PV Cell equivalent circuit model

- Find the maximum power point voltage, maximum power point current, and maximum output power of a 156 x 156 mm cell with equivalent circuit parameters in the chart below
  - when the sun has irradiance of the standard test conditions (1000 W/m^2)
    - V_{max} = I_{max} = P_{max} =
  - for early in the morning when the irradiance is only 500 W/m^2
    - V_{max} = I_{max} = P_{max} =

- Find the maximum power point voltage, maximum power point current, and maximum output power at standard test conditions (1000W/m^2) for cell made of the same material but of smaller area = 100 x 100 mm.
    - V_{max} = I_{max} = P_{max} =

Cell parameters

J_L (mA/cm^2 @ 1000 W/m^2)	38
J_0 (mA/cm2)	1.00E-10
n	1
T (K)	300
R_p (W-cm^2)	10,000
R_s (W-cm^2)	1.2