EELE408 Photovoltaics

Overview

Wave – Particle Duality

- Light behaves as both a wave and a particle
  - Wave Properties $c = \nu\lambda$
    - Refraction
    - Diffraction
    - Interference
  - Particle Properties $E = h\nu$
    - Emission and Absorption of Light
    - Blackbody Radiation
    - Photoelectric effect

c: speed of light
ν: frequency
λ: wavelength
E: Energy
h: Planck's Constant

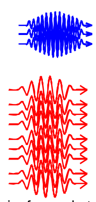
$c = 3\times10^{8}(m/s)$

$h = 6.636\times10^{-34}(J-s) = 4.136\times10^{-15}(eV-s)$

Photon Flux & Energy Density

$$\text{Photon Flux} = \frac{\text{Number of Photons}}{(\text{second})(\text{Area})} = \Phi$$

$$\text{Energy Density}: (\text{Photon Flux})(\text{Energy per Photon}): H\left(\frac{W}{m^2}\right) = \Phi\left(\frac{hc}{\lambda}(J)\right)$$



For the same intensity of light shorter wavelengths require fewer photons, since the energy content of each individual photon is greater

Blackbody Radiation

- Ideal absorber and emitters of electromagnetic radiation
  - The hotter the body the more radiation emitted
  - The hotter the body the higher the energy of the spectrum peak
- Classical physics unable to explain blackbody radiation
  - 1900-Max Planck: Quantization of Energy Radiation
  - 1905-Albert Einstein: Photoelectric Effect

Planck's Formula

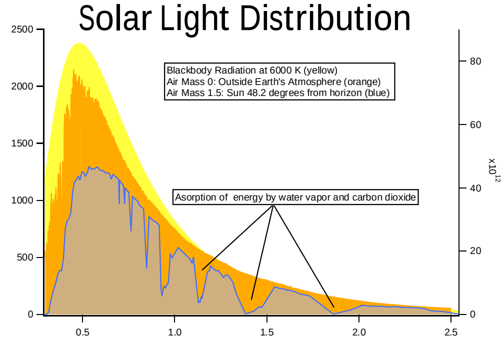
$$E(\nu) = \frac{8\pi h\nu^3}{c^3\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]}d\nu\left(\frac{J-s}{m^3}\right)$$

Integrate over all energies to get the intensity emitted into a hemisphere

$$H = \frac{c}{4}\int_0^\infty E(\nu)d\nu = \sigma T^4$$

H: intensity of radiation (W/m^2)
Stefan-Boltzmann Constant σ = 5.67x10-8 (W/(m^{2}K^4)

Solar Light Distribution

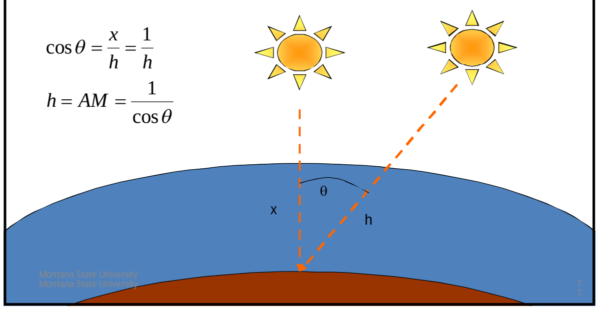


Air Mass

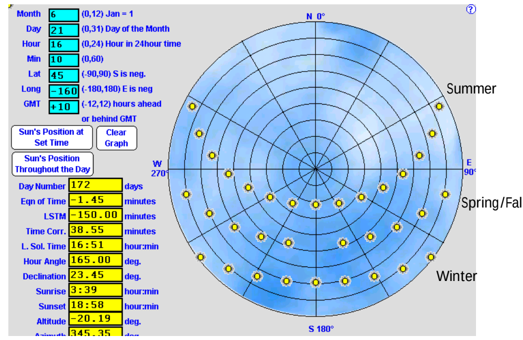
- The path length that light takes through the atmosphere normalized to the shortest possible path length

$$\cos\theta = \frac{x}{h} = \frac{1}{h}$$

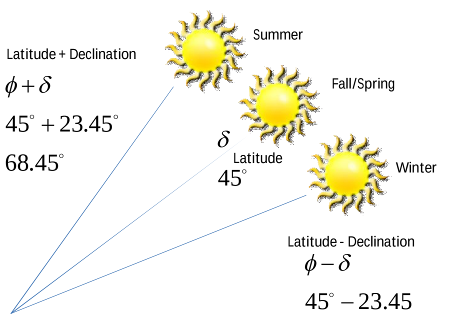
$$h = AM = \frac{1}{\cos\theta}$$



Polar Plot of Sun Position for Bozeman



Peak Elevation Angle (Bozeman)



Latitude + Declination

$\phi + \delta$

$45^\circ + 23.45^\circ$

68.45°

δ

Latitude

45°

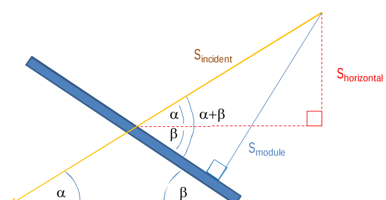
Latitude - Declination

$\phi - \delta$

$45^\circ - 23.45$

21.55°

Solar Radiation on a Tilted Surface



$\alpha =$ elevation angle

$\beta =$ tilt angle of panel

$\delta =$ declination angle

$\phi =$ latitude

$\alpha = 90^\circ - \phi + \delta$ (at solar noon)

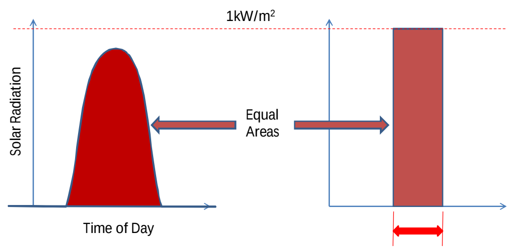
$$S_{horizontal} = S_{incident} \sin\alpha$$

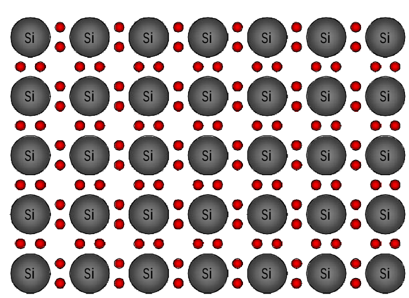
$$S_{module} = S_{incident} \sin(\alpha + \beta)$$

$$S_{module} = \frac{S_{horizontal} \sin(\alpha + \beta)}{\sin\alpha}$$

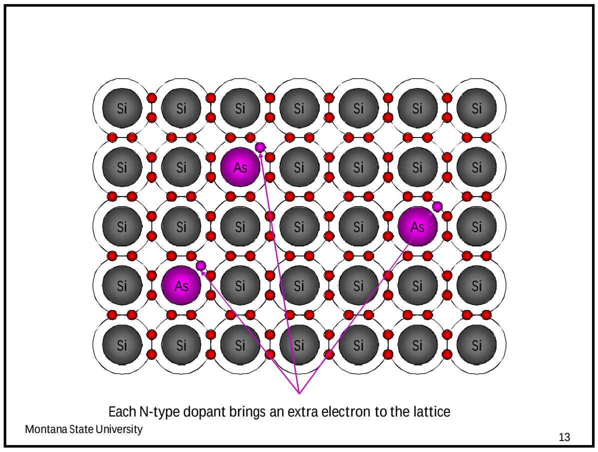
Peak Sun Hours

Area under curves = Solar Insolation





Poor conductor: No free electrons to carry current
Need to engineer electrical properties (conduction)


Si
As
Each N-type dopant brings an extra electron to the lattice
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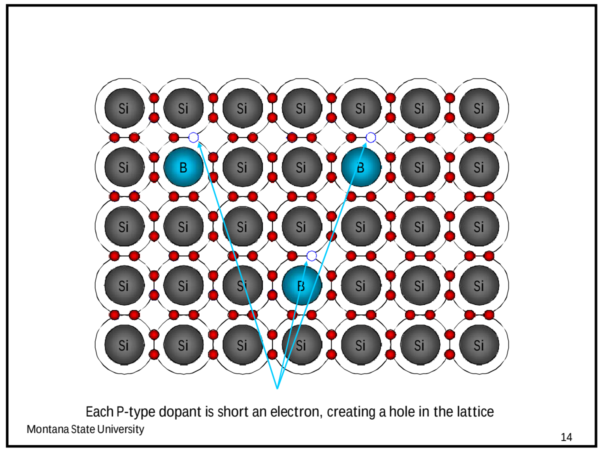
Si
B
Each P-type dopant is short an electron, creating a hole in the lattice
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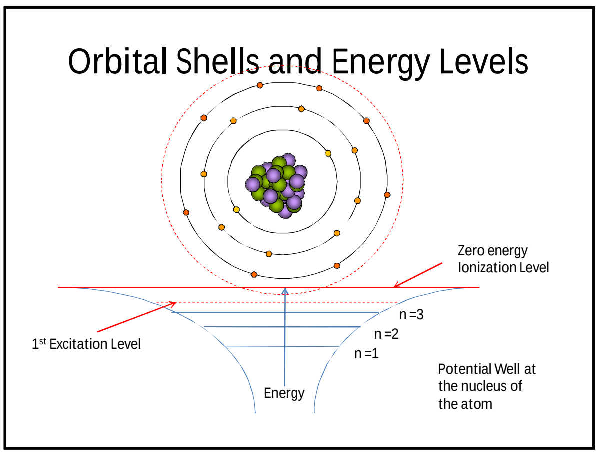
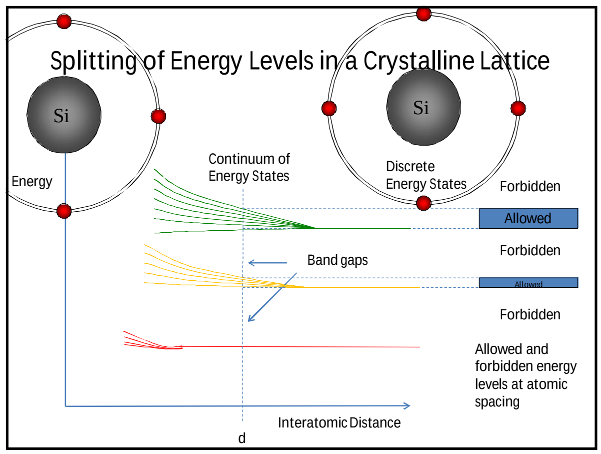
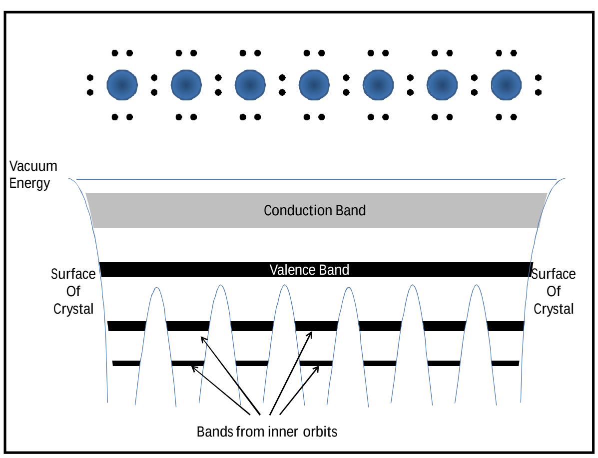
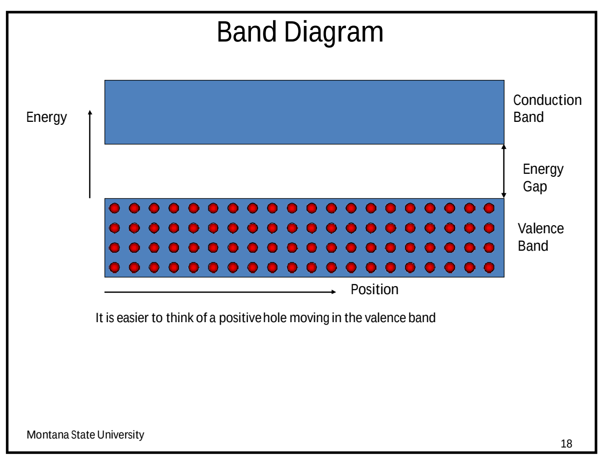

Orbital Shells and Energy Levels
Zero energy
Ionization Level
n =3
n =2
n =1
1st Excitation Level
Potential Well at
the nucleus of
the atom
Energy


Splitting of Energy Levels in a Crystalline Lattice
Si
Si
Energy
Continuum of
Energy States
Discrete
Energy States
Forbidden
Allowed
Forbidden
Band gaps
Allowed
Forbidden
Allowed and
forbidden energy
levels at atomic
spacing
Interatomic Distance
d


Vacuum
Energy
Conduction Band
Valence Band
Surface
Of
Crystal
Surface
Of
Crystal
Bands from inner orbits


Band Diagram
Energy
Conduction
Band
Energy
Gap
Valence
Band
Position
It is easier to think of a positive hole moving in the valence band
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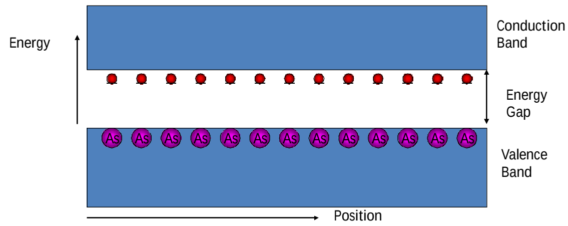
N-Type Doping

Doping the silicon lattice with atoms with 5 valence electrons (V) create sites in the band diagram that require little energy to break the bond to the dopant atom and become free to move in the lattice or in other words move into the conduction band.



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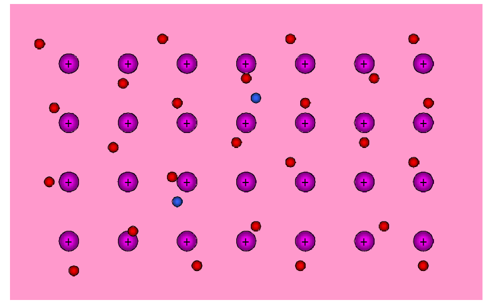
N type Material

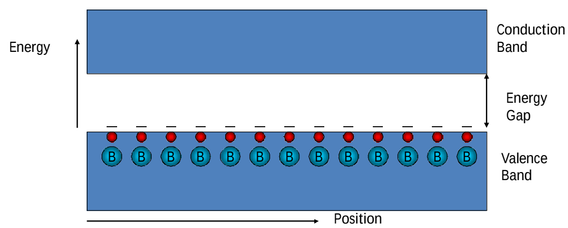
Majority Charge Carriers are Negative electrons



Few holes

P-Type Doping

Doping the silicon lattice with atoms with 3 valence electrons (III) create sites in the band diagram that require little energy to trap an electron into the dopant atom. Holes are created in the valence band that are free to move.



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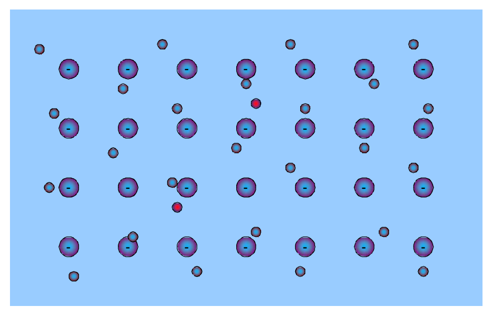
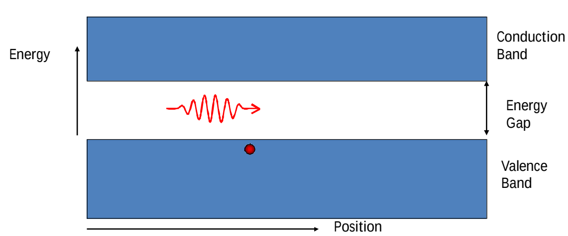
P type Material

Majority Charge Carriers are Positive holes



Few electrons

$E_{ph}=E_G$



When the photon energy is equal to the gap energy, the photon is again absorbed but no thermal energy is generated.

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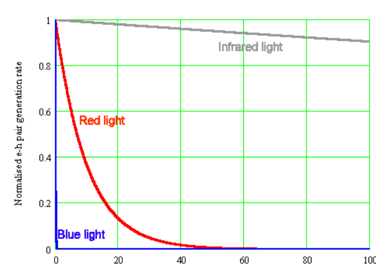
Generation is wavelength dependent



The generation rate in silicon for several wavelengths of light.

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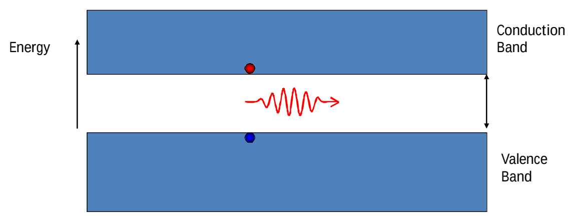
Band to Band Recombination



- Dominate effect in lasers and LED's
- In Si PV devices relatively unimportant since Si is an indirect material

Diffusion Current

- Rate of diffusion depends on the speed of the particles which is temperature dependent
- Redistributes carrier concentration such as induced by photogeneration without an external force applied to device

$$J_e = qD_e \frac{dn}{dx} \qquad D_e = \frac{kT}{q}\mu_e$$

$$J_h = -qD_h \frac{dp}{dx} \qquad D_h = \frac{kT}{q}\mu_h$$

Diffusion is proportional to temperature and mobility

Current is proportional to gradient and diffusion constant

Drift Current

$$J = \sigma E$$

$$J_e = qnv_d = q\mu_e nE$$

$$J_h = q\mu_h pE$$

$$\sigma = \frac{1}{\rho} = \frac{J}{E} = q\mu_e n + q\mu_h p$$

N-type	$\sigma \Rightarrow q\mu_e N_D$	$n >> p$	$n \approx N_D$
P-type	$\sigma \Rightarrow q\mu_h N_A$	$p >> n$	$p \approx N_A$

Drift and Diffusion Currents

$$\vec{J}_n = q\mu_n n\vec{E} + qD_n \nabla n$$

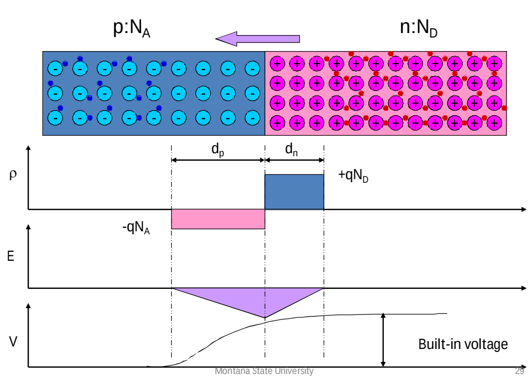
$$\vec{J}_p = q\mu_p p\vec{E} - qD_p \nabla p$$

- Mobility and Diffusion are related to each other by the Einstein Equation:

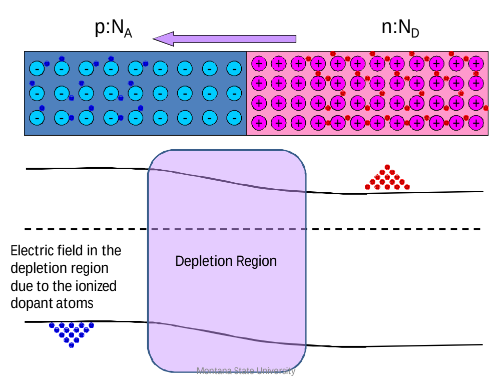
$$D_n = \frac{kT}{q}\mu_n$$

$$D_p = \frac{kT}{q}\mu_p$$

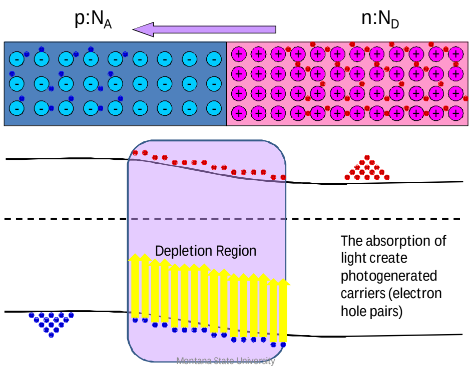
pn Junction in Thermal Equilibrium



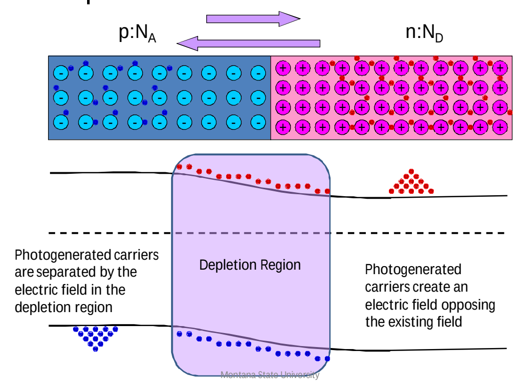
pn Junction in Thermal Equilibrium



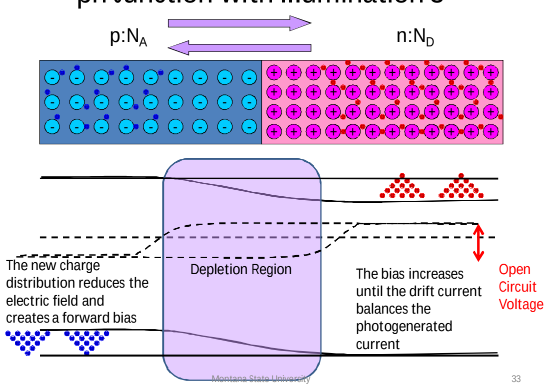
pn Junction with Illumination 1



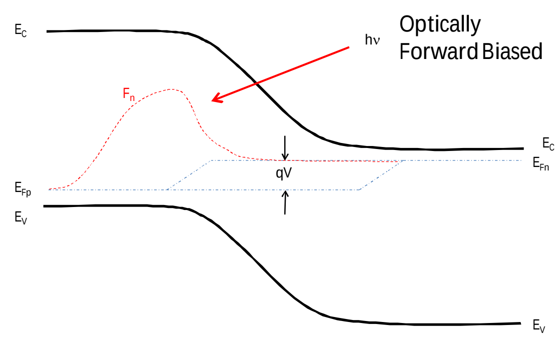
pn Junction with Illumination 2



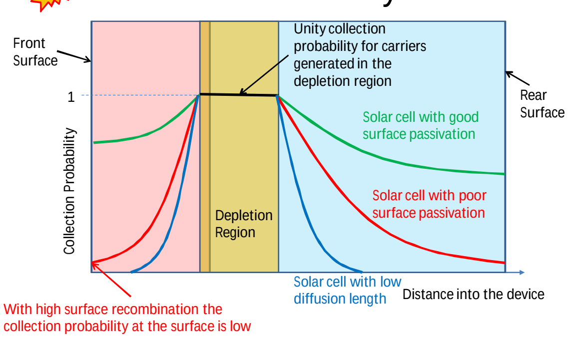
pn Junction with Illumination 3



Forward Bias



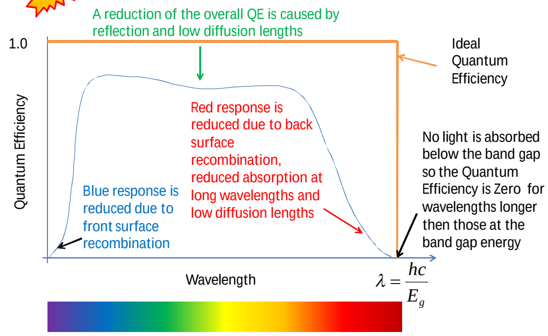
Collection Probability Chart



Quantum Efficiency

- The ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell
- If all the photons at a certain wavelength are absorbed and the resulting minority carriers are collected then the QE at that wavelength is unity
- The QE for photons below the band gap energy is zero

Quantum Efficiency Chart

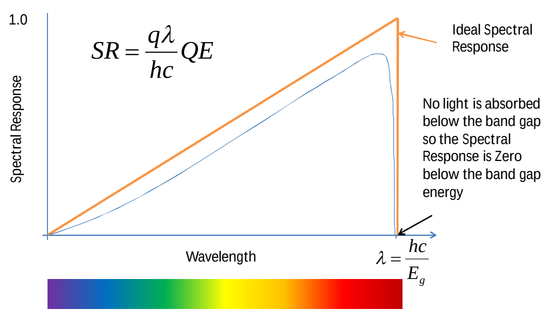


Spectral Response

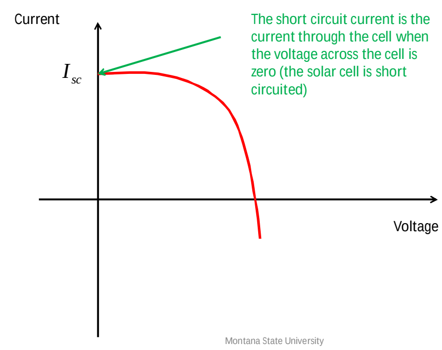
- Ratio of current generated by the solar cell to the power incident on the solar cell
- Limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap (Same as QE)
- Any energy above the band gap energy is not utilized by the solar cell and instead goes to heating the solar cell
- This is a measured quantity and used to calculate the Quantum Efficiency

$$SR = \frac{q\lambda}{hc} QE$$

Spectral Response



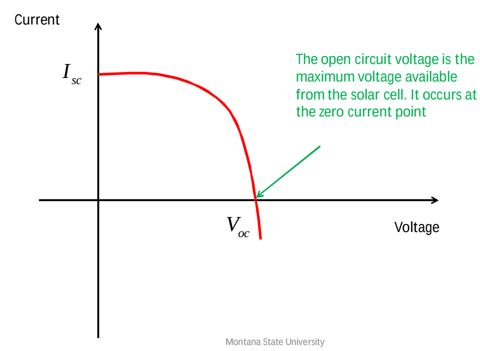
Short Circuit Current Point



Short Circuit Current Dependence:

- Area of Solar Cell
  - To remove the dependence on solar cell area, it is common to use the Short Circuit Current Density (J_{sc} in mA/cm^2)
- Intensity of Light
  - I_{sc} is directly dependent on the number of photons entering the cell
- Spectrum of Light
  - For most measurements the spectrum is standardized to AM1.5
- Optical Properties of the Cell
  - Reflection and absorption
- Collection Probability
  - Chiefly depends on surface passivation and minority carrier lifetime

Open Circuit Voltage Point



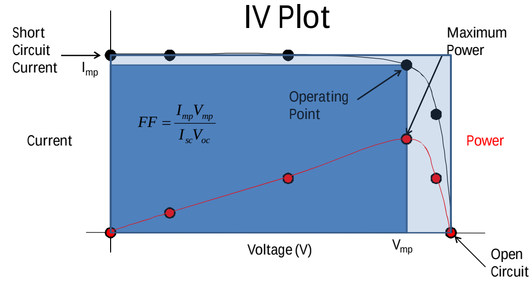
Open Circuit Voltage

- Corresponds to the amount of forward bias on the cell due to the bias generated by the illumination of the cell
- Solve for the Voltage when the net current is set to zero

$$0 = I_0\left[\exp\left(\frac{qV_{oc}}{nkT}\right) - 1\right] - I_L$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

IV Plot



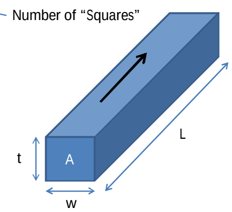
$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}$$

Volt (V)	0	0.1	0.3	0.5	0.54	0.57
Current (A)	1.3	1.3	1.3	1.2	0.75	0
Power (W)	0	0.13	0.39	0.6	0.4	0

Sheet Resistivity

$$R = \frac{\rho}{A}\frac{L}{} = \frac{\rho L}{(t)(w)} = \frac{\rho}{t}\left(\frac{L}{w}\right)$$

Number of "Squares"



$\rho_s = \frac{\rho}{t}$ (Ohms / Square)

ρ_s = Sheet Resistivity

ρ = Resistivity of the layer

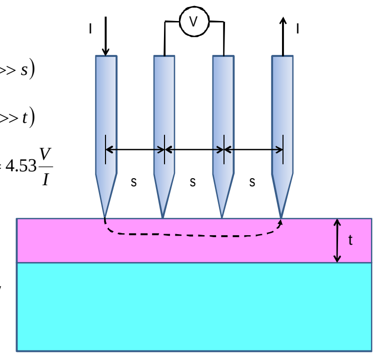
t = Thickness of the layer

4-point Probe

$\rho = 2\pi\, s\frac{V}{I} \quad (t >> s)$

$\rho = \frac{\pi}{\ln 2}\frac{t\,V}{I} \quad (s >> t)$

$\rho_s = \frac{\rho}{t} = \frac{\pi}{\ln 2}\frac{V}{I} = 4.53\frac{V}{I}$



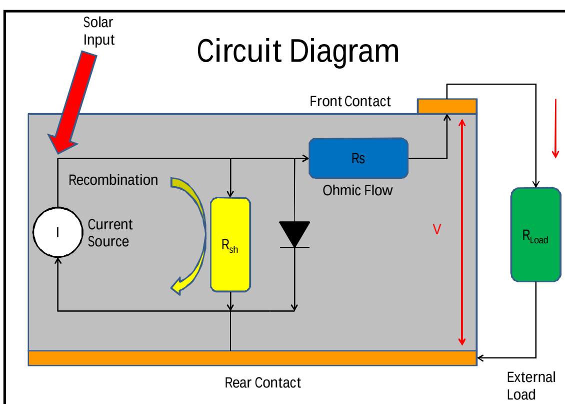
The typical sheet resistivity for the emitter in silicon solar cells is 30-100 Ω/□

Efficiency

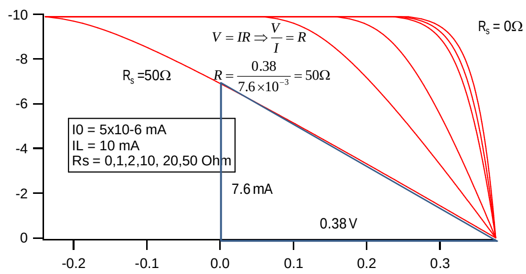
- Most commonly used parameter to compare the performance of one solar cell to another
- Defined as the ratio of energy output by the solar cell to input energy from the sun
- Efficiency depends on:
  - Spectrum
  - Intensity
  - Temperature

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

Circuit Diagram



Effect of Series Resistance



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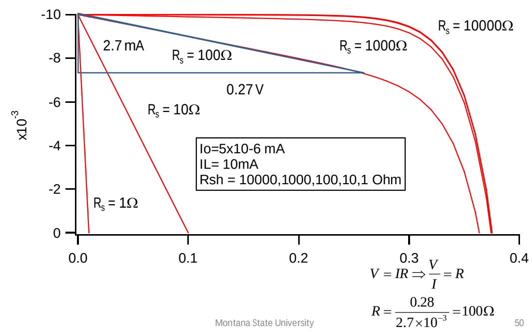
Effect of Shunt Resistance



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Multi-Junction III-V Cells

- Stacked p-n junctions on top of each other
- Each junction has a different band gap energy so each will respond to a different part of the solar spectrum
- Very high efficiencies, but more expensive
- Each junction absorbs what it can and lets the remaining light pass onto the next junction
- Widely used for space applications because they are very expensive
- Overall record for electrical efficiency is 35.2%

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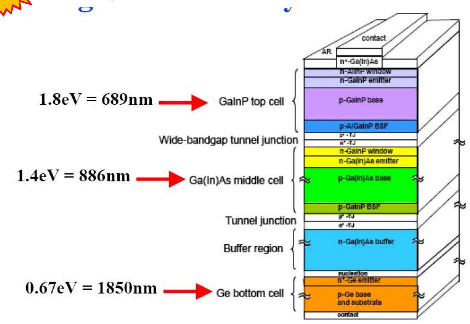
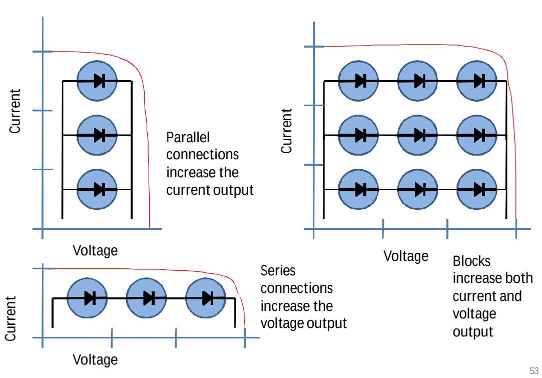
Highest Efficiency Device



Solar Cell Panels



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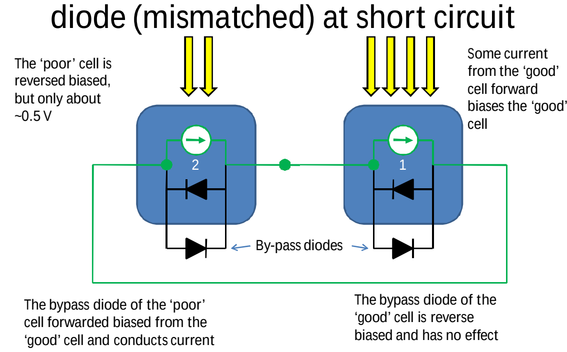
Series connected solar cells with by-pass diode (mismatched) at short circuit



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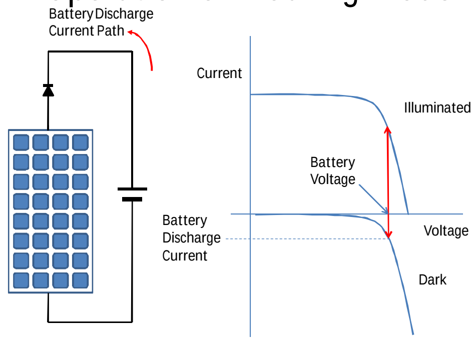
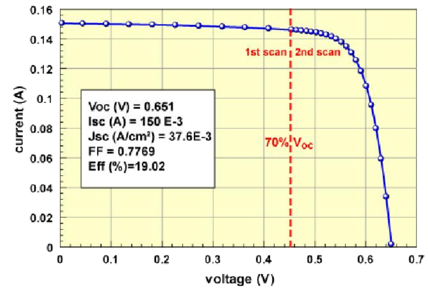
Operation of Blocking Diode

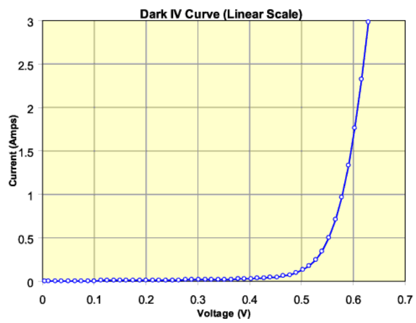


Automated Electronics

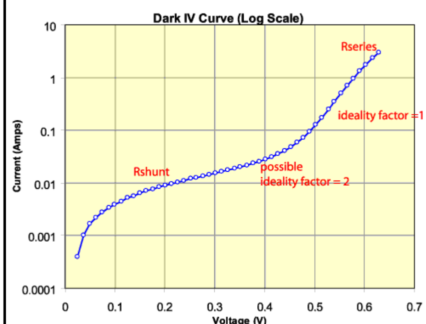


Two sweeps 0-70% of Voc then 70%-100% of Voc in smaller increments

IV Dark (linear)

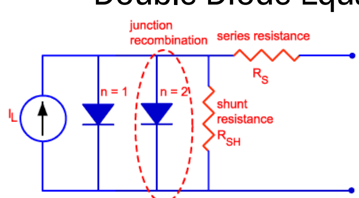


IV Dark (semilog)



Semilog IV plot reveals more information about the diode. Different regions of the IV curve are dominated by different loss mechanisms

Double Diode Equations



Small fluctuations in the light intensity overwhelm the effects of the second diode. More common to use the double diode equation in the dark

Light

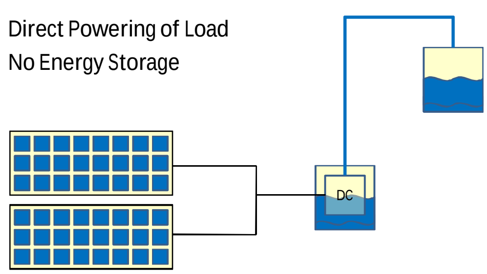
$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT} - 1\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT} - 1\right) - \frac{V+JR_s}{R_{shunt}}$$

Dark

$$J = -J_{01}\exp\left(\frac{q(V+JR_s)}{kT} - 1\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT} - 1\right) - \frac{V+JR_s}{R_{shunt}}$$

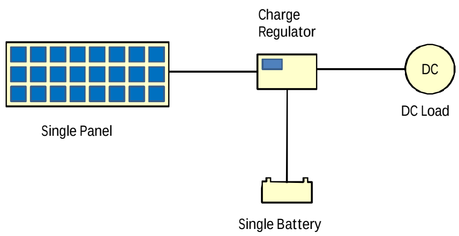
Simple DC

- Direct Powering of Load
- No Energy Storage



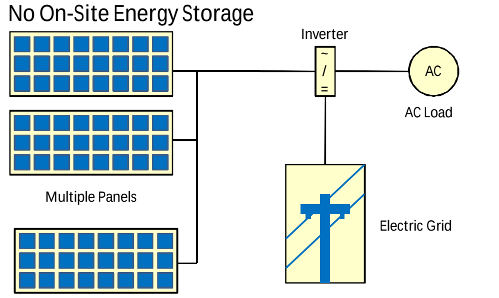
Small DC

- Home and Recreational Use

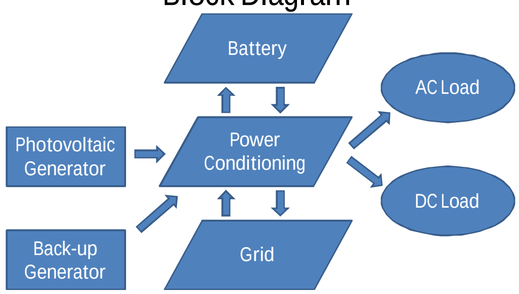


Utility Grid Connected

- No On-Site Energy Storage

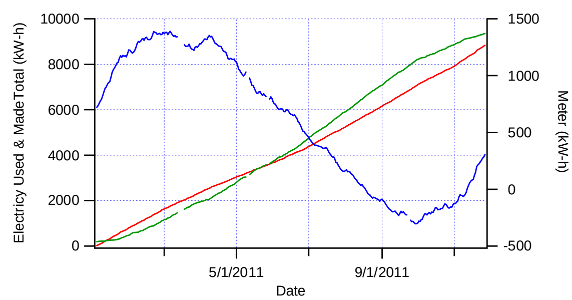


Photovoltaic System Design Block Diagram



Not all the subsystems will be necessary

Electric Use, Made & Meter Total



Final Lab Report (Wafer Number)

- Background
  - Fabrication Sequence
  - Device Cross Section
- Measurements
  - N+ Final Sheet Resistivity
  - P+ Final Sheet Resistivity
  - Front Al Sheet Resistivity
  - Back Al Sheet Resistivity
  - Front Al Thickness
- Wafer Testing
  - Pre-anneal
  - Post-anneal
- Device Testing
  - IV curves (4)
    - Resistance Estimation
    - Fill Factor
    - Efficiency Estimations
  - PV Curves
    - Max power point
  - Dark I-V curves (SDA)
    - Linear
    - Semilog
- Analysis
  - 4 solar cell data table
  - Series resistance calculations
  - Annealing impact
  - Class Data Table
  - 4 devices Variances
  - Comparison of Class Data
- Summary
  - Results
    - Maximum Voltage
    - Maximum Current Density
    - Maximum Fill Factor
    - Efficiency
  - Course recommendations