University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Solar Cell and LED

Instructor: Professor Hua Bao

NANO ENERGY LAB

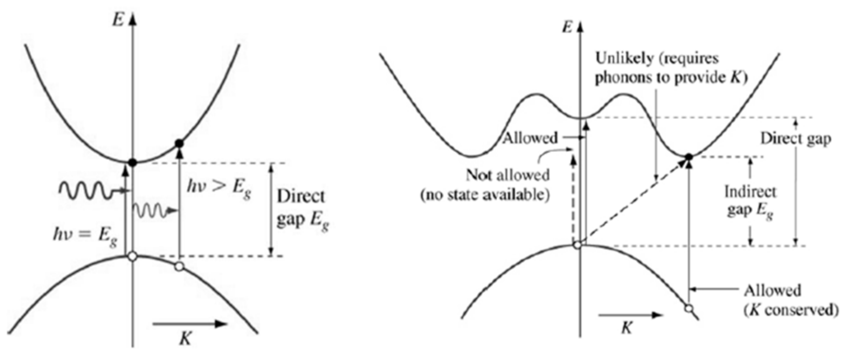


# Optical Generation

**Both energy and momentum conservation needs to be satisfied.**

The momentum of a photon is small

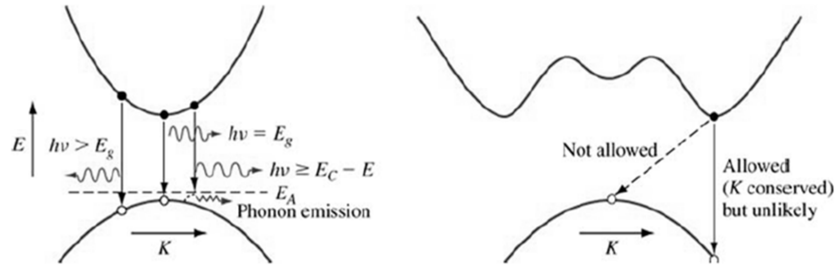
**Direct Bandgap (e.g. GaAs)** **Indirect Bandgap (e.g. Si)**



# Optical Recombination

The momentum of a photon is small

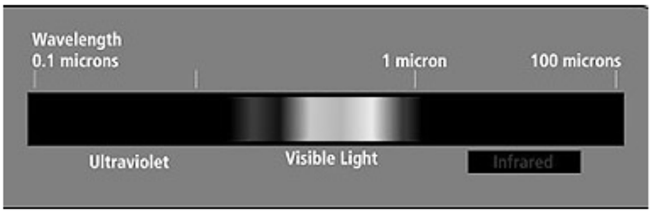
**Direct Bandgap (e.g. GaAs)** **Indirect Bandgap (e.g. Si)**

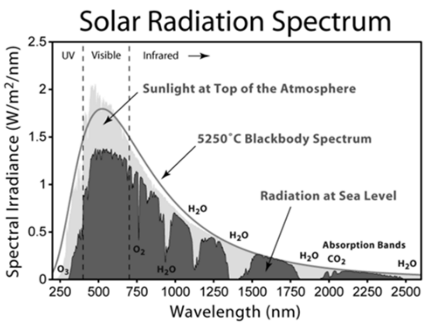



Would you expect radiative recombination (light emission) to be significant in silicon?

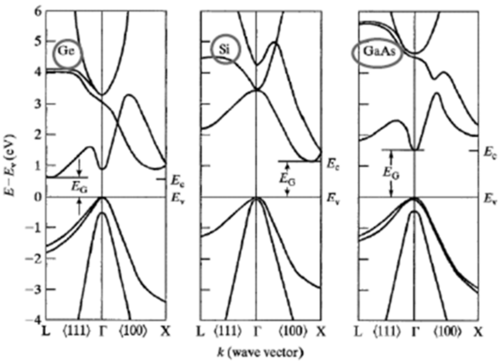


# Light Spectrum



# Band Gap



- Onset of photon absorption
- The energy of photon that is emitted.

Energy unit to wavelength unit.

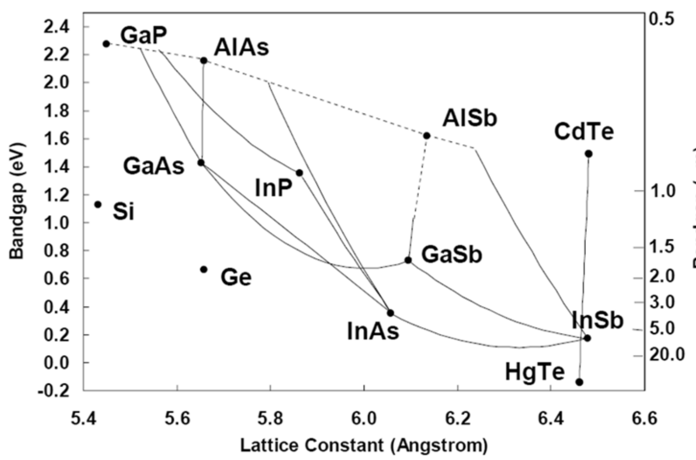
$$\lambda(\mu m) = \frac{1.24}{E(eV)}$$

Si ~ 1.1 um =1100 nm
Ge ~ 1.8 um = 1800 nm
GaAs ~ 0.87 um = 870 nm



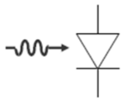
# Semiconductor Materials

**Operating wavelength depends on band gap energy**



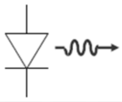
# Semiconductor Optoelectronic Diodes

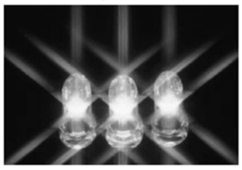
Detectors convert optical signals into electrical signals



- Photodetectors: primary purpose to detect photons
- Solar Cells: primary purpose is photo-to electrical energy conversion

Emitters are a source of optical radiation

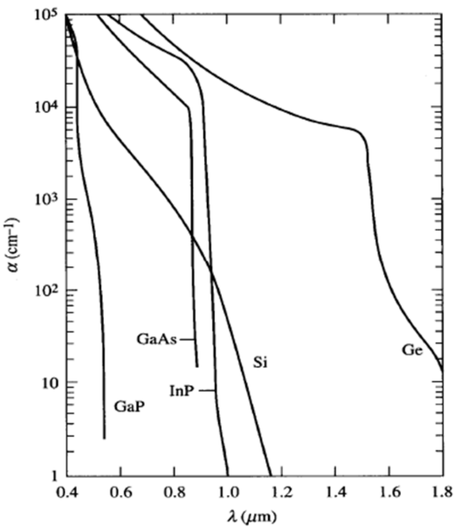




- Light-emitting diodes (LEDs)
- Lasers –may be obtained using optical cavity

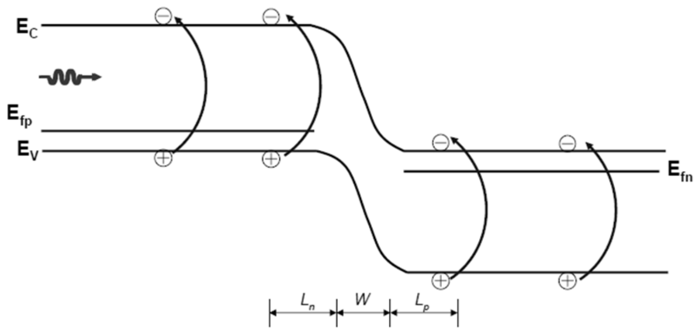


# Optical Absorption Depth




$$I = I_0 \exp(-\alpha x)$$

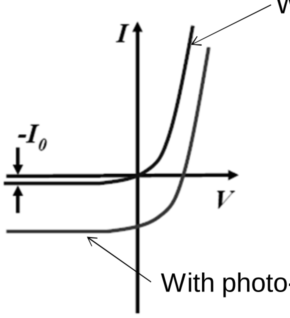
# PN-Junction Photodiode

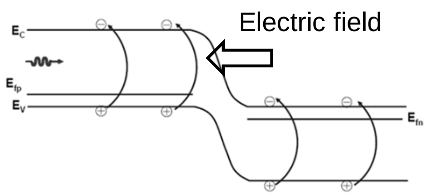



- Minority carriers generated near the depletion region will diffuse to the depletion region and be swept across by the electric field, thereby contributing to current flow.
- Minority carriers generated away from the depletion region will recombine before reaching the depletion region and therefore not contribute to current flow.



# Solar Cell



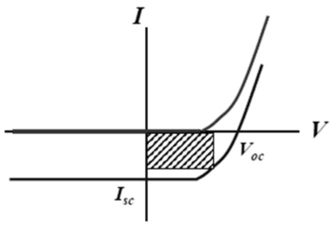

A reverse going current due to photo generation

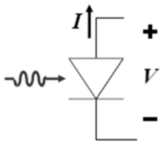
$$I_L = -qA(L_N + W + L_P)G_L$$

$$I = I_{dark} + I_L$$

The shift in the I-V curve caused by photo generation leads to electrical power generation

# Power Generation




$V_{oc}$ Open circuit voltage
$I_{sc}$ Short circuit current

Fill Factor: $FF = \frac{P_{max}}{I_{sc}V_{oc}}$

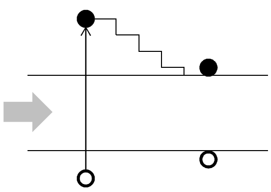
Power conversion efficiency $\eta = \frac{FF\ I_{sc}V_{oc}}{P_{in}}$

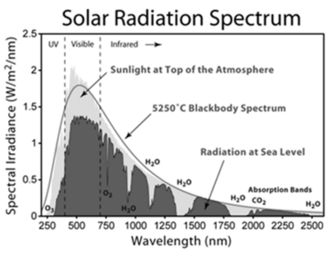


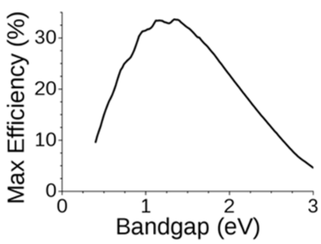
# Shockley-Queisser Limit for Solar Cell Efficiency

Every photon with energy (hv) > Eg creates one electron-hole pair

Thermalization Loss






To break this limit:
1. Multi-junction solar cell
2. Concentrator solar cell
3. Quantum dot solar cell?

## Why is silicon a good solar cell material?

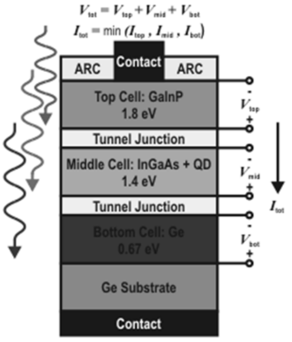
Typically want :
Direct band gap semiconductor (so that absorption depth is small)
-- but silicon is indirect band gap

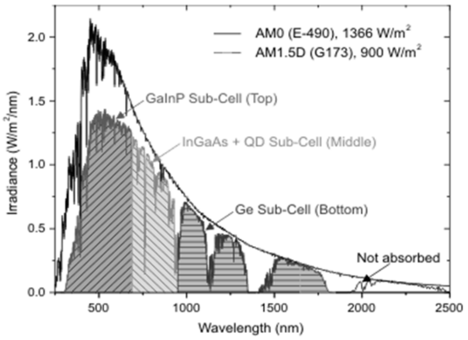
$E_g$ ~ 1.4 eV (Silicon has 1.1 eV)

However, silicon can be made very pure, so recombination times are long.



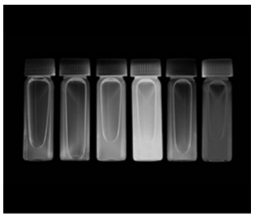
## Multi-junction Cell



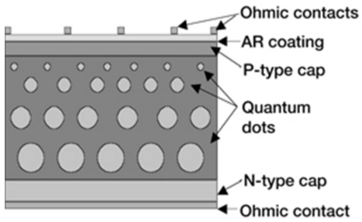




http://sunlab.site.uottawa.ca/research.php

# Quantum Dot Solar Cell

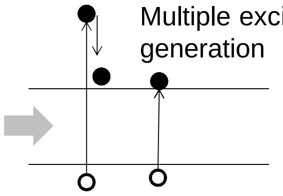


http://www.grc.nasa.gov/WWW/RT/RT2001/5000/5410bailey1.html



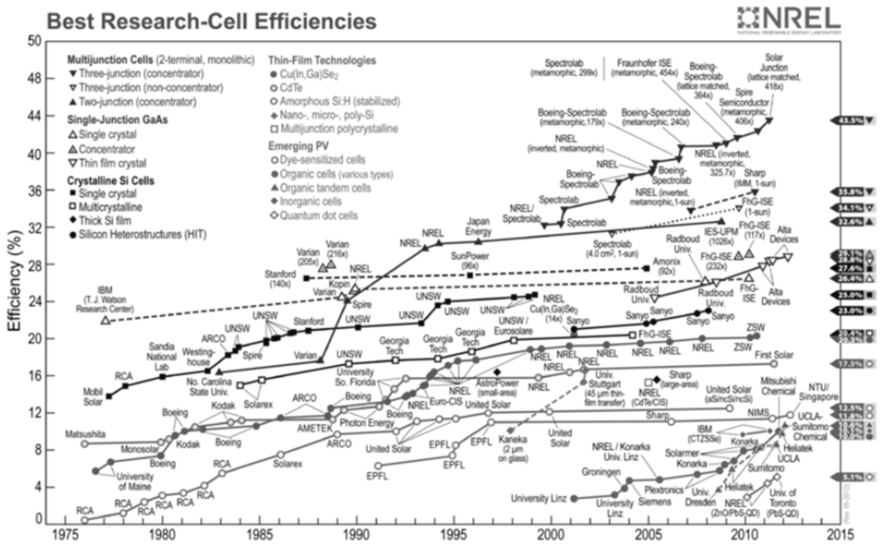

http://nanoe.ece.drexel.edu/wiki/index.php/Quantum_Dot_Challenge

1. Tunable band gap by size control
2. Possible multiple exciton generation.



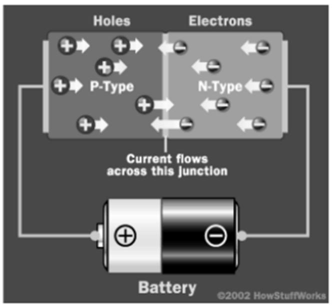


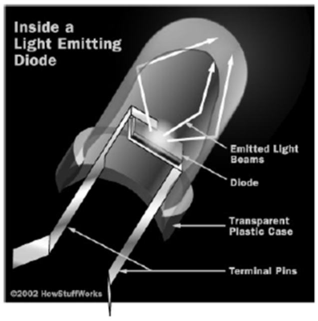

# Solar Cell Efficiency



# Light Emitting Diode (LED)

- Directly produce light through electron relaxation in a solid
- Compact, efficient light emitters
- Lifetime ~100,000 hours
- Challenges for lighting: white light, efficiency, cost

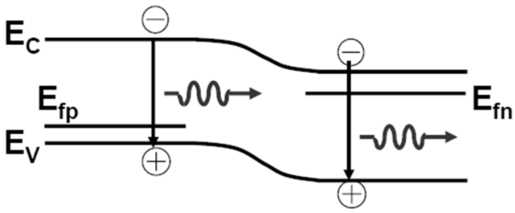





# Light Emitting Diode (LED)

Forward bias diode –minority carrier recombination in form of radiative recombination




External efficiency: η = photo power out / electrical power in

# LED

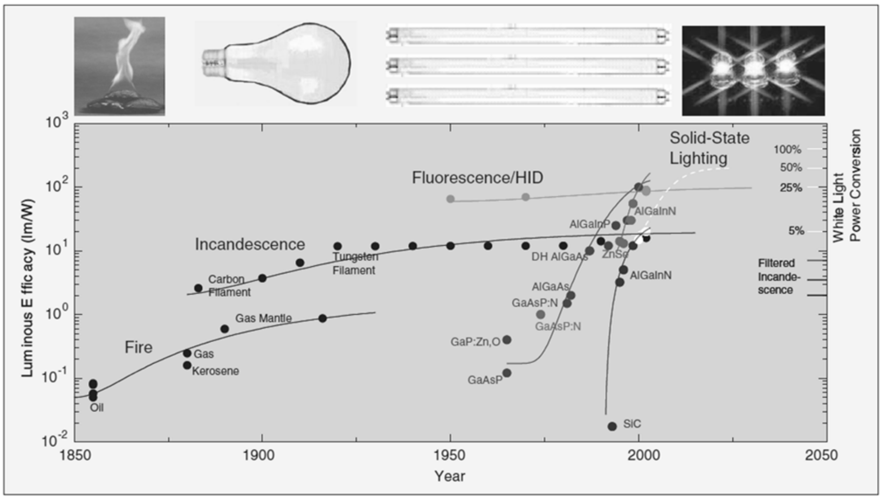
- Direct band gap
- Band gap value between 1.77 eV and 3.10 eV (to be visible)
- Be amenable to the formation of pn-junction diode.
- No elemental or compound semiconductors meet these requirements

Alloy

| Semiconductor | Color | Peak $\lambda (\mu m)$ | External Efficiency $\eta$ (%) | Performance (lumens/watt)† |
|---|---|---|---|---|
| *Established Materials* | | | | |
| $GaAs_{0.6}P_{0.4}$ | Red | 0.650 | 0.2 | 0.15 |
| $GaAs_{0.35}P_{0.65}$:N | Orange-Red | 0.630 | 0.7 | 1 |
| $GaAs_{0.14}P_{0.86}$:N | Yellow | 0.585 | 0.2 | 1 |
| GaP:N | Green | 0.565 | 0.4 | 2.5 |
| GaP:Zn-O | Red | 0.700 | 2 | 0.40 |
| *Recent Additions* | | | | |
| AlGaAs | Red | 0.650 | 4–16 | 2–8 |
| AlInGaP | Orange | 0.620 | 6 | 20 |
| AlInGaP | Yellow | 0.585 | 5 | 20 |
| AlInGaP | Green | 0.570 | 1 | 6 |
| SiC | Blue | 0.470 | 0.02 | 0.04 |
| GaN | Blue | 0.450 | 2 | 0.6 |



# Lighting History




J. Tsao, IEEE Circuits and Devices Vol20, No 3, pp 28-37

## Summary

- Basic concepts about solar cell… efficiency, fill factor, open circuit voltage, short-circuit current
- Limiting factors for solar cell efficiency
- Basic concepts about LED