Physics of Solar Cells

How do solar cells work?

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Introduction and Scope

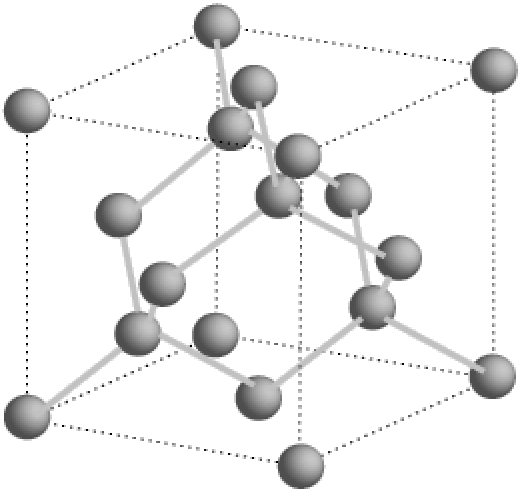
- Material: single crystal silicon
  - 85% of solar cells are made from silicon
  - VERY well understood
- Focus on physics
  - Optical Properties
  - Electrical Properties
  - P-n junctions
  - Solar cell
  - Limitations and opportunities

What do we know about silicon?

- A lot!
- It’s a very abundant element (~26% of the earth’s crust).
- We know it’s crystal structure.
- We know most of its optical and electrical properties.
- We know how to grow large single crystals of it.
- We know how to purify it.
- We know how to passivate it’s surface.
- Why?
  - It’s a single element semiconductor => the science is relatively easy
  - It has many commercial applications, and the advancement of these applications requires this knowledge.

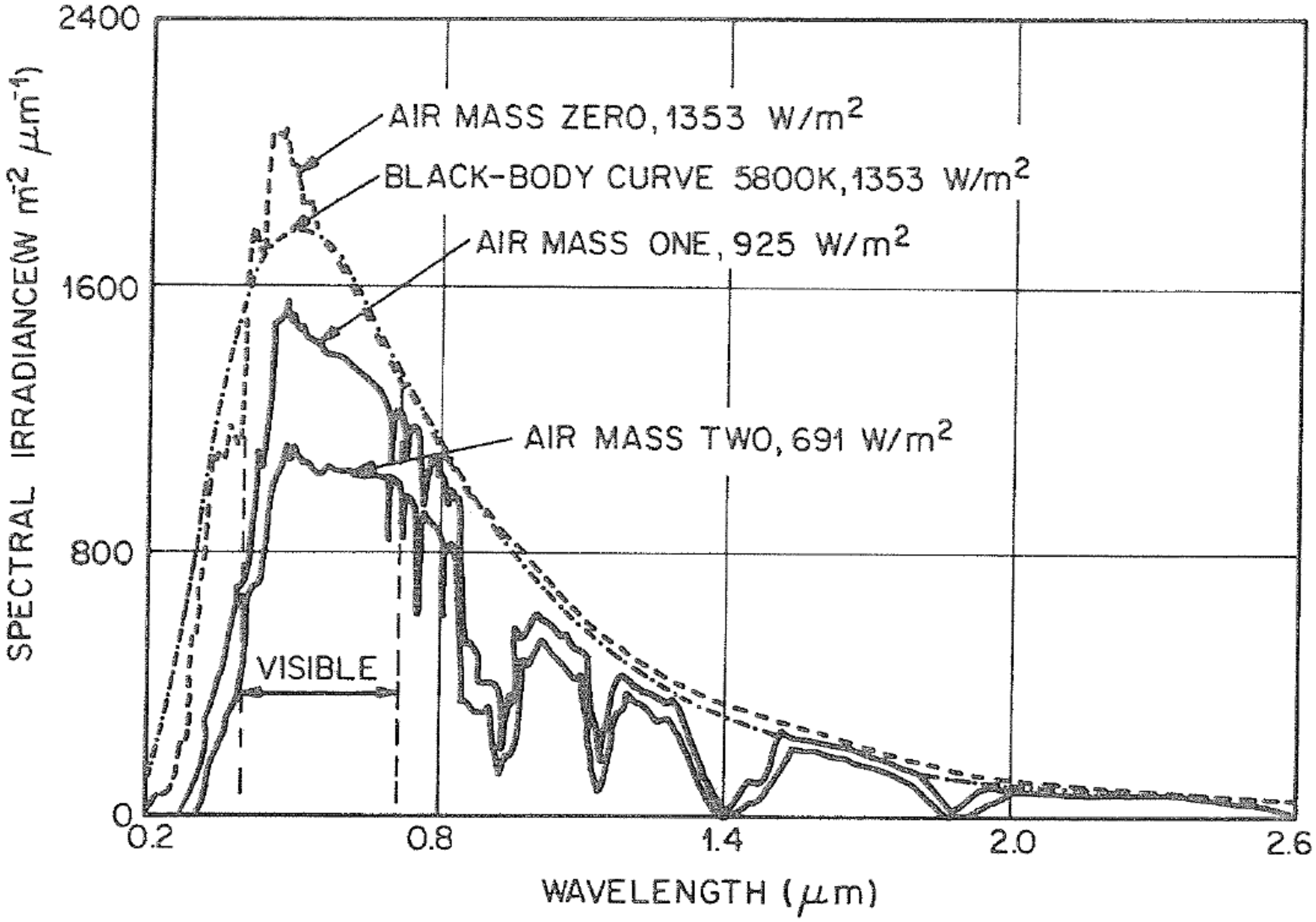
Crystal structure of silicon

- **Silicon: 14 electrons**
  - **2 1s and 8 2s and 2p core electrons.**
  - **4 valence electrons --- often hybridizes to sp^3.**
  - **In crystal, the Si atoms are 4-corrdinated.**
  - **Forms a face-centered cubic crystal with two atoms per unit cell.**
  - **Same crystal structure as diamond (C) or germanium (Ge).**
  - **Semiconductor with a band gap E_g~1.15 eV.**
  - **Silicon can also be amorphous or polycrystalline.**



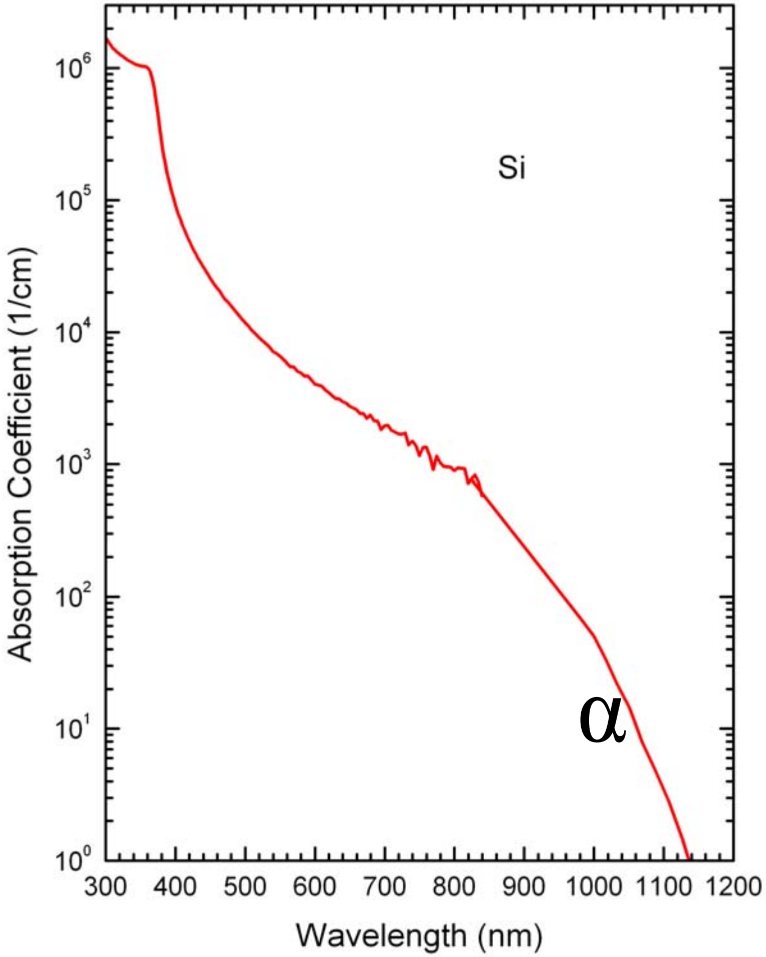
after Kittel

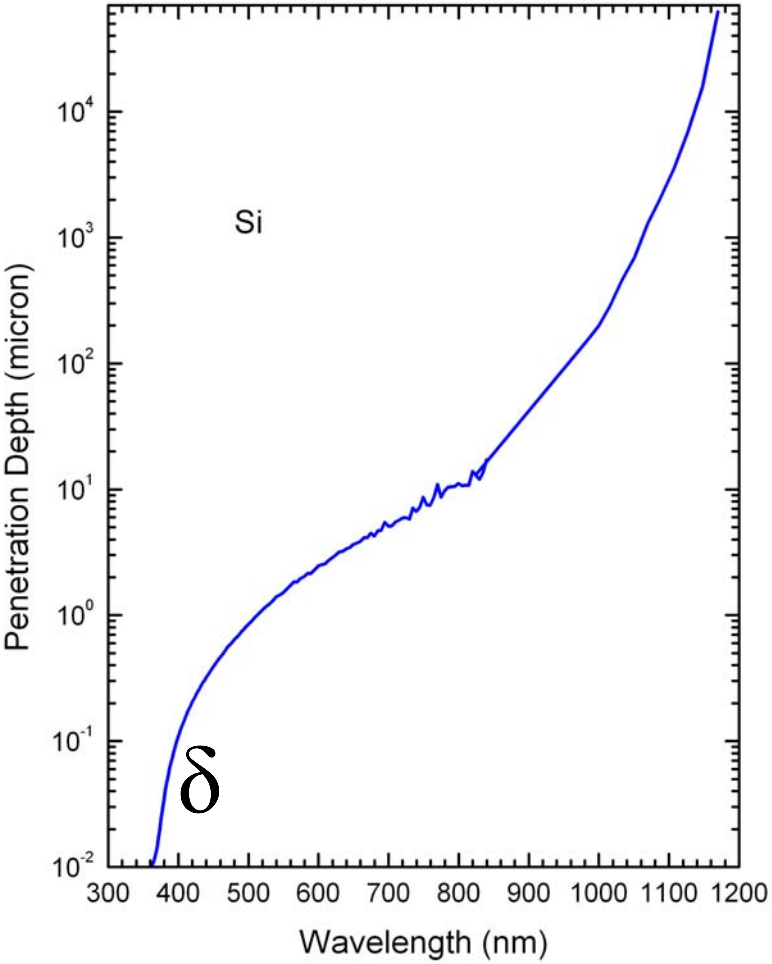
Solar Spectrum



Absorption Coefficient of Silicon

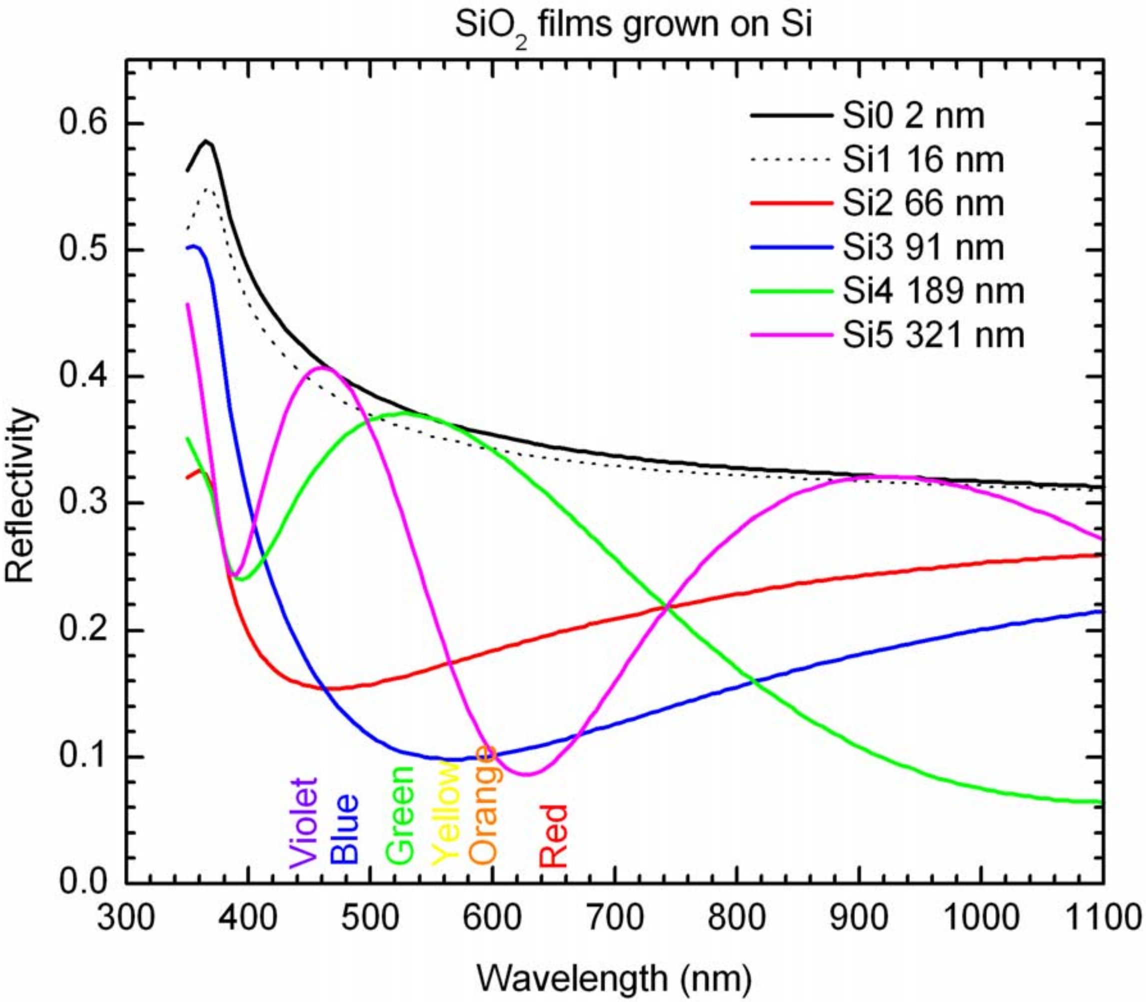
1. The average depth that the light is absorbed depends on wavelength





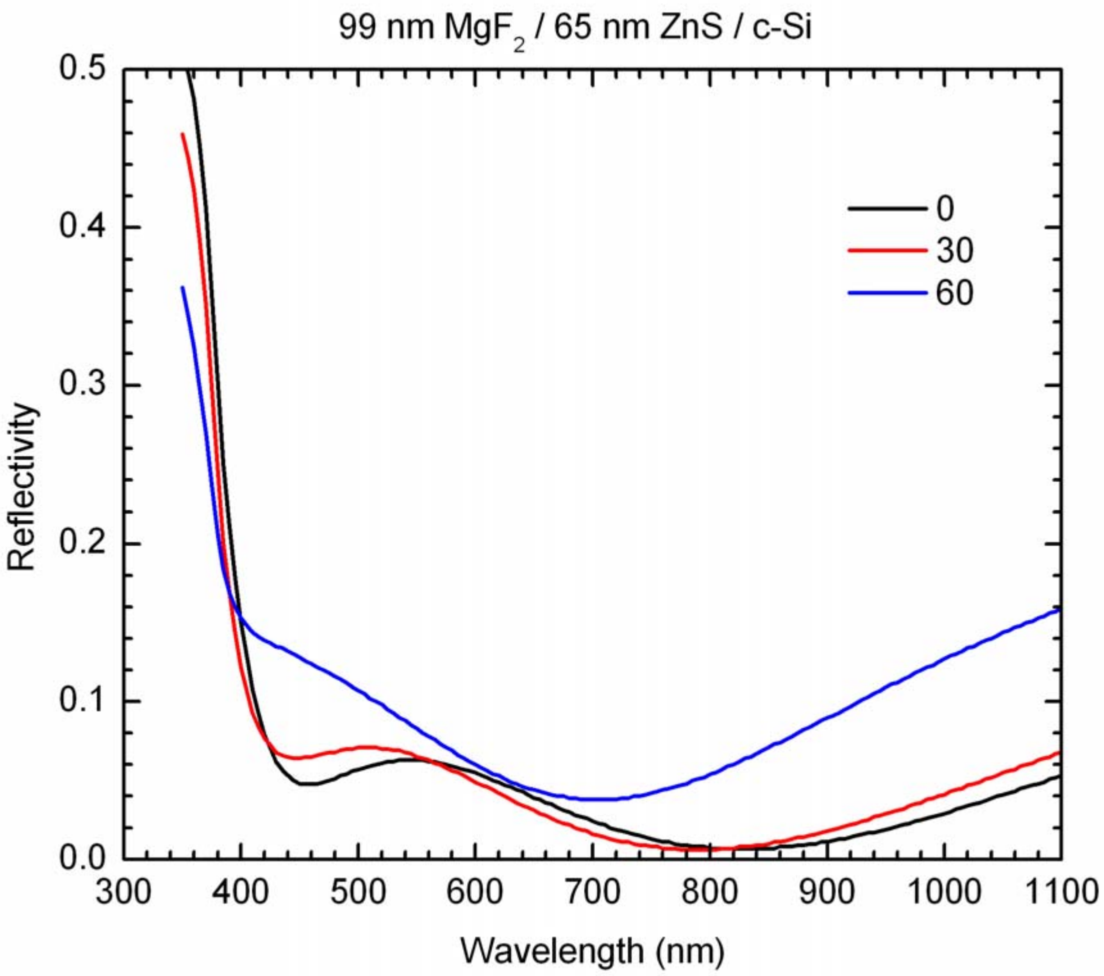
$$I = I_o e^{-\alpha d} = I_o e^{-d/\delta}$$

Reflectivity of Silicon



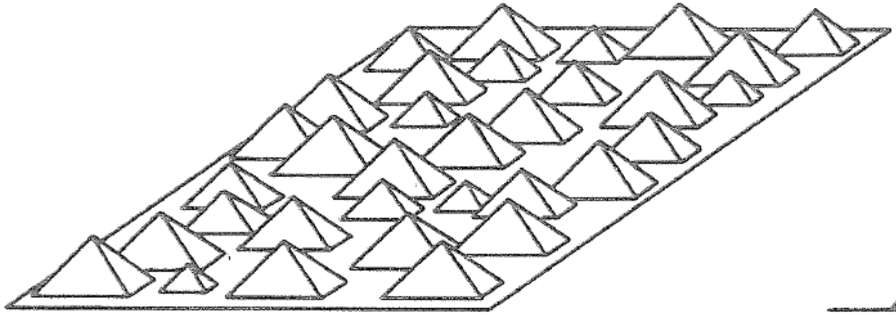
Anti-reflection coatings

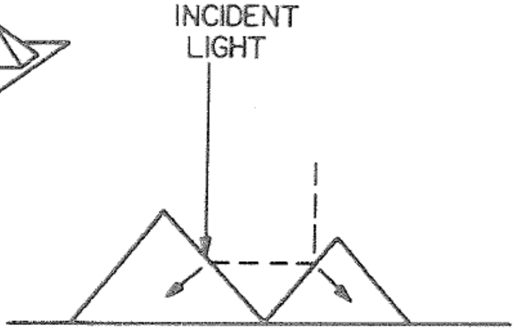
Use 2 or more layers to reduce the reflectivity even more.

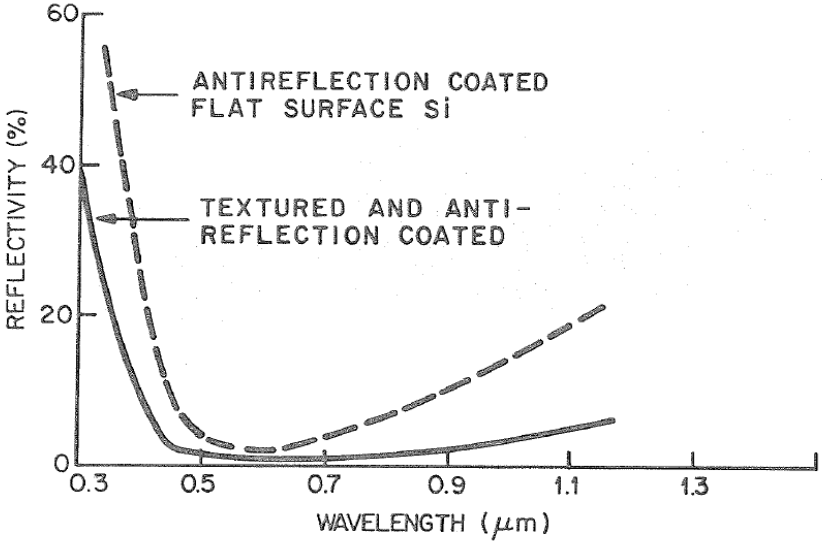


Other ways to reduce reflection:

Surface Texturing

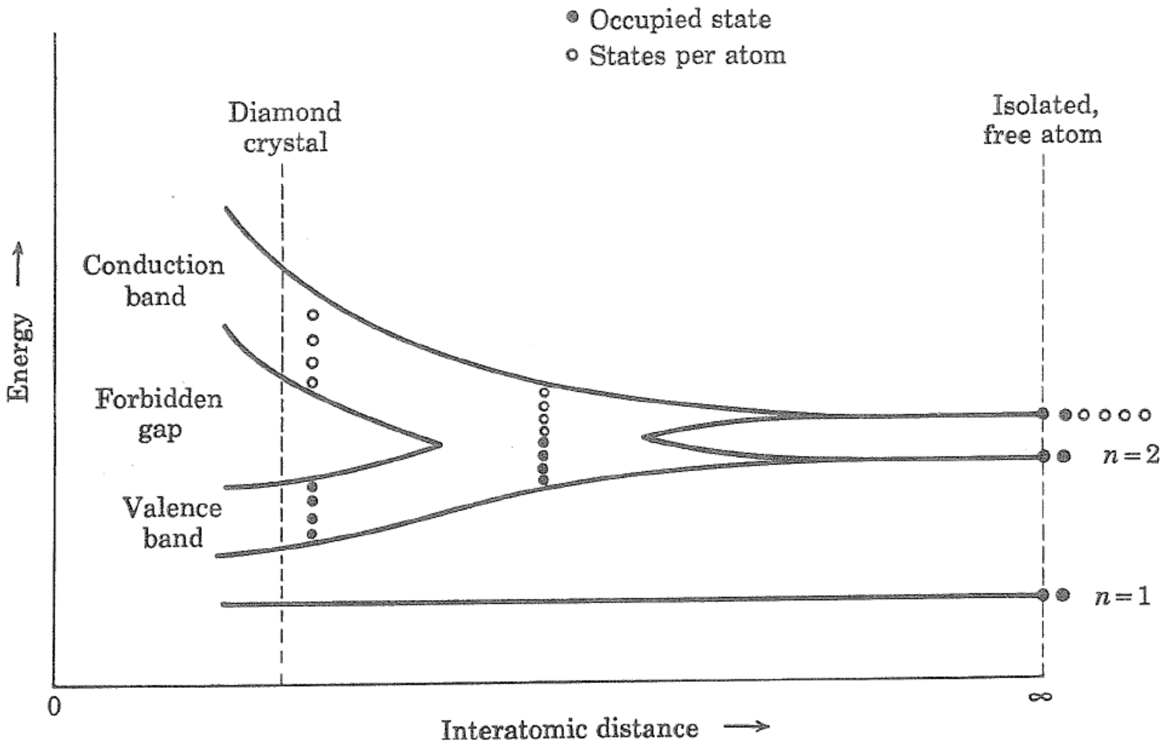






How do we understand this? Energy Bands in Solids

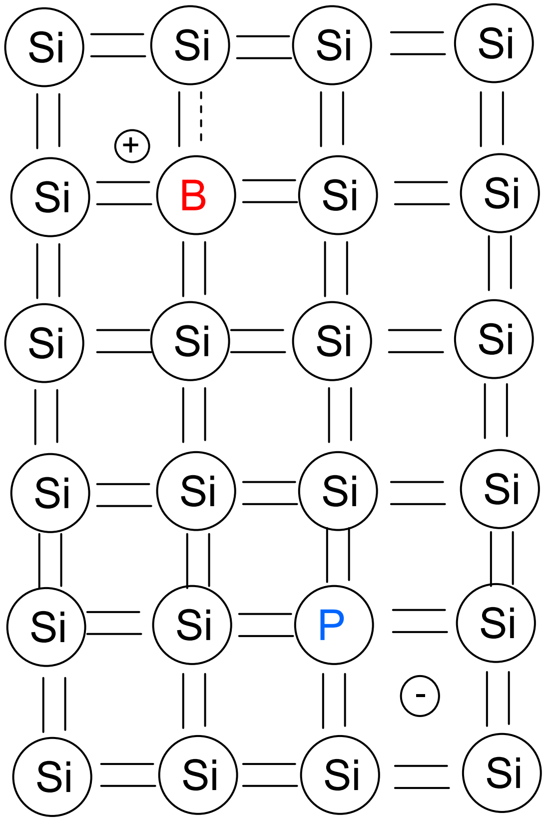
- **Thought experiment**
- **Isolated atoms: discrete energy levels**
- **Bring closer together: Begin to form bands**
- **Depending on the material, get metallic behavior or semiconductor /insulator behavior**

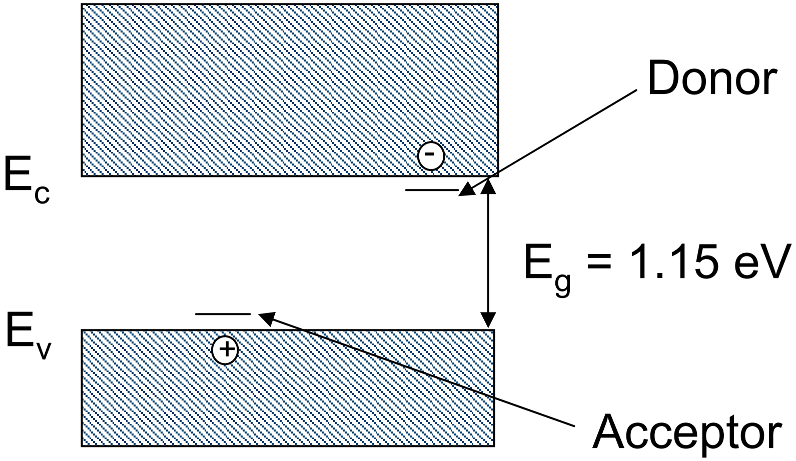


- **For Insulators or semiconductors, there are some energy values that have no electron states => band gap**
- **Light with an energy less than the band gap will pass through the material.**

Doping: Donors and acceptors

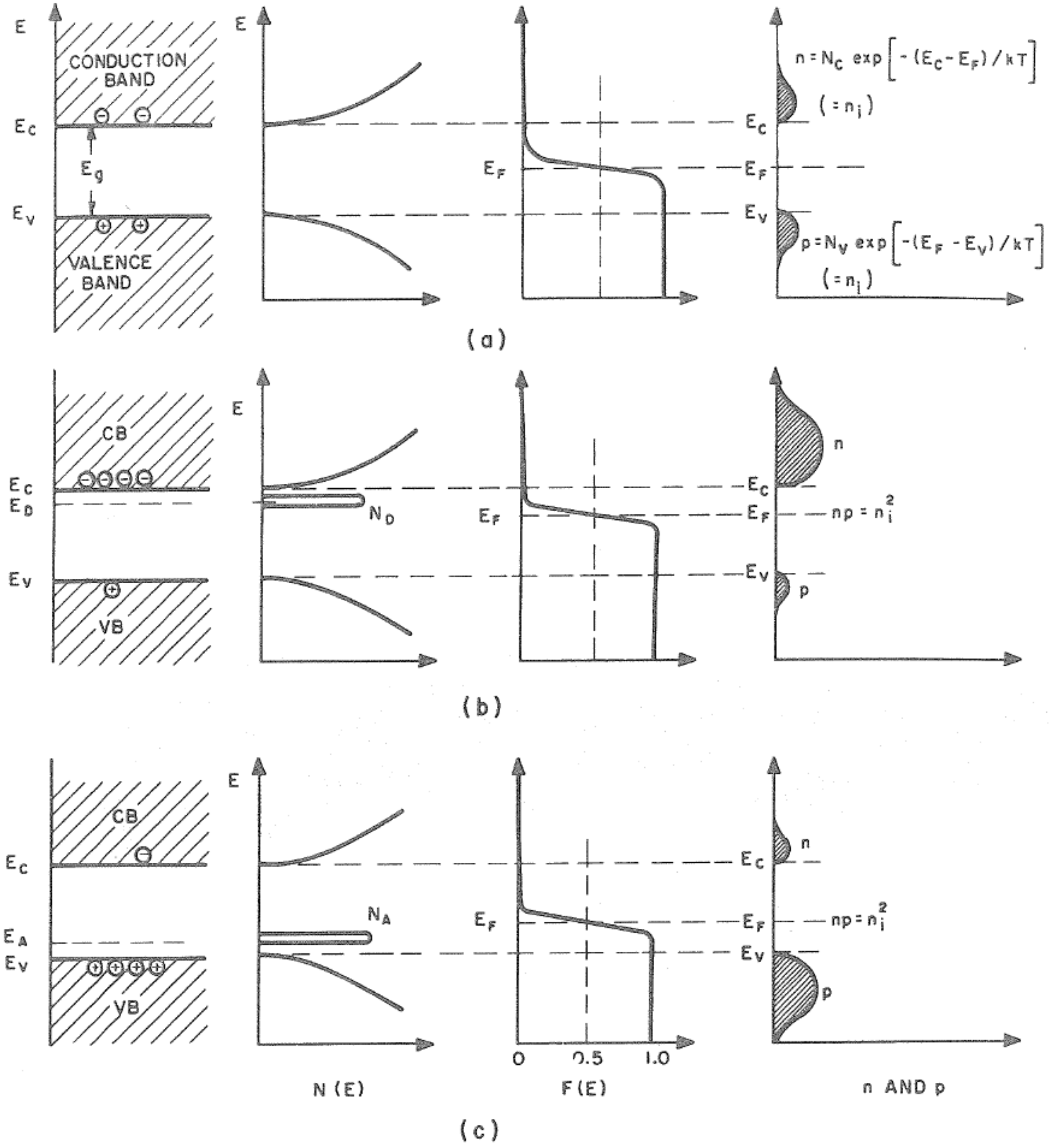
- **If you insert a group 3 atom (B, Ga) into a silicon lattice site, 3 of the bonds will be satisfied, but one will not. This leaves a "hole."**
- **If you insert a group 5 atom (P, As, Sb) into a silicon lattice site, the 4 Si bonds are satisfied, but one electron is nearly free.**





Numbers (/cm^3):	
# Si atoms	5 X 10^{22}
Intrinsic	2 X 10^{10} e and h
1 Ω-cm n-type	5 X 10^{15} e
Minority carrier	8 X 10^{4} h

Fermi level for Doped Semiconductor



$$n_i^2 = np$$

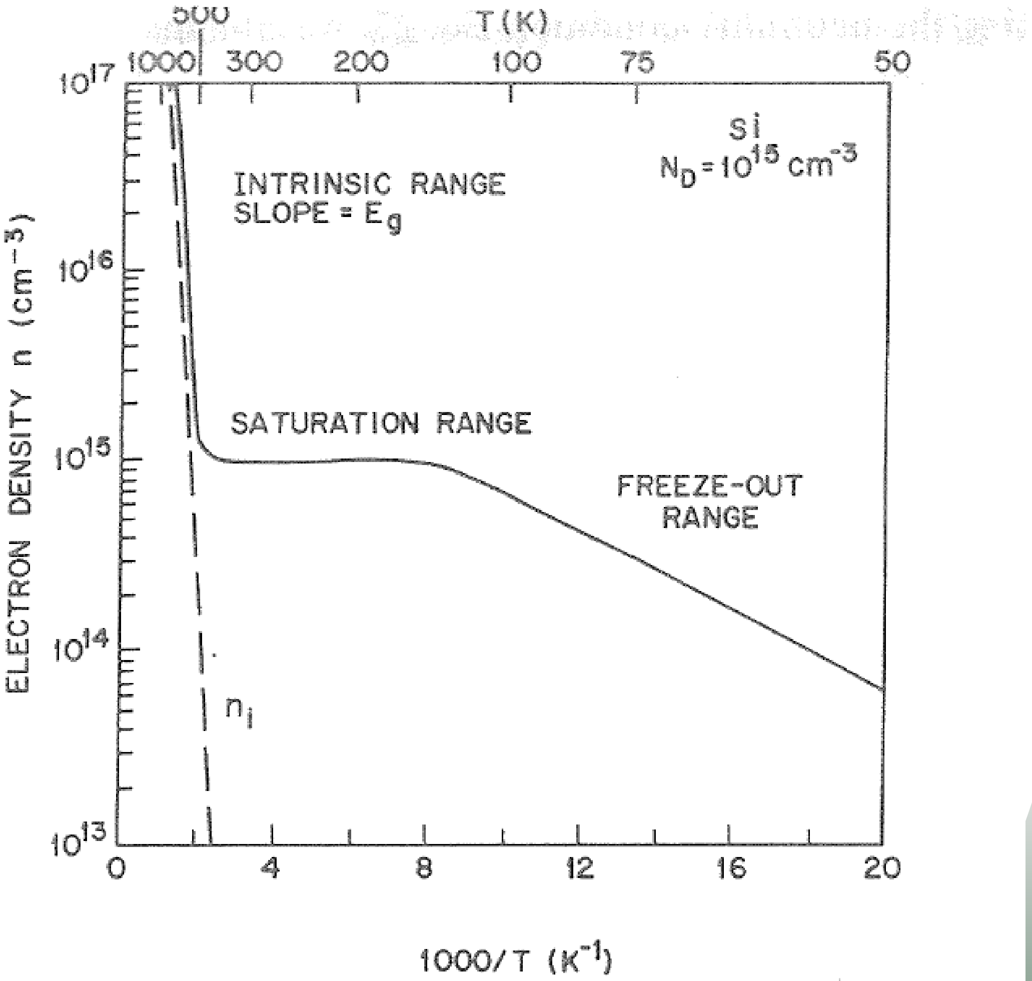
$$= Const * T^{3/2} \exp\left(\frac{-E_g}{2k_bT}\right)$$

$$F(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{k_\mathbf{B}T}\right]}$$

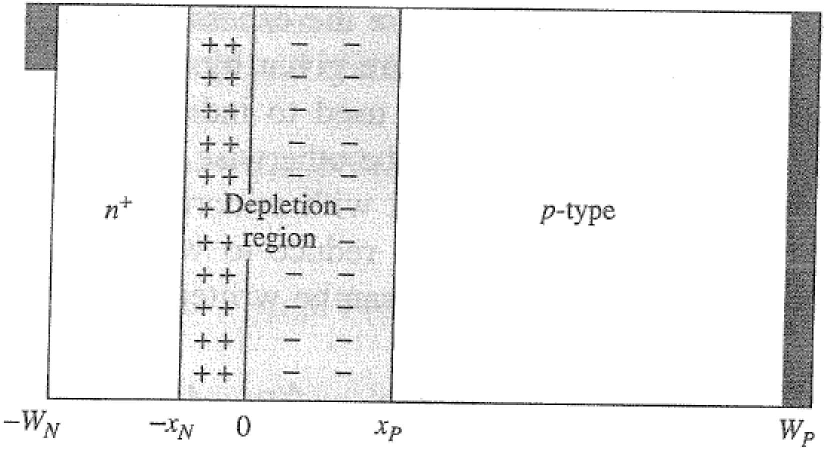
$$n = \int_{E_c}^{\infty} F(E)N(E)dE$$

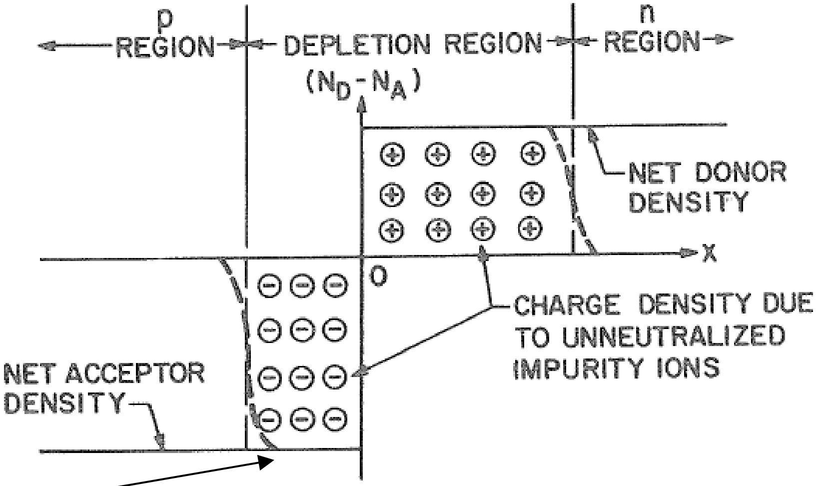
Majority Carrier concentration vs Temperature

- **At very low temperatures, freeze-out => not enough thermal energy to promote all the extra electrons on the donor atoms to the conduction band**
- **Saturation Range: electron concentration equals donor concentration**
- **Intrinsic range: number of electrons ~ number of holes.**

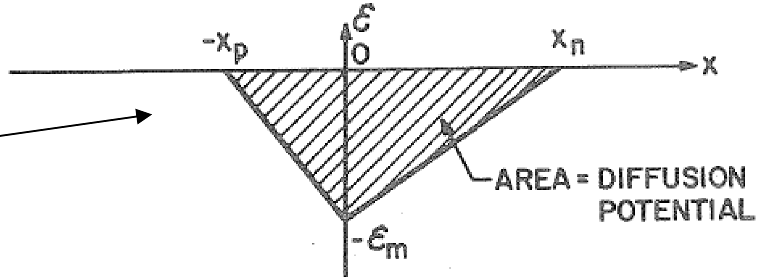


p-n junction: charge transfer

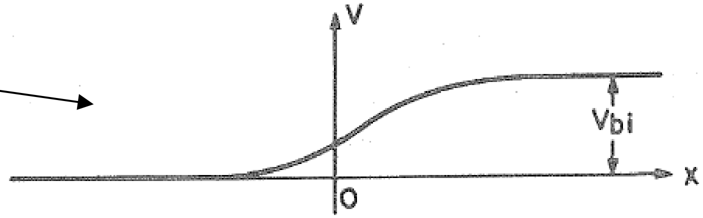




- **Contact p-region to n-region, get charge transfer**



- **Unneutralized impurity ions => electric field => potential**



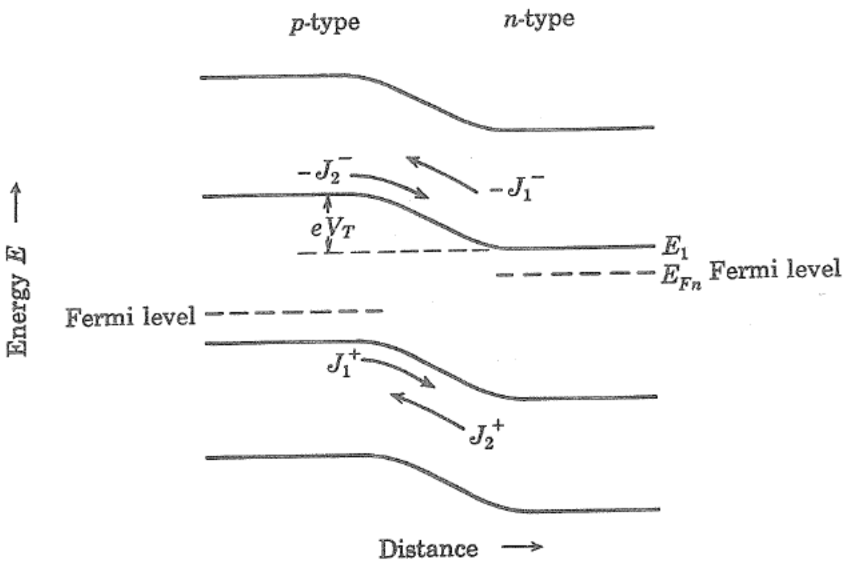
- **Poisson's Equation**

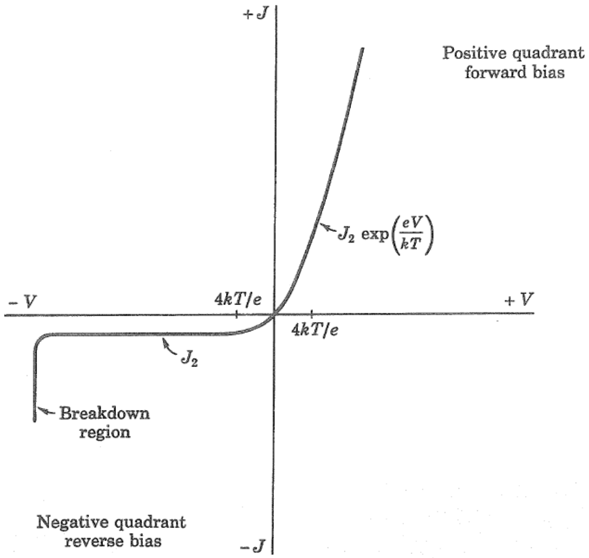
$$-\frac{\partial^2 V}{\partial x^2} = \frac{\partial \xi}{\partial x} = \frac{\rho(x)}{\varepsilon_s}$$

Current-Voltage: Shockley Equation (simplified)

- **Remember electrons have – charge, holes have + charge**
- **J_2^+ and J_2^- are saturation current densities, and do not depend on voltage (for all reverse biases and forward biases $<V_{bi}$)**
- **J_1^+ and J_1^- are the injection current densities and depend strongly on voltage**
- **Shockley Equation:**

$$J = J_s\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$



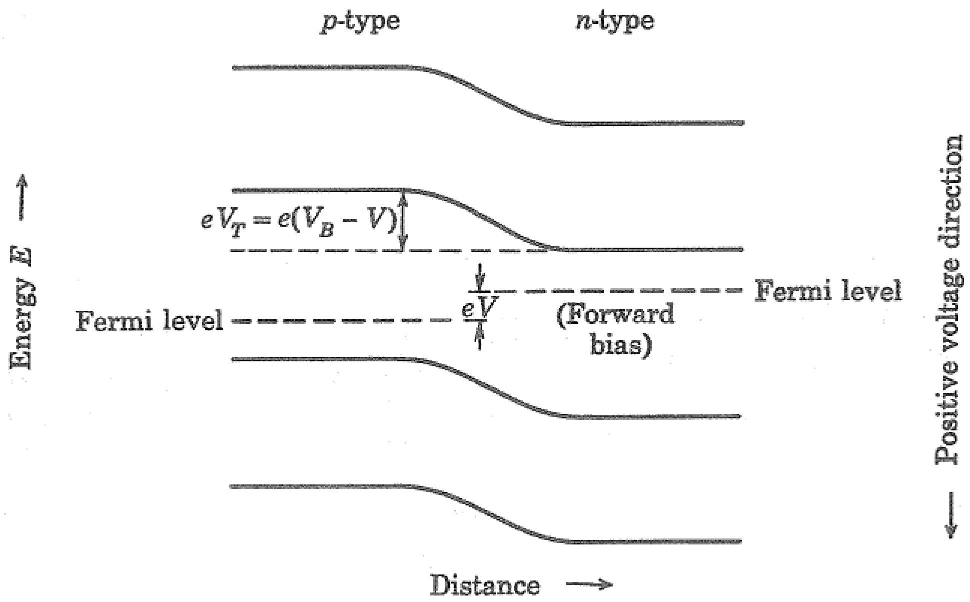


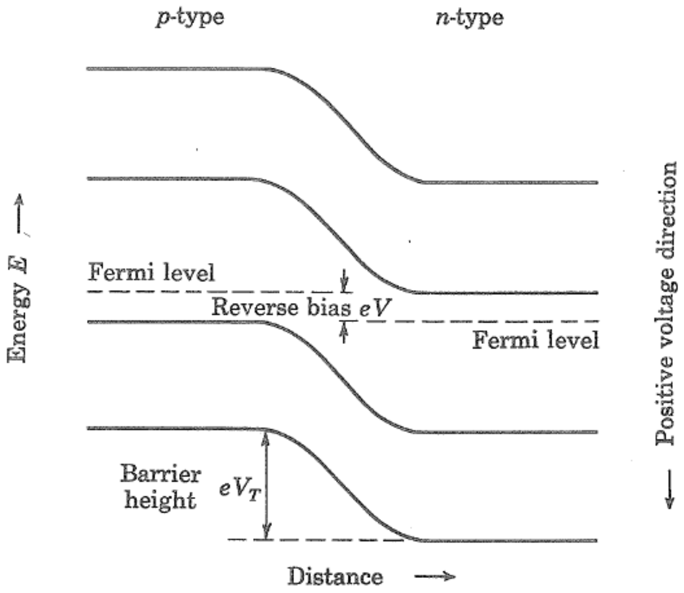
Current-Voltage

- **Apply a voltage => change the positions of the bands**

$$V_T = V_{bi} - V_{applied}$$

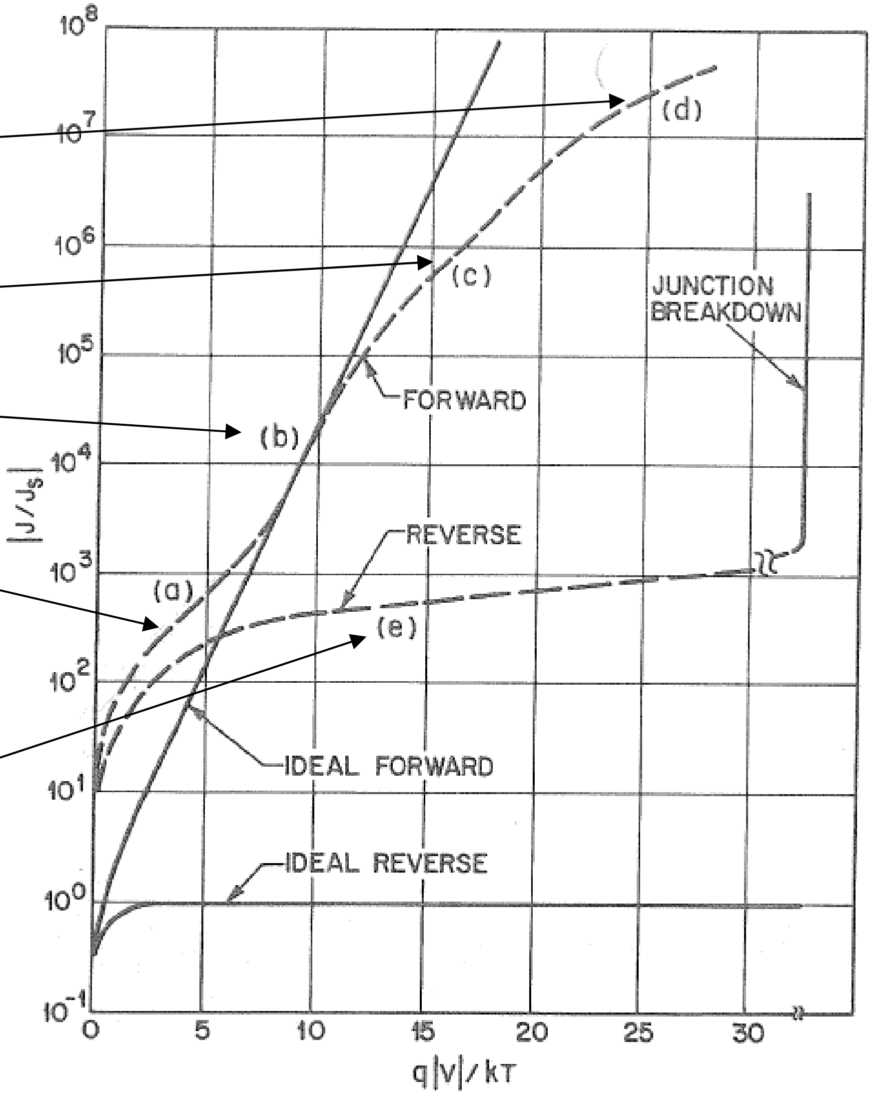
- **We also change the depletion width => Change the capacitance of the device**





Real Diode I-V curve

- **(d) Series resistance**
- **(c) High Injection**
- **(b) Diffusion current**
- **(a) Generation Recombination**
- **(e) Reverse leakage due to surface effects and generation recombination**

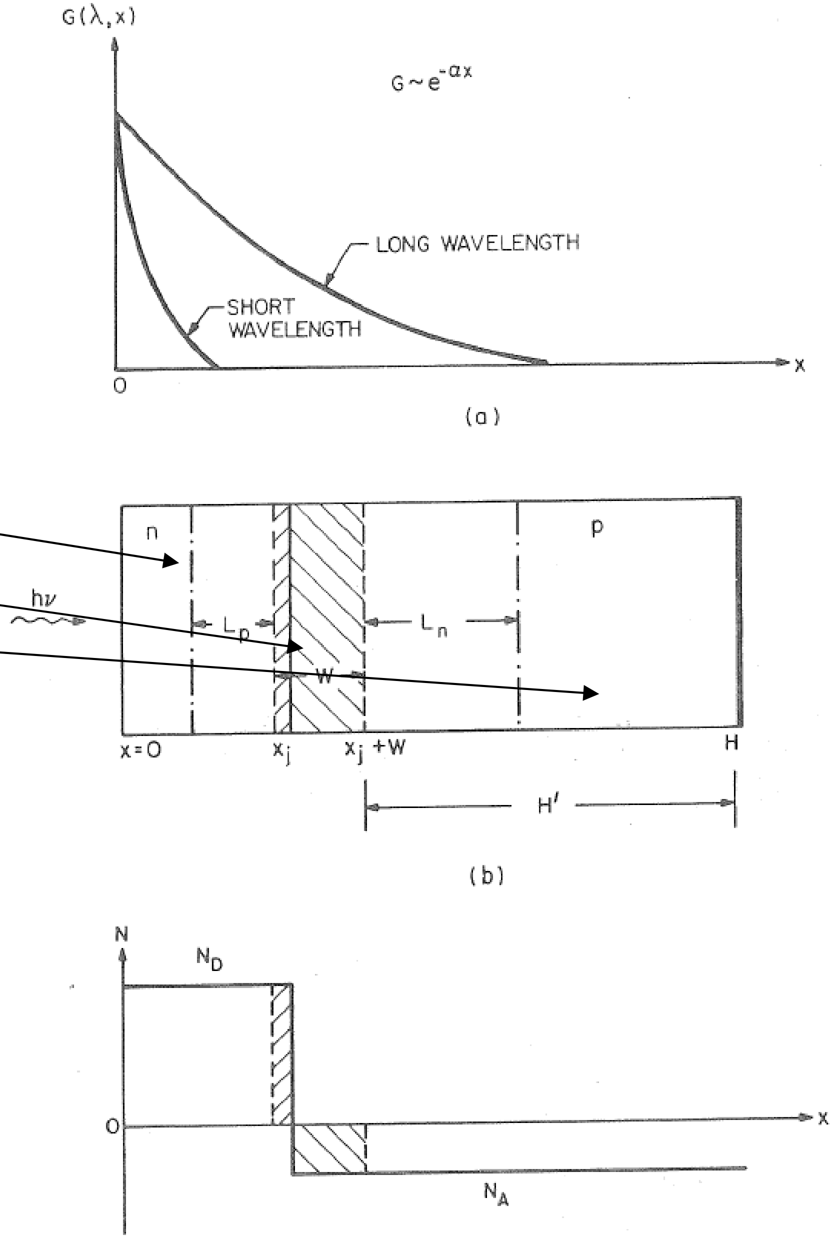


Schematic picture of a solar cell

- **Light absorption depends upon the wavelength-dependent absorption coefficient.**

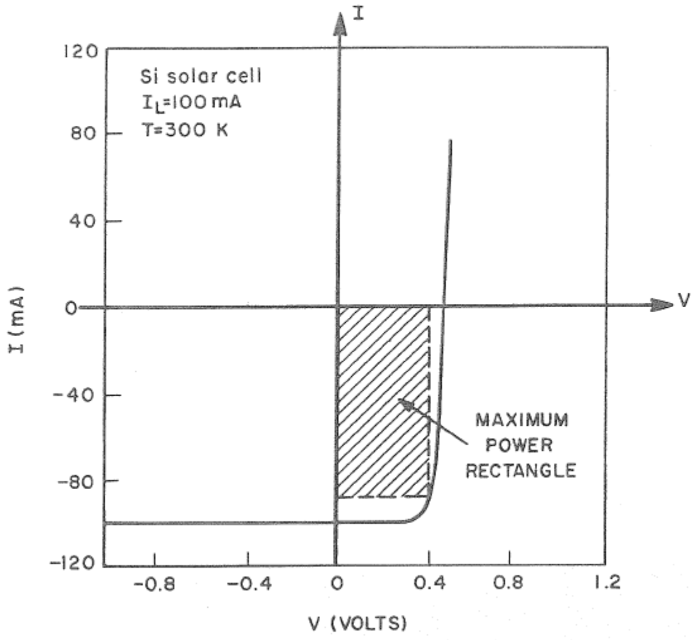
- **Emitter**
- **Depletion Region**
- **Base**

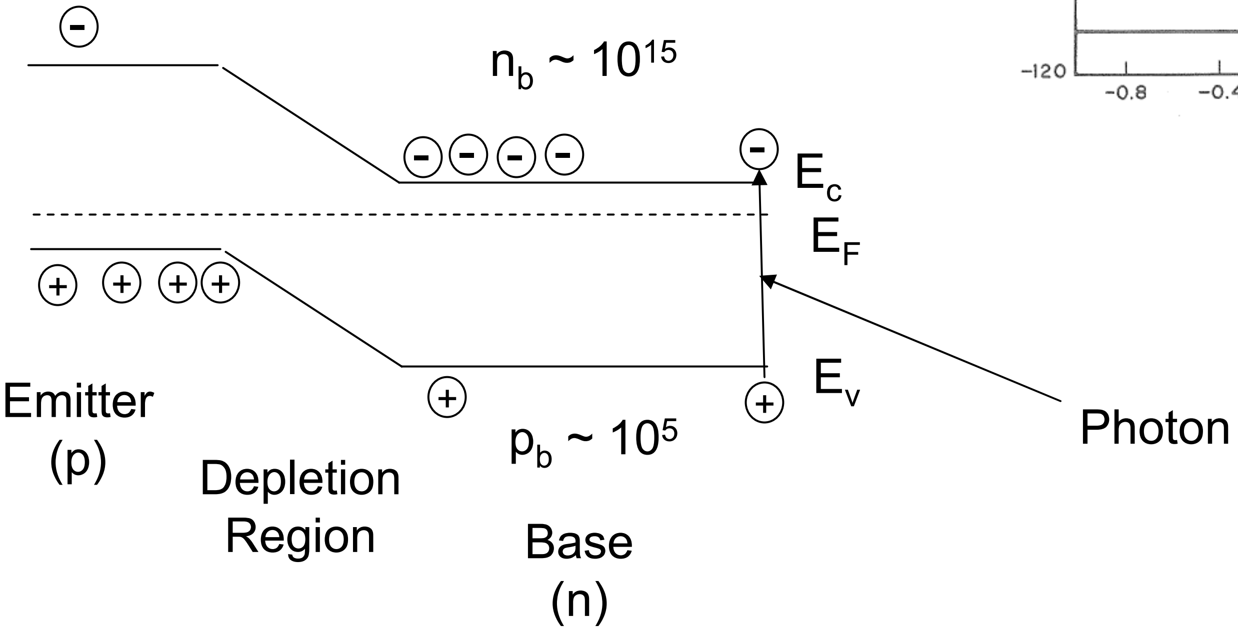
- **Usually the emitter (here, the n-region) is heavily doped, the base (here, the p-region) lighter doped.**



Solar Cell I-V Curve

- **A silicon solar cell is just a silicon p-n junction illuminated by sunlight**
- **Generation current is now substantial, changing the I-V curve**





$n_b \sim 10^{15}$

E_c

E_F

E_v

Photon

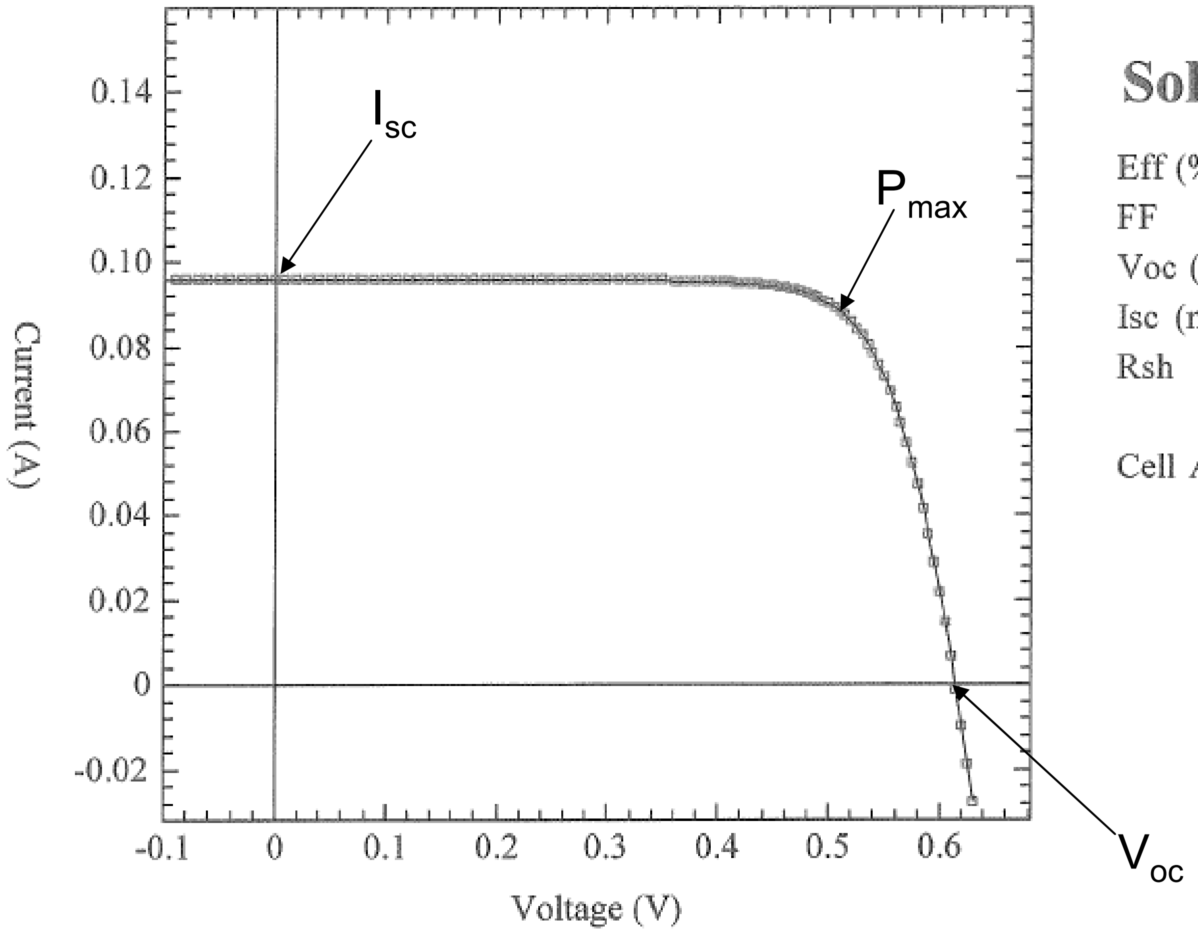
Emitter
(p)

Depletion
Region

$p_b \sim 10^5$

Base
(n)

Actual Illuminated I-V



Solar Cell Data

Eff (%)	11.26 ± 0.02
FF	0.765 ± 0.002
Voc (V)	0.614 ± 0.000
Isc (mA/cm2)	23.99 ± 0.01
Rsh	Large
Cell Area (cm2)	4.00

Quantum Efficiency (Spectral Response)

- Internal Spectral Response (Amps/Watt)

$$SR(\lambda) = \frac{J}{eF(1-R)}$$

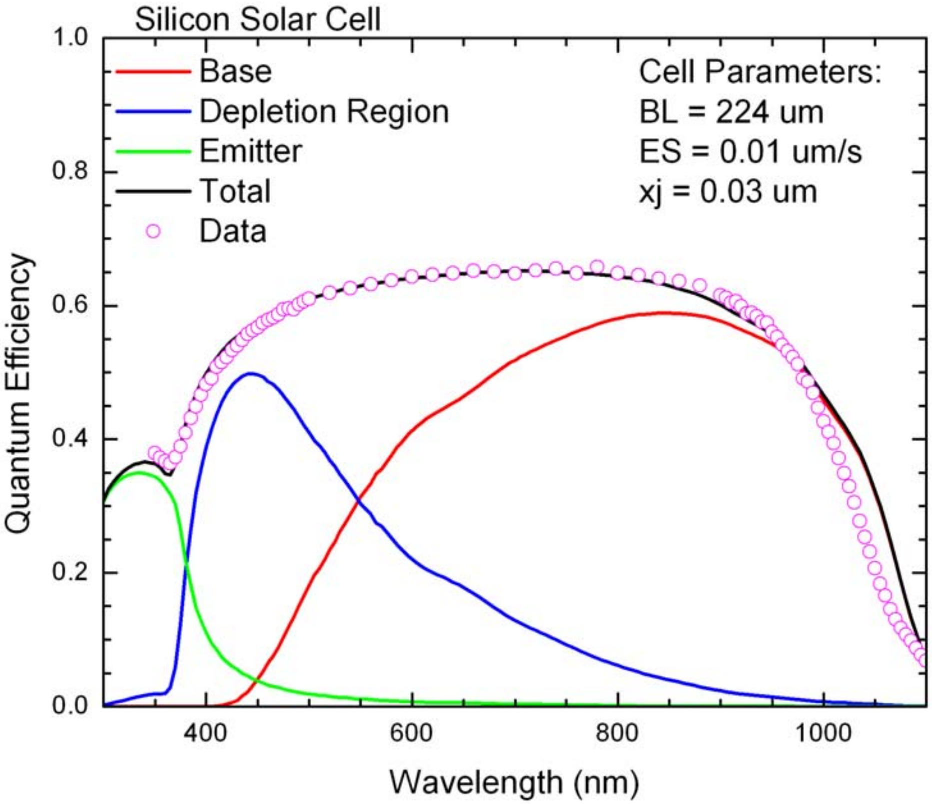
- Quantum Efficiency (0-1)

$$QE(\lambda) = \frac{SR(\lambda)}{\lambda} \times \frac{hc}{e} \cong \frac{SR(\lambda)}{\lambda}\left(1240\frac{W-nm}{Amp}\right)$$

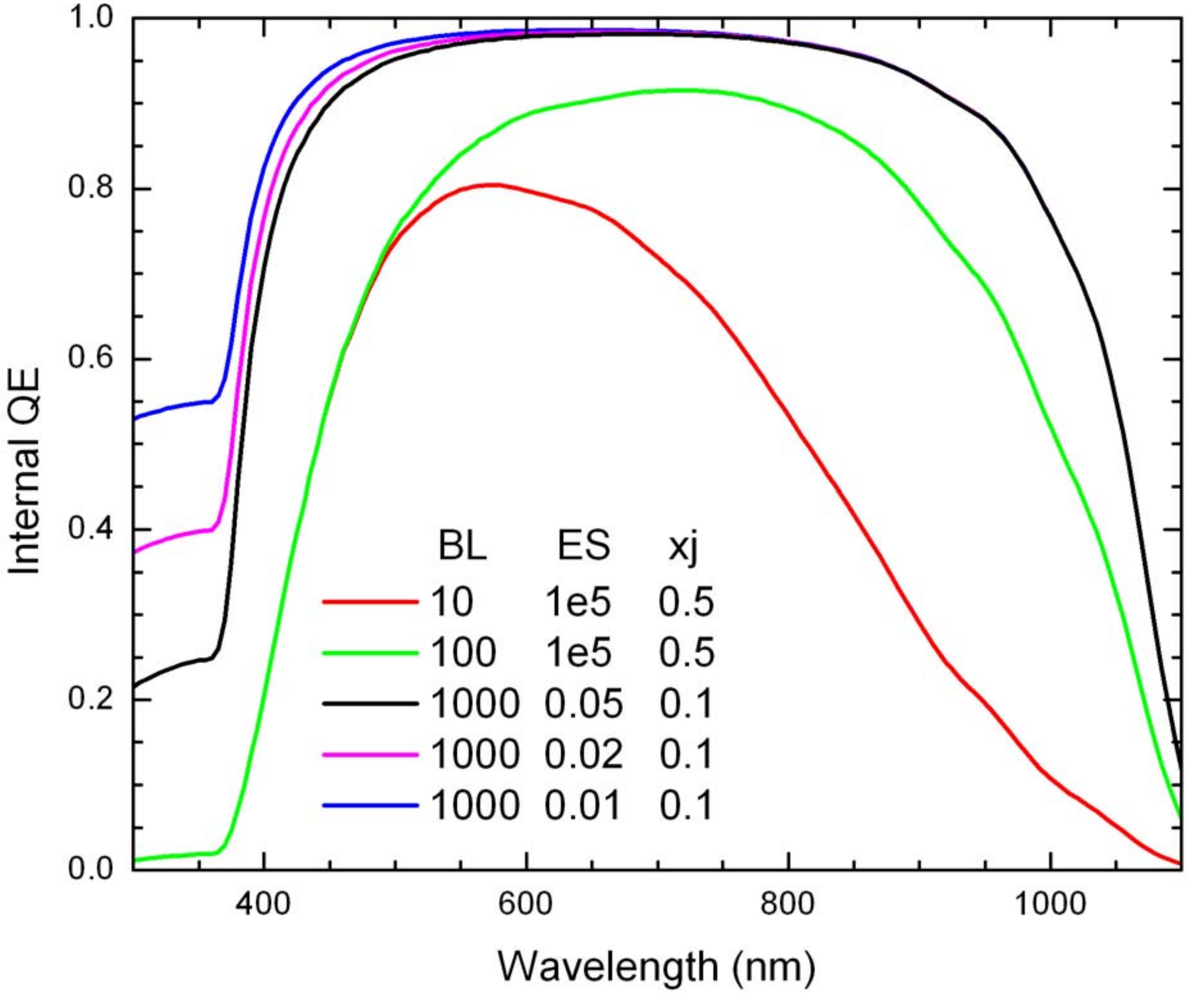
- Base Diffusion Length

$$L_b = \sqrt{D\tau}$$

- Surface recombination velocity: Phenomenological boundary condition relating to surface recombination



QE Dependence on Cell Parameters

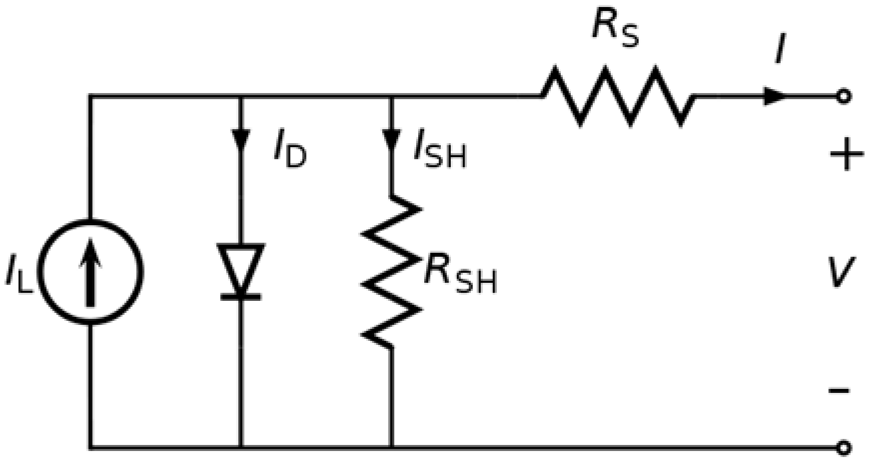


BL = Base Diffusion Length (um)
ES = Emitter Surface Rec. Vel (um/s)
xj = junction depth (um)

Equivalent Circuit for Solar Cell

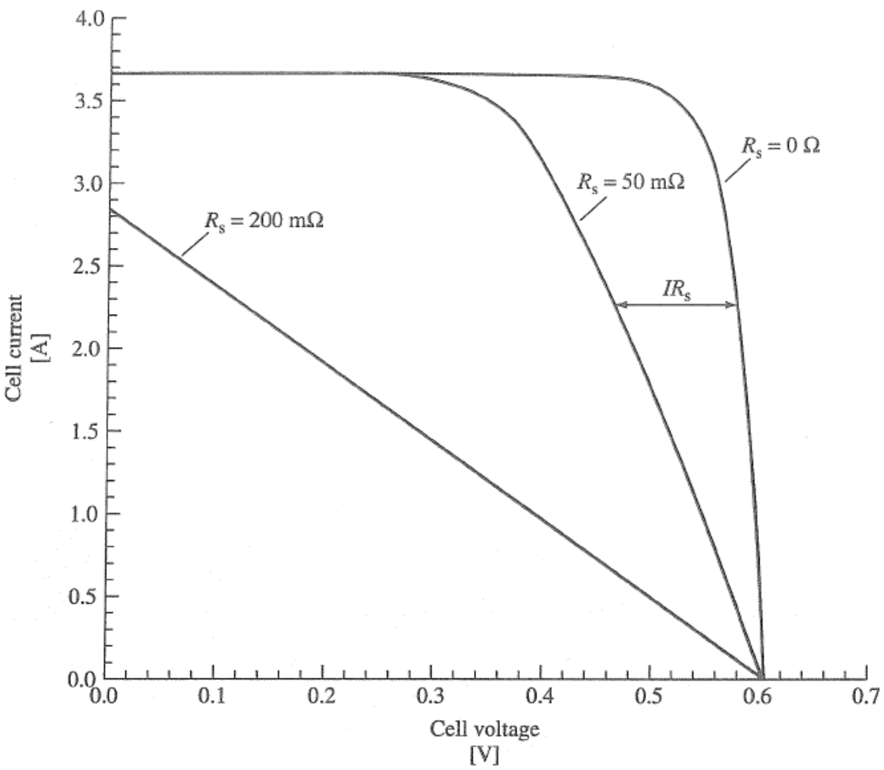
How an electrical engineer sees a solar cell…

- **Light Source as a current source**
- **P-n junction diode**
- **Shunt Resistance R$_s$**
- **Series Resistance R$_{sh}$**

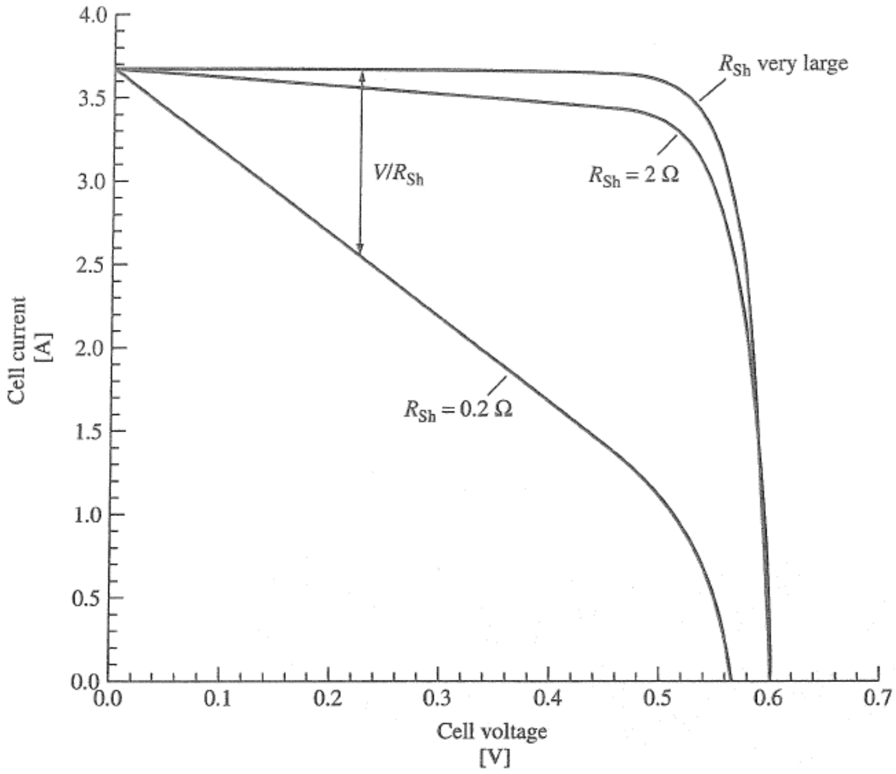


$$I_{out} + I_{photon} - \frac{V - IR_s}{R_{sh}} + I_s = I_s \exp\left(\frac{e}{k_B T}(V - I_{out} R_s)\right)$$

Effects of Resistance



Series



Shunt

Main Losses to efficiency

- **Thermal: Photon of energy E is absorbed. The energy $E-E_g$ is lost to heat since the electrons and holes thermalize to their respective band edges**

- **Non-absorbed light: Light with energy $E<E_g$ passes through the cell**

- **Reflected light: Photons are reflected instead of absorbed into the material**

- **Recombination: Photons absorbed deep within a material generate e-h pairs that cannot diffuse to the junction before recombination**

- **Surface recombination: Surface states recombine electron-hole pairs in the emitter region**

- **Shunt and Series Resistance: Reduce maximum power point**

Natural limits to efficiency