EELE408 Photovoltaics
Lecture 09: Semiconductor Device Physics

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Gauss's Law

- Charge Distributions create Electric fields

$$\nabla \cdot \vec{D} = \rho \qquad \vec{D} = \varepsilon \vec{E} \Rightarrow \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon}$$

- In one dimension

$$\nabla \cdot \vec{E} \equiv \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} \Rightarrow \frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

2

Charge Density in Semiconductor

- Electrons in conduction band contribute a negative charge
- Holes contribute a positive charge
- An ionized donor impurity has a net positive charge
- An ionized acceptor impurity contributes a negative charge

$$\rho = q\left(p - n + N_D^+ - N_A^-\right)$$

- Under normal conditions most dopants are ionized

$$N_D^+ \approx N_D \qquad N_A^- \approx N_A$$

3

Current Density Equations

- Diffusion Current $\quad J_e = qD_e \frac{dn}{dx} \quad J_h = -qD_h \frac{dp}{dx}$
- Drift Current $\quad J_e = q\mu_e nE \quad J_h = q\mu_h pE$
- Total Current $\quad J_e = q\mu_e nE + qD_e \frac{dn}{dx} \quad J_h = q\mu_h pE - qD_h \frac{dp}{dx}$
- Einstein Relationship

$$D_e = \left(\frac{kT}{q}\right)\mu_e \quad D_h = \left(\frac{kT}{q}\right)\mu_h$$

4

Continuity Equations

- Net generation rate (G)
- Net recombination rate (R)

$$\frac{1}{q}\frac{dJ_e}{dx} = R - G \qquad \frac{1}{q}\frac{dJ_h}{dx} = -(R - G)$$

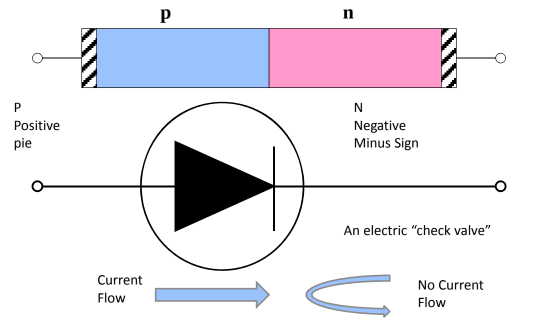
5

P-N Junction

- Solar Cell is a large area P-N junction or a diode: electrons can flow in one direction but not the other (usually)
- Created by a variation in charge carriers as a function of position
- Carriers (electrons & holes) are created by doping the material
  - N: group V (Phosphorus) added (extra electron→ negative)
  - P: Group III (Boron)added (short electron (hole)→ positive)

6

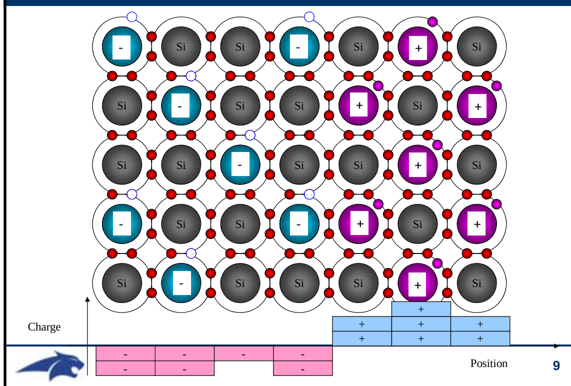
p-n Junction



Creation of PN Junction

- High concentration of electrons in n-side
- High concentration of holes in p-side
- Electrons diffuse out of n-side to p-side
- Electrons recombine with holes (filling valence band states)
- The neutral dopant atoms (P) in the n-side give up an electron and become positive ions
- The neutral dopant atoms (B) in the p-side capture an electron and become negative ions

Diffusion until Equilibrium



Creation of Electric Field

- Electric fields are produced by charge distributions
- Fields flow <u>from</u> positive charges (protons, positive ions, holes) and flow <u>toward</u> negative charges (electrons, negative ions)
- Free charges move in electric fields
  - Positive in the direction of field (holes)
  - Negative opposite to the electric field (electrons)

Creation of Depletion Region

- The local dopant ions left behind near the junction create an electric field area called the <u>depletion region</u>
- Any free carriers would be swept out of the depletion region by the forces created by the electric field (depleted of free carriers)
- The depletion area grows until it reaches equilibrium where the created electric field stops the diffusion of electrons

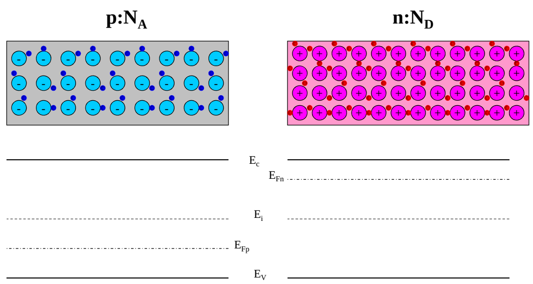
Creation of a Potential

- Changes in the electric field create a potential barrier to stop the diffusion of electrons from the n-side to the p-side
- The p-n junction has a built-in potential (voltage) that is a function of the doping concentrations of the two areas

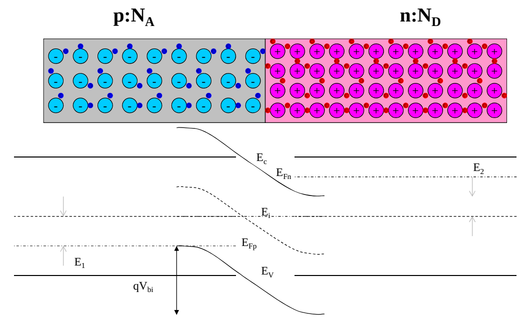
$$\vec{E} = -\nabla V$$

pn Junction in Thermal Equilibrium

A system in thermal equilibrium can have only one Fermi Level



pn Junction in Thermal Equilibrium



Calculation of the Built-in Voltage

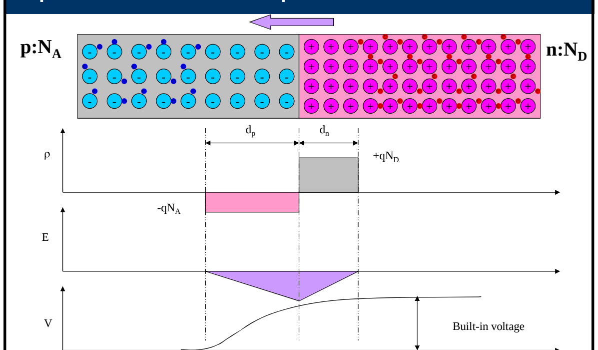
$$qV_{bi} = E_g - E_1 - E_2 = E_g - kT\ln\left(\frac{N_V}{N_A}\right) - kT\ln\left(\frac{N_C}{N_D}\right)$$

$$qV_{bi} = E_g - kT\ln\left(\frac{N_C N_V}{N_A N_D}\right)$$

$$n_i^2 = N_V N_C e^{-\frac{E_g}{kT}} \Rightarrow E_g = -kT\ln\left(\frac{n_i^2}{N_V N_C}\right)$$

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

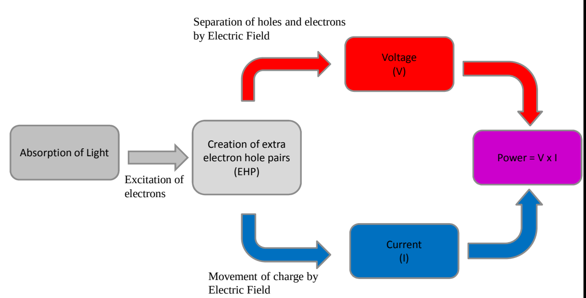
pn Junction in Thermal Equilibrium



Operation of PN Junction

- When sunlight is absorbed by the cell it unbalances the equilibrium by creating excessive electron-hole pairs.
- The internal field separates the electrons from the holes
- Sunlight produces a voltage opposing and exceeding the electric field in the internal depletion region, this results in the flow of electrons in the external circuit wires

Photovoltaic Effect

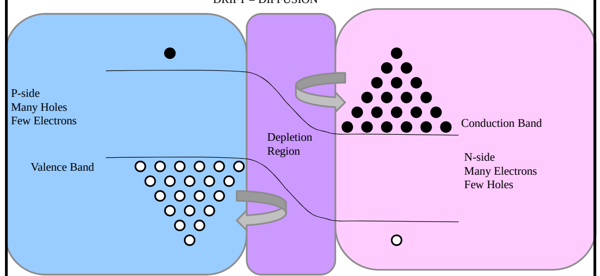


Solar Cell Voltage

- In silicon, the electrons will need to overcome the potential barrier of 0.5 - 0.6 volts → any electrons(electricity) produced will be produced at this voltage

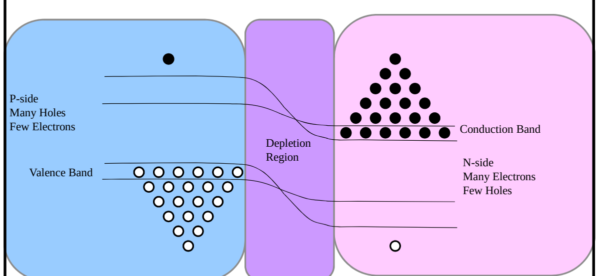
Diode Equilibrium Behavior

DRIFT = DIFFUSION



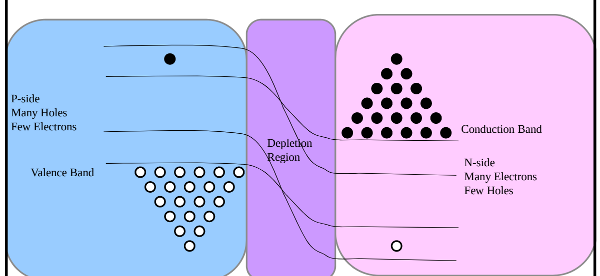
Potential Barrier Stops Majority of Carriers from Leaving Area

Forward Bias Behavior



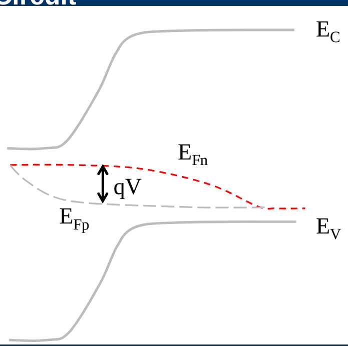
Reduces Potential Barrier
Allows Large Diffusion Current

Reverse Bias Behavior



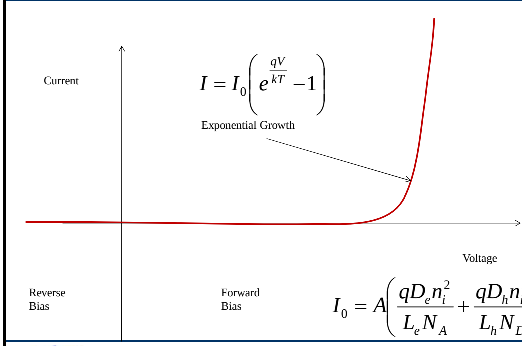
Increases Potential Barrier
Very Little Diffusion Current

Illuminated PN Junction at Open Circuit



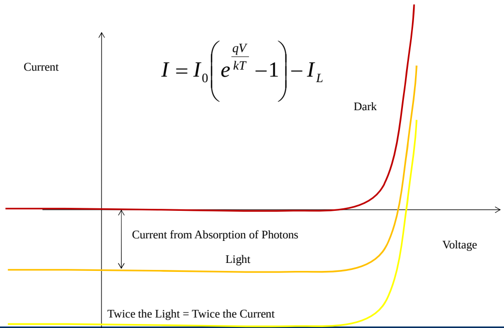
Diode I-V Characteristics

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

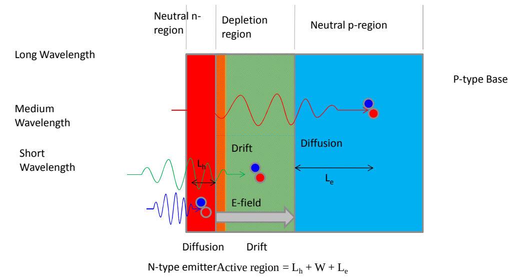


$$I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A} + \frac{qD_h n_i^2}{L_h N_D}\right)$$

Solar Cell I-V Characteristics



Active Region



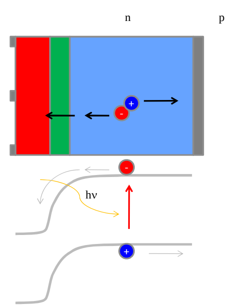
$$I_L = qAG(L_e + W + L_h)$$

Light Current

- Proportional to:
  - The Area of the solar cell (A)
    - Make cells large
  - The Generation rate of electron hole pairs (G)
    - Intensity of Light
  - The active area (L_e + W + L_h)
    - Make diffusion length long (very pure materials)

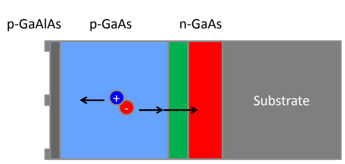
$$I_L = qAG(L_e + W + L_h)$$

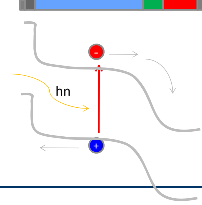
Single Crystal Solar Cell



Bulk of substrate (p-type) silicon absorbs incident light. Minority carriers (electrons) diffuse to junction where they are swept across by the built in field. Device is typically several hundred microns thick

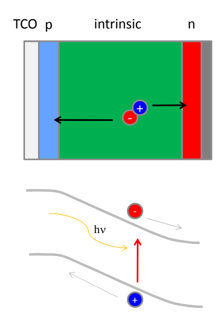
Gallium Arsenide Solar Cell





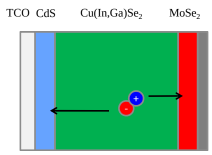
Thin passivating layer (GaAlAs) prevents minority carrier (electrons) recombination at surface. Grown on an inexpensive substrate to reduce cost

Amorphous Silicon Solar Cell



p-i-n structure: EHP generated in the intrinsic region that separates heavily doped p and n regions. The charge separation is assisted by the built-in electric field increasing the collection efficiency. Top contact is usually a transparent conducting oxide (TCO)

Indium-Gallium Diselenide Solar Cell



Compound semiconductors: the front is formed by a wide gap window material which transmits most of the incident light to the absorber layer where virtually all the EHP are produced. Typically a few microns thick.