EELE408 Photovoltaics
Lecture 08: Carrier Transport

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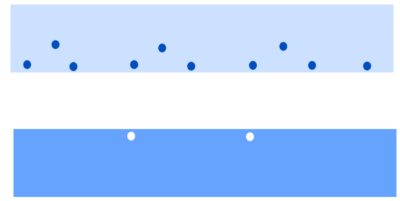
Free Carriers

- Free Carriers
  - Electrons in the conduction band
  - Holes in the valence band
  - Move randomly
  - Velocity is a function of the temperature called thermal velocity



Thermal Velocity

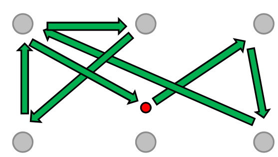
- Thermal velocity is the average velocity of carriers
- Carrier velocities are spread across a distribution centered at the thermal velocity

$$\frac{1}{2}m_e^* v_{th}^2 = \frac{3}{2}kT$$

Equipartition of Energy: each degree of freedom corresponds to 1/2kT of energy

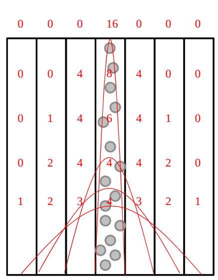
Random Motion of Electron

- An electron moves in a random direction until it scatters off a defect or lattice atom
- Since each direction is equally likely, the net motion of the electron is zero



Diffusion Example

- Carrier movement from areas of high concentration to areas of lower concentration
  - ¼ move right
  - ¼ move left
  - ½ stay put
- Process continues until a uniform concentration results



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

$$J_e = qD_e \frac{dn}{dx}$$

$$J_h = -qD_h \frac{dp}{dx}$$

Current is proportional to gradient and diffusion constant

$$D_e = \frac{kT}{q}\mu_e$$

$$D_h = \frac{kT}{q}\mu_h$$

Diffusion is proportional to temperature and mobility

Mobility

$$F = ma \rightarrow a = \frac{F}{m} \rightarrow a = \frac{qE}{m}$$

$$\bar{v}_d = at = \frac{qE}{m_e^*} t_r$$

v_d : drift velocity
t_r : relaxation time (time between collisions)
m_e : mobility (ease of motion through material)

$$\mu_e = \frac{v_d}{E} = \frac{q t_r}{m_e^*}$$

$$\mu_e = 65 + \frac{1265}{1+\left(\frac{N(cm^{-3})}{8.5\times10^{16}}\right)^{0.72}}\left(\frac{cm^2}{V-s}\right)$$

$$\mu_h = 47.7 + \frac{447.3}{1+\left(\frac{N(cm^{-3})}{6.3\times10^{16}}\right)^{0.76}}\left(\frac{cm^2}{V-s}\right)$$

Mobility is a function of the total doping concentration (scattering sites). For good quality silicon empirical equations relate the mobility to the level of dopants

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Mobility Dependences

- Impurities and crystal defects will decrease mobility
  - More scattering sites
- Increase in temperature decreases mobility
  - Less severe at high doping concentrations (already a large number of scattering sites)
  - Raised temperature increases atomic vibration that makes "larger" scatter targets
- Large electric fields decrease mobility
  - Increases drift velocity to near thermal velocities
  - Decreases time between collisions

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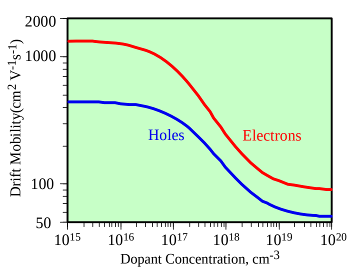
Drift mobility function of TOTAL scattering sites



The variation of the drift mobility with dopant concentration in Si for electrons and holes

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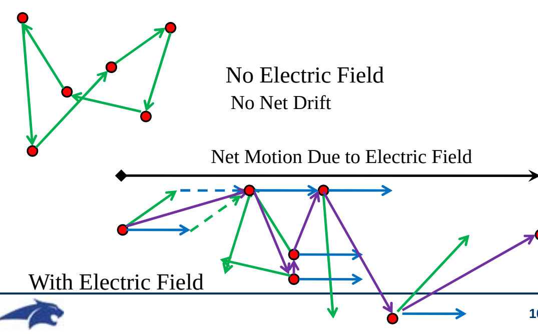
Drift

- The random motion of electrons can be given a preferred direction by the application of an electric field to the material



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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	$\sigma \Rightarrow q\mu_h N_A$	$p >> n$	$p \approx N_A$

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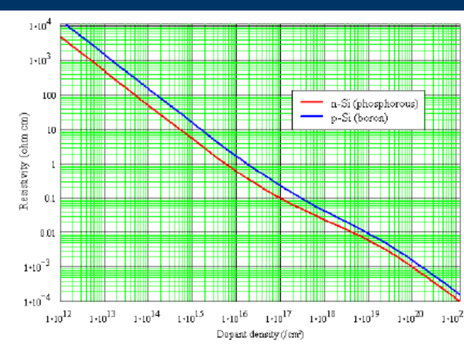
Doping vs Resistivity



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Drift and Diffusion Currents

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

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

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

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

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

Derive Einstein's Relation

- Two semiconductors with different n-type doping densities
- In equilibrium
- Zero current density

Derivation

$$\vec{J}_n = q\mu_n n\vec{E} + qD_n \nabla n = 0 \Rightarrow 1-D: \mu_n n E_x = -D_n \frac{dn}{dx}$$

$$\vec{E} = -\nabla V \Rightarrow 1-D: E_x = \frac{dV}{dx}$$

$$\mu_n n \frac{dV}{dx} = -D_n \frac{dn}{dx} \Rightarrow \frac{1}{n}\frac{dn}{dx} = -\frac{\mu_n}{D_n}\frac{dV}{dx}$$

$$\ln\left(\frac{n_2}{n_1}\right) = -\frac{\mu_n}{D_n}(V_2 - V_1) \Rightarrow \frac{n_2}{n_1} = e^{-\frac{\mu_n}{D_n}(V_2 - V_1)}$$

$$\text{Boltzmann Statistics}: n = n_i e^{\frac{E_F - E_i}{kT}} \Rightarrow \frac{n_2}{n_1} = \frac{e^{\frac{E_F - E_{i2}}{kT}}}{e^{\frac{E_F - E_{i1}}{kT}}} = e^{-\frac{E_{i2} - E_{i1}}{kT}} = e^{-q\frac{V_2 - V_1}{kT}}$$

$$\frac{n_2}{n_1} = e^{-\frac{\mu_n}{D_n}(V_2 - V_1)} = e^{-q\frac{V_2 - V_1}{kT}} \Rightarrow \frac{\mu_n}{D_n}(V_2 - V_1) = q\frac{V_2 - V_1}{kT}$$

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

Example

Consider Gallium Arsenide at T=300K with $N_A = 0$ and $N_D = 10^{16}/cm^3$. Assume complete ionization and calculate the drift current density if an applied field of E=10V/cm is applied

$$n \approx 10^{16}/cm^3 \qquad p = \frac{n_i^2}{n} = \frac{(1.8\times10^6)^2}{10^{16}} = 3.24\times10^{-4}/cm^3$$

$$\vec{J}_{drift} = q(\mu_n n + \mu_p p)\vec{E} \approx q\mu_n n\vec{E}$$

$$= (1.6\times10^{-19}C)(8500cm^2/V-s)(10^{16}/cm^3)(10V/cm) = 136A/cm^2$$

Drift current usually due to primary carrier (e- in n-type and h+ in p-type)