carrier concentration review

\[ n_i = \sqrt{N_c N_v e^{\frac{-E_g}{2k_B T}}} \]

\[ n_0 = \frac{N_D}{N_c} = N_D \]

\[ p_0 = n_i^2 / n_0 \]

Fig. 2.22 from R.F. Pierret, *Semiconductor Device Fundamentals*
### Key Equations in Equilibrium

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_0 = N_e e^{(E_f - E_c)/k_B T}$</td>
<td>Electron Density</td>
</tr>
<tr>
<td>$P_0 = N_v e^{(E_f - E_v)/k_B T}$</td>
<td>Hole Density</td>
</tr>
<tr>
<td>$N_c = 2 \left( \frac{m_e k_B T}{2 \pi \hbar^2} \right)^{3/2}$</td>
<td>Electron Fermi Energy</td>
</tr>
<tr>
<td>$N_v = 2 \left( \frac{m_h k_B T}{2 \pi \hbar^2} \right)^{3/2}$</td>
<td>Hole Fermi Energy</td>
</tr>
<tr>
<td>$N_0 = N_i e^{(E_f - E_i)/k_B T}$</td>
<td>Impurity Density</td>
</tr>
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</tr>
<tr>
<td>$n_i P_0 = n_i^2$</td>
<td>Impurity Fermi Energy</td>
</tr>
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<td>$n_i = \sqrt{N_c N_v} e^{-E_f/2k_B T}$</td>
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<tr>
<td>$n_i = 1.00 \times 10^{10}$ cm$^{-3}$</td>
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### Question: Why does $np = n_i^2$? 

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Why is $np = n_i^2$?

\[ G(T) \text{ cm}^{-3}\cdot s^{-1} \quad R = Cnp \]

\[ G = R \quad np = \frac{G}{C} = n_i^2 \]

Outline

1. Current (drift)
2. Mobility, resistivity, etc.
1. Current (drift)

2. Mobility, resistivity, etc.

semi-conductor in equilibrium

\[ \langle KE \rangle = \frac{3}{2} k_B T \]

\[ \langle KE \rangle = \frac{1}{2} m^* \langle v^2 \rangle \]

\[ \sqrt{\langle v^2 \rangle} = v_{rms} = \sqrt{\frac{3k_B T}{m^*}} \]

\[ v_{rms} = 10^7 \text{ cm/s} \]
current flow

1) random walk with a small bias from left to right

2) assume that electrons “drift” to the right at an average velocity, \( v_d \)

3) what is \( I \)?

drift current and velocity

\[
I = -\frac{Q}{t_i} \\
Q = -qnAL \\
t_i = \frac{L}{v_d} \\
I = nq\nu_dA \\
J_{nx} = -nq\nu_{dx} \text{ A/cm}^2 \\
J_{px} = pq\nu_{dx} \text{ A/cm}^2
\]
velocity and electric field

\[ v_{dn} = -\mu_n E \]

\[ \mu_n = \left( \frac{q\tau}{m_n} \right) \text{cm}^2/\text{V-s} \]

\[ v_{dp} = +\mu_p E \]

\[ \mu_p = \left( \frac{q\tau}{m_p} \right) \text{cm}^2/\text{V-s} \]

“high-field transport”

“low-field” or “near-equilibrium” or “linear” transport

velocity vs. field

Fig. 3.4 (Drift velocity plot—Si)

from R.F. Pierret, Semiconductor Device Fundamentals, Fig. 3.4
drift current

\[ v_{dn} = -\mu_n E \]

\[ v_{dp} = +\mu_p E \]

\[ J_{nx} = -nq\nu_{dx} \text{ A/cm}^2 \]

\[ J_{px} = p\nu_{dx} \text{ A/cm}^2 \]

mobility vs. doping

\[ \mu = \frac{q\tau}{m} \text{ cm}^2/V\cdot s \]

Fig. 3.5(a) (Si carrier mobilities)

from R.F. Pierret, *Semiconductor Device Fundamentals*, Fig. 3.5 (a)
mobility vs. temperature

\[ \mu_n \propto T^{3/2} \]

increasing mobility suggests the presence of charged impurity scattering

\[ \mu_n \propto T^{-3/2} \]

decreasing mobility suggests the presence of lattice scattering.

\[ \mu = \left( \frac{q \tau}{m} \right) \text{cm}^2/\text{V-s} \]

re-cap

\[ J_n = -nq \nu_n \text{ A/cm}^2 \]
\[ \nu_{dn} = -\mu_n \mathcal{E} \]
\[ J_p = +pq \nu_p \text{ A/cm}^2 \]
\[ \nu_{dp} = +\mu_p \mathcal{E} \]

\[ \mathcal{E} = -\frac{dV}{dx} \text{ V/cm} \]
\[ \mathcal{E} = -\frac{V}{L} \text{ V/cm} \]

n-type semiconductor

\[ \nu_j = -\mu_n \mathcal{E}_x \]

\[ -V + \]

\[ x \]

\[ I \]
current, conductivity, resistivity

\[ J_{nx} = nq\mu_n E_x \text{ A/cm}^2 \quad J_{px} = p\mu_p E_x \text{ A/cm}^2 \quad \sigma_n = nq\mu_n \text{ (units?)} \]

\[ J_{nx} = \sigma_n E_x \text{ A/cm}^2 \quad J_{px} = \sigma_p E_x \text{ A/cm}^2 \quad \sigma_p = p\mu_p \]

\[ J_x = J_{nx} + J_{px} = (\sigma_n + \sigma_p)E_x = \sigma E_x \text{ A/cm}^2 \]

\[ J_x = \sigma E_x \text{ A/cm}^2 \quad E_x = \frac{1}{\sigma} J_x = \rho J_x \text{ V/cm} \]

\[ \rho = \frac{1}{\sigma} = \frac{1}{\frac{1}{nq\mu_n} + \frac{1}{p\mu_p}} \text{ \Omega-cm} \]

resistivity vs. doping density

From R.F. Pierret, *Semiconductor Device Fundamentals*, Fig. 3.8
1. Current (drift) ✓

2. Mobility, resistivity, etc. ✓