Carrier Transport

Carrier Diffusion
Carrier diffusion

- All random movement has the tendency of ‘diffusion’
  - Particle transport from higher density part to lower density part until balanced either in homogeneous density or balanced by other induced effect
- Diffusion of charged particle induces current
  - Diffusion current density: (note the sign and why?)

\[
J_{n\text{-dif}} = eD_n \nabla n \quad J_{p\text{-dif}} = -eD_p \nabla p
\]

<table>
<thead>
<tr>
<th></th>
<th>$\mu_n$ (cm$^2$/V-s)</th>
<th>$D_n$ (cm$^2$/s)</th>
<th>$\mu_p$ (cm$^2$/V-s)</th>
<th>$D_p$(cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1350</td>
<td>35</td>
<td>480</td>
<td>12.4</td>
</tr>
<tr>
<td>GaAs</td>
<td>8500</td>
<td>220</td>
<td>400</td>
<td>10.4</td>
</tr>
<tr>
<td>Ge</td>
<td>3900</td>
<td>101</td>
<td>1900</td>
<td>49.2</td>
</tr>
</tbody>
</table>
Total Current Density

- Combining drift and diffusion current.

\[ J = e n \mu_n E + e p \mu_p E + e D_n \nabla n - e D_p \nabla p \]
Diffusion current: Example

The electron concentration in silicon is given by \( n(x) = 1e15 \exp(-x/L) \) cm\(^{-3}\) \((x>0)\) where \( L = 1e-4 \) cm. The electron diffusion coefficient is \( D_n = 25 \) cm\(^2\)/s. Determine the electron diffusion current density at (a) \( x=0 \), (b) \( x=1e-4 \) cm, and (c) \( x \to \infty \).

\[
J_{n-dif} = eD_n \nabla n
\]

\[
J_x = eD_n \frac{dn}{dx} = -eD_n \frac{10^{15}}{L} e^{-x/L} = -e \times 25 \text{ cm}^2/\text{s} \frac{10^{15} \text{ cm}^{-3}}{10^{-4} \text{ cm}} e^{-x/L} = -1.6 \times 25 e^{-x/L} \text{ A/cm}^2
\]

\( x = 0 \Rightarrow J_x = -1.6 \times 25 \text{ A/cm}^2 = -40 \text{ A/cm}^2 \)

\( x = L \Rightarrow J_x = -1.6 \times 25 \times \exp(-1) \text{ A/cm}^2 = -14.7 \text{ A/cm}^2 \)

\( x \to \infty \Rightarrow J_x \to 0 \text{ A/cm}^2 \)
If carrier concentration is a function of position, the difference between Fermi level $E_F$ and the intrinsic Fermi level $E_{Fi}$ must be a function of position.

But at equilibrium, Fermi level must be the same for all positions.

Therefore, the intrinsic Fermi level and therefore the bandedges has to change with the position.

This implies an induced electric field

\[ n_0 = n_i \exp\left( \frac{E_F - E_{Fi}}{kT} \right) \]

\[ p_0 = n_i \exp\left( - \frac{E_F - E_{Fi}}{kT} \right) \]

\[ n_0 p_0 = n_i^2 \]
The induced electric field is proportional to the gradient of the function dependent intrinsic Fermi level or equivalently function dependent bandedges.

Similarly, applied electric field also ‘bends’ bandedges and intrinsic Fermi level.

\[ E = \frac{1}{e} \nabla E_{Fi} = \frac{1}{e} \nabla E_c = \frac{1}{e} \nabla E_v \]
Induced Electric Field and Carrier density

\[
E = \frac{1}{e} \nabla E_{Fi}
\]

- for n-type extrinsic semiconductors

\[
n_0 = n_i \exp \left[ \frac{E_F - E_{Fi}}{kT} \right] = N_d
\]

\[
E = -\frac{kT}{e} \frac{1}{n_0} \nabla n_0 = -\frac{kT}{e} \frac{1}{N_d} \nabla N_d
\]
Induced Electric Field and Doping: Example

- Assume that the donor impurity concentration in a semiconductor is given by
  \[ N_d(x) = 10^{15} \exp\left(-\frac{x}{L}\right) \text{(cm}^{-3}\text{)} \]
  for \( x > 0 \) and where \( L = 1 \times 10^{-4} \text{ cm} \). Determine the electric field induced in the material due to this impurity concentration.

  \[ E = -\frac{kT}{e} \frac{1}{N_d} \nabla N_d \]

  \[ E_x = -\frac{kT}{e} \frac{1}{N_d} \frac{dN_d}{dx} = 0.0259 \times \frac{1}{L} = 259 \text{ V/cm} \]

- note the exponential doping profile gives rise to a constant induced field.
Induced Electric Field and Doping: Example

- Determine the induced electric field in a semiconductor in thermal equilibrium given a linear variation in doping concentration. Assume that the donor concentration in an n-type semiconductor at T=300K is given by,

\[ N_d = 10^{16} - 10^{19}x \text{ (cm}^{-3}\text{)} \]

where \( x \) is given in cm and ranges between 0<\( x <1 \) um

\[ E = -\frac{kT}{e} \frac{1}{N_d} \nabla N_d \]

\[ E_x = -\frac{kT}{e} \frac{1}{N_d} \frac{dN_d}{dx} = 0.0259 \times \frac{10^{19}}{10^{16} - 10^{19}x} \text{ V/cm} \]

at \( x=0 \), for example \( E_x = 25.9 \text{ V/cm} \)
The Einstein Relation

- Assume there is no electrical connections, the induced electrical field will induce a drift current that exactly balance the diffusion current for each type of carriers. This gives rise to the Einstein relation

\[ 0 = J_n = e n \mu_n E + e D_n \nabla n \]

but the induced electric field is

\[ E = -\frac{kT}{e} \frac{1}{n} \nabla n \]

therefore

\[ \frac{D_n}{\mu_n} = \frac{kT}{e} \]

similarly for holes

\[ \frac{D_p}{\mu_p} = \frac{kT}{e} \]
At thermal equilibrium

\[ n_0 p_0 = n_i^2 \]

when in nonequilibrium state, excess carriers are (typically) excited in pairs

\[ n = n_0 + \delta n \quad p = p_0 + \delta p \quad \delta p = \delta n \]

recombination can be approximated as

\[ \frac{dn}{dt} = \alpha_r (n_i^2 - np) \]

to the first order, or for low-level injection

\[ \frac{d\delta n}{dt} = -\alpha_r (n_0 + p_0) \delta n \]
Excess Carrier Life Time

\[ \frac{d\delta n}{dt} = -\alpha_r (n_0 + p_0) \delta n = -\frac{\delta n}{\tau_{ex}} \]

- \( \tau_{ex} \) is called the excess carrier life time
- for n-type material \( n_0 >> p_0 \) and
  \[ \tau_{ex} \approx \frac{1}{\alpha_r n_0} \]
- for p-type material \( p_0 >> n_0 \) and
  \[ \tau_{ex} \approx \frac{1}{\alpha_r p_0} \]
Generation-Recombination Processes

- Band-to-Band Generation and Recombination
  - recombination-generation centers: defects, surface states, etc.

- Auger Recombination
HW4: Chapter 4

- 4.2, 7, 17, 24, 28, 35, 38, 44, 54