Chapter 3
Carrier Action
Three primary types of carrier action occur inside a semiconductor:

- **Drift**: charged particle motion in response to an applied electric field.
- **Diffusion**: charged particle motion due to concentration gradient or temperature gradient.
- **Recombination-Generation**: a process where charge carriers (electrons and holes) are annihilated (destroyed) and created.
Mobile electrons and atoms in the Si lattice are always in random thermal motion.

- Electrons make frequent collisions with the vibrating atoms.
- “Lattice scattering” or “phonon scattering” increases with increasing temperature.
- Average velocity of thermal motion for electrons: $\sim 1/1000 \times$ speed of light at 300 K (even under equilibrium conditions).

**Other scattering mechanisms:**

- Deflection by ionized impurity atoms.
- Deflection due to Coulombic force between carriers or “carrier-carrier scattering.”
  - Only significant at high carrier concentrations.

The net current in any direction is zero, if no electric field is applied.
When an electric field (e.g. due to an externally applied voltage) is applied to a semiconductor, mobile charge-carriers will be accelerated by the electrostatic force.

This force superimposes on the random motion of electrons.

\[ F = -q\mathcal{E} \]

Electrons drift in the direction opposite to the electric field \( \rightarrow \) Current flows.

- Due to scattering, electrons in a semiconductor do not achieve constant velocity nor acceleration.
- However, they can be viewed as particles moving at a constant average drift velocity \( v_d \).
\( \nu_d t \) All holes this distance back from the normal plane will cross the plane in a time \( t \)

\( \nu_d t A \) All holes in this volume will cross the plane in a time \( t \)

\( p \nu_d t A \) Holes crossing the plane in a time \( t \)

\( q \rho \nu_d t A \) Charge crossing the plane in a time \( t \)

\( q \rho \nu_d A \) Charge crossing the plane per unit time,

\[ \Rightarrow \text{Hole drift current} \quad I_{P\text{drift}} \quad \text{(Ampere)} \]

\( q \rho \nu_d \) Current density associated with hole drift current,

\[ J_{P\text{drift}} \quad \text{(A/m}^2) \]
Drift Velocity vs. Electric Field

\[ \nu_d = \mu_p \mathcal{E} \]
\[ \nu_d = -\mu_n \mathcal{E} \]

- Linear relation holds in low field intensity, \( \sim 5 \times 10^3 \) V/cm
\[ \mu \text{ has the dimensions of } \nu / \mathcal{E} : \left[ \frac{\text{cm/s}}{\text{V/cm}} = \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \right] \]

Electron and hole mobility of selected \textit{intrinsic} semiconductors \((T = 300 \text{ K})\)

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>InAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_n) ((\text{cm}^2/\text{V} \cdot \text{s}))</td>
<td>1400</td>
<td>3900</td>
<td>8500</td>
<td>30000</td>
</tr>
<tr>
<td>(\mu_p) ((\text{cm}^2/\text{V} \cdot \text{s}))</td>
<td>470</td>
<td>1900</td>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>
For holes,
\[ I_{P|\text{drift}} = q p v_d A \]
\[ J_{P|\text{drift}} = q p v_d \]

In low-field limit,
\[ v_d = \mu_p E \]
\[ J_{P|\text{drift}} = q \mu_p p E \]

Similarly for electrons,
\[ J_{N|\text{drift}} = -q n v_d \]
\[ v_d = -\mu_n E \]
\[ J_{N|\text{drift}} = q \mu_n n E \]
Impedance to motion due to lattice scattering:
- No doping dependence
- Decreases with decreasing temperature

Impedance to motion due to ionized impurity scattering:
- Increases with $N_A$ or $N_D$
- Increases with decreasing temperature
Carrier mobility varies with doping:
- Decrease with increasing total concentration of ionized dopants.

Carrier mobility varies with temperature:
- Decreases with increasing $T$ if lattice scattering is dominant.
- Decreases with decreasing $T$ if impurity scattering is dominant.
\[ J_{N|\text{drift}} = -qnv_d = q\mu_n n\mathcal{E} \]

\[ J_{P|\text{drift}} = qpv_d = q\mu_p p\mathcal{E} \]

\[ J_{\text{drift}} = J_{N|\text{drift}} + J_{P|\text{drift}} = q(\mu_n n + \mu_p p)\mathcal{E} = \sigma\mathcal{E} \]

- **Conductivity** of a semiconductor: \( \sigma = q(\mu_n n + \mu_p p) \)
- **Resistivity** of a semiconductor: \( \rho = 1/\sigma \)
Resistivity Dependence on Doping

- For $n$-type material:
  \[ \rho \approx \frac{1}{q \mu_n N_D} \]

- For $p$-type material:
  \[ \rho \approx \frac{1}{q \mu_p N_A} \]
Consider a Si sample at 300 K doped with $10^{16}$/cm$^3$ Boron. What is its resistivity?

$N_A = 10^{16}$ cm$^{-3}$, $N_D = 0$  \hspace{1cm} (N_A >> N_D \rightarrow p$-type)

$p \approx 10^{16}$ cm$^{-3}$, $n \approx 10^4$ cm$^{-3}$

$$\rho = \frac{1}{q\mu_n n + q\mu_p p} \approx \frac{1}{q\mu_p p} \approx \frac{1}{(1.6 \times 10^{-19})(437)(10^{16})}$$

$\approx 1.430$ Ω cm
Example

Consider the same Si sample, doped additionally with $10^{17}$/cm$^3$ Arsenic. What is its resistivity now?

$N_A = 10^{16}$ cm$^{-3}$, $N_D = 10^{17}$ cm$^{-3}$ \((N_D > N_A \rightarrow n$-type\))

\[ n \approx N_D - N_A = 9 \times 10^{16} \text{ cm}^{-3}, \quad p \approx n_i^2/n = 1.11 \times 10^3 \text{ cm}^{-3} \]

\[
\rho = \frac{1}{q\mu_n n + q\mu_p p} \\
\approx \frac{1}{q\mu_n n} \\
\approx [(1.6 \times 10^{-19})(790)(9 \times 10^{16})]^{-1} \\
\approx 0.0879 \ \Omega \cdot \text{cm}
\]

- $\mu_n$ is to be taken for the value at $N = N_A + N_D = 1.1 \times 10^{17}$ cm$^{-3}$
- $\mu n \approx 790 \text{ cm}^2/\text{V}\cdot\text{s}$
Example

Consider a Si sample doped with $10^{17}$ cm$^{-3}$ As. How will its resistivity change when the temperature is increased from $T = 300$ K to $T = 400$ K?

The temperature dependent factor in $\sigma$ (and therefore $\rho$) is $\mu_n$.

From the mobility vs. temperature curve for $10^{17}$ cm$^{-3}$, we find that $\mu_n$ decreases from 770 at 300 K to 400 at 400 K.

As a result, $\rho$ increases by a factor of:

$$\frac{770}{400} = 1.93$$
Electron kinetic energy

Increasing electron energy

$E_c$

Hole kinetic energy

Increasing hole energy

$E_v$

$E_c$ represents the electron potential energy:

$$\text{P.E.} = E_c - E_{\text{reference}}$$

$E_{\text{ref}}$ is arbitrary
Until now, $E_c$ and $E_v$ have always been drawn to be independent of the position.

When an electric field $\mathcal{E}$ exists inside a material, the band energies become a function of position.

Variation of $E_c$ with position is called "band bending"
The potential energy of a particle with charge \(-q\) is related to the electrostatic potential \(V(x)\):

\[
P.E. = -qV
\]

\[
V = -\frac{1}{q}(E_c - E_{\text{reference}})
\]

\[
\mathcal{E} = -\nabla V = -\frac{dV}{dx}
\]

\[
\mathcal{E} = \frac{1}{q} \frac{dE_c}{dx} = \frac{1}{q} \frac{dE_v}{dx} = \frac{1}{q} \frac{dE_i}{dx}
\]

- Since \(E_c\), \(E_v\), and \(E_i\) differ only by an additive constant
■ Particles diffuse from regions of higher concentration to regions of lower concentration, due to random thermal motion (Brownian Motion).
Thermal motion causes particles to move into an adjacent compartment every \( \tau \) seconds.
\[ \mathbf{J}_{N|\text{diff}} = qD_N \frac{dn}{dx} \]

\[ \mathbf{J}_{P|\text{diff}} = -qD_P \frac{dp}{dx} \]

- \( D \) is the diffusion coefficient, in \([\text{cm}^2/\text{sec}]\)

**Diffusion Currents**

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Electron flow  Current flow

Hole flow  Current flow
Total Currents

\[ J = J_N + J_P \]

\[
J_N = J_{N|\text{drift}} + J_{N|\text{diff}} = q\mu_n n\mathcal{E} + qD_N \frac{dn}{dx}
\]

\[
J_P = J_{P|\text{drift}} + J_{P|\text{diff}} = q\mu_p p\mathcal{E} - qD_P \frac{dp}{dx}
\]

- **Drift current** flows when an electric field is applied.
- **Diffusion current** flows when a gradient of carrier concentration exist.
In equilibrium, there is no net flow of electrons or:
\[ J_N = 0, \quad J_P = 0 \]

The drift and diffusion current components must balance each other exactly.

A built-in electric field of ionized atoms exists, such that the drift current exactly cancels out the diffusion current due to the concentration gradient.

\[ J_N = q\mu_n n\varepsilon + qD_N \frac{dn}{dx} = 0 \]
Current Flow Under Equilibrium Conditions

Consider a piece of non-uniformly doped semiconductor:

\[ n = N_C e^{(E_F - E_c)/kT} \]

\[ \frac{dn}{dx} = - \frac{N_C}{kT} e^{(E_F - E_c)/kT} \frac{dE_c}{dx} \]

\[ = - \frac{n}{kT} \frac{dE_c}{dx} \]

\[ \frac{dn}{dx} = - \frac{q}{kT} n \mathcal{E} \]

- Under equilibrium, \( E_F \) inside a material or a group of materials in intimate contact is not a function of position.
**Einstein Relationship between \( D \) and \( \mu \)**

- But, under equilibrium conditions, \( J_N = 0 \) and \( J_P = 0 \)

\[
J_N = q\mu_n n\mathcal{E} + qD_N \frac{dn}{dx} = 0
\]

\[
q\mathcal{E}\mu_n - qn\mathcal{E} \frac{q}{kT} D_N = 0
\]

\[
\frac{D_N}{\mu_n} = \frac{kT}{q}
\]

Similarly,

\[
\frac{D_P}{\mu_p} = \frac{kT}{q}
\]

- Einstein Relationship

Further proof can show that the **Einstein Relationship** is valid for a non-degenerate semiconductor, both in equilibrium and non-equilibrium conditions.
Example: Diffusion Coefficient

What is the hole diffusion coefficient in a sample of silicon at 300 K with $\mu_p = 410$ cm$^2$/V.s?

\[ D_p = \left( \frac{kT}{q} \right) \mu_p \]

\[ = \frac{25.86 \text{ meV}}{1 \text{ e}} \cdot 410 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} \]

\[ = 25.86 \text{ mV} \cdot 410 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \]

\[ = 10.603 \text{ cm}^2/\text{s} \]

\[ \frac{1 \text{ eV}}{1 \text{ e}} = 1 \text{ V} \]

\[ 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \]

• Remark: $kT/q = 25.86$ mV at room temperature
Recombination–Generation

- **Recombination**: a process by which conduction electrons and holes are annihilated in pairs.
- **Generation**: a process by which conduction electrons and holes are created in pairs.

- Generation and recombination processes act to change the carrier concentrations, and thereby indirectly affect current flow.
### Generation Processes

#### Band-to-Band

- Thermal energy or Light
- $E_c$ and $E_v$

#### R–G Center

- Thermal energy
- $E_c$ and $E_v$
- $E_T$: trap energy level

#### Impact Ionization

- $\mathcal{E} = \frac{1}{q} \frac{dE_c}{dx}$
- Release of energy
- $E_c$ and $E_G$
- $E_v$

**Notes:**
- Due to lattice defects or unintentional impurities
- Also called indirect generation
- Only occurs in the presence of large $\mathcal{E}$
Recombination Processes

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Band-to-Band

- Rate is limited by minority carrier trapping
- Primary recombination way for Si

R–G Center

Auger

- Occurs in heavily doped material
1. Problem 3.6, Pierret’s “Semiconductor Device Fundamentals”.

2. Problem 3.12, from (a) until (f), for Figure P3.12(a) and Figure P3.12(f), Pierret’s “Semiconductor Device Fundamentals”.

3. The electron concentration in silicon at $T = 300$ K is given by

$$n(x) = 10^{16} \exp \left( -\frac{x}{18} \right) \text{cm}^{-3}$$

where $x$ is measured in $\mu$m and is limited to $0 \leq x \leq 25$ $\mu$m. The electron diffusion coefficient is $D_N = 25$ cm$^2$/s and the electron mobility is $\mu_n = 960$ cm$^2$/(Vs). The total electron current density through the semiconductor is constant and equal to $J_N = -40$ A/cm$^2$. The electron current has both diffusion and drift current components.

Determine the electric field as a function of $x$ which must exist in the semiconductor. Sketch the function.