Semiconductor Device Physics

Lecture 3

http://zitompul.wordpress.com

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Chapter 3

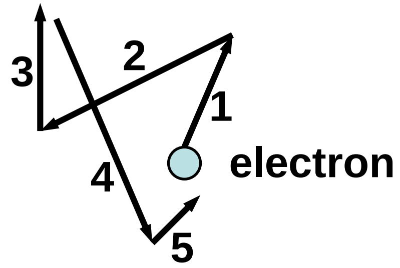
Carrier Action

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.

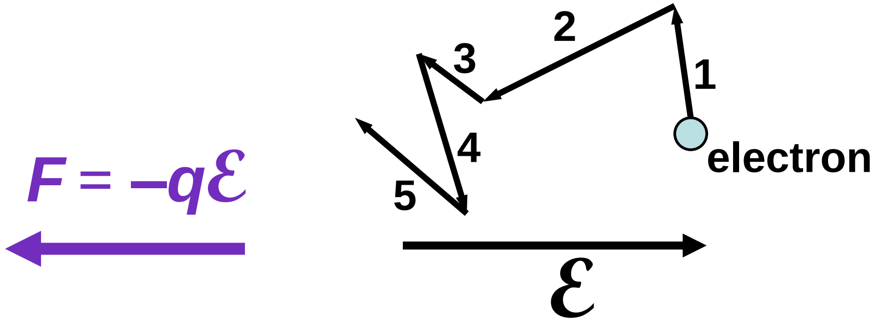
Carrier Scattering

- 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: ~1/1000 x 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.



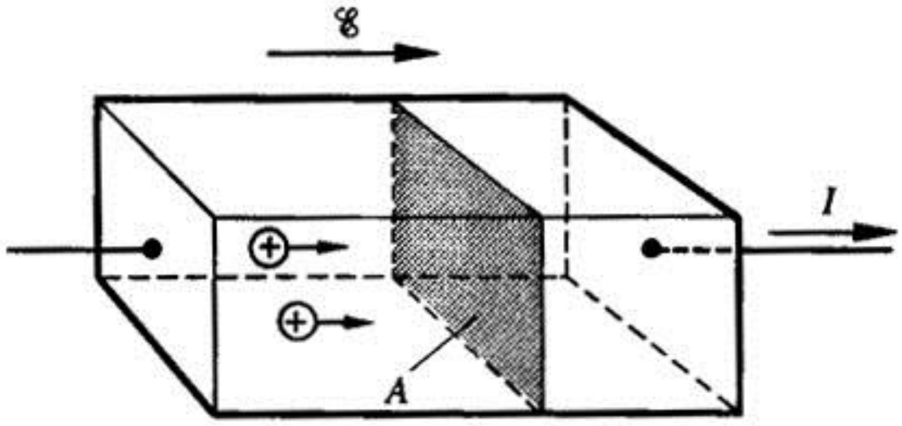
Carrier Drift

- 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.



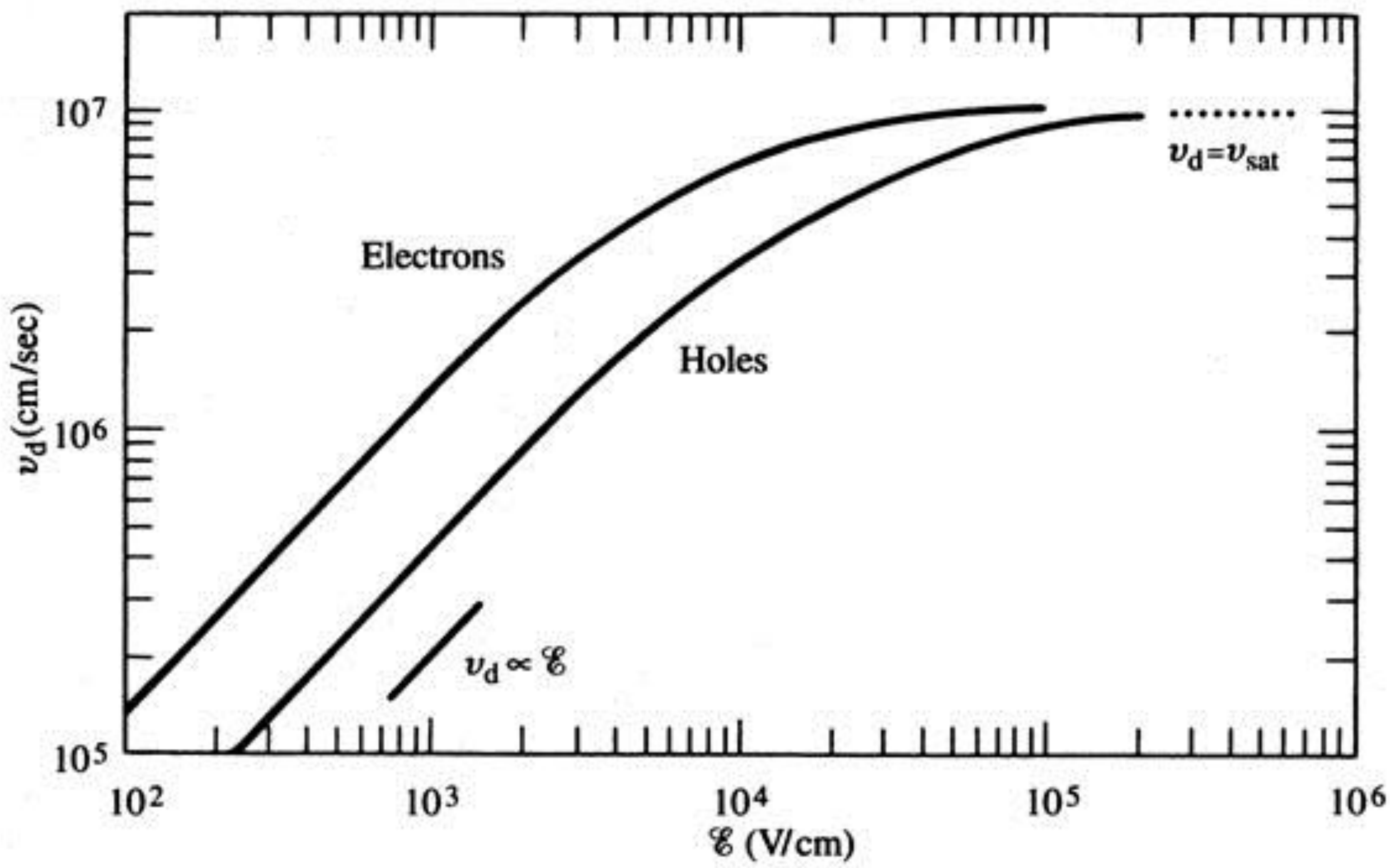
- Electrons drift in the direction opposite to the electric field → Current flows.
  - **Due to scattering, electrons in a semiconductor do not achieve constant velocity nor acceleration.**
  - **However, they can be viewed as particles moving at a constant average drift velocity v_d.**

Drift Current



$v_d\ t$	All holes this distance back from the normal plane will cross the plane in a time *t*
$v_d\ t\ A$	All holes in this volume will cross the plane in a time *t*
$p\ v_d\ t\ \mathrm{A}$	Holes crossing the plane in a time *t*
$q\ p\ v_d\ t\ \mathrm{A}$	Charge crossing the plane in a time *t*
$q\ p\ v_d\ A$	Charge crossing the plane per unit time, $\Rightarrow$ Hole drift current $\boldsymbol{I}_{\mathrm{P\vert drift}}$ (Ampere)
$q\ p\ v_d$	Current density associated with hole drift current, $\mathbf{J}_{\mathrm{P\vert drift}}$ (A/m^2)

Drift Velocity vs. Electric Field



$$v_d = \mu_p \mathcal{E}$$
$$v_d = -\mu_n \mathcal{E}$$

- **Linear relation holds in low field intensity, ~5×10³ V/cm**

Hole and Electron Mobility

μ has the dimensions of $v/\mathcal{E}$: $\left[\dfrac{\text{cm/s}}{\text{V/cm}} = \dfrac{\text{cm}^2}{\text{V}\cdot\text{s}}\right]$

Electron and hole mobility of selected
intrinsic semiconductors (T = 300 K)

	Si	**Ge**	**GaAs**	**InAs**
μ_n (cm^2/V·s)	1400	3900	8500	30000
μ_p (cm^2/V·s)	470	1900	400	500

Hole and Electron Mobility

- For holes,

$$I_{\mathrm{P|drift}} = qpv_{\mathrm{d}}A$$

• Hole current due to drift

$$\mathbf{J}_{\mathrm{P|drift}} = qpv_{\mathrm{d}}$$

• Hole current density due to drift

- In low-field limit,

$$v_{\mathrm{d}} = \mu_{\mathrm{p}}\mathcal{E}$$

$$\mathbf{J}_{\mathrm{P|drift}} = q\mu_{\mathrm{p}}p\mathcal{E}$$

• μ_p : hole mobility

- Similarly for electrons,

$$\mathbf{J}_{\mathrm{N|drift}} = -qnv_{\mathrm{d}}$$

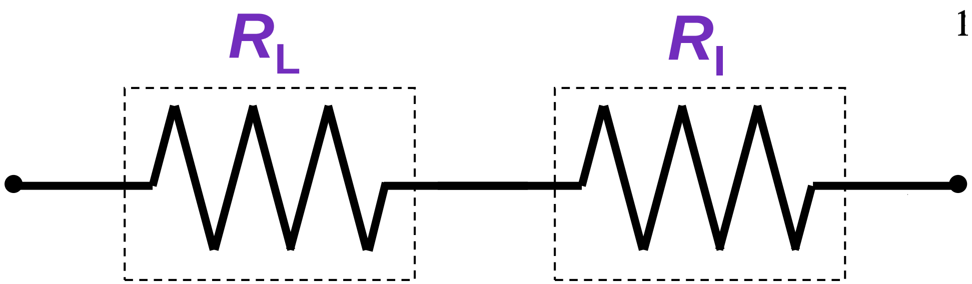
• Electron current density due to drift

$$v_{\mathrm{d}} = -\mu_{\mathrm{n}}\mathcal{E}$$

$$\mathbf{J}_{\mathrm{N|drift}} = q\mu_{\mathrm{n}}n\mathcal{E}$$

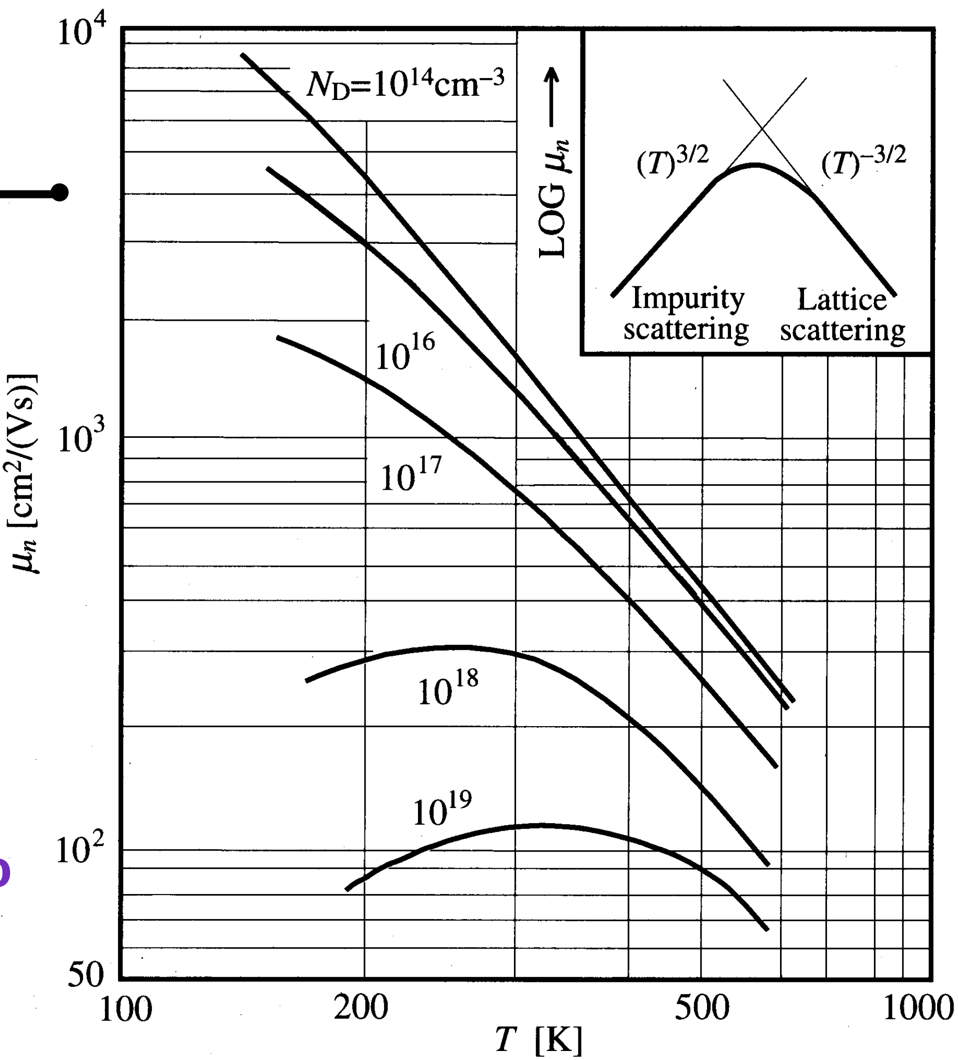
• μ_n : electron mobility

Temperature Effect on Mobility



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**



Temperature Effect on Mobility

- 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.

Conductivity and Resistivity

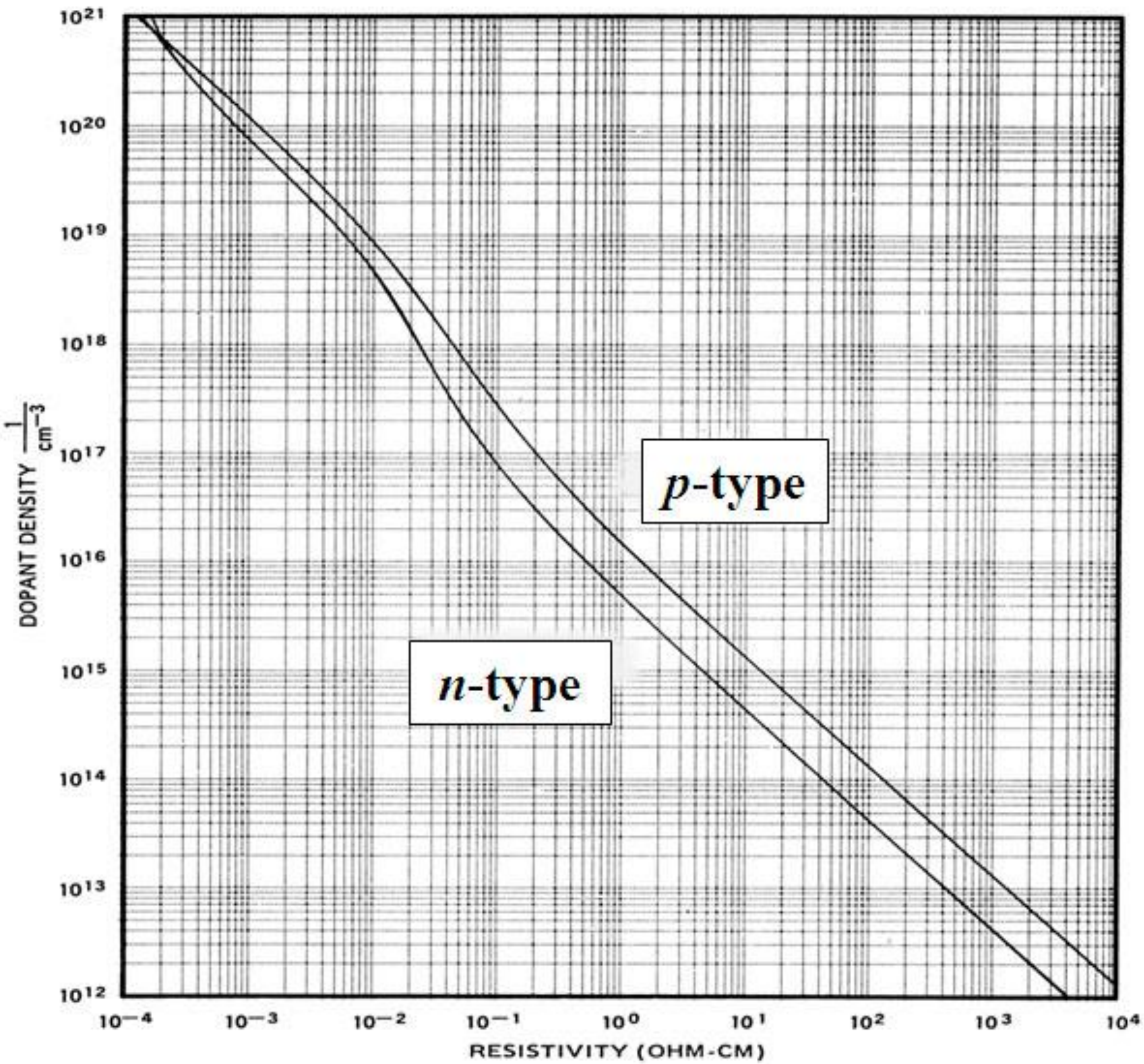
$$\mathbf{J}_{\mathrm{N|drift}} = -qnv_{\mathrm{d}} = q\mu_{\mathrm{n}}n\mathcal{E}$$

$$\mathbf{J}_{\mathrm{P|drift}} = qpv_{\mathrm{d}} = q\mu_{\mathrm{p}}p\mathcal{E}$$

$$\mathbf{J}_{\mathrm{drift}} = \mathbf{J}_{\mathrm{N|drift}} + \mathbf{J}_{\mathrm{P|drift}} = q(\mu_{\mathrm{n}}n + \mu_{\mathrm{p}}p)\mathcal{E} = \sigma\mathcal{E}$$

- **Conductivity** of a semiconductor: $\sigma = q(\mu_{\mathrm{n}}n + \mu_{\mathrm{p}}p)$
- **Resistivity** of a semiconductor: $\rho = 1/\sigma$

Resistivity Dependence on Doping



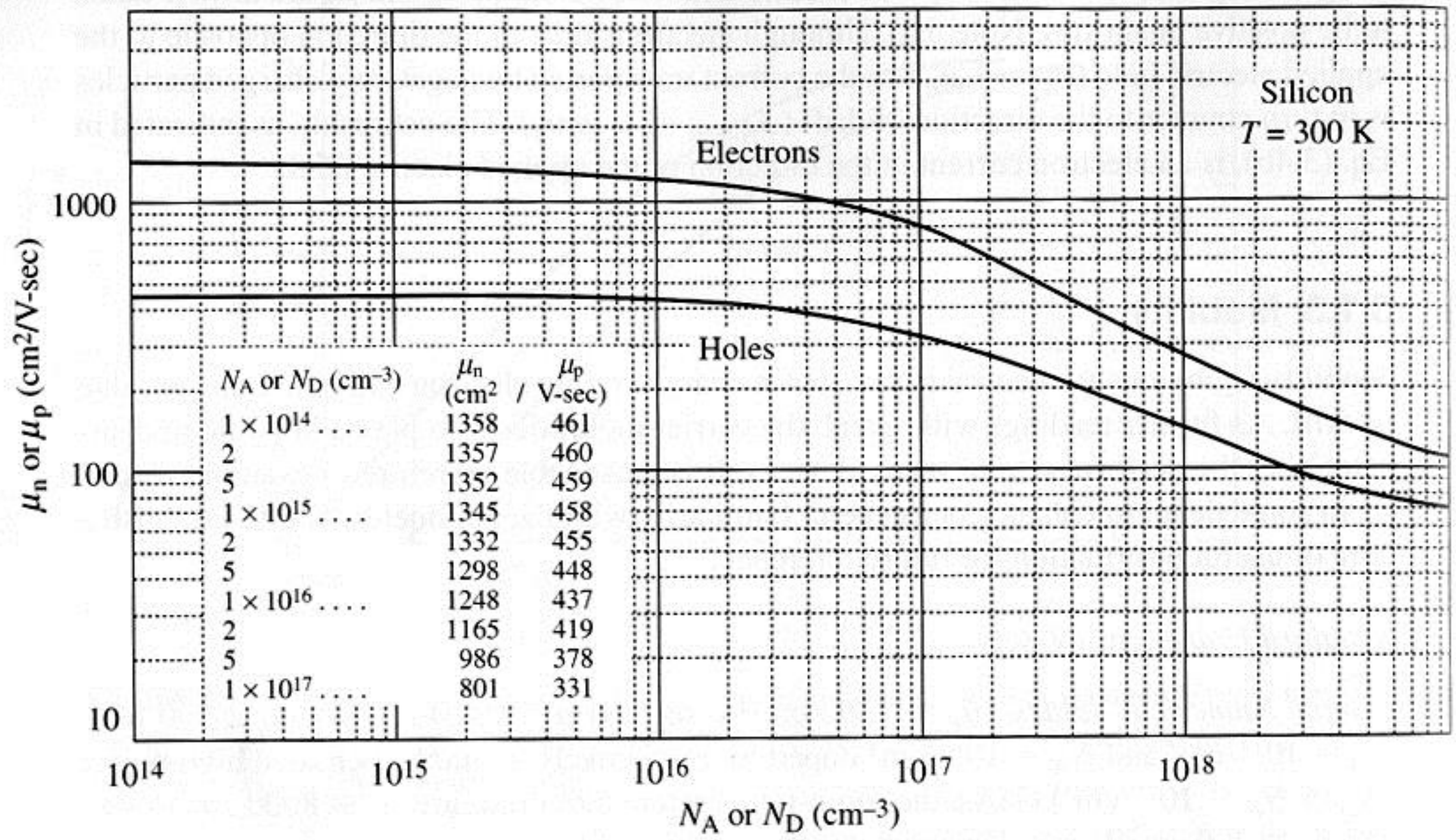
- **For *n*-type material:**

$$\rho \cong \frac{1}{q\mu_n N_D}$$

- **For *p*-type material:**

$$\rho \cong \frac{1}{q\mu_p N_A}$$

Carrier Mobility as Function Doping Level



N_A or N_D (cm⁻³)	μ_n (cm² / V-sec)	μ_p (cm² / V-sec)
1×10^{14}	1358	461
2	1357	460
5	1352	459
1×10^{15}	1345	458
2	1332	455
5	1298	448
1×10^{16}	1248	437
2	1165	419
5	986	378
1×10^{17}	801	331

Example

- Consider a Si sample at 300 K doped with $10^{16}/\text{cm}^3$ Boron. What is its resistivity?

$N_A = 10^{16}\ \text{cm}^{-3}$, $N_D = 0$ **($N_A \gg N_D \rightarrow$ *p*-type)**

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

$$\rho = \frac{1}{q\mu_{\text{n}} n + q\mu_{\text{p}} p}$$

$$\approx \frac{1}{q\mu_{\text{p}} p}$$

$$\approx [(1.6\times10^{-19})(437)(10^{16})]^{-1}$$

$$\approx \underline{\underline{1.430\ \Omega\cdot\text{cm}}}$$

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)**

$n \approx N_D - N_A = 9\times10^{16}$ cm^{-3}, $p \approx n_i^2/n = 1.11\times10^3$ cm^{-3}

$$\rho = \frac{1}{q\mu_n n + q\mu_p p}$$

$$\approx \frac{1}{q\mu_n n}$$

$$\approx [(1.6\times10^{-19})(790)(9\times10^{16})]^{-1}$$

$$\approx \underline{\underline{0.0879\ \Omega\cdot\text{cm}}}$$

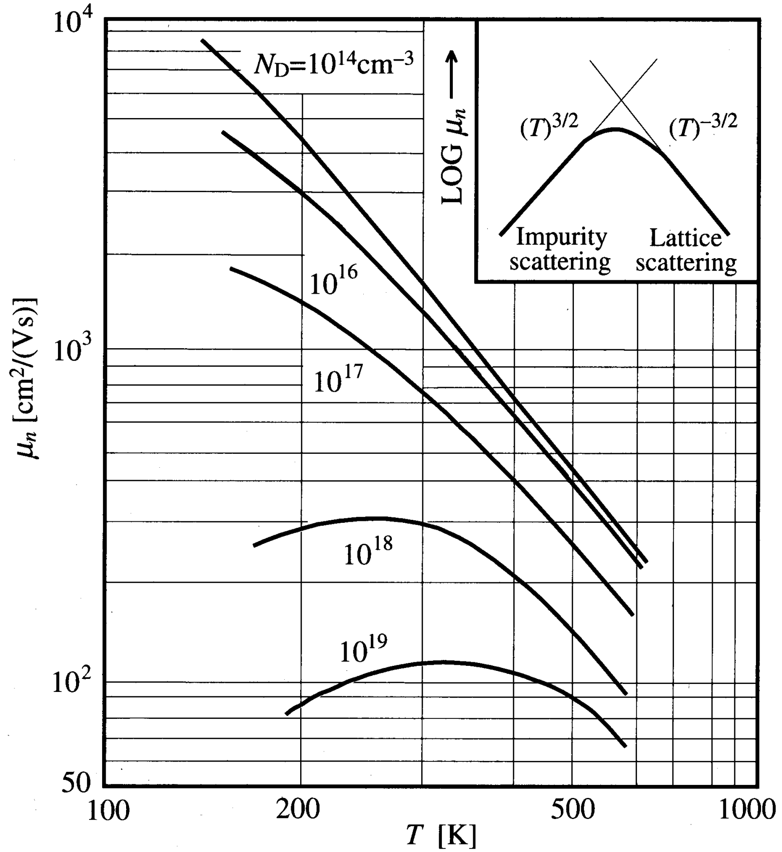
- **μ_n is to be taken for the value at $N = N_A + N_D = 1.1\times10^{17}$ cm^{-3}**
- **$\mu n \approx$ 790 cm^2/V·s**

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 σ (and therefore ρ) is μ_n.

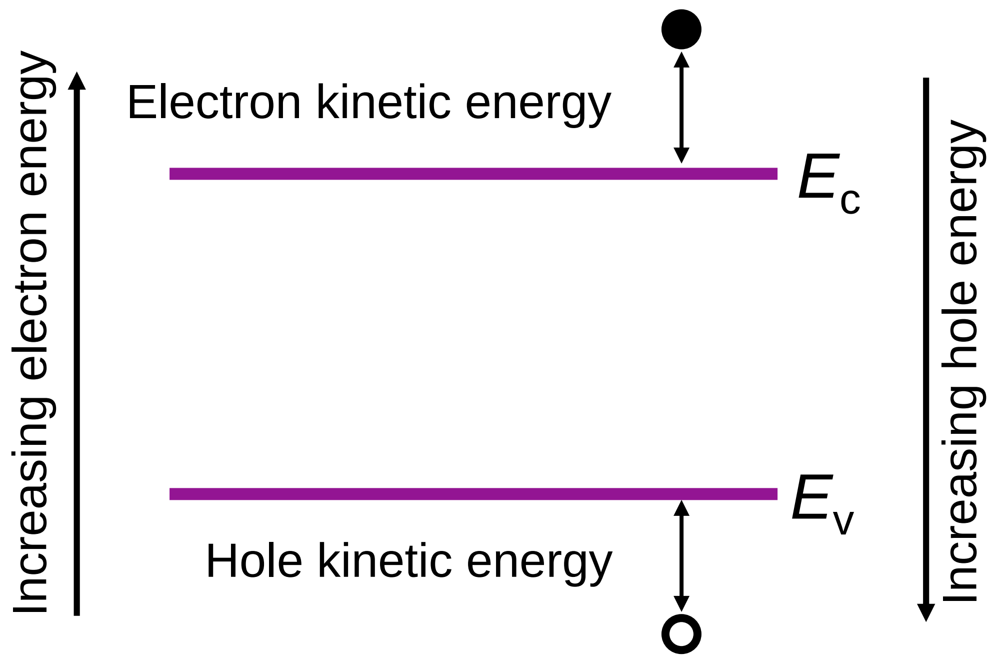
From the mobility vs. temperature curve for 10^{17}cm^{-3}, we find that μ_n decreases from 770 at 300 K to 400 at 400 K.

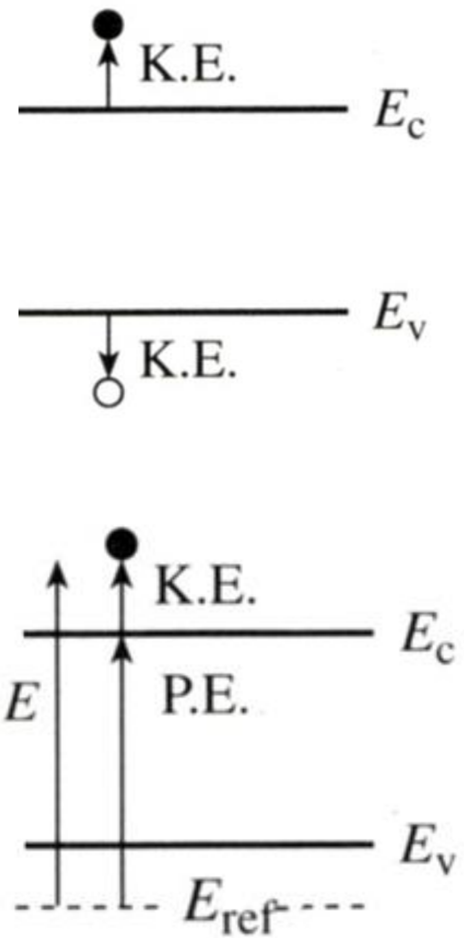


As a result, ρ **increases** by a factor of:

$$\frac{770}{400} = \underline{\underline{1.93}}$$

Potential vs. Kinetic Energy





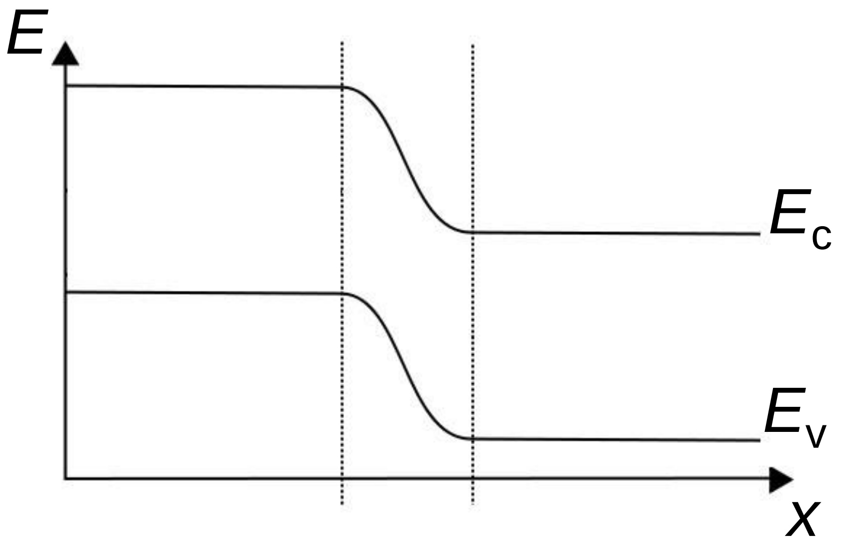
- E_c represents the electron potential energy:

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

- E_{ref} is arbitrary

Band Bending

- 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"***

Band Bending

- The potential energy of a particle with charge $-q$ is related to the electrostatic potential $V(x)$:

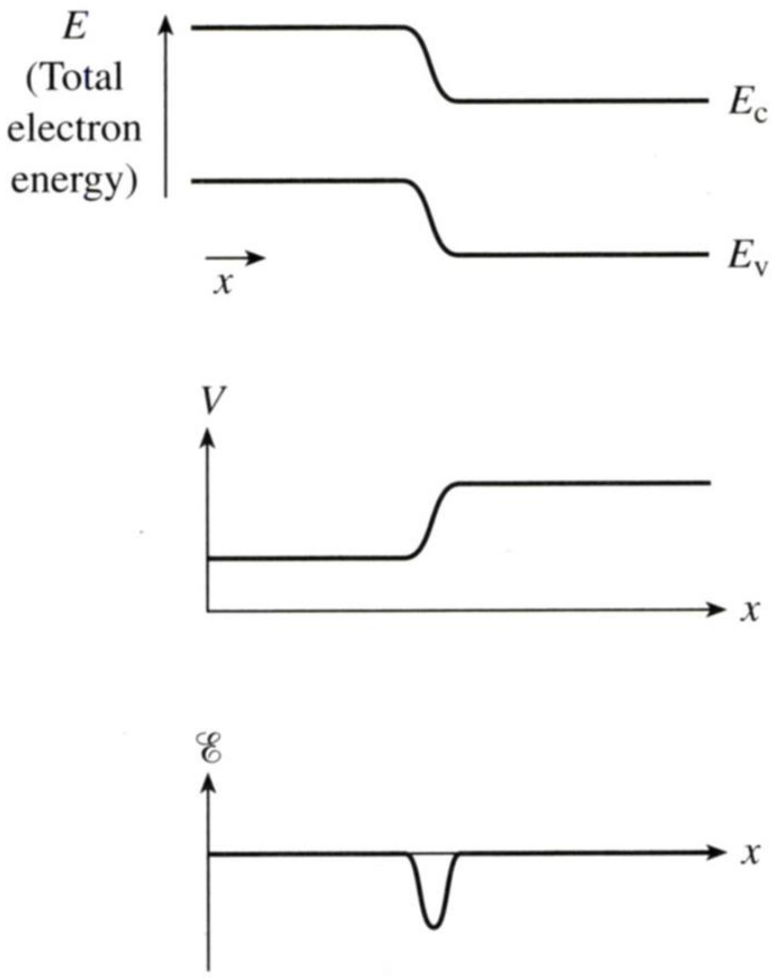
$$\text{P.E.} = -qV$$

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

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

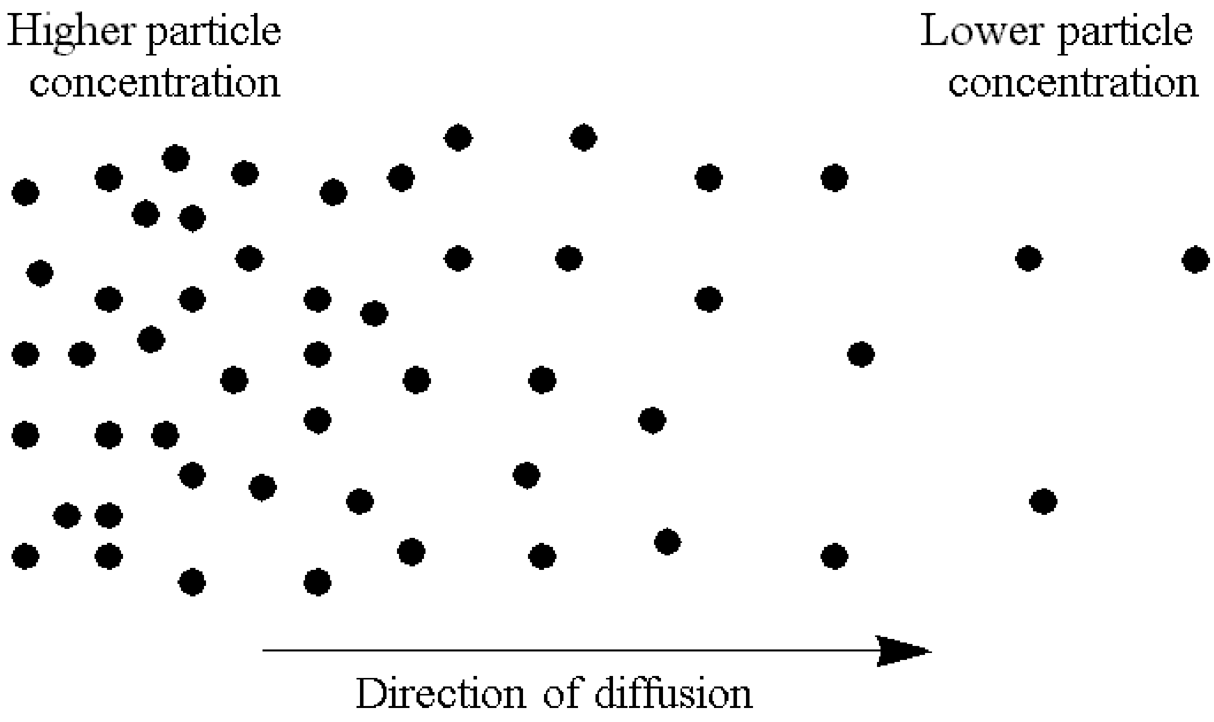
$$\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx} = \frac{1}{q}\frac{dE_v}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

  - **Since E_c, E_v, and E_i differ only by an additive constant**



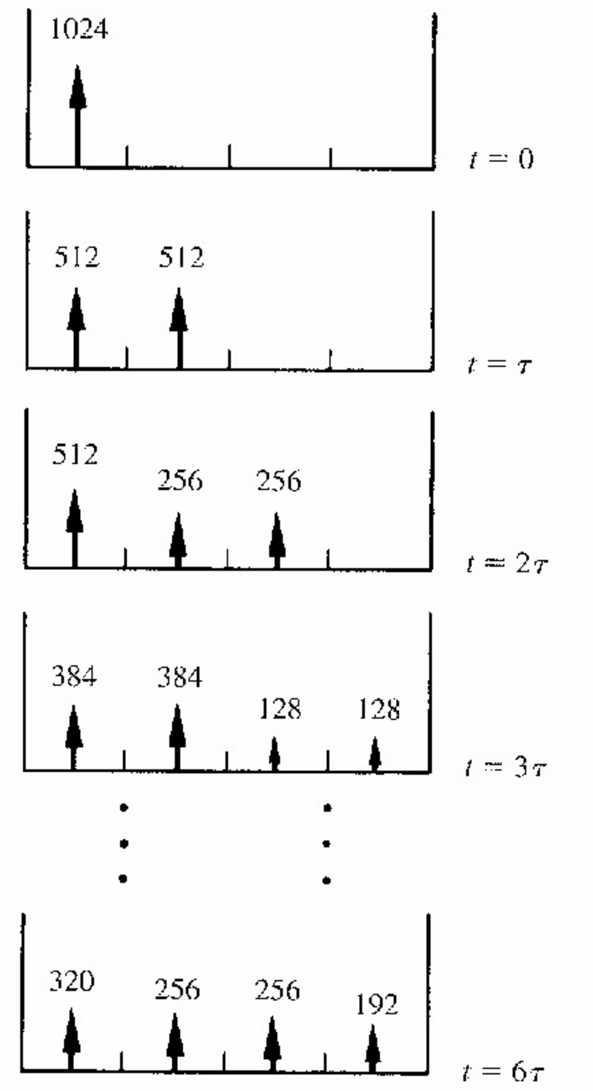
Diffusion

- Particles diffuse from regions of higher concentration to regions of lower concentration region, due to random thermal motion (Brownian Motion).



1-D Diffusion Example

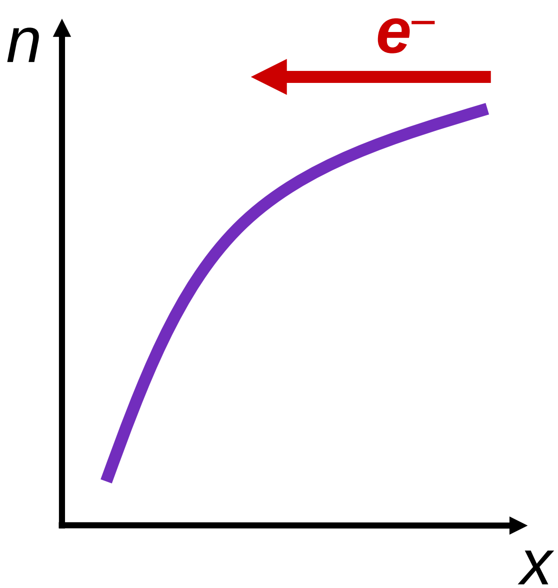
- Thermal motion causes particles to move into an adjacent compartment every τ seconds.



Diffusion Currents

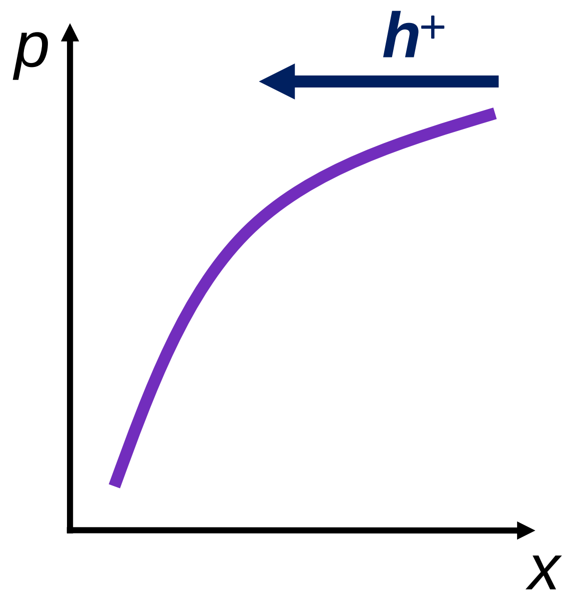
$$\mathbf{J}_{\mathrm{N|diff}} = qD_{\mathrm{N}} \frac{dn}{dx}$$

$$\mathbf{J}_{\mathrm{P|diff}} = -qD_{\mathrm{P}} \frac{dp}{dx}$$



← Electron flow

Current flow →



← Hole flow

← Current flow

- ***D*** **is the** ***diffusion coefficient*****, in [cm^2/sec]**

Total Currents

$$\mathbf{J} = \mathbf{J}_{\mathrm{N}} + \mathbf{J}_{\mathrm{P}}$$

$$\mathbf{J}_{\mathrm{N}} = \mathbf{J}_{\mathrm{N|drift}} + \mathbf{J}_{\mathrm{N|diff}} = q\mu_{\mathrm{n}} n\mathcal{E} + qD_{\mathrm{N}}\frac{dn}{dx}$$

$$\mathbf{J}_{\mathrm{P}} = \mathbf{J}_{\mathrm{P|drift}} + \mathbf{J}_{\mathrm{P|diff}} = q\mu_{\mathrm{p}} p\mathcal{E} - qD_{\mathrm{P}}\frac{dp}{dx}$$

- **Drift current** flows when an electric field is applied.
- **Diffusion current** flows when a gradient of carrier concentration exist.

Current Flow Under Equilibrium Conditions

- In equilibrium, there is no net flow of electrons or :

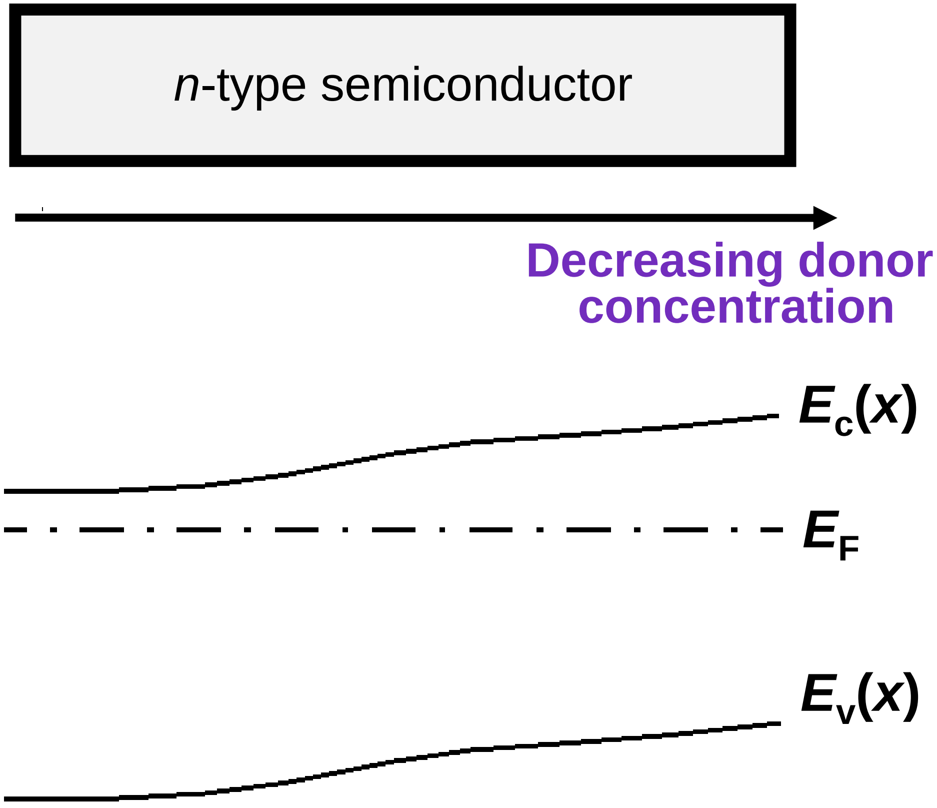
$$\mathbf{J}_{\mathrm{N}} = 0, \;\; \mathbf{J}_{\mathrm{P}} = 0$$

- 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.

$$\mathbf{J}_{\mathrm{N}} = q\mu_{\mathrm{n}} n\mathcal{E} \; + \; qD_{\mathrm{N}}\frac{dn}{dx} = 0$$

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 μ

- But, under equilibrium conditions, $\mathbf{J}_N = 0$ and $\mathbf{J}_P = 0$

$$\mathbf{J}_{\mathrm{N}} = q\mu_{\mathrm{n}} n\mathcal{E} + qD_{\mathrm{N}}\frac{dn}{dx} = 0$$

$$qn\mathcal{E}\mu_{\mathrm{n}} - qn\mathcal{E}\frac{q}{kT}D_{\mathrm{N}} = 0 \longrightarrow \frac{D_{\mathrm{N}}}{\mu_{\mathrm{n}}} = \frac{kT}{q}$$

Similarly, $$\frac{D_{\mathrm{P}}}{\mu_{\mathrm{p}}} = \frac{kT}{q}$$

- 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 $\mu_p = 410\ \mathrm{cm}^2 / \mathrm{V.s}$?

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

$$= \frac{25.86\ \mathrm{meV}}{1\mathrm{e}} \cdot 410\ \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$$

$$= 25.86\ \mathrm{mV} \cdot 410\ \frac{\mathrm{cm}^2}{\mathrm{V}\cdot\mathrm{s}}$$

$$= \underline{\underline{10.603\ \mathrm{cm}^2/\mathrm{s}}}$$

$$\frac{1\ \mathrm{eV}}{1\ \mathrm{e}} = 1\ \mathrm{V}$$

$$1\ \mathrm{eV} = 1.602 \times 10^{-19}\ \mathrm{J}$$

- **Remark:** ***kT/q*** **= 25.86 mV at room temperature**

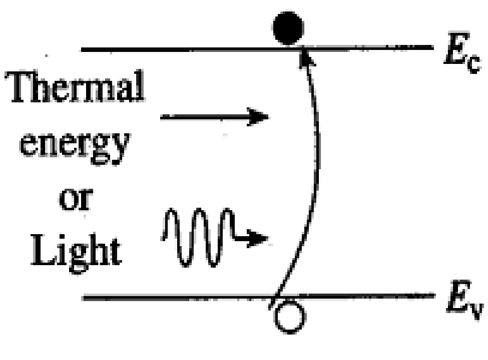
Recombination–Generation

- **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.

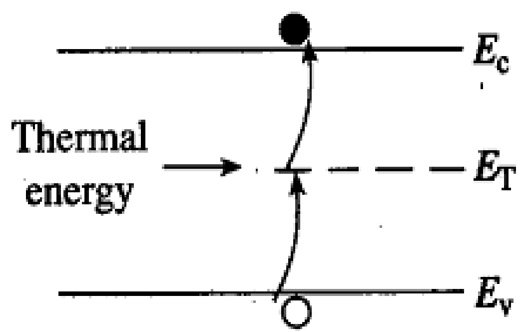
- Generation and recombination processes act to change the carrier concentrations, and thereby indirectly affect current flow.

Generation Processes

Band-to-Band



R–G Center

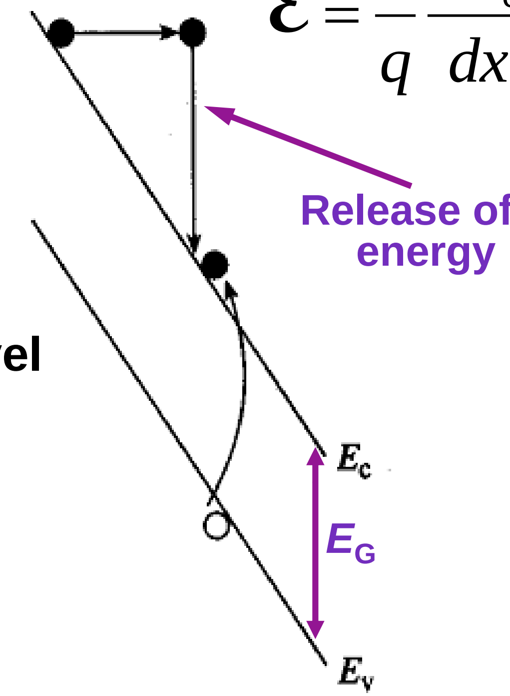


E_T: trap energy level

- Due to lattice defects or unintentional impurities
- Also called indirect generation

Impact Ionization

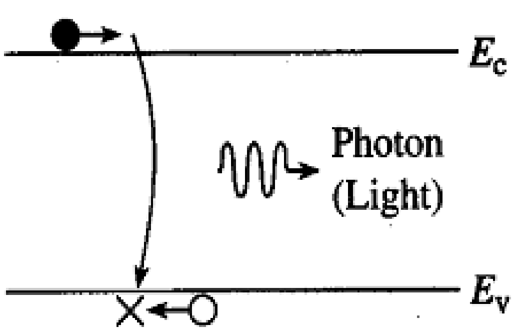
$$\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx}$$



- Only occurs in the presence of large $\mathcal{E}$

Recombination Processes

Band-to-Band



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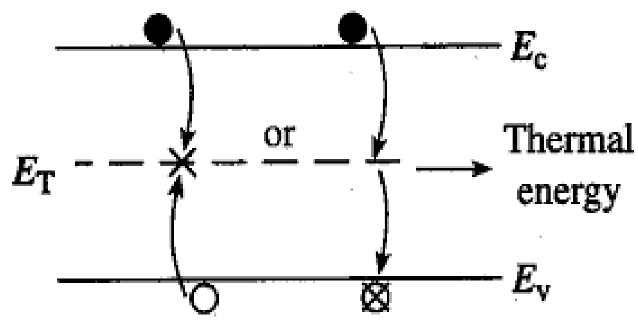
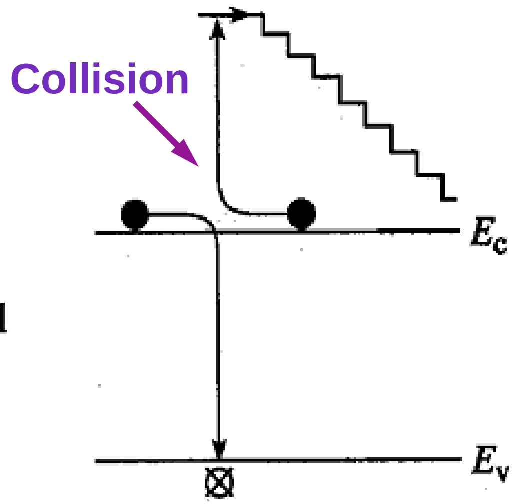


- Rate is limited by minority carrier trapping
- Primary recombination way for Si

Auger



- Occurs in heavily doped material

Homework 2

- 1. (4.17)
  Problem 3.6, Pierret's "Semiconductor Device Fundamentals".
- 2. (4.27)
  Problem 3.12, from (a) until (f), for Figure P3.12(a) and Figure P3.12(f), Pierret's "Semiconductor Device Fundamentals".
- 3. (5.28)
  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 μm and is limited to $0 \le x \le 25$ μm. The electron diffusion coefficient is D_N = 25 cm^2/s and the electron mobility is μ_n = 960 cm^2/(Vs). The total electron current density through the semiconductor is constant and equal to $\mathbf{J}_N$ = –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.