Semiconductor Engineering

:Semiconductor Physics and Devices

Chapter 1. Semiconductor Electronics

Objectives

Overview of the physical electronics of semiconductor

- Energy band theory
- Doping principle
- Free carrier statistics
- Drift and diffusion

Electronic properties of materials

How do we know the electrical properties materials?

Resistance: *R*

$$R = V/I$$ *From Ohm's law*

the current *I* flowing through a bar of homogeneous material with uniform cross section when a voltage *V* is applied across it, we can find its resistance *R*

Resistivity: ρ

$$\rho = R\frac{A}{L}$$

is related to the resistance of the bar by a geometric ratio where L and A are the length and cross-sectional area of the sample

FREE CARRIERS IN SEMICONDUCTORS

the electronic properties of solids was to the familiar linear relationship that is often found between the current flowing through a sample and the voltage applied across it

This relationship is known as Ohm's law: $V = IR$

To accomplish this we first develop a picture of the kinetic properties of free electrons without any external fields.

low to moderate fields

the high-field case

FREE CARRIERS IN SEMICONDUCTORS

Carrier (electron or hole) in semiconductor

electrons (and holes) in semiconductors are almost "free particles" in the sense that they are not associated with any particular lattice site

The influences of crystal forces are incorporated in an *effective mass* that differs somewhat from the free-electron mass

Using the laws of statistical mechanics,

Electrons and holes have the thermal energy associated with classical free particles: $\frac{1}{2}kT$ units of energy per degree of freedom

where k is Boltzmann's constant
T is the absolute temperature

➡ This means that electrons in a crystal at a finite temperature are not stationary, but are moving with random velocities

Thermal Velocity

Kinetic energy of the electron

the mean-square thermal velocity v_{th} of the electrons is approximately* related to the temperature by the equation

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

where m_n^* is the effective mass of conduction-band electrons.
For silicon m_n^* = 0.26 m_o
(where m_o is the free electron rest mass), and v_{th} is calculated from Equation 1.2.1 to be 2.3 × 10^7 cm s^{-1} at T = 300 K.

The electrons may be pictured as moving in random directions through the lattice, colliding among themselves and with the lattice.
At thermal equilibrium, the motion of the system of electrons is completely random so that <u>the net current in any direction is zero</u>

Thermal Velocity

Kinetic energy of the electron

No electric field applied

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

Average thermal velocity of conduction electron in three dimensional space (~10^7 cm/s @ 300K)

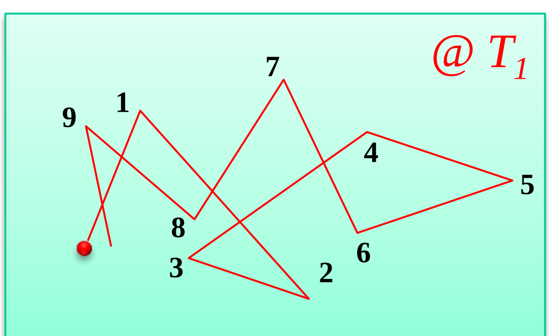
The electron in semiconductors move rapidly in all direction.

Series of random scattering from collision with scattering centers (lattice atoms, impurity)

- Average distance between collision : mean free path (l ~ 10^{-5} cm)
- Average time between collision : mean free time (τ_c ~ 1ps)

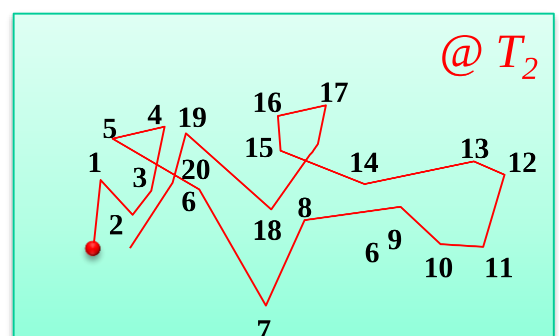
$v_{th} = l / \tau_c$

E = *0*



$T_1 < T_2$

E = *0*



Drift Velocity

When an electric field E is applied to the semiconductors,

Electric field applied

Electrons experience force : $-q\mathbf{E}$

→ Accelerate the electrons

→ additional velocity components created : **drift velocity**

The momentum applied to the electron : $-q\mathbf{E}\tau_c$
The momentum gained : $m^*_n v_n$

momentum = force × time
= mass × velocity

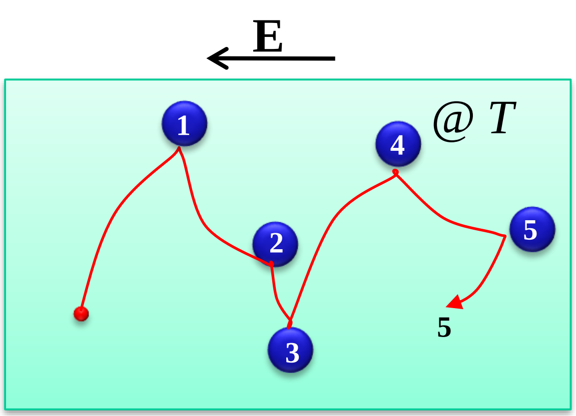
$$-q\mathbf{E}\tau_c = m^*_n v_n \quad \Rightarrow \quad v_n = -\frac{q\tau_c}{m^*_n}\mathbf{E}$$

→ electron drift velocity proportional to **E**

Proportionality factor : electron mobility μ_n [cm^2/Vs]

Electron drift velocity : $v_n = -\mu_n \mathbf{E}$

Hole drift velocity : $v_p = \mu_p \mathbf{E}$



Drift Velocity

When an electric field E is applied to the semiconductors,

Electric field applied

The proportionality factor is an important property of the electron called the *mobility* and is designated by the symbol μ_n

$$\mu_n = \frac{q\tau_c}{m^*_n}$$

Because $v_n = -\mu_n \mathbf{E}$, the mobility describes how easily an electron moves in response to an applied field.

the current density flowing in the direction of the applied field can be found by summing the product of the charge on each electron times its velocity over all electrons *n* per unit volume.

$$J_n = \sum_{i=1}^{n} -qv_i = -nqv_d = nq\mu_n \mathbf{E}$$

Drift Velocity

When an electric field E is applied to the semiconductors,

Electric field applied

For hole,
A hole with zero kinetic energy resides at the valence-band edge E_v
The kinetic energy of a hole in the valence band is therefore measured by *(Ev - E).*
If a band edge is tilted (E-field applied), the hole moves upward on an electron energy-band diagram

The hole mobility μ_p

$$\mu_p = \frac{q\tau_{cp}}{m^*_p}$$

The total current can be written as the <u>sum of the electron and hole current</u>

$$J = J_n + J_p = (nq\mu_n + pq\mu_p)\,\mathbf{E}$$

→ conductivity σ of the semiconductor

$$\sigma = q\mu_n n + q\mu_p p$$

Mobility and Scattering

Quantum-mechanical calculations indicate that a perfectly periodic lattice does not scatter free carriers;
→ the carriers do not interchange energy with a stationary, perfect lattice.

However, at any temperature above absolute zero the atoms that from the lattice vibrate.

These vibrations disturb periodicity and allow energy to be transferred between the carriers and the lattice.

→ scattering processes lead to heating of the semiconductor. The dissipation of this heat is often a limiting factor in the size of semiconductor devices. A device must be large enough to avoid heating to temperatures at which it no longer functions

The interactions with lattice vibrations can be viewed as collisions with energetic "particles" called *phonons.*
Phonons, like photons, have energies quantized in units of $h\nu$, where ν is the lattice-vibrational frequency and h is Planck's constant

Mobility and Scattering

Mobility related with mean free time between collisions

→ determined by various scattering mechanism

(Lattice scattering, Impurity scattering)

Lattice scattering

: thermal vibration of the lattice atoms at non-zero temperature

→ lattice vibration energy transferred to the electrons

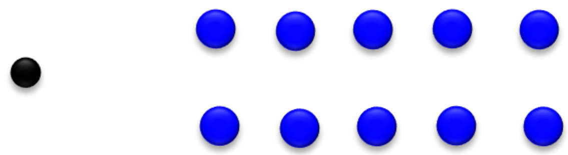
→ lattice vibration increase with increasing temperature

→ mobility decrease with increasing temperature

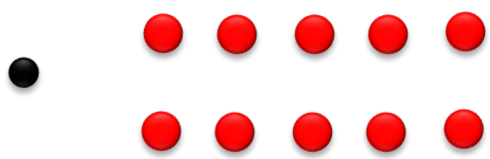
→ lattice scattering dominate at high temperature

Mobility due to lattice scattering : $\mu_l \propto T^{-3/2}$: theoretical analysis

At low temperature



At high temperature



Mobility and Scattering

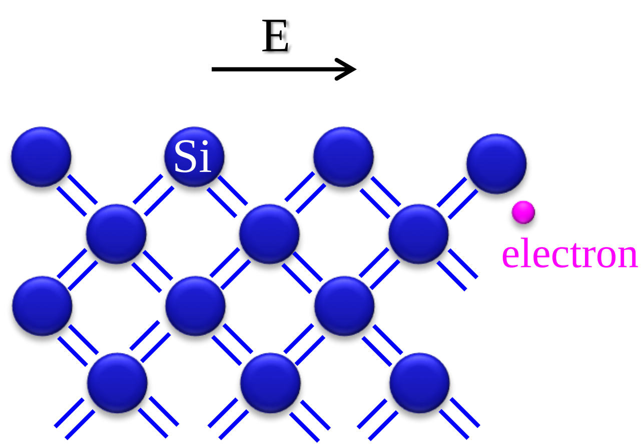
Impurity scattering :

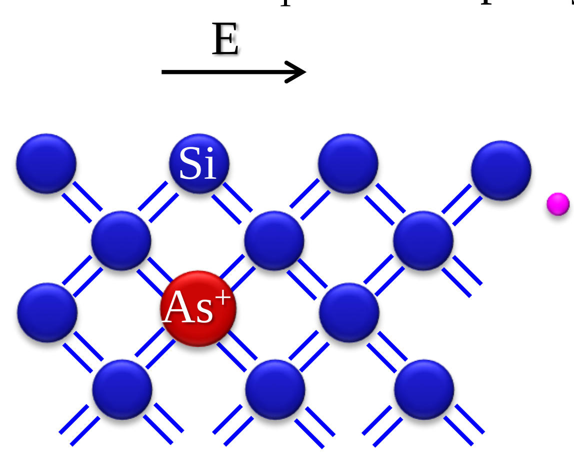
when charge carrier travels around ionized impurities (donor or acceptor)

→ charge carrier path deflected due to Coulomb force
→ ionization scattering depends on concentration of ionized impurity (N_T)
→ at higher temperature, carriers move faster
→ carriers remain near the impurity ion for very short time
→ impurity scattering less significant at higher temperature

Mobility due to impurity scattering : $\mu_i \propto T^{3/2} / N_T$

N_T : total impurity concentration





Impurity scattering :

the mobilities of electrons and holes in silicon at room temperature

In lightly-doped material, the mobility resulting from ionized impurity scattering is higher than that due to lattice scattering.

At higher dopant concentrations, however, scattering by ionized impurities becomes comparable to or greater than that resulting from lattice vibrations, and the total mobility decreases.

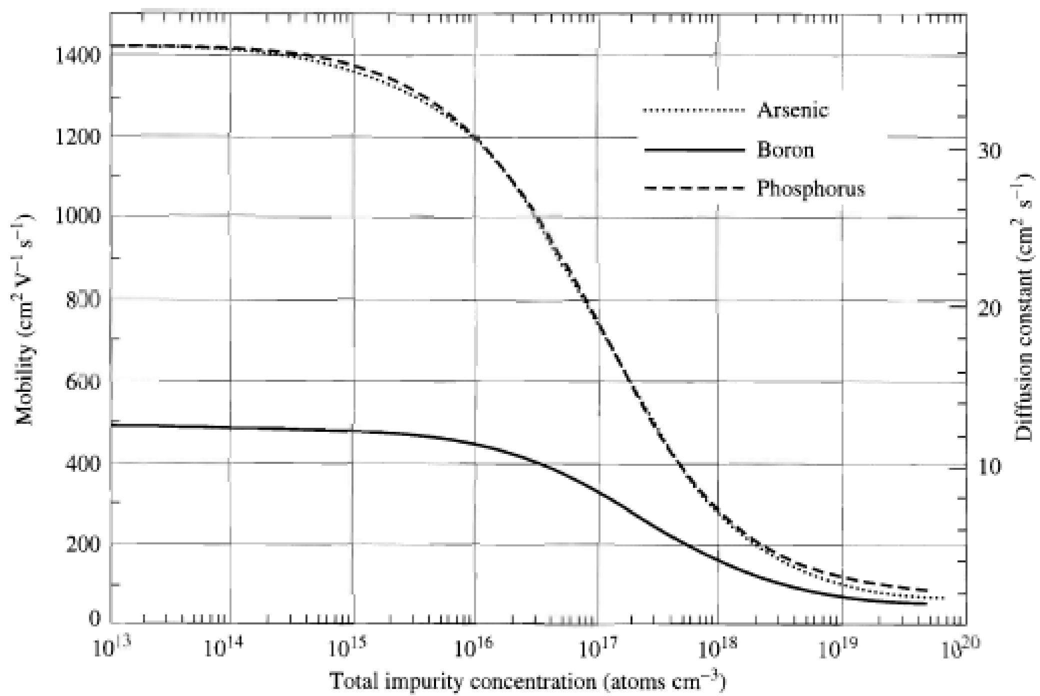


FIGURE 1.16 Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration. The values plotted are the results of curve fitting measurements from several sources. The mobility curves can be generated using Equation 1.2.10 with the following values of the parameters [3].

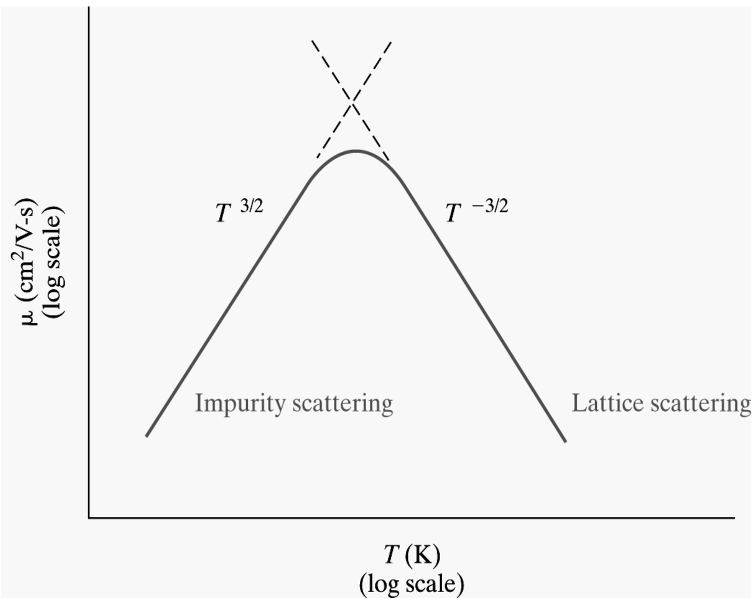
Parameter	Arsenic	Phosphorus	Boron
μ_{min}	52.2	68.5	44.9
μ_{max}	1417	1414	470.5
N_{ref}	9.68×10^{16}	9.20×10^{16}	2.23×10^{17}
α	0.680	0.711	0.719

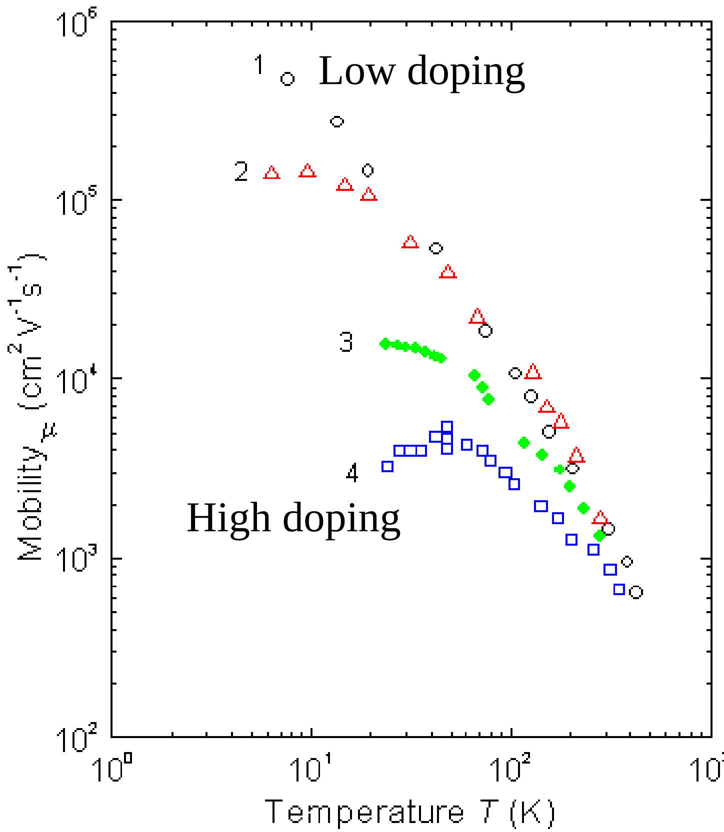
Mobility and Scattering

Effect of temperature on mobility

Total mobility

$$\frac{1}{\mu} = \frac{1}{\mu_i} + \frac{1}{\mu_l}$$

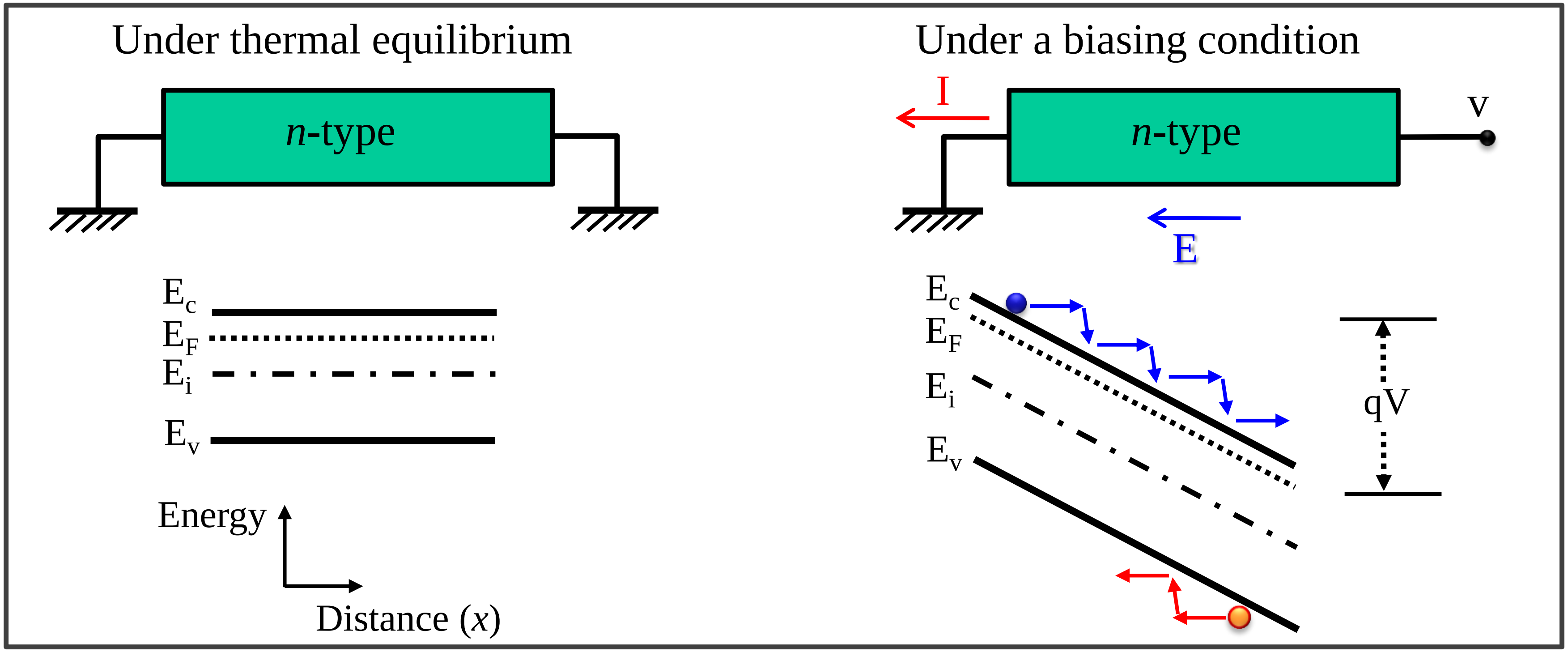




- At low T : impurity scattering dominates
- At high T : lattice scattering dominates

- low doping : lattice scattering dominates
- high doping : impurity scattering dominates at low temperature

Resistivity



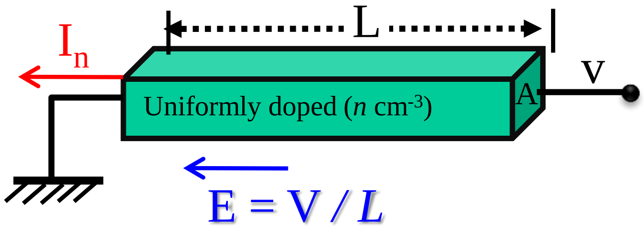
When electric field E is applied to a semiconductor, electron experiences a force -*q*E .

$$-q\mathrm{E} = \text{gradient of electron potential energy} = -\frac{dE_C}{dx} = -\frac{dE_i}{dx} \Rightarrow \mathrm{E} = \frac{1}{q}\frac{dE_i}{dx}$$

We can define electrostatic potential, Ψ as $\mathrm{E} \equiv -\frac{d\Psi}{dx}$

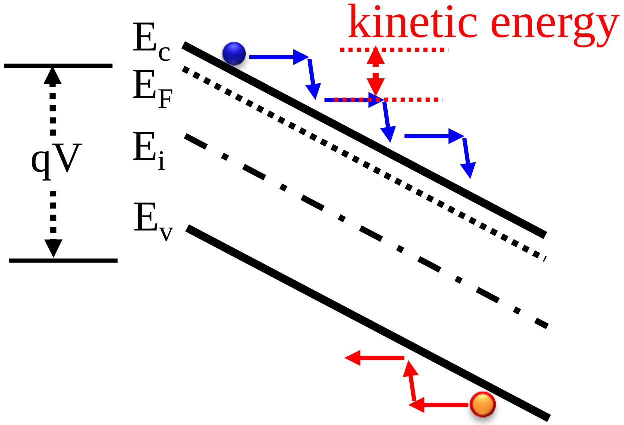
Resistivity

Under a applied electric field



Potential energy and E_i decrease linearly with distance.

$$E = \frac{1}{q}\frac{dE_i}{dx}$$ ➡ Electric field is constant in *x*-direction.



Electron move opposite direction of electric field.

→ Increase of kinetic energy.

→ Electron loses kinetic energy by collision with lattic

→ Repeat several times (opposite direction for holes)

➔ Conduction process under applied electric field

➔ Drift current

Current in a semiconductor with carrier concentration (n / cm^3) an applied electric field E

Electron current : $$J_n = \frac{I_n}{A} = \sum_{i=1}^{n}(-qv_i) = -qnv_n = qn\mu_n E$$ ⬅ $v_n = -\mu_n E$

Hole current : $$J_p = qpv_p = qp\mu_p E$$ ⬅ $v_p = \mu_p E$

Resistivity

Total current in a semiconductor under a applied electric field E

$$J = J_n + J_p = (qn\mu_n + qp\mu_p)\mathrm{E} = \underbrace{q(n\mu_n + p\mu_p)}_{\sigma}\mathrm{E}$$

$$\sigma = q(n\mu_n + p\mu_p)$$ → Conductivity of semiconductor

Resistivity of semiconductor

$$\rho \equiv \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)}$$

i) For *n*-type semiconductor ($n >> p$)

$$\rho = \frac{1}{qn\mu_n}$$

ii) For *p*-type semiconductor ($p >> n$)

$$\rho = \frac{1}{qp\mu_p}$$

Diffusion Current

Drift current

→ flows when an electric field is applied and which follows Ohm's law. Ohmic behavior is observed in metals and semiconductors and is probably familiar from direct experience

Additional important component of current in semiconductor

→ if a spatial variation of carrier energies or densities exists within the material.

➡ *Diffusion current.*

*Diffusion current is generally not an important consideration in metals because metals have very high conductivities

Origin of diffusion current.

The lower conductivity and the possibility of nonuniform densities of carriers and of carrier energies makes diffusion an important process affecting current flow in semiconductors

Diffusion Current

To understand the origin of diffusion current, we consider the hypothetical case of an n-type semiconductor with an electron density that varies only in one dimension

no electric fields are applied

the semiconductor is at a uniform temperature so that the average energy of electrons does not vary with *x;* only the density *n(x)* varies

On the average, the electrons crossing the plane $x = 0$ from the left in Figure 1.19 start at approximately $x = -\lambda$ after a collision where λ is the *mean-free path* of an electron, given by $\lambda = v_{th}\tau_{cn}$

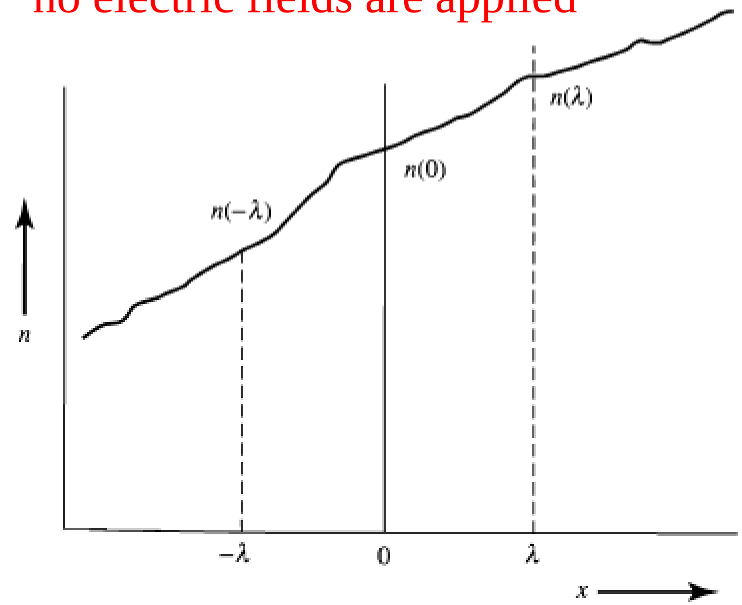


FIGURE 1.19 Electron concentration *n* versus distance *x* in a hypothetical one-dimensional solid. Boundaries are demarcated λ units on either side of the origin where λ is a collision mean-free path.

The average rate (per unit area) of electrons crossing the plane $x = 0$ from the left, therefore, depends on the density of electrons that started at $x = -\lambda$ and is

$$\Rightarrow \frac{1}{2}n(-\lambda)v_{th}$$

The factor (1/2) appears because half of the electrons travel to the left and half travel to the right after a collision at $x = -\lambda$

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Diffusion Current

The average rate (per unit area) of electrons crossing the plane $x = 0$ from the right, therefore, depends on the density of electrons that started at $x = \lambda$ and is

$$\frac{1}{2}n(\lambda)v_{th}$$

the net rate or flux of particle flow per unit area from the left to right (denoted F)

$$F = F_1 - F_2 = \frac{1}{2}v_{th} \cdot [n(-\lambda) - n(\lambda)]$$

$$= \frac{1}{2}v_{th} \cdot \left\{\left[n(0) - \lambda\frac{dn}{dx}\right] - \left[n(0) + \lambda\frac{dn}{dx}\right]\right\}$$

Approximate the density at $x = \pm\lambda$ by the first two terms of a Taylor series expansion

$$= -v_{th}\lambda\frac{dn}{dx}$$

$$J_n = -qF = q\lambda v_{th}\frac{dn}{dx}$$

Because each electron carries a charge $-q$, the particle flow corresponds to a current

The *diffusion current* is proportional to the spatial derivative of the electron density and arises because of the random thermal motion of charged particles in a concentration gradient

Diffusion Current

For an electron density that increases with increasing *x*, the gradient is positive, as is the current.
Because electrons to flow from the higher density region at the right to the lower density region at the left and current flows in the direction opposite to that of the electron

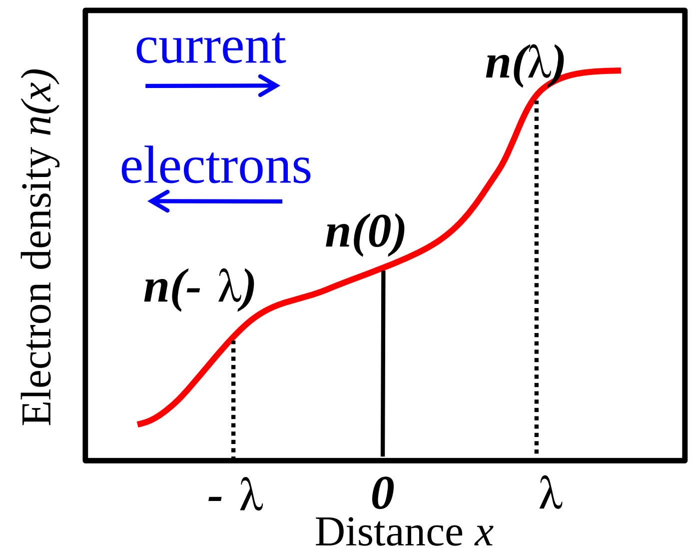
$$J_n = q\lambda v_{th}\frac{dn}{dx}$$

Using $\lambda = v_{th}\tau_{cn}$ $\mu_n = \frac{q\tau_{cn}}{m_n^*}$

$$J_n = q\left(\frac{kT}{q}\mu_n\right)\frac{dn}{dx}$$

→ Diffusion coefficient (diffusivity)

Electron density at uniform temperature



$$D_n = \left(\frac{kT}{q}\right)\mu_n$$ ----- Einstein relation

Relationship between two important constant (diffusivity & mobility)
→ Related to the carrier transport by diffusion and drift in semiconductor

Diffusion Current

The current due to carrier diffusion is

$$J_n = -qF = qD_n \frac{dn}{dx}$$

$$J_p = qF = -qD_p \frac{dp}{dx}$$

→ Diffusion current results from the random thermal motion of carriers in a concentration gradient

When an electric field is applied to a semiconductor with concentration gradient

→ Total current at any point is the sum of the **drift** and **diffusion** components

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx}$$

→ Electron current

- Drift : $J_n = qn\mu_n \mathrm{E}$
- Diffusion : $J_n = qD_n \frac{dn}{dx}$

$$J_p = q\mu_p pE - qD_p \frac{dp}{dx}$$

→ Hole current

- Drift : $J_p = qp\mu_p \mathrm{E}$
- Diffusion : $J_p = -qD_p \frac{dp}{dx}$

Total conduction current

$$J_{cond} = J_n + J_p$$

Physics of the Hall Effect

The *Hall effect*, named for American physicist E. H. Hall who discovered it in 1879, is a direct consequence of the force exerted on charged carriers moving in a magnetic field

The force on a particle having charge q and moving in a magnetic field $\vec{B}$ with velocity $\vec{v}$ (both variables being vector quantities) is written

$$\vec{F} = q\vec{v} \times \vec{B}$$

where the vector cross product (×) signifies the product of the vector magnitudes times the sine of the angle between them.

The Hall effect is usually used with an extrinsic semiconductor so that one carrier dominates and the other has a negligible density

Physics of the Hall Effect

$$\vec{F} = q\vec{v} \times \vec{B}$$

the current carriers (electrons or holes) in a conductor experience a force in a direction perpendicular to both the magnetic field and the carrier velocity (applied electrical field).

In the steady state, this force is balanced by an induced electric field that results from a slight charge redistribution

These forces must balance because there can be no net steady-state motion of the carriers in the transverse direction.

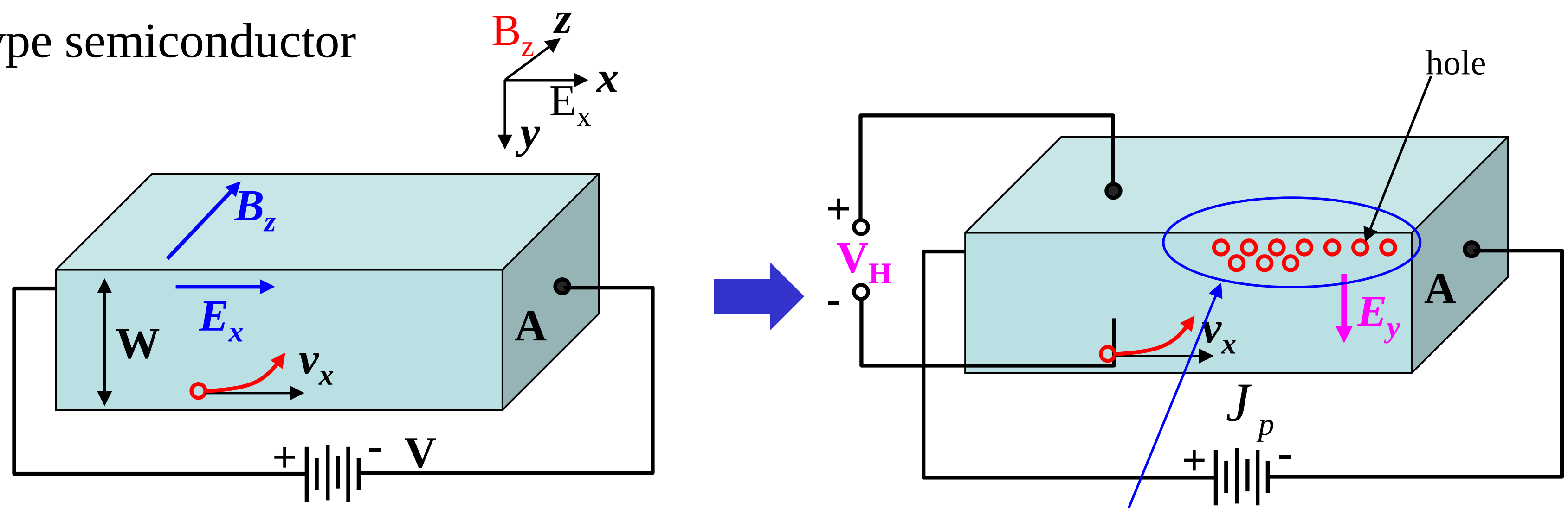
➔ Hole accumulation at the end of the materials ← direction perpendicular to both the magnetic field and electrical field

→ Electric field established (E_y) : Hall effect

The induced electric field is called the *Hall field* E_H. Integrating the Hall field with respect to position across the width of the conductor produces the *Hall voltage* V_H

Physics of the Hall Effect

p-type semiconductor



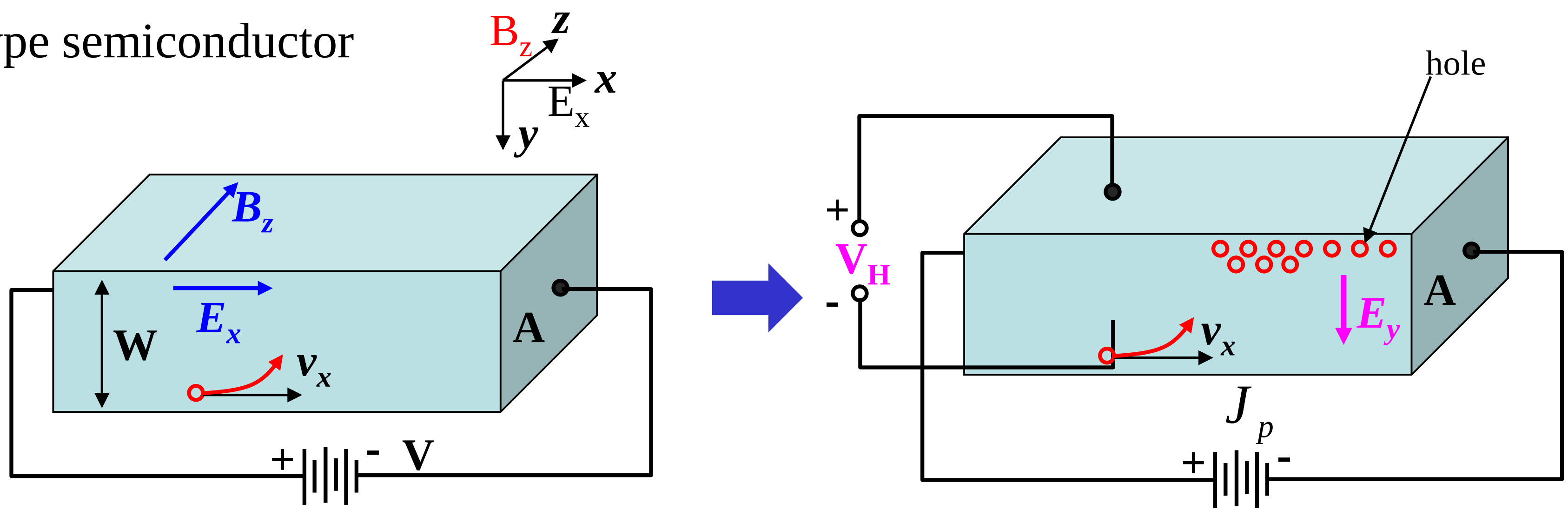
- Apply { Electric field along *x*-direction : E_x ; Magnetic field along *z*-direction : B_z }

- Force generated { E_x : holes move toward *x*-direction ; Lorentz force to upward $= qv \times B = qv_xB_z$ }

➔ Hole accumulation at the top
→ Electric field established (E_y) : Hall effect
→ Electric field balance with Lorentz force

Physics of the Hall Effect

p-type semiconductor



current flow is in the positive x-direction, the magnetic field is in the positive z-direction, and the Hall field is therefore along the y-direction

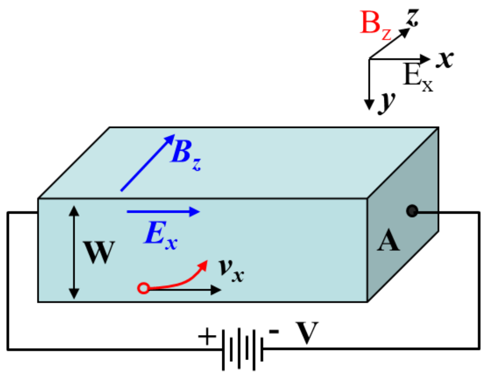
The magnetic force deflects both holes and electrons in the negative y-direction and induces a Hall field toward positive *y* for holes, and in the opposite direction for electrons

Consider the drift velocity v_x of the current carriers. Equating the magnitudes of the magnetic and Hall-field forces

Physics of the Hall Effect

the Hall field can be written in terms of the current and the applied magnetic field as

$$E_y = \left(\frac{J_p}{qp}\right) B_z = \left(\frac{1}{qp}\right) J_p B_z = R_H J_p B_z$$



$$R_H \equiv \frac{1}{qp}$$: Hall coefficient (for hole)

$$R_H \equiv -\frac{1}{qn}$$: Hall coefficient (for electron)

$$R_H = \frac{E_y}{J_p B_z}$$

→ Terminal voltage $V_H = E_y W$

: **Hall voltage**

→ We can know the carrier concentration & the carrier type of semiconductor

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