Transport Properties of Solids:
Carrier Transport Phenomena in Semiconductors

Net flow of electrons and holes creates currents – there are two such transport mechanisms: **DRIFT** and **DIFFUSION.** Carrier transport phenomena are the foundation for determining the semiconductor's current-voltage characteristics.

Temperature gradients can also create carrier movement, but since semiconductor devices are small, this effect can usually be ignored. We will assume thermal equilibrium only.

Drift Current

An applied E-field will produce a force on electrons and holes so they will experience net movement provided that there are available energy states into which they may move.

The resulting **drift current** is a function of concentration of mobile electrons and holes and net drift velocity of these charge carriers

Average drift velocity is related to the electric field by a parameter called mobility.

Mobility gives an indication of how well a carrier moves through a semiconductor *i.e.* charge carriers do not move totally unimpeded. They are involved with collisions with semiconductor atoms and ionized atoms.

Drift current density and mobility

- Consider a volume of positive charge density R moving at an average drift velocity v_d. Then the drift current density is given by $J_{drf} = Rv_d$ (J has units of Amps/cm^2)
- If the volume charge density is due to holes, then $J_{h,drf} = (ep)v_{dh}$ **(1)**
- Equation of motion of a positively charged hole in an E-field is $F = m_h^* a = eE$
- Due to collisions with impurities and lattice, velocity of charged particles does not increase linearly with time.
- Hole accelerates due to E-field, collides, and looses at least most of its energy. It again accelerates and gains energy and is involved in another scattering process etc.
- Overall, the particle will gain an average drift velocity, which for low electric fields, is directly proportional to E

$$v_{dh} = \mu_h E$$

where μ is the proportionality factor **called the mobility** (units of cm^2 V^{-1} s^{-1}) – it describes how well a particle will move in an E-field

Drift current density and mobility

- By combining the above expression with (1) on previous slide

$$\longrightarrow J_{h,drf} = e\mu_h pE$$

i.e. Drift due to holes is in SAME direction as applied E-field

- Similarly, for electrons

$$J_{e,drf} = Rv_{de} = (-en)v_{de} \qquad v_{de} = -\mu_e E$$

$$J_{e,drf} = (-en)(-\mu_e E) = e\mu_e nE$$

Note: net motion of electron is opposite to E-field direction.

- Hence conventional drift current due to electrons is also in the **SAME** direction as applied E-field – even though movement is in the opposite direction

- Both electrons and holes contribute to drift current, hence total drift current density is

$$J_{drf} = e(\mu_e n + \mu_h p)E$$

Mobility

A dc electric field does not produce a steadily increasing current because of collisions with the lattice vibrations (phonons) and impurities/imperfections.

	μ_e ($cm^2 V^{-1} s^{-1}$)	μ_h ($cm^2 V^{-1} s^{-1}$)
Si	1350	480
GaAs	8500	400
Ge	3900	1900

Typical mobility values at 300K and low doping concentrations

We therefore write $m_h^*\left(\frac{d\mathbf{v}}{dt} + \frac{\mathbf{v}}{\tau_{ch}}\right) = e\mathbf{E}$

The effect of the second term in the bracket is to cause **v** to decay exponentially to zero with a time constant τ (mean time between collisions) when the field is removed.

v is the drift velocity i.e. the additional velocity associated with departure from thermal equilibrium given by the Fermi distribution function.

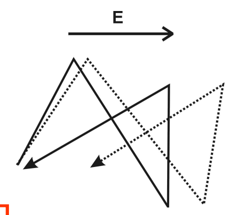
For a dc electric field only, the above equation has the steady-state solution (for holes)

$$\mathbf{v}_h = \frac{e\tau_{ch}}{m_h^*}\mathbf{E}$$

http://en.wikipedia.org/wiki/Drift_velocity

Mobility

- Solid lines shows random thermal velocity of a hole with zero E-field.
- Mean time between collisions is $\tau_{ch.}$
- Apply small E-field (dotted line) → net drift of hole in same direction as field.
- Hole mobility is therefore given by $$\mu_h = \frac{v_{dh}}{E} = \frac{e\tau_{ch}}{m_h^*}$$
- And similarly for electrons $$\mu_e = \frac{e\tau_{ce}}{m_e^*}$$
  (where τ_{ce} is the mean time between collisions for an electron)



- There are TWO collision (scattering) mechanisms that dominate in semiconductors:
  - **PHONON** or **LATTICE** scattering
  - **IONISED IMPURITY** scattering

Scattering Mechanisms

- For T > 0K, atoms of lattice have thermal energy that causes them to vibrate - disrupts perfectly periodic potential used in earlier analysis. Such a perfect periodicity would otherwise allow electrons to move unimpeded.
- Vibrations in lattice results in interactions between electron/hole and atoms – **"phonon scattering".** Scattering theory states, to 1st order, that $$\mu_L \propto T^{-3/2}$$
- Impurity atoms are ionised at room temperature so that a Coulomb interaction exists between electrons/holes and ionised impurities. It results in scattering, and also alters the velocity characteristics of the charge carriers. To first order:

  (where $N_I = N_d^+ + N_a^-$ is the total ionised impurity concentration) $$\mu_I \propto \frac{T^{+3/2}}{N_I}$$
- i.e. *For lattice scattering:* the probability of scattering occurring increases as temperature increases, and therefore mobility decreases .
- And, for *ionised impurity scattering:* If T goes up, the random thermal velocity of a carrier increases, reducing the time the carrier spends in the vicinity of the Coulomb force, reducing the scattering effect and increasing the mobility. If N_I goes up, then probability of scattering also goes up, and value of μ_I goes down.

Mobility

- If τ_L is mean time between collisions due to lattice scattering, then dt / τ_L is the probability of a lattice scattering event occurring in time *dt*. Similarly for ionised impurity scattering τ_I.

- If the two scattering processes are independent, then the total probability of a scattering event occurring in time *dt* is the sum of the individual events *i.e.*

$$\frac{dt}{\tau} = \frac{dt}{\tau_I} + \frac{dt}{\tau_L} \qquad \text{(Matthiessen's Rule)}$$

- Hence, comparing this with equations on slide 15.5 →

$$\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}$$ where μ is the net mobility.