

# **Lecture 7**

## **Drift and Diffusion Currents**

**Reading:**

**Pierret 3.1-3.2**

# Ways Carriers (electrons and holes) can change concentrations

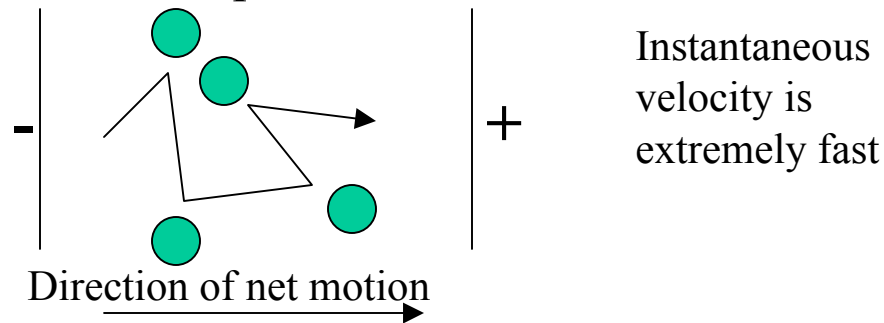
- Current Flow:
  - Drift: charged particle motion in response to an electric field.
  - Diffusion: Particles tend to spread out or redistribute from areas of high concentration to areas of lower concentration
- Recombination: Local annihilation of electron-hole pairs
- Generation: Local creation of electron-hole pairs

# Drift

- Direction of motion:

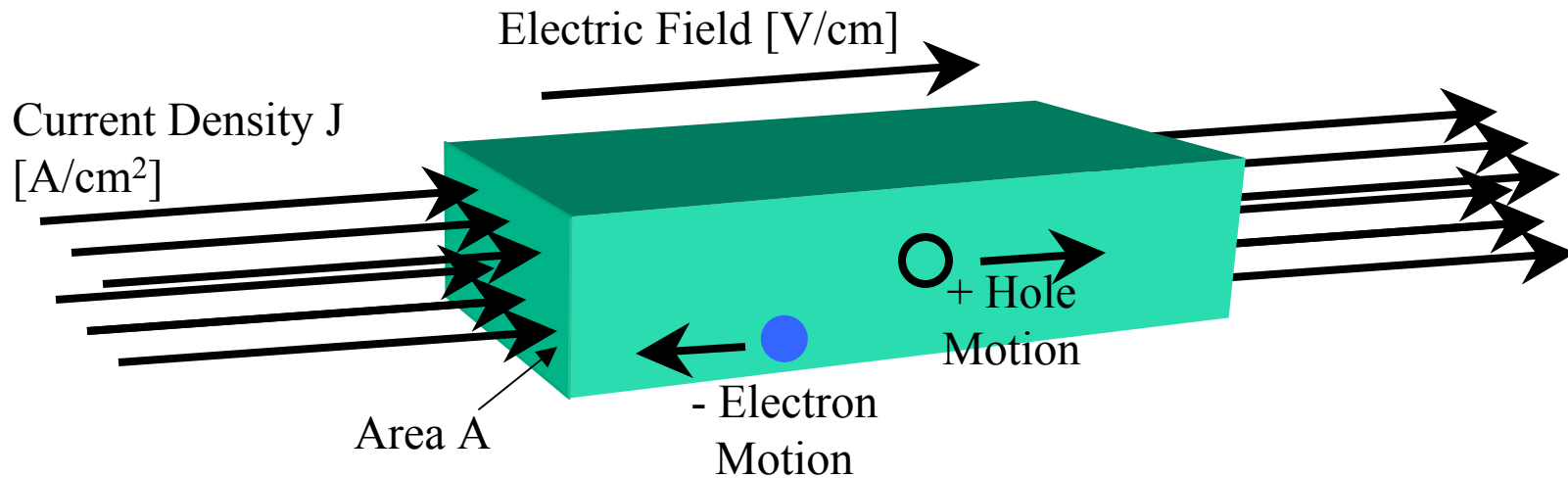
- Holes move in the direction of the electric field (from + to -)
- Electrons move in the opposite direction of the electric field (from - to +)

- Motion is highly non-directional on a local scale, but has a net direction on a macroscopic scale



- Average net motion is described by the drift velocity,  $v_d$  with units cm/second
- Net motion of charged particles gives rise to a current

# Drift



Given current density  $J$  ( $I=J \times \text{Area}$ ) flowing in a semiconductor block with face area  $A$  under the influence of electric field  $E$ , the component of  $J$  due to drift of carriers is:

$$J_p|_{\text{Drift}} = q p v_d \quad \text{and} \quad J_n|_{\text{Drift}} = q n v_d$$

Hole Drift current density

Electron Drift current density

# Drift

At low electric field values,

$$J_p = qp\mu_p E \quad \text{and} \quad J_n = qn\mu_n E$$

$\mu$  is the “mobility” of the semiconductor and measures the ease with which carriers can move through the crystal.  $[\mu]=\text{cm}^2/\text{V-Second}$

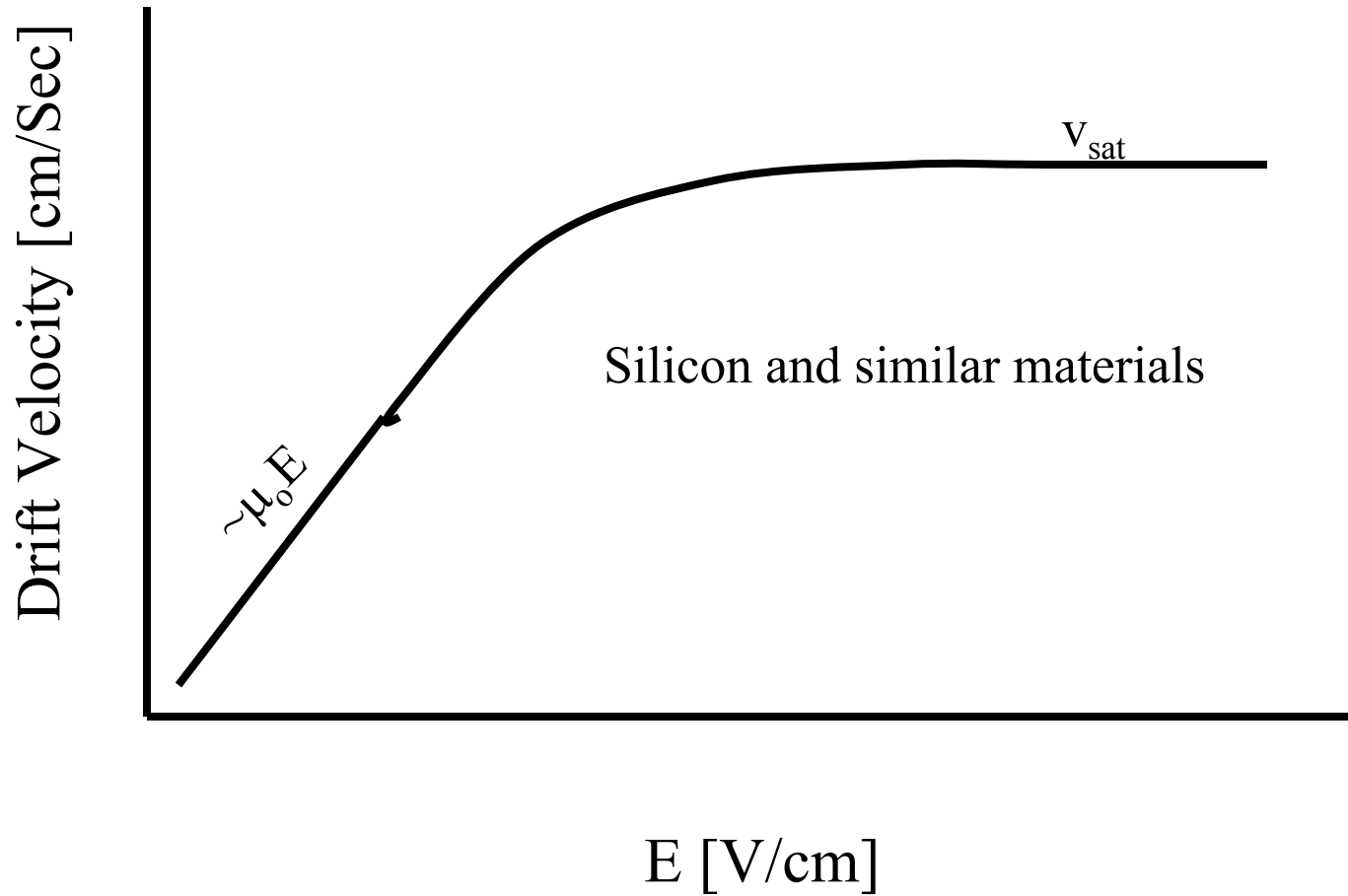
Thus, the drift velocity increases with increasing applied electric field.

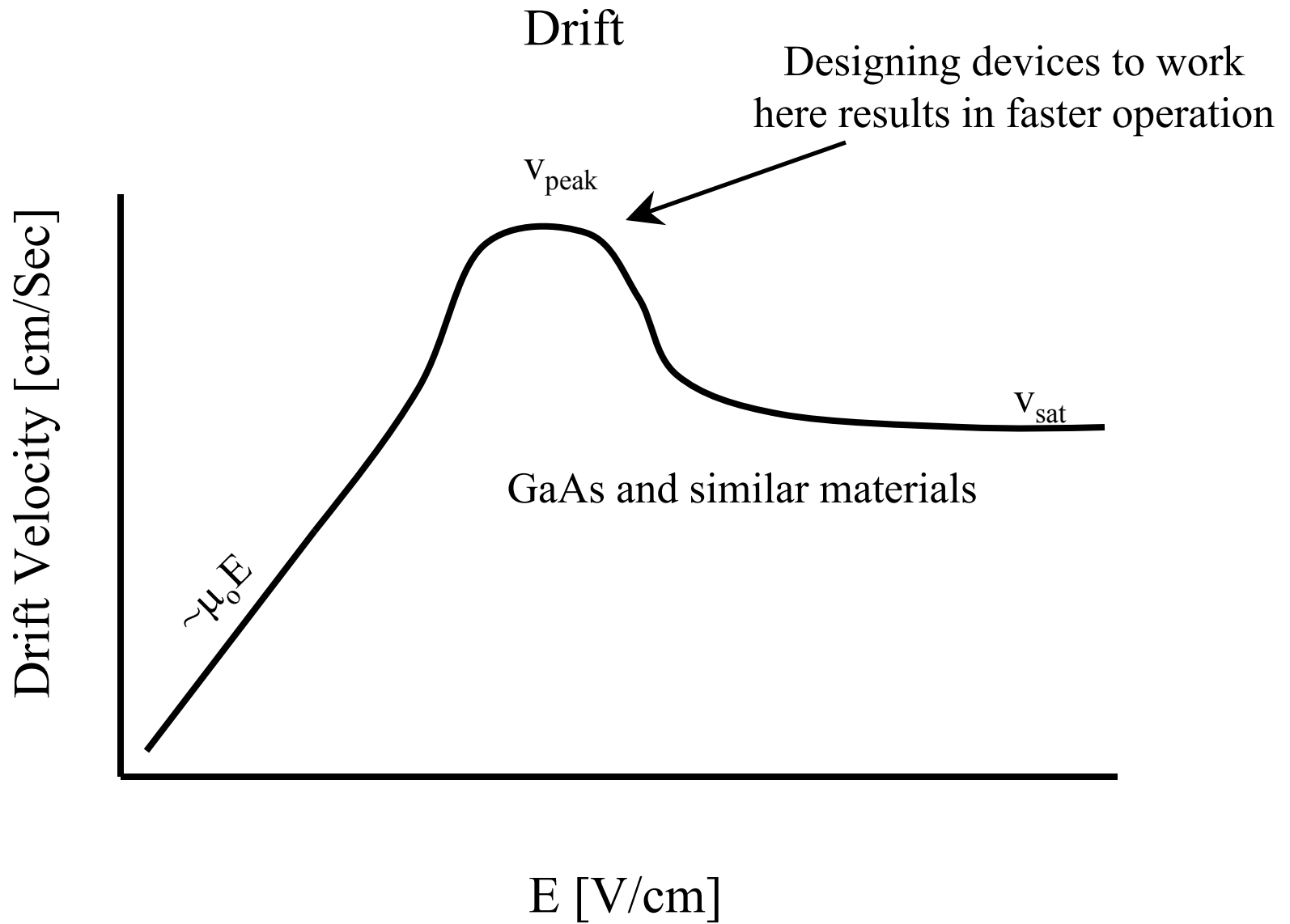
More generally, for Silicon and Similar Materials the drift velocity can be empirically given as:

$$v_d = \frac{\mu_o E}{\left[ 1 + \left( \frac{\mu_o E}{v_{sat}} \right)^\beta \right]^{1/\beta}} \cong \begin{cases} \mu_o E & \text{when } E \rightarrow 0 \\ v_{sat} & \text{when } E \rightarrow \infty \end{cases}$$

where  $v_{sat}$  is the saturation velocity

# Drift





# Drift

## Mobility

$\mu$  is the “mobility” of the semiconductor and measures the ease with which carriers can move through the crystal.  $[\mu] = \text{cm}^2/\text{V}\cdot\text{Second}$

$\mu_n \sim 1360 \text{ cm}^2/\text{V}\cdot\text{Second}$  for Silicon @ 300K

$\mu_p \sim 460 \text{ cm}^2/\text{V}\cdot\text{Second}$  for Silicon @ 300K

$\mu_n \sim 8000 \text{ cm}^2/\text{V}\cdot\text{Second}$  for GaAs @ 300K

$\mu_p \sim 400 \text{ cm}^2/\text{V}\cdot\text{Second}$  for GaAs @ 300K

$$\mu_{n,p} = \frac{q \langle \tau \rangle}{m_{n,p}^*}$$

Where  $\langle \tau \rangle$  is the average time between “particle” collisions in the semiconductor.

Collisions can occur with lattice atoms, charged dopant atoms, or with other carriers.



# Resistivity and Conductivity

Ohms Law States:  $J = \sigma E = E/\rho$

where  $\sigma$  =conductivity [1/ohm-cm] and  $\rho$ =resistivity [ohm-cm]

Adding the electron and hole drift currents (at low electric fields),

$$J = J_p|_{\text{Drift}} + J_n|_{\text{Drift}} = q(\mu_n n + \mu_p p)E$$

Thus,

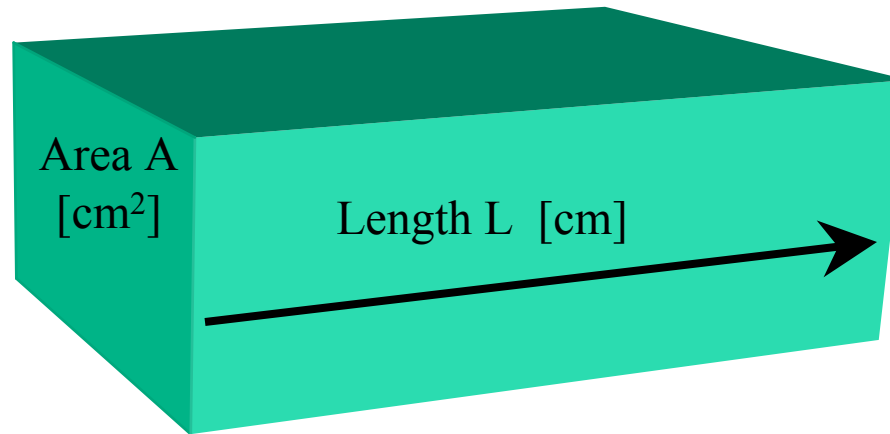
$$\sigma = q(\mu_n n + \mu_p p) \text{ and } \rho = 1/[q(\mu_n n + \mu_p p)]$$

But since  $\mu_n$  and  $\mu_p$  change very little and  $n$  and  $p$  change several orders of magnitude:

$$\sigma \sim q\mu_n n \text{ for n-type with } n \gg p$$

$$\sigma \sim q\mu_p p \text{ for p-type with } p \gg n$$

# Do not confuse Resistance and Resistivity or Conductance and Conductivity



Resistance to current flow along length L (I.e. the electric field is applied along this samples length).

$$R = \rho L / A \quad \text{or in units, } [\text{ohm-cm}][\text{cm}] / [\text{cm}^2] = [\text{ohms}]$$

# Energy Band Bending under Application of an Electric Field

Energy Band Diagrams represent the energy of an electron.

When an electric field is applied, energies become dependent on their position in the semiconductor.

If only energy  $E_g$  is added, then all energy would go to generating the electron and hole pair.  $\rightarrow$  No energy left for electron/hole motion. (I.e the electron only has potential energy, and no kinetic energy).

If energy  $E > E_g$  is added, then the excess energy would allow electron/hole motion. (Kinetic energy).

$$\text{KE of electrons} = E - E_c \text{ for } E > E_c$$

$$\text{KE of holes} = E_v - E \text{ for } E < E_v$$

# Energy Band Bending under Application of an Electric Field

“Elementary” physics says that...

$$PE = -qV,$$

where PE = potential energy, q=electron charge and V=electrostatic potential

But we can also say that  $PE = E_c - E_{\text{arbitrary fixed Reference}}$  Or...

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

“Elementary” physics says that...  $E = -\nabla V$

or

$$E = -\frac{dV}{dx} \text{ in one direction}$$

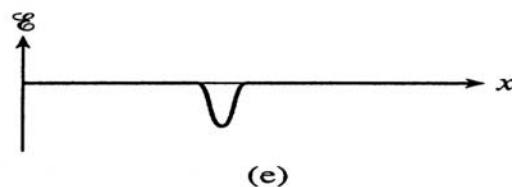
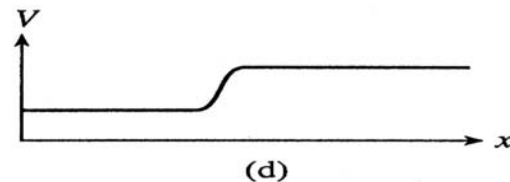
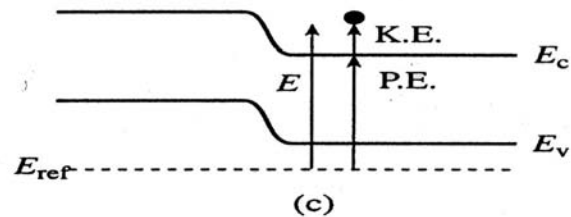
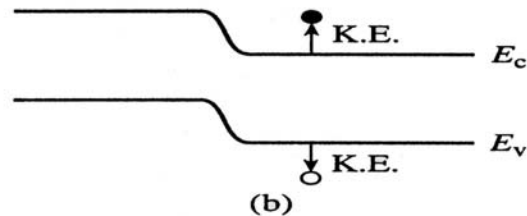
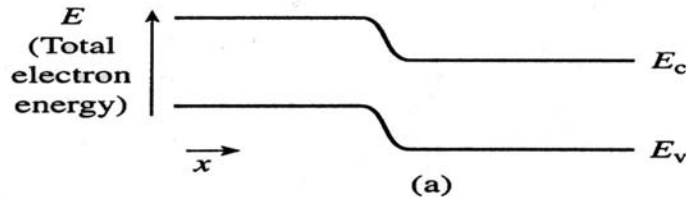
Thus,

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

If an electric field exists in the material, the conduction, valence and intrinsic energies will vary with position!

# Energy Band Bending under Application of an Electric Field

## Band Bending

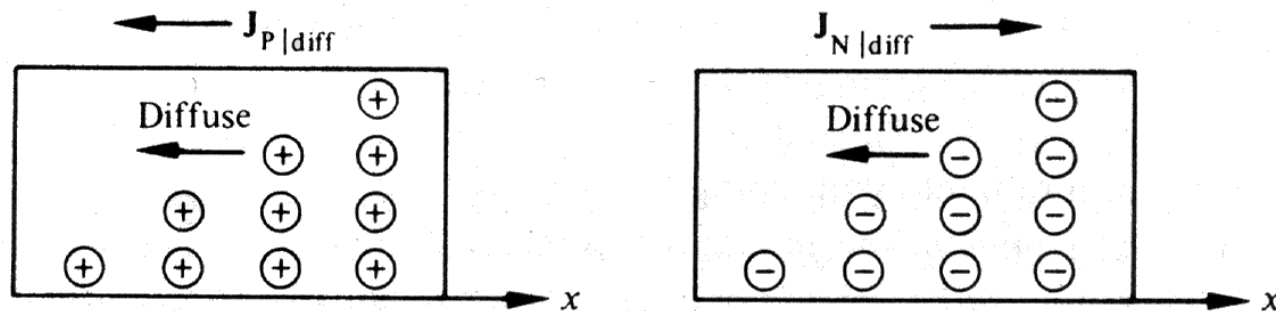


# Diffusion

Nature attempts to reduce concentration gradients to zero.

Example: a bad odor in a room.

In semiconductors, this “flow of carriers” from one region of higher concentration to lower concentration results in a “diffusion current”.



**Figure 3.12** Visualization of electron and hole diffusion on a macroscopic scale.

# Diffusion

Ficks law describes diffusion as the flux,  $F$ , (of particles in our case) is proportional to the gradient in concentration.

$$F = -D\nabla \eta$$

*where  $\eta$  is the concentration and  $D$  is the diffusion coefficient*

Derivation of Ficks Law at <http://users.ece.gatech.edu/~gmay/ece3040> lecture #8

For electrons and holes, the diffusion current density (flux of particles times  $-/+q$ ) can thus, be written as,

$$J_p |_{Diffusion} = -qD_p \nabla p \quad \text{or} \quad J_n |_{Diffusion} = qD_n \nabla n$$

Note in this case, the opposite sign for electrons and holes

# Total Current

*Since...*

$$J_p = J_p |_{\text{Drift}} + J_p |_{\text{Diffusion}} = q\mu_p pE - qD_p \nabla p$$

*and*

$$J_n = J_n |_{\text{Drift}} + J_n |_{\text{Diffusion}} = q\mu_n nE + qD_n \nabla n$$

*and*

$$J = J_p + J_n$$