Lecture 7

Drift and Diffusion Currents

Reading:

Notes and Anderson[2] sections 3.1-3.4

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

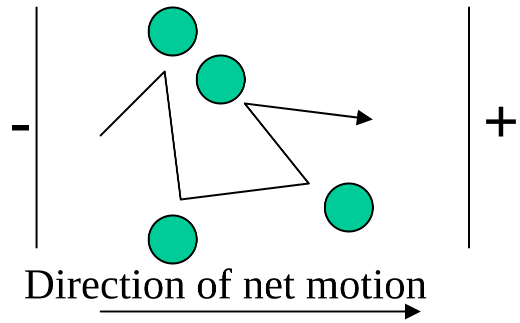
Drift

•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

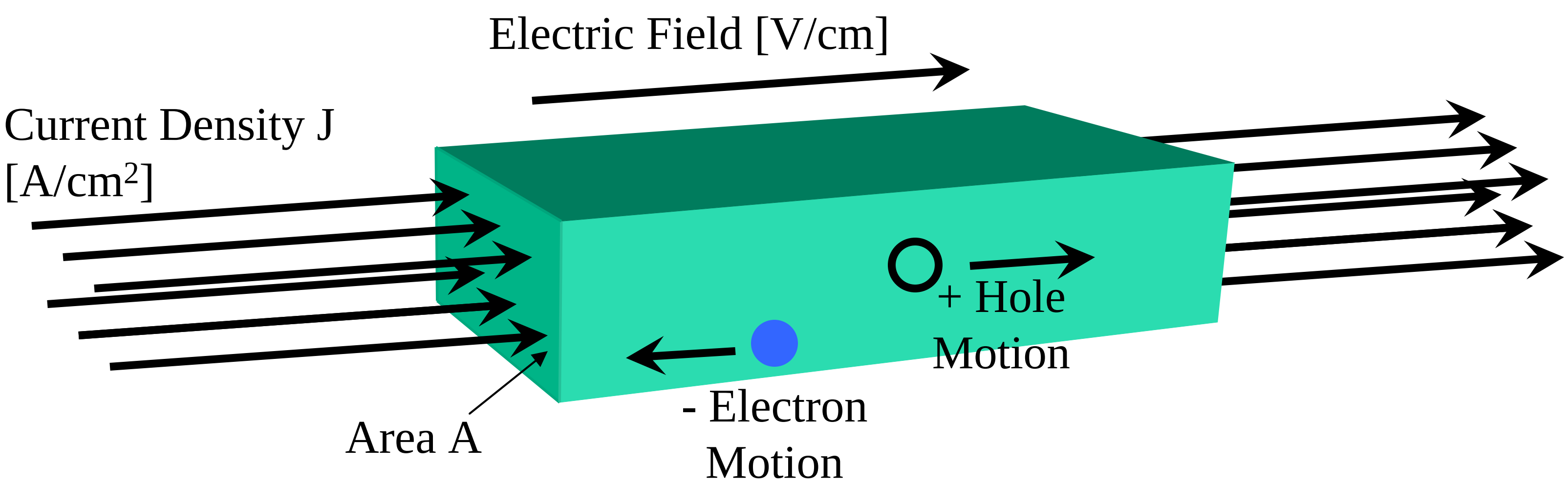


Instantaneous velocity is extremely fast

•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 x 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:

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

Hole Drift current density

Electron Drift current density

Drift

At low electric field values,

$J_p = qp\mu_p E$ and $J_n = qn\mu_n E$

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

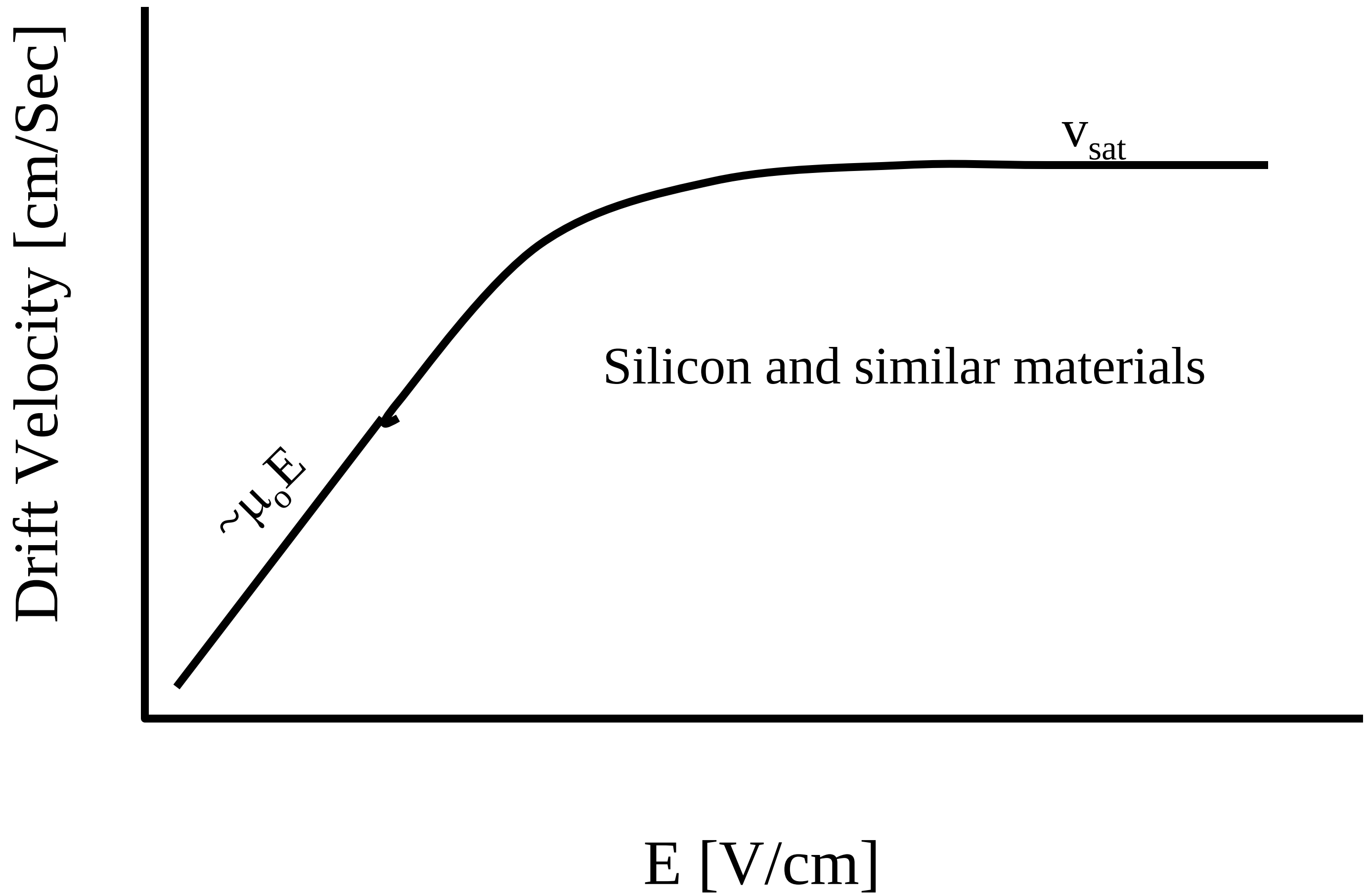
Thus, the drift velocity increases with increasing applied electric field.

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

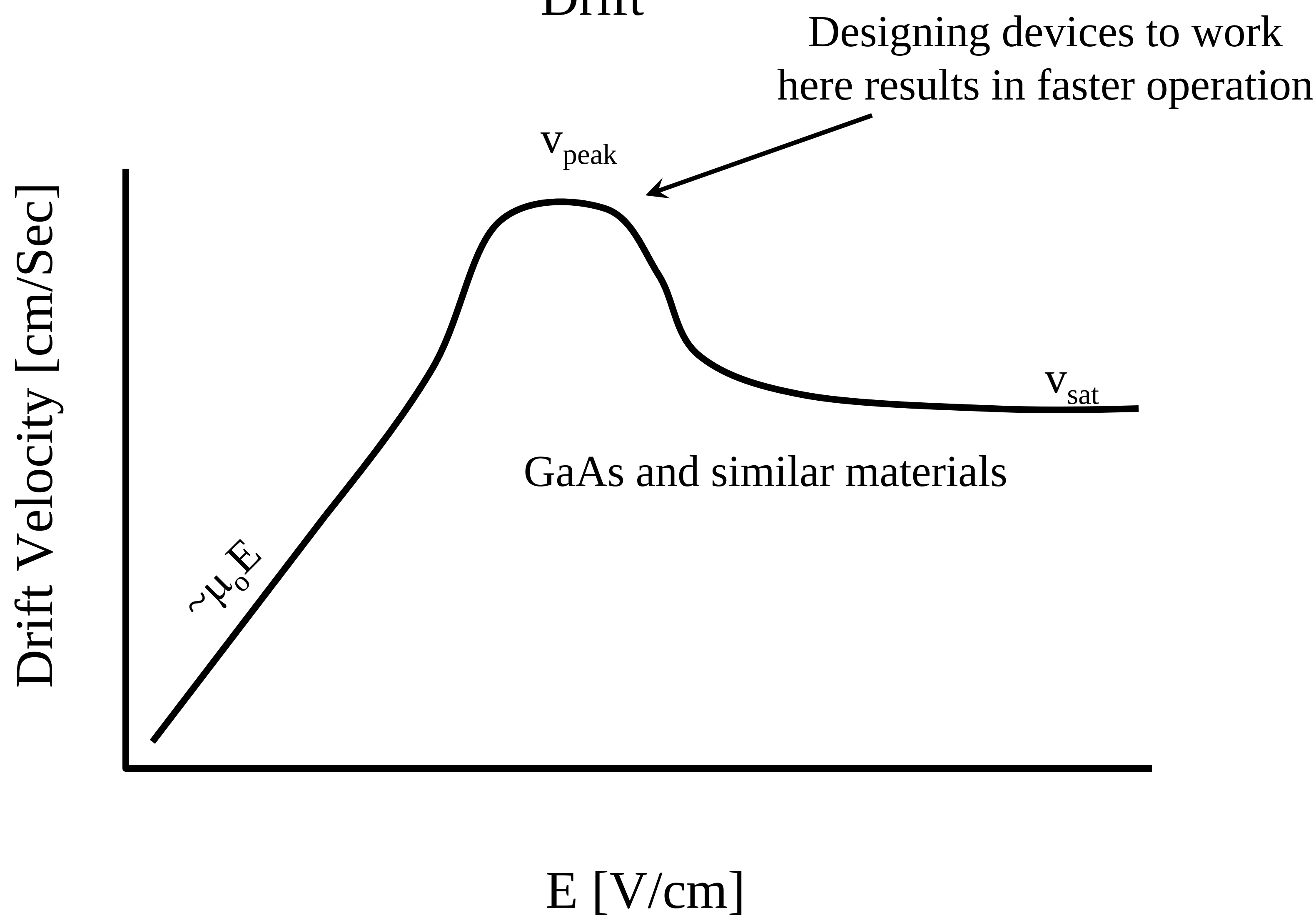
$$v_d = \frac{\mu_o E}{\left[1+\left(\frac{\mu_o E}{v_{sat}}\right)^{\beta}\right]^{1/\beta}} \cong \begin{cases} \mu_o E & when\ E \to 0 \\ v_{sat} & when\ E \to \infty \end{cases}$$

where v_{sat} is the saturation velocity

Drift


Drift Velocity [cm/Sec]
v_{sat}
Silicon and similar materials
$\sim\mu_o E$
E [V/cm]

Drift


Designing devices to work
here results in faster operation
v_{peak}
v_{sat}
GaAs and similar materials
$\sim\mu_o E$
Drift Velocity [cm/Sec]
E [V/cm]

Drift

Mobility

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

μ_n~1360 cm^2/V-Second for Silicon @ 300K

μ_p~460 cm^2/V-Second for Silicon @ 300K

μ_n~8000 cm^2/V-Second for GaAs @ 300K

μ_p~400 cm^2/V-Second for GaAs @ 300K

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

Where <τ> 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 σ =conductivity [1/ohm-cm] and ρ=resistivity [ohm-cm]

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

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

Thus,

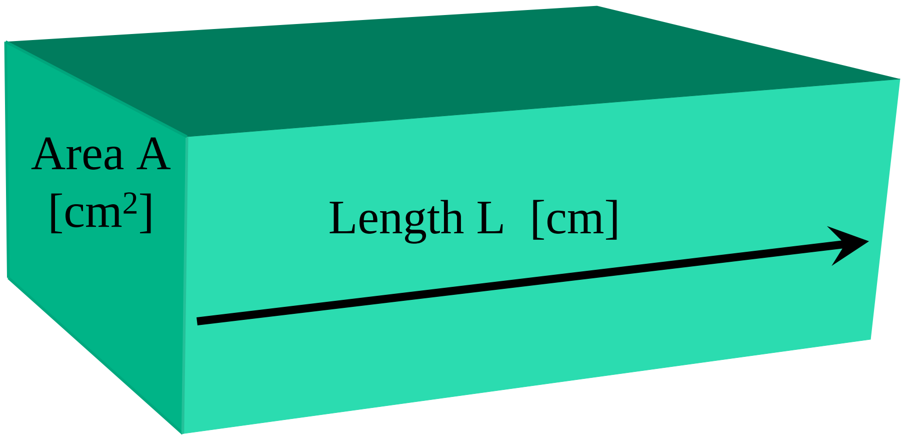
$$\boxed{\sigma = q(\mu_n n + \mu_p p) \text{ and } \rho=1/[q(\mu_n n + \mu_p p)]}$$

But since μ_n and μ_p change very little and n and p change several orders of magnitude:

$\sigma \sim= q\mu_n n$ for n-type with n>>p

$\sigma \sim= q\,\mu_p p$ for p-type with p>>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).

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

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).

KE of electrons = $E-E_c$ for $E>E_c$

KE of holes = E_v-E 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…

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

"Elementary" physics says that… $E = -\nabla V$

$$or$$

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

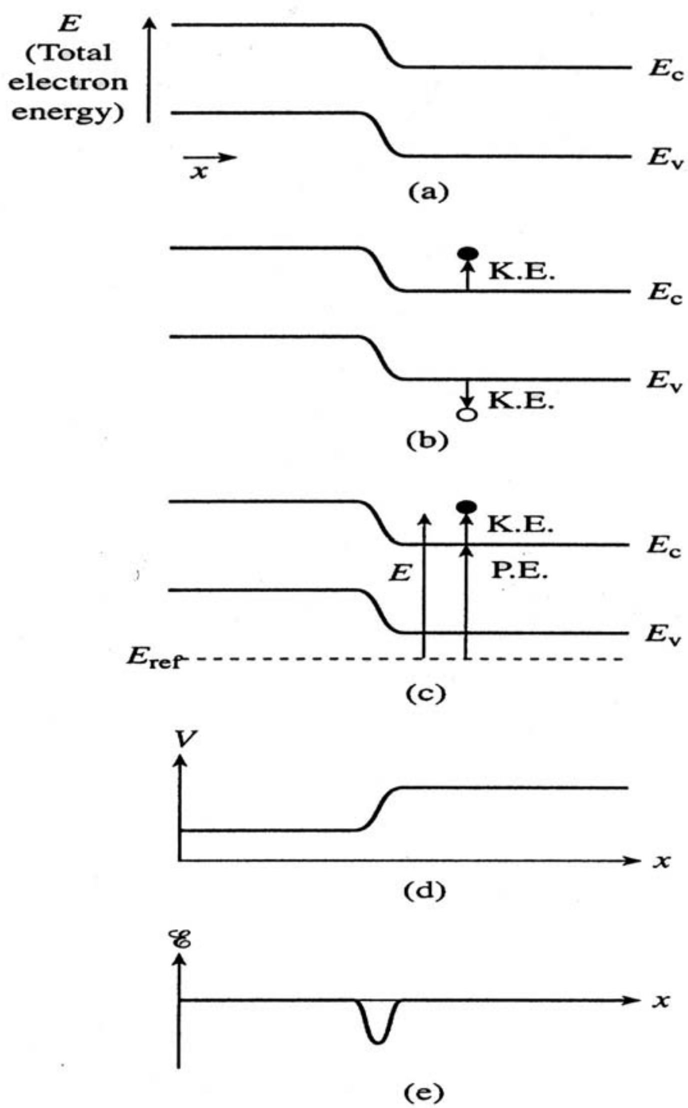
$$Thus,$$

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

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



(a) Sample energy band diagram;

(b) Carrier kinetic energies;

(c) Electronic potential energy;

(d) Potenital;

(e) Electric field.

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".

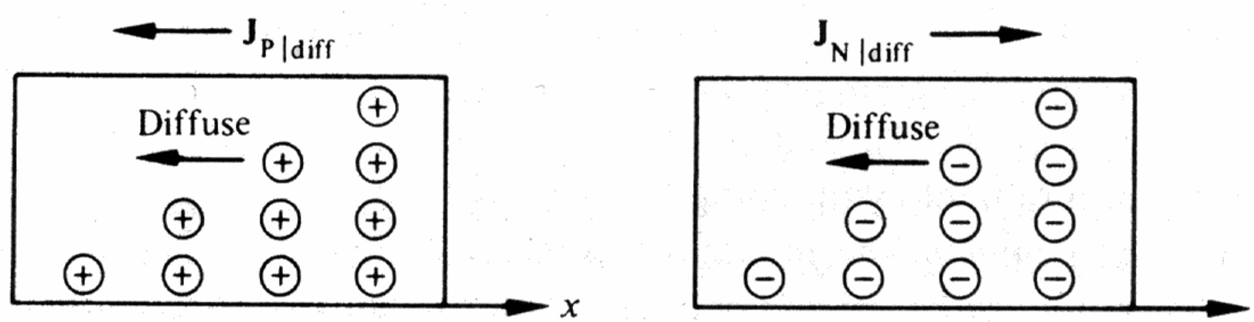


Figure 3.12 Visualization of electron and hole diffusion on a macroscopic scale.

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 η *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,

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

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

Total Current

Since...

$$\boxed{\begin{aligned} &J_p = J_p\,|_{Drift} + J_p\,|_{Diffusion} = q\mu_p pE - qD_p\nabla p \\ &and \\ &J_n = J_n\,|_{Drift} + J_n\,|_{Diffusion} = q\mu_n nE + qD_n\nabla n \\ &and \\ &J = J_p + J_n \end{aligned}}$$