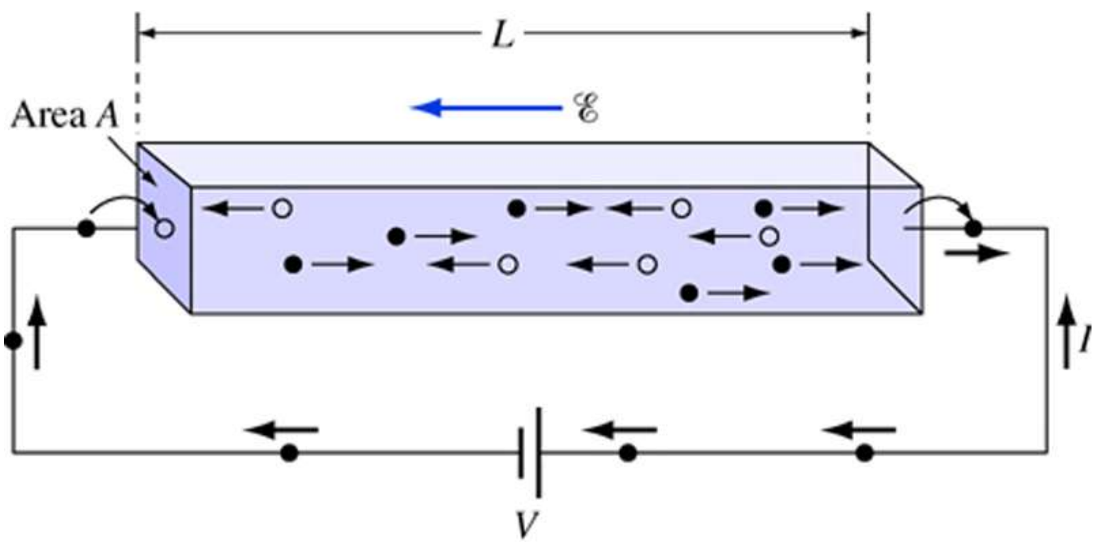
Moving Charge Carriers

Electron mobility

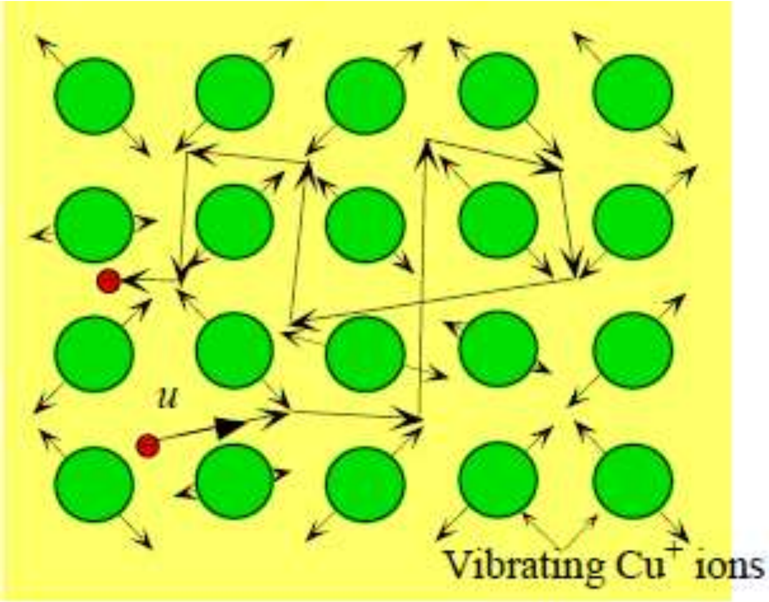
- In solid-state physics, the **electron mobility** characterizes how quickly an electron can move through a metal or semiconductor, when pulled by an electric field.
- In semiconductors, there is an analogous quantity for holes, called **hole mobility**.
- The term **carrier mobility** refers in general to both electron and hole mobility in semiconductors.

How carrier moves…

- When a voltage is applied to a sample, an electric field is induced. This forces a movement in both the electrons and the holes.



Electron movement



In the absence of any electric field, An electron moves about randomly in a metal, obeying the laws of Brownian motion. That is, they just jitter around.

Brownian motion

- At finite temperature, the kinetic energy of a sample is equal to its thermal energy.
- $\frac{1}{2} m v^2 = \frac{1}{2} K_B T$

  where

  K is Boltzman constant at T=300K

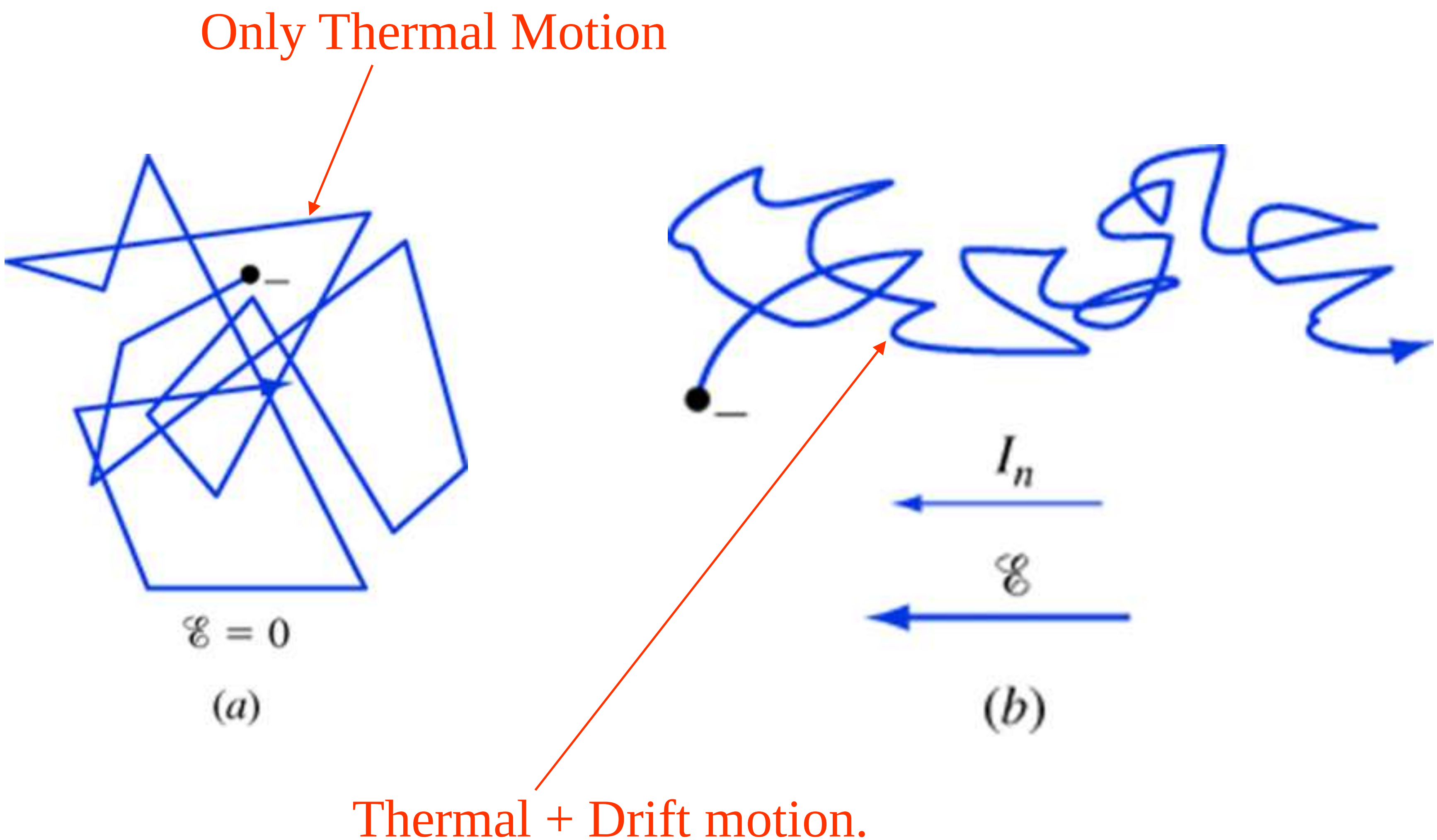
  $K_B T = 25$ meV
- This is very small amount of energy, but if we multiply with an electron’s mass, we get…

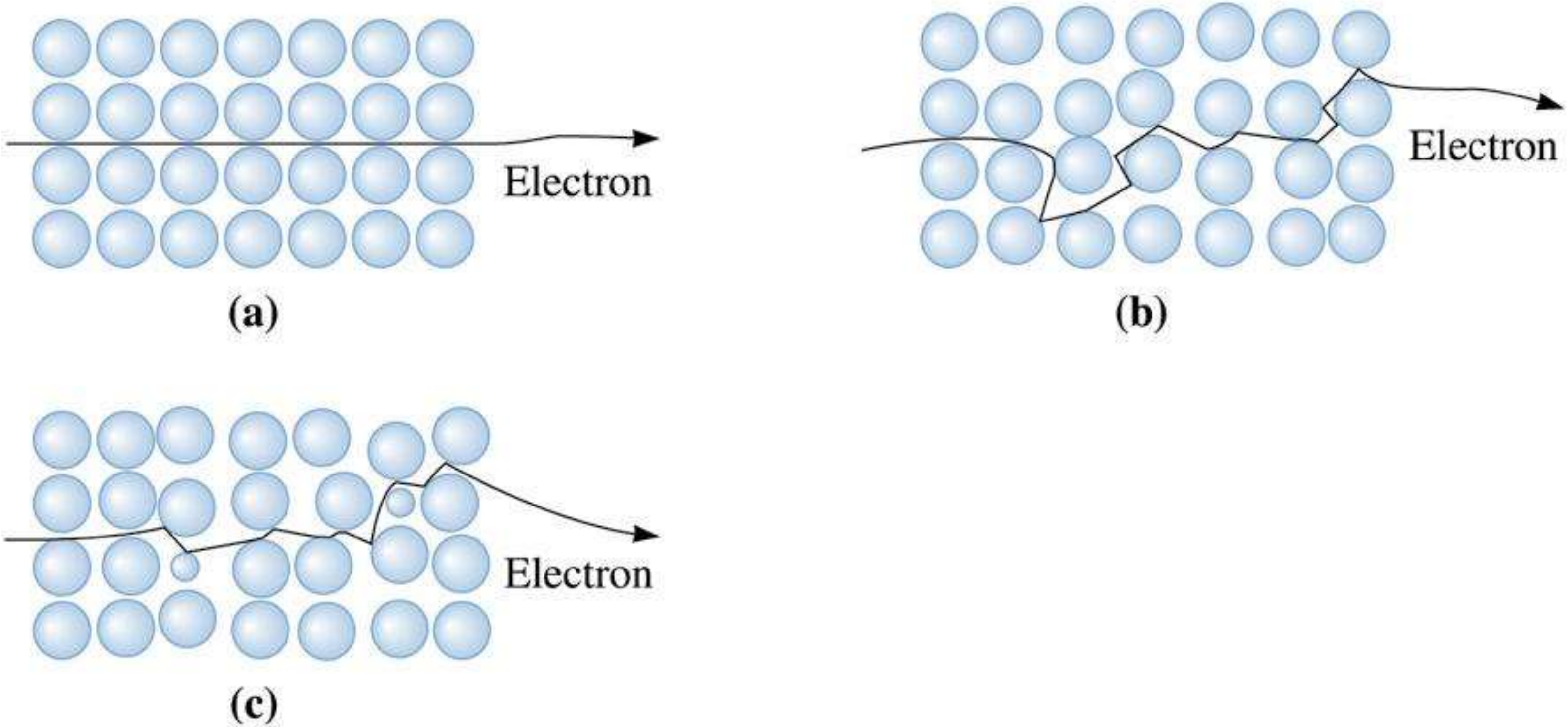
  $v = 10^7$cm/sec approx

The motion of an electron in a crystal. The electron changes direction randomly whenever it makes a collision.

(a) Under no applied field there is no net progress in any particular direction.

(b) When a field is applied, the electron tends to drift in some particular direction. A trajectory such as this would be found only under very high fields.

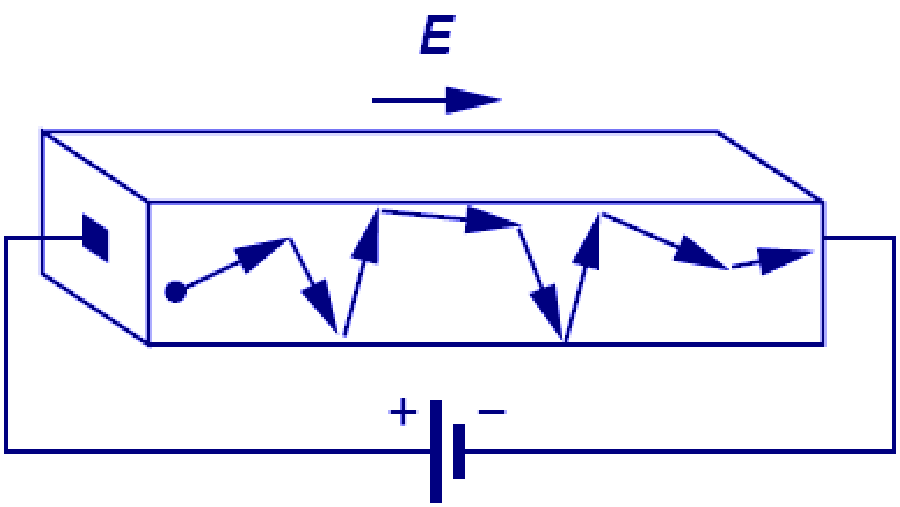




Movement of an electron through
(a) a perfect crystal
(b) a crystal heated to a high temperature
(c) a crystal containing atomic level defects. Scattering of the electrons reduces the mobility and conductivity.

Carrier Drift

- The process in which charged particles move because of an electric field is called ***drift***.
- Charged particles within a semiconductor move with an average velocity proportional to the electric field.
  - The proportionality constant is the carrier ***mobility***.



Hole velocity $\vec{v}_h = \mu_p \vec{E}$

Electron velocity $\vec{v}_e = -\mu_n \vec{E}$

<u>Notation</u>:
$\mu_p \equiv$ hole mobility (cm^2/V·s)
$\mu_n \equiv$ electron mobility (cm^2/V·s)

μ_p vs μ_n

- For Si:

$$\mu_p = 480\ cm^2/v.s$$

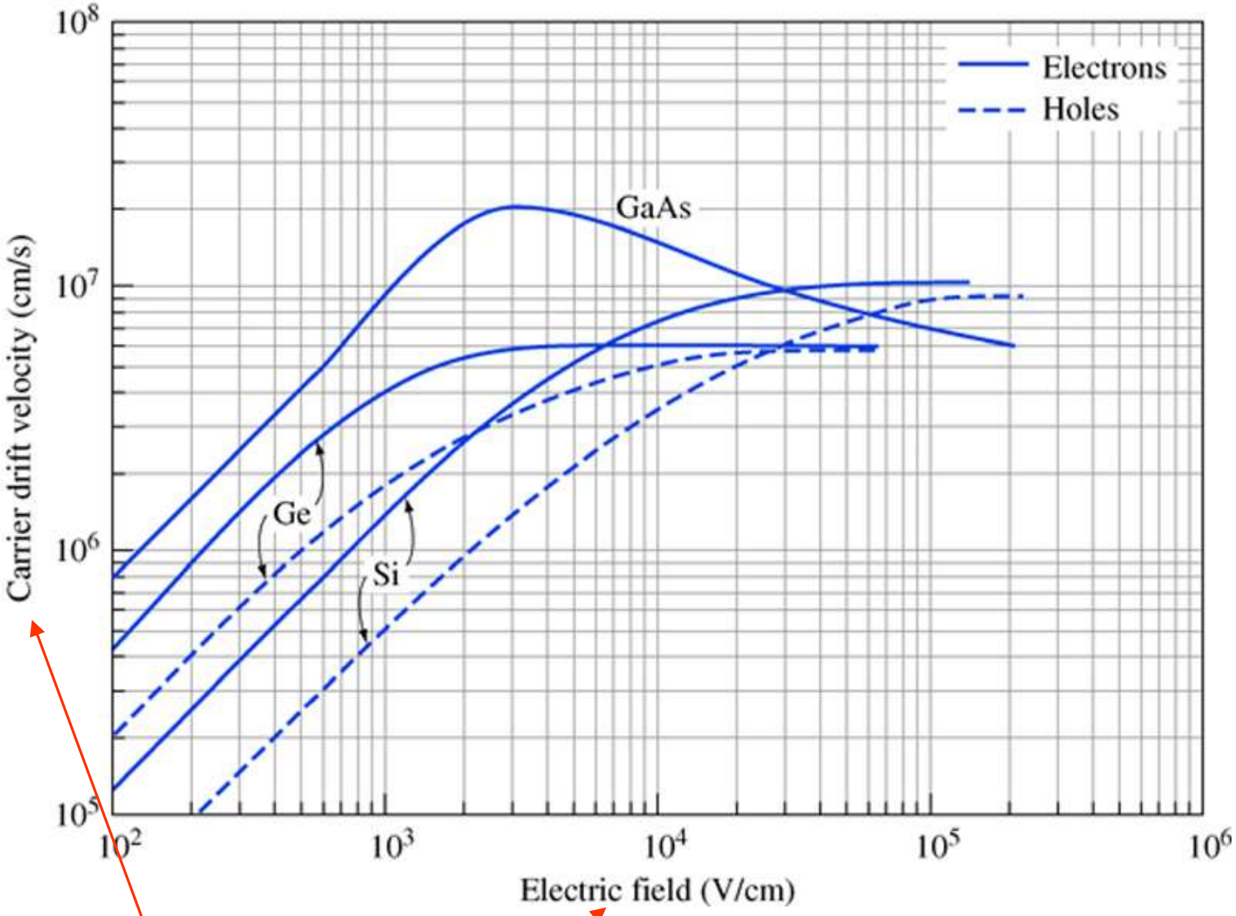
$$\mu_n = 1350\ cm^2/v.s$$

So……

$\mu_n = 2.5\ \mu_p$

The experimentally measured dependence of the drift velocity on the applied field.

At room temperature

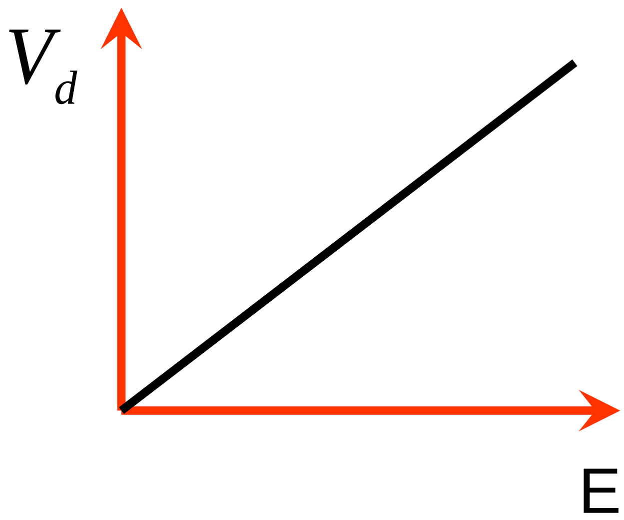


$$\upsilon_{drift} = \mu E$$

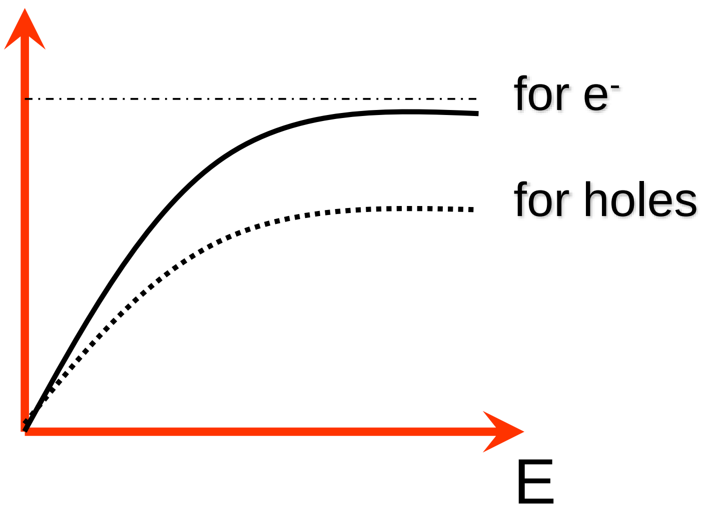
Saturated Drift Velocities

$$V_d = \mu E$$

So one can make a carrier go as fast as we like just by increasing the electric field!!!



(a) Implication of above eqn.



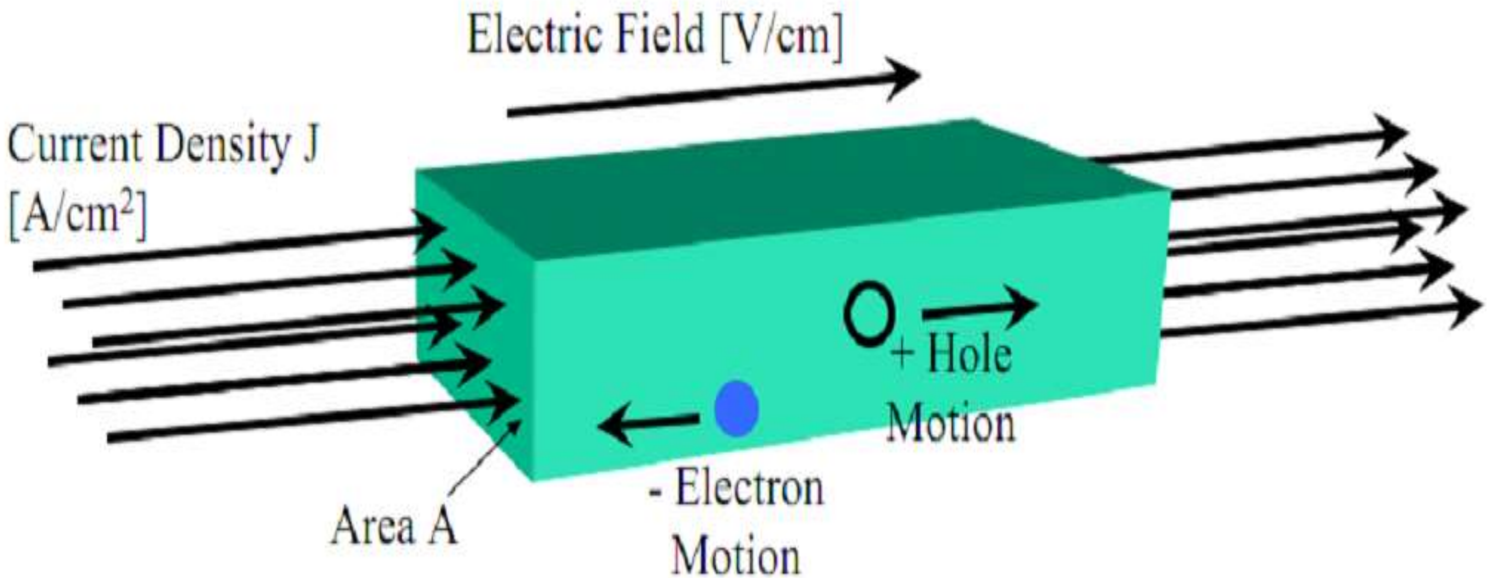
(b) Actual drift velocity

Saturated Drift Velocities

- The equation of $V_d = \mu.E$ does not imply that $\mathbf{V_d}$ increases linearly with applied field **E.**

- $\mathbf{V_d}$ increases linearly for low values of **E** and then it saturates at some value of $\mathbf{V_d}$ which is close $\mathbf{V_{th}}$ at higher values of **E**.

- Any further increase in **E** after saturation point does not increase $\mathbf{V_d}$, instead it warms up the crystal.



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 Current Equations

For undoped or intrinsic semiconductor ;

For electron

$$J_n = nqE\mu_n$$

drift current for electrons

number of free electrons per unit volume

mobility of electron

For hole

$$J_p = pqE\mu_p$$

drift current for holes

number of free holes per unit volume

mobility of holes

Conductivity and Resistivity

$$J_{p,drift} = qp\mu_p E \qquad J_{n,drift} = -qn(-\mu_n E)$$

$$J_{tot,drift} = J_{p,drift} + J_{n,drift} = qp\mu_p E + qn\mu_n E$$

$$J_{tot,drift} = q(p\mu_p + n\mu_n)E \equiv \sigma E$$

- The ***conductivity*** of a semiconductor is $\boxed{\sigma \equiv qp\mu_p + qn\mu_n}$
  - Unit: 1/ohm-cm
- The ***resistivity*** of a semiconductor is $\rho \equiv \dfrac{1}{\sigma}$
  - Unit: ohm-cm

Diffusion current

- Diffusion : Nature attempts to reduce concentration gaps to zero.

  e.g. spreading of drop of ink in water.
- In semiconductors, this “flow of carriers” from one region of higher concentration to lower concentration results in a “diffusion current”.

Diffusion Current

- Diffusion current density =charge × carrier flux

$$J_n^{diff} = qD_n \frac{dn}{dx}$$

$$J_p^{diff} = -qD_p \frac{dp}{dx}$$

Where D_p is the diffusion constant. For holes and electrons diffusing in intrinsic Si, typical values would be D_p=12cm^2/sec and D_n=34cm^2/sec.

❖ Total Current Density

When both an electric field and a concentration gap is present, the total current density becomes;

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

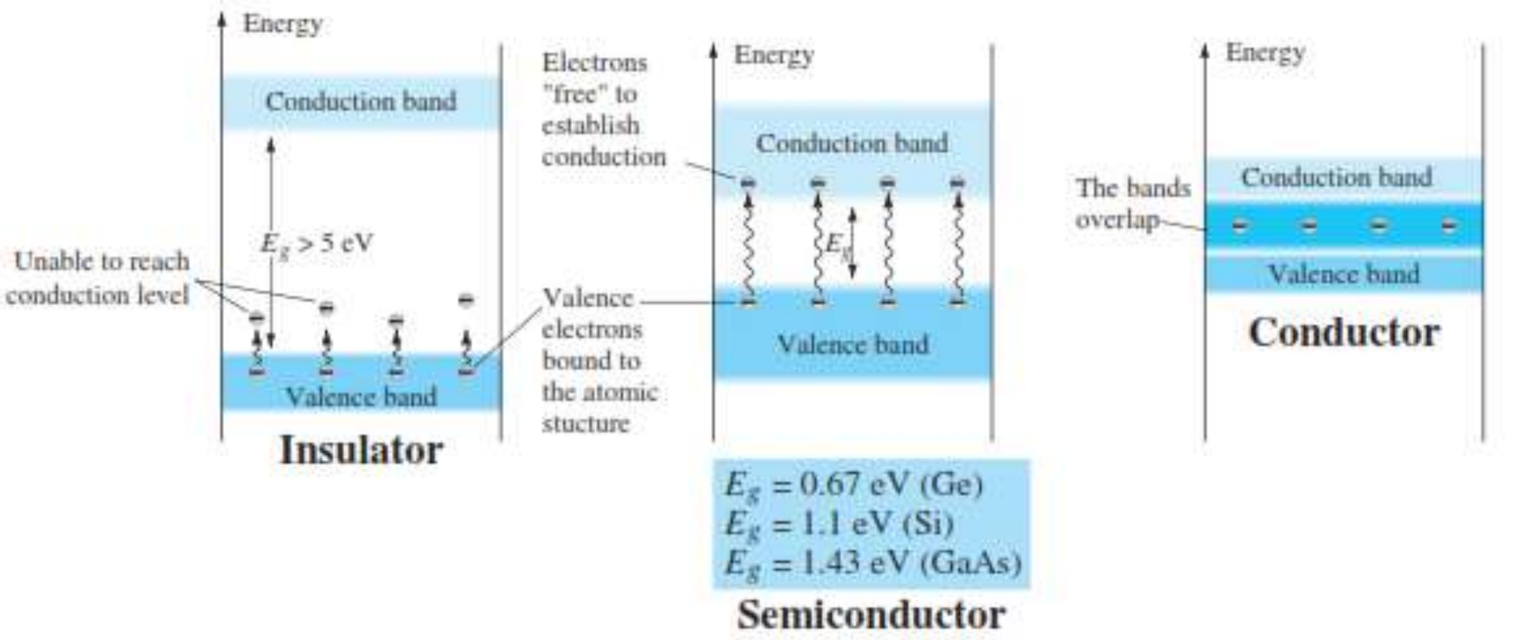
$$J_p = q\mu_p pE - qD_p \frac{dp}{dx}$$

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

Diffusion current versus drift current

Diffusion current	Drift current
(WHEN). Diffusion current occurs even though there isn't an electric field applied to the semiconductor .	Drift current depends on the electric field applied on the p-n junction diode.
(WHY) It depends on constants Dp and Dn, and +q and -q, for holes and electrons respectively but it is independent of permittivity.	It depends upon permittivity.
(WHERE) Direction of the diffusion current depends on the change in the carrier concentrations.	Direction of the drift current depends on the polarity of the applied field.

Energy Levels



The farther an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.