# Semiconductor Fundamentals – (III)

2.5 Boltzmann approximation & $E_F$, n, p

2.6 Carrier drift and diffusion

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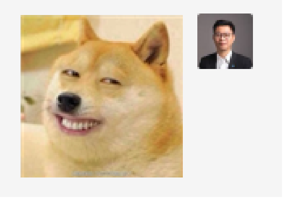
# Semiconductor Fundamentals – (III)

**2.5 Boltzmann approximation & $E_F$, n, p**

2.6 Carrier drift and diffusion



# Last lecture:

- **Negative charges**:
  - Conduction electrons (density = $\boldsymbol{n}$) mobile
  - Ionized acceptor atoms (density = $N_A^-$) immobile
- **Positive charges**:
  - Holes (density = $\boldsymbol{p}$) mobile
  - Ionized donor atoms (density = $N_D^+$) immobile
- The net charge density (C/cm$^3$) in a semiconductor is

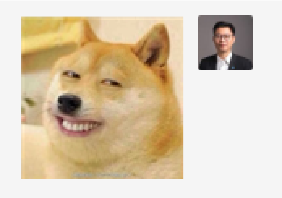
$$\rho = q(p - n + N_D^+ - N_A^-)$$

- Law of Mass Action: $n \times p = n_i^2$

How to deduce the relationship between $E_F$ and n/p?

# **2.5** Boltzmann approximation & $E_F$, n, p

- **Fermi function and Fermi level**



- Density of States
- Boltzmann Approximation
- Electron and Hole Concentrations

# Thermal Equilibrium

- **No external forces** are applied:
  - electric field = 0, magnetic field = 0
  - mechanical stress = 0
  - no light

- **Dynamic situation** in which every process is **balanced** by its **inverse process**
  - Electron-hole pair (EHP) generation rate = EHP recombination rate

- **Thermal agitation** → electrons and holes exchange energy with the crystal lattice and each other

→ Every energy state in the conduction band and valence band has a certain probability of being occupied by an electron

# Statistical Thermodynamics: Fermi energy

- The Fermi energy, $E_F$, is the energy associated with a particle, which is in thermal equilibrium with the system of interest. The energy is strictly associated with the particle and does not consist even in part of heat or work. This same quantity is called the electro-chemical potential, m, in most thermodynamics texts.

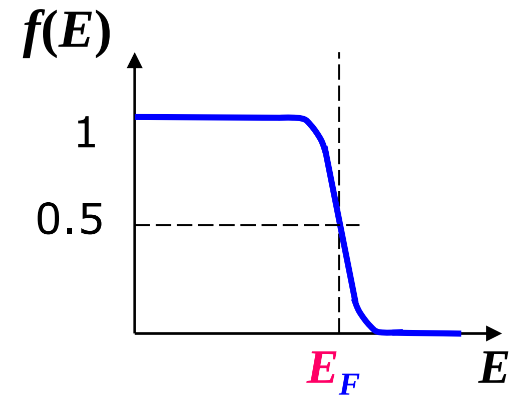
- http://hyperphysics.phy-astr.gsu.edu/Hbase/solids/fermi.html#c2
- http://hyperphysics.phy-astr.gsu.edu/Hbase/solids/fermi.html#c1

# Fermi function and Fermi level

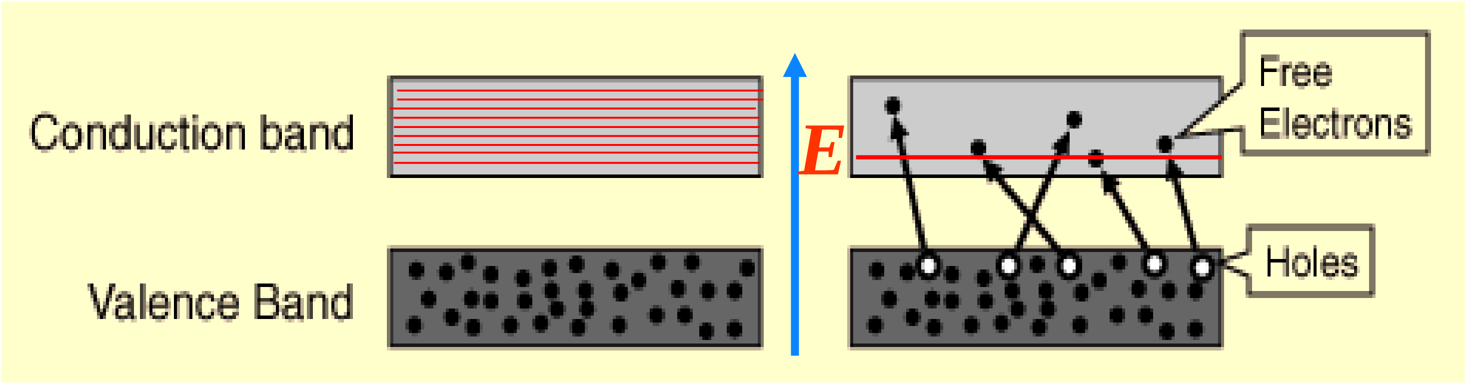
**PL**

- **Probability** that a **state** at energy level, $E$, is occupied by one electron is,

$$f(E) = \frac{1}{1+\exp(\frac{E-E_F}{kT})}$$




- $f(E)$: Fermi-Dirac function
- An increase in $E$ will reduce $f(E)$
- **$E_F$ --- Fermi-level**
  - **When $E = E_F$, $f(E=E_F)$ = 0.5.**

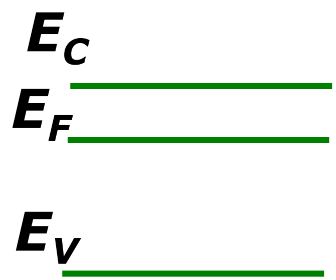


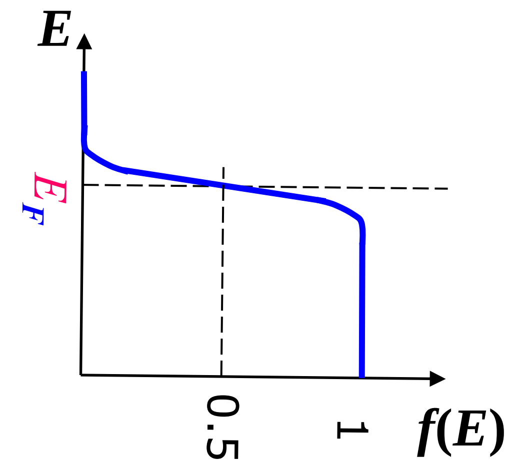

**textbook P.66**

# Fermi function and Fermi level

- **Probability** that a **state** at energy level, *E*, is occupied by one electron is,

$$f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$



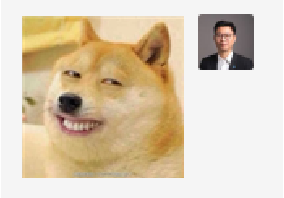

- $f(E)$: Fermi-Dirac function
- An increase in $E$ will reduce $f(E)$
- **$E_F$ --- Fermi-level**
  - **When $E = E_F$, $f(E=E_F)$ = <u>0.5</u>.**

1. **Simplify** Fermi-Dirac function: **Boltzmann Approximation**

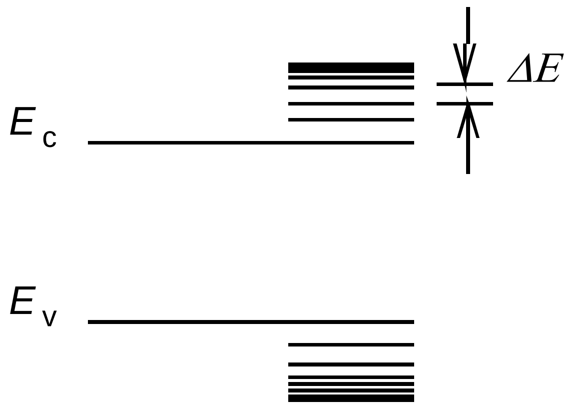
2. What is the **states' density**? (**Density of States**)

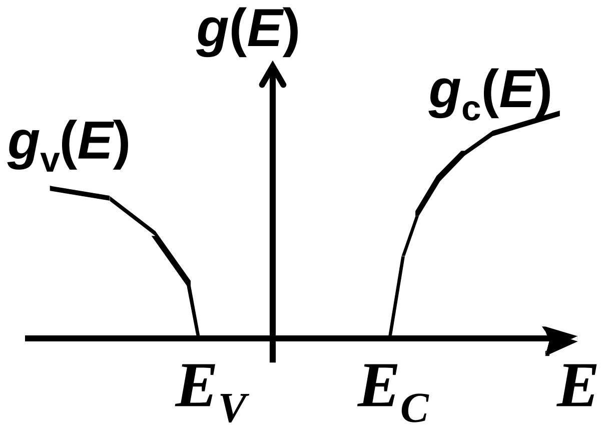
# **2.5** Boltzmann approximation & $E_F$, n, p

- Fermi function and Fermi level
- **Density of States**
- Boltzmann Approximation
- Electron and Hole Concentrations



# Density of States




$g(E)\Delta E$ = number of states per cm$^3$ in the energy range between $E$ and $E+\Delta E$

Near the band edges:

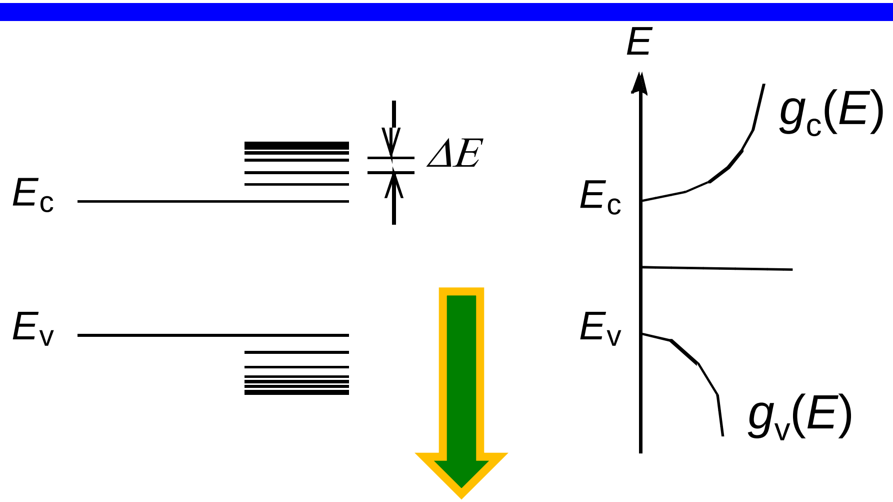
$$g_c(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_c)}}{\pi^2 \hbar^3} \qquad \boxed{E \geq E_c}$$

density of states in the **conduction band**

$$g_v(E) = \frac{m_p^* \sqrt{2m_p^*(E_v - E)}}{\pi^2 \hbar^3} \qquad \boxed{E \leq E_v}$$

density of states in the **valence band**

# Density of States




*g*(*E*)*dE* = number of states per cm³ in the energy range between *E* and *E*+*dE*

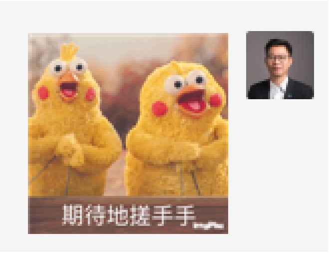
Near the band edges:

$$g_c(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_c)}}{\pi^2 \hbar^3} \qquad E \geq E_c$$

$$g_v(E) = \frac{m_p^* \sqrt{2m_p^*(E_v - E)}}{\pi^2 \hbar^3} \qquad E \leq E_v$$

# **2.5** Boltzmann approximation & $E_F$, n, p

- Fermi function and Fermi level
- Density of States
- **Boltzmann Approximation**

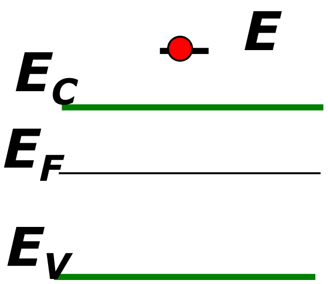



- Electron and Hole Concentrations

# Boltzmann Approximation

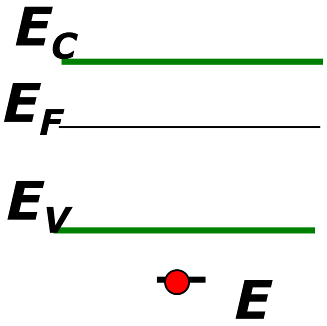
$$f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$

$$\text{If } E - E_F > 3kT,\ f(E) \cong e^{-(E-E_F)/kT}$$




**because of exp[(E-$E_F$)/(kT)] >> 1**

$$\text{If } E_F - E > 3kT,\ f(E) \cong 1 - e^{(E-E_F)/kT}$$



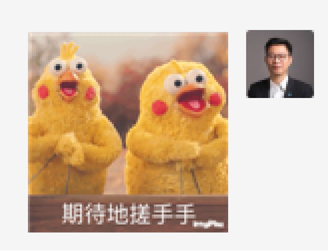

**<u>Probability</u>** that a **state** is **empty**:

$$\underline{1 - f(E)} \cong e^{(E-E_F)/kT} = e^{-(E_F-E)/kT}$$

**Probability that a state is occupied by a hole**

# **2.5** Boltzmann approximation & $E_F$, n, p

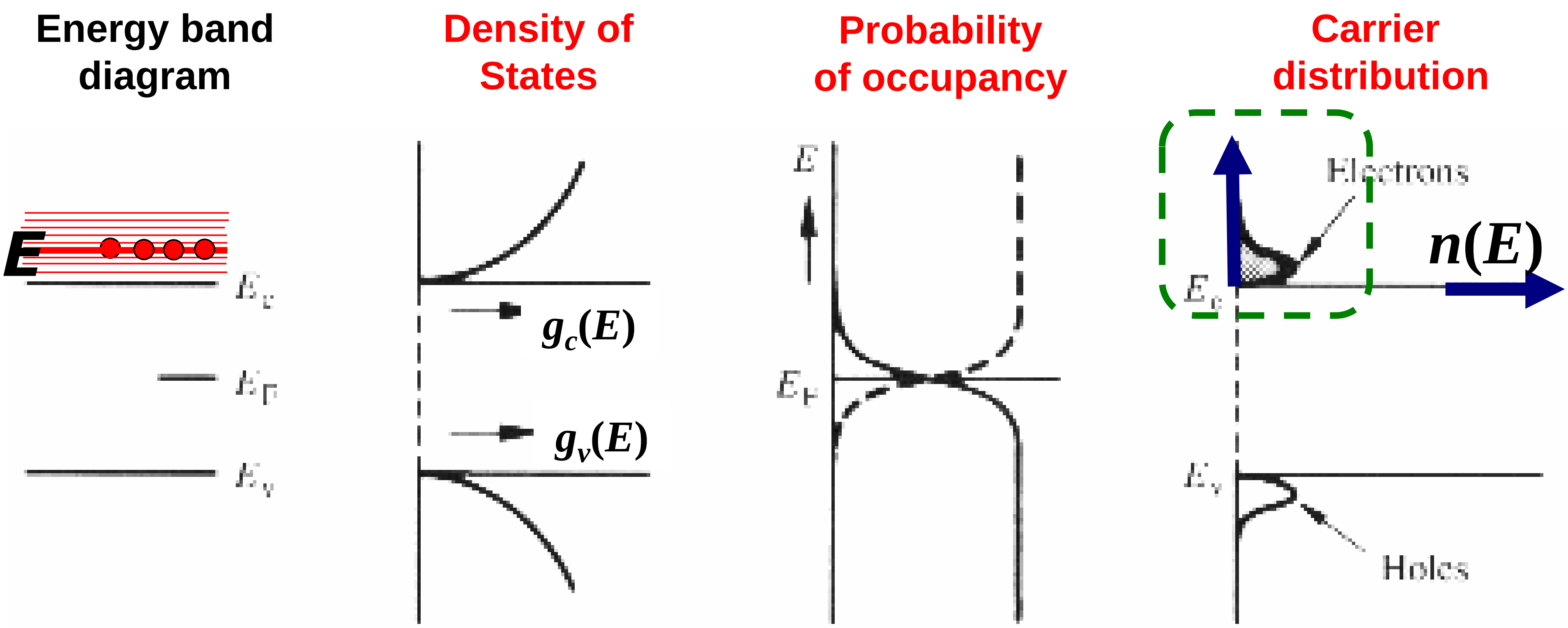
- Fermi function and Fermi level
- Density of States
- Boltzmann Approximation




- **Electron and Hole Concentrations**

# Equilibrium Distribution of Electrons

- Obtain ***n*(*E*)** by multiplying $g_c(E)$ and ***f*(*E*)**



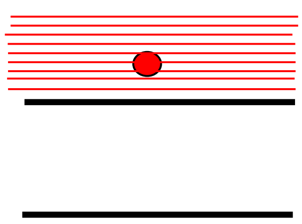
# Equilibrium Electron Concentrations

- **Integrate *n*(*E*)** over all the energies in the conduction band to obtain *n*:

$$n = \int_{E_c}^{\infty\ \text{(top of conduction band)}} \boxed{g_c(E) f(E)}\, dE$$

- By using the Boltzmann approximation, and extending the integration limit to ∞, we obtain

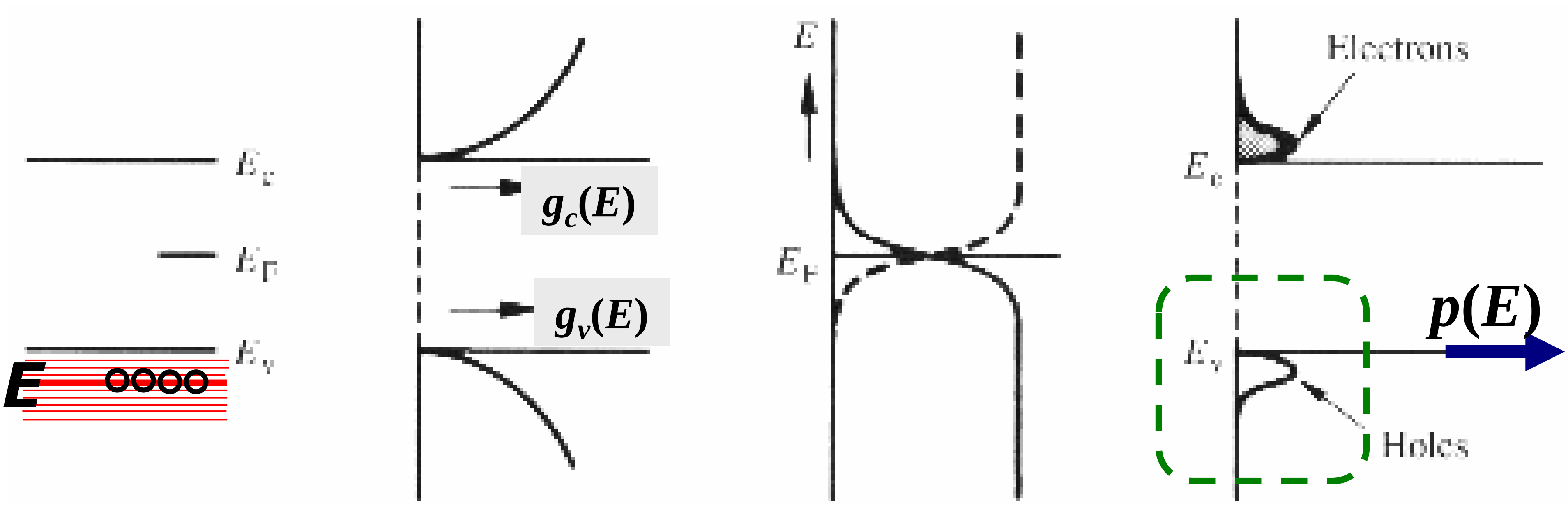
$$n = N_c e^{-(E_c - E_F)/kT} \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$



# Equilibrium Distribution of Holes

- Obtain ***p*(*E*)** by multiplying $g_v(E)$ and $1\text{-}f(E)$

**Energy band diagram** | **Density of States** | **Probability of occupancy** | **Carrier distribution**



# Equilibrium Hole Concentrations

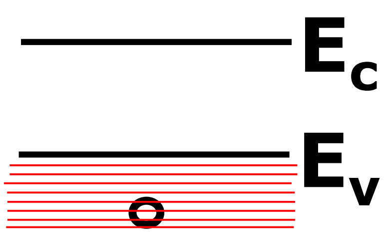
- **Integrate *p*(*E*)** over all the energies in the valence band to obtain *p*:

$$p = \int_{\text{of valenceband}}^{E_v} g_v(E)\left[1 - f(E)\right] dE$$

**$-\infty$**

- By using the Boltzmann approximation, and extending the integration limit to **$-\infty$**, we obtain

$$p = N_v e^{-(E_F - E_v)/kT} \quad \text{where} \quad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$



# Intrinsic Carrier Concentration

$$np = \left(N_c e^{-(E_c - E_F)/kT}\right)\left(N_v e^{-(E_F - E_v)/kT}\right)$$

$$= N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_g/kT}$$

$$= n_i^2$$

**Law of Mass Action**

$$n_i = \sqrt{N_c N_v} e^{-E_g/2kT}$$

# Electron and hole concentrations

$$n = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

$$p = N_V \exp\left[\frac{-(E_F - E_V)}{kT}\right]$$

$$n \cdot p = n_i^2$$

**p.83,ref1,** $E_{Fi} \approx E_i$

$$n_i = N_C \exp\left[\frac{-(E_C - E_i)}{kT}\right]$$

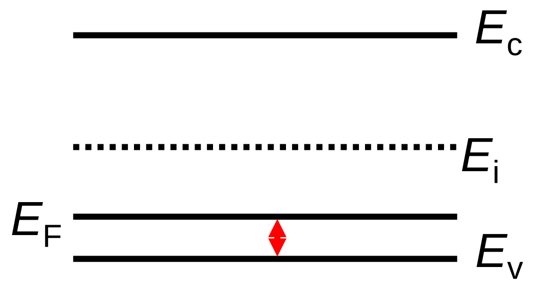
$$n_i = N_V \exp\left[\frac{-(E_i - E_V)}{kT}\right]$$

$$n = n_i \exp\left[\frac{(E_F - E_i)}{kT}\right]$$

$$p = n_i \exp\left[\frac{-(E_F - E_i)}{kT}\right]$$

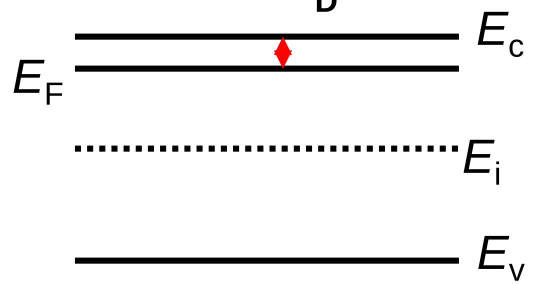
**At RT**

$p = N_A$




**At RT**

$n = N_D$



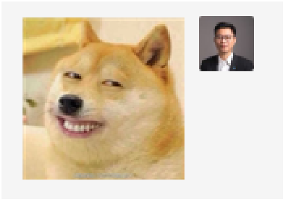
# **HW3**: Energy-band diagram

Question: Where is $E_F$ for $n = 10^{17}$ cm$^{-3}$ ?

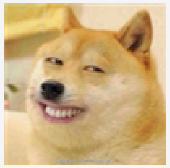
# Semiconductor Fundamentals – (III)

2.5 Boltzmann approximation & $E_F$, n, p

**2.6 Carrier drift and diffusion**



# 2.6 Carrier drift and diffusion




- **Carrier scattering**

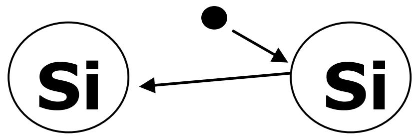
- Carrier drift:
  - *Carrier mobility*
  - *Conductivity & Resistivity*
  - *Energy band model*

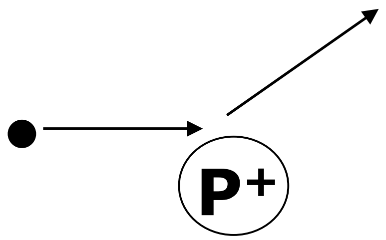
- Carrier diffusion

**Reading: Chapter 2.6**

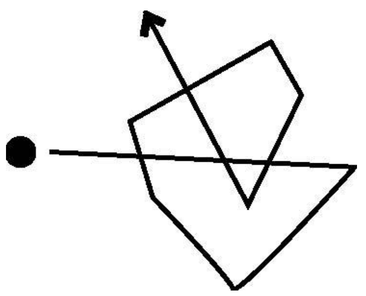
# Thermal Motion

- In thermal equilibrium, **carriers** are **not sitting still**:
  - undergo **collisions** with **vibrating Si atoms** (Brownian motion)
  - electrostatically **interact** with **charged dopants** and with each other



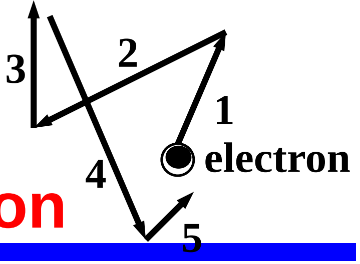

- Characteristic **time constant** of thermal motion
  - **mean free time** between collisions:
  - $\tau_c \equiv$ collision time [s]
  - In between collisions, carriers acquire high velocity: $\mathbf{v_{th}} \equiv$ **thermal velocity** [cm/s]
  - ...but get nowhere! (on average)



- Characteristic **length** of thermal motion:
  - $\lambda \equiv$ **mean free path** [cm], $\lambda = \mathbf{v_{th}}\, \tau_c$

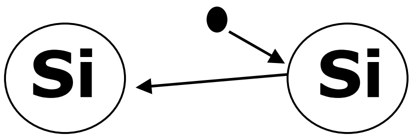
# Carrier Scattering

random motion

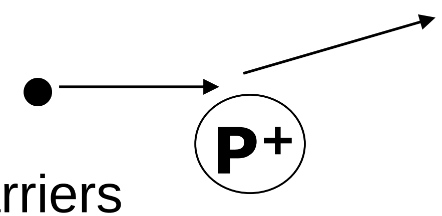



- **Mobile electrons** and atoms in the Si lattice are always in **random thermal motion**.
  - **Average velocity** of thermal motion for electrons in Si:

    ~**$10^7$ cm/s @ 300K**
  - Electrons make frequent "**collisions**" with the **vibrating atoms**
    - "**Lattice Scattering**" or "**Phonon Scattering**"




  - Other scattering mechanisms:
    - deflection by **ionized impurity atoms**
    - deflection due to **Coulombic** force between carriers




- **The average current in any direction is zero, if no electric field is applied**.

# Effective Mass

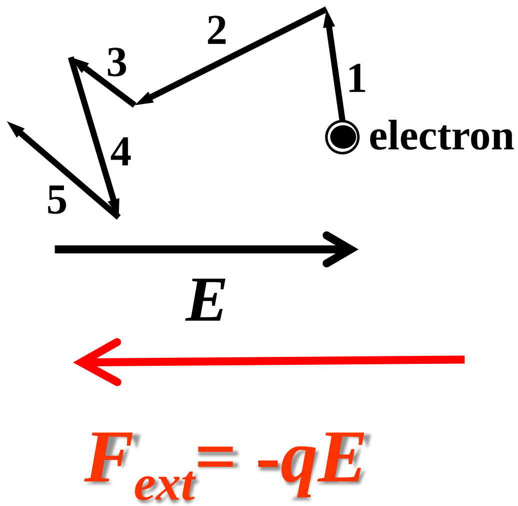
- Under an **externally applied force, $F_{ext}$,** the movement of electrons (or holes) is influenced by the positively charged protons and by negatively charged electron in the lattice. So, the movement in the crystal is different from that in vacuum.
- The total force $F_{total}$

$$F_{total} = F_{ext} + F_{\text{int}} = ma$$

where $a$ is the acceleration, $F_{int}$ is the internal force. We can write

$$F_{ext} = m^{*}a$$

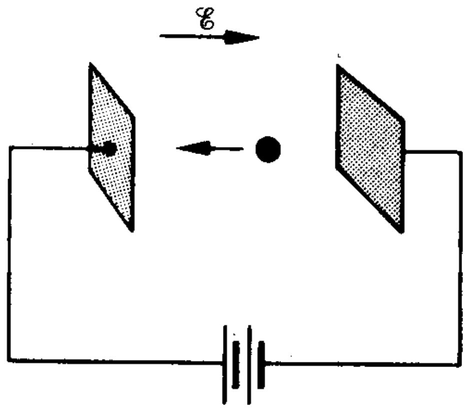
where $m^*$ is called **effective mass**.




Notation: $m_n^*$ for electrons, $m_p^*$ for holes,

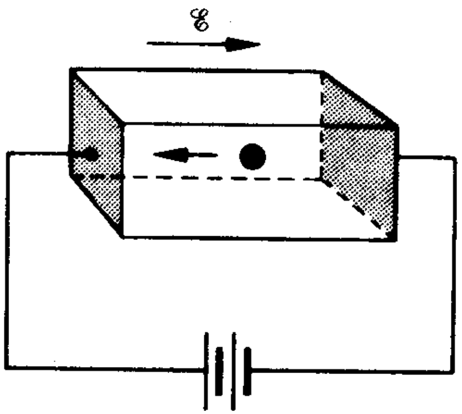
# Electrons as Moving Particles

**In vacuum**




$$F = (-q)\mathrm{E} = m_o a$$

**In semiconductor**




$$F_{ext} = (-q)\mathrm{E} = m_n^* a$$

where $m_n^*$ is the electron effective mass.

If $\tau_{cn}$ is electron mean free time between collisions,

$$|a| = dv/dt \approx v_e/\tau_{cn}$$

$$|a| = q\mathrm{E}/m_n^*$$

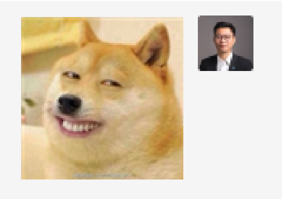
$$\Rightarrow \quad v_e = \frac{q\tau_{cn}\mathrm{E}}{m_n^*}, \quad v_h = \frac{q\tau_{cp}\mathrm{E}}{m_p^*}$$

**average *drift velocity***

# 2.6 Carrier drift and diffusion

- Carrier scattering

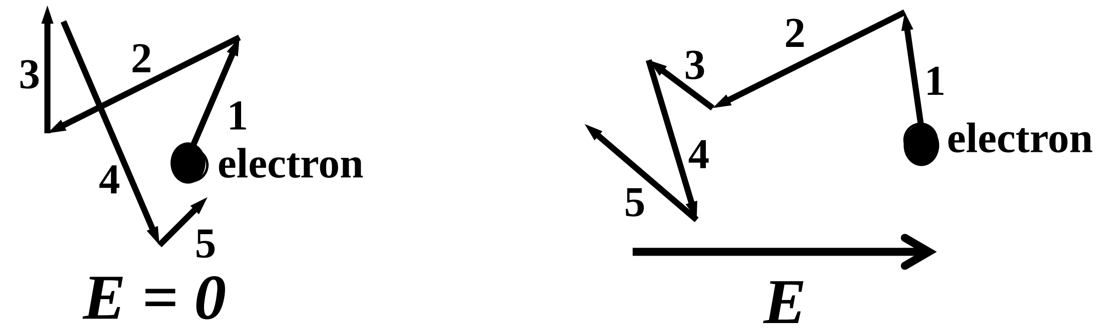
- **Carrier drift:**
  - *Carrier mobility*
  - *Conductivity & Resistivity*
  - *Energy band model*



- Carrier diffusion

# Carrier Drift

- **When an electric field** (*e.g.*, due to an externally applied voltage) **is applied to a semiconductor, mobile charge-carriers will be accelerated by the electrostatic force. This force superimposes on the random motion of electrons:**



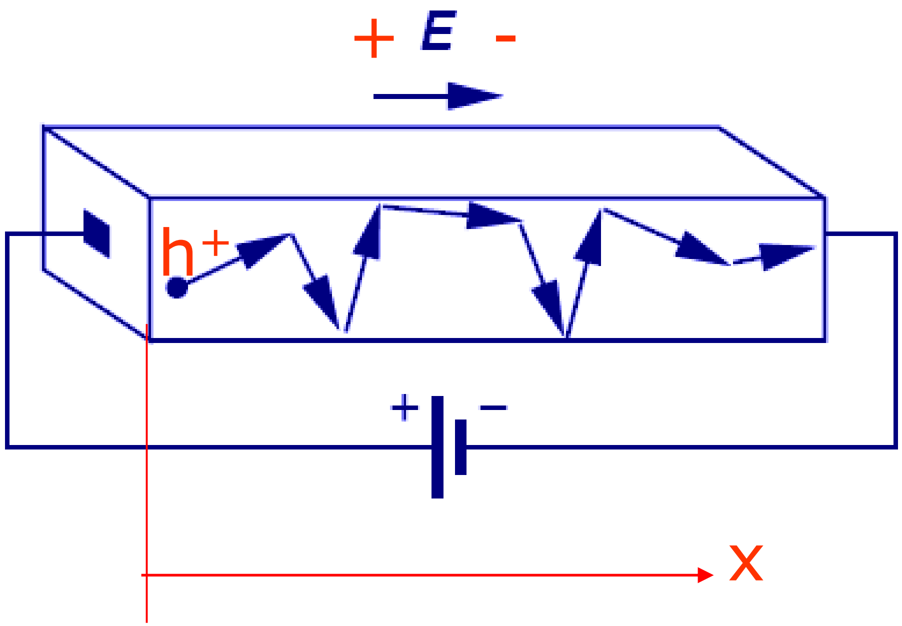

- **Electrons *drift* in the direction opposite to the *E*-field**

  **→ Current flows**

❖ **Because of scattering, electrons in a semiconductor do not achieve constant acceleration. However, they can be viewed as classical particles moving at a <u>constant average *drift velocity*</u>.**

# 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***.



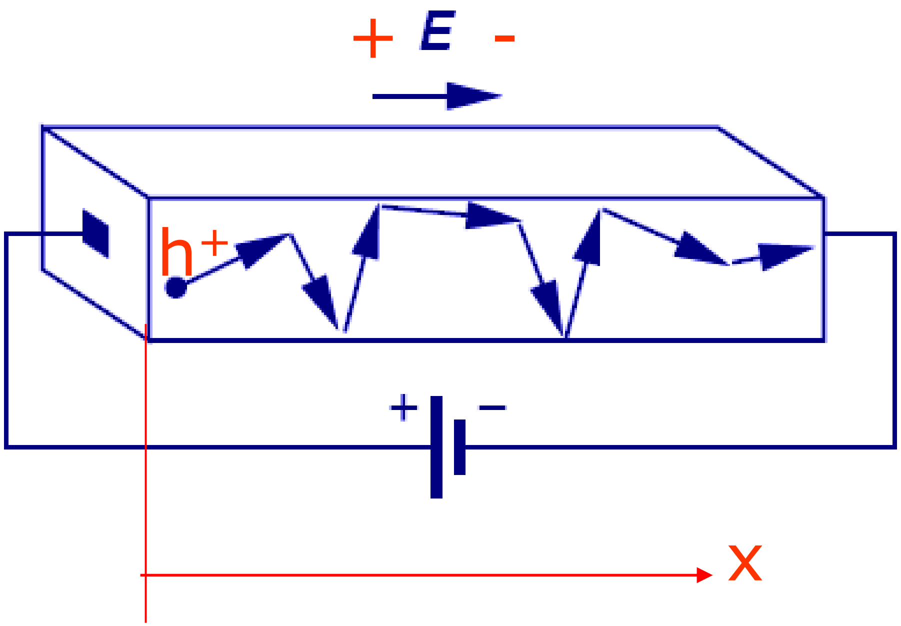

**Hole velocity** $\vec{v}_h = \mu_p \vec{E}$

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

# Carrier Drift

$$v_e = \frac{q\tau_{cn}\mathrm{E}}{m_n^*}, \qquad v_h = \frac{q\tau_{cp}\mathrm{E}}{m_p^*} \qquad \Rightarrow$$

$$\boxed{\mu_n = \frac{q\tau_{cn}}{m_n^*}, \qquad \mu_p = \frac{q\tau_{cp}}{m_p^*}}$$




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

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

**Notation:**

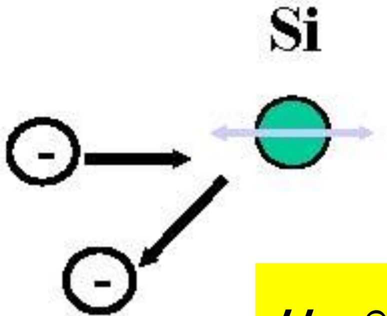
$\mu_p \equiv$ hole mobility ($cm^2/V \cdot s$)

$\mu_n \equiv$ electron mobility ($cm^2/V \cdot s$)

$1/\mu = 1/\mu_L + 1/\mu_I$

# *Carrier Mobility*

- Mobile carriers are always in random thermal motion. If no electric field is applied, the average current in any direction is zero.




- **Mobility is reduced by**

1) collisions with the vibrating atoms

"phonon scattering"

$\mu_L \propto T^{-3/2}$

2) deflection by ionized impurity atoms "Coulombic scattering"



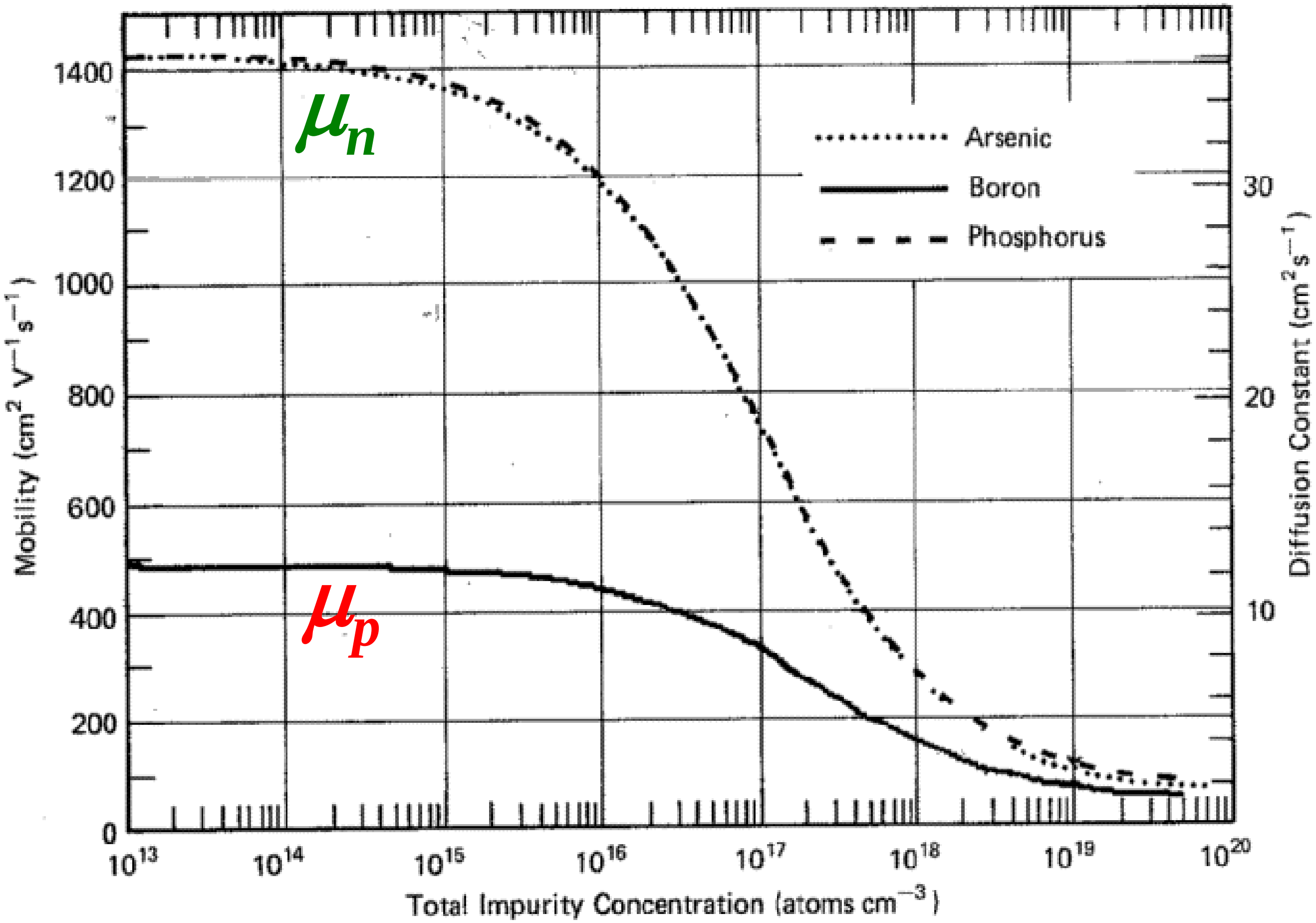
$\mu_I \propto T^{+3/2} / N_I$

# Drift Velocity and Carrier Mobility

**Mobile charge-carrier drift velocity is proportional to applied *E*-field:**

$$\boxed{|\,v\,| = \mu E}$$

$\mu$ is the ***mobility*** **(Units: cm²/V•s)**

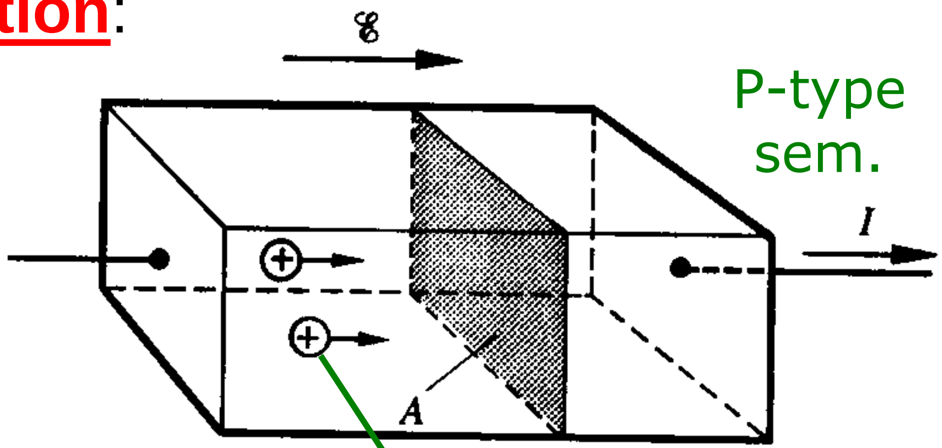



**Note: Carrier mobility depends on *total* dopant concentration ($N_D$ + $N_A$) !**

# Drift Current

- **Drift current** is **proportional** to the **carrier velocity** and **carrier concentration**:

**1)** $p$---hole density
**2)** q =$1.6\times10^{-19}$ C
--- One electron charge
**3)** Charges passing through 'A' per second
--- The definition of **current**.




| |
|---|
| $v_h\, t\, A$ = volume from which **all holes** cross plane in **time *t*** |
| $p\, v_h\, t$ A = **# of holes** crossing plane in **time *t*** |
| $q\, p\, v_h\, t$ A = **charge** crossing plane in **time *t*** |
| $q\, p\, v_h A$ = **charge** crossing plane **per unit time** = **hole current** |

➔ **Hole current per unit area (*i.e.* current density)** $J_{p,drift} = q\, p\, v_h$

# Electrical Conductivity $\sigma$

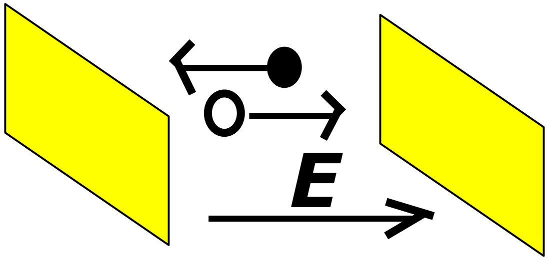
Negatively charged electron

Direction of electron drift

**When an electric field is applied, current flows due to drift of mobile electrons and holes:**

**electron current density:** $$J_n = (-q)nv_e = qn\mu_n E$$

**hole current density:** $$J_p = (+q)pv_h = qp\mu_p E$$




**total current density:** $$J = J_n + J_p = (qn\mu_n + qp\mu_p)E$$

$$J = \sigma E$$

★ ***conductivity*** $$\boxed{\sigma \equiv qn\mu_n + qp\mu_p}$$ **Units: $(\Omega \cdot cm)^{-1}$**

# Electrical Resistivity $\rho$

$$\boxed{\rho \equiv \frac{1}{\sigma} = \frac{1}{qn\mu_n + qp\mu_p}}$$

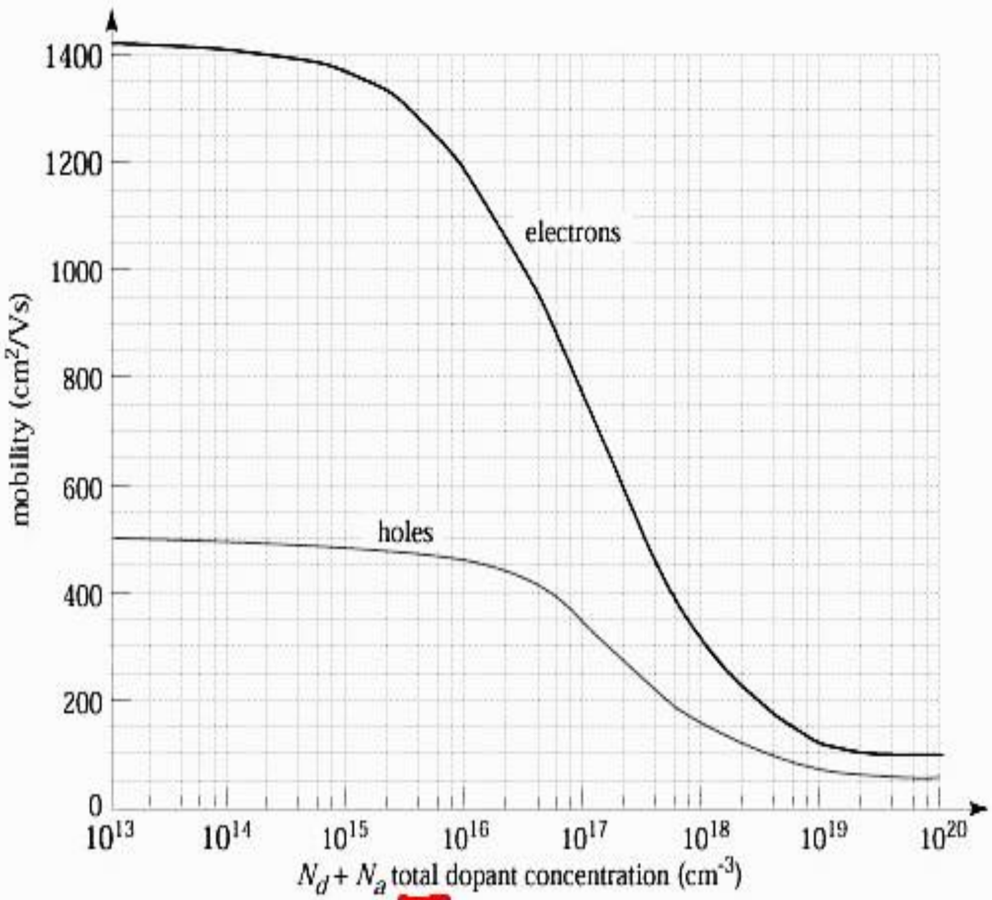
$$\rho \cong \frac{1}{qn\mu_n}$$ **for n-type material**

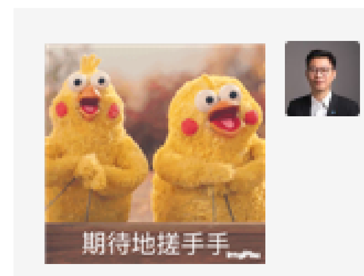
$$\rho \cong \frac{1}{qp\mu_p}$$ **for p-type material**

**(Units: ohm•cm)**

# HW4

- Estimate the **resistivity** of a **Si sample** doped with **phosphorus** to a concentration of **$10^{15}$ cm$^{-3}$** and **boron** to a concentration of **$10^{17}$ cm$^{-3}$**.




$\rho \simeq$ ?

- The **electron mobility** and **hole mobility** are **700 cm$^2$/Vs** and **350 cm$^2$/Vs**, respectively. **(Why??)**

# Example 1

**Consider a Si sample doped with $10^{16}/cm^3$ Boron. What is its resistivity?**

***Answer:***

$N_A = 10^{16}/cm^3$ , $N_D = 0$ ($N_A >> N_D \rightarrow$ p-type)

$\rightarrow p \approx 10^{16}/cm^3$ and $n \approx 10^4/cm^3$

$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qp\mu_p}$$

$$= \left[(1.6\times10^{-19})(10^{16})(450)\right]^{-1} = 1.4\,\Omega\cdot\text{cm}$$

From $\mu$ *vs.* ( $N_A + N_D$ ) plot

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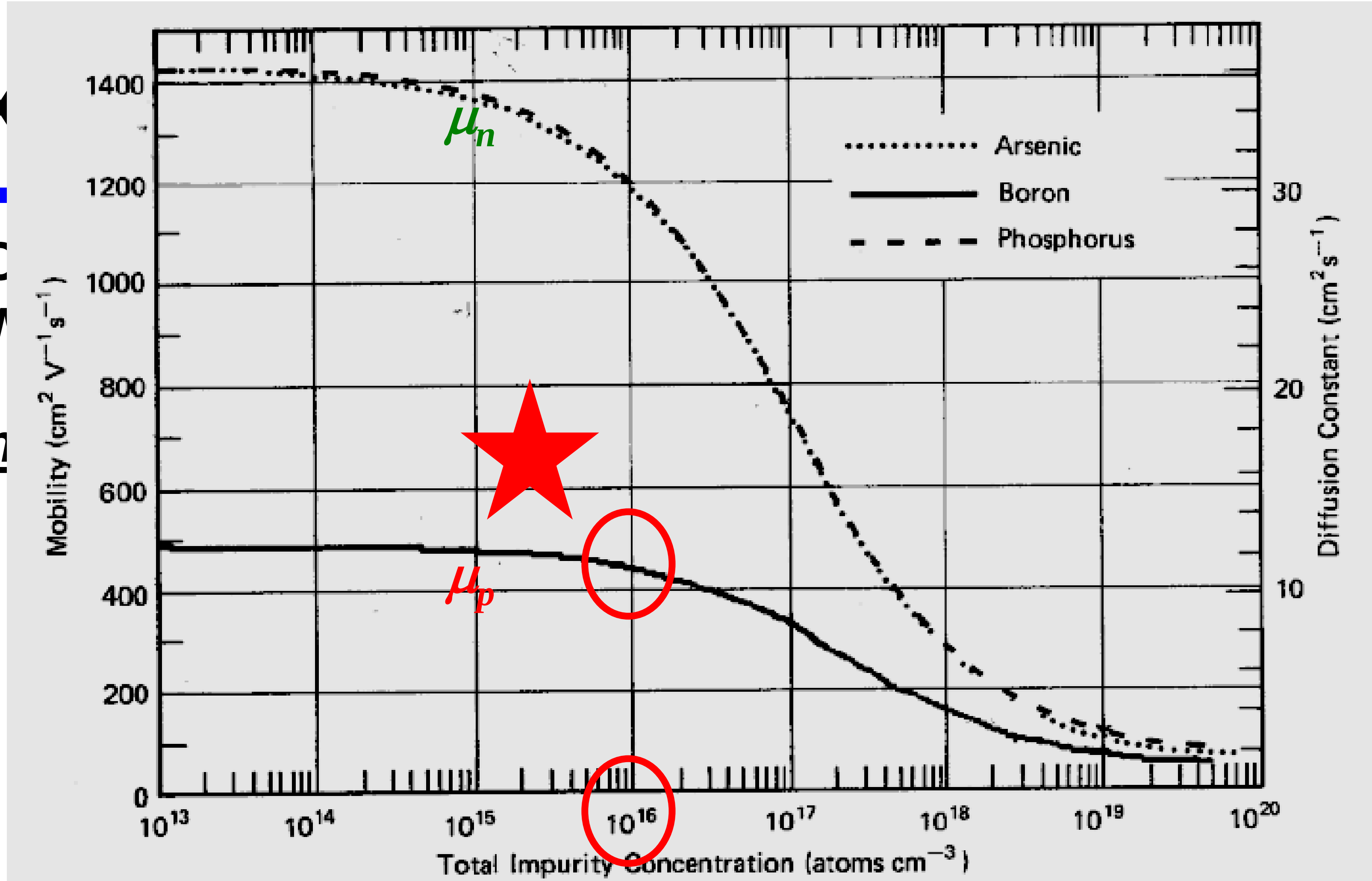



$$= \left[(1.6\times10^{-19})(10^{16})(450)\right]^{-1} = 1.4\,\Omega\cdot\mathrm{cm}$$

**From $\mu$ *vs.* ( $N_A + N_D$ ) plot**

# Example 2

**Consider the same Si sample, doped *additionally* with $10^{17}/cm^3$ Arsenic. What is its resistivity?**

***Answer:***

$N_A = 10^{16}/cm^3$, $N_D = 10^{17}/cm^3$ ($N_D >> N_A \rightarrow$ n-type)

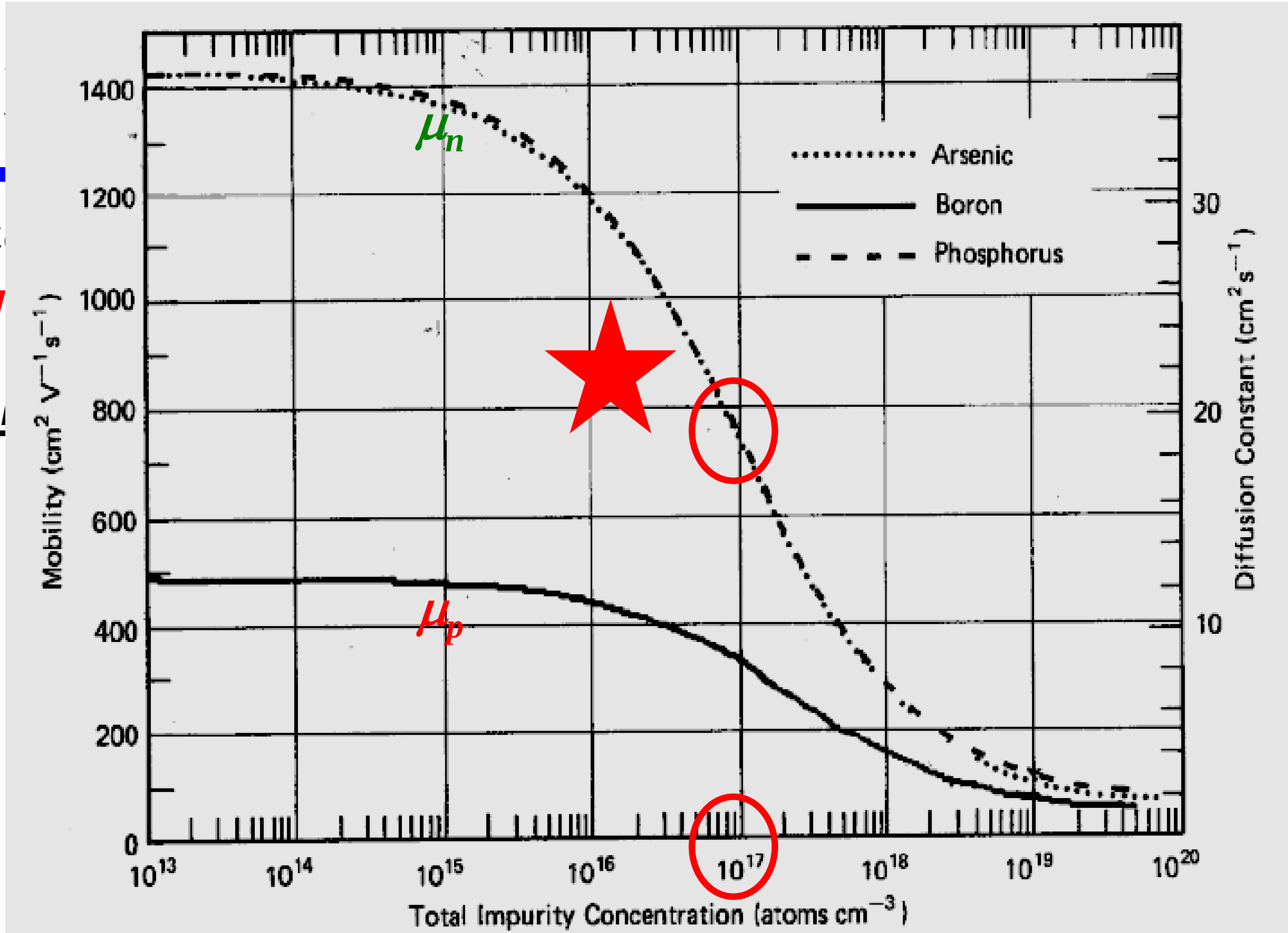
$\rightarrow n \approx 9 \times 10^{16}/cm^3$ and $p \approx 1.1 \times 10^3/cm^3$

$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qn\mu_n}$$

$$= \left[(1.6\times10^{-19})(9\times10^{16})(700)\right]^{-1} = 0.10\,\Omega\cdot\text{cm}$$

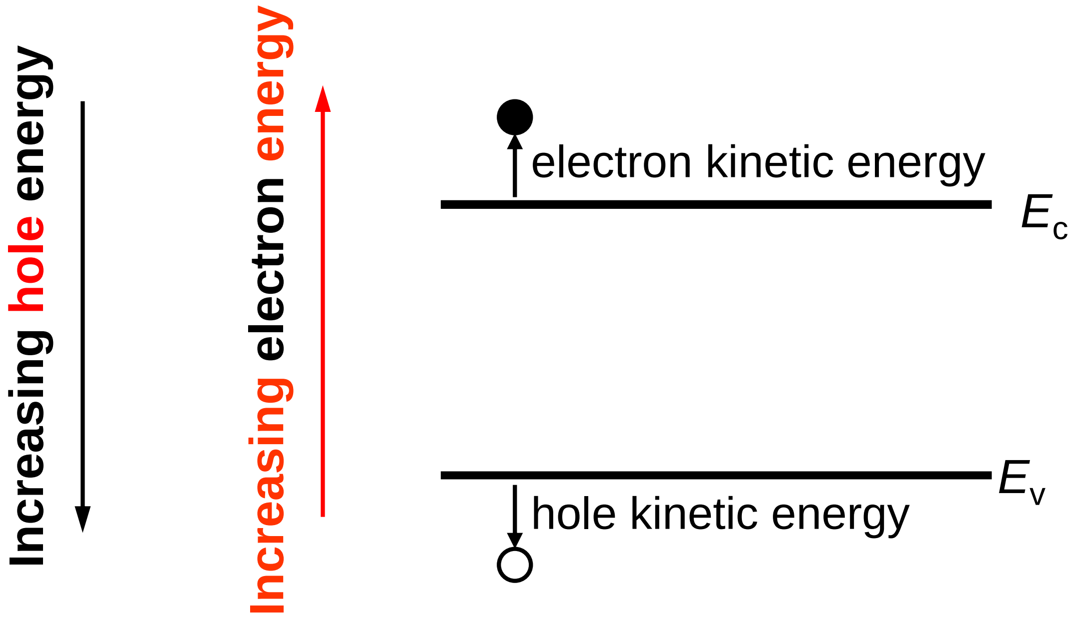
**The sample is converted to n-type material by adding more donors than acceptors, and is said to be "compensated".**

**From $\mu$ vs. ( $N_A + N_D$ ) plot**



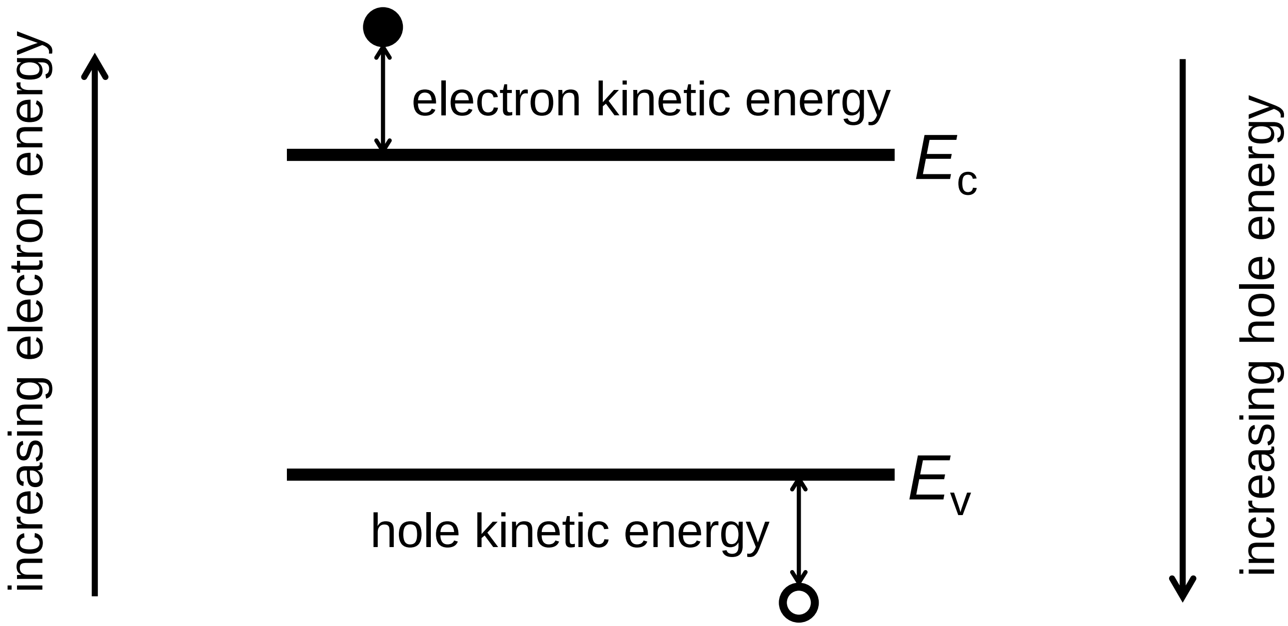

**The sample is converted to n-type material by adding more donors than acceptors, and is said to be "compensated".**

# Electrons and Holes (Band Model)




- **Electrons and holes** tend to seek **lowest-energy** positions
  - **Electrons** tend to **fall**
  - **Holes** tend to **float up** (like bubbles in water)

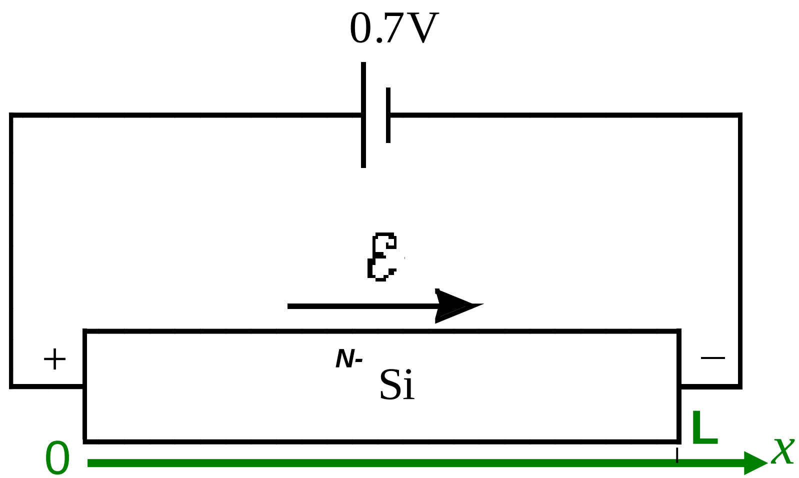
# Potential *vs.* Kinetic Energy

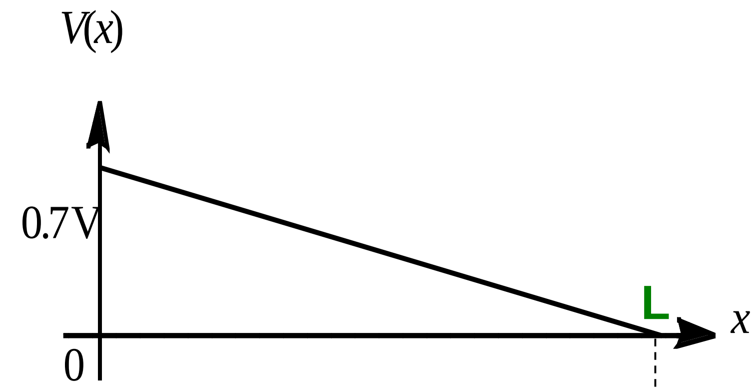



**$E_c$ represents the electron potential energy:**

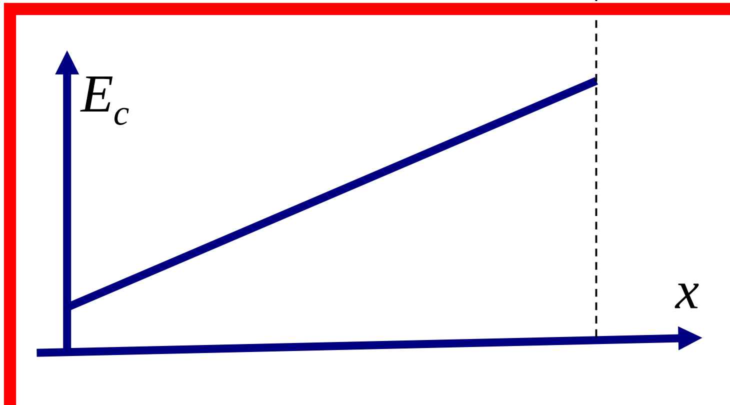
$$\text{P.E.} = E_c - E_{\text{reference}}$$

# Electrostatic Potential, *V*




- The **potential energy** of a particle with charge -*q* is related to the electrostatic **potential *V(x)***:



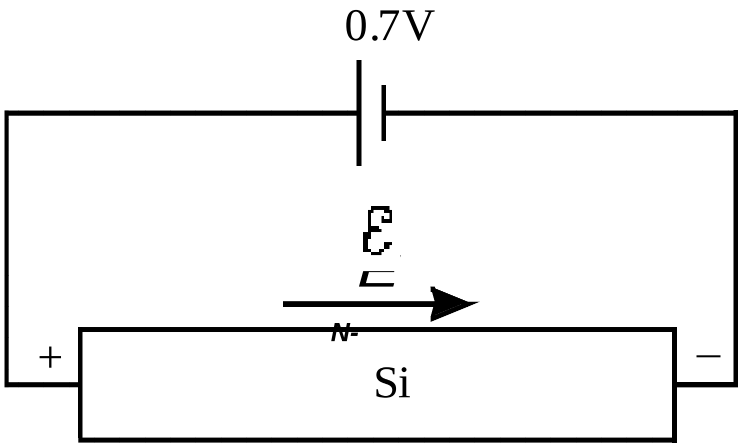

$$\text{P.E.} = -qV$$

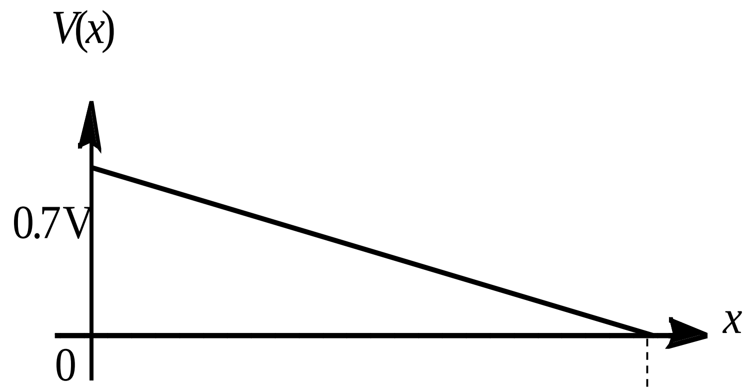
$$V = \frac{1}{q}(E_{\text{reference}} - E_{\text{c}})$$

$E_{\text{reference}}$ is constant

# Electric Field, $\varepsilon$

$$\mathcal{E} = -\frac{dV}{dx}$$

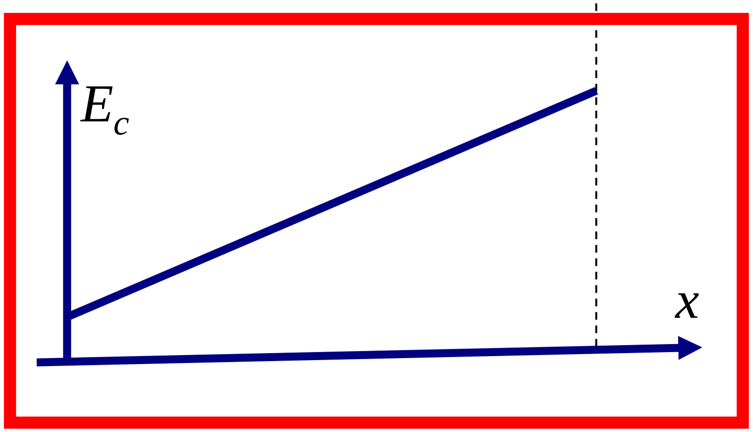



$$V = \frac{1}{q}\left(E_{\text{reference}} - E_{\text{c}}\right)$$

$$\Downarrow$$

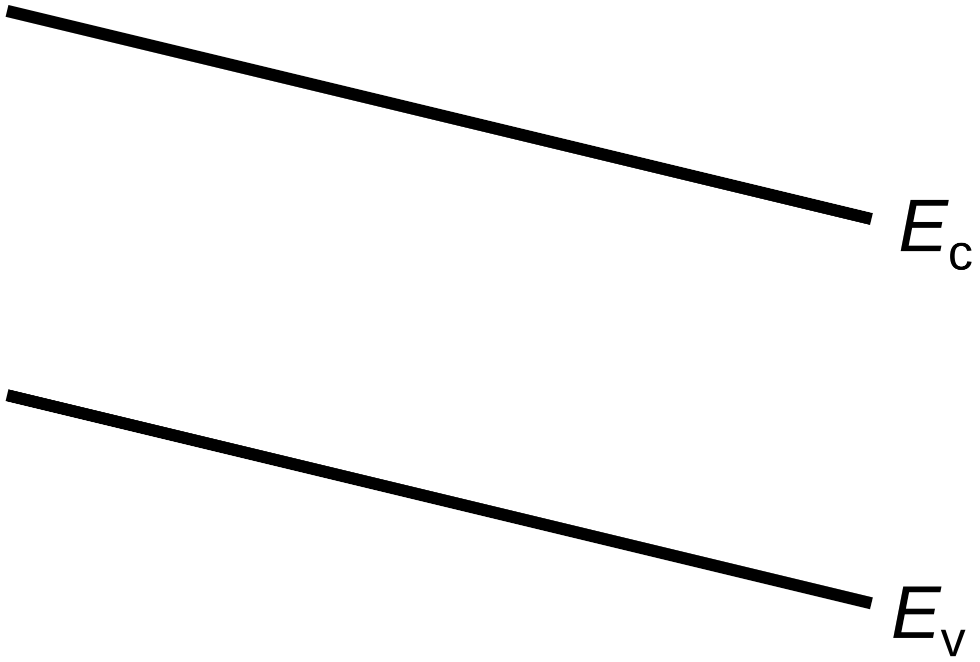
$$\boxed{\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_{\text{c}}}{dx}}$$




- **Variation of $E_c$** with position is called "***band bending***."

# HW 5: Carrier Drift (Band Diagram Visualization)

$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$




Q1: what is the **direction** of **electric field**?

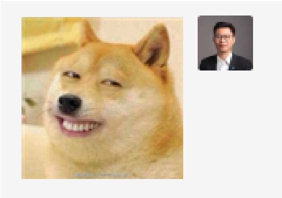
Q2: what is the **direction** of **carriers' drift**?

# 2.6 Carrier drift and diffusion

- Carrier scattering

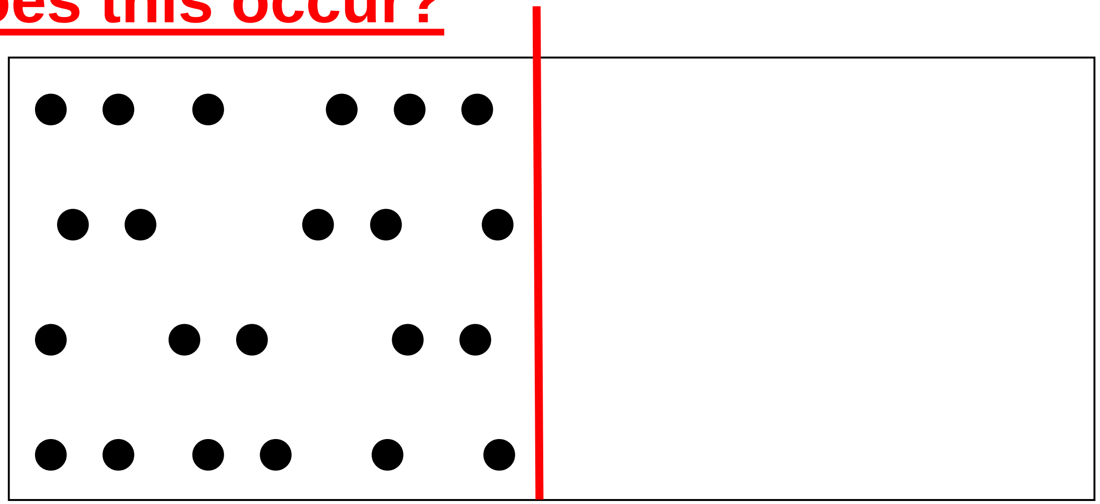
- Carrier drift:
  - *Carrier mobility*
  - *Conductivity & Resistivity*
  - *Energy band model*

- **Carrier diffusion**



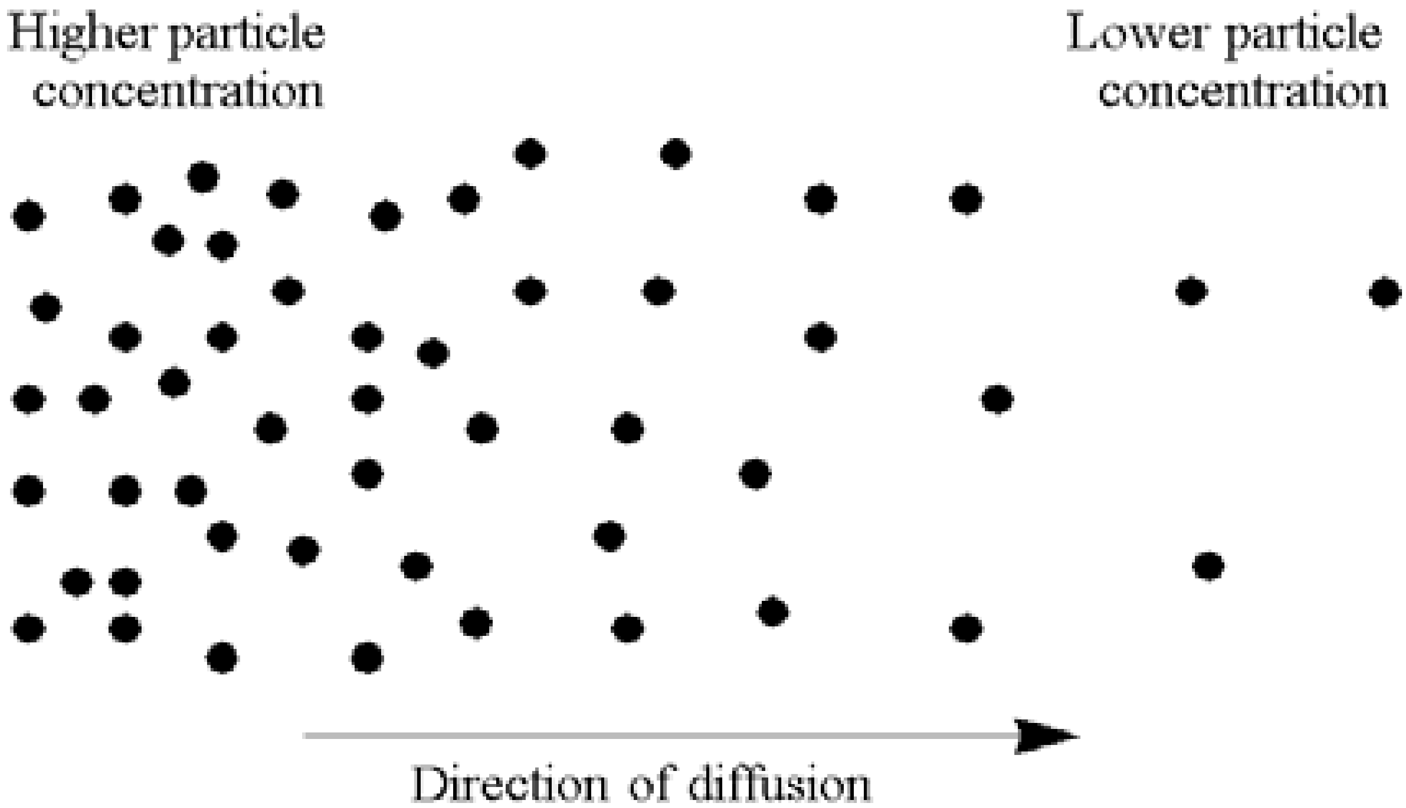
# Diffusion

- **Diffusion occurs when there exists a concentration gradient**
- **In the figure below, imagine that we fill the left chamber with a gas at temperate *T***
- **If we suddenly remove the divider, what happens?**
- **The gas will fill the entire volume of the new chamber.**
- **How does this occur?**



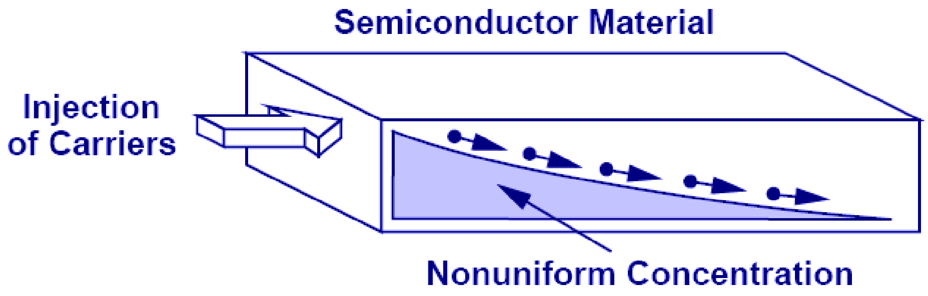
# Diffusion

- Particles **diffuse** from **higher concentration** to **lower concentration** locations.



# Carrier Diffusion

- Due to thermally induced random motion, mobile particles tend to move from a region of **high concentration** to a region of **low concentration**.
  - Analogy: ink droplet in water
- Current flow due to **mobile charge diffusion** is proportional to the **carrier concentration gradient**.
  - The **proportionality constant** is the ***diffusion constant***.




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

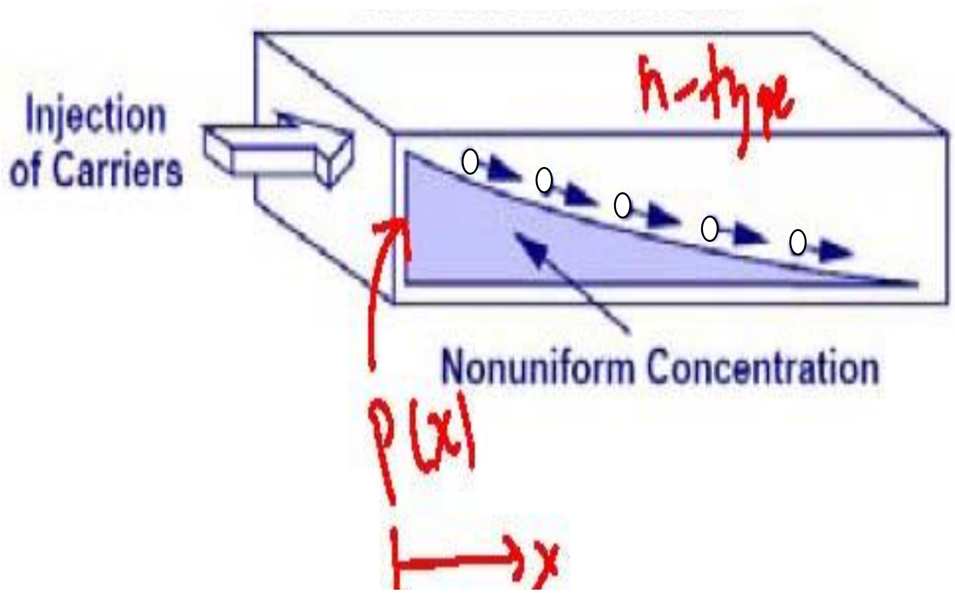
**Notation:**

$D_p \equiv$ **hole diffusion constant (cm$^2$/s)**

$D_n \equiv$ **electron diffusion constant (cm$^2$/s)**

# Carrier Diffusion

- Current flow due to **mobile charge diffusion** is proportional to the **carrier concentration gradient**.
  - The **proportionality constant** is the ***diffusion constant***.




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

**Notation:**

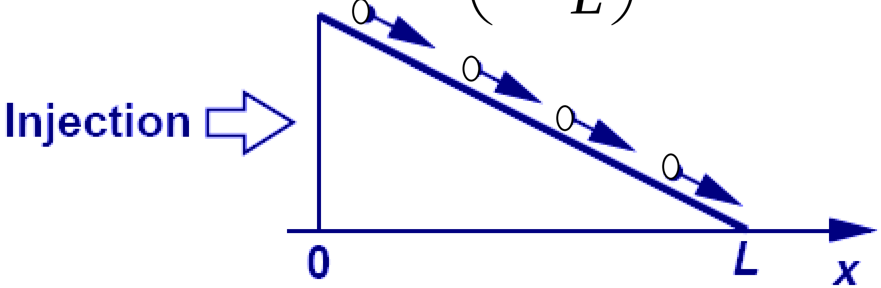
$D_p \equiv$ hole diffusion constant ($cm^2/s$)

$D_n \equiv$ electron diffusion constant ($cm^2/s$)

# Diffusion Examples

Linear **concentration profile** → **constant** diffusion current

$$p = N\left(1 - \frac{x}{L}\right)$$

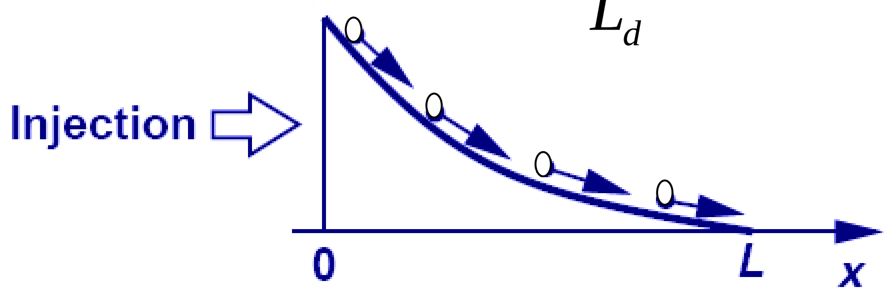



$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= qD_p \frac{N}{L}$$

Non-linear **concentration profile** → **varying** diffusion current

$$p = N \exp\frac{-x}{L_d}$$




$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= \frac{qD_p N}{L_d} \exp\frac{-x}{L_d}$$

# **Total Diffusion** Current

- Due to the non-uniform distribution of carriers

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

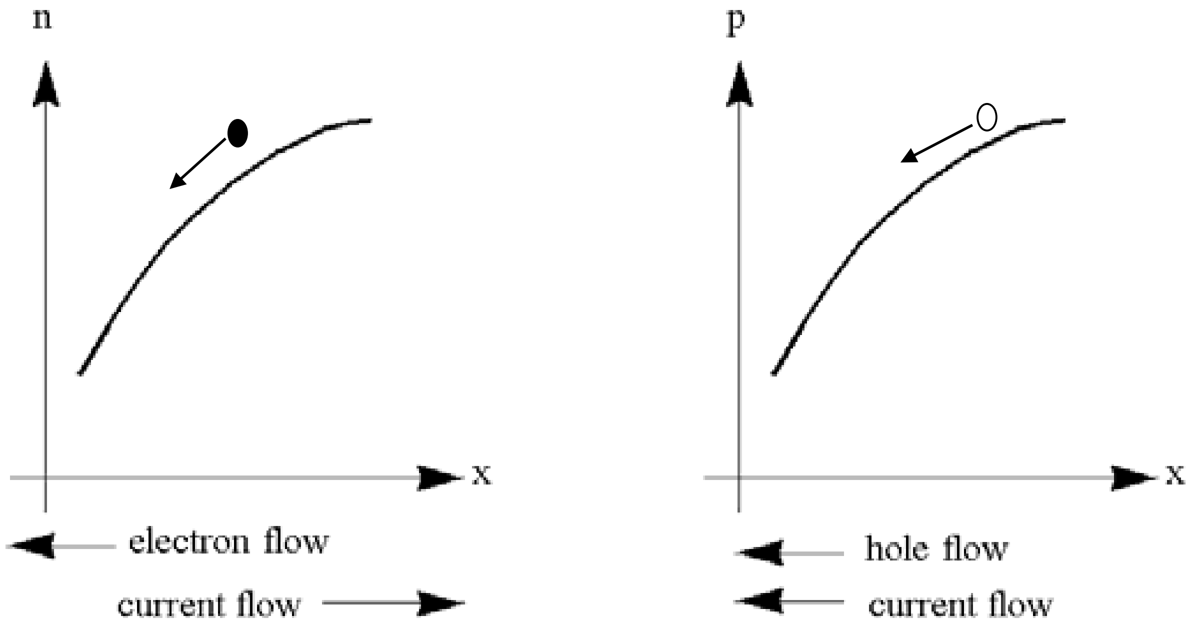
- $D_n$ --- electron diffusion constant
- Driving force: **thermal energy**, not electric field
- $dn/dx$--- density gradient
- **Total diffusion current**
  - $\boldsymbol{J = J_n + J_p}$

# Total Diffusion Current

- Diffusion current within a semiconductor consists of **hole** and **electron** components:

$$J_{p,diff} = -qD_p \frac{dp}{dx} \qquad J_{n,diff} = qD_n \frac{dn}{dx}$$

$$J_{tot,diff} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$



# **Total** current

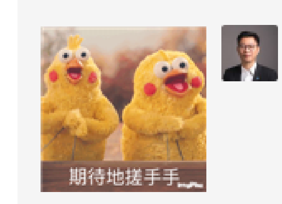
- The **total current** flowing in a semiconductor is the sum of **drift current** and **diffusion current**:

$$\boxed{J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff}}$$

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

$$J_{p,diff} = -qD_p \frac{dp}{dx}, \qquad J_{n,diff} = qD_n \frac{dn}{dx}$$

# Einstein Relation




- The **characteristic constants** for **drift** and **diffusion** are related:

$D_n = \frac{kT}{q} \mu_n$

$D_p = \frac{kT}{q} \mu_p$

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}} \simeq 26 \text{ mV}$$

at $T = 300\text{K}$

- Note that $\frac{kT}{q} \cong 26\,\text{mV}$ at **room temperature** (300K)
  - This is often referred to as the “**thermal voltage**”.

# Important Constants

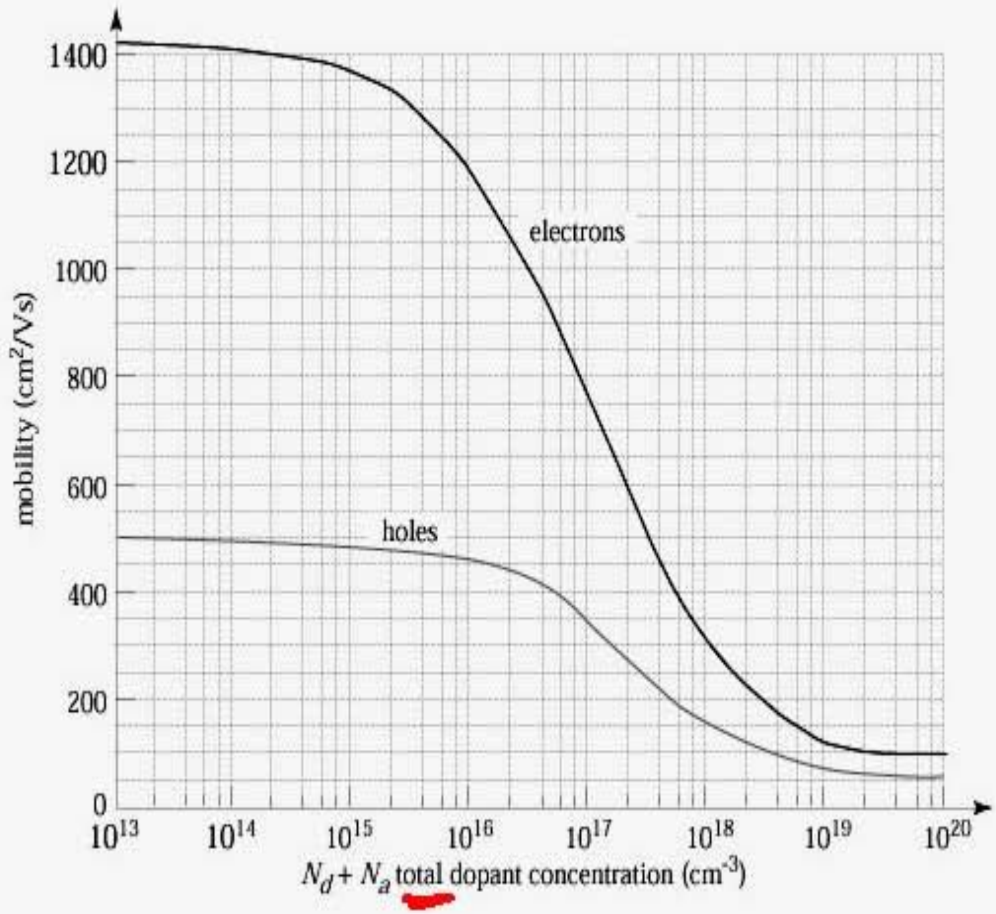
- Electronic charge, $q = 1.6\times10^{-19}$ C
- Permittivity of free space, $\varepsilon_o = 8.854\times10^{-14}$ F/cm
- Boltzmann constant, $k = 8.62\times10^{-5}$ eV/K
- Planck constant, $h = 4.14\times10^{-15}$ eV•s
- Free electron mass, $m_o = 9.1\times10^{-31}$ kg
- Thermal voltage $kT/q$ = 26 mV, at T=300K

# HW3: Energy-band diagram

Question: Where is $E_F$ for $n = 10^{17}$ cm$^{-3}$ ?

$$n = n_i \exp\left[\frac{(E_F - E_i)}{kT}\right]$$

# HW4




$N_D = 10^{15}\ cm^{-3}$, $N_A = 10^{17}\ cm^{-3}$

$N_A - N_D \approx 10^{17}\ cm^{-3}$

$p = 10^{17}\ cm^{-3}$, $n \approx 10^{3}\ cm^{-3}$

negligible

$\sigma = \cancel{q\mu_n n} + q\mu_p p$

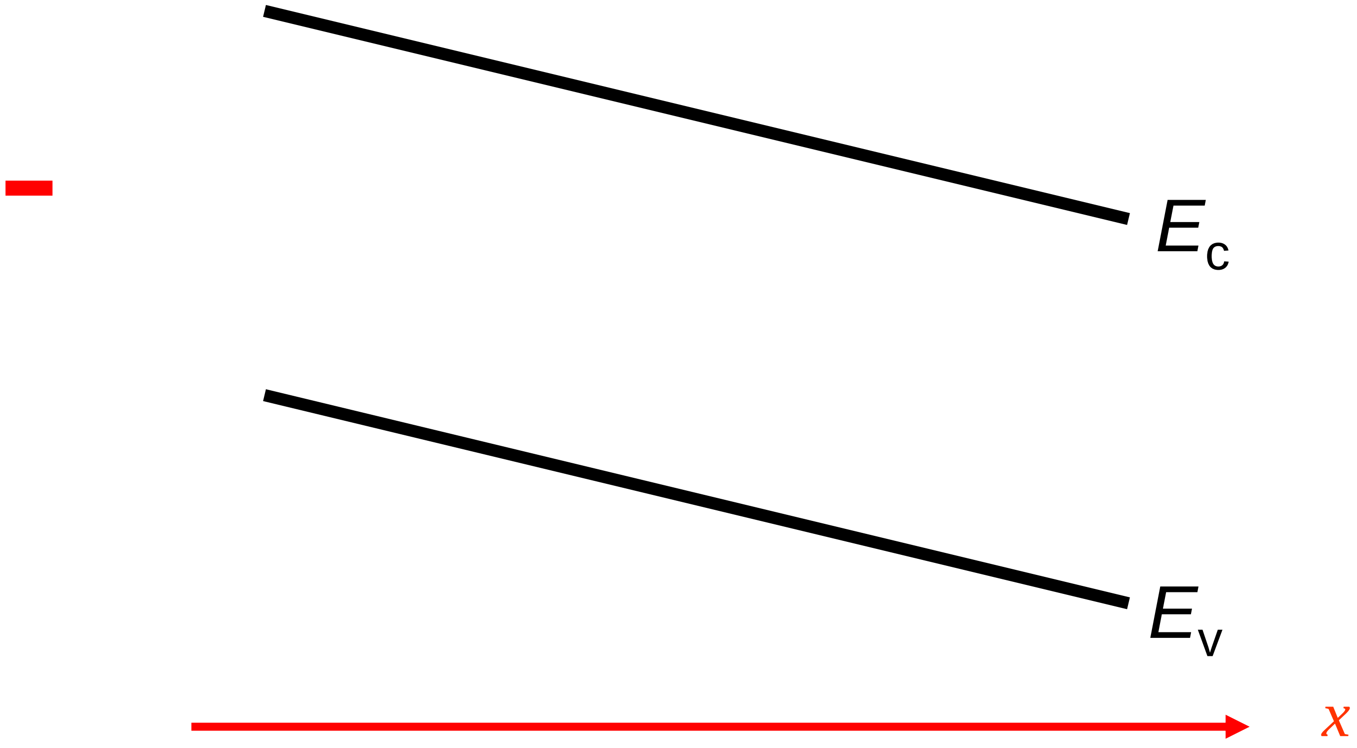
$\sigma = 1.6\times10^{-19}(350)(10^{17})$

$\approx 5\times10^{0}$

$\boxed{\rho \approx 0.2\ \Omega\text{-cm}}$

- The electron mobility and hole mobility are 700 $cm^2/Vs$ and 350 $cm^2/Vs$, respectively.

# HW5: Carrier Drift (Band Diagram Visualization)




Q1: what is the direction of electric field?

Q2: what is the direction of carriers' drift?