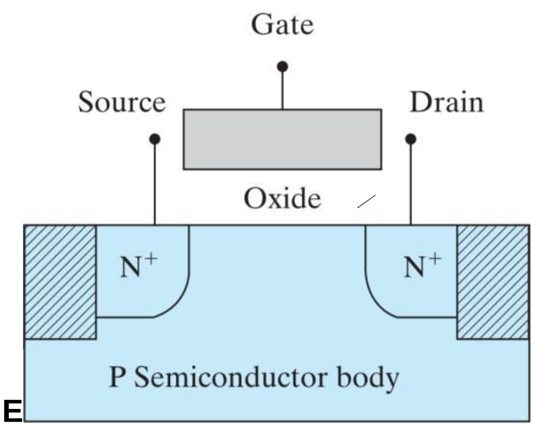
Semiconductor fundamentals_B

EE302

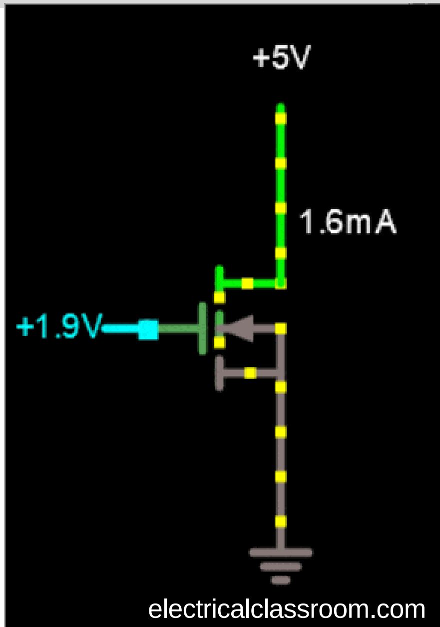
Prof. Sangyoon Han

Fall 2023



References:

- (C. Hu) Chapter 1
- (R. Pierret) Chapter 1
- Materials from SE393 (Prof. Hongki Kang)



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Alternative Expressions for *n* and *p*

- **Expression of carrier concentration using the intrinsic energy level, E_i**
- **Assume an intrinsic semiconductor ($E_F = E_i$)**
  - $n = n_i = N_C e^{-\frac{E_C - E_i}{kT}}$
  - $p = n_i = N_v e^{-\frac{E_i - E_v}{kT}}$
  - $N_C = n_i e^{\frac{E_C - E_i}{kT}}$
  - $N_v = n_i e^{\frac{E_i - E_v}{kT}}$

$$n = N_C e^{-\frac{E_C - E_F}{kT}}$$

$$p = N_V e^{-\frac{E_F - E_v}{kT}}$$

  - $n = n_i e^{\frac{E_C - E_i}{kT}} e^{-\frac{E_C - E_F}{kT}} = n_i e^{\frac{E_F - E_i}{kT}}$
  - $p = n_i e^{\frac{E_i - E_v}{kT}} e^{-\frac{E_F - E_v}{kT}} = n_i e^{\frac{E_i - E_F}{kT}}$

n_i and the np product

$$n = N_c e^{-(E_c - E_f)/kT} \qquad p = N_v e^{-(E_f - E_v)/kT}$$

- **Multiplication of *n* and *p*?**

- **For intrinsic semiconductor (*n* = *p* = n_i)**

Assumptions?

$$np = n_i^2$$

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

  - **n_i is the intrinsic carrier concentration.**

$$\left.\begin{aligned} n_i &\simeq 2 \times 10^6/\text{cm}^3 && \text{in GaAs} \\ &\simeq 1 \times 10^{10}/\text{cm}^3 && \text{in Si} \\ &\simeq 2 \times 10^{13}/\text{cm}^3 && \text{in Ge} \end{aligned}\right\} \text{ at room temperature}$$

Charge Neutrality Relationship

- **What are the charged entities inside of semiconductors?**
  1. **Electron**
  2. **Hole**
  3. **Ionized donor (+)**
  4. **ionized acceptor (-)**
- **For uniformly doped smemiconductor in equilibrium, charge neutrality should satisfy (*why?*)**

Assumes total ionization of dopants

Carrier Concentration Calculations

- **Uniformly doped semiconductor under equilibrium condition**
- **Nondegenerate, Total ionization**

$$np = n_i^{\,2} \qquad\qquad p - n + N_D - N_A = 0$$

$$\frac{n_i^2}{n} - n + N_D - N_A = 0$$

$$n^2 - (N_D - N_A)n - n_i^2 = 0$$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

$n_i \approx 10^{10}/cm^3$ (Si)
N_A or $N_D > 10^{14}/cm^3$

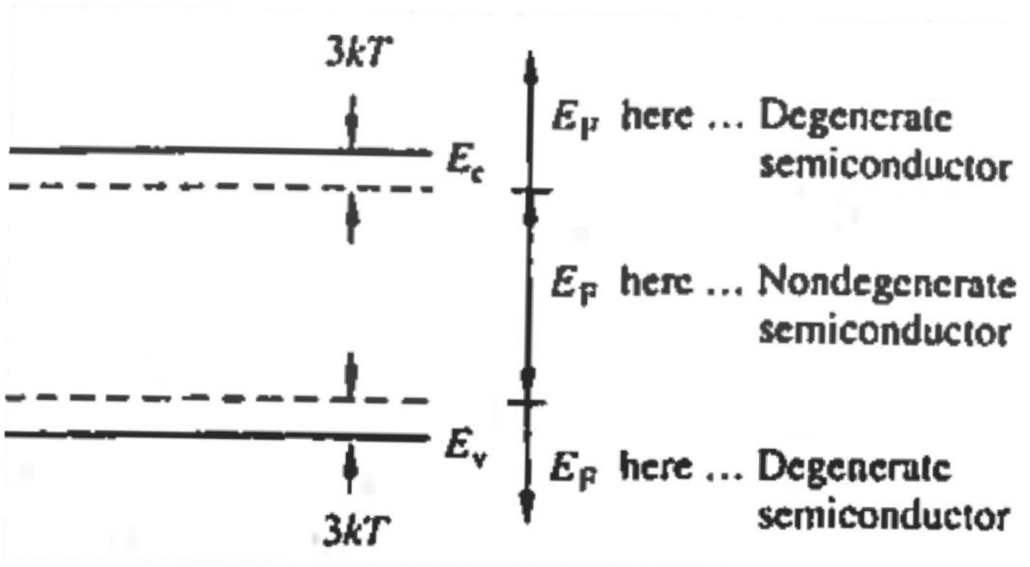
1. Intrinsic semiconductor

- ***$N_A = 0$, $N_D = 0$***
- ***$n = n_i$, $p = n_i$***

2. Doped semiconductor (mostly one-type, and larger than n_i)

- $(N_D - N_A \approx N_D \gg n_i)$
  - ***$n = N_D$, $p = n_i^2/N_D$***
- $(N_A - N_D \approx N_A \gg n_i)$
  - ***$n = n_i^2/N_A$, $p = N_A$***

Example



- If the semiconductor is <u>in equilibrium</u> and <u>nondegenerate</u>.
- ***What is the hole concentration in an n-type semiconductor with 10^{15} cm^{-3} of donors?***
- $n = 10^{15}$ cm^{-3}
- $p = 10^{5}$ cm^{-3}

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

3. Compensated semiconductor

- N_A = , N_D =
- n = , p =

4. Doped semiconductor ($n_i \gg |N_D - N_A|$)

- N_A = , N_D =
- n = , p =

Determination of E_F (Fermi Level)

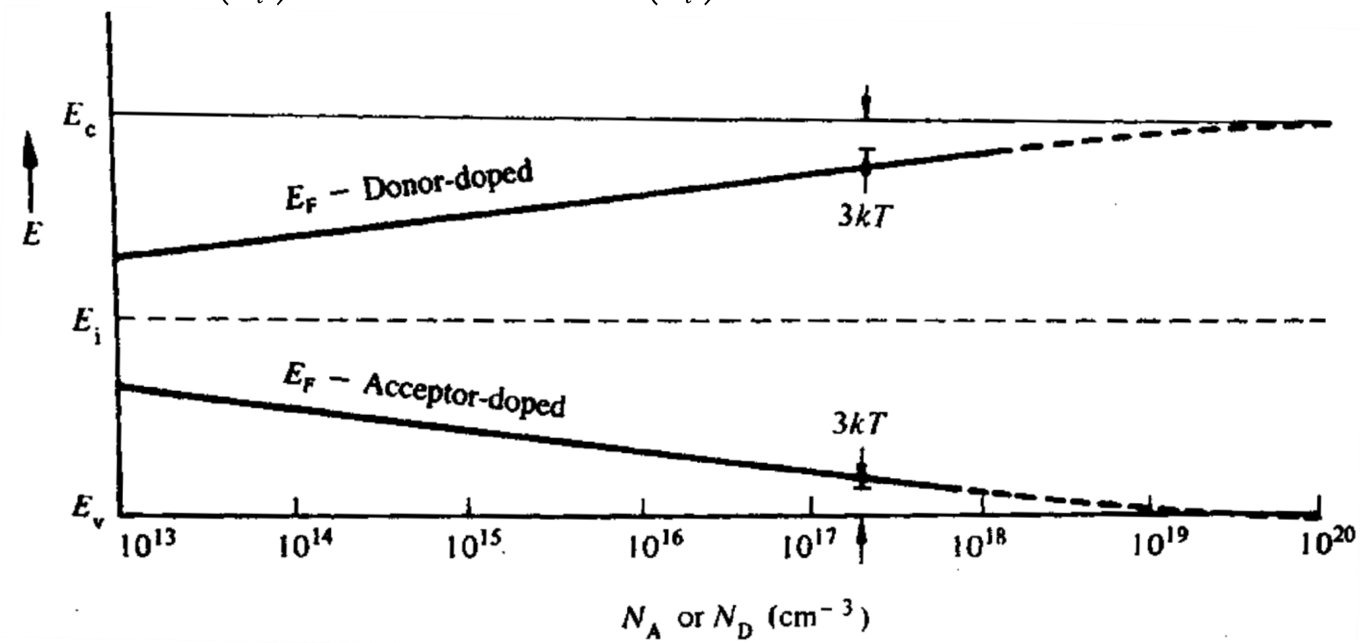
$$n = N_c e^{-(E_c - E_f)/kT} \qquad p = N_v e^{-(E_f - E_v)/kT}$$

- **First, look at the intrinsic energy level**
- ***n = p & $E_F = E_i$***
  - $n = N_C e^{-\frac{E_C - E_i}{kT}}, p = N_v e^{-\frac{E_i - E_v}{kT}}$,
  - $\frac{N_v}{N_c} = \left[\frac{m_p^*}{m_n^*}\right]^{\frac{3}{2}}$
  - $E_i = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ ln\left(\frac{m_p^*}{m_n^*}\right)$
  - **Condition for the intrinsic level to be exactly at the midgap?**

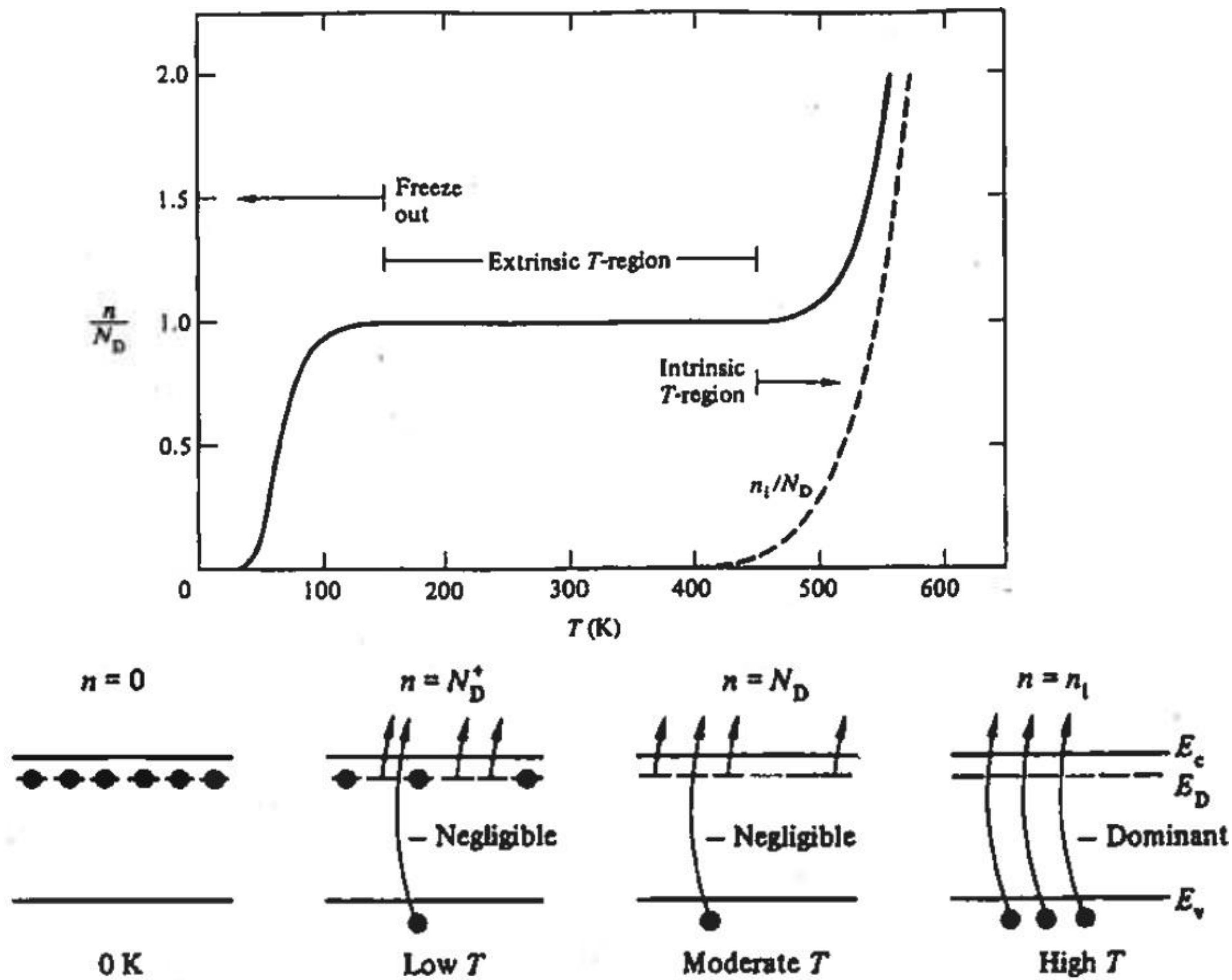
Determination of E_F (Fermi Level)

$$n = n_i e^{\frac{E_F - E_i}{kT}}, \qquad p = n_i e^{\frac{E_i - E_F}{kT}}$$

- **Fermi level** in doped semiconductor (nondegenerate, total ionization)
- $E_F - E_i = kT \ln\left(\frac{n}{n_i}\right) = -kTln\left(\frac{p}{n_i}\right)$
- $E_F - E_i = kT \ln\left(\frac{N_D}{n_i}\right), \quad E_i - E_F = kTln\left(\frac{N_A}{n_i}\right)$

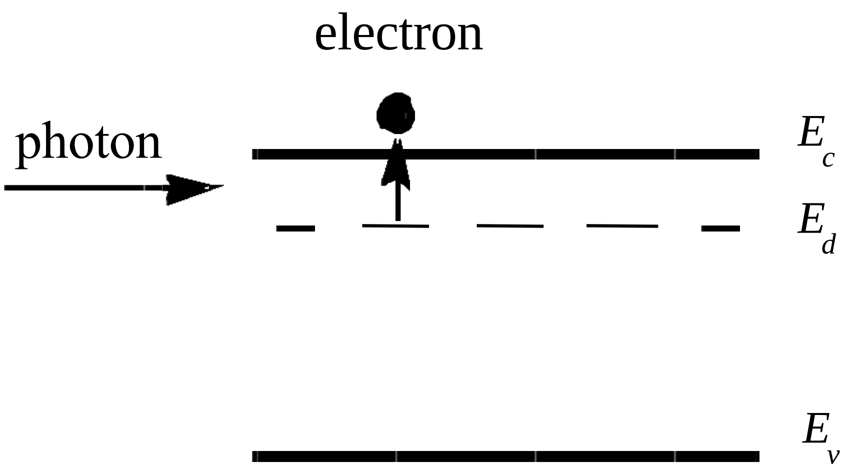


Carrier Concentration Temperature Dependence



Infrared Detector Based on Freeze-out

- To image the black-body radiation emitted by tumors requires a photodetector that responds to $h\varpi$'s around 0.1 eV.
- In doped Si operating in the freeze-out mode, conduction electrons are created when the infrared photons provide the energy to ionized the donor atoms.



Modern Semiconductor Devices for Integrated Circuits (C. Hu)

Summary

- **Studied carriers within a semiconductor under "rest" or equilibrium conditions.**
- **Visualization models**
  - **Bonding model**
  - **Energy band model**
- **Carrier concentration ➔ Charge (**and the flow of carrier…**)**
  - **DOS**
  - **Fermi function**
  - **Dopant energy levels and concentration**
  - **Temperature**
- **Qualitative and Quantitative understanding of carriers in semiconductor**
  - **Which was supposed to be understood by Quantum Mechanics.**

Carrier action

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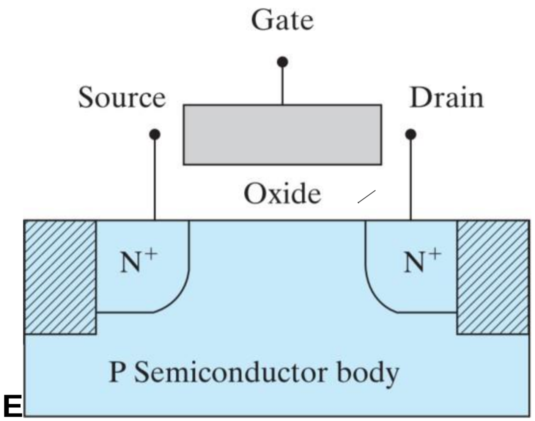

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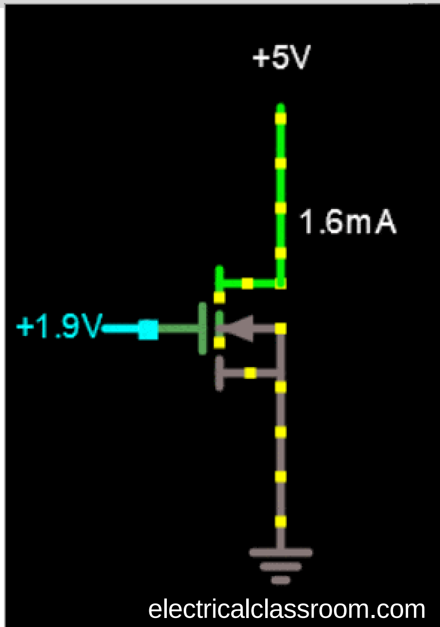
References:
- (C. Hu) Chapter 2
- (R. Pierret) Chapter 3
- Materials from SE393 (Prof. Hongki Kang)

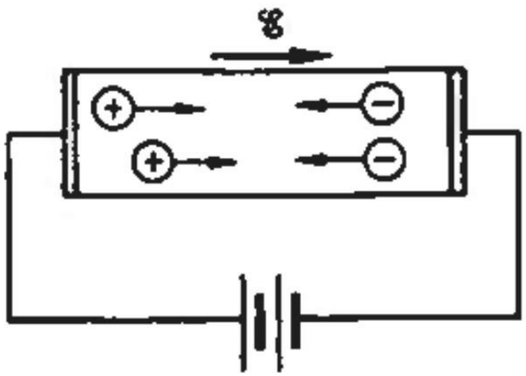


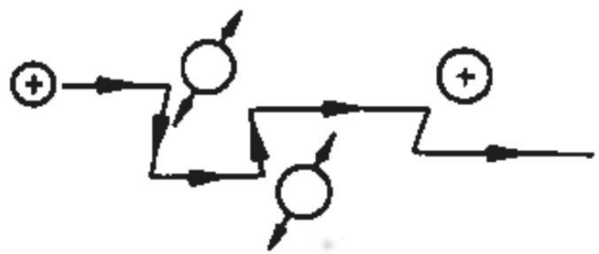
Overview

- **Carrier action inside of semiconductor**
  - **Drift**
  - **Diffusion**
  - **Recombination-Generation (R-G)**

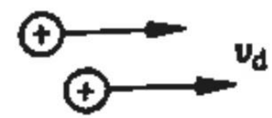
- **These contribute to ‘non-zero’ current components in electronic devices.**

Drift current



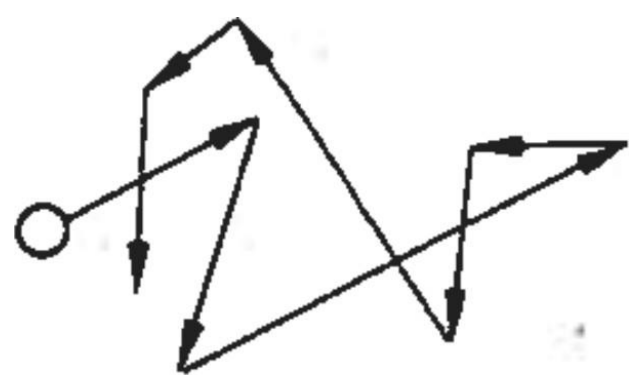


microscopic



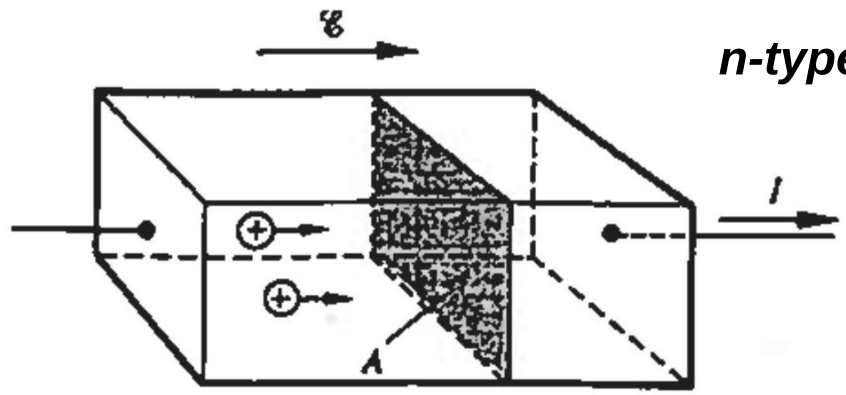
macroscopic

- **Drift – *charged* particle motion by applied *electric field***
- **Direction for holes and electrons under the same E-field?**
- **Microscopic**
- **Macroscopic**



Random thermal motion of carrier

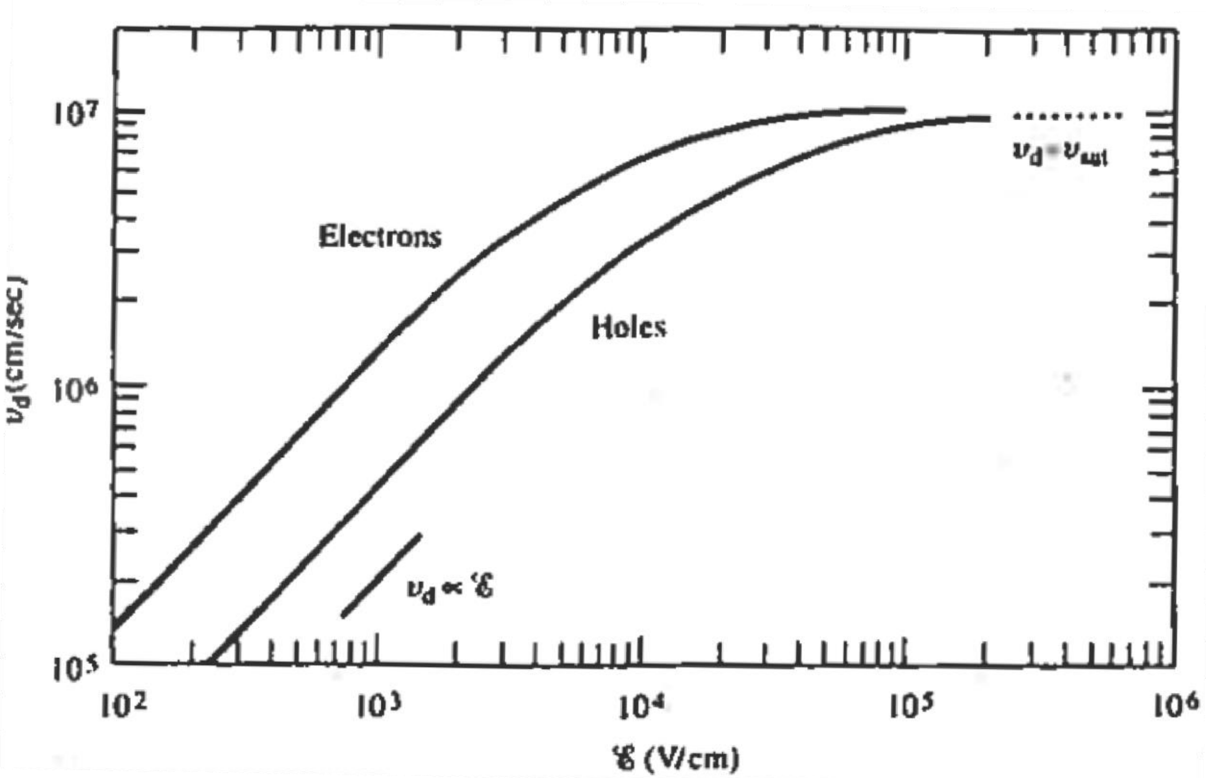
Drift Current



n-type? p-type?

- **Current *I* = *dQ/dt***
- **In the perspective of *holes***
  - $v_d tA$ – volume for holes that will cross the plane in a time *t*
  - $pv_d tA$ – # of holes that will cross the plane in a time *t*
  - $qpv_d tA$ **– amount of charge that will cross the plane in a time *t* (*dq*)**
  - $I_{P|drift} = qpv_d\, A$
- **Drift current density:** $J_{P|drift} = qpv_d$ $J_{N|drift} =$
- **Direction?**

Drift Velocity



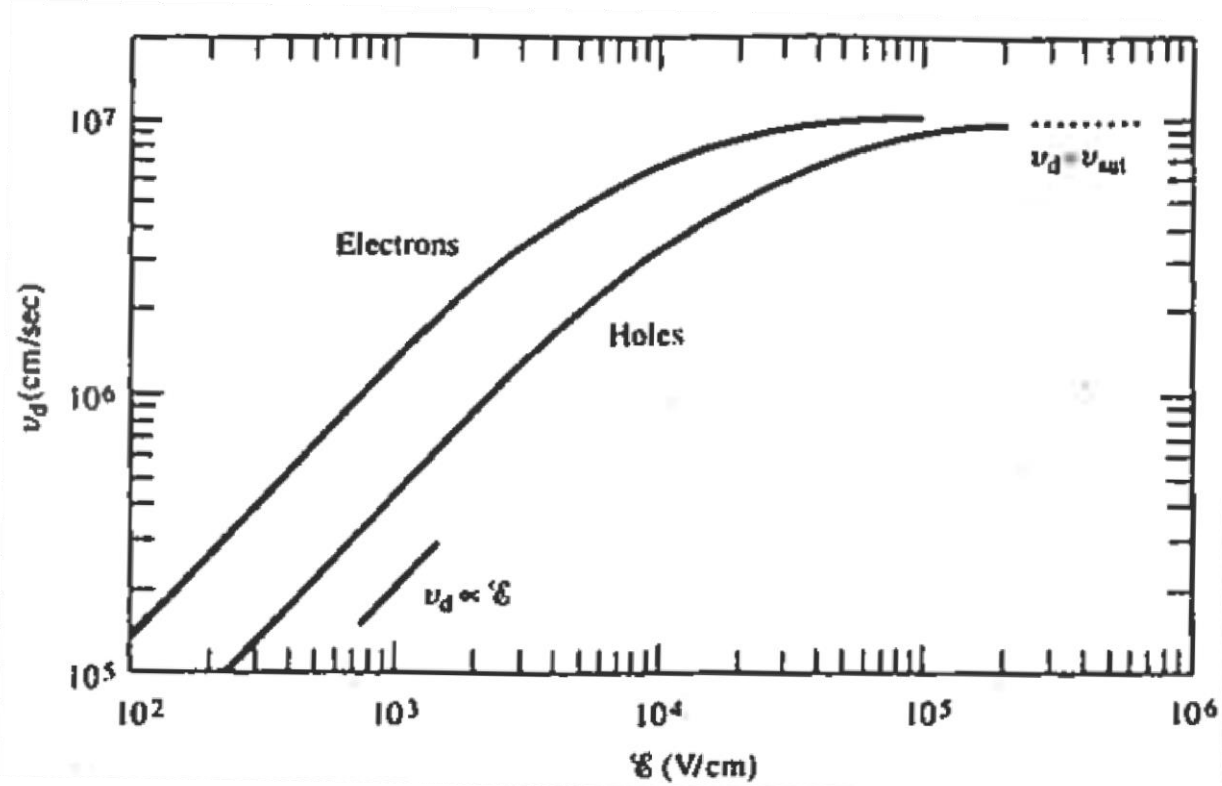
- **Relationship between *Electric field* and *Carrier velocity* (*n*, *p*)**

- $$v_d = \frac{\mu_o E}{\left[1+\left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{\frac{1}{\beta}}}$$

(When $E \rightarrow 0$) $v_d = \mu_o E$

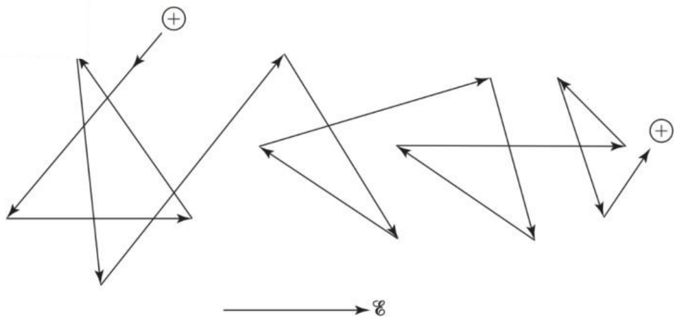
(When $E \rightarrow \infty$) $v_d = v_{sat}$

Drift Velocity saturation (just for your information)



$$m_p v = q\mathscr{E}\tau_{mp}$$

$$v = \frac{q\mathscr{E}\tau_{mp}}{m_p}$$



- $v_{thermal} \approx speed\ of\ light * \frac{1}{1000}$

Current density

$$v_d = \mu_o E \begin{cases} \mu_p E \text{ (hole)} \\ -\mu_n E \text{ (electron)} \end{cases}$$

Drift current density:

$J_{P|drift} = qpv_d$ (hole)

$J_{n|drift} = -qnv_d$ (electron)

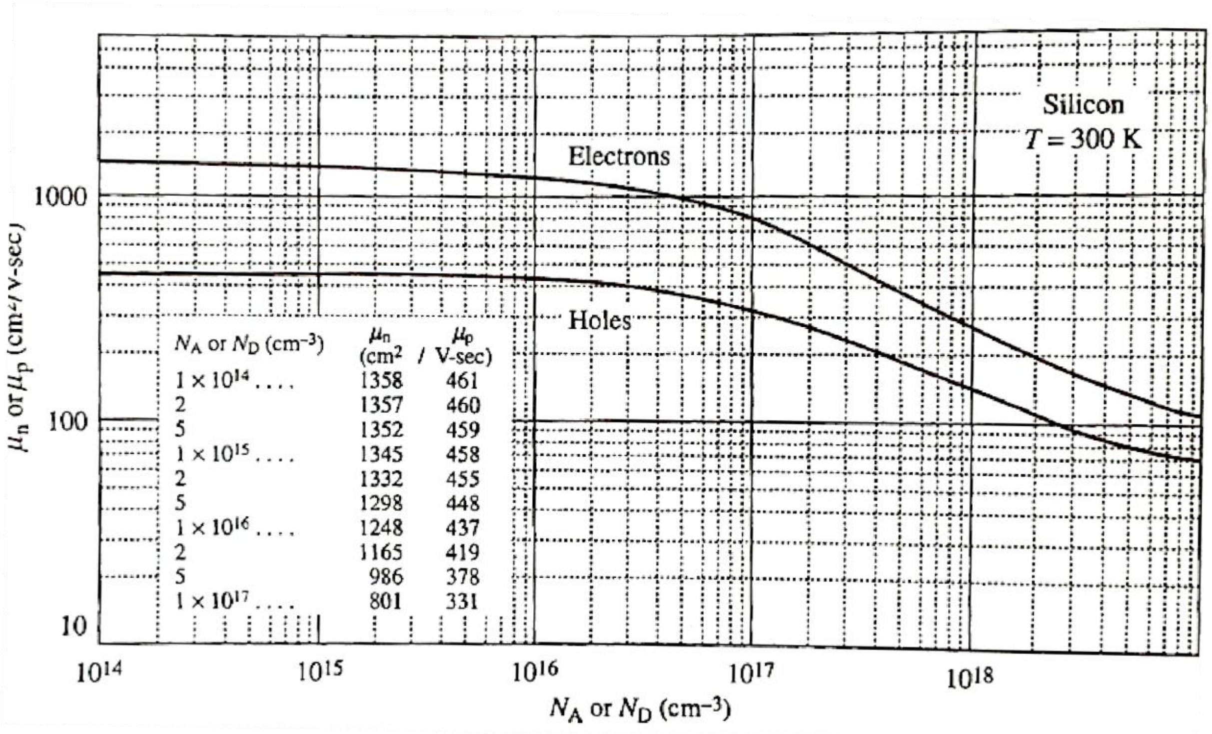
Drift current density:

$J_{P|drift} = q\mu_p pE$ (hole)

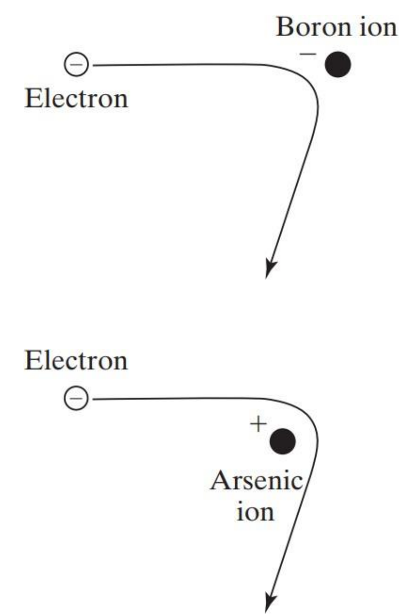
$J_{n|drift} = q\mu_n nE$ (electron)

- $\mu_p \equiv$ **mobility (hole)**
- $\mu_n \equiv$ **mobility (electron)**

Mobility (μ)

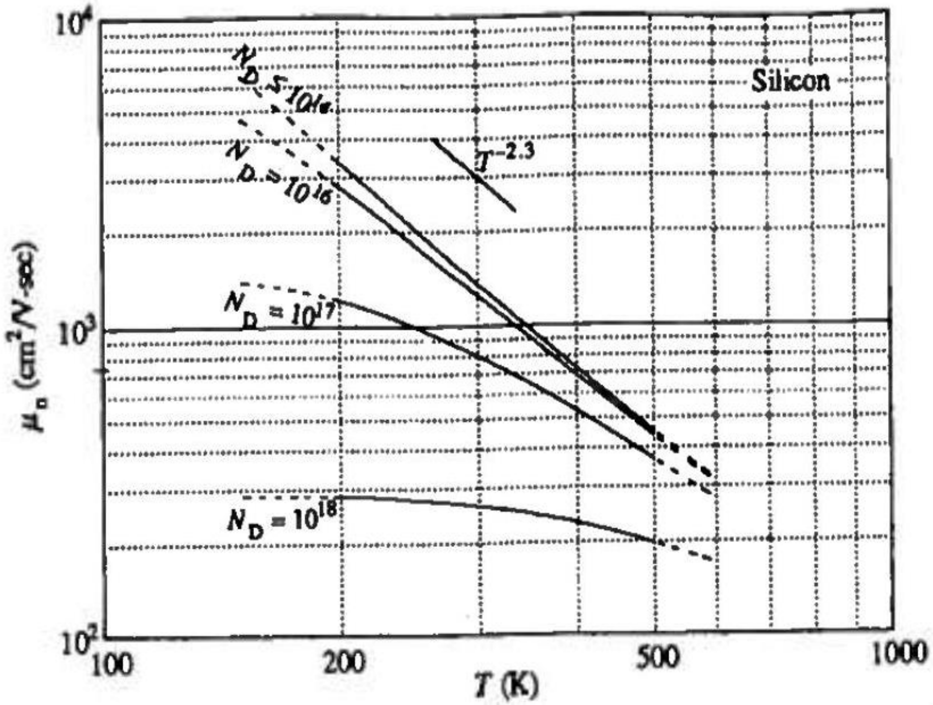


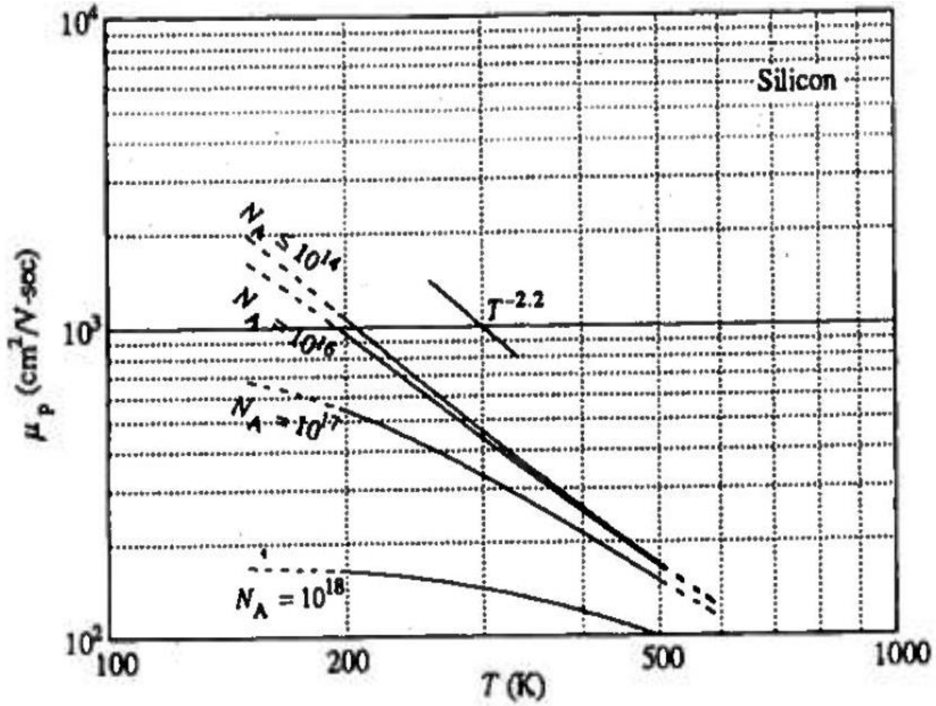
N_A or N_D (cm^{-3})	μ_n (cm^2 /	μ_p V-sec)
1×10^{14}	1358	461
2	1357	460
5	1352	459
1×10^{15}	1345	458
2	1332	455
5	1298	448
1×10^{16}	1248	437
2	1165	419
5	986	378
1×10^{17}	801	331



- ***μ*** **– one of the most representative semiconductor parameter**
- **Strongly related to *scattering***
  - **Doping concentration**
  - **Temperature (lattice scattering)**

Mobility (μ)





- ***μ*** **– one of the most representative semiconductor parameter**
- **Strongly related to *scattering***
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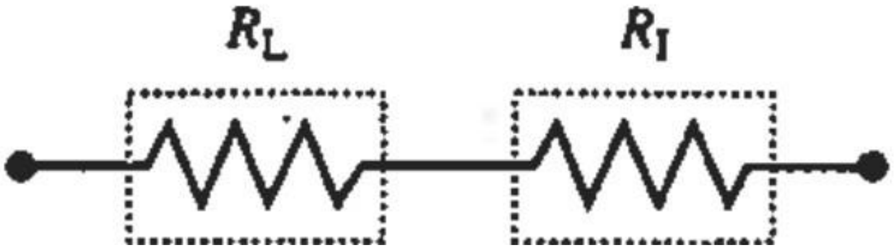
Mobility (μ)



Due to lattice scattering

Due to Ionized impurity scattering

Carrier motion impedance

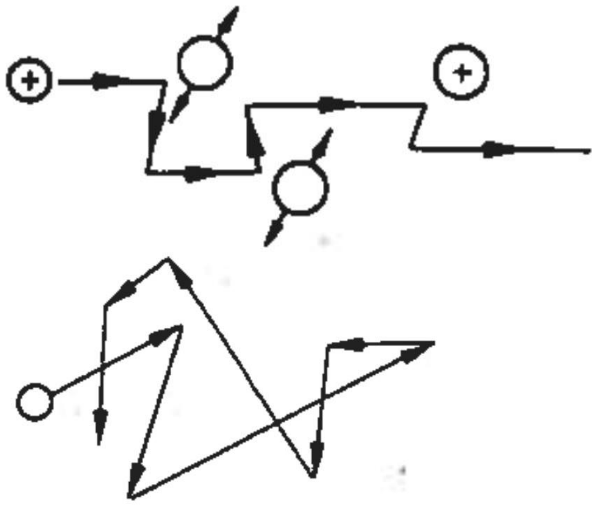
$$R_{total} = R_L + R_I$$

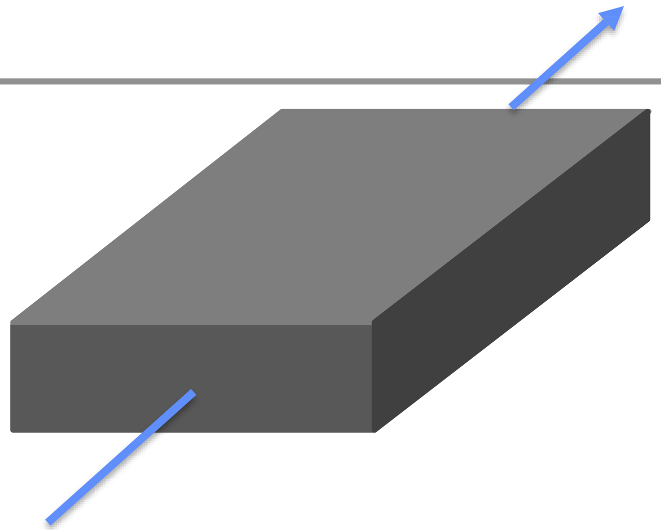
$$\mu = q\langle\tau\rangle/m^*$$

$\langle\tau\rangle$: **Mean free time between collisions**

m^*: **Effective mass for conductivity**

- **Doping dependence**
- **Temperature dependence**



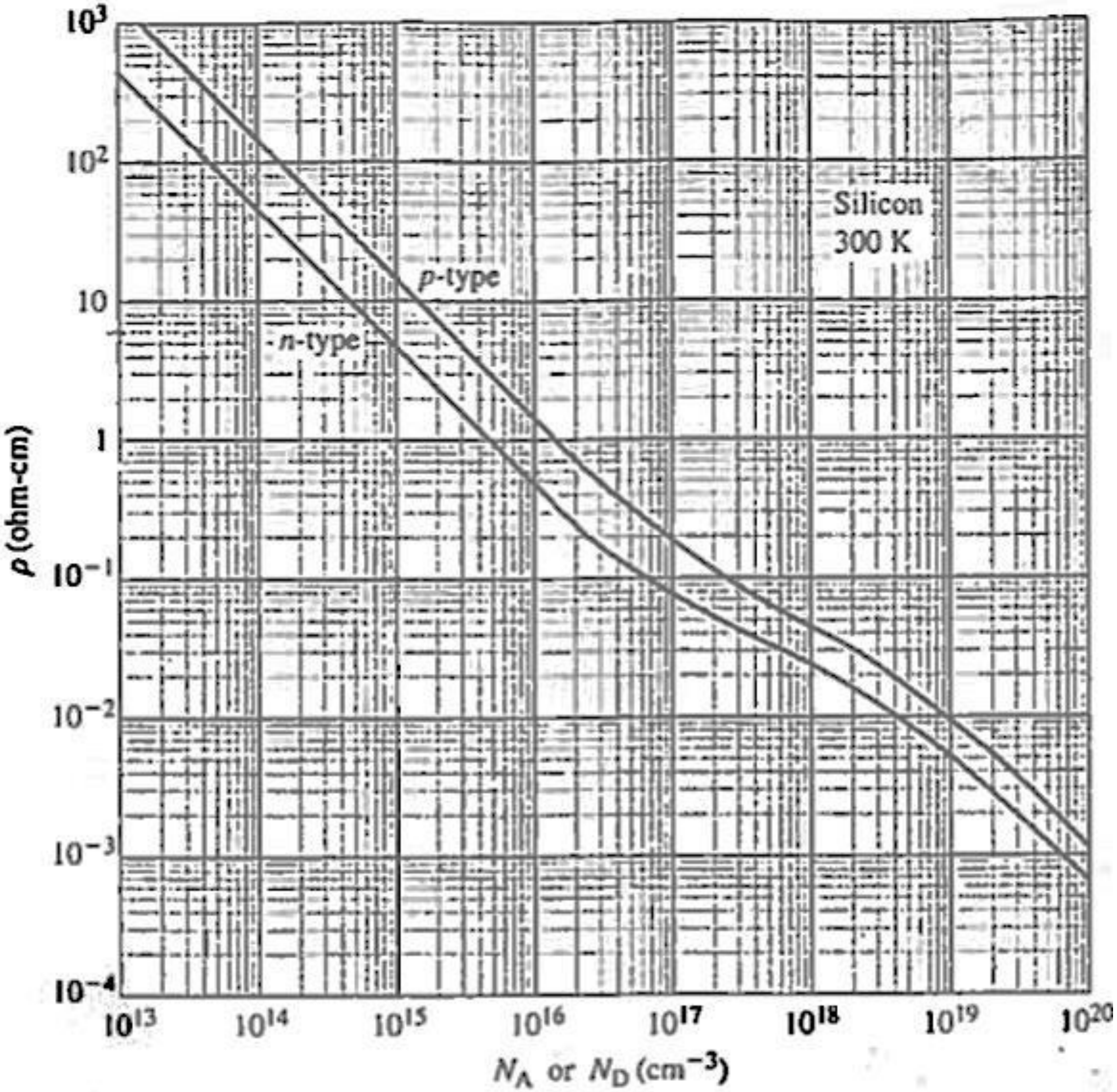


- **Resistivity (ρ) of metal (right)**
- **How about semiconductor?**
  - **Drift**
  - **Current density,** $J = \sigma E$ **(σ : conductivity)**
  - $E = \left(\frac{1}{\sigma}\right) J = \rho J$ **(ρ = 1/σ : resistivity)**
  - $J_{drift} = J_{N|drift} + J_{P|drift} = q(\mu_n n + \mu_p p)E$
  - $\sigma = q(\mu_n n + \mu_p p)$
  - $\rho = 1/q(\mu_n n + \mu_p p)$

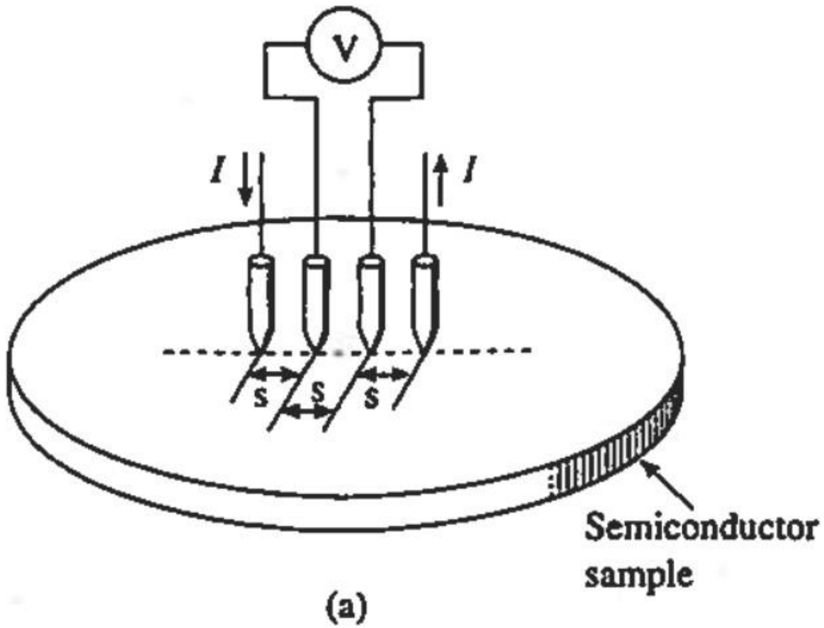
(n-type: N_D): $\rho \approx$

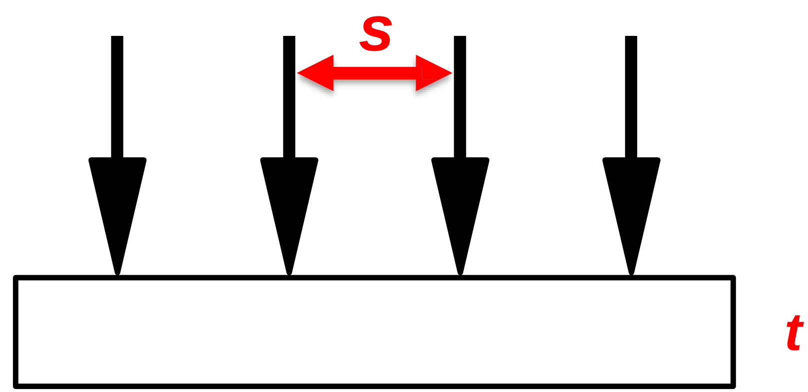
(p-type: N_A): $\rho \approx$

Resistivity



Resistivity (Four-point probe)





- **Sample thickness**
- **Probe spacing (s)**

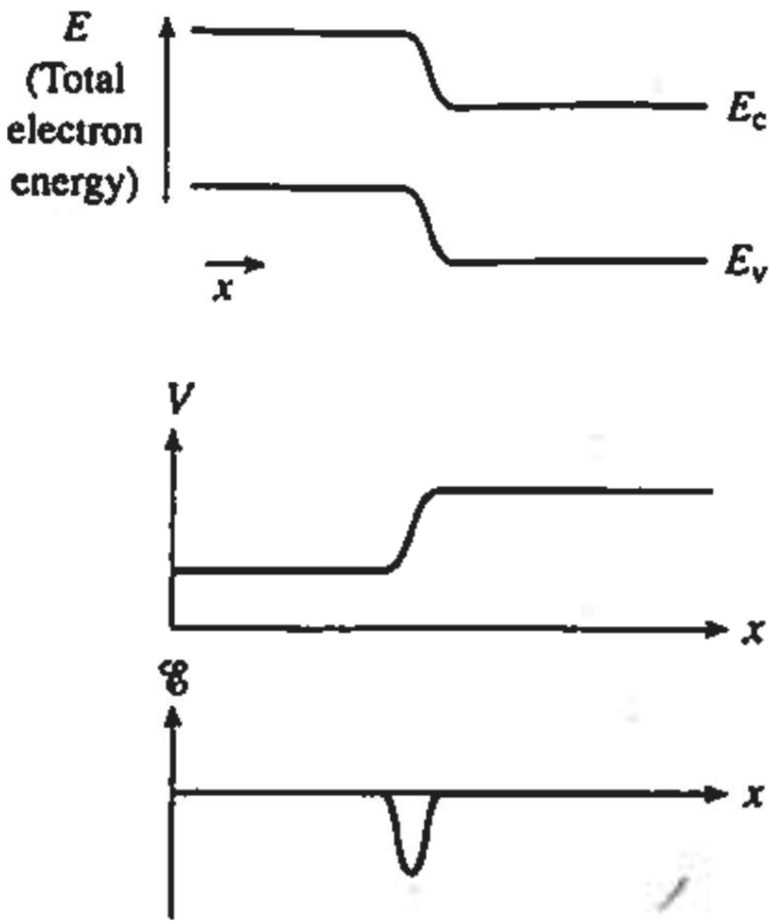
$$\rho = 2\pi s \left(\frac{V}{I}\right)\Gamma$$

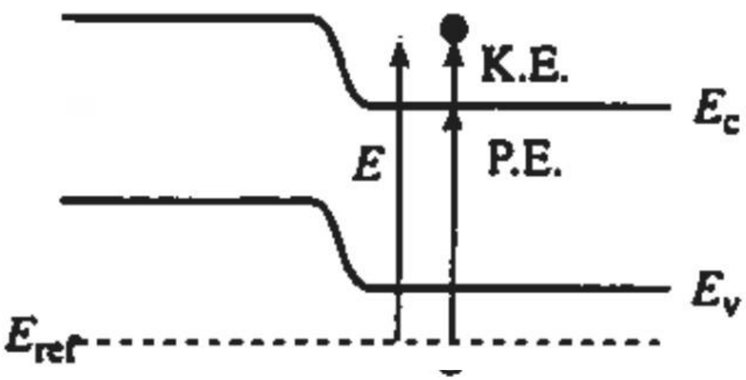
$$\Gamma = 1 \qquad \text{(t >> s)}$$

$$\Gamma = \frac{t}{2s\ln 2} \qquad \text{(t << s)}$$

Band Bending

- **What does band bending mean?**





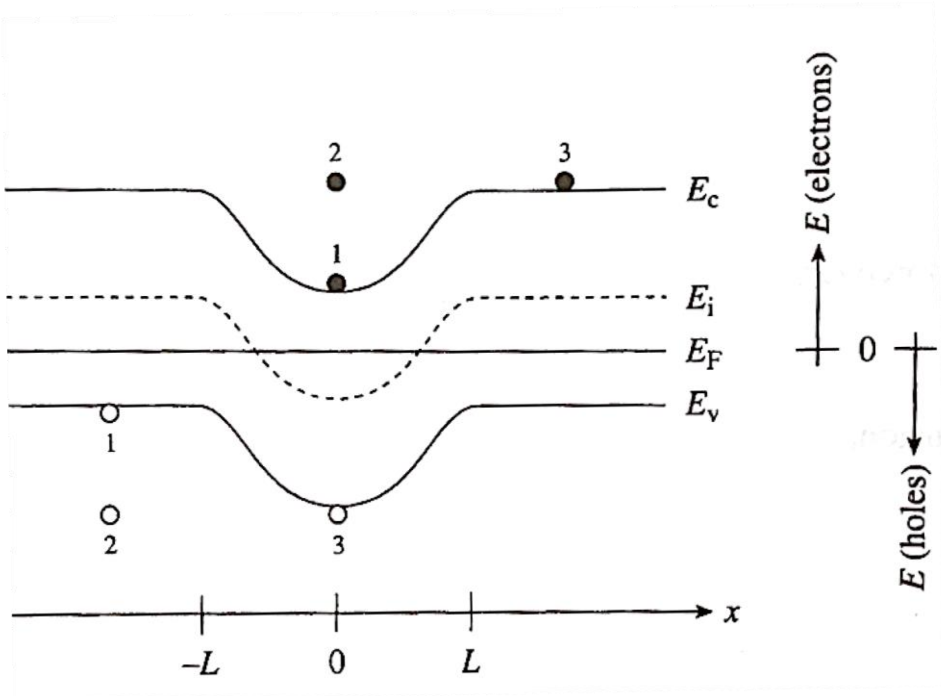
Potential Energy = $(-q)V = E_c - E_{ref}$

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

$$E = -\nabla V$$

$$\boldsymbol{E = \frac{1}{q}\left(\frac{dE_c}{dx}\right) = \frac{1}{q}\left(\frac{dE_v}{dx}\right) = \frac{1}{q}\left(\frac{dE_i}{dx}\right)}$$

Band Bending – Example

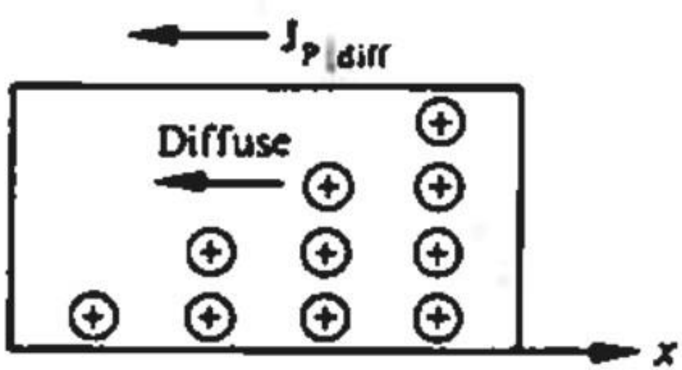


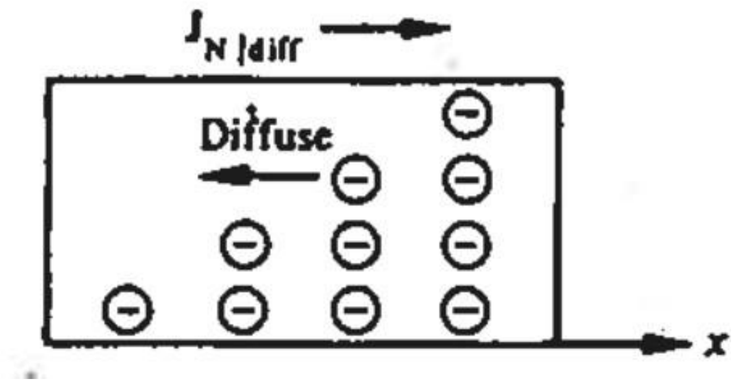
- **Electrostatic potential, *V*(*x*)?**
- **Electric field, *E*(*x*)?**

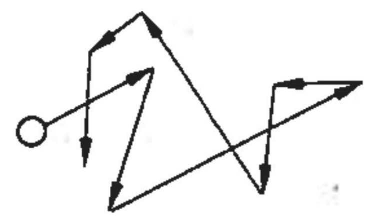
$$E = \frac{1}{q}\left(\frac{dE_c}{dx}\right) = \frac{1}{q}\left(\frac{dE_v}{dx}\right) = \frac{1}{q}\left(\frac{dE_i}{dx}\right)$$

Diffusion current

- Diffusion = "Redistribution of carriers by *random thermal motion"*
  - Not by interparticle repulsion
  - Not along different energy states
  - But along locations (over 3D space)
  - *On average*, net movement of carriers from *high* to *low* concentration





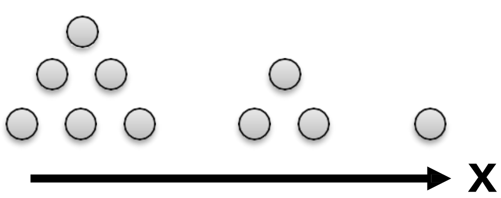


Diffusion Currents

- n(x,y,z), p(x,y,z)
- $\nabla n \neq 0, \nabla p \neq 0$
- Fick's law (of diffusion)
  - Flux of particles, F (particles/cm^2 · sec)

    $$F = -D\nabla n \text{ or } -D\nabla p$$
  - D: diffusion coefficient (cm^2/sec)
- Diffusion current density, J = (charge) x (flux)
  - $J_{P|diff} = -qD_p\nabla p$
  - $J_{N|diff} = qD_n\nabla n$

$$\nabla F = \frac{\partial F}{\partial x}\mathbf{i} + \frac{\partial F}{\partial y}\mathbf{j} + \frac{\partial F}{\partial z}\mathbf{k}$$



$\frac{\partial F}{\partial x}$ 0

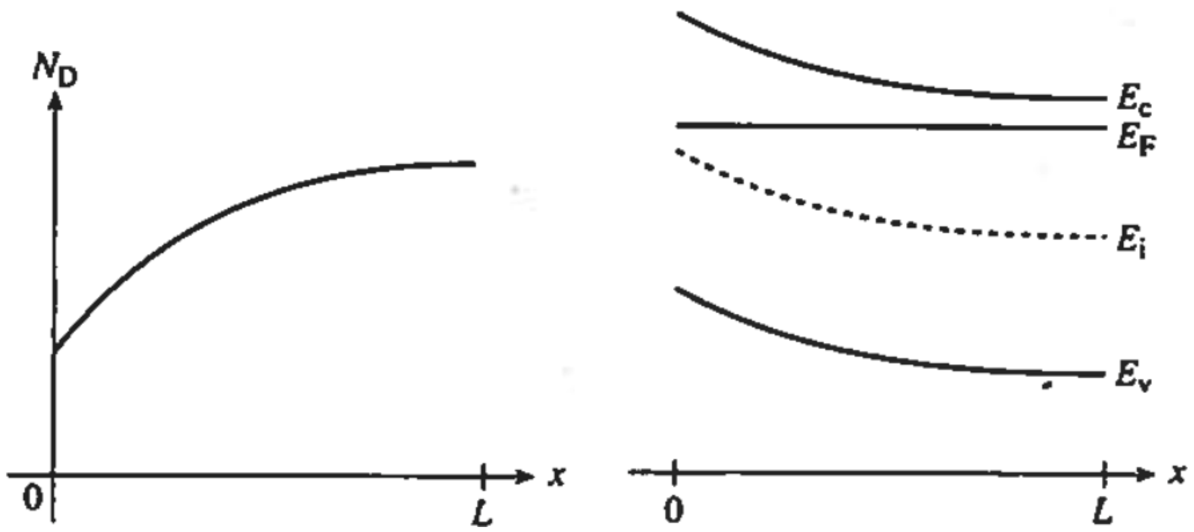
Total Currents

- **Total carrier current: *Drift* + *Diffusion***
  - $\mathbf{J_P} = \mathbf{J_{P|drift}} + \mathbf{J_{P|diff}} = q\mu_p pE - qD_p\nabla p$
  - $\mathbf{J_N} = \mathbf{J_{N|drift}} + \mathbf{J_{N|diff}} = q\mu_n nE + qD_n\nabla n$
  - $\mathbf{J} = \mathbf{J_N} + \mathbf{J_P}$

- **Note that (+/–) sign for drift and diffusion are different.**

Relating Diffusion Coefficients/Mobilities

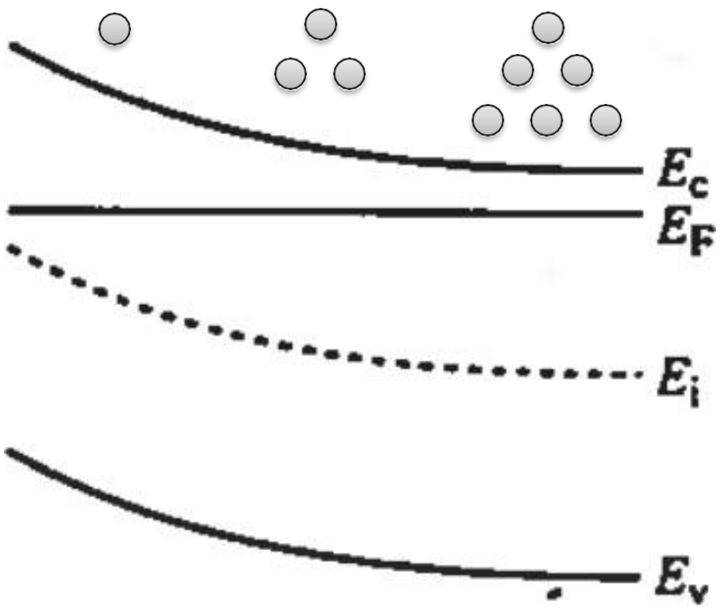
- **Constancy of the Fermi Level**



- **Non-uniformly doped semiconductor**
- **Under equilibrium conditions,**
  - $\nabla E_F = 0; \frac{\partial E_F}{\partial x} = \frac{\partial E_F}{\partial y} = \frac{\partial E_F}{\partial z} = 0$
  - **Fermi level is constant over space.**

Relating Diffusion Coefficients/Mobilities

- **Current Flow under Equilibrium Conditions**
- **Total current in this equilibrium condition must be *zero*.**
- **How?**



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

$$J_N = J_{N|drift} + J_{N|diff}$$
$$= q\mu_n n E + qD_n \nabla n$$

Relating Diffusion Coefficients/Mobilities

- $\mathbf{J_N} = \mathbf{J_{N|drift}} + \mathbf{J_{N|diff}} = \boldsymbol{q\mu_n nE} + \boldsymbol{qD_n \nabla n} = \mathbf{0}$ (under equilibrium)
  - $E = \frac{1}{q}\frac{dE_i}{dx}$
  - $n = n_i e^{\frac{E_F - E_i}{kT}}$
  - $\frac{dn}{dx} =$

- $\boldsymbol{q\mu_n nE + qD_n \nabla n = q\mu_n nE + qD_n\left(-\frac{q}{kT}nE\right) = 0}$

- $\boxed{\boldsymbol{\frac{D_n}{\mu_n} = \frac{kT}{q}}}$ **Einstein Relationship**
  (it is also valid in *non-equilibrium* condition)

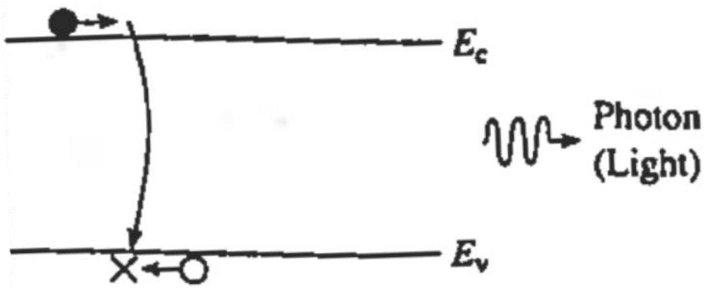
Recombination–Generation

- **Perturbation – Deviation from equilibrium state**
  - **Excess or Deficit of carrier concentration from equilibrium values**
  - **How is the change compansated (or stablized)?**

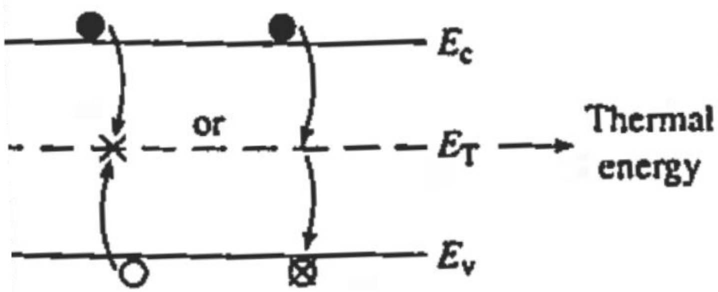
- **Recombination (R)**
  - **A process whereby e^-, h^+ are destroyed (removed).**
- **Generation (G)**
  - **A process whereby e^-, h^+ are created.**

- **When the devices operate, these are mostly in *non-equilibrium* state.**
  - ***R-G processes* occur by many different mechanisms.**

Recombination–Generation

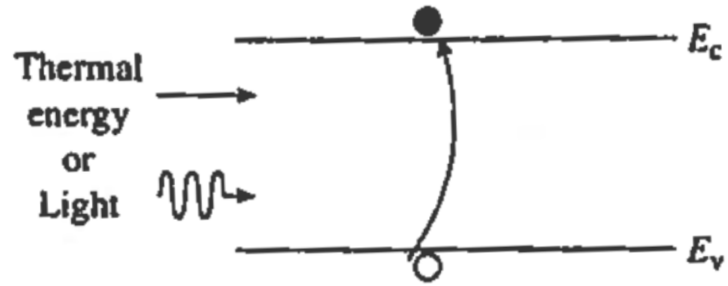


(a) Band-to-band recombination

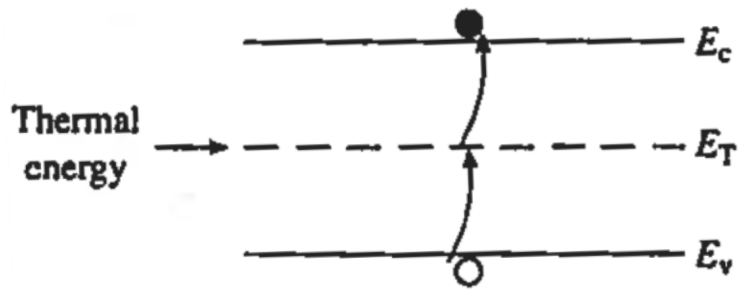


(b) R–G center recombination

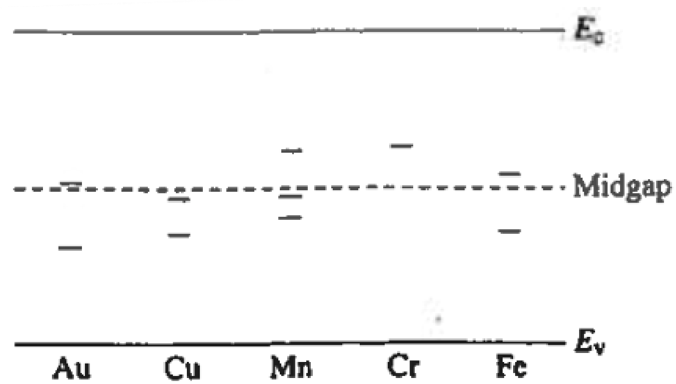
- **R–G centers**
  - **Lattice defects (intrinsic defects)**
  - **Special impurity atoms ⇒**



(d) Band-to-band generation

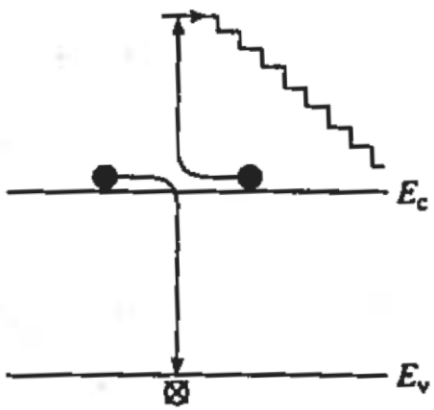


(e) R–G center generation

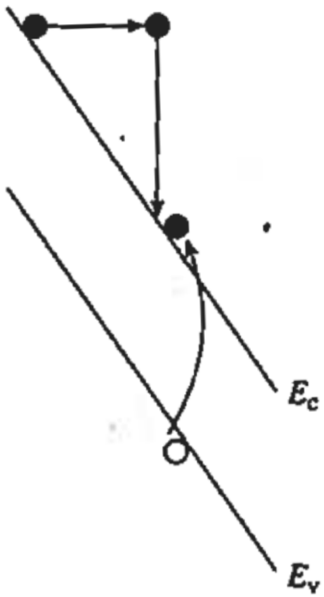


Deep traps

Recombination–Generation



(c) Auger recombination



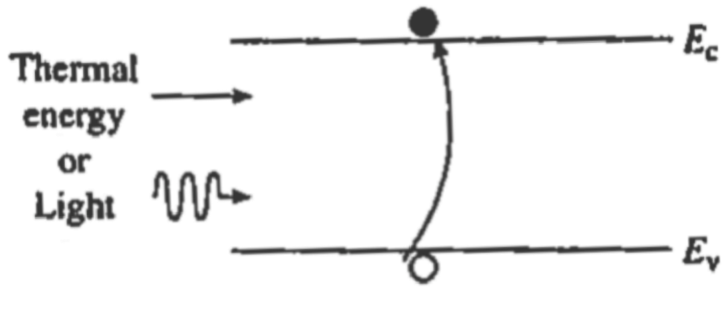
(f) Carrier generation via impact ionization

- **Auger recombination**
  - **<u>When carrier concentration is high</u>, and thus more collisions occur.**
- **Impact ionization**
  - **<u>At high E-field</u> & easy to obtain high energy**
- **In other conditions, the other mechanism in a previous slide dominates.**

Carrier lifetime (τ)

$$n \equiv n_0 + n'$$

$$p \equiv p_0 + p'$$



(d) Band-to-band generation

$$n' \equiv p'$$ **Due to charge neutrality**

$$\frac{dn'}{dt} = -\frac{n'}{\tau} = -\frac{p'}{\tau}$$

$$\text{Recombination rate} = \frac{n'}{\tau} = \frac{p'}{\tau}$$

- n', p': **excess carrier concentrations (e.g. created by light)**