EE105 – Fall 2015
Microelectronic Devices and Circuits:
Basic Semiconductors

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Excellent Reference for Module 2:

Chenming Hu, *Modern Semiconductor Devices for Integrated Circuits*, 2010

downloadable from:

https://people.eecs.berkeley.edu/~hu/Book-Chapters-and-Lecture-Slides-download.html

Silicon: Group IV Element

P-type dopant

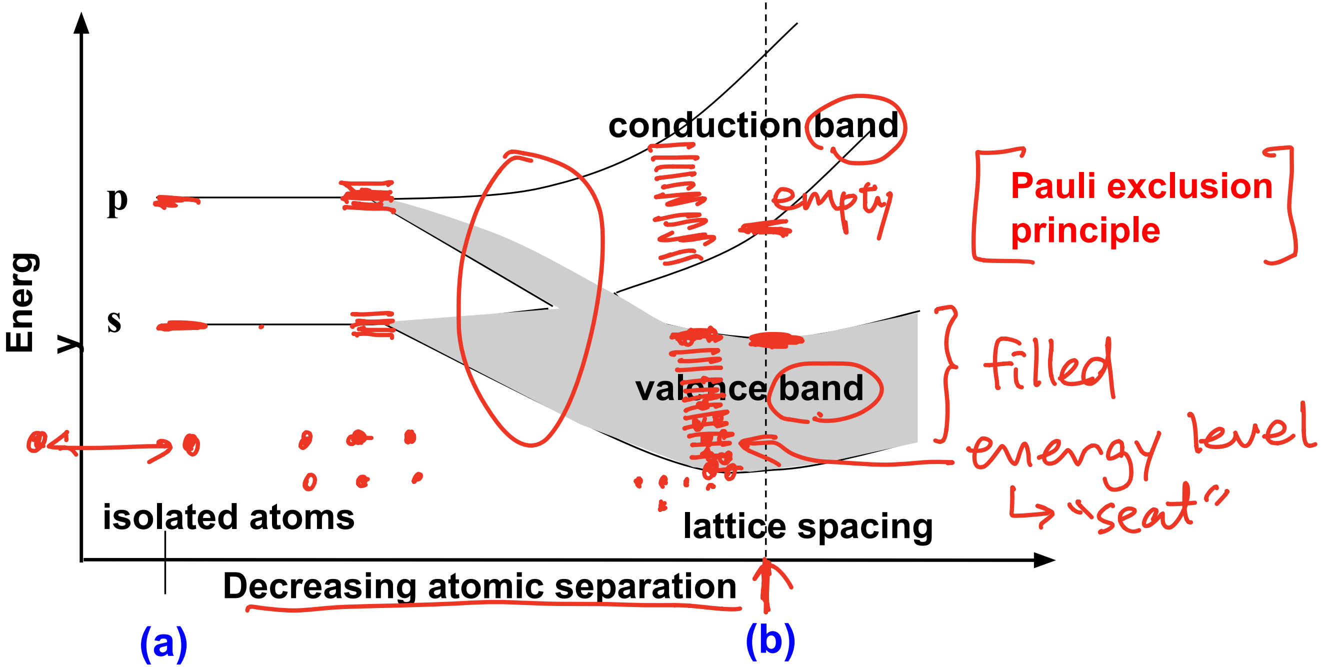
N-type dopant

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	GASES
1 H 1.00797																1 H 1.00797	2 He 4.0026
3 Li 6.939	4 Be 9.0122											5 B 10.811	6 C 12.0112	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.183
11 Na 22.9898	12 Mg 24.312											13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	*57 La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	‡89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 ? (271)	111 ? (272)	112 ? (277)						

Resistivity of Typical Materials

- **Conductors**
  - **Copper: 1.7 x 10^{-6} Ω-cm** (or 1.7 x 10^{-8} Ω-m) $\rho = \frac{1}{\sigma}$
  - **Aluminum: 2.8 x 10^{-6} Ω-cm**
- **Insulators**
  - **SiO_2: 10^{18} Ω-cm**
- **Semiconductor**
  - **Silicon: 10^{-3} to 10^{3} Ω-cm**
  - **A wide range of resistivity,**
  - **Can be controlled by "doping" of impurities or electrical bias**

From Atoms to Crystals



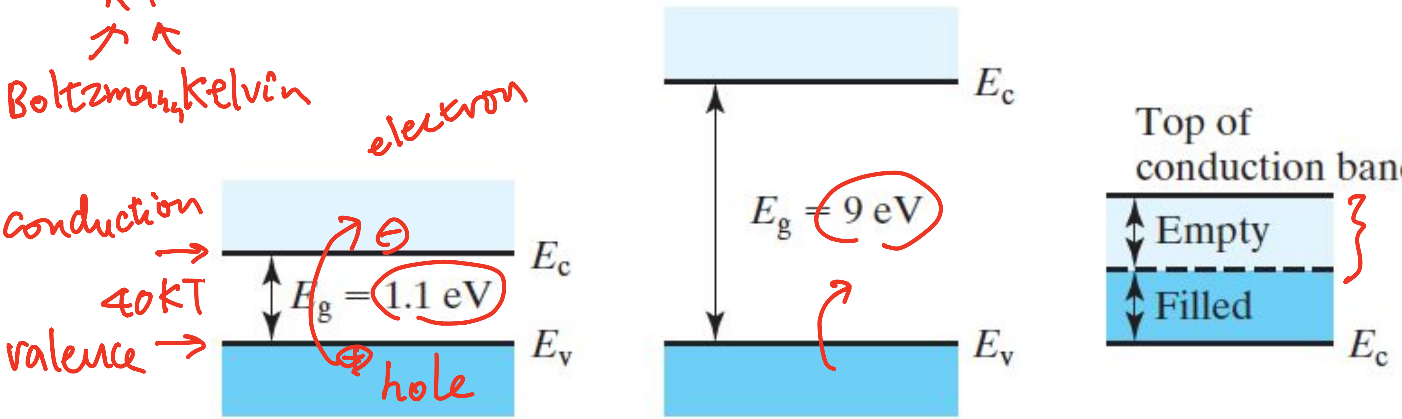
- Energy states of Si atom (a) expand into energy bands of Si crystal (b).
- The lower bands are filled and higher bands are empty in a semiconductor.
- The highest filled band is the *valence band.*
- The lowest empty band is the *conduction band*

Energy Band Diagram of Various Materials

$1.6\times10^{-19}\,J = 1\,eV$

$kT = 25\,meV$

Boltzman Kelvin

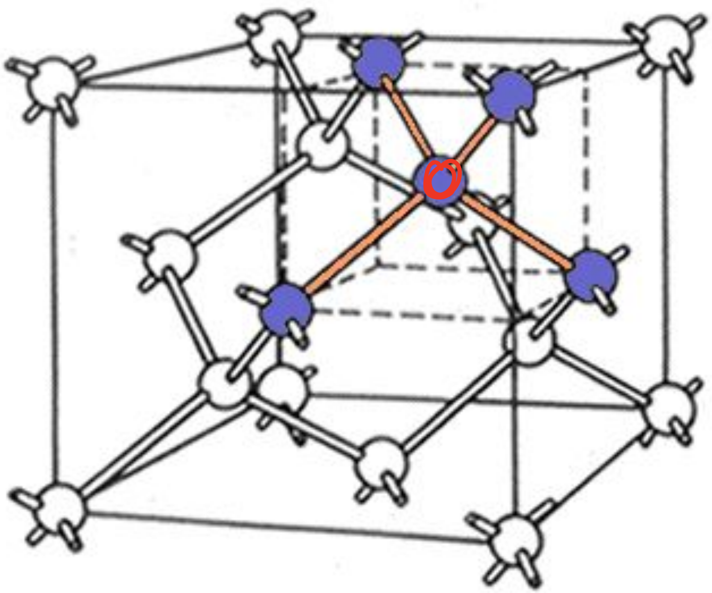


(a) Si, semiconductor (b) SiO_2, insulator (c) Conductor

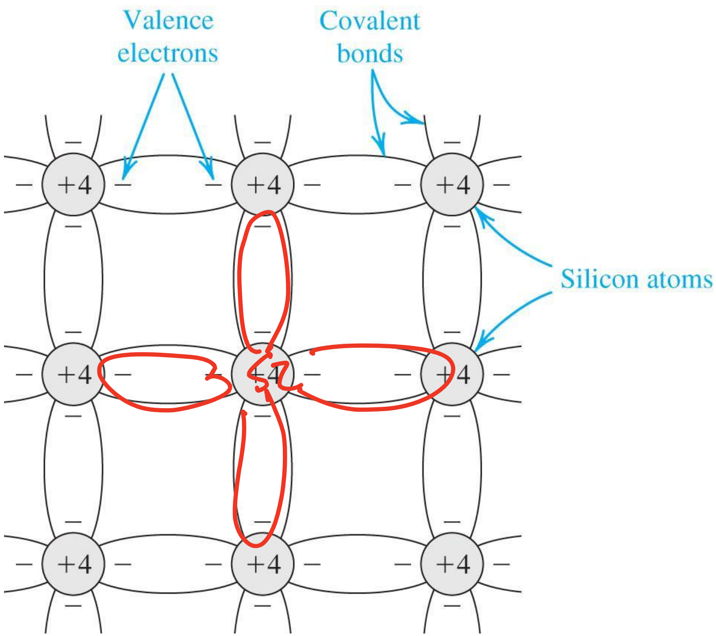
$E_g \sim 10\text{'s}\,kT$ $E_g \gg 100\,kT$

Silicon

Crystalline Structure (Diamond Cubic)

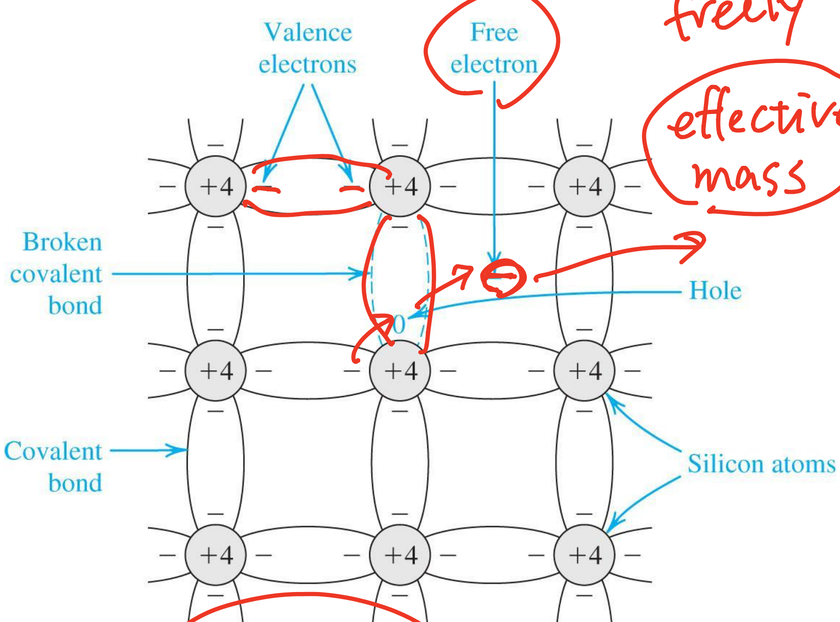


Schematic Two-Dimensional Representation



At 0 Kelvin, all electrons are "locked" in covalent bonds
→ Behave like insulator

Electrons and Holes



move freely

effective mass

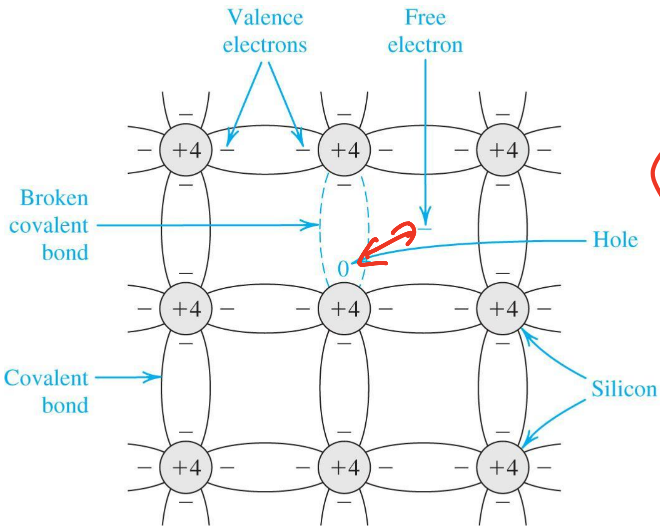
Quantum Mechanics

- At room temperature, thermal energy breaks some covalent bonds, creating free electrons and "holes"
- Hole: empty space left by electron
  - Hole "moves" as adjacent electron move into its space
  - Treat hole like a positively charged particle

$m_e^* \sim 0.25\, m_e$

Intrinsic Semiconductor

SiC
GaN



Intrinsic semiconductor

$n = p = n_i$

n : electron concentration $[\text{cm}^{-3}]$

p : hole concentration $[\text{cm}^{-3}]$

$n_i = BT^{\frac{3}{2}} e^{-\frac{E_g}{2kT}}$: instrinsic carrier concentration

B : material dependent constant

T : temperature in Kelvin

E_g : bandgap energy (=1.12 eV for Si)

k : Boltzmann's constant = $8.62\text{x}10^{-5}$ eV/K

At room temperature ($T = 300K$)

Si $\quad n_i = 1.5 \times 10^{10}$ $[\text{cm}^{-3}]$

Note: There are 5×10^{22} atoms/cm^3, so the number of free electrons and holes are very small

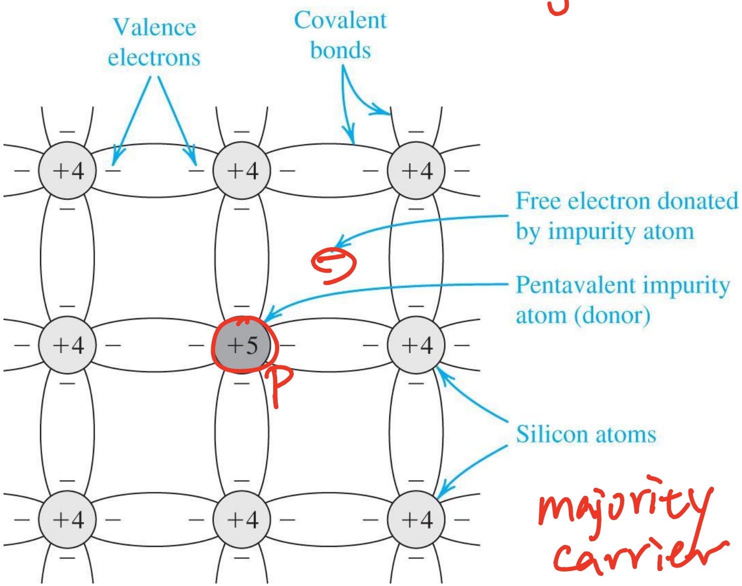
$\frac{n_i}{[Si]} = 10^{-12}$

In general, $np = n_i^2$

N-Type Semiconductor

4 5
B C
Si P
Ga As

Negative



majority carrier

$[P] \sim 10^{15} \sim 10^{19} \frac{1}{cm^3}$

$n \cdot P = n_i^2$ $\quad n_i = 10^{10} \frac{1}{cm^3}$

Mass Action Law $\quad n = 10^{17}$

Minority $\rightarrow P = 10^3$

Electron concentration can begreatly increased by replacing some Si atoms with P (phosphorus) or As (Arsenic), which have 5 shell electrons (one more than Si).

P or As are called "donors"

$n_n = N_D$ (donor impurtiy concentration)

$p_n = \dfrac{n_i^2}{N_D}$ where $n_i = 1.5 \times 10^{10}$ [cm^{-3}]

Subscript n refers to n-type semiconductor (n stands for "negative", referring to the charge carried by electrons)

In n-type semiconductor, $n_n >> n_i >> p_n$

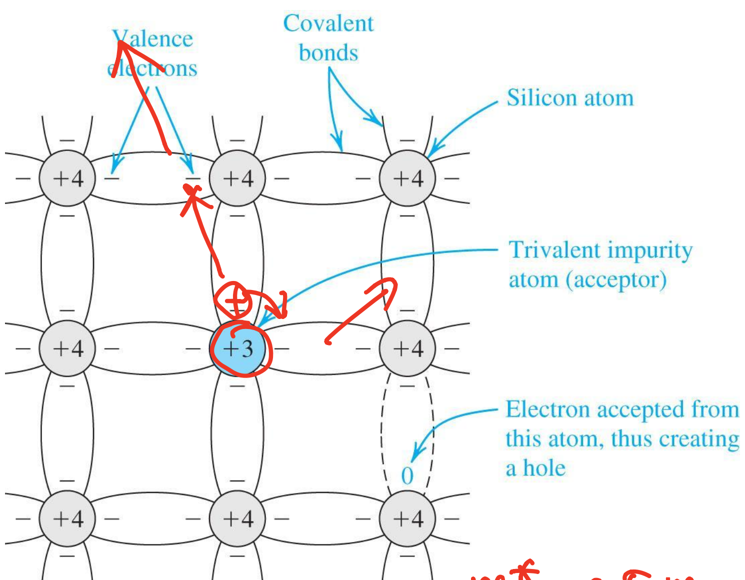
e.g., $N_D = 10^{17}$ cm^{-3}, $n_n = 10^{17}$, $p_n = 2.2 \times 10^3$

Electrons are "majority" carriers,

holes are "minority" carriers

P-Type Semiconductor

Positive



Hole concentration can begreatly increased by replacing some Si atoms with B (boron), which has 3 shell electrons (one less than Si).

B is called "acceptors"

$p_p = N_A$ (acceptor impurtiy concentration)

$n_p = \dfrac{n_i^2}{N_A}$ where $n_i = 1.5 \times 10^{10}$ [cm^{-3}]

The subscript p refers to p-type semiconductor (p stands for "positive", referring to the charge carried by holes)

In p-type semiconductor, $p_p >> n_i >> n_p$

e.g., $N_A = 10^{17}$ cm^{-3}, $p_p = 10^{17}, n_p = 2.2 \times 10^3$

Holes are "majority" carriers, electrons are "minority" carriers

$m_h^* = 0.5\, m_e$

$np = n_i^2$

$p = 10^{17}$

$n \doteq 10^3$

How Electron (or Hole) Move

$\frac{1}{2}mv^2 = kT$

$$v^2 = \frac{25\times10^{-3} \times 1.6\times10^{-19}\,(J) \times 2}{10^{-30}\,(kg)} = \frac{100\times10^{-22}}{10^{-30}} = 10^{10}$$

$v = 10^5$ m/sec

$= 10^7$ cm/sec

$\rightarrow$ 200,000 mph

$c = 3\times10^{10}$ cm/sec

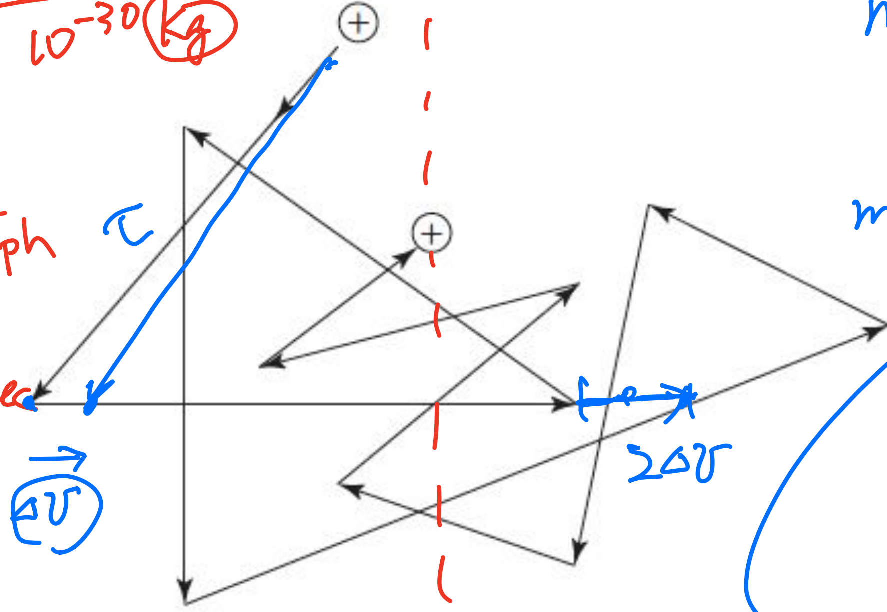
$mv = F\Delta t$

$\uparrow$ average velocity

$mv = (qE)\tau$

$v = \left(\frac{q\tau}{m}\right)\cdot E$

τ = mean free time bt collision



No Electric Field

$v = \mu E$

$\uparrow$ mobility

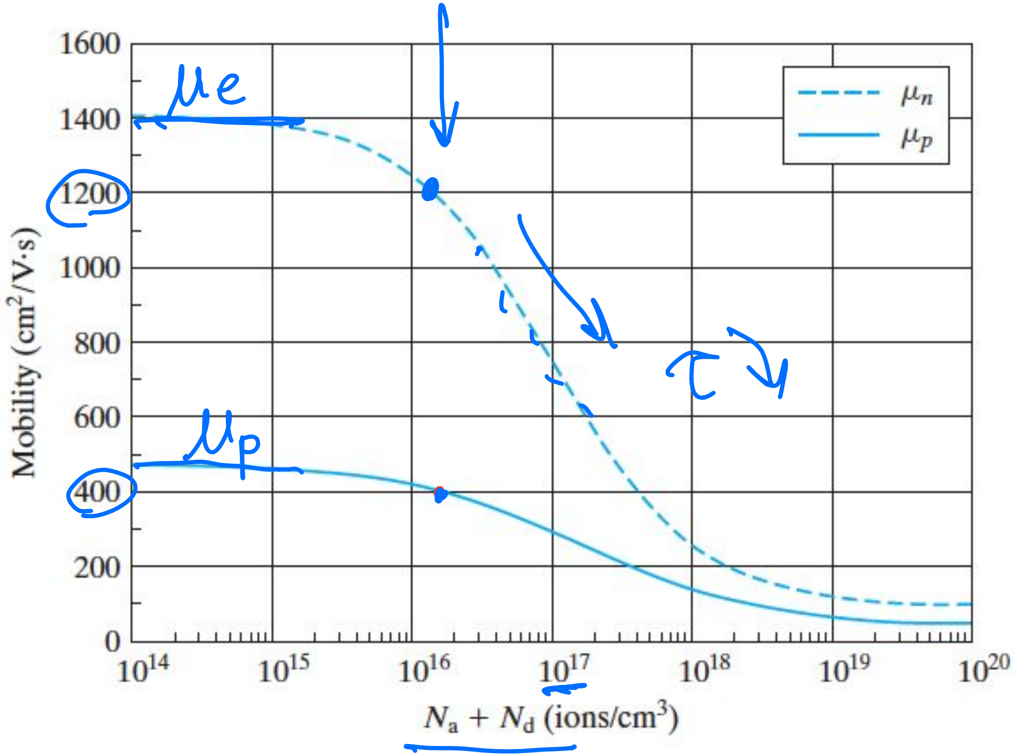
$\longrightarrow \vec{E}$

Mobility of Common Semiconductors

TABLE 2–1 • Electron and hole mobilities at room temperature of selected lightly doped semiconductors.

		Si	Ge	GaAs	InAs
μ_n (cm^2/V·s)	3x	1400	3900	8500	30, 000
μ_p (cm^2/V·s)	1x	470	1900	400	500

Mobility vs Dopant Concentration



$\mu = \frac{q\tau}{m}$

doping $\rightarrow$ $\mu \searrow$

Current: Movement of Charged Particles (Electrons and Holes)

v_{th} Δv

τ: mean free time

$m \cdot \Delta v = \Delta P = F \cdot \tau = (q \cdot E) \cdot \tau \Rightarrow \Delta v = \left(\frac{q\tau}{m}\right) \cdot E = \mu E$

momentum

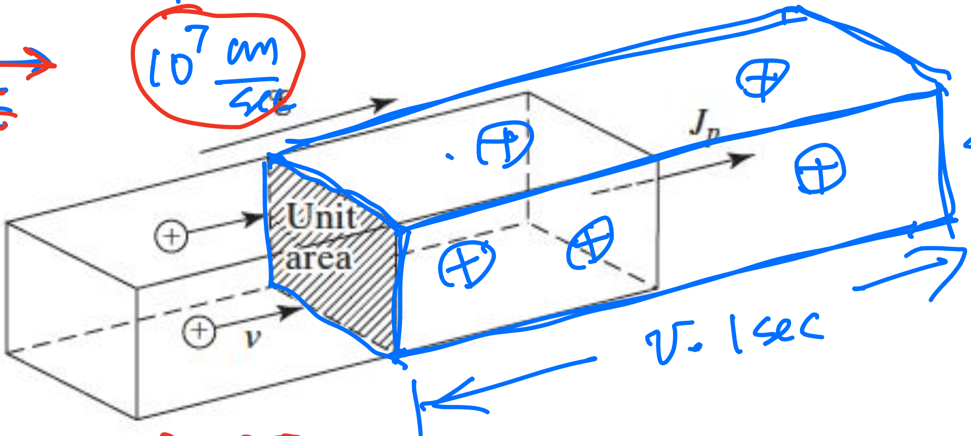
v_{avg}

$v = v_{th} + \Delta v$

τ: function of temp, impurity conc.

$10^7 \frac{cm}{sec}$

E



$1 \times 1 \times (v \times 1\,sec) \times n$

$v \cdot 1\,sec$

$J = n \cdot q \cdot v$

$= n q \mu E$

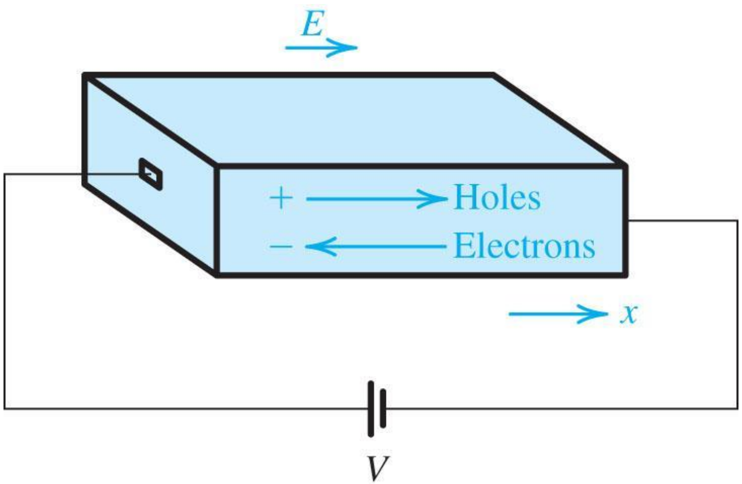
$\frac{I}{Area} = \sigma E$

$= \frac{1}{\rho} E$

$\frac{1}{2} m v^2 = kT$

BSAC

Current in Semiconductor (1): Drift Current



When an electrical field, E, is applied, holes moves in the direction of E, while electrons move opposite to E :

$$\begin{cases} v_{p-drift} = \mu_p E, & \mu_p : \text{ hole mobility} \\ v_{n-drift} = -\mu_n E, & \mu_n : \text{ electron mobility} \end{cases}$$

In intrinsic Si, $\mu_n = 1350\ \text{cm}^2/\text{V}\cdot\text{s}$

$\mu_p = 480\ \text{cm}^2/\text{V}\cdot\text{s}$ (Note: $\mu_n \approx 2.5\mu_p$)

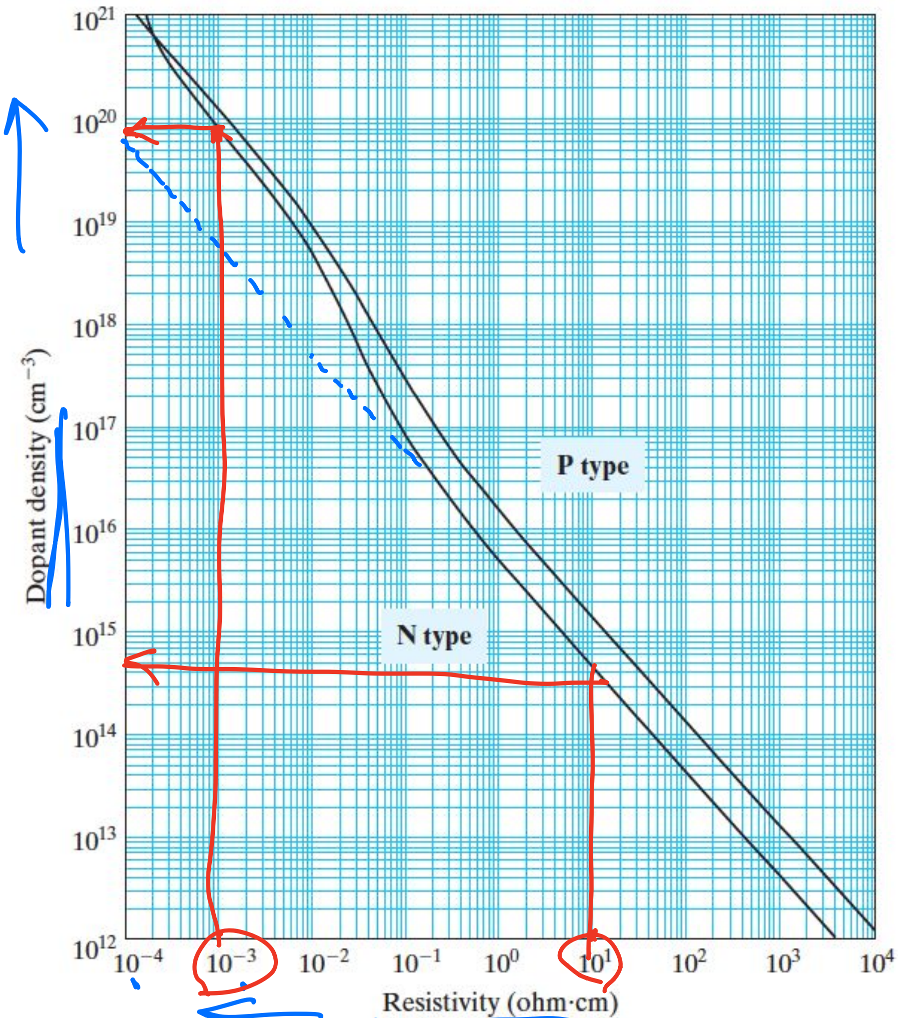
Current density, J [A/cm^2]

$$J = qpv_{p-drift} + qnv_{n-drift} = q(p\mu_p + n\mu_n)E = \sigma E$$

where $\sigma = q(p\mu_p + n\mu_n)$ is conductivity [S/cm]

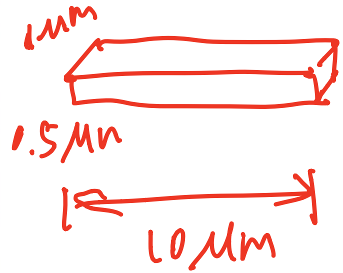
Resistivity $\rho = \dfrac{1}{\sigma}$ [Ω-cm]

Resistivity vs Dopant Concentration



n or p

$N_D + N_A$



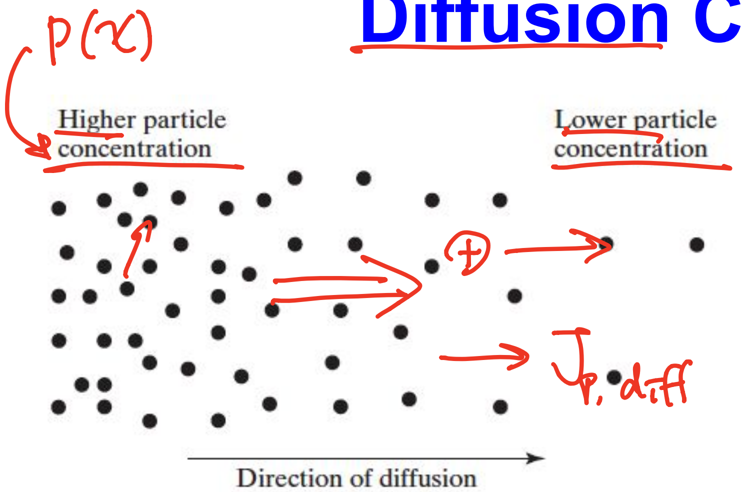
$$R = \rho \cdot \frac{l}{A}$$

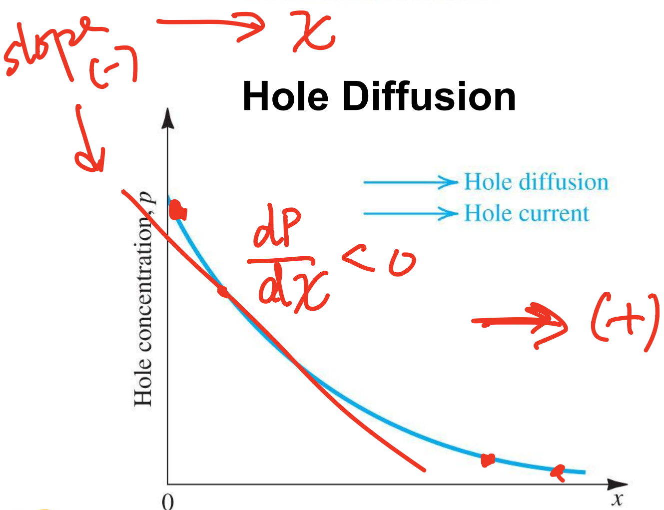
$$\frac{1}{nq\mu_n + pq\mu_p}$$

$$\parallel$$

$$\rho = \frac{1}{\sigma}$$

Current in Semiconductor (2): Diffusion Current - Holes





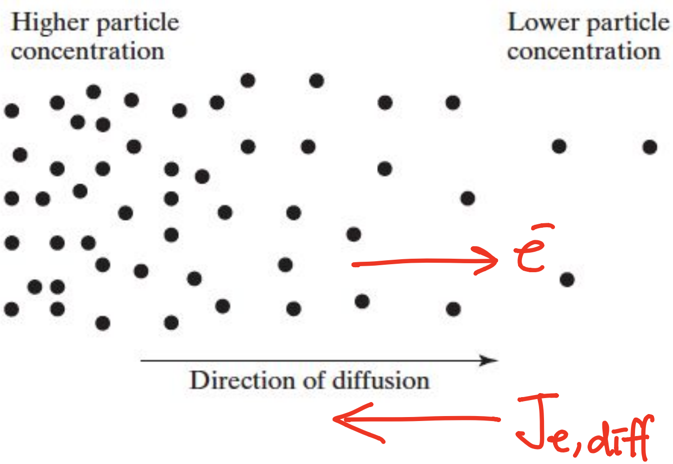
- If hole distribution is non-uniform, holes will move from high to low concentration areas
- Flux ∝ - [conc. gradient] $-\frac{dP(x)}{dx}$
- Current flows since holes carry charge:

$$J_{p-diff} = qD_p\left(-\frac{dp(x)}{dx}\right)$$

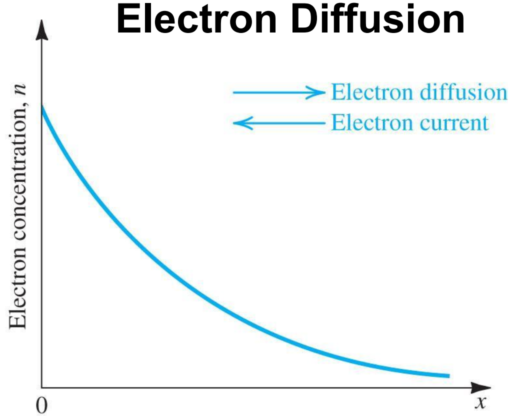
D_p: hole diffusion coef. [cm²/s]

- Note: since hole carries positive charge, hole diffusion and hole current are in the same direction

Current in Semiconductor (2): Diffusion Current - Electrons



Electron Diffusion



- **Similarly, electron diffusion also causes current to flow, but in opposite direction since electron carries negative charge**

electron

$$J_{n-diff} = (-q)D_n\left(-\underbrace{\frac{dn(x)}{dx}}_{\text{flux}}\right)$$

$$= qD_n\frac{dn(x)}{dx}$$

D_n: electron diffusion coef. [cm^2/s]

J_{n-diff} : [A/cm^2]

- **In Si,**
  - **D_n = 35 cm^2/s**
  - **D_p = 12 cm^2/s**

$\frac{\mu_n}{\mu_p} = 3$

$\frac{D_n}{D_p} \sim 3$

Einstein Relationship

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

25 mV

V_T : Thermal voltage

At room temperature, $V_T = 26$ mV

$$J_n = \underbrace{nq\mu_n E}_{\text{drift}} + \underbrace{q \cdot D_n \frac{dn}{dx}}_{\text{diffusion}}$$

In equilibrium $J_n = 0$

$$E = -\frac{d\phi}{dx}$$

ϕ : electrostatic potential

$E : \left[\frac{V}{cm}\right]$

$\phi : [V]$

n follows Boltzmann dist

$$\boxed{n = n_0 e^{\frac{q\phi}{kT}}} = n_0 e^{-\frac{(-q)\phi}{kT}}$$

$$\frac{dn}{dx} = n_0 \left(\frac{q}{kT}\right) \frac{d\phi}{dx} \cdot e^{\frac{q\phi}{kT}} = n \frac{d\phi}{dx} \frac{q}{kT}$$

$$\mu_n = \frac{D_n}{V_T} = 35 \times 40 = 1400$$

$$J_n = \cancel{n}\cancel{q}\mu_n \left(-\frac{d\phi}{dx}\right) + \cancel{q} D_n \cdot \cancel{n}\left(\frac{d\phi}{dx}\right)\frac{q}{kT} = 0$$

$$\frac{d\, e^{f(x)}}{dx} = \frac{d f(x)}{dx} \cdot e^{f(x)}$$

$$D_n \left(\frac{q}{kT}\right) = \mu_n \Rightarrow \frac{D_n}{\mu_n} = \frac{kT}{q} = V_T = 25\text{mV}$$