EE105
Microelectronic Devices and Circuits:
Basic Semiconductors

Prof. Ming C. Wu

wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

Excellent Reference for Module 2: EE130

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			IB	IIB	IIIA	IVA	VA	VIA	VIIA	INERT 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

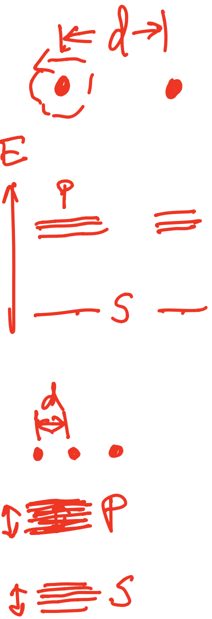
- **Conductors**
  - **Copper: 1.7 x 10^{-6} Ω-cm** (or 1.7 x 10^{-8} Ω-m)
  - **Aluminum: 2.8 x 10^{-6} Ω-cm**

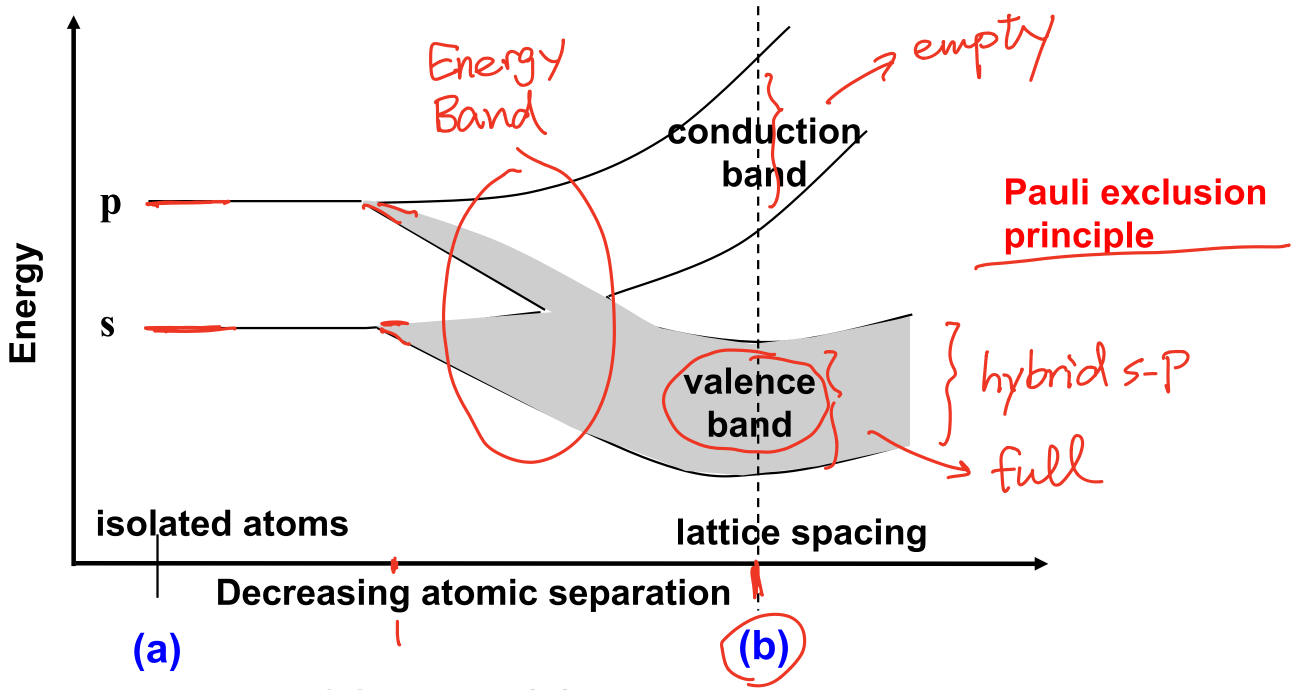
10^{24} x

- **Insulators**
  - **SiO_2: 10^{18} Ω-cm**

- **Semiconductor**
  - **Silicon: 10^{-3} to 10^{3} Ω-cm** 10^{6} x
  - **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*

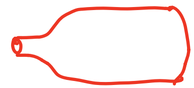
Energy Band Diagram of Various Materials

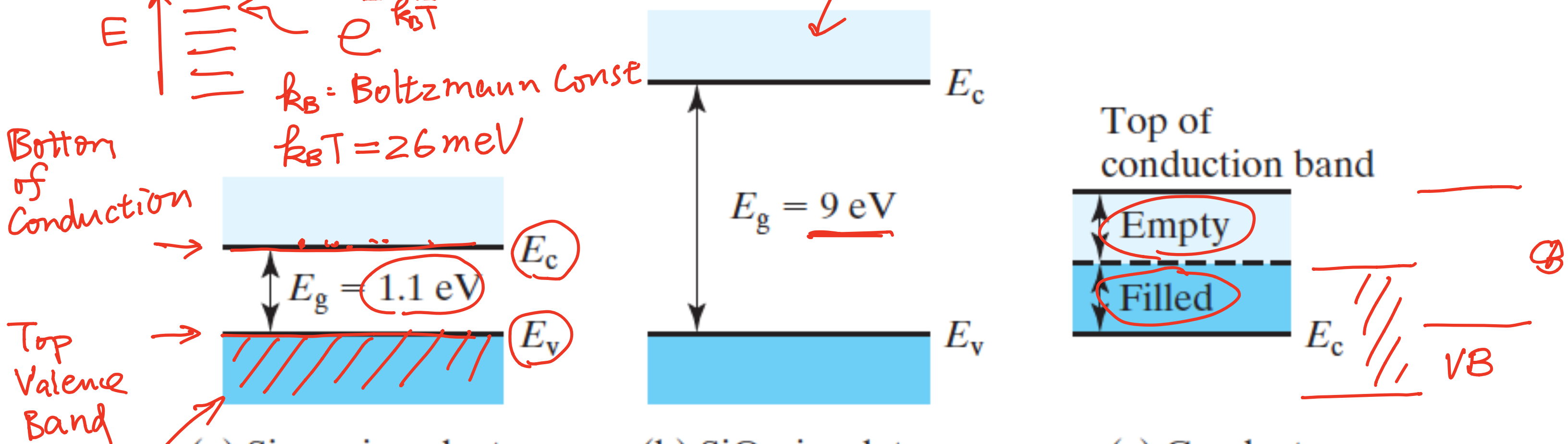
Boltzmann Distribution

E ↑ ← $e^{-\frac{E}{k_BT}}$

k_B: Boltzmann Const

$k_BT = 26\,meV$





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

10^{22} atom/cm³

Eg: Bandgap Energy

$1\,eV = 1.6 \times 10^{-19}\,J$

Si $E_g = 1.1\,eV$

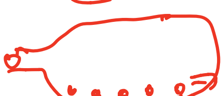
$n \sim e^{-\frac{E_g}{k_BT}} = e^{-\frac{1.1}{26\times10^{-3}}} \approx e^{-40} \approx 10^{-20}$

$\hookrightarrow e^{-\frac{9}{k_BT}} = (e^{-20})^9$

$= 10^{-180}$

Band

liquid = electr

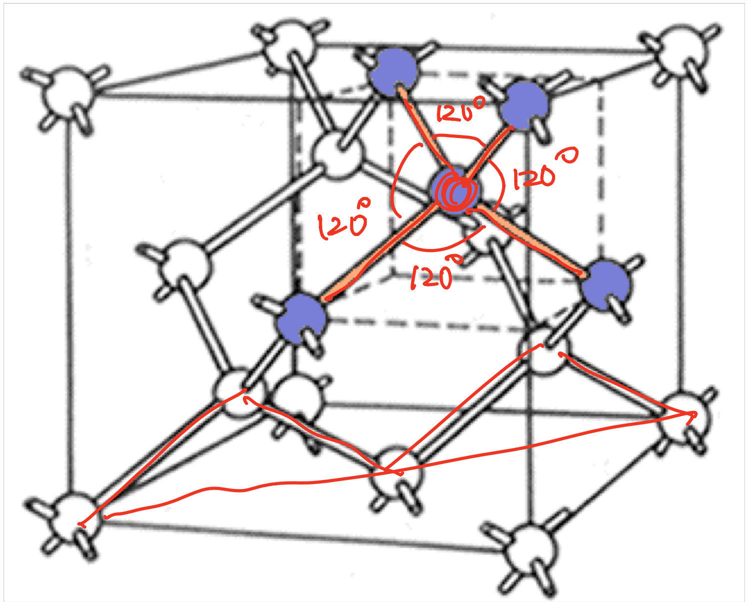


BSAC

Silicon

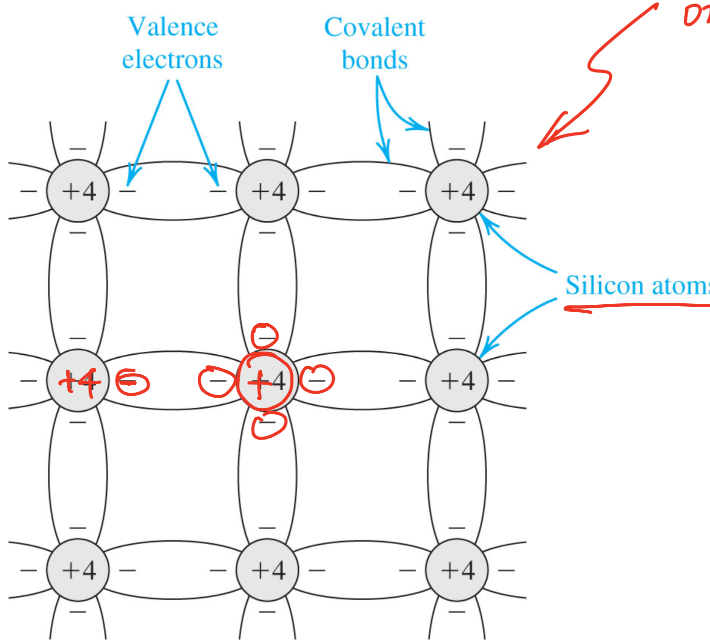
Simplified 2-d Illustration only

Crystalline Structure (Diamond Cubic)



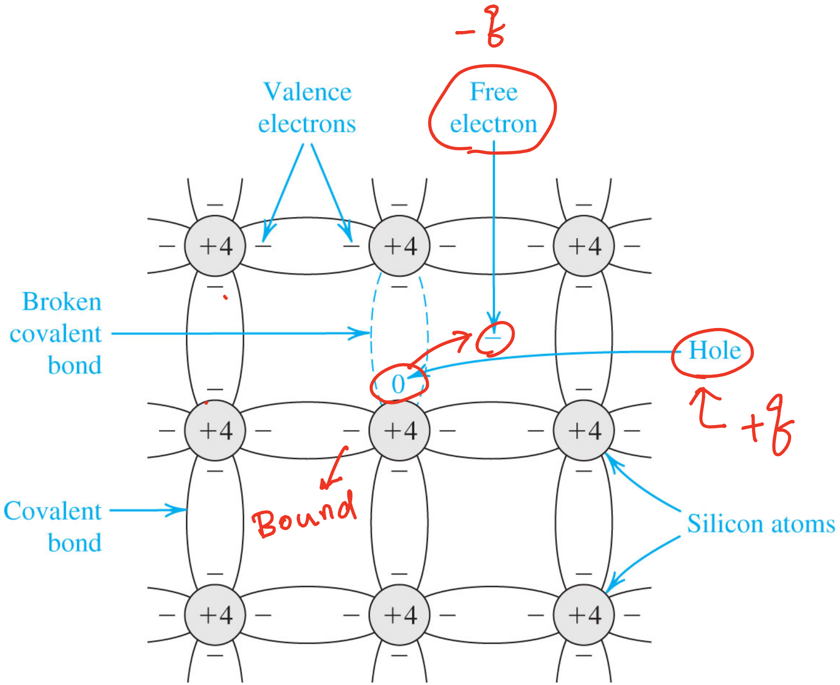
Top

Schematic Two-Dimensional Representation



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

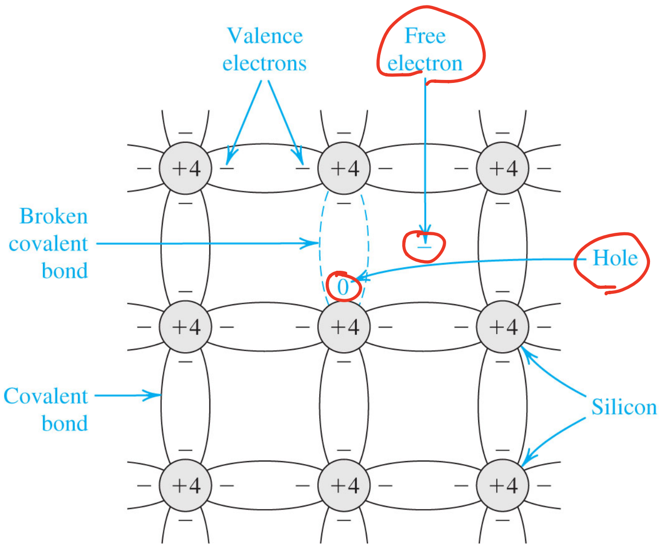
Electrons and Holes



- **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**

Thermal Energy ~ $k_B T = 26\,meV$
keep track of "free" electrons
"free" hole

Intrinsic Semiconductor



Intrinsic semiconductor

$n = p = n_i$

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

p : hole concentration [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 ($T = 300K$)

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

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

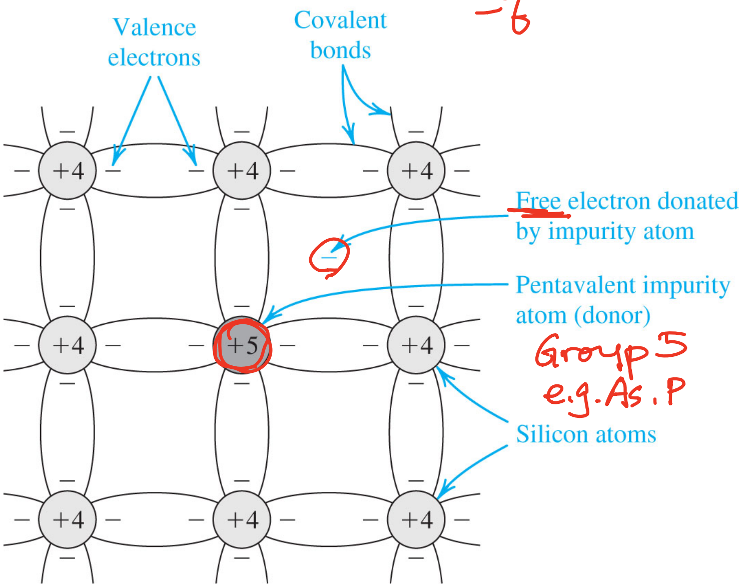
In general, $np = n_i^2$

Handwritten notes: [$\frac{1}{cm^3}$] electron conc. → ; hole conc. [$\frac{1}{cm^3}$] ; $\sim 2 \times 10^{20}$

Mass Action Law
In semiconductor
$n \times p = n_i \times n_i = n_i^2$

N-Type Semiconductor

Negative $-q$



Electron concentration can be greatly 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)

$p_n = \frac{n_i^2}{N_D}$ 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

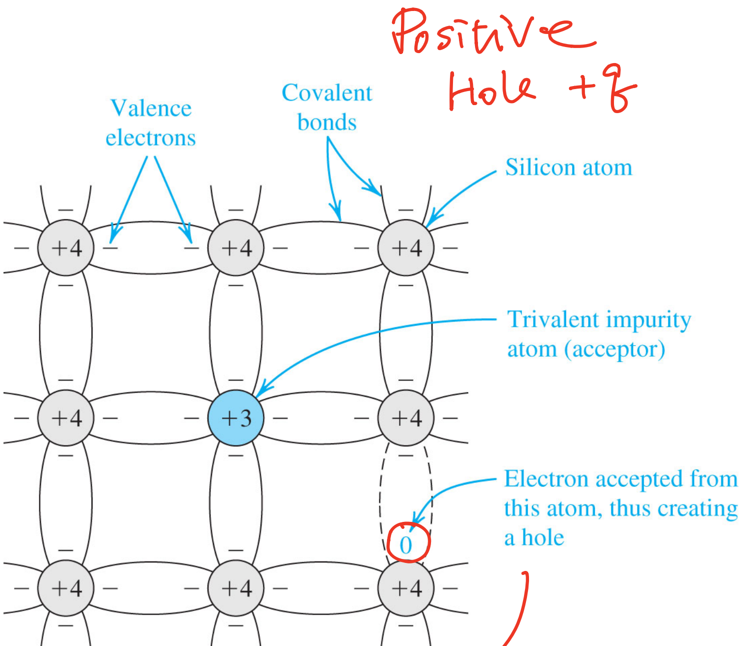
$n_n = N_D$: Donor Conc.

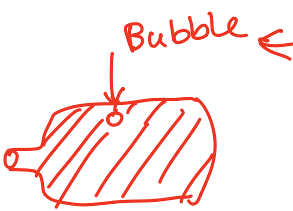
$n_n * p_n = n_i^2 \simeq 2\times 10^{20}$

$p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D} = \frac{2\times 10^{20}}{10^{17}} = 2\times 10^{3}$

$p_n << n_n$

P-Type Semiconductor





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)

$n_p = \frac{n_i^2}{N_A}$ 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

How Electron (or Hole) Move

$\frac{1}{2} m v^2 = k_B T = 26\,meV = 26\times10^{-3} \times 1.6\times10^{-19}\,J$

$\uparrow$ $9\times10^{-31}\,kg$

$v^2 = \frac{5\times2\times10^{-22}}{10^{-30}} = \frac{10^{-21}}{10^{-30}} = 10^9$

$v_{th} = 3\times10^5\,\frac{m}{s} = 3\times10^7\,\frac{cm}{s}$

mean free time (τ)

ΔP = Force·time = $(qE)\cdot\tau$ momentum

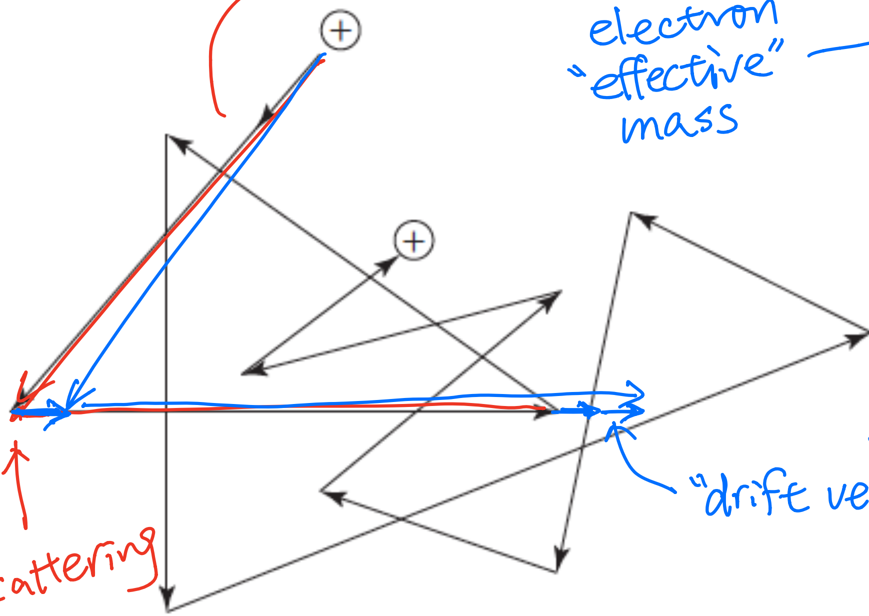
electron "effective" mass

$\Delta P = m^* v = (qE)(\tau)$

$v = \frac{qE\tau}{m^*} \propto E$

$v = \mu E$

$\mu = \left(\frac{q\tau}{m^*}\right)$ ← mobility



Scattering
- Impurity
- Thermal energy of Si lattice = Phonon

No Electric Field

→ E ← electric field

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) electron	1400	3900	8500	30,000
μ_p (cm^2/V·s) hole	470	1900	400	500

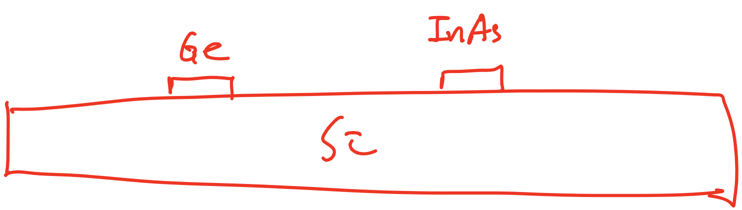
GaAs: III V

InAs: III V

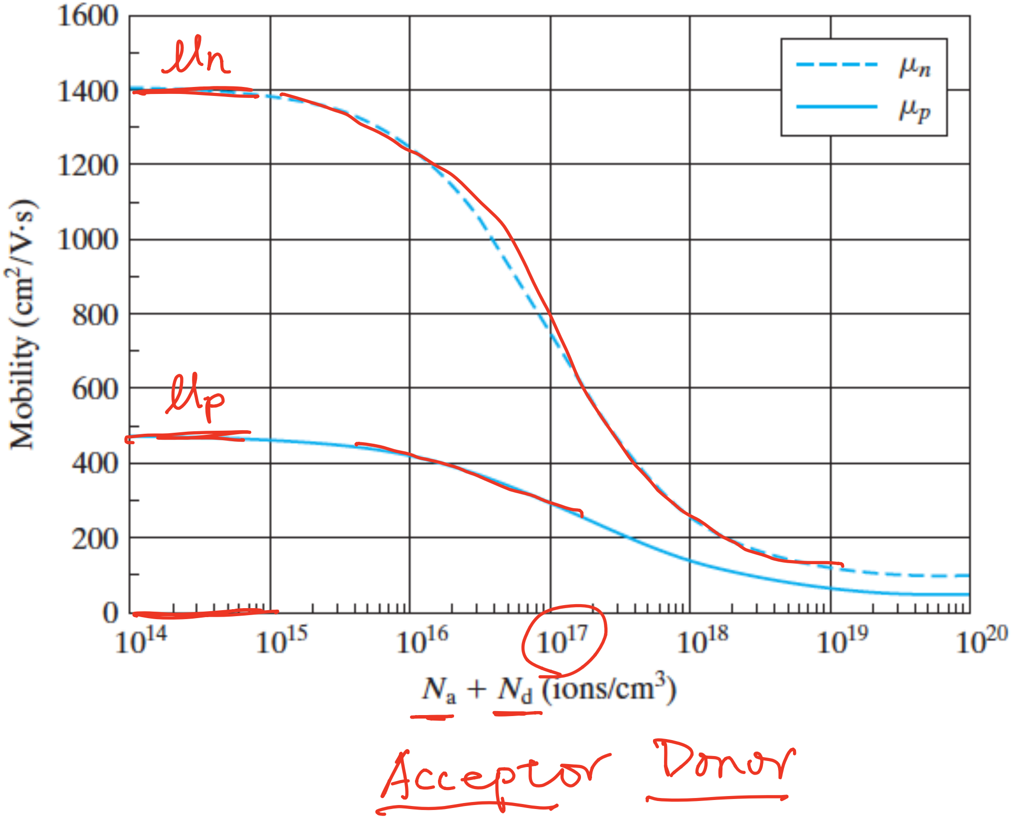
$\mu_n = 3\mu_p$

1900 (Ge): p-type transistor

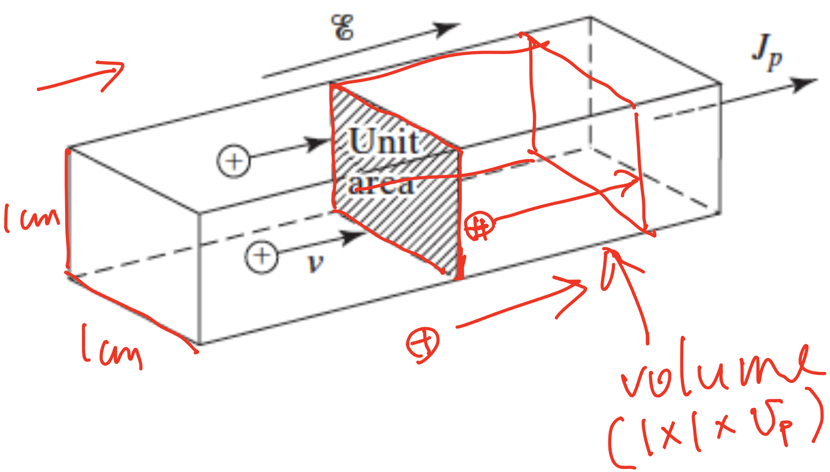
30,000 (InAs): n-type



Mobility vs Dopant Concentration



Current: Movement of Charged Particles (Electrons and Holes)



$$I = J \cdot \text{Area}$$

I: [Amp]

J: current density $\left[\frac{A}{cm^2}\right]$

$$J_p = p(+q)\,v_p = p \cdot v_p \cdot q$$

v_p: hole velocity

$$v_p = \mu_p E$$

$$J_n = n q v_n$$

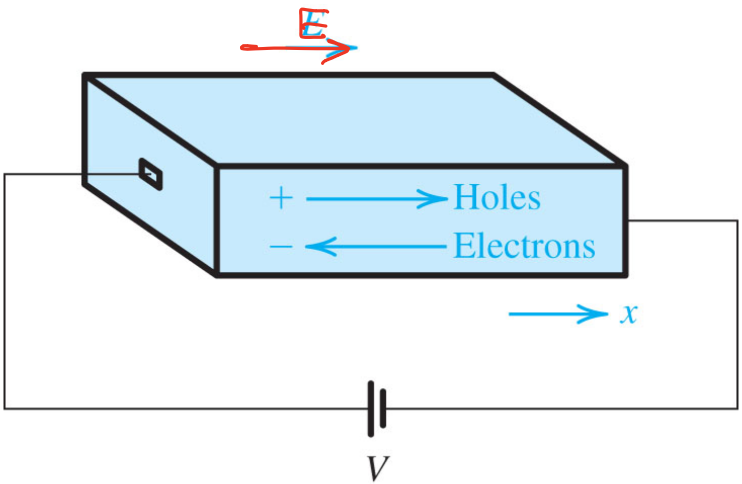
$$v_n = \mu_n E$$

Current in Semiconductor (1): Drift Current

$R=\rho\frac{L}{A}$

← electron $-q$

→ hole $+q$



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: $\mu_n \approx 2.5\mu_p$)

$J_n = (-q)\cdot n\cdot(-\mu_n E)$

$= nq\mu_n E$

$I = \frac{1}{R}\cdot V = \frac{A}{\rho\cdot L} E\cdot L$

$J = \sigma\cdot E = \frac{1}{\rho}\cdot E$

Current density, J [A/cm^2]

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

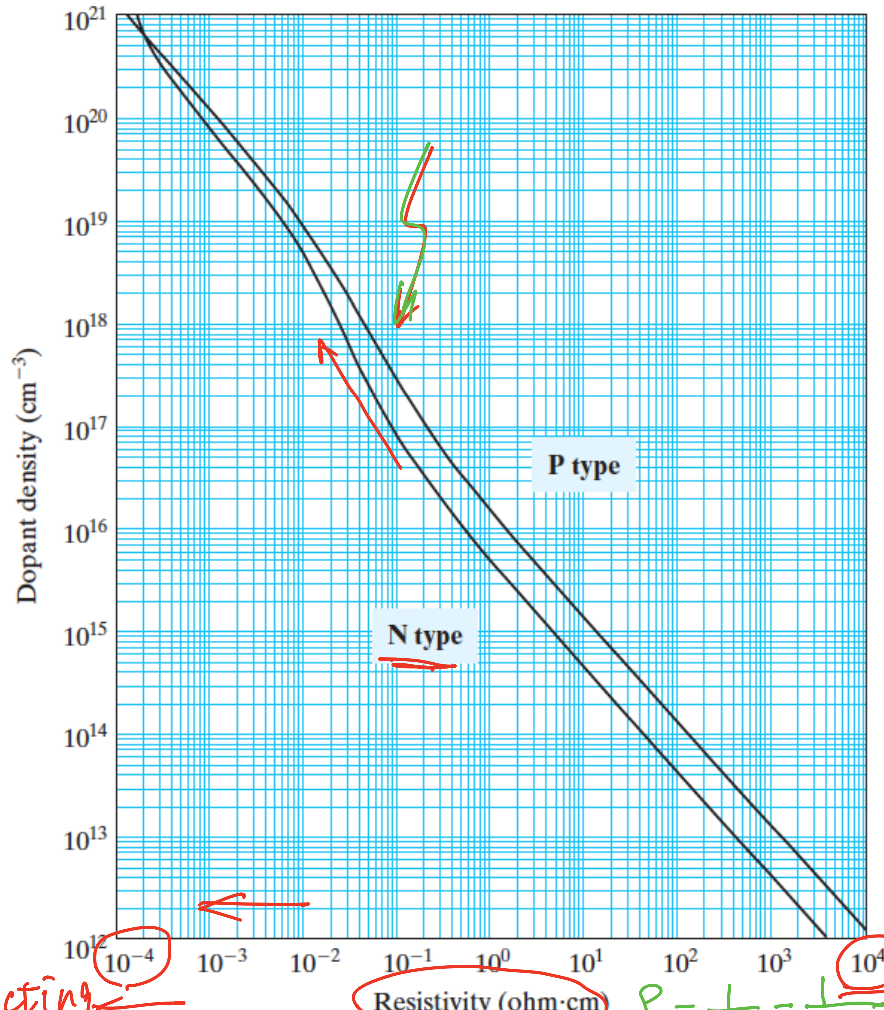
where $\sigma = q(p\mu_p + n\mu_n)$ is conductivity [S/cm]

N-type n

P-type p

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

Resistivity vs Dopant Concentration

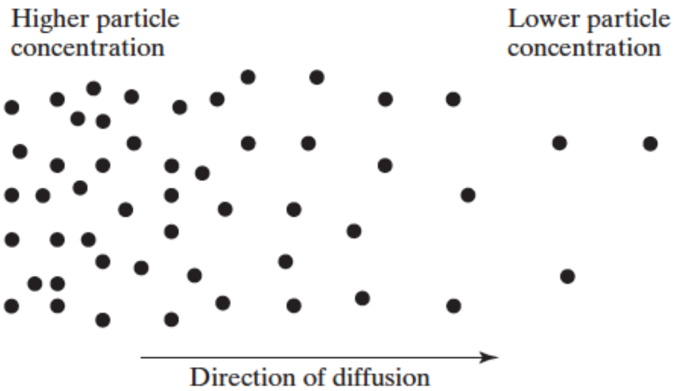


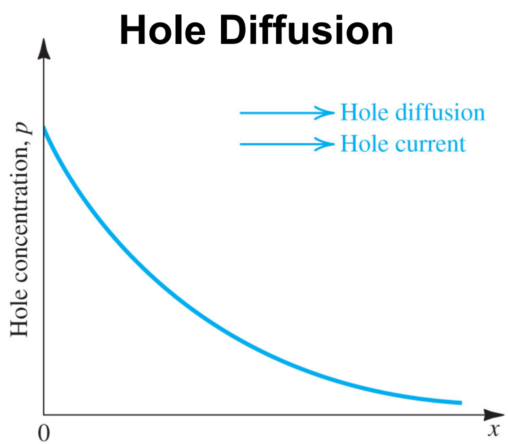
conducting

Insulating

$\rho = \frac{1}{\sigma} = \frac{1}{n \mu_n q}$

Current in Semiconductor (2): Diffusion Current - Holes





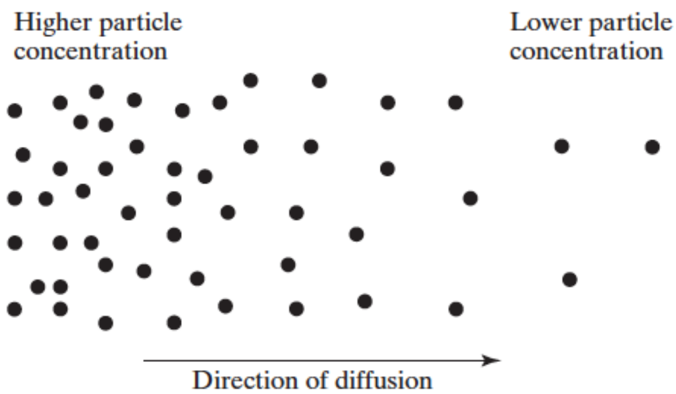
- **If hole distribution is non-uniform, holes will move from high to low concentration areas**
- **Flux ∝ - [conc. gradient]**
- **Current flows since holes carry charge:**

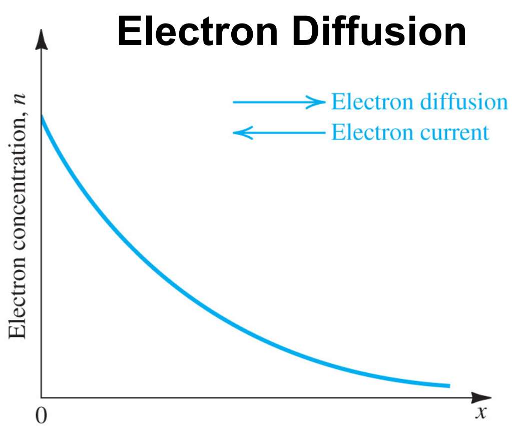
$$J_{p-diff} = qD_p\left(-\frac{dp(x)}{dx}\right)$$

D_p: hole diffusion coef. [cm^2/s]

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

Current in Semiconductor (2): Diffusion Current - Electrons





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

$$J_{n-diff} = (-q)D_n\left(-\frac{dn(x)}{dx}\right)$$
$$= qD_n\frac{dn(x)}{dx}$$

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**

Einstein Relationship

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

V_T : Thermal voltage

At room temperature, $V_T = 26$ mV

Proof: Total electron current:

$$J_n = J_{n-drift} + J_{n-diff} = qn(x)\mu_n E + qD_n \frac{dn(x)}{dx}$$

$$E = -\frac{d\phi}{dx}, \quad \phi : \text{ potential}$$

$$n(x) = n_0 e^{-\frac{(-q\phi)}{kT}} = n_0 e^{\frac{\phi}{V_T}} : \text{ Boltzmann distribution}$$

In equilibrium, no net current flow

$$\Rightarrow \; qn(x)\mu_n E + qD_n \frac{dn(x)}{dx} = 0$$

$$n(x)\mu_n E + D_n \frac{dn(x)}{d\phi}\frac{d\phi}{dx} = 0$$

$$n(x)\mu_n E + D_n \left(\frac{1}{V_T} n(x)\right)(-E) = 0$$

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