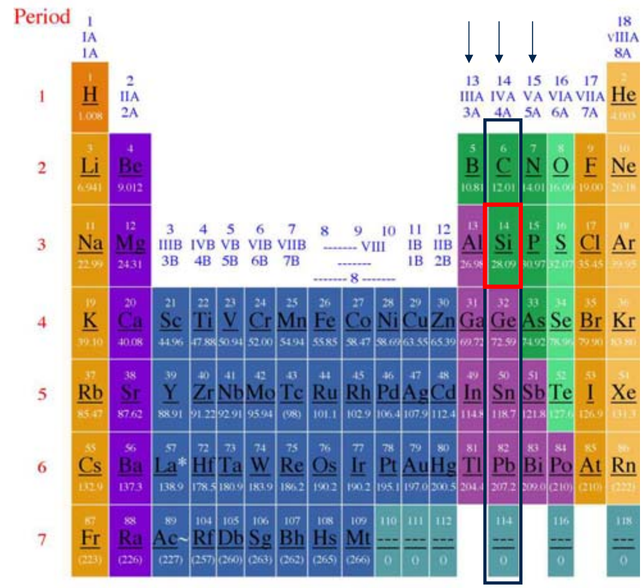
EE105 - Spring 2007
Microelectronic Devices and Circuits

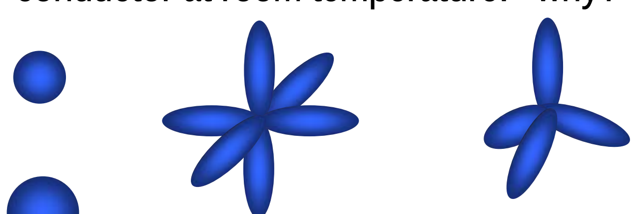
Lecture 2
Semiconductor Basics

Periodic Table of Elements



Electronic Properties of Silicon

- Silicon is in Group IV (atomic number 14)
  - Atom electronic structure: $1s^2 2s^2 2p^6 3s^2 3p^2$
  - Crystal electronic structure: $1s^2 2s^2 2p^6 3(sp)^4$
  - Diamond lattice, with 0.235 nm bond length
- Very poor conductor at room temperature: why?



$(1s)^2$

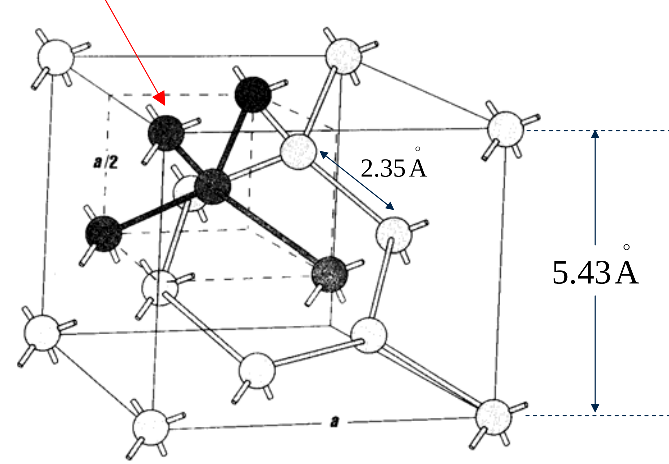
$(2s)^2$

$(2p)^6$

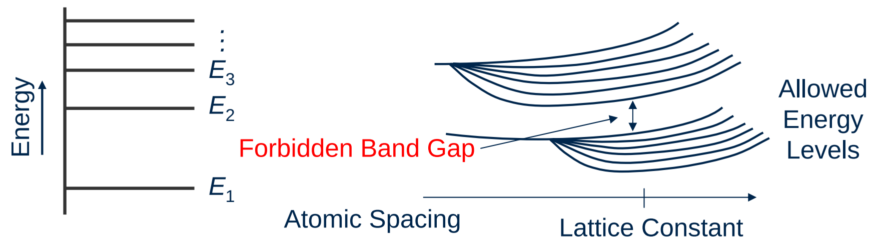
$(3sp)^4$
Hybridized State

The Diamond Structure

3sp Tetrahedral Bond

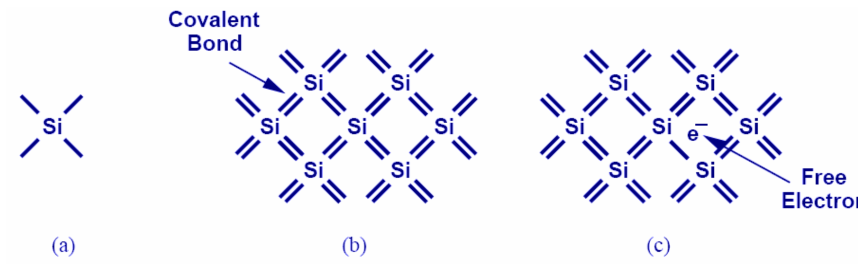


States of an Atom



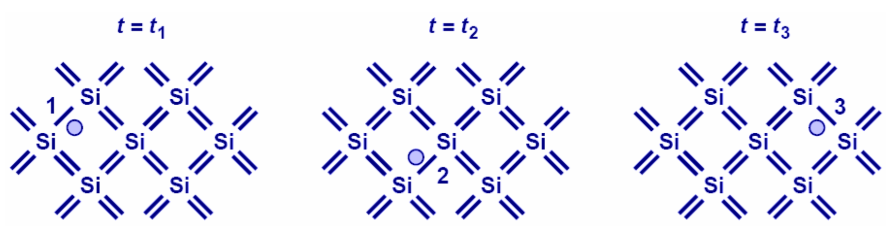
- Quantum Mechanics: The allowed energy levels for an atom are discrete (2 electrons with opposite spin can occupy a state)
- When atoms are brought into close contact, these energy levels split
- If there are a large number of atoms, the discrete energy levels form a “continuous” band

Silicon



- Si has four valence electrons. Therefore, it can form covalent bonds with four of its neighbors.
- When temperature goes up, electrons in the covalent bond can become free.

Electron-Hole Pair Interaction



- With free electrons breaking off covalent bonds, holes are generated.
- Holes can be filled by absorbing other free electrons, so effectively there is a flow of charge carriers.

Free Electron Density as a Function of Temperature

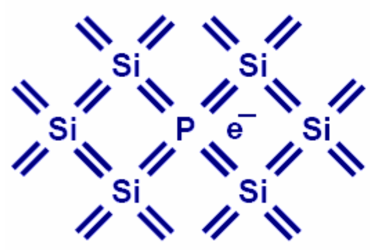
$$n_i = 5.2\times10^{15} T^{3/2} e^{\frac{-E_g}{2kT}} \quad electrons/cm^3$$

$$n_i(T = 300^0 K) = 1.08\times10^{10} \quad electrons/cm^3$$

$$n_i(T = 600^0 K) = 1.54\times10^{15} \quad electrons/cm^3$$

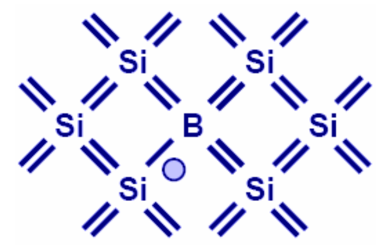
- E_g, or bandgap energy, determines how much effort is needed to break off an electron from its covalent bond.
- There exists an exponential relationship between the free-electron density and bandgap energy.

N Type Doping



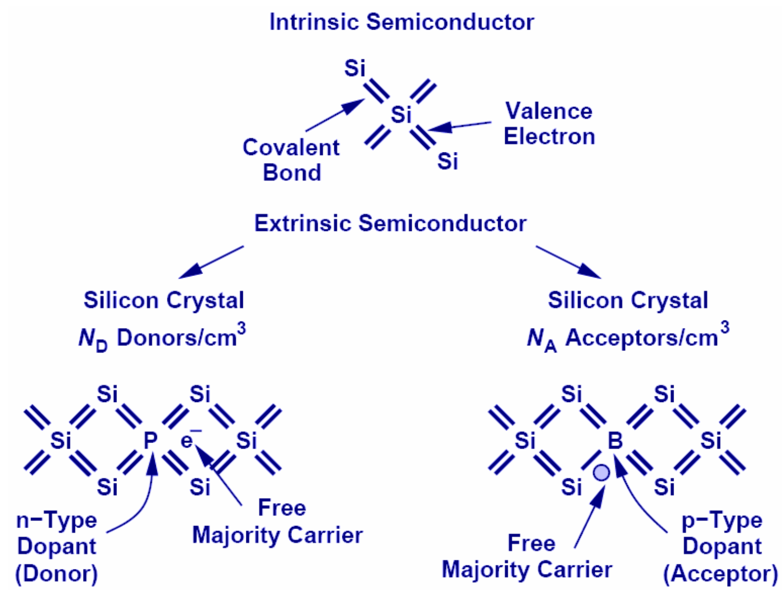
- If Si is doped with group-V elements such as phosphorous (P) or arsenic (As), then it has more electrons and becomes N type (electron).
- Group-V impurities are called Donors

P Type Doping



- If Si is doped with group-III elements such as boron (B), then it has more holes and becomes P type.
- Group-III impurities are called Acceptors

Summary of Charge Carriers



Thermal Equilibrium (Pure Si)

- Balance between generation and recombination determines $n_o = p_o$
- Strong function of temperature: T = 300 K

$$G = G_{th}(T) + G_{opt}$$
$$R = k(n \times p)$$
$$G = R$$
$$k(n \times p) = G_{th}(T)$$
$$n \times p = G_{th}(T)/k = n_i^2(T)$$
$$n_i(T) \cong 10^{10}\ \text{cm}^{-3} \text{ at } 300\text{K}$$

Mass Action Law

- The product of electron and hole densities is ALWAYS equal to the square of intrinsic electron density, regardless of doping levels

$$p_o \cdot n_o = n_i^2 \qquad (T = 300\text{K},\ n_i = 10^{10}\text{cm}^{-3})$$

	Majority Carrier Conc. = Doping Conc.	Minority Carrier Conc. (Mass Action Law)
N-Type	$n_0 = N_d^+ \cong N_d$	$p_0 \cong \frac{n_i^2}{N_d}$
P-Type	$p_0 = N_a^- \cong N_a$	$n_0 \cong \frac{n_i^2}{N_a}$

Compensated Doping

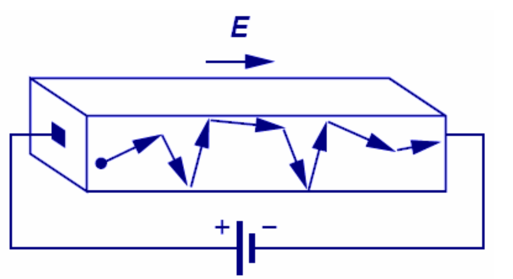
- Si is doped with both donor and acceptor atoms:
  - More donors than acceptors: $N_d > N_a$ → N type

$$n_o = N_d - N_a \qquad p_o = \frac{n_i^2}{N_d - N_a}$$

  - More acceptors than donors: $N_a > N_d$ → P type

$$p_o = N_a - N_d \qquad n_o = \frac{n_i^2}{N_a - N_d}$$

First Charge Transportation Mechanism: Drift



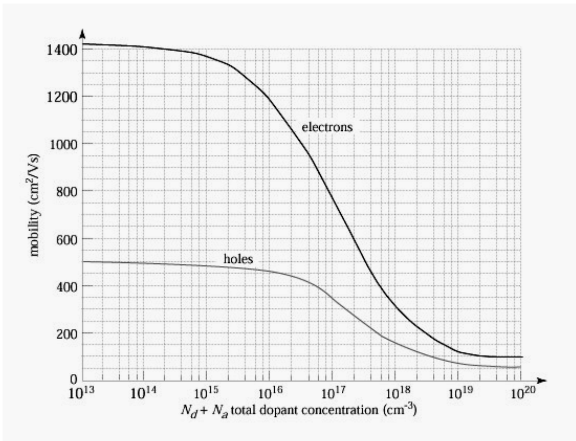
Mobility

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

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

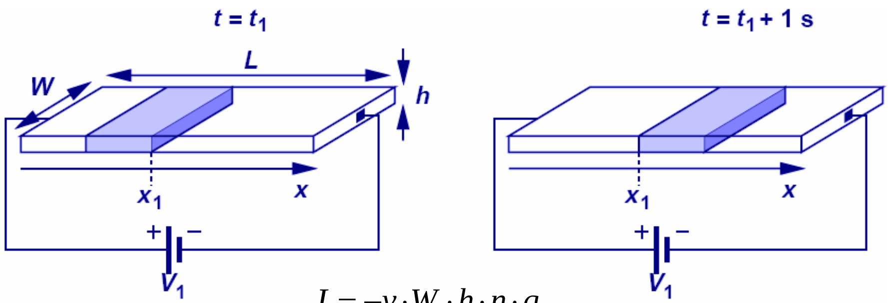
- The process in which charge particles move because of an electric field is called drift.
- Charge particles will move at a velocity that is proportional to the electric field.

Mobility vs. Doping in Silicon at 300K



- Typical values $\mu_n = 1350$ V-sec / cm^2
  $\mu_p = 450$ V-sec / cm^2

Current Flow: General Case



$$I = -v \cdot W \cdot h \cdot n \cdot q$$
$$J = \frac{I}{Wh} = -v \cdot n \cdot q$$

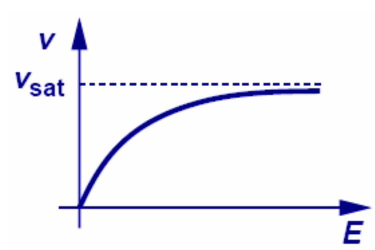
- Electric current is calculated as the amount of charge in *v* meters that passes thru a cross-section if the charge travel with a velocity of v m/s.

Current Flow: Drift

$$J_n = \mu_n E \cdot n \cdot q$$
$$J_p = \mu_p E \cdot p \cdot q$$
$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$
$$= q(\mu_n n + \mu_p p)E$$

- Since velocity is equal to μE, drift characteristic is obtained by substituting *v* with μE in the general current equation.
- The total current density consists of both electrons and holes.

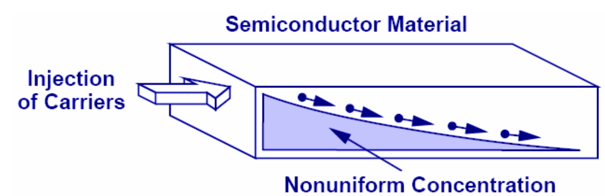
Velocity Saturation

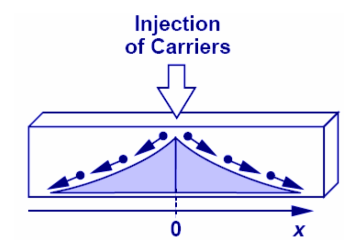


$$\mu = \frac{\mu_0}{1 + bE}$$
$$v_{sat} = \frac{\mu_0}{b}$$
$$v = \frac{\mu_0}{1 + \frac{\mu_0 E}{v_{sat}}} E$$

- A topic treated in more advanced courses is velocity saturation.
- In reality, velocity does not increase linearly with electric field. It will eventually saturate to a critical value.

Second Charge Transportation Mechanism: Diffusion





- Charge particles move from a region of high concentration to a region of low concentration.

Current Flow: Diffusion

Diffusion Coefficient

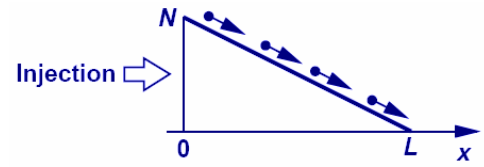
$$J_n = qD_n \frac{dn}{dx}$$

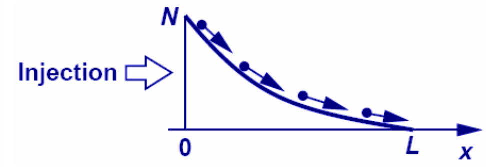
$$J_p = -qD_p \frac{dp}{dx}$$

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

- Diffusion current is proportional to the gradient of charge (dn/dx) along the direction of current flow.
- Total diffusion current density consists of both electrons and holes.

Example: Linear vs. Nonlinear Charge Density Profile

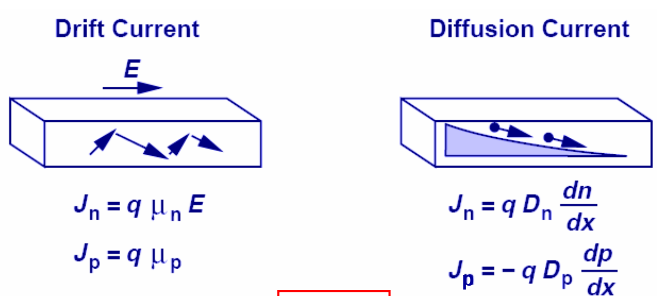




$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L} \qquad J_n = qD \frac{dn}{dx} = \frac{-qD_n N}{L_d} \exp \frac{-x}{L_d}$$

- Linear charge density profile means constant diffusion current, whereas nonlinear charge density profile means varying diffusion current.

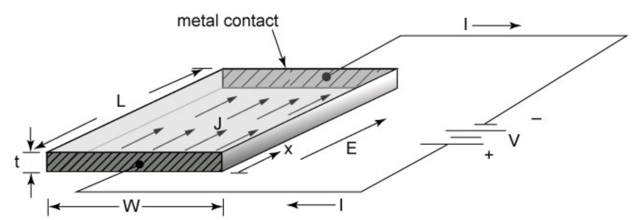
Einstein's Relation



$$\frac{D}{\mu} = \frac{kT}{q}$$

- While the underlying physics behind drift and diffusion currents are totally different, Einstein's relation provides a link between the two.

Resistivity of Uniformly Doped Si



$$J_n = \mu_n E \cdot n \cdot q = \sigma \cdot E$$

$$\sigma = nq\mu_n$$

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

$V = R \cdot I$ Ohm's Law

$$V = E \cdot L$$

$$I = J \cdot tW$$

$$J = \frac{I}{A} = \frac{V}{RtW} = \frac{EL}{RtW} = \left(\frac{L}{RtW}\right) E = \sigma E$$

$$R = \frac{1}{\sigma} \frac{L}{tW} = \rho \frac{L}{tW}$$

Sheet Resistance (R_S)

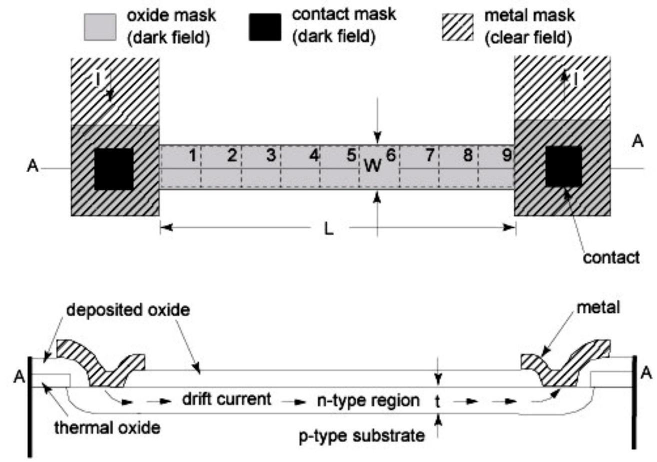
- IC resistors have a specified thickness – not under the control of the circuit designer
- Eliminate thickness, *t*, by absorbing it into a new parameter: the sheet resistance (R_S)

$$R = \rho \frac{L}{Wt} = \left(\frac{\rho}{t}\right)\left(\frac{L}{W}\right) = R_S\left(\frac{L}{W}\right)$$

↑ "Number of Squares"

Using Sheet Resistance (R_S)

- Ion-implanted (or "diffused") IC resistor



Idealizations

- Why does current density J_n "turn"?
- What is the thickness of the resistor?
- What is the effect of the contact regions?