上海科技大学
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EE115 Analog Circuits
Semiconductors

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PEARL 电力电子与再生能源实验室

Outline

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- Semiconductors
  - Intrinsic Semiconductors
  - Doped Semiconductors
  - Current Flow in Semiconductors
- Reading: SEDTRA/SMITH book pages 136-149

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Silicon: Group IV Element

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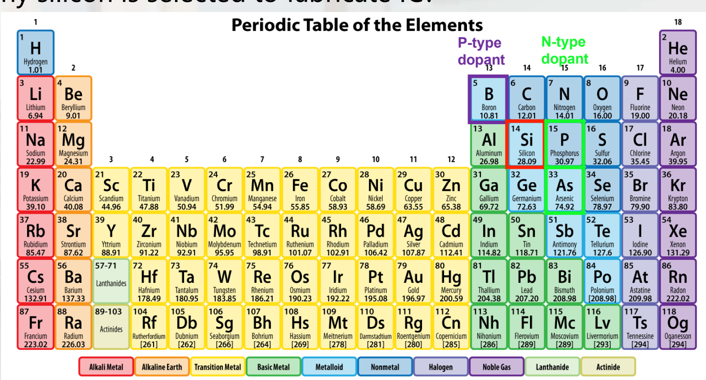
- Why silicon is selected to fabricate IC?



Silicon

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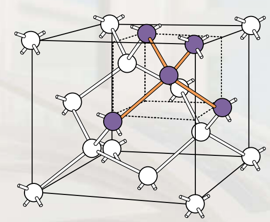
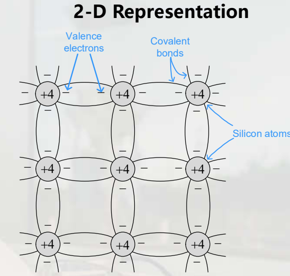
Crystalline Structure (Diamond Cubic)



2-D Representation



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

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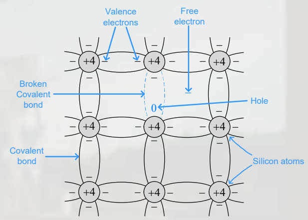
Electrons and Holes

- **Thermal Generation:**
  - 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
- **Recombination**
  - Free electrons and holes move randomly through the silicon crystal structure
  - Some electrons may fill some of the holes



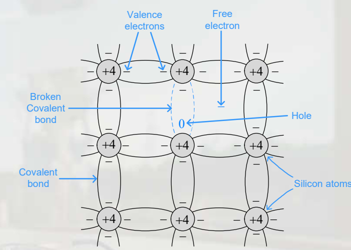
Intrinsic Semiconductor

- Intrinsic semiconductor
  - $n = p = n_i$
  - n: electron concentration$/cm^3$
  - p: hole concentration$/cm^3$
  - $n_i = BT^{3/2}e^{-E_g/(2kT)}$: intrinsic carrier concentration
    - B: material dependent constant
    - T: temperature in Kelvin
    - E_g: **bandgap** energy (=1.12 eV for Si)
    - k: Boltzmann's constant = 8.62x10^{-5} eV/K
  - At room temperature (T = 300 K)

$$n_i = 1.5 \times 10^{10}/cm^3$$

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

In general, $np = n_i^2$



N-Type Semiconductor

- 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 impurity concentration)
  - $p_n = n_i^2/N_D$ where $n_i = 1.5\times10^{10}$/cm^3
- Subscript n refers to n-type semiconductor (n = **negative**)
- In n-type semiconductor, $n_n >> n_i >> p_n$
  - e.g., $N_D = 10^{17}$ /cm^3, $n_n = 10^{17}$ /cm^3, p_n = 2.2 $\times10^3$/cm^3
- Electrons are "**majority**" **carriers**
- Holes are "**minority**" **carriers**

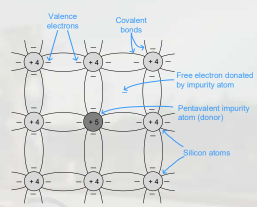


Fig. A silicon crystal doped by a pentavalent element.

P-Type Semiconductor

- Hole concentration can be greatly 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)
  - $n_p = n_i^2/N_A$ where $n_i = 1.5\times10^{10}$ /cm^3
- Subscript p refers to p-type semiconductor (p = **positive**)
- In p-type semiconductor, $p_p >> n_i >> n_p$
  - e.g., $N_A = 10^{17}$ /cm^3, $p_p = 10^{17}$/cm^3, n_p = 2.2 $\times10^3$ /cm^3
- Holes are "majority" carriers
- Electrons are "minority" carriers

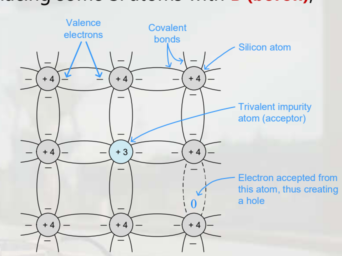


Fig. A silicon crystal doped with boron, a trivalent impurity.

Current in Semiconductor (1) Drift Current

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

$$\begin{cases} v_{p-drift} = \mu_p E \\ v_{n-drift} = -\mu_n E \end{cases}$$

where, μ_p is **hole mobility;** μ_n is **electron mobility;**

- In intrinsic Si, μ_n =1350 cm²/(V·s)
  μ_p = 480 cm²/(V·s) ($\mu_n \approx 2.5\mu_p$)
  Current density, J [A/cm²]
  $J = qpv_{p-drift} - qnv_{n-drift} = q(p\mu_p + n\mu_n)E = \sigma E$

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

- **Resistivity** ρ= 1/σ [Ω·cm]

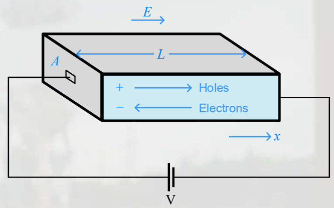

Fig. An electric field *E* established in a bar of silicon causes drift currents in the direction of *E*.

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Current in Semiconductor (2) Diffusion Current

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- **Diffusion**: particles move from high to low concentrations. As electrons and holes diffuse, currents flow because they carry charges.

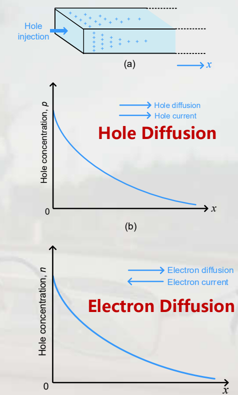
$$J_{p-diff} = -qD_p \frac{dp(x)}{dx}$$

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

where D_p and D_n are hole and electron **diffusion coefficients/diffusivity** [cm²/s]

- In instrinsic Si, D_p =12.4cm²/s, D_n= 35cm²/s
  Total diffusion current density, J_{diff} [A/cm²]

$$J_{diff} = -qD_p \frac{dp(x)}{dx} + qD_n \frac{dn(x)}{dx}$$



Example

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Consider a bar of silicon with a hole concentration profile described by

$$p(x) = p_o e^{-x/L_p}$$

Let $p_o = 10^{16}/cm^3$, $L_p = 1\mu m$, and $D_p = 12cm^2/s$.
Find the hole-current density at $x = 0$.
If the cross-sectional area of the bar is 100 μm², find the current I_{Dp}.

Solution:

$$J_{D,p} = -qD_p \frac{dp(x)}{dx} = -qD_p \frac{d}{dx}\left[p_0 e^{-x/L_p}\right] = q\frac{D_p}{L_p} p_0 e^{-x/L_p}$$

$$J_{D,0}(0) = q\frac{D_p}{L_p} p_0 = 1.6\times10^{-19} \times \frac{12}{1\times10^{-4}} \times 10^{16} = 192 \text{ A/cm}^2$$

$$I_{D,p} = J_{D,p} \times \text{A} = 192\times100\times10^{-8} = 192\mu\text{A}$$

Einstein Relation

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The Einstein relation connects the diffusion coefficient D and the mobility μ of carriers (electrons and holes)

$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T = \frac{k_B T}{q}$; where V_T is thermal voltage. At room temperature, V_T = 26 mV

- 1. Diffusion Current:
  $$J_d = -qD\frac{dn}{dx}$$
- 2. Drift Current
  $$J_{drift} = qn\mu_n E$$
- 3. At thermal equilibrium
  $$J_d + J_{drift} = 0$$

Substitute

$$D\frac{dn}{dx} = n\mu_n E \;\Rightarrow\; \frac{D}{\mu_n} = \frac{nE}{dn/dx}$$

- 4. Boltzmann Distribution:
  $$n(x) = n_0 \exp\left[-\frac{q\phi(x)}{k_B T}\right]$$
  $$\frac{dn}{dx} = -n\frac{q}{k_B T}\frac{d\phi}{dx} = \frac{nqE}{k_B T}$$

Substitute

$$\frac{D}{\mu} = \frac{k_B T}{q}$$