

EE115 Analog Circuits

Semiconductors

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Outline

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



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Silicon: Group IV Element

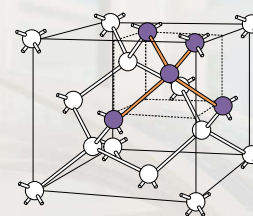
- Why silicon is selected to fabricate IC?

1	Periodic Table of the Elements																18																
1 H Hydrogen 1.01																	2 He Helium 4.00																
3 Li Lithium 6.94	4 Be Beryllium 9.01															10 Ne Neon 20.18																	
5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 18.99									16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95																		
11 Na Sodium 22.99	12 Mg Magnesium 24.31															19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Tc Technetium 98.91	43 Ru Ruthenium 101.07	44 Rh Rhodium 101.07	45 Pd Palladium 106.42	46 Ag Silver 107.87	47 Cd Cadmium 112.41	48 In Indium 114.82	49 Sn Tin 118.71	50 Sb Antimony 121.76	51 Te Tellurium 127.60	52 I Iodine 126.90	53 Xe Xenon 131.29	54 Kr Krypton 83.80																
55 Rb Rubidium 85.47	56 Sr Strontium 87.62	57 Y Yttrium 88.91	58 Zr Zirconium 91.22	59 Nb Niobium 92.91	60 Ta Tantalum 180.94	61 Hf Hafnium 178.49	62 Ta Tantalum 180.94	63 W Tungsten 183.85	64 Re Rhenium 186.21	65 Os Osmium 190.23	66 Ir Iridium 192.22	67 Pt Platinum 195.08	68 Au Gold 196.97	69 Hg Mercury 200.59	70 Tl Thallium 204.38	71 Pb Lead 207.20	72 Bi Bismuth 208.98	73 Po Polonium (209)	74 At Astatine 210	75 Rn Radon 222.02													
87 Fr Francium 223.02	88 Ra Radium 226.03	89 Ac Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)																
Alkalal Metal		Alkaline Earth		Transition Metal		Basic Metal		Metalloid		Nonmetal		Halogens		Noble Gas		Lanthanide		Actinide															

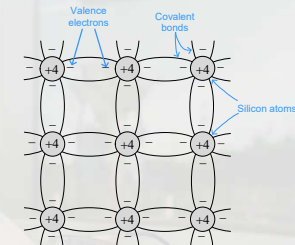
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Silicon

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:

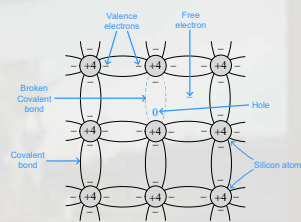
- At room temperature, thermal energy breaks some covalent bonds, creating free electrons and "holes"

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



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Intrinsic Semiconductor

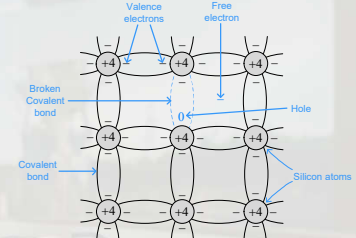
Intrinsic semiconductor

- $n = p = n_i$
- 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 = 8.62×10^{-5} eV/K
- At room temperature ($T = 300$ K)

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

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

$$\text{In general, } np = n_i^2$$



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

- Subscript n refers to n-type semiconductor (n = **negative**)

- In n-type semiconductor, $n_n \gg n_i \gg p_n$
 - e.g., $N_D = 10^{17} / \text{cm}^3$, $n_n = 10^{17} / \text{cm}^3$, $p_n = 2.2 \times 10^3 / \text{cm}^3$

- Electrons are **"majority" carriers**
- Holes are **"minority" carriers**

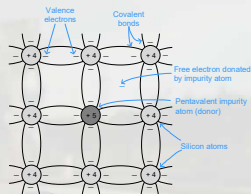


Fig. A silicon crystal doped by a pentavalent element.

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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 impurity concentration)
- $n_p = n_i^2 / N_A$ where $n_i = 1.5 \times 10^{10} / \text{cm}^3$

- Subscript p refers to p-type semiconductor (p = **positive**)

- In p-type semiconductor, $p_p \gg n_i \gg n_p$
 - e.g., $N_A = 10^{17} / \text{cm}^3$, $p_p = 10^{17} / \text{cm}^3$, $n_p = 2.2 \times 10^3 / \text{cm}^3$

- Holes are **"majority" carriers**
- Electrons are **"minority" carriers**

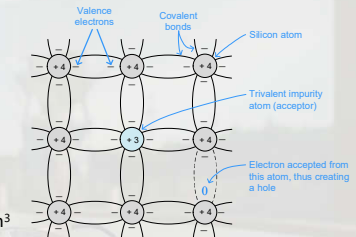


Fig. A silicon crystal doped with boron, a trivalent impurity.

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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 .

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

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

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

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

Current density, J [A/cm^2]

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

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

- Resistivity** $\rho = 1/\sigma$ [$\Omega\cdot\text{cm}$]

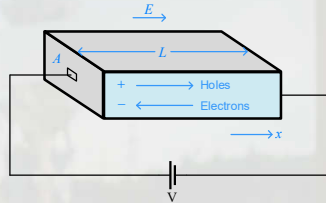


Fig. An electric field E established in a bar of silicon causes drift currents in the direction of E .



Current in Semiconductor (2) Diffusion Current

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

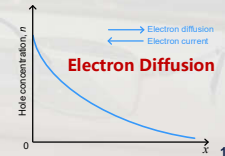
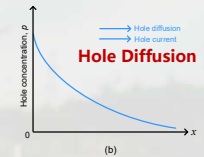
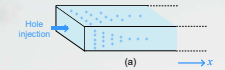
$$J_{p-diff} = -q D_p \frac{dp(x)}{dx}$$

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

where D_p and D_n are hole and electron **diffusion coefficients/diffusivity** [cm^2/s]

- In intrinsic Si, $D_p = 12.4 \text{ cm}^2/\text{s}$, $D_n = 35 \text{ cm}^2/\text{s}$
Total diffusion current density, J_{diff} [A/cm^2]

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



Example

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

$$p(x) = p_0 e^{-x/L_p}$$

Let $p_0 = 10^{16} / \text{cm}^3$, $L_p = 1 \mu\text{m}$, and $D_p = 12 \text{ cm}^2/\text{s}$.

Find the hole-current density at $x = 0$.

If the cross-sectional area of the bar is $100 \mu\text{m}^2$, find the current $I_{D,p}$.

Solution:

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

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

$$I_{D,p} = J_{D,p} \times A = 192 \times 100 \times 10^{-8} = 192 \mu\text{A}$$

Einstein Relation

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

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

- 1. Diffusion Current:

$$J_d = -q D \frac{dn}{dx}$$

- 2. Drift Current

$$J_{drift} = q n \mu_n E$$

- 3. At thermal equilibrium

$$J_d + J_{drift} = 0$$

- 4. Boltzmann Distribution:

$$n(x) = n_0 \exp \left[-\frac{q \phi(x)}{k_B T} \right]$$

$$\frac{dn}{dx} = -n \frac{q}{k_B T} \frac{d\phi}{dx} = \frac{n q E}{k_B T}$$

Substitute

Substitute

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

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