

# Reading

Adel S. Sedra and Kenneth C. Smith, **Microelectronic Circuits** 7<sup>th</sup> Edition, *Oxford University Press*, 2014.

- Chapter 3.1-3.3

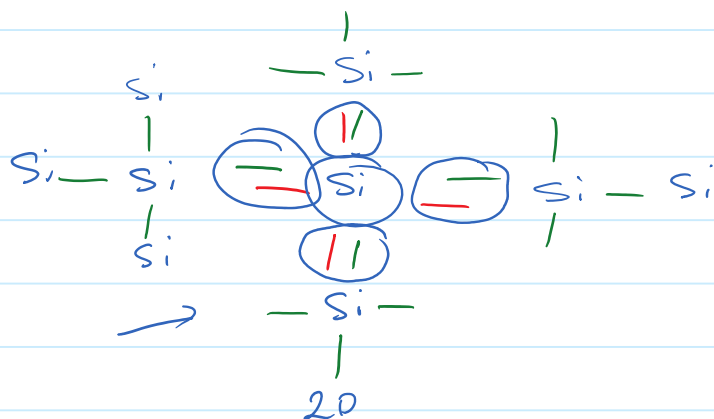
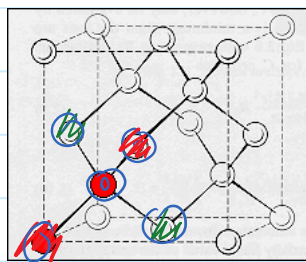
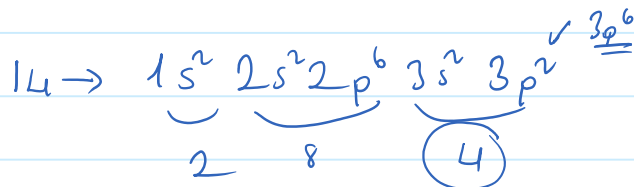


## Si Atom

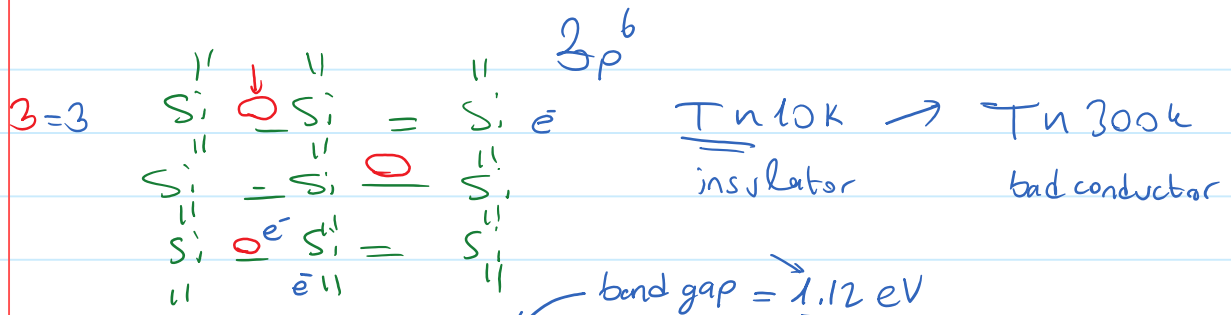
# Periodic Table of the Elements

The image shows a periodic table of elements with various annotations. The table is color-coded by groups: IA (red), IIA (orange), IIIA (yellow), IVA (green), VA (light green), VIA (teal), VIIA (dark teal), and VIIIA (pink). Elements are labeled with their symbol, atomic number, and name. Annotations include:

- A blue arrow pointing to Hydrogen (H) with labels: "Atomic Number" (1), "Symbol" (H), "Name" (Hydrogen), and "Atomic Weight" (1.008).
- A blue circle around Silicon (Si) with a label: "Silicon is a metalloid element (color of background)".
- A legend for element categories: Alkali metals (red), Alkaline earth metals (orange), Transition metals (green), Lanthanides (light blue), Actinides (dark blue), Reactive nonmetals (yellow), Post-transition metals (light green), Noble gases (pink), and Unknown chemical properties (grey).
- A legend for element states: Solid (red), Liquid (orange), and Gaseous (green).
- A legend for element groups: IA, IIA, IIIA, IVA, VA, VIA, VIIA, and VIIIA.



# Intrinsic Si



$$n_i = B \cdot T^{3/2} e^{-E_g / 2kT}$$

$\uparrow$   
 $7.3 \times 10^{15} \text{ cm}^{-3} \text{ K}^{-3/2}$

$6 \times 10^{23}$   
 $\div 8$   
 $\times 14$

$n = p = n_i$   
 $\downarrow$   
 $\pm e / \text{cm}^{-3}$

$np = n_i^2$

## Example

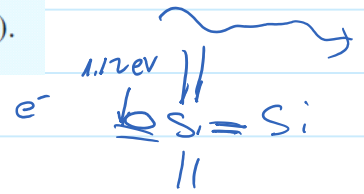
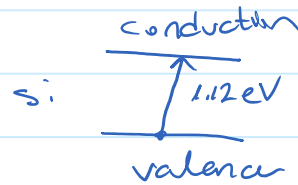
Calculate the value of  $n_i$  for silicon at room temperature ( $T \approx 300$  K).

$$n_i = B T^{3/2} e^{-\frac{E_g}{2kT}}$$

$$= 7.3 \times 10^5 \cdot 300^{3/2} \cdot e^{-\frac{1.12}{2 \times 8.62 \times 10^{-5} \times 300}}$$

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

$$\rightarrow n = n_i = p$$



# N-Type Semiconductor

## Periodic Table of the Elements

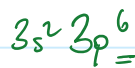
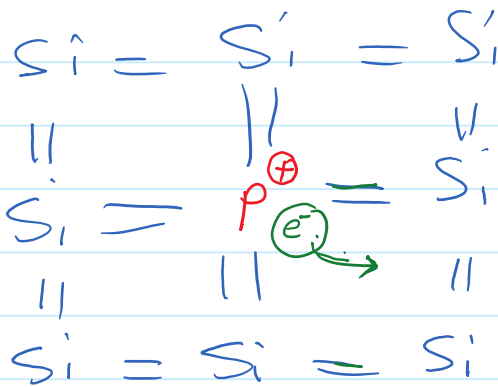
Periodic Table of the Elements

Legend:

- State of matter (color of name): GAS (blue), LIQUID (green), SOLID (red), UNKNOWN (black)
- Subcategory in the metal-metalloid-semiconductor trend (color of background):
  - Alkali metals (orange)
  - Alkaline earth metals (yellow)
  - Transition metals (blue)
  - Post-transition metals (light blue)
  - Metalloids (green)
  - Nonmetals (light green)
  - Reactive nonmetals (pink)
  - Noble gases (purple)
  - Unknown chemical properties (grey)

Highlighted elements for N-type semiconductor:

- Silicon (Si) - Group 14, Period 3
- Phosphorus (P) - Group 15, Period 3



conduction

valance

$$\frac{10^{18}}{10^{15}} \text{ p / cm}^3$$

$$n = N_D + n_i \approx N_D$$

p n-type  $e^-$   $n = N_D$  majority

$$np = n_i^2 \Rightarrow p = \frac{n_i^2}{n} \Rightarrow p = \frac{n_i^2}{N_D}$$

$$n = N_D$$

## P-Type Semiconductor

# Periodic Table of the Elements

1A

1

H

Hydrogen

1.00794

2

He

Helium

4.002602

3

Li

Lithium

6.941

4

Be

Beryllium

9.012182

5

Na

Sodium

22.98976928

6

Mg

Magnesium

24.304

7

K

Potassium

39.0983

8

Ca

Calcium

40.078

19

Rb

Rubidium

85.4678

20

Sr

Strontium

87.62

55

Cs

Cesium

132.90545196

56

Ba

Barium

137.327

87

Fr

Francium

223

88

Ra

Radium

226

91-92

Actinides

93

Ac

Actinium

227

94

Th

Thorium

232

95

Pa

Protactinium

231

96

U

Uranium

238

97

Np

Neptunium

237

98

Pu

Plutonium

244

99

Am

Americium

243

100

Cm

Curium

247

101

Bk

Berkelium

247

102

Cf

Californium

251

103

Es

Einsteinium

252

104

Fm

Fermium

257

105

Md

Mendelevium

258

106

No

Nobelium

259

107

Lr

Lanthanum

138.90547

13

Al

Aluminum

26.9815385

14

Si

Silicon

28.0855836

15

P

Phosphorus

30.973761998

16

S

Sulfur

32.06

17

Cl

Chlorine

35.453

18

Ar

Argon

39.948

31

Ga

Gallium

69.723

32

Ge

Germanium

72.64

33

As

Arsenic

74.9216

34

Se

Selenium

78.96

35

Br

Bromine

79.904

36

Kr

Krypton

83.798

49

In

Indium

114.818

50

Sn

Tin

118.710

51

Sb

Antimony

121.757

52

Te

Tellurium

127.6

53

I

Iodine

126.90549

54

Xe

Xenon

131.29

81

Tl

Thallium

204.3833

82

Pb

Lead

207.2

83

Bi

Bismuth

208.9804

84

Po

Polonium

209

85

At

Astatine

210

86

Rn

Radon

222

101

Dy

Dysprosium

162.50014

102

Ho

Terbium

158.92534

103

Er

Erbium

157.254

104

Tm

Thulium

158.92534

105

Yb

Ytterbium

173.05468

106

Lu

Lutetium

174.96706

Atomic Number →

1

← Symbol

Name:

Hydrogen

← Atomic Weight

Electrons per shell:

1

State of matter (color of name):

S

GAS

LIQUID

SOLID

(H<sub>2</sub>O)(H<sub>2</sub>O<sub>2</sub>)

Subcategory in the metal-metalloid-nonmetal bond (color of background):

Alkali metals

Alkaline earth metals

Transition metals

Lanthanides

Actinides

Metalloids

Nonmetals

Reactive nonmetals

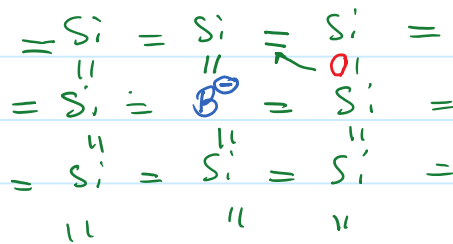
Noble gases

!! Irrelevant chemical properties

2A

4A

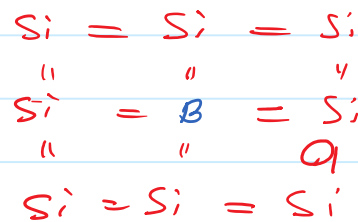
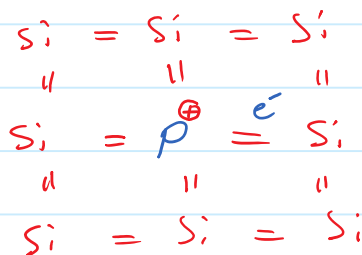
5A



$$\underline{N_A} \quad 10^{18} \text{ B cm}^3$$

$$\rho = N_A$$

$p$ -type  $\rightarrow$  hole  $\rightarrow p = N_A$        $n_p = n_i^2$        $\Rightarrow n = \frac{n_i^2}{p}$



$$1P \rightarrow 1$$
$$N_D \rightarrow \boxed{N_D = n}$$

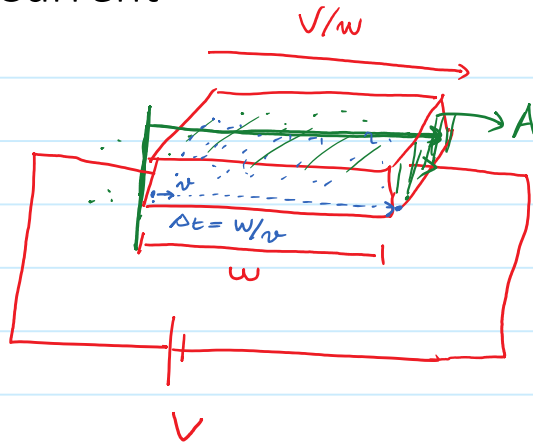
$$N_A \rightarrow N_A = p$$

## Example

Consider an  $n$ -type silicon for which the dopant concentration  $N_D = 10^{17}/\text{cm}^3$ . Find the electron and hole concentrations at  $T = 300$  K.

$$\boxed{n = N_D = 10^{17} \text{ e}^-/\text{cm}^3}$$
$$\uparrow \quad \downarrow \quad \Rightarrow \quad \rho = \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = \underline{\underline{2.25 \times 10^3 \text{ h}/\text{cm}^3}}$$

# Drift Current



$$v_p = E \cdot \mu_p$$

$\text{cm}^2 \text{ Volts/cm}^3$

$$\Delta Q = w \cdot A \cdot \rho \cdot q$$

$$I = \frac{\Delta Q}{\Delta t} = \frac{w A \rho \cdot q}{w/v}$$

$$I = \frac{w A \rho \cdot q}{w} \cdot E \mu_p$$

$$I/A = J = \rho q \cdot E \mu_p$$

$$J = p q E \mu_p - n q E \mu_n = E (q p \mu_p - q n \mu_n)$$

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

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

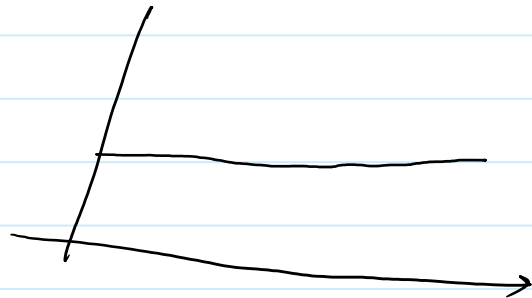
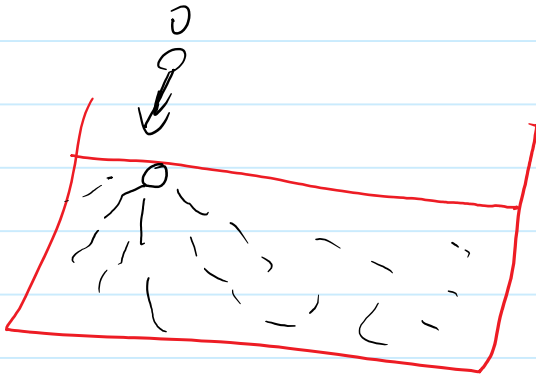
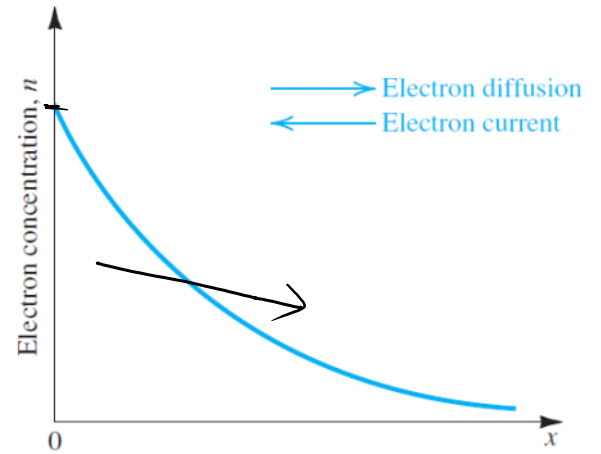
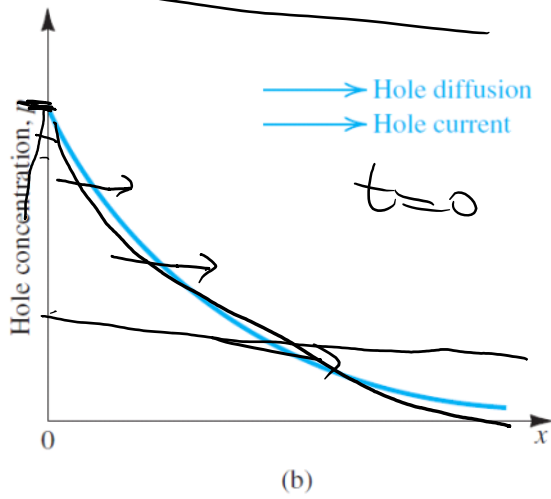
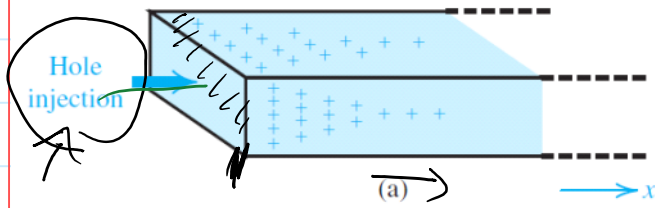
$$J = \sigma E \Rightarrow \frac{I}{A} = \sigma \cdot \frac{V}{w} \Rightarrow V = \left( \frac{1}{\sigma} \frac{w}{A} \right) \cdot I$$



## Example

Find the resistivity of (a) intrinsic silicon and (b)  $p$ -type silicon with  $N_A = 10^{16}/\text{cm}^3$ . Use  $n_i = 1.5 \times 10^{10}/\text{cm}^3$ , and assume that for intrinsic silicon  $\mu_n = 1350 \text{ cm}^2/\text{V} \cdot \text{s}$  and  $\mu_p = 480 \text{ cm}^2/\text{V} \cdot \text{s}$ , and for the doped silicon  $\mu_n = 1110 \text{ cm}^2/\text{V} \cdot \text{s}$  and  $\mu_p = 400 \text{ cm}^2/\text{V} \cdot \text{s}$ . (Note that doping results in reduced carrier mobilities.)

# Diffusion Current

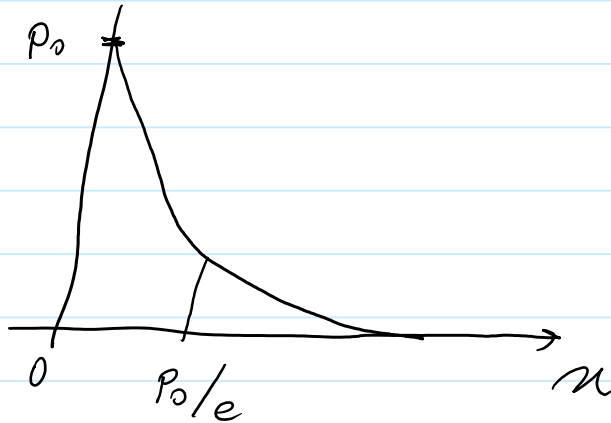


## Example

Consider a bar of silicon in which a hole concentration profile described by

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

is established. Find the hole-current density at  $x = 0$ . Let  $p_0 = 10^{16}/\text{cm}^3$ ,  $L_p = 1 \mu\text{m}$ , and  $D_p = 12 \text{ cm}^2/\text{s}$ . If the cross-sectional area of the bar is  $100 \mu\text{m}^2$ , find the current  $I_p$ .



$$J_p = -q D_p \frac{dp(x)}{dx}$$

$$J_n = q D_n \frac{dn(x)}{dx}$$

$$J_p = q \frac{D_p}{L_p} p_0 = 192 \text{ A/cm}^2$$