RRB-JE 2024

Railway Recruitment Board

Junior Engineer Examination

Electrical Engineering

Basic Electronics

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY
PUBLICATIONS

Basic Electronics

Contents

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Chapter 1

Semiconductor Physics

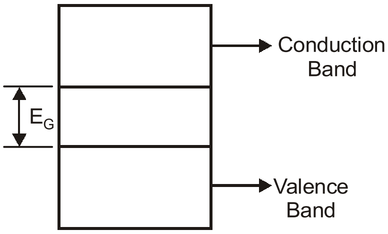
1.1 Introduction

A material whose conductivity lies between the metal and insulator is known as semiconductor.

Example : Silicon, Germanium

Energy Gap (E_G) or Band Gap

- The minimum energy required to detach an electron from valence band to conduction band is equal to it's Energy Gap (E_G).



- Energy band gap E_g is a function of temperature and tends to decrease as the temperature increases.
- At any temperature T,

$$E_g(T) = E_{go} - \beta T$$

E_{go} = Energy Band Gap at 0°K

β = Material constant (Unit : eV/°K)

Energy band structure of an insulator, a semiconductor and a metal

Insulator

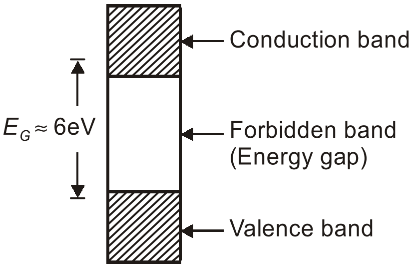
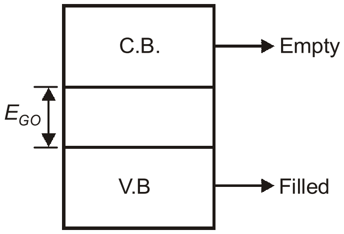


Fig. (a)

Example : Diamond

- Large forbidden band separates the filled valence band from the vacant conduction band. So electron cannot acquire sufficient applied energy hence conduction is impossible. All insulators are bad conductors of current at any temperature.

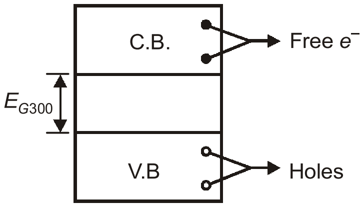
Semiconductor



Semiconductor at 0°K

Fig. (b)

- At 0°K, semiconductor behave as insulator because at 0°K conduction band is empty and there is no charge carrier in conduction band.



Semiconductor at 300 k

- At 300 K free charge carriers are available, so semiconductor will contribute some current at 300 K.
- A material for which the width of forbidden energy band is relatively small (~1 eV) is called semiconductor

$$E_{G300} = 0.72 \text{ eV for Ge}$$
$$E_{G300} = 1.1 \text{ eV for Si}$$
$$E_G = 0.785 \text{ eV for Ge \& } 1.21 \text{ eV for Si at } 0° \text{ K}$$

NOTE:

Conduction in semiconductors does not obey ohm's law and will increase rapidly than voltage, i.e. semiconductors are non-linear resistors.

Metal

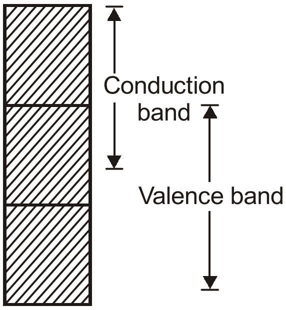


Fig. (c)

- Metals have overlapping valence and conduction bands.
- Metal are good conductor of current even at 0°K.

  [**Example :** Copper (Cu) and Aluminium (Al)]

1.2 Transport Phenomena in Semiconductors

Mobility

- Mobility is the proportionality constant which essentially gauges how easily current carriers (i.e. electrons or holes) can move through a piece of semiconductor.
- When an electric field (E) is applied to a conductor or semiconductor then the charge carriers (electrons or holes) starts flowing in it with velocity known as drift velocity (v).
- Mobility is the proportionality constant that relates the drift velocity to the electric field strength in a semiconductor.

  Hence, mobility of a carrier is given by

$$\boxed{\mu = \frac{v}{|E|}} \qquad ...(1.1)$$

- The unit of mobility is m^2/volt-sec.
- Electron mobility is always higher than hole mobility. For a particular material electron can travel faster and contribute more current than hole.

Conductivity

- The conductivity of a material can be related to the number of charge carriers present in the material. In case of conductors the conductivity is given as:

$$\sigma = n e \mu \qquad ...(1.2)$$

where,

n = number of free charge carriers

e = charge of e^-

= 1.602×10^{-19} col.

μ = mobility of e^-

σ = conductivity

- In semiconductor there are two types of charge carriers, i.e. electron and holes, hence the resultant conductivity of a semiconductor depend upon:
  - The concentration of the mobile charge carriers (i.e. electrons and holes) and
  - The mobility of the charge carriers.

  ∴ conductivity due to electrons

$$\sigma_n = n e \mu_n$$

  and conductivity due to holes

$$\sigma_p = p e \mu_p$$

  Where, μ_n and μ_p are the mobility of electrons and holes respectively.

  Total conductivity of a semiconductor.

$$\sigma = \sigma_n + \sigma_p$$

$$= ne\mu_n + pe\mu_p \qquad ...(1.3)$$

- In case of intrinsic (Pure) semiconductors the electrons and holes are always present in equal concentration

  $$n = p = n_i$$

  Therefore, conductivity of intrinsic semiconductors.

  $$\sigma_i = n_i e(\mu_p + \mu_n) \quad \text{...(1.4)}$$

  Where, $n_i = n = p$ and is called intrinsic concentration.

  Intrinsic resistivity is given as:

  $$\rho_i = \frac{1}{\sigma_i} \quad \text{...(1.5)}$$

  The unit of resistivity is ohm-m.

  For good conductor, $n \cong 10^{28}$ electrons/m^3

  For insulator, $n \cong 10^7$ electrons/m^3

  For semiconductor the concentration of mobile charge carriers lies between these two values.

Current Density

$$\boxed{\begin{aligned} J &= nev \\ &= \rho v \\ &= ne\,\mu E \end{aligned}} \quad \text{...(1.6)}$$

J → current density (current / area)

n → carrier concentration (no. of carriers / m^3)

v → velocity in meter per second

ρ → ne (charge density in coulombs / m^3)

- For metals, $J = ne\mu E$
- For semiconductors, $J = ne\mu_n E + pe\mu_p E$

  $$J = (n\mu_n + p\mu_p)eE$$

Intrinsic Semiconductors

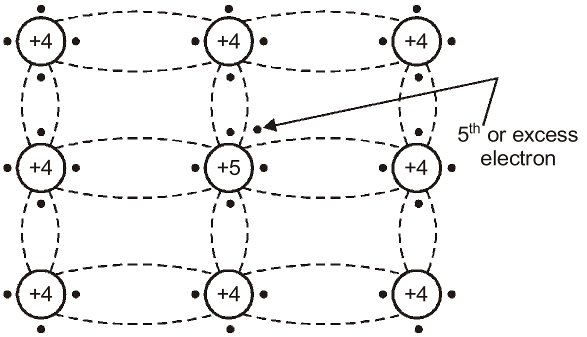
- At absolute zero, all the valence electrons are tightly bound to the parent atoms. No free electrons are available for conduction.
- The intrinsic semiconductor behaves as a perfect insulator at absolute zero.
- At room temperature, sufficient thermal energy is supplied to break the covalent bond, thereby, generating electron-hole pairs.
- The concentration of free electrons and holes will always be equal in an intrinsic semiconductor.

  $$n = p = n_i \qquad (n_i = \text{intrinsic concentration})$$

Extrinsic Semiconductors

- In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by introducing impurities into the crystal.
- This process, called doping, is the most common technique for varying the conductivity of semiconductors.
- When a crystal is doped such that the equilibrium carrier concentration are different from the intrinsic carrier concentration, the material is said to be extrinsic.

(i) N-Type Semiconductor



- If suitable **pentavalent** impurities (antimony, phosphorus and arsenic) are added to intrinsic silicon or Ge, such impurities donate excess (negative) electron carriers, and therefore referred to as donor or n-type impurities.
- This excess electron loosely bound to its parent atom, is relatively free to move within the *n*-type material.
- When impurities are introduced in the material, additional levels are created in the energy bond structure, usually within the band gap. For *n*-type impurity, it is called "Donor Level".
- In case of Germanium, donor level is only 0.01 eV (0.05 eV in silicon) below the conduction band, and therefore at room temperature almost all the excess electrons of the donor material are raised into the conduction band.
- N-type semiconductor at 0°K is a perfect insulator.
- Donor energy level (E_D) does not depend upon temperature.
- Energy band diagram of *n*-type semiconductor.

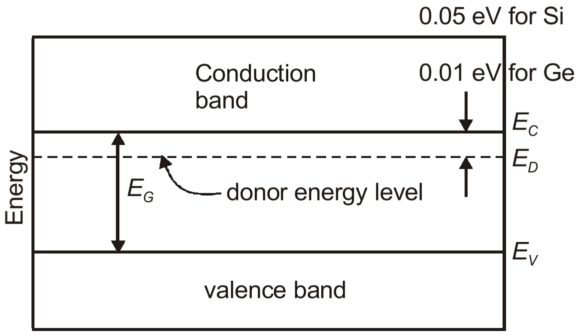
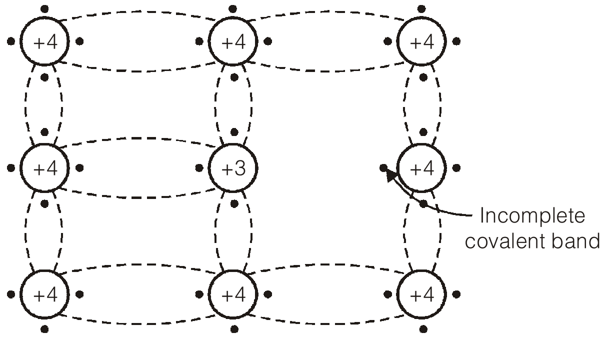


Fig. (a)

- If intrinsic semiconductor is doped with *n* type impurities, not only does the number of electrons increase, but the no. of holes decreases below that which would be available in the intrinsic semiconductor. The reason for the decrease in the no. of holes is that the larger no. of electrons present increases the rate of recombination of electrons with holes.
- In n-type semiconductor, majority carriers are electrons and minority carriers are holes.

(ii) p-type Semiconductor



- If **trivalent impurity** (Boron, Aluminium, Gallium or Indium) is added to an intrinsic semiconductor, only three of the covalent bonds can be filled and such impurities make available positive carriers because they create holes which can accept electrons. These impurities are referred to as acceptor or p-type impurities.
- Energy band diagram of p-type semiconductor.

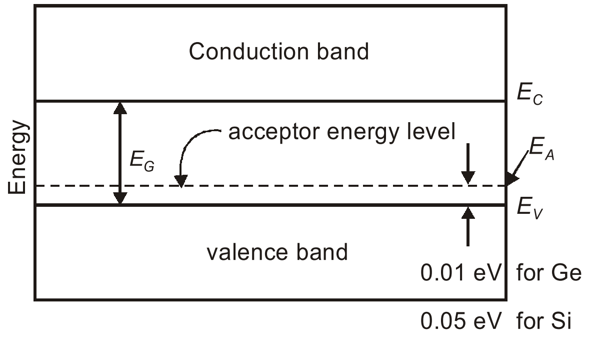


Fig. (b)

- A very small amount of energy is required for an electron to leave the valence band and occupy the acceptor energy level, it follows that holes generated in the valence band by these electrons constitute the largest number of carriers in the semiconductor material.
- The acceptor atom introduces an energy level near the valence band known as Acceptor Energy Level (E_A).
- Acceptor Energy level exist just above the valence band. It represents the energy level of all the trivalent impurities.
- p-type semiconductor at 0°K behave as insulator.
- At room temperature, enough thermal energy is available to excite electrons from the valence band to acceptor level.
- Acceptor Energy level (E_A) does not depend upon temperature.
- In p-type semiconductor, majority carriers are holes and minority carriers are electrons.

Standard Doping Levels

1. Moderate Doping : 1 in ($10^6 - 10^8$) : P, N
2. Lightly Doped : 1 in 10^{11} : P^-, N^-
3. Heavily Doped : 1 in 10^3 : P^+, N^+

1 in 10^6 is read as "1 impurity atom in 10^6 atoms".

Mass-action Law

- Under thermal equilibrium (at constant temperature), the product of positive and negative concentrations is a constant independent of the amount of donor and acceptor impurity doping. i.e.

$$\boxed{np = n_i^2} \quad \text{...(1.7)}$$

- The intrinsic concentration is a function of temperature.

Charge density in a semiconductor

$N_D \rightarrow$ concentration of donor atoms.
$N_A \rightarrow$ concentration of acceptor atoms.
$\because$ semiconductor is electrically neutral
$\therefore$ Total positive charge = Total negative charge

i.e. $$\boxed{N_D + p = N_A + n} \quad \text{...(1.8)}$$

$\Rightarrow$ For an n type material. $N_D + p = n$. Because, $n >> p$

$\therefore$ $\boxed{n \approx N_D \text{ or } n_n \approx N_D}$ 'n' subscript represent 'n' type material

$\therefore$ concentration p_n of holes in n-type will be given by

$$n_n p_n = n_i^2$$

$$\therefore \quad \boxed{p_n = \frac{n_i^2}{N_D}} \quad \text{...(1.9)}$$

- For a p type material

$$p_p \approx N_A$$

$$\therefore \quad n_p p_p \approx n_i^2$$

$$\therefore \quad \boxed{n_p \simeq \frac{n_i^2}{N_A}} \quad \text{...(1.10)}$$

here 'p' subscript represent 'p' type material.

NOTE:

If concentration of donor atoms added to a p-type semiconductor exceeds the acceptor concentration i.e. ($N_D > N_A$), the specimen changes from p-type to n-type semiconductor. N_D is replaced by ($N_D - N_A$) in above equation (1.9).

1.3 Expression for Minimum Conductivity in Semiconductor

- Conductivity of semiconductor is given as

$$\sigma = nq\mu_n + pq\mu_p$$

- For minimum conductivity

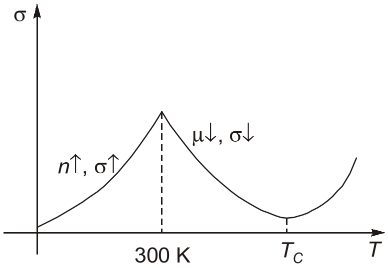
$$n = n_i\sqrt{\frac{\mu_p}{\mu_n}} \quad \text{and} \quad P = n_i\sqrt{\frac{\mu_n}{\mu_p}}$$

- $\sigma_{\min} = 2n_i\sqrt{\mu_n\mu_p}\cdot q$

Effect of Temperature on Conductivity of Intrinsic Semiconductor

- For intrinsic semiconductor, $\sigma = n_i q(\mu_n + \mu_p)$
- As temperature increases, $n_i \uparrow\uparrow$ and $\mu\downarrow \Rightarrow \sigma\uparrow$ as $T\uparrow$
- Conductivity of intrinsic semiconductor increases with temperature.

Effect of Temperature on Conductivity of Extrinsic Semiconductor



0 < T < 300 K:

Conductivity increases with the temperature. Because of thermal energy, electrons from valence band gets excited to Acceptor level (in p-type semiconductors) and free electrons from Donor Level gets excited to conduction band (in n-type semiconductors).

300 K < T < T_c:

Majority carrier concentration will remain almost independent of Temperature ($N_D >> n$ or $N_A >> P$). As temperature increases, mobility decreases and therefore, conductivity decreases with temperature.

T > T_c:

At $T = T_C$ (curie temperature) minority carrier concentration will become equal to majority carrier concentration and the extrinsic semiconductor will become intrinsic semiconductor. Above curie temperature, conductivity increases with temperature.

1.4 Electrical Properties of Ge and Si

Intrinsic concentration

$$\boxed{n_i^2 = A_0T^3e^{-\left(\frac{E_{G0}}{KT}\right)}} \qquad ...(1.11)$$

$E_{G0} \rightarrow$ energy gap at 0°K in eV

$K \rightarrow$ Boltzman's constant in eV / °K.

$A_0 \rightarrow$ constant independent of temp.

Energy Gap

E_G depends on temperature.

For Si, $E_G(T) = 1.21 - 3.60 \times 10^{-4}$ T

at $T = 0°$ K

$$\boxed{E_G(T) = 1.21\,\text{eV}}$$

For Ge, $E_G(T) = 0.785 - 2.23 \times 10^{-4}\,T$

At $T = 0°\,K$,

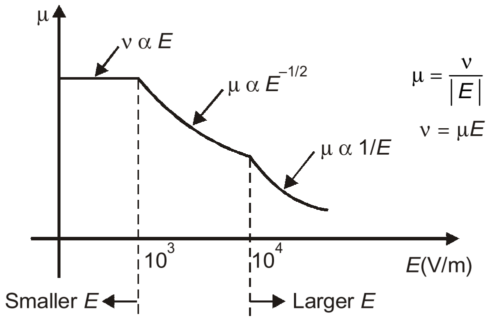
$$\boxed{E_G(T) = 0.785\text{ eV}}$$

at $T = 300°K$ (room temperature)

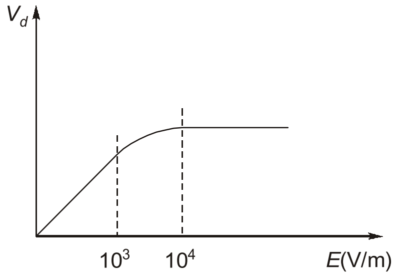
for Si, $E_G(T) = 1.1$ eV

for Ge, $E_G(T) = 0.72$ eV

Mobility Vs Electric Field Intensity for a Semiconductor



Variation of Drift Velocity with Electric Field Intensity in Semiconductor



Variation with Electric Field Intensity

For $E < 10^3$ V/cm in Silicon, $\mu \rightarrow$ constant

$10^3 < E < 10^4$ V/cm, $\mu_n \propto E^{-1/2}$

$E > 10^4$ V/cm, $\mu_n \propto E^{-1}$ and for this higher field i.e. $E > 10^4$ V/cm, $\mu_n \propto E^{-1}$ and carrier speed approaches the constant value of 10^7 cm/s.

- For smaller value of (E) applied, mobility (μ) of charge carriers will remain almost constant.
- For smaller value of electric field (E) applied, the drift velocity linearly increases with electric field (E).
- For large electric field applied, mobility of charge carrier will be very small.
- At high electric field intensity applied, the drift velocity (v) will remain almost constant.
- Mobility of charge carrier decreases with temperature.

Generation of Electron-Hole Pairs:

The breaking of covalent bond in a semiconductor leads to generation of charge carriers, i.e., a pair of electrons and holes.

Student's Assignments

1. Which of the following materials is semiconductor
(a) Chromium (b) Selenium
(c) Bismuth (d) Silica

2. Under thermal equilibrium in semiconductor the ratio of number of holes to the number of conduction electrons is
(a) 1/2 (b) infinity
(c) 1 (d) 2

3. Fermi energy level for P-type extrinsic semiconductor lies _______
(a) at middle of the band gap
(b) close to conduction band
(c) close to valence band
(d) none of these

4. The donor atoms in an n-type semiconductor at normal temperature ________.
(a) carry a positive charge
(b) carry a negative charge
(c) are neutral
(d) none of these

5. Resistivity of a semiconductor depends on
(a) the length of the semiconductor specimen
(b) cross-sectional area of the semiconductor specimen
(c) volume of the semiconductor
(d) the atomic nature of semiconductor

6. Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the
(a) diffusion current
(b) drift current
(c) recombination current
(d) induced current

7. Donor impurity atom in a semi-conductor result in new _________.
(a) wide energy band
(b) narrow energy band
(c) discrete energy level just below conduction level
(d) discrete energy level just above valence level

8. The resistivity of a uniformly doped n-type silicon sample is 0.5 Ω-cm. If the electron mobility (μ_n) is 1250 cm^2/V-sec, then the donor impurity concentration (N_D) in the sample is
(a) 2×10^{16}/cm^3 (b) 1×10^{16}/cm^3
(c) 2.5×10^{15}/cm^3 (d) 5×10^{15}/cm^3

9. A semiconductor has a band gap of 2eV. The wavelength of radiation emitted from the semiconductor when electrons and hole recombine is
(a) 625 nm (b) 625 μm
(c) 625 mm (d) 625 cm

10. A silicon sample is uniformly doped with 10^{16} phosphorous atoms/cm^3 and 2×10^{16} Boron atoms/cm^3. If all the dopants are full ionized, the material is
(a) n-type with carrier concentration of 10^{16}/cm^3.
(b) p-type with carrier concentration of 10^{16}/cm^3.
(c) p-type with carrier concentration of 2×10^{16}/cm^3.
(d) n-type with carrier concentration of 2×10^{16}/cm^3.

11. At absolute zero, an intrinsic semiconductor
(a) becomes superconductor
(b) disintegrates into pieces
(c) behaves like an insulator
(d) becomes extrinsic semiconductor

12. On applying an electric field of intensity 10 V/cm across a semiconductor at a certain temperature, the average drift velocity of free electrons is measured to be 70 m/s. Then, the electron mobility is
(a) 7×10^4 cm^2/V-s (b) 700 cm^2/V-s
(c) 7 m^2/V-s (d) 700 m^2/V-s

13. The temperature coefficient of an intrinsic semiconductor is
(a) zero (b) positive
(c) negative (d) like that of metals

14. The carrier mobility in a semiconductor is 0.4 m^2/V-S. It's diffusion constant at 300°K will be (in m^2/s)
(a) 0.43 (b) 0.16
(c) 0.04 (d) 0.01

15. In a homogeneously doped n-type semiconductor bar, holes are injected at one end of the bar. How will the hole flow to the other end?
(a) By drift mechanism only
(b) By diffusion mechanism only
(c) By combination of drift and diffusion mechanism
(d) By recombination mechanism

Q.16 A specimen of intrinsic germanium with the density of charge carriers of $2.5 \times 10^{13}/cm^3$, is doped with donor impurity atoms such that there is one donor impurity atom for every 10^6 germanium atoms. The density of germanium atoms is $4.4 \times 10^{22}/cm^3$. The hole density would be
(a) $4.4 \times 10^{16}/cm^3$ (b) $1.4 \times 10^{10}/cm^3$
(c) $4.4 \times 10^{10}/cm^3$ (d) $1.4 \times 10^{16}/cm^3$

Q.17 If for intrinsic Silicon at 27°C, the charge concentration and mobilities of free-electrons and holes are 1.5×10^{16} per m^3, 0.13 m^2/(Vs) and 0.05m^2/(Vs) respectively, its conductivity will be
(a) $2.4 \times 10^{-3}\ (\Omega\text{-m})^{-1}$
(b) $3.15 \times 10^{-3}\ (\Omega\text{-m})^{-1}$
(c) $5 \times 10^{-4}(\Omega\text{-m})^{-1}$
(d) $4.32 \times 10^{-4}(\Omega\text{-m})^{-1}$

STUDENT'S ASSIGNMENTS ANSWER KEY

1. (b)	**2.** (c)	**3.** (c)	**4.** (a)	**5.** (d)
6. (a)	**7.** (c)	**8.** (b)	**9.** (a)	**10.** (b)
11. (c)	**12.** (b)	**13.** (c)	**14.** (d)	**15.** (b)
16. (b)	**17.** (d)			

STUDENT'S ASSIGNMENTS EXPLANATIONS

2. (c)

At thermal equilibrium,

$$n = P = n_i$$

3. (c)

$$E_F = E_V + kT\ln\left(\frac{N_V}{N_A}\right)$$

4. (a)

As donor gives one electron, they are positively charged. Acceptor like Boron takes an electron and hence negatively charged.

5. (d)

Resistance depends upon length, area of cross-section, volume but resistivity of material depends upon its crystal structure and atomic nature.

8. (b)

$$\sigma = qN_D\mu_n$$

$$\Rightarrow \quad N_D = \frac{\sigma}{q\mu_n} = \frac{1}{\rho q\mu_n}$$

$$\Rightarrow \quad N_D = \frac{1}{0.5 \times 1.6 \times 10^{-19} \times 1250}$$

$$\Rightarrow \quad N_D = 1 \times 10^{16}/cm^3$$

9. (a)

$$\lambda = \frac{12500}{E_g} \quad \text{(in Å)}$$

$$\lambda = \frac{12500}{2} = 6250\ \text{Å}$$

$$= 625\ \text{nm}$$

10. (b)

$$N_A = 2 \times 10^{16}\ \text{atoms/cm}^3$$

$$N_D = 10^{16}\ \text{atoms/cm}^3$$

The material is p-type and carrier concentration:

$N_A - N_D = 10^{16}$ atoms/cm^3