XMUT204 Electronic Design

Tutorial 1: Semiconductor and Diode Properties (Answer)

Section A: Atomic and Material Properties

1. If the atomic number of a neutral atom is 6, how many electrons does the atom have? How many protons? [2 marks]

   Answer: 6 electrons, 6 protons.

2. What is the number of electrons that can exist in the 3rd shell of an atom? [2 marks]

   Answer: 18 electrons ($N_e = 2n^2$).

3. For each of the energy band shown on the figure given below, determine the class of materials based on relative comparisons. [3 marks]

   Answer: A – Insulator, B – Semiconductor, and C – Conductor.

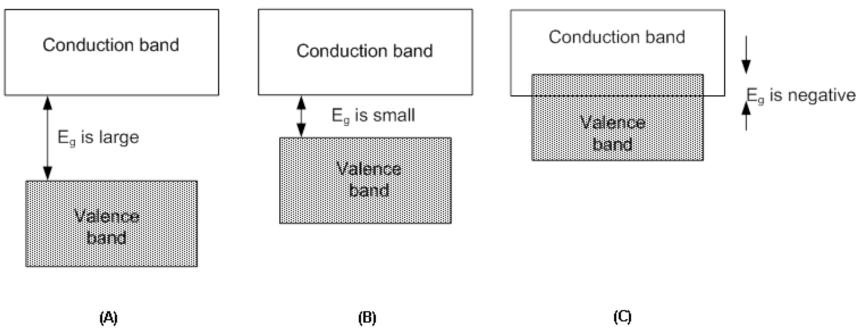


Figure 1: Various materials according to a number energy band configurations

4. A certain atom has four valence electrons. What type of atom is it? [2 marks]

   Answer: Tetravalent material such as carbon, silicon, etc.

5. In a silicon crystal, how many covalent bonds does a single atom form? [2 marks]

   Answer: 4 covalent bonds.

6. Calculate conductivity of carbon nanotubes material if it has 16 x 10^{23} conduction electrons per cm^3 and the mobility of electron is 150 cm-2/Vs. [2 marks]

Answer:

Conductivity of the carbon nanotubes material (σ) is:

$$\sigma = ne\mu = (16 \times 10^{23})(1.6 \times 10^{-19})(150) = 3.84 \times 10^{7}\ (\Omega\text{m})^{-1}$$

7. What is the resistance of a tungsten wire that has diameter of 2 mm and length of 5 m? Note that a tungsten has resistivity coefficient, $\rho = 4.76 \times 10^{-8}\,\Omega$m. [4 marks]

Answer:

Area of the tungsten wire (A) with diameter (d) of 2 mm is:

$$A = \pi\left(\frac{d}{2}\right)^2 = \pi\left(\frac{2 \times 10^{-3}}{2}\right)^2 = 3.14 \times 10^{-6}\ \text{m}^2$$

Resistance of the wire (R) is:

$$R = \frac{\rho L}{A} = \frac{L}{\sigma A} = \frac{(4.76 \times 10^{-8})(5)}{3.14 \times 10^{-6}} = 7.58 \times 10^{-2}\ \Omega/\text{m}$$

Section B: Semiconductors

1. What happen when heat is added to silicon? [2 marks]

Answer: Atoms in the silicon get excited, some electrons and holes are produced and traversing from valence band to conduction band overcoming gap band energy levels since gap band is quite narrow in semiconductor materials.

2. Name the two energy bands at which current is produced in silicon? [2 marks]

Answer: valence band and conduction band, with conceptual gap band existed in between.

3. Describe the process of doping and explain how it alters the atomic structure of silicon. [2 marks]

Answer: doping is adding external material to intrinsic silicon. Depending on the type of material (p or n material) the doped semiconductor will have relevant material characteristics.

4. What is antimony? What is boron? [4 marks]

Answer:

Antimony is one of Group 15 elements in the periodic table. It is commonly used for alloy and catalyst. It is also sometime used for semiconductor materials.

Boron is one of Group 13 elements in periodic table. It is commonly used for making p-dopant semiconductor material.

5. How is the electric field across the PN junction created? [2 marks]

   Answer: It is created to oppose or due to the formation of combination of electrons and holes in the depletion junction area.

6. Because its barrier potential, can a diode be used as a voltage source? Explain? [2 marks]

   Answer: it is not an energy source, but it consumes energy to overcome this barrier potential when it is forward biased.

7. Determine the number of atom in a lattice of GaAs crystal as shown below. Calculate the number of Ga and As atoms in the lattice for one cm^3 of material (note that length of each side of the lattice is 1.2 nm). [8 marks]

   Answer:

   Number of Ga and As atoms in the lattice are calculated from:

   - Ga Atoms = 8 x 1/8 atoms (in the corners of the lattice) + 6 x 1/2 atoms (on the face/side of the lattice) = 4 Ga atoms/lattice.
   - As atoms = 4 x 1 atom (inside the lattice) = 4 As atoms/lattice.

   Number of cells in 1 cm^3 of GaAs material is:

$$\text{No GaAs cells} = \frac{1}{(\text{length})^3} = \frac{1}{(1.2 \times 10^{-7})^3} = 5.79 \times 10^{22} \text{ cells}$$

   Number of Ga and As atoms in 1 cm^3 of GaAs material is:

$$\text{No GaAs atoms} = (4 + 4) \times \text{No of GaAs cells}$$

$$= (8)(5.79 \times 10^{22}) = 4.63 \times 10^{23} \text{ atoms}$$

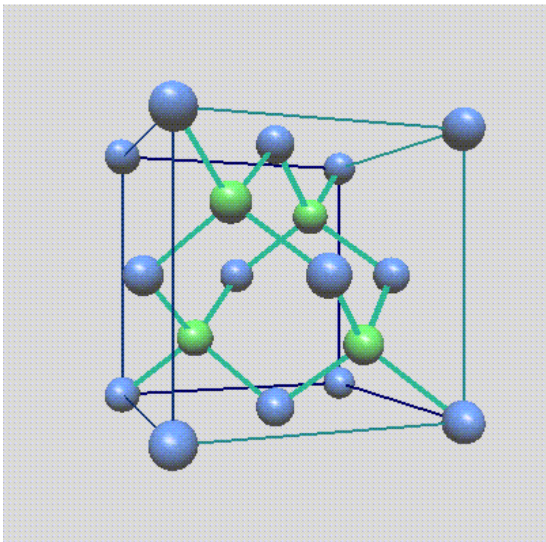


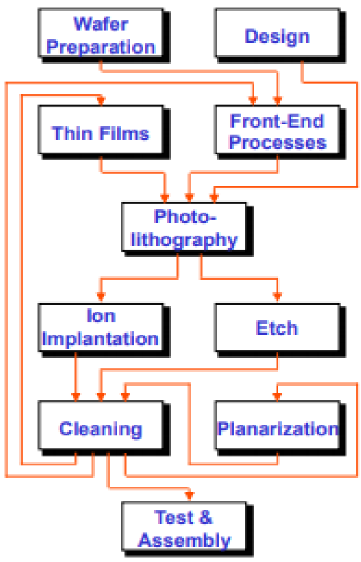
Figure 2: GaAs Crystal Lattice

Section C: Microfabrication

1. Describe the steps required in manufacturing of semiconductor devices. [6 marks]

Answer:

a. Design
b. Wafer preparation
c. Front-end processes
d. Photolithography
e. Etch
f. Cleaning
g. Thin films
h. Ion implantation
i. Planarization
j. Test and assembly

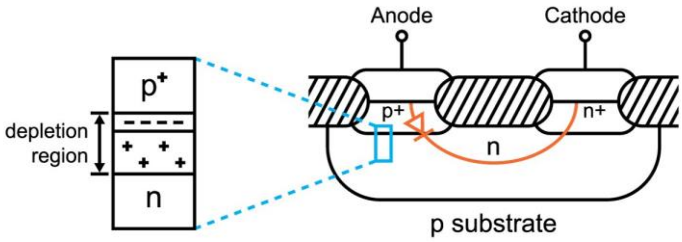


2. With help from relevant diagrams, describe the materials that make up the semiconductor layer structures of simple diode, BJT and MOSFET transistors. [6 marks]

Answer:

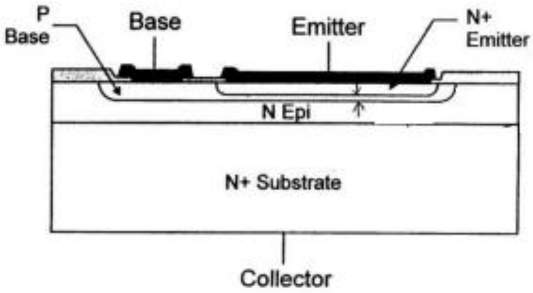
Diode
A simple diode is formed when a p-type semiconductor material is integrated with a lightly

doped n- type semiconductor material.



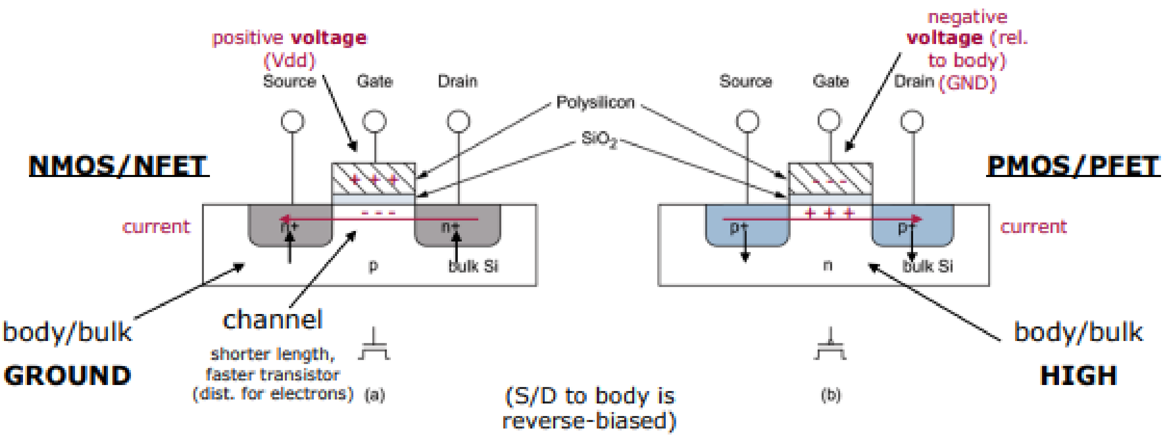
BJT

Transistors like the bipolar junction transistor (BJT) has three electrodes and two pn junctions.



MOSFET

A thin gate oxide located between the other two electrodes of the transistor insulates the gate on the MOSFET.



Section D: Diode Characteristics

1. When the n-type semiconductor is joined with the p-type semiconductor, a PN junction is formed.
   a. Describe how the electric field in the PN junction influence the movement of the charges in the diode. [4 marks]

b. Calculate the built-in potential in the diode junction made of unspecified PN materials (e.g. *p-doped part*: doping level (N_p) = 1.5 x 10^{15} cm^{-3} and *n-doped part*: doping level (N_n) = 7.5 x 10^{16} cm^{-3}). [2 marks]

Note: The amount of atoms of the intrinsic semiconductor (n_i) is 1 x 10^{10} cm^{-3} and $V_T = 0.025$ V.

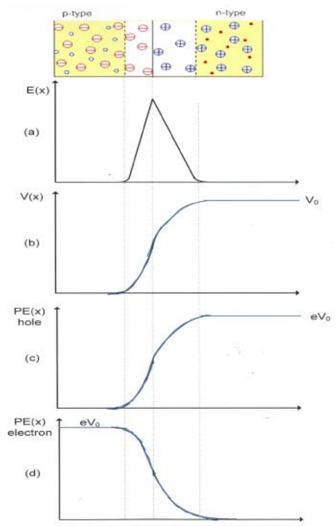
Solution

a. For the given PN junction:

Due to the space charge layer, we will then have an internal electric field across the junction; the direction of this field will be from the positive ions on the n-side to the negative ions on the p-side.

The direction of this field will then oppose the movement of charge carriers due to diffusion.

An electron which enters this internal electric field will then experience a force ($F = qE$) and drift from the p-side to the n-side under the influence of the field, while a hole that enters this field will drift from the n-side to the p-side under influence of the field.



b. The built-in potential in the diode junction is found from the following equation:

$$V_0 = V_T \ln\left[\frac{N_A N_B}{(n_i)^2}\right]$$

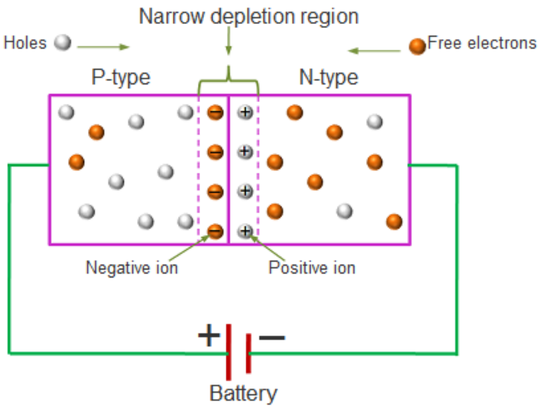
$$= (0.025)\ln\left[\frac{(7.5\times10^{16})(1.5\times10^{15})}{(1\times10^{10})^2}\right]$$

$$= (0.025)\ln(11.25\times10^{11}) = 0.751 \text{ V}$$

2. Describe with an aid of diagram the semiconductor material characteristics of the diode when it is forward biased and reverse biased. [4 marks]

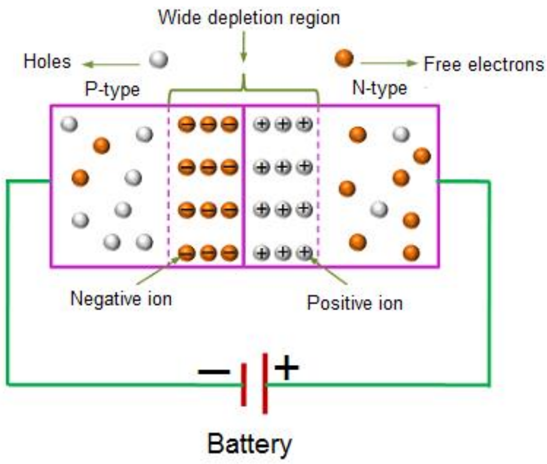
Solution

Forward Bias of PN regions of the Diode:



With a diode is being forward biased in the circuit, the depletion region in the diode is becoming narrower, resulting in easier conduction of the current in the circuit. This is due to excess electrons in the P-type and holes in the N-type being attracted by their corresponding terminals of the battery.

Reverse Bias of PN regions of the Diode:

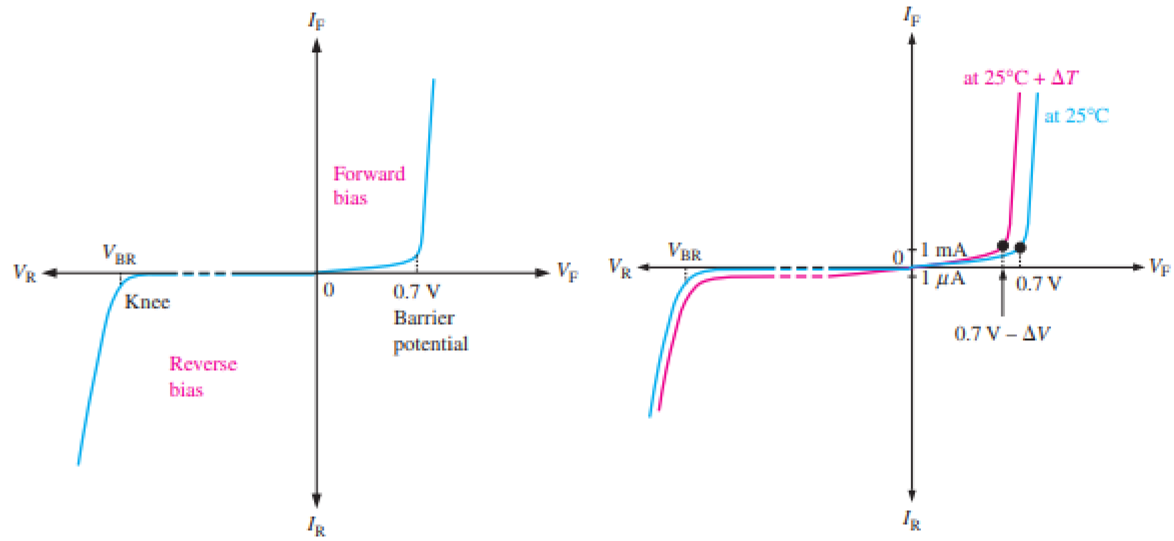


With a diode is being reversed biased in the circuit, the depletion region in the diode is becoming wider, resulting in harder conduction of the current in the circuit. This is due to excess electrons in the P-type and holes in the N-type being repelled by their corresponding terminals of the battery.

3. The process of applying the external voltage to a PN junction semiconductor diode is called biasing.

   a. Describe the characteristics of diode by referring to the diode's V-I curve plot. [4 marks]

   b. Briefly explain how temperature influences characteristics of the diode. [4 marks]



Solution

a. Description of the diode as shown in the given V-I curve plot.

Forward bias:

- Zero volt and zero current.
- Voltage drop across diode (V_d = 0.7 V).
- Barrier potential.
- Current increase dramatically after barrier potential.

Reversed bias:

- Knee voltage.
- Slope = ΔV_d / ΔI_d = impedance of diode (Z_d).
- Breakdown voltage.
- Current decrease dramatically after breakdown voltage.
- Max reversed biased voltage.

b. Temperature could influence the V-I curve:

- Increasing the temperature could shift the curve towards y-axis in the plot. This would make the forward bias voltage of the diode less than before and therefore the reverse bias voltage would increase slightly.
- Decreasing the temperature would provide the opposite effect towards the temperature characteristics of the diode.

4. Forward biasing means putting a voltage across a diode that allows current to flow easily, while

reverse biasing means putting a voltage across a diode in the opposite direction

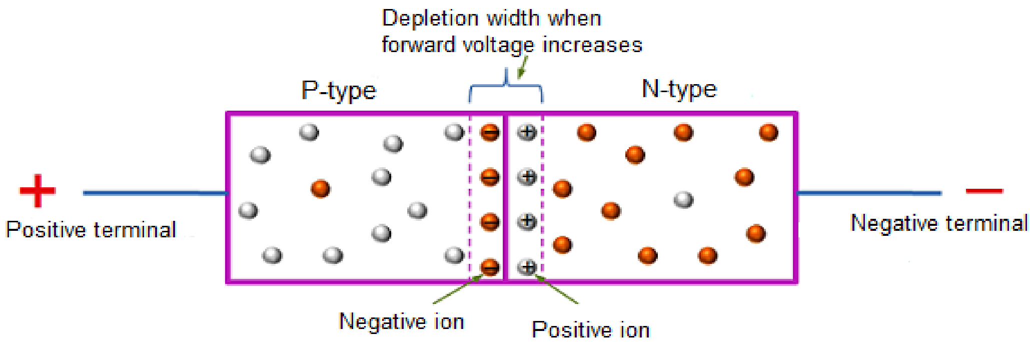
a. To forward bias a diode, to which region must the positive terminal of a voltage source be connected? [4 marks]

b. Explain why a series resistor is necessary when a diode is forward-biased. [2 marks]

c. By referring to its datasheet, determine the forward bias voltage of 1N4148 diode (see Appendix 1). [2 marks]

Solution

a. To forward bias the P-type region (anode) of the diode must be connected with the positive terminal and N-type region (cathode) with the negative terminal.



This later on would reduce the width of the depletion region of the diode making current to flow easily in the circuit.

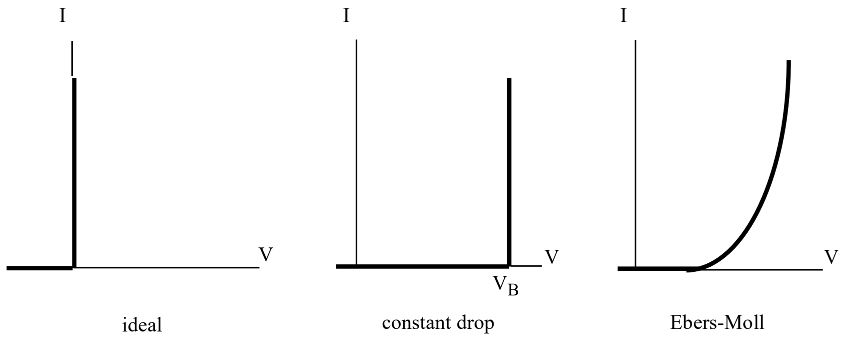
b. This series resistor limits the amount of current flows in the diode, especially during the turn on period of the circuit operation in which a large rushing current would flow in the circuit.

c. From the datasheet of 1N4148 diode, its forward bias voltage is approximately 1 V which is determined at the diode's forward current of 10 mA test condition.

5. Sketch and describe the feasibility of several potential models of diode. [6 marks]

Solution

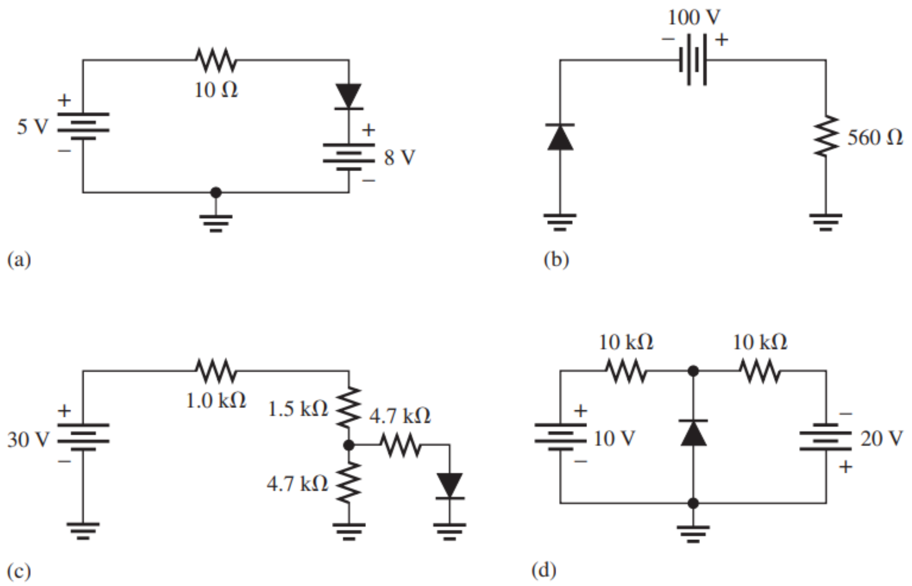
There are at least three models of diode covered in the course: ideal, constant drop and Ebers-Moll models. All three diode models' V-I curve characteristics are outlined in the figures given below.



For a simple circuit that doesn’t need precision analysis, the ideal and constant drop models would be sufficient for most applications.

But, the Ebers-Moll model would provide more comprehensive model that could closely match values found in the practical applications.

6. For the diode circuits given in the figures below, determine:



a. Whether each silicon diode is forward-biased or reversed-biased. [4 marks]

Solution

Circuit (a) is reversed bias.

Circuit (b) is forward bias.

Circuit (c) is forward bias.

Circuit (d) is forward bias.

b. The voltage across each diode, assuming the practical and ideal + voltage source models. [2 marks]

Solution

Practical model = $V_d + i_d R_d$

Ideal model = V_d = 0.7 V

c. The voltage across each diode, assuming the ideal diode + voltage source model . [4 marks]

Solution

For circuit (a): Voltage across diode (V_d) is = -3 V

For circuit (b): Voltage across diode (V_d) is = 0.7 V

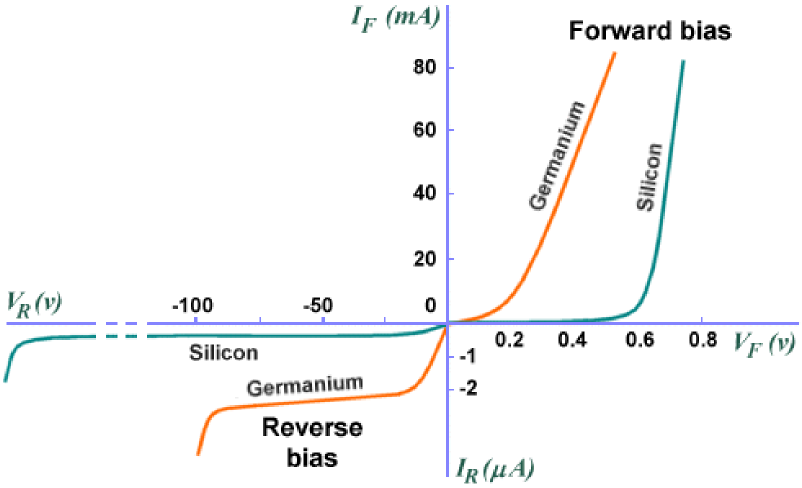
For circuit (c): Voltage across diode (V_d) is = 0.7 V

For circuit (d): Voltage across diode (V_d) is = 0.7 V

7. The V-I curve of a diode is typically a graph showing the current flow (on the y-axis) at different forward voltages (on the x-axis). This graph provides engineers with a visual record of the operating characteristics of the component.
   a. Compare the V-I curves of Germanium diode with Silicon diode. [2 marks]
   b. Sketch a load line of the diode assuming that an input voltage source of 25 V and 2 kΩ limiting resistor. From the sketch determine approximately the V and I values for condition of operation of the diode circuit. [6 marks]

Solution

a. Comparison of V-I curve of the germanium and silicon diodes: Forward bias and reverse bias voltage of silicon-based diode is larger than germanium diode.



b. The load line of the given circuit is shown for an input voltage source of 25 V and 2 kΩ limiting resistor. By referring to the diagram given below, as a result:

The voltage (V_o) at $I_F = 0$:

$$V_o = 25 \text{ V}$$

The current (I_o) at $V_F = 0$:

$$I_o = \frac{V_o}{R}$$

$$= \frac{25}{2 \times 10^3} = 12.5 \text{ mA}$$

For the given circuit, the operating condition for the diode is indicated by the points: V_x and I_x.