SEMICONDUCTOR OPTOELECTRONICS
Questions & Problems for Revision

PART-I: Semiconductor Physics for Optoelectronics

Note: The bold numbers in brackets indicate typical marks allocated to the question in a one-hour written test for 25 marks (or 2 hr written-test for 50 marks)

1) What subject does the course title *Semiconductor Optoelectronics* refer to, and what is its importance? (Explain briefly) **(2)**

2) Draw qualitatively the *E-k* diagrams for an *n*-type and a *p*-type *degenerate semiconductor* at 0 K. (For both cases, indicate the positions of the Fermi levels; show the filled portions of the bands by shaded regions.) **(2)**

3) Given that the density of states in a semiconductor is

$$\rho_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2} \rightarrow \text{Conduction Band}$$

$$\rho_v(E) = \frac{1}{2\pi^2}\left(\frac{2m_v}{\hbar^2}\right)^{3/2}(E_v-E)^{1/2} \rightarrow \text{Valence Band}$$

   a) Obtain expressions for the carrier concentrations *n* and *p* in a semiconductor, under the 'Boltzmann approximation'. **(3)**
   b) Consider a particular sample of *InP* (E_g = 1.36 eV at 300 K) for which E_f lies exactly in the middle of the bandgap. Calculate the concentration of electrons in the conduction band of this sample. (Given: $m_v = 0.5m_0$; $m_c = 0.07m_0$) **(2)**
   c) Is the above sample an *n*-type or a *p*-type semiconductor? (Give reason for your answer) **(1)**

4)
   a) What do you understand by the term 'density of states'? Why is it necessary to know the density of states in the study of semiconductor devices? (Explain briefly) **(3)**

   b) Show that the *density of states* for a semiconductor *quantum well* at energies $E(q = 1)$, $E(q = 2)$, etc. in the conduction band, for example, are the same as that for the bulk semiconductor. **(3)**

5) The carrier concentrations in the valence band and conduction band of a semiconductor in thermal equilibrium (under the Boltzmann approximation) are given by -

$$p = N_v e^{(E_v - E_F)/kT}\;; \qquad n = N_c e^{(E_F - E_C)/kT}$$

Show that the *law of mass action* is not valid in the junction region of a forward biased *p-n* diode. **(3)**

6) Indium Phosphide (InP) is a direct bandgap material with $m_v = 0.5m_0$. For this material, calculate the number of states between the valence band edge and an energy level that is 0.1eV below the valance band edge. **(3)**

7) Consider a certain type of semiconductor material in which the *density of states* (in the *k-space* is given by

$$\rho(k) = \frac{k}{\pi\, d}$$

where d is a constant. Obtain an expression for $\rho_c(E)$ near the band edge, and plot qualitatively its variation with *E*. **(2)**

8) If the effective mass of electrons in the conduction band for the above semiconductor (in the previous question) is 0.10 m_0 and d = 100 nm, determine the number of available states in the conduction band up to the level 0.2 eV above E_c. **(3)**

9) Show that under Boltzmann approximation, the carrier concentration of holes in the valance band of a semiconductor is given by

$$p = N_v\; e^{\frac{(E_v - E_f)}{kT}}$$

(3)

10) What is meant by *bandgap engineering*? State any two methods that could be employed to 'engineer' the bandgap of semiconductor devices. (Explain briefly how do these methods result in bandgap engineering). **(4)**

11) What are *ternary*- and *quaternary* (compound) semiconductors? State two important reasons for using ternary and quaternary semiconductors in Optoelectronics. (No explanation) **(2)**

12) Consider a double heterostructure made up of $GaAs_{0.6}P_{0.4}$/GaAs/ $GaAs_{0.6}P_{0.4}$ layers, wherein the thickness of the GaAs layer is 10 nm; the dopant concentrations are such that both GaAs and $GaAs_{0.6}P_{0.4}$ are characterized by the same Fermi energy. The direct bandgap energy (in eV at 300 K) of the ternary compound $GaAs_{1-x}P_x$ is given by

$$E_g(x) = 1.424 + 1.150x + 0.176x^2;\; 0 \le x \le 0.45$$

a) If the conduction- and valence band-edge discontinuities are in the ratio of 60:40, draw qualitatively the energy band diagram corresponding to the double heterostructure. (Indicate clearly the values of the energy discontinuities.) **(3)**

b) Does the above structure form a quantum well? (Justify your answer by your own calculations/data). Given $m_c = 0.067 m_0$ **(2)**

13) $Ga_{0.47}In_{0.53}As$ (with E_g = 0.72 eV) is a widely used photodetector material in the receivers of optical fiber communication systems. Give any two important reasons for the choice of this detector material. **(2)**

14) Consider the formation of a heterojunction between *p*-$Ga_{0.7}Al_{0.3}As$ and *n*-GaAs. Given that the *electron affinity* of GaAs is 4.1 eV, $(E_f - E_v)_{GaAlAs}$ = 0.3 eV, $(E_c - E_f)_{GaAs}$ = 0.2 eV. Draw the energy band diagram of the (unbiased) *p-n* junction. Calculate the magnitude of *band-edge discontinuities*, and indicate the same in the energy band diagram. (You may assume that the conduction- and valence band-edge discontinuities are in the ratio of 65:35) **(3)**

15) The direct bandgap energy (in eV) of the ternary compound $GaAs_{1-x}P_x$ is given by

$$E_g(x) = 1.424 + 1.150x + 0.176x^2; \; 0 \le x \le 0.45$$

What alloy composition of $GaAs_{1-x}P_x$ would correspond to a bandgap wavelength of 680 nm? **(3)**

16) What is meant by *Strained layer epitaxy?* From a device engineer's point of view, explain briefly the advantage and constraints associated with it. **(3)**

17) What are strained-layer quantum wells? Explain briefly with the help of relevant diagrams, and mention their importance in *Semiconductor Optoelectronics*. Name two widely used processes to fabricate semiconductor quantum well structures. **(3+1)**

18) The *critical thickness* of layers, for epitaxial growth of defect-free strained layers on a semiconductor substrate, is given by

$$d_c = \frac{a_s}{2|\varepsilon|}$$

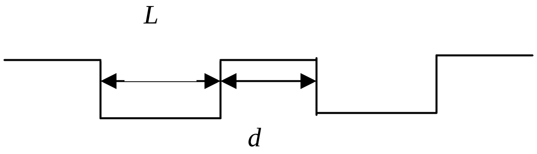
where ε is the *strain* and a_s is the lattice constant of the substrate. What does the above mean to a device-engineer? (Elucidate, with the help of some typical materials and numbers involved, how the critical thickness varies with strain). **(3)**

19) When do we talk of *quasi Fermi levels* in a semiconductor? What does the energy separation between these levels indicate? State one situation each when the separation between the quasi Fermi levels would be positive, and negative. **(2+2)**

20) Consider a thin sheet of GaAs of dimensions 1mm × 1mm × 5 nm that forms a quantum well. If the effective mass of electrons in the conduction band is 0.07 m_0, draw a schematic variation of the density of states with electron energy in the conduction band. Mark the axes with relevant numbers. **(4)**

21) Consider a semiconductor laser whose active (emission) region comprises of the double heterostructure $Ga_{0.7}Al_{0.3}As$/ GaAs/ $Ga_{0.7}Al_{0.3}As$. Which of the following wavelengths may the laser emit: 630 nm, 730 nm, 830 nm, 930 nm? Justify your answer. **(3)**

22) Consider a semiconductor heterostructure device comprising of alternate layers of high- and low bandgap materials, that result in a periodic potential variation for conduction band electrons as shown in the figure:



Assume that the width of the potential well (L) is small enough so as to support only one electron eigenstate E_0 in a single (isolated) well. Plot qualitatively the energy eigenvalues of electrons as a function of the number of wells in the device when i) $d = 0.2\,L$, ii) $d = L$, and iii) $d = 10\,L$. (Plot three different figures corresponding to the above three cases). **(3)**

23) A particular double heterostructure (DH) has 80nm thick layer of a semiconductor **A** (*Eg* = 1.5 eV) sandwiched between two thicker layers of another semiconductor **B** (*Eg* = 2.0 eV). Given that the effective mass of electrons at room temperature is $m_c = m_0$ in both semiconductors **A** and **B**. Determine whether the given DH forms a quantum well or not? **(3)**

24) Consider the following four binary semiconductors:

GaP: (5.45, 2.26) AlP: (5.46, 2.45) GaAs: (5.65, 1.42) AlAs: (5.66, 2.16)

The numbers in the brackets give the lattice constant (in Å) and bandgap energy (in eV), respectively.

a) Making use of the given numbers, draw qualitatively the positions of these compounds on the 'lattice constant' vs. 'bandgap energy' diagram. **(1)**
b) Which ternary compound is lattice matched to GaP? **(1)**
c) Which ternary compounds would correspond to a bandgap wavelength of 0.62 μm? Also, from your plot, approximately estimate their compositions. **(2)**
d) Which compound (with different compositions) would represent the area enclosed by the polygon (obtained by joining the points corresponding to the binary compounds)? **(1)**

25) What is an *Ohmic contact*? Under what conditions does a Schottky junction behave like an Ohmic contact? (Explain briefly with the help of relevant diagrams.) **(3)**

26) Draw typical I-V characteristics of a Schottky junction diode and an ideal ohmic contact. How would one achieve a near ohmic contact using a Schottky junction diode, in spite of a Schottky barrier? (Explain briefly with the help of energy band diagram) **(4)**