PART-II: Light Emission & Absorption, Amplification & Modulation in Semiconductors

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) Using the \( E-k \) diagram, depict the phenomena of radiative-, nonradiative-, and phonon-assisted radiative transitions from the conduction band to the valance band in a direct bandgap semiconductor. (Draw three separate diagrams to depict the three cases) (3)

2) What is a ‘phonon-assisted radiative transition’? Depict such a transition in the \( E–k \) diagram, and write down the corresponding momentum conservation equation. What is the role of the phonon? Explain briefly. (3)

3) a) How is the optical joint density of states, \( \rho \), different from the density of states \( \rho_c \) and \( \rho_v \) in a semiconductor? (Explain briefly the need to define \( \rho \) in Optoelectronics) (3)

b) Given \( \rho_c \) and \( \rho_v \), obtain an expression for \( \rho \) in a direct bandgap semiconductor, under the parabolic approximation of the band structure. (2)

4) Silicon is an indirect bandgap semiconductor with \( E_g = 1.1 \) eV, and InP is a direct bandgap material with \( E_g = 1.35 \) eV at 300 K. Draw a qualitatively correct plot representing the variation of absorption coefficient as a function of wavelength for these two materials. Briefly reason out the nature of the curves. (3)

5) a) Consider a lightly doped direct bandgap semiconductor, with \( E_g = 1.42 \) eV at 300K, in thermal equilibrium. Starting from the definition of probability of emission \( f_e(\nu) \), estimate the numerical value of \( f_e(\nu) \) for photons of energy \( h\nu \approx E_g \). (3)

b) Show that the probability of emission (in a) above) can be increased by orders of magnitude by 'pumping' the semiconductor into quasi-equilibrium. (2)

6) The spontaneous emission spectrum of a particular semiconductor is given by

\[
r_{sp}(\nu) = K_0 \frac{x^{1/2}}{e^{x}} ; \quad x = \frac{(h\nu - E_g)}{(2kT)}
\]

Eq.(1)

where \( K_0 \) is a constant.

a) Obtain an expression for the wavelength at which peak emission would occur. (2)

b) If the above semiconductor has a bandgap \( E_g = 1.35 \) eV at 300K, and \( K_0 = 10^9 \) (photons/s/cc/Hz), draw qualitatively the emission spectrum corresponding to Eq.(1). What are the (numerical values of the) coordinates of the peak? (3)

7) A particular semiconductor material of bandgap \( E_g = 1.35 \) eV at 300 K behaves as a laser amplifier when pumped suitably. If the amplification bandwidth is 6 THz, draw qualitatively the variation of gain with photon energy. (Indicate the range of photon energy over which amplification is possible). (2)
8) The gain coefficient of a semiconductor laser amplifier is given by

\[ \gamma = \frac{\lambda^2}{8\pi} \frac{1}{\tau_r} \rho(\nu) f_g(\nu) \]

where \( f_g(\nu) \) is the Fermi inversion factor, and \( \rho(\nu) \) is the optical joint density of states

\[ \rho(\nu) = \frac{1}{\pi h^2} (2m_e)^{\nu/2} (h\nu - E_g)^{\nu/2} \]

a) Considering a GaAs laser amplifier operating at 300K (\( E_g = 1.42 \text{ eV} \)), if the injection current through the device is such that the separation between the quasi Fermi levels is 1.48 eV, draw a schematic representing the variation of gain with photon energy. (Briefly explain the nature of the curve) (2)
b) What is the amplification frequency-range (\( \Delta \nu \)) of this amplifier? (1)
c) If the gain medium (at a) above) is cooled to 200K, what qualitative changes one would see in the gain variation? (Show this change in the same diagram drawn at a) above. Neglect the temperature dependence of \( E_g \).) (1)

9) The energy band diagram (indicating the various energy levels) of the active medium of a particular semiconductor laser amplifier is shown in the figure below:

<table>
<thead>
<tr>
<th>( E (\text{eV}) )</th>
<th>Energy levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.15</td>
<td>( E_{fc} )</td>
</tr>
<tr>
<td>-4.23</td>
<td>( E_c )</td>
</tr>
<tr>
<td>-4.98</td>
<td>( E_{fv} )</td>
</tr>
<tr>
<td>-5.00</td>
<td>( E_v )</td>
</tr>
</tbody>
</table>

Laser light from a ‘coarse WDM system’, operating with three different wavelengths – 1.45, 1.55, and 1.65 \( \mu \text{m} \) – pass through the above amplifier. If the input powers at the three wavelengths are 1 mW each, then what qualitative changes can we expect in the output powers at each of these wavelengths? ( Briefly justify your answer.) (5)

10) a) What is meant by 'gain saturation' in an optical amplifier? (Explain briefly the physical reason for gain saturation) (2)
b) The small-signal gain coefficient (\( \gamma_0 \)) of an SOA at a particular frequency is 60 cm\(^{-1}\) and the length of the gain medium is 500 \( \mu \text{m} \). If the saturation power \( P_s = 10 \text{ mW} \) for this amplifier, then how would you determine the saturation characteristics? (Calculate the saturation characteristics of this SOA) (3)

11) What is Franz-Keldysh effect? Draw a neat schematic of an electro-absorption modulator based on the Franz-Keldysh effect. (Indicate in the figure, typical dimensions of the various layers, and the materials employed.) Also, estimate the typical extinction ratio of the modulator if used for digital communication. (1+3+1)

12) What is meant by ‘quantum confined Stark effect’ (QCSE)? How does one make use of QCSE to realize high-speed modulators for optical communication? (Explain clearly with the help of relevant schematic diagrams) (1+4)