SEMICONDUCTOR OPTOELECTRONICS
Questions & Problems for Revision

PART-III: Semiconductor Light Sources

<u>Note:</u> 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) Why is it necessary to use *direct bandgap materials* to realize efficient semiconductor photon source? Explain clearly with the help of relevant diagrams and the *physics* involved. **(3)**

2) Starting from the definitions of probabilities of absorption and emission of photons in a semiconductor, obtain the condition under which the probability of emission exceeds that of absorption. **(3)**

3) The spectral distribution of an LED can be represented by an expression of the form:

$$I(\nu) = K(h\nu - E_g)^{1/2}\ e^{-(h\nu - E_g)/kT}; \qquad h\nu \geq E_g$$

where K is a constant. Obtain an expression for the wavelength corresponding to the peak of the emission spectrum. **(3)**

4) The spectral variation of the *spontaneous emission rate* (per unit volume) of a particular photon source is given by

$$r_{sp}(\nu) = \frac{D_0}{\left[a_0^2 + (\nu - \nu_0)^2\right]}$$

which is centered at the wavelength λ_0 = 1.50 μm; $D_0 = 4\times10^{39}\,\mathrm{s^{-3}m^{-3}}$ and $a_0 = 10^{12}$ Hz are constants.

   i) Plot qualitatively the spectral variation of $r_{sp}(\nu)$. (Mark the position of the peak and the magnitude of the peak value on the axes.) **(2)**
   ii) Determine the *linewidth* of the source (in Hz) **(1)**
   iii) What is the power generated by the source (per unit volume) at the *line center*? **(2)**

5) The *radiation pattern* of a particular surface-emitting LED shows a *Lambertian* distribution. Compare the radiation pattern of this LED with that of a typical edge-emitting LED. (Draw the radiation patterns for the two LEDs and explain briefly.) **(3)**

6) The *responsivity* of an LED, emitting at 620 nm wavelength, is given to be 5 μW/mA. When a biasing power supply of 2V is connected across the LED, the current through the LED is 80 mA. Calculate –
   a) The output optical power **(1)**
   b) The *external quantum efficiency* of the device **(1)**
   c) The *wall-plug efficiency* of the LED **(1)**

7) (a) The *radiative* and *nonradiative* (excess carrier) recombination times for the doped semiconductor GaP:N are 800 ns and 200 ns, respectively. What is the *internal quantum efficiency* of this material? **(1)**

(b) If the above material is used in the fabrication of an LED, emitting yellow light at 570 nm wavelength, calculate the optical power generated when the forward current through the LED is 40 mA. **(2)**

8) The frequency dependence of the modulation index for a particular LED is given by

$$m(\omega) = e^{-w^2\tau^2}$$

where τ is the carrier recombination time, which is 4 ns in this case. Estimate the 3 dB modulation bandwidth (in Hz) of the LED. **(2)**

9) Surface-emitting LEDs are widely used in a number of displays.
   a) Draw a schematic showing the structure of a simple surface-emitting LED. **(3)**

   b) You are asked to make a display-panel using LEDs to display a variety of alpha-numeric characters in different languages. What scheme/configuration would you employ to do this? (The control circuit required is not your botheration!) **(2)**

10) Consider a GaAs LED emitting at 850 nm peak wavelength, at 20°C. Draw a typical variation of the output spectrum of this LED. If the temperature of the device is increased to 40°C and then to 60°C, how would it affect the emission spectrum? Draw qualitatively the corresponding emission spectra and justify your plot. **(3)**

11) What are *gain-guided* and *index-guided* lasers? How does one decide on the choice between these two types of lasers, for use in any particular application/device? Explain briefly. **(3)**

12) A buried heterostructure laser has a cavity length of 400 μm, and the active area is limited to a width of 5 μm in the transverse direction. The cleaved facets provide an end-face reflection of 30% each, and there are no other losses in the cavity. The absorption coefficient of the material is 400 cm^{-1} (when there is no injection current), and the transparency current density is 1 kA/cm^2. Estimate the threshold current of this laser. **(3)**

13) The ternary compound $Al_xGa_{1-x}As$ is a direct bandgap material which is lattice-matched to GaAs in the range $0 \le x \le 0.4$, and its bandgap is given by

$$E_g(x) = 1.424 + 1.247\,x$$

If you were to design a gain-guided Fabry-Perot laser emitting at 805 nm wavelength using this material system, what compositions would you choose for the various layers in the laser chip? Draw a neat diagram of the structure of the laser and indicate the composition and typical dimensions of the various layers. **(2+3)**

14) If you were to design a DFB laser for operation at 1.55 μm, what material composition and period would you choose? (Explain logically, and give the answer). **(4)**

15) a) Why does one employ high-reflectivity Bragg stacks in the construction of VCSELs?(Explain briefly) **(2)**
b) In a particular VCSEL emitting at 800 nm, the Bragg stack comprises of 20 periods of alternate layers of GaAs (n = 3.6) and $Al_{0.1}Ga_{0.9}As$ (n = 3.5). Calculate the thickness of the Bragg stack. **(2)**

16) What are the basic differences in *structure*, *operation*, and *output* of an edge-emitting LED and a DH laser diode? Explain briefly. **(3)**

17) A normal laser diode consists of a *double heterostructures*, typically of *cavity length* ≈ 300 μm and thickness of the active layer ≈ 0.1 μm, and the cavity is made up of *cleaved facets*. Explain clearly, giving precise reasons/justification for choosing such structure and dimensions. **(4)**

18) A semiconductor DH laser has a cavity length of 400 μm. The cleaved facets provide an end-face reflection of 30% each, and assume that there are no other losses in the cavity. If the confinement factor is 0.75, calculate the threshold gain coefficient for this laser. **(3)**

19)

a) Which type of semiconductor laser <u>and</u> device package is widely employed in present-day high-speed optical communication system? Give one reason each for the particular choice. **(3)**

b) What practical measures are employed in handling laser diodes for protection against damage by ESD? **(2)**

20) 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*

$$\rho(\nu) = \frac{1}{\pi\hbar^2}(2m_r)^{3/2}(h\nu - E_g)^{1/2}$$

Further, assume that the *peak gain coefficient* is given by the following linear relation:

$$\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)$$

where symbols have their usual meaning.

Consider an $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ laser amplifier operating at 300K (Eg = 0.95 eV). At the operating current of the laser amplifier, the excess carrier concentration in the active region is 1.5×10^{18} /cc, and the corresponding separation between the quasi Fermi levels is 0.96 eV. Given that the transparency carrier concentration = 1.20×10^{18} /cc, α_a = 500 cm^{-1}, and refractive index = 3.5 for the laser medium; neglect the dependence of Eg on carrier concentration.

a) Calculate the peak gain coefficient and the amplification frequency-range ($\Delta\nu$) of this amplifier? **(2)**

b) Draw a schematic representing the variation of gain with photon energy. (Briefly explain the nature of the curve and mark the axes.) **(2)**

c) If the length of the active medium is 200 μm, what is the *single-pass gain* of this amplifier at the frequency corresponding to the peak gain? **(1)**

d) If the two ends of the amplifier medium are coated with mirrors, each of reflectivity 50%, calculate the threshold carrier concentration. (You may neglect scattering and diffraction losses in the medium) **(2)**

e) Estimate the number of longitudinal modes present in the laser output at the operating current. (You may make use of your gain curve drawn at b) above). **(2)**