Solve the following questions. There are 13 questions, for a total of 25 marks.

1. (1 mark) In the context of radiative processes, semiconductors can be modeled as ______

   A. three-level systems

   B. two-level systems

   C. four-level systems

   D. one-level systems

2. (1 mark) Which are the fundamental radiative processes proposed by Einstein?

   A. Absorption, spontaneous emission, and stimulated emission

   B. Surface recombination, Auger recombination, SRH recombination

   C. Direct recombination, Auger recombination, SRH recombination

   D. Absorption, random emission, and forced emission

3. (1 mark) Choose the correct rate equation for stimulated emission process.

   A. $\frac{dN_2}{dt} = A_{21}N_2u(\nu)$

   B. $\frac{dN_2}{dt} = B_{21}N_2u(\nu)$

   C. $\frac{dN_2}{dt} = -A_{21}N_2u(\nu)$

   D. $\frac{dN_2}{dt} = -B_{21}N_2u(\nu)$

   E. $\frac{dN_2}{dt} = -B_{21}N_1u(\nu)$

   F. $\frac{dN_2}{dt} = -A_{21}N_1u(\nu)$

4. (1 mark) The relation between Einstein's **A** and **B** coefficients is given by ______

   A. $A_{21} = \frac{8\pi h\nu^3}{c^3}B_{21}$

   B. $B_{21} = \frac{8\pi h\nu^3}{c^3}A_{21}$

   C. $A_{21} = \frac{c^3}{8\pi h\nu^3}B_{21}$

D. $B_{21} = \frac{8\pi h\nu}{c^3} A_{21}$

E. $A_{21} = \frac{8\pi h\nu}{c^3} B_{21}$

F. $A_{21} = \frac{c^3}{8\pi h\nu} B_{21}$

5. (2 marks) Given below are the two statements.

   $S1$: It is difficult to build a blue laser compared to red laser.

   $S2$: Spontaneous emission becomes stronger with increasing frequency.

   A. Statement $S1$ is true and $S2$ is false

   B. Statement $S1$ is false and $S2$ is true

   C. Both Statements $S1$ and $S2$ are true. $S2$ is the correct explanation of $S1$.

   D. Statement $S1$ is true and $S2$ is true and $S2$ is not the correct explanation of $S1$

   E. Statement $S1$ and $S2$ are false

6. (1 mark) The radiative and non-radiative lifetimes of an emitter material are given by τ_r and τ_{nr} respectively. In which of the following cases, will the material be an efficient light emitter?

   A. $\tau_r >> \tau_{nr}$

   B. $\tau_r = \tau_{nr}$

   C. $\tau_r << \tau_{nr}$

   D. $\tau_r > \tau_{nr}$

   E. $\tau_r < \tau_{nr}$

   F. Emission efficiency of a material is independent of radiative and non-radiative lifetimes.

7. (1 mark) The acronym LASER stands for _______

   A. Light Amplification by Spontaneous Emission Radiation

   B. Light Amplification by Stimulated Emission Radiation

   C. Light Amplification in SEmiconductor Region

   D. Light Attenuation in SEmiconductor Region

   E. Light Attenuation by Stimulated Emission Radiation

F. Light Attenuation by Spontaneous Emission Radiation

8. (2 marks) Which of the following statement(s) is/are true with respect to LASERs?

A. They are incoherent sources

B. They are coherent sources

C. Photon generation is dominated by stimulated emission

D. Photon generation is dominated by spontaneous emission

E. They are polychromatic sources

F. They are monochromatic sources

G. They are suitable for lighting applications

H. They are suitable for optical communication due to higher bandwidth

9. (2 marks) Consider the I-V characteristics of various diodes made up of different materials as shown in the figure 1 below:

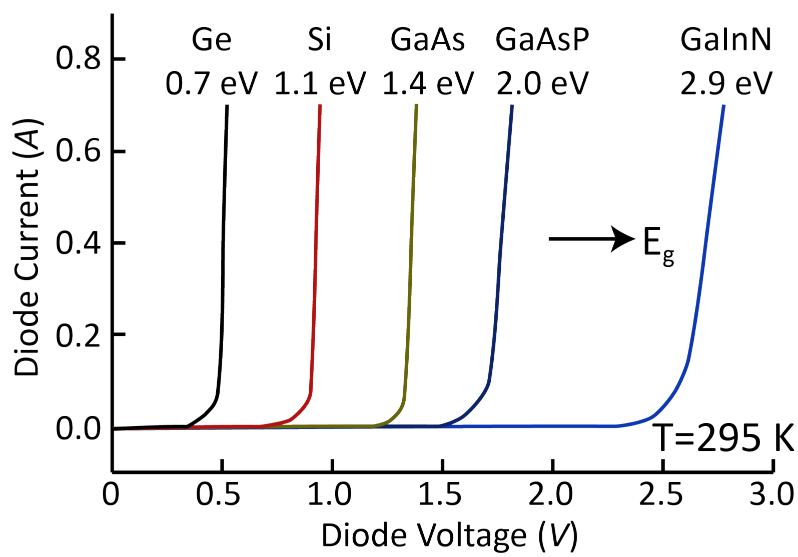

Figure 1: LED diodes I-V characteristics

(a) *(1 mark)* Which of the following diodes can be used as LEDs? (*Hint: Which are the direct bandgap semiconductors?*)

A. GaAs, GaAsP

B. Si, Ge

C. **GaAs, GaAsP, GaInN**

D. Ge, Si, GaAs

E. All of them

(b) *(1 mark)* Choose the correct statement with respect to the wavelength of light emitted by diodes.

A. $\lambda_{GaAs} > \lambda_{GaAsP} > \lambda_{GaInN}$

B. $\lambda_{GaAs} < \lambda_{GaAsP} < \lambda_{GaInN}$

C. $\lambda_{Ge} > \lambda_{Si} > \lambda_{GaAs} > \lambda_{GaAsP} > \lambda_{GaInN}$

D. $\lambda_{Ge} < \lambda_{Si} < \lambda_{GaAs} < \lambda_{GaAsP} < \lambda_{GaInN}$

E. $\lambda_{GaAs} = \lambda_{GaAsP} = \lambda_{GaInN}$

F. $\lambda_{Ge} = \lambda_{Si} = \lambda_{GaAs} = \lambda_{GaAsP} = \lambda_{GaInN}$

10. (6 marks) Consider the bandgap-composition graph of III-V compound semiconductors as shown in figure 2 below:

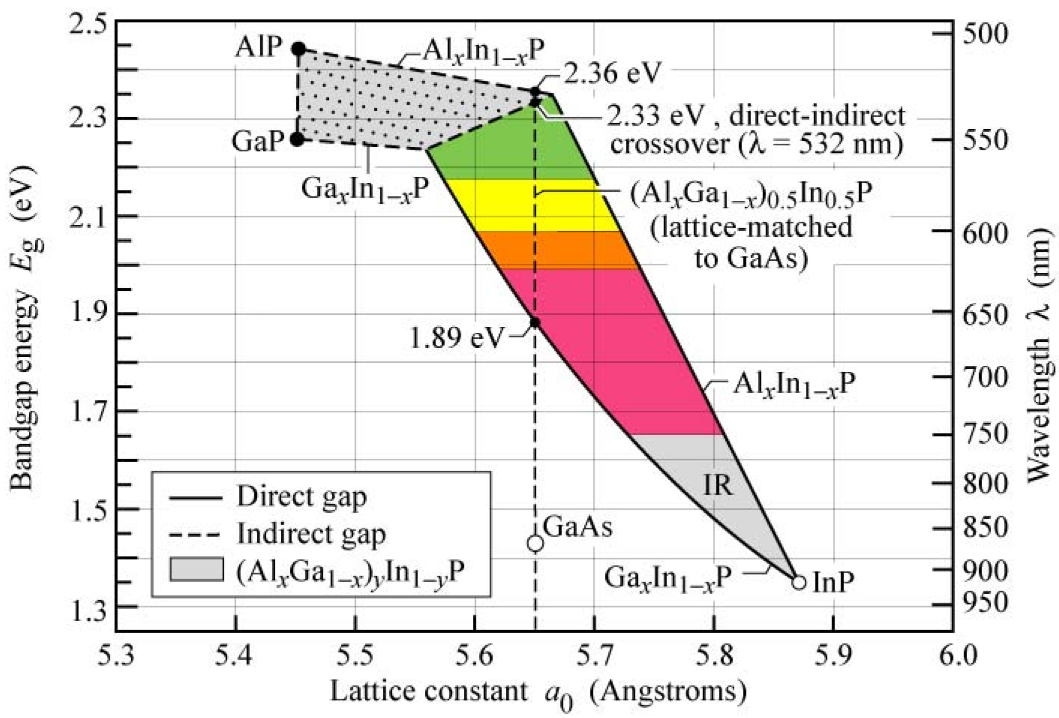

Figure 2: Compound semiconductors (Reproduced from E F Schubert, Light Emitting Diodes, Cambridge University Press)

(a) *(2 marks)* A graduate student wants to fabricate a red LED, emitting at wavelength $\lambda = 650\ nm$.

Referring to the data given in figure 2, which compound will you suggest him/her to choose?

A. $Al_xIn_{1-x}P$

B. $Ga_xIn_{1-x}P$

C. GaAs

D. InP

E. $(Al_xGa_{1-x})_{0.5}In_{0.5}P$

(b) *(2 marks)* Now, his/her advisor wants to know why he/she chose the given material. Support your answer with proper justification.

A. The suggested material is lattice-matched to GaAs substrate and is a direct bandgap semiconductor for $x \sim 0.5$.

B. The suggested material is lattice-matched to InP substrate and is an indirect bandgap semiconductor for $x \sim 0.4$.

C. The suggested material is lattice-matched to GaAs substrate and is an indirect bandgap semiconductor for $x \sim 0.5$.

D. The suggested material is lattice-matched to GaP substrate and is an indirect bandgap semiconductor for $x \sim 0.5$.

E. GaAs is a direct bandgap semiconductor with emission wavelength $\sim 650\ nm$

F. InP is a direct bandgap semiconductor with emission wavelength $\sim 650\ nm$

(c) *(2 marks)* Another graduate student wants to fabricate a yellow LED, emitting at wavelength $\lambda = 575\ nm$. Referring the data given in figure 2, which compound will you suggest him/her to choose?

A. $Al_xIn_{1-x}P$

B. $Ga_xIn_{1-x}P$

C. GaAs

D. InP

E. $(Al_xGa_{1-x})_{0.5}In_{0.5}P$

11. (2 marks) How do you define internal quantum efficiency (IQE) and external quantum efficiency (EQE) with respect to LEDs?

A. $\text{IQE} = \dfrac{\text{No.of photons generated}}{\text{No.of carriers extracted}}$, $\text{EQE} = \dfrac{\text{No.of photons injected}}{\text{No.of photons generated}}$

B. $\text{IQE} = \dfrac{\text{No.of photons generated}}{\text{No.of carriers injected}}$, $\text{EQE} = \dfrac{\text{No.of photons extracted}}{\text{No.of photons generated}}$

C. $\text{IQE} = \dfrac{\text{No.of photons extracted}}{\text{No.of carriers injected}}$, $\text{EQE} = \dfrac{\text{No.of photons generated}}{\text{No.of photons extracted}}$

D. $\text{IQE} = \dfrac{\text{No.of carriers injected}}{\text{No.of photons extracted}}$, $\text{EQE} = \dfrac{\text{No.of photons extracted}}{\text{No.of carriers injected}}$

12. (1 mark) What is/are the necessary condition(s) required for lasing to occur?

A. Stimulated emission

B. III-V semiconductor

C. An optical cavity

D. Gain media, stimulated emission, and an optical cavity

E. Low temperature

F. High current

13. (4 marks) Consider the structures shown in figure 3 below:

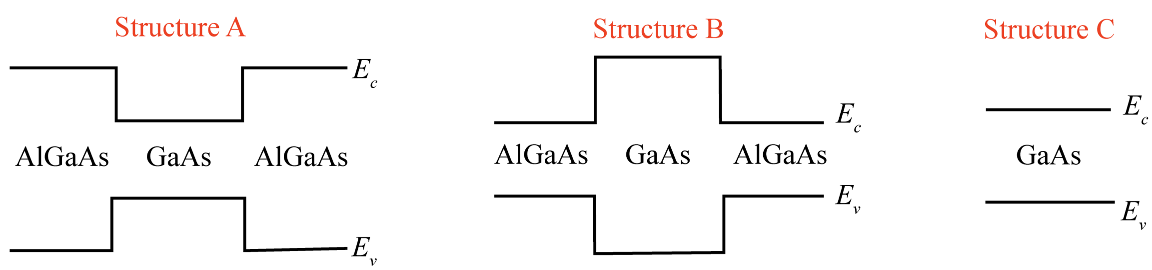

Figure 3: Band diagrams of potential semiconductor lasers

(a) *(2 marks)* Referring to structure A, which of the following is/are correct statement(s)?

A. Bandgap of AlGaAs is smaller than the bandgap of GaAs

B. Bandgap of AlGaAs is larger than the bandgap of GaAs

C. Bandgap of AlGaAs is equal to the bandgap of GaAs

D. Refractive index of AlGaAs is higher than that of GaAs

E. Refractive index of AlGaAs is smaller than that of GaAs

F. Refractive index of AlGaAs is equivalent to that of GaAs

(b) *(2 marks)* Which structure will you prefer for fabricating a GaAs laser and why?

A. Structure A as it confines both electrons and photons, being a double heterostructure

B. Structure B as it confines both electrons and photons, being a double heterostructure

C. Structure C as it is easy to fabricate

D. Structure A and B as they confine both electrons and photons, being double heterostructures

E. All the structures as they consist of GaAs material