19
lasers & semiconductors

Learning Outcomes

Candidates should be able to:

(a) recall and use the terms spontaneous emission, stimulated emission and population inversion in related situations.

(b) explain the action of a laser in terms of population inversion and stimulated emission. (Details of the structure and operation of a laser are not required.)

(c) describe the formation of energy bands in a solid.

(d) distinguish between conduction band and valence band.

(e) use band theory to account for the electrical properties of metals, insulators and intrinsic semiconductors, with reference to conduction electrons and holes.

(f) analyse qualitatively how n- and p-type doping change the conduction properties of semiconductors.

(g) discuss qualitatively the origin of the depletion region at a p-n junction and use this to explain how a p-n junction can act as a rectifier.

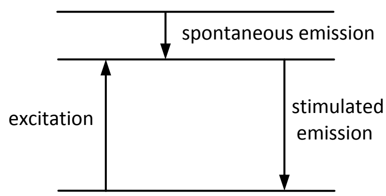
19•1 Basic principles of lasers

MCQs

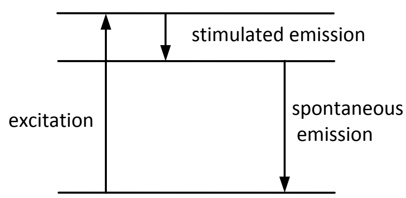
1. In a helium-neon laser, helium atoms collide with neon atoms and excite them. It produces a population inversion which allows stimulated emission.

Which of the following neon energy level diagram correctly shows the excitation of the neon atoms by the helium atoms, the spontaneous infra-red emission from the neon, and the stimulated emission of red light?

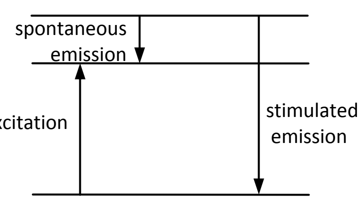
(A)



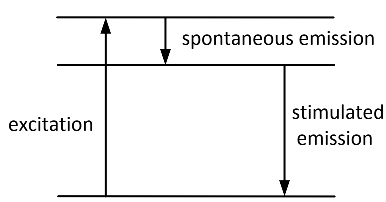
(B)



(C)



(D)



2. Which of the following is not a characteristic of laser beam?

(A) It has high penetration power.
(B) It is an intense monochromatic beam.
(C) It is a coherent unidirectional radiation.
(D) It is not divergent.

3. The process of lasing involve an incident photon stimulating the emission of another photon with

(A) same energy and phase.
(B) same energy but different phase.
(C) different energy and phase.
(D) different energy but same phase

4. What is stimulated emission in laser?

(A) an electron from a higher energy level falling to a lower level.
(B) a charged particle causing light to be emitted from an excited atom.
(C) a charged particle being emitted from an atom as a result of a high energy photon hitting the atom.
(D) a photon causing another photon of the same frequency to be emitted from an excited atom

5. A helium gas laser emits pulses of light of wavelength 620 nm. If the power of the helium gas is 4 W and emits pulses that last 30 ms, calculate the number of photons emitted by the laser.

(A) 1.98×10^{17} (B) 2.75×10^{17}
(C) 3.36×10^{17} (D) 3.74×10^{17}

Questions – 19.1

1. The figure below is a schematic diagram of the production of laser light in a helium-neon laser. Helium atoms are excited to its excited state by means of collisions with energetic electrons. These excited helium atoms then collide with the unexcited neon atoms and they exchange energies, causing the neon atoms to move to the *metastable* state (E_3) to achieve *population inversion*. When the neon atoms de-excite to E_2, they emit the familiar red He-Ne laser light.

(a) Explain the terms *metastable* state and *population inversion*.

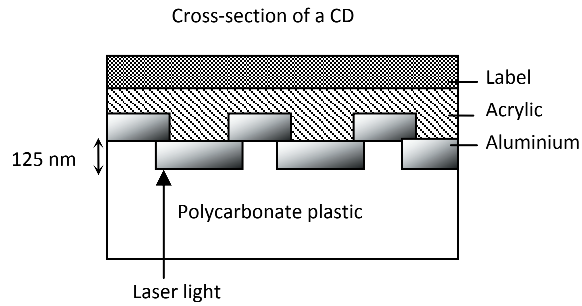
(b) Explain why it is important in the production of laser to excite an atom to a metastable state.

(c) State four differences between laser light and light from a filament lamp.

Laser light	Light from filament lamp

(d) By means of energy-band diagrams, explain the difference in electrical conductivity of an insulator and a semiconductor.

2. (a) The diagram shows a cross-section through a compact disc (CD). The metal layer of a CD is the recording surface and contains narrow ridges, which form a spiral around the disc.



Red monochromatic laser light of wavelength 780 nm is used to view these ridges. When the light meets a ridge some of it scatters in all direction and some interferes destructively with light reflected from neighbouring valleys. When this occurs, the player is able to read the information from the disc.

(i) Explain the meaning of the term "monochromatic".

(ii) If the ratio of the speed of the laser light in air to the speed of the laser light in the polycarbonate plastic is 1.55, show that the wavelength of the laser light in the polycarbonate plastic is approximately 500 nm.

(iii) The height of the ridges on a CD is approximately 125 nm. Use your answer in (a)(ii) to explain how destructive interference occurs.

(iv) The infrared laser standard was fixed in 1980 because of the reliability and availability of relatively inexpensive lasers, which emit at 780 nm. However, blue light lasers are now being developed and the technology called Blu-Ray is fast emerging. These blue light lasers have a wavelength about one half of the red light lasers. Will it be possible to play existing CDs using a Blu-Ray player? Explain your answer.

(v) Music from a CD is played with the speaker placed near the open end of a tube which is closed at the far end. As the CD is played, it was observed that at some instances the music was much louder near the open end of the tube. Explain.

(b) (i) Explain the phenomenon of diffraction, stating an important condition for significant diffraction to occur.

(ii) A diffraction grating with 300 lines per millimeter is being used in a typical light experiment. Different types of light are allowed to fall normally on a diffraction grating and the resultant pattern formed is to be studied. The first light source to be studied is a white light consisting of wavelengths between 400 nm and 700 nm.

1. Find the maximum order of the complete spectrum that can be observed.
2. Find the order of the pure spectrum before the first overlapping between two higher order spectra.

(iii) The next experiment is of light from a low pressure sodium lamp. Light from the lamp consists mostly of two wavelengths, 588.99 nm and 589.59 nm.

1. State and explain quantitatively the problem that would likely arise in observing the spectral lines?
2. Suggest a refinement to the set up to help overcome this problem.

3. Wavelength of light from laser A (helium-neon gas mixture) is 632.8nm, laser B (carbon dioxide gas) 10.6µm, and laser C (gallium arsenide semiconductor) 840nm.

Order these lasers according to decreasing energy intervals between the two quantum states responsible for laser action.

4. A 4.0 W laser emits a beam of wavelength 633 nm. Calculate the energy of each photon and the number of photons emitted in 0.05s.

5. A laser beam of wavelength 211nm is used. The energy of each photon is 6.284×10^{-19} J. What is the energy of each photon? Given that the number of photons emitted in 0.10s is 6.37×10^{17}, calculate the energy of the beam in 0.10s.

6. (a) Distinguish between *spontaneous emission* and *stimulated emission*. [2]

(b) One of the conditions for lasing to occur is that *population inversion* must be achieved. Explain what is meant by *population inversion* and state how it might be achieved. [2]

(c) Pulsed dye lasers emit light of wavelength 585 nm in 0.45 ms pulses to remove skin blemishes such as birthmarks. The beam is usually focused onto a circular spot of 5.0 mm in diameter. The output of one such laser is given to be 20.0 W.

(i) What is the energy of each photon? [2]

(ii) How many photons per unit area are delivered to the blemish during each pulse? [3]

⓳•❷ Energy bands, conductors and insulators

Questions – 19.2

1. Using the band theory of conduction, explain why the electrical resistance of an intrinsic semiconductor material decreases as its temperature rises.

You may explain your answers with the aid of a diagram. [4]

2. (a) A three-level laser system is shown in Figure 2.1 below, where E_2 is the meta-stable state.

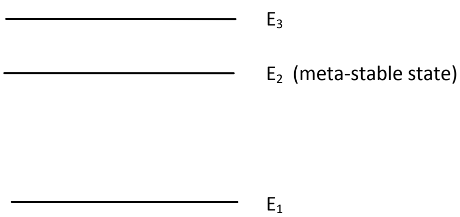


Figure 2.1

(i) Explain what is meant by *meta-stable* state.

(ii) Using Figure 2.1, explain the action of a laser in terms of population inversion and stimulated emission.

(iii) A four-level laser system is shown in Figure 2.2. A student commented that this system is more efficient than a three-level laser system.

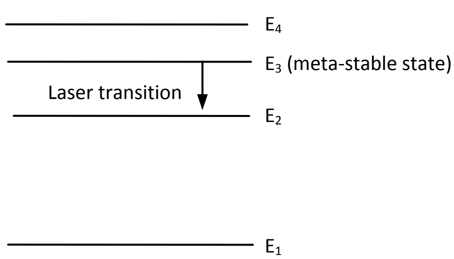


Figure 2.2

Explain why the student is correct.

(b) (i) On Figure 2.3, draw and label clearly the changes to the band diagrams for semiconductors due to n- and p-type doping.

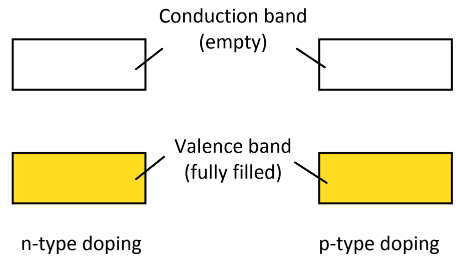


Figure 2.3

(ii) Using Figure 2.3, explain how the n-type doping changes the conduction property of a semiconductor.

(iii) What is the difference between n- and p=type semiconductors in terms of conduction?

3. Describe the formation of energy bands in a solid.

4. Distinguish between conduction band and valence band.

5. Use band theory to account for the electrical properties of metals, insulators and intrinsic semiconductors. (You may find diagrams useful.)

6. (a) Describe, in terms of band theory, the conduction of electrons through an intrinsic semiconductor. [3]

(b) The addition of one part per million of arsenic will decrease the resistivity of silicon by a factor of 10^5. This doped silicon is p-type silicon.

State two differences between p-type silicon and n-type silicon. [2]

(c) Discuss, using the idea of a depletion layer, how a p-n junction can act as a rectifier. [4]

⓳•❸ Semiconductors

MCQs

1. Which of the following statement is correct about the conduction of electricity in solids?

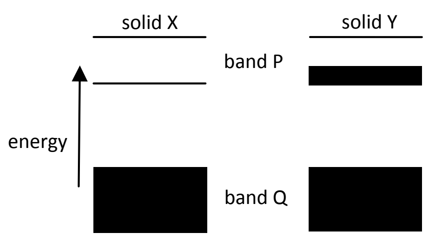
(A) Free electrons are found both in the conduction band and in the valence band.

(B) In metal, there is a large energy gap between the conduction band and the valence band.

(C) Presence of impurities in an intrinsic semiconductor is used to increase its resistance.

(D) In an intrinsic semiconductor, electrons travel in the opposite direction to holes.

2. The following diagram illustrates the upper energy bands in the two different classes of solid at absolute zero. The shaded areas represent occupied electron energy levels.



What are bands P and Q, and classes X and Y of solids?

(A) P: conduction, Q: valence,
X: intrinsic semiconductor, Y: metal

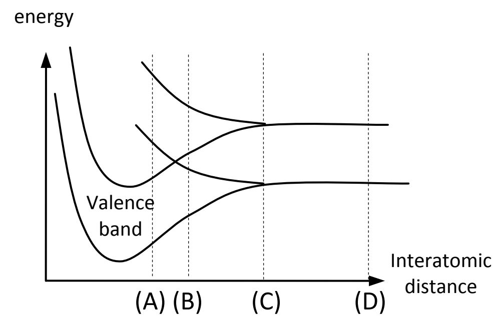
(B) P: conduction, Q: valence,
X: metal, Y: intrinsic semiconductor

(C) P: valence, Q: conduction,
X: intrinsic semiconductor, Y: metal

(D) P: valence, Q: conduction,
X: metal, Y: intrinsic semiconductor

3. Energy levels for electrons in materials vary with the separation of atoms as shown for a semiconductor material in which the valence band is filled and the conduction band at low temperatures is empty.

At which separation does the graph show the material behaving as a semiconductor at room temperature?



4. Which of the following statements about a semiconductor diode in forward bias is incorrect?

(A) The applied potential difference from the source of e.m.f. opposes the junction potential

(B) Electrons and holes are urged away from the p-n junction

(C) The n-type material of the diode is connected to the negative terminal of the source of e.m.f.

(D) Electrons in the n-type side of the diode will cross steadily to the p-type side

Questions – 19.3

1. What is *doping*? Describe the two types of doping for semiconductors, using examples.

2. Analyse qualitatively how n- and p-type doping change the conduction properties of semiconductors using the band theory.

3. (a) Use population inversion and stimulated emission to explain the action of a laser. [5]

(b) (i) State the main charge carriers in an n-type and a p-type semiconductor. [1]

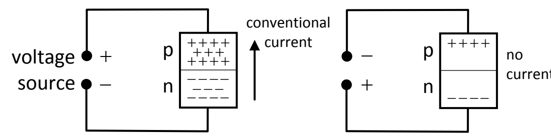
(ii) Analyse qualitatively how n- and p-type doping change the conduction properties of semiconductors. [4]

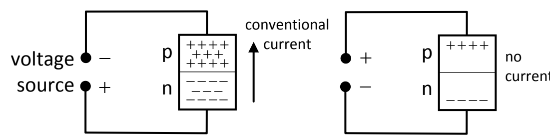
19•4 Depletion region of a p-n junction

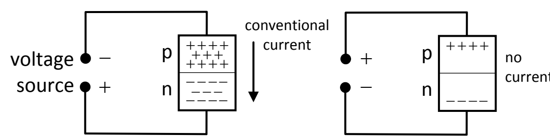
MCQs

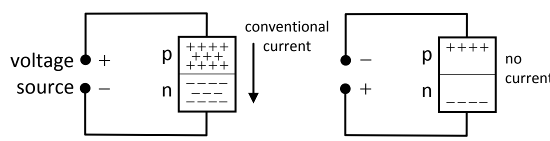
1. The symbols + + + and – – – represent the majority carriers in the p-type and n-type sides of a p-n junction.

Which of the following pair of diagrams correctly illustrates how a p-n junction acts as a rectifier?

(A)


(B)


(C)


(D)


2. In a p-n junction, free electrons near the junction in the n-type material diffuse across the junction into the p-type material. Diffusion occurs because

(A) the concentration of electrons in n-type material is small and in p-type material is large.

(B) the concentration of electrons in n-type material is large and in p-type material is small.

(C) the small potential across the depletion layer cause electrons to diffuse continuously across the p-n junction.

(D) of difference thermal agitation of atoms in the n-type and p-type material.

3. To produce a n-type semiconductor, the doping of intrinsic Germanium (with 4 valence electrons) will require a dopant with

(A) same number of valence electrons.

(B) 3 valence electrons.

(C) 5 valence electrons.

(D) no valence electrons.

4. At room temperature, the change carriers inside a p-type semi-conductor are

(A) holes only.

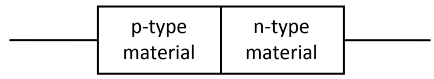
(B) electrons only.

(C) positive ions.

(D) both holes and electrons

Questions – 19.4

1. The diagram below shows a junction formed between slices of p-type and of n-type semiconductor material.



(a) Draw an arrow to indicate the direction of movement of electrons as the two slices are brought into contact.

(b) Describe the origin of the depletion region at the junction.

(c) Draw the symbol for a battery, connected so as to increase the width of the depletion region.

2. (a) The acronym of Laser is Light *Amplification* by Stimulated Emission of Radiation. Explain how stimulated emission can lead to *Amplification* in the gain medium of a laser. [2]

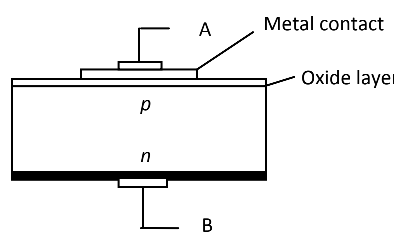
(b) A Young's double slit experiment usually involves the use of a primary slit. Explain why a similar experiment repeated with laser as the light source does not need a primary slit. [2]

(c) A p-n junction can be used as a rectifier in an a.c. circuit. How does the depletion zone affect the conduction of current during reverse bias. [4]

3. (a) Explain briefly the conditions necessary for the production of a laser beam. [3]

(b) A p-n junction constitutes a fundamental unit of a semiconductor device.

The figure below shows a single crystal of silicon within which *n*-type and *p*-type regions have been formed as shown. The surface of the crystal has been covered with an insulating oxide layer through which a metallic contact is arranged to the top surface.



(i) Explain using band theory how electrical conduction takes place in

1. the *n*-type region of the crystal and [2]
2. the *p*-type region of the crystal. [2]

(ii) Explain how an electric field comes into existence across the junction between the *n*-type and *p*-type regions. [2]

(iii) Give a suitable sketch graph (in a single graph) to illustrate what happens when a potential difference is applied to the metal contacts making

1. contact A positive with respect to B, and
2. contact B positive with respect to A. [1]

Answer keys:

⓳•❶

MCQs

1. D
2. A
3. A
4. B
5. D

Questions

2. (a)(ii) 503.1 nm

   (b)(ii) only one pure spectrum

3. A, C, B

4. $N = 6.37 \times 10^{17}$

5. $P = 0.667$ W

6. (c)(i) 3.40×10^{-19} J

   (c)(ii) $\frac{N}{A} = 1.34 \times 10^{21}$

⓳•❷

Questions

1. (a)(i) kg, K, current, mol

   (b)(i) $kg^{-1}\ m^{3}\ s^{-2}$, $kg\ m^{2}\ s^{-1}$

⓳•❸

MCQs

1. D
2. A
3. D
4. B

Questions

3. (b)(i) n-type: electrons

   p-type: holes

⓳•❹

MCQs

1. D
2. B
3. C
4. D