EEE 333 - Optical Communication Devices

Lecture 3
Optical emission from semiconductors
The p-n junction

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1 The p–n junction

• intrinsic semiconductor is a perfect crystal with no impurities or lattice defects

• valence and conduction bands separated by a bandgap E_g.

• At a temperature above absolute zero, thermal excitation creates carriers by raising electrons from the valence to the conduction band, leaving holes in the valence band.

• In thermal equilibrium, the Fermi-Dirac distribution function describes energy-level occupation and the probability that an electron occupies a particular energy level.

$$P(E) = \frac{1}{1 + \exp\left(E - E_{\mathrm{F}}\right)/KT} \tag{1}$$

Where

K : Boltzmann's constant

E_F : Fermi energy or Fermi level

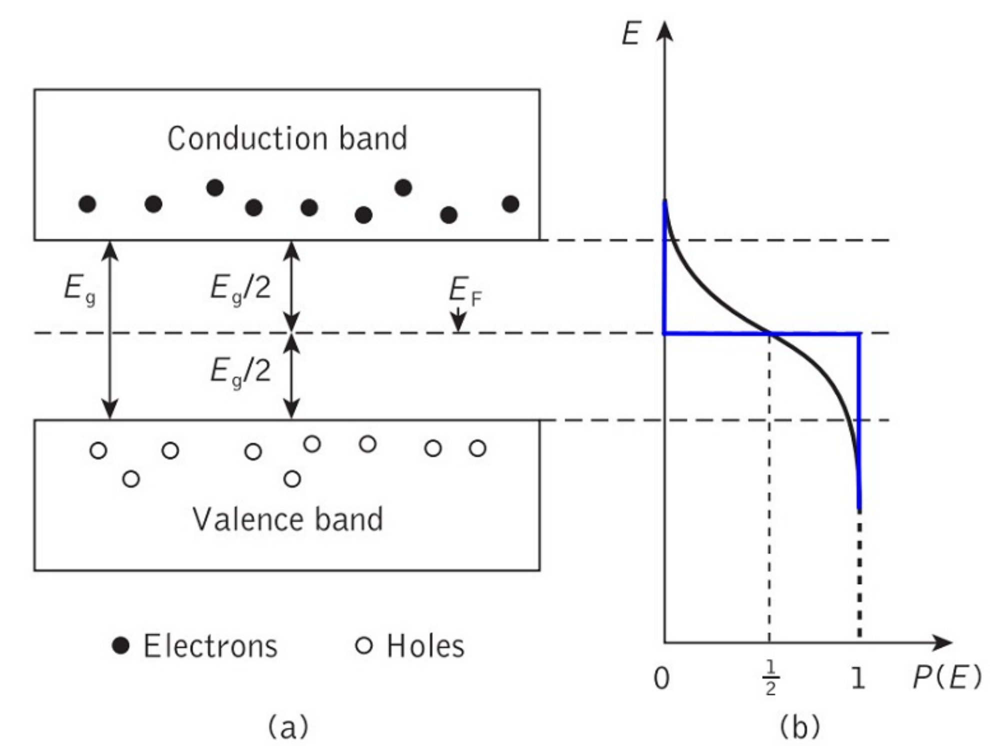

Figure 1: (a) The energy band structure of an intrinsic semiconductor at a temperature above absolute zero, showing an equal number of electrons and holes in the conduction band and the valence band respectively. (b) The Fermi–Dirac probability distribution corresponding to (a) (note that the blue distribution correspond to Fermi–Dirac probability distribution at 0K)

To create an extrinsic semiconductor the material is doped with impurity atoms which create either more free electrons (donor impurity) or holes (acceptor impurity).

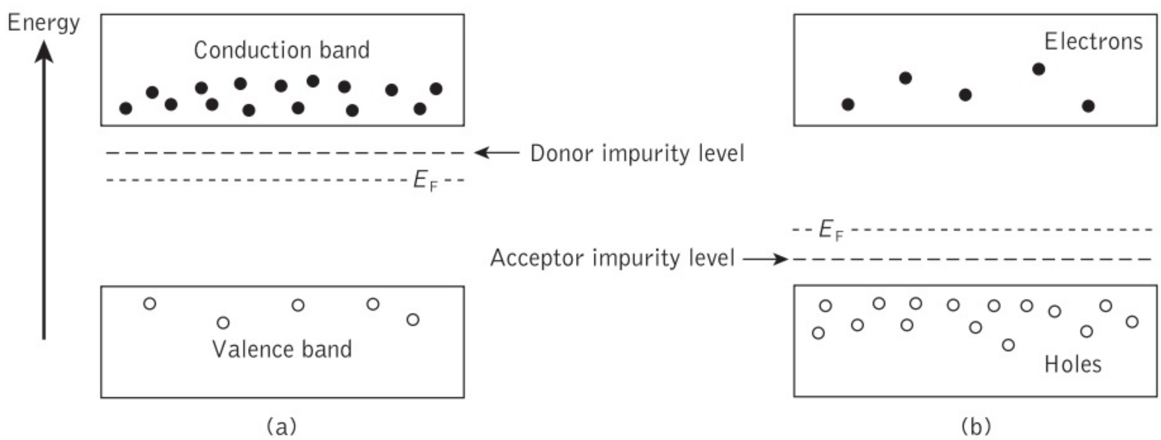

Figure 2: Energy band diagrams: (a) n-type semiconductor; (b) p-type semiconductor

• The p–n junction diode is formed by creating adjoining p- and n-type semiconductor layers in a single crystal, A thin depletion region or layer is formed at the junction.

• A potential barrier between the p- and n-type regions is established due to the presence of positive and negative ions in depletion region , prevents the net flow of carriers from one region to another.

• The width of depletion region is dependent upon the carrier concentrations (doping)

• When an external positive voltage is applied to the p-type region , both the depletion region width and the resulting potential barrier are reduced (forward biased).

• In forward bias electrons from the n-type region and holes from the p-type region can flow more readily across the junction into the opposite type region.

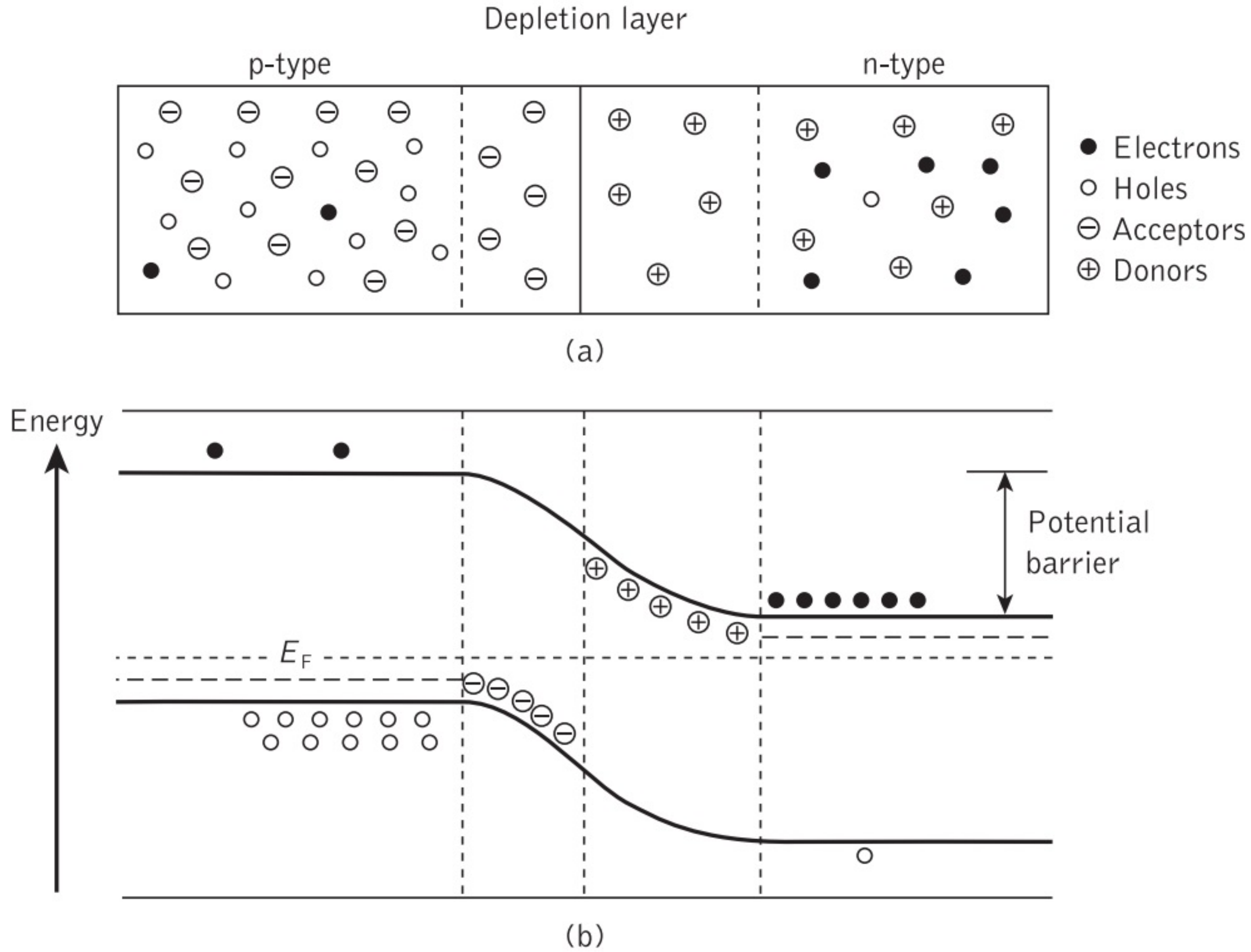

Figure 3: (a) The impurities and charge carriers at a ***p*–*n*** junction. (b) The energy band diagram corresponding to (a)

2 Spontaneous Emission

The increased concentration of minority carriers in the opposite type region in the forward-biased *p*–*n* diode leads to the recombination of carriers across the bandgap. This process is shown in the following figure.

Note that the energy released by this electron–hole recombination is approximately equal to the bandgap energy E_g.

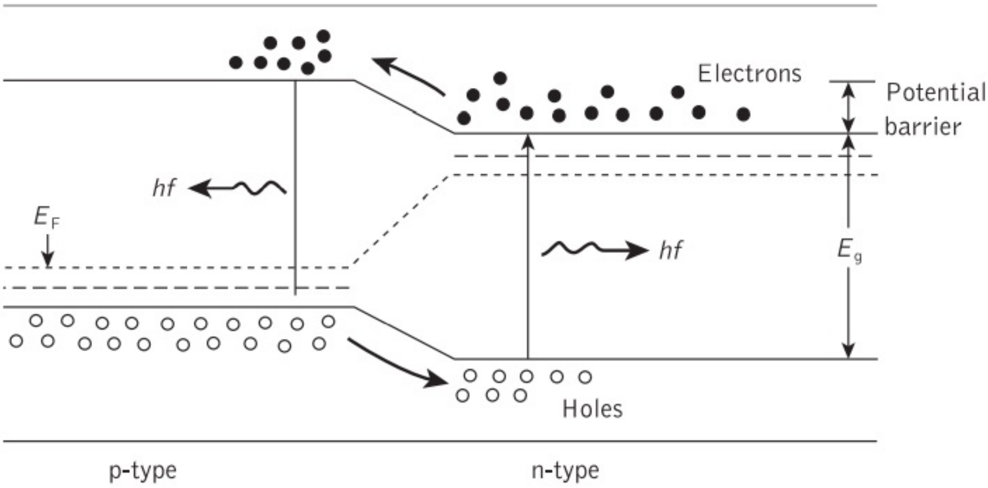

Figure 4: The p–n junction with forward bias giving spontaneous emission of photons

The recombination may be radiative or nonradiative

in nonradiative the energy released is dissipated in the form of lattice vibrations and thus heat

in radiative the energy is released with the creation of a photon, therefore :

$$E_g = hf = \frac{hc}{\lambda} \tag{2}$$

Where

c **: velocity of light**

λ **: wavelength**

Substituting the appropriate values for h and c and rearranging gives:

Where

$$\lambda = \frac{1.24}{E_g} \tag{3}$$

E_g **in (eV)**

λ **in (μm)**

this spontaneous emission of light from within the diode structure is known as electroluminescence.

How to encourage electroluminescence ?

Select select an appropriate semiconductor material. (the direct bandgap semiconductor material)

3 Direct and indirect bandgap semiconductors

before starting :

minority carrier lifetime : the average time that the minority carrier remains in a free state before recombination

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- **direct bandgap semiconductor material electrons and holes on either side of the forbidden energy gap have the same value of crystal momentum and thus direct recombination is possible.**
- **In other words : the energy maximum of the valence band occurs at the same value of electron crystal momentum as the energy minimum of the conduction band.**
- **Therefore when electron–hole recombination occurs the momentum of the electron remains constant and the energy released (E_g), may be emitted as light (photon)**
- **The minority carrier lifetime is short (10^{-8} to 10^{-10} s).**
- **Example : GaAs**

- **indirect bandgap semiconductor material electrons and holes on either side of the forbidden energy gap have the different values of crystal momentum and thus direct recombination is possible.**
- **In other words : the energy maximum of the valence band occurs at different value of electron crystal momentum as the energy minimum of the conduction band.**
- **Therefore For electron–hole recombination to take place it is essential that the electron loses momentum such that it has a value of momentum corresponding to the maximum energy of the valence band. The conservation of momentum requires the emission or absorption of a third particle, a (phonon)**
- **The minority carrier lifetime longer (the combination is relatively slow) (10^{-2} to 10^{-4} s). Therefore these materials give insignificant levels of electroluminescence.**
- **Example : Si**

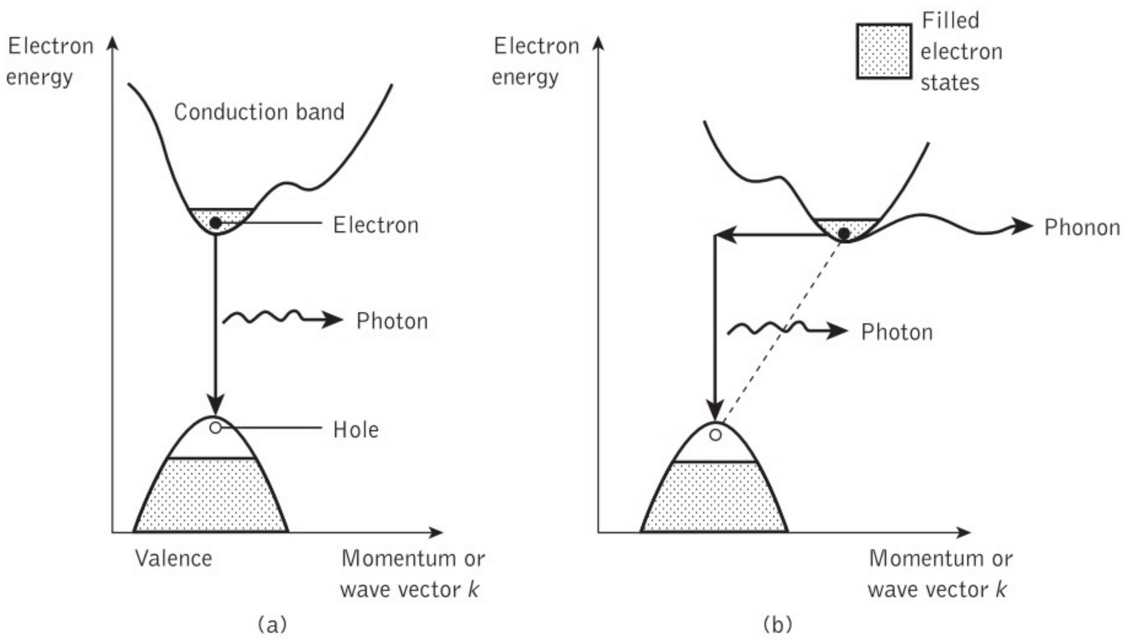

Figure 5: Energy–momentum diagrams showing the types of transition: (a) direct bandgap semiconductor; (b) indirect bandgap semiconductor

The radiative minority carrier lifetime τ_r

$$\tau_r = [B_r(N + P)]^{-1} \tag{4}$$

Where

N : majority carrier concentrations in the n-type

P : majority carrier concentrations in the p-type

B_r : recombination coefficient

Direct bandgap semiconductor devices in general have a much higher internal quantum efficiency. This is the ratio of the number of radiative recombinations (photons produced within the structure) to the number of injected carriers which is often expressed as a percentage

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1. Q Compare the approximate radiative minority carrier lifetimes in gallium arsenide and silicon when the minority carriers are electrons injected into the p-type region which has a hole concentration of 10^{18} cm^{-3} . The injected electron density is small compared with the majority carrier density.

$\boxed{1.\ \mathrm{A}}$ In the p-type region the hole concentration determines the radiative carrier lifetime as $P >> N$. Hence:

$$\tau_r = [B_r(N + P)]^{-1} \simeq [B_r P]^{-1}$$

Thus for gallium arsenide:

$$\begin{aligned}\tau_r &\simeq \left[7.21 \times 10^{-10} \times 10^{18}\right]^{-1} \\ &= 1.39 \times 10^{-9} \\ &= 1.39 \text{ ns}\end{aligned}$$

For silicon:

$$\begin{aligned}\tau_r &\simeq \left[1.79 \times 10^{-15} \times 10^{18}\right]^{-1} \\ &= 5.58 \times 10^{-4} \\ &= 0.56 \text{ ms}\end{aligned}$$

Thus the direct bandgap gallium arsenide has a radiative carrier lifetime factor of around 2.5×10^{-6} less than the indirect bandgap silicon.

4 Other radiative recombination processes

How to use an indirect bandgap semiconductor as useful electroluminescent material ?

To increase electron–hole recombination (reduce the carrier lifetime), new energy levels may be introduced into the bandgap by impurities or lattice defects which will convert it to a direct bandgap semiconductor

5 Stimulated emission and lasing

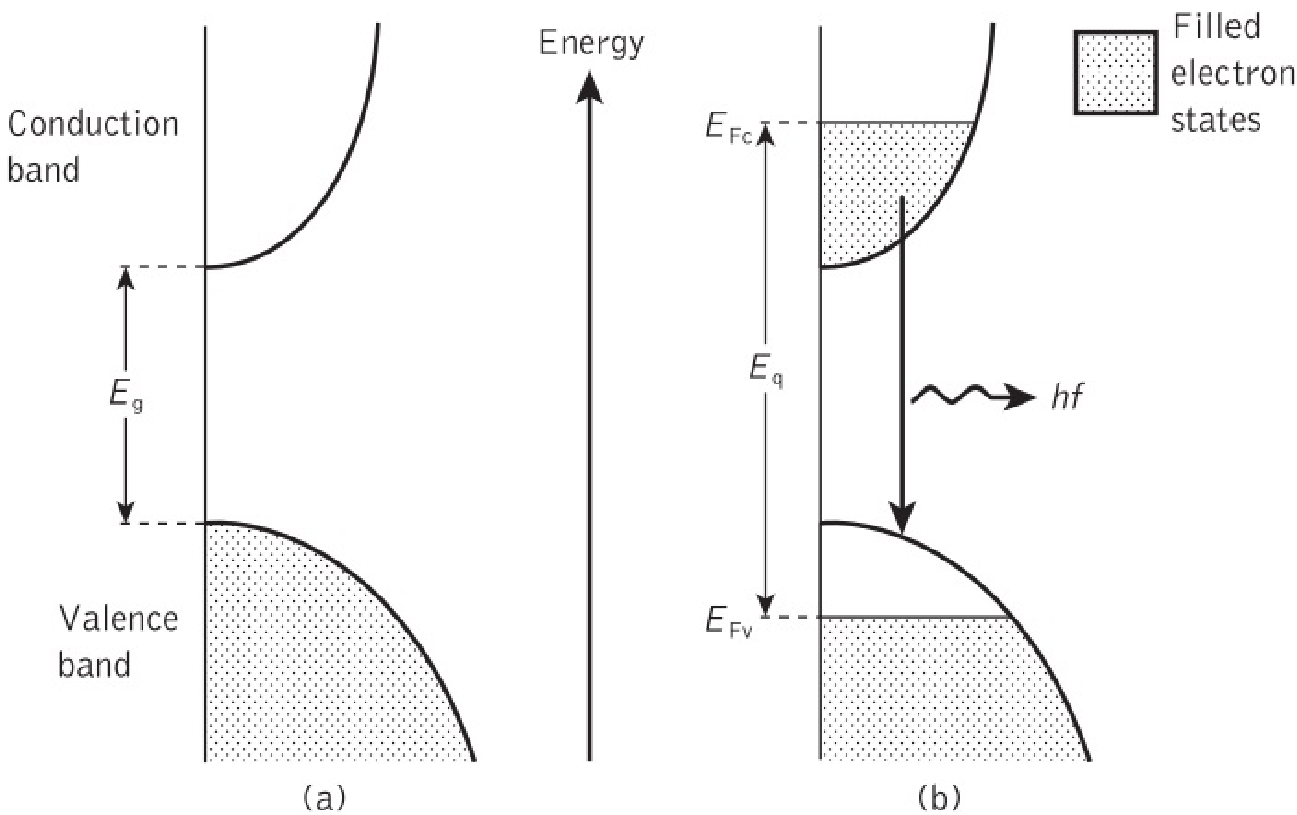

Figure 6: The filled electron states for an intrinsic direct bandgap semiconductor at absolute zero : (a) in equilibrium; (b) with high carrier injection

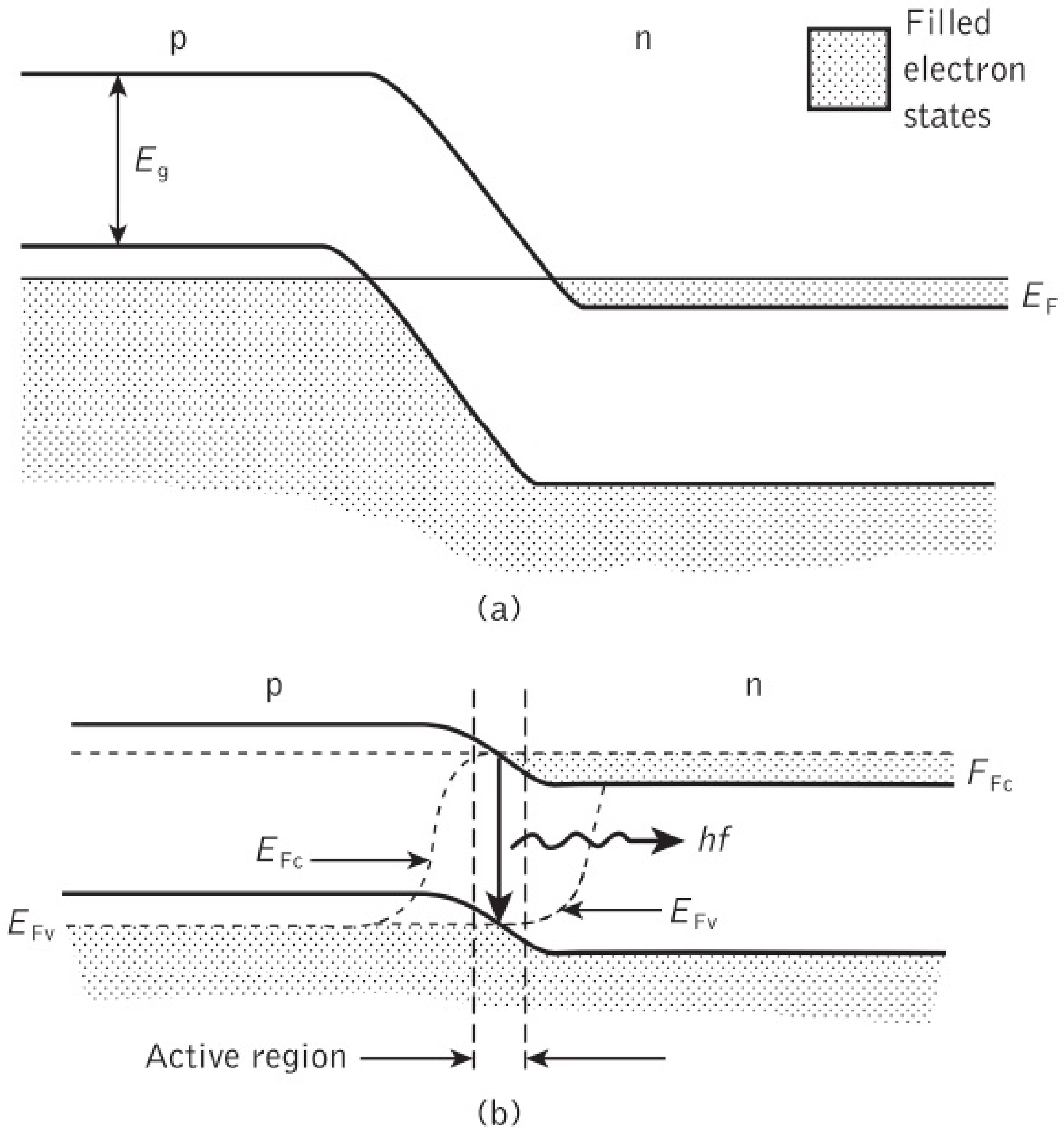

Figure 7: The degenerate p–n junction: (a) with no applied bias; (b) with strong forward bias such that the separation of the quasi-Fermi levels is higher than the electron–hole recombination energy hf in the narrow active region. Hence stimulated emission is obtained in this region

To increase stimulated emission, population inversion is used

Population inversion may be obtained at a p–n junction by heavy doping (degenerative doping) of both the p- and n-type material.

Heavy p-type doping with acceptor impurities causes a lowering of the Fermi level or boundary between the filled and empty states into the valence band.

Similarly, degenerative n-type doping causes the Fermi level to enter the conduction band of the material

In case of degenerative doping the emitted photo energy varies from E_g to $E_{\mathrm{Fc}} - E_{\mathrm{Fv}}$

$$E_{\mathrm{Fc}} - E_{\mathrm{Fv}} > hf > E_{\mathrm{g}}$$

when a forward bias nearly equal to the bandgap voltage is applied and hence there is direct conduction. At high injection carrier density in such a junction there exists an active region near the depletion layer that contains simultaneously degenerate populations of electrons and holes, therefore stimulated emission happens and any radiation of this frequency which is confined to the active region will be amplified.

MCQ Questions

1. Q What is an intrinsic semiconductor?

(a) A semiconductor with impurities intentionally added to its crystal structure

(b) A semiconductor with no impurities or lattice defects in its crystal structure

(c) A semiconductor with a disordered crystal structure

(d) A semiconductor with a non-uniform crystal structure

2. Q What is an extrinsic semiconductor?

(a) A semiconductor with no impurities or lattice defects in its crystal structure

(b) A semiconductor with a disordered crystal structure

(c) A semiconductor doped with impurity atoms to alter its electrical properties

(d) A semiconductor with a non-uniform crystal structure

3. Q What is nonradiative recombination?

(a) Recombination in which the energy released creates a photon

(b) Recombination in which the energy released is dissipated as heat through lattice vibrations

(c) Recombination in which impurity atoms are involved

(d) Recombination in which the semiconductor crystal is cooled

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4. Q What is radiative recombination?

(a) Recombination in which the energy released creates a photon

(b) Recombination in which the energy released is dissipated as heat through lattice vibrations

(c) Recombination in which impurity atoms are involved

(d) Recombination in which the semiconductor crystal is cooled

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5. Q The relation between the wavelength and the energy gap E_g

(a) $\lambda = \dfrac{1.24}{E_g}$ (b) $\lambda = 1.24 \times E_g$ (c) $\lambda = \dfrac{2.48}{E_g}$ (d) $\lambda = 2.48 \times E_g$

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6. Q What is electroluminescence in a semiconductor?

(a) The process by which impurity atoms are added to the semiconductor crystal

(b) The process by which a semiconductor crystal is heated to its melting point

(c) The process by which a semiconductor emits light by spontaneous emission

(d) The process by which a semiconductor absorbs light and converts it into electrical energy

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7. Q What type of semiconductor material is preferred to encourage electroluminescence?

(a) An indirect bandgap semiconductor material

(b) A direct bandgap semiconductor material

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8. Q What is minority carrier lifetime in a semiconductor?

(a) The average time that a minority carrier remains in a free state before recombination

(b) The average time that a charge carrier spends in the conduction or valence band

(c) The average time that a free electron or hole remains in the crystal lattice

(d) The average time that it takes for an electric field to accelerate a charge carrier

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9. Q Why is direct recombination possible in a direct bandgap semiconductor?

(a) Electrons and holes on either side of the energy bandgap have the same value of crystal momentum

(b) The energy maximum of the valence band occurs at a different value of crystal momentum than the energy minimum of the conduction band

(c) Electrons and holes have different values of crystal momentum

(d) Direct recombination is not possible in direct bandgap semiconductors

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10. Q gallium arsenide is an example of :

(a) direct bandgap semiconductor

(b) indirect bandgap semiconductor

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11. Q Which of the following is true regarding indirect bandgap semiconductors?

(a) They have a shorter minority carrier lifetime compared to direct bandgap materials.

(b) They are suitable for light emission applications due to high probability of radiative recombination.

(c) The recombination process requires the emission or absorption of a photon.

(d) The recombination process requires the emission or absorption of a phonon, resulting in low probability of radiative recombination

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12. Q silicon is an example of :

(a) direct bandgap semiconductor

(b) indirect bandgap semiconductor

13. Q Two semiconductor materials (A) and (B), the radiative carrier lifetime material (A) is 2.86×10^5 times more than radiative carrier lifetime material (B), so :

(a) (A) is direct bandgap semiconductor material, while (B) is indirect bandgap semiconductor material

(b) (A) is indirect bandgap semiconductor material, while (B) is direct bandgap semiconductor material

(c) both (A) and (B) are direct bandgap semiconductor materials

(d) Not enough information

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14. Q What is the equation for radiative minority carrier lifetime in a semiconductor?

(a) $\tau_r = [B_r(N + P)]$

(b) $\tau_r = [B_r(N - P)]$

(c) $\tau_r = [B_r(N + P)]^{-1}$

(d) $\tau_r = [B_r(N - P)]^{-1}$

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15. Q How can an indirect bandgap semiconductor be made suitable for use as an electroluminescent material?

(a) By increasing the minority carrier lifetime

(b) By decreasing the impurity concentration

(c) By introducing new energy levels into the bandgap by impurities or lattice defects

(d) By increasing the lattice vibrations

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16. Q In a degenerate p-n junction, what causes the active region near the depletion layer to have degenerate populations of electrons and holes?

(a) The presence of lattice defects in the material

(b) The application of a reverse bias to the junction

(c) The use of direct bandgap materials in the junction

(d) The application of a forward bias to the junction

Answers :

$\boxed{\textbf{1. A}}$ (b)

$\boxed{\textbf{2. A}}$ (c)

$\boxed{\textbf{3. A}}$ (b)

$\boxed{\textbf{4. A}}$ (a)

$\boxed{\textbf{5. A}}$ (a)

$\boxed{\textbf{6. A}}$ (c)

$\boxed{\textbf{7. A}}$ (b)

$\boxed{\textbf{8. A}}$ (a)

$\boxed{\textbf{9. A}}$ (a)

$\boxed{\textbf{10. A}}$ (a)

$\boxed{\textbf{11. A}}$ (d)

$\boxed{\textbf{12. A}}$ (b)

$\boxed{\textbf{13. A}}$ (b)

$\boxed{\textbf{14. A}}$ (c)

$\boxed{\textbf{15. A}}$ (c)

$\boxed{\textbf{16. A}}$ (d)