



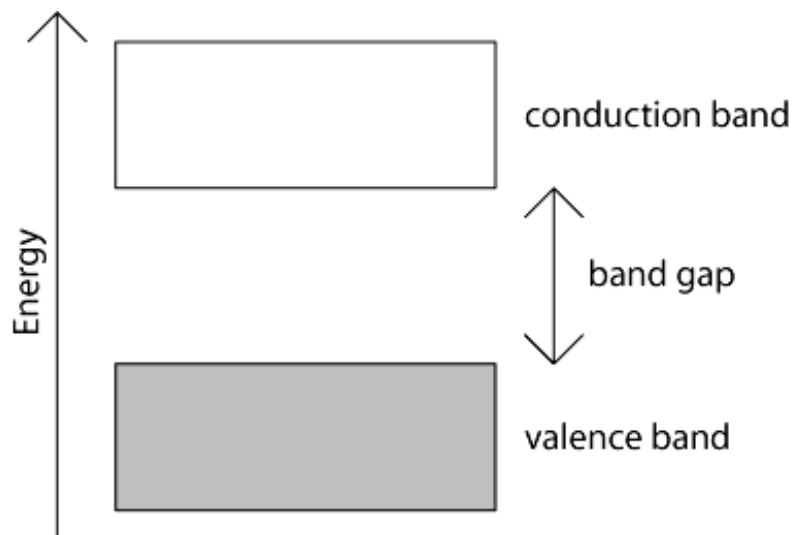
- Answer all the following question
- Illustrate your answers with sketches when necessary
- No. of questions: 3 in one page
- Total Mark: 60 Marks

Question (1) (18 marks)

(A) Discuss in details the concept of energy bands within solids? Explain the main difference between insulators, conductors and semiconductors? **(6 marks)**

In case of a single isolated atom an electron in any orbit has definite energy. When atoms are brought together and combine to form molecules as in solids, an atom is influenced by the forces from other atoms. Hence an electron in any orbit can have a range of energies rather than single energy. The range of the energetic levels of atoms is represented by a near-continuum of levels called *energy band*. The energetic levels are occupied by the electrons (distributed according to Pauli Exclusion Principle), starting with the lowest energy value level.

The electrons that contribute to the electrical conduction occupy the higher (partially filled) energy band which is called *the conduction band*. The highest energy band that is fully occupied with electrons is called *the valence band*. The Valence band and conduction band are separated by an energy gap in which no electrons normally exist this gap is called the *forbidden gap*. A conventional form of the energy bands in a solid material is indicated in figure



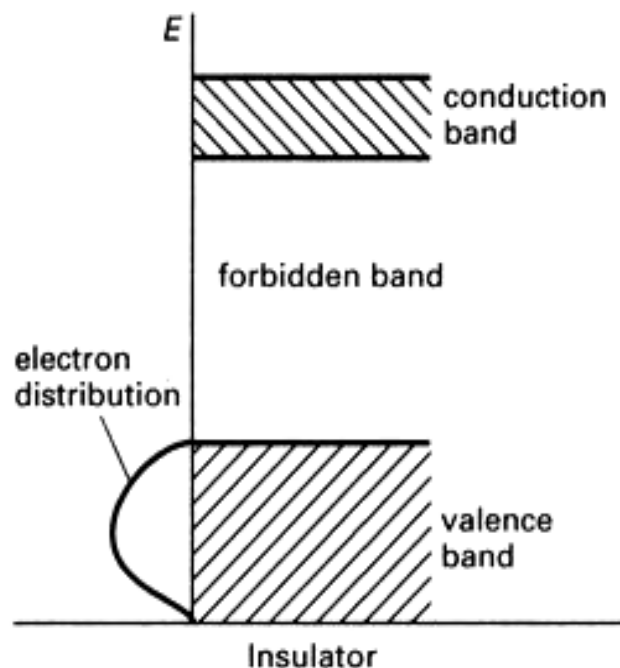
Electrons in conduction band are either escaped from their atoms (free electrons) or only weakly held to the nucleus. Thereby by the electrons in conduction band may be easily moved around within the material by applying relatively small amount of energy; (either by increasing the temperature or by focusing light on the material etc....). This is the reason why the conductivity of the material increases with increase in temperature. But much larger amount of energy must be applied in order to extract an electron from the valence band because electrons in valence band are usually in the normal orbit around a nucleus.

For a given material, the forbidden gap may be large, small or non-existent. According to energy bands, materials can be classified as:

- Insulators
- conductors
- Semiconductors.

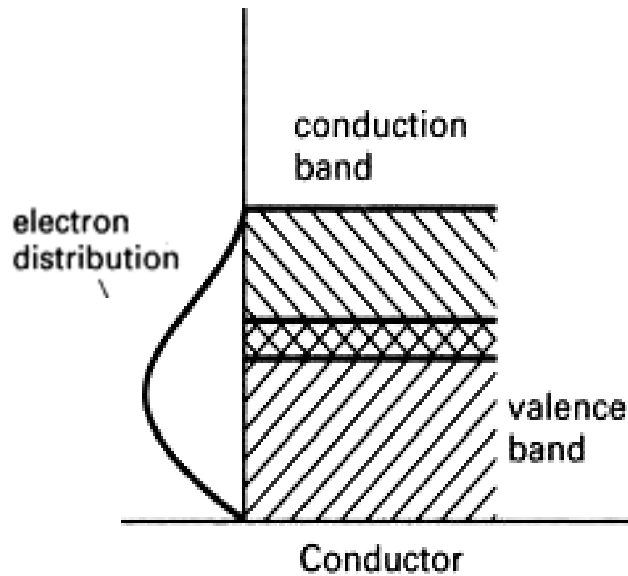
Insulators

In case of insulators, the forbidden energy gap is extremely high. On the other hand its valence band is fully filled with the electrons, whereas its conduction band is empty. For example, in diamond, the approximate value of forbidden energy gap is nearly 6 eV. In normal case, electrons would not acquire enough energy (thermally or optically) to cross the large energy gap of such materials. Thus electrons can not jump into the conduction band, and as a result these materials are insulators.



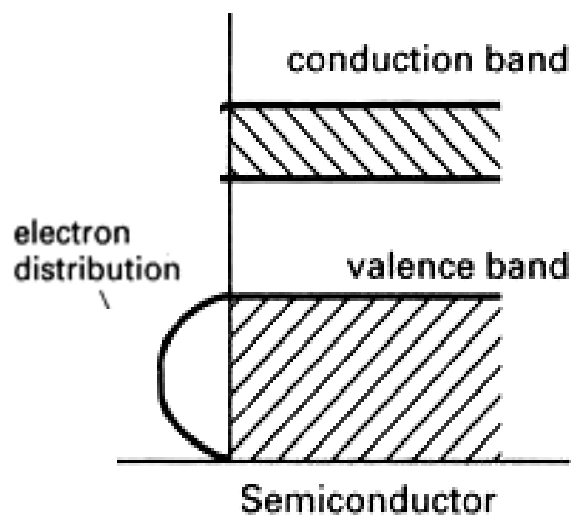
Conductors

In case of metals, electrons fill the conduction band partially. The overlapping of both the bands (i.e. valence and conduction band) also takes place. For example, iron, copper and all other metals show that no forbidden energy gap is present. Consequently, there is no energy gap to cross in order to reach the conduction band, and any energy that is added to the electron is sufficient to propel it into the conduction band. There are many electrons that are free to move about a conductor, so it is very easy for current to flow if an external electric field is applied.



Semiconductors

In case of semiconductors the conduction band is empty and the valence band is fully filled with electrons. The energy gap is very small. This energy gap is nearly of 1eV. For example, in silicon and germanium the energy gap is nearly 1.1 eV and 0.72 eV respectively. At normal temperatures, the thermal (or optical) energy is sufficient to propel some electrons from the valence band into the conduction band, allowing some electrons to be free to conduct current. The number of free charge carriers increases with supplied energy, so the conductivity of a semi-conductor can be manipulated by outside potentials.



(B) Compare the main characteristics of direct energy gap and indirect energy gap in semiconductors? **(6 marks)**

In direct band gap materials, the minimum energy of the conduction band lies directly above the maximum energy of the valence band in momentum space energy (Figure 2 shows the E-k plot of a direct band gap material). In this material, free electrons at the bottom of the conduction band can recombine directly with free holes at the top of the valence band, as the momentum of the two particles is the same. This transition from conduction band to valence band involves photon emission (takes care of the principle of energy conservation). This is known as direct recombination. Direct recombination occurs spontaneously. GaAs is an example of a direct band-gap material.

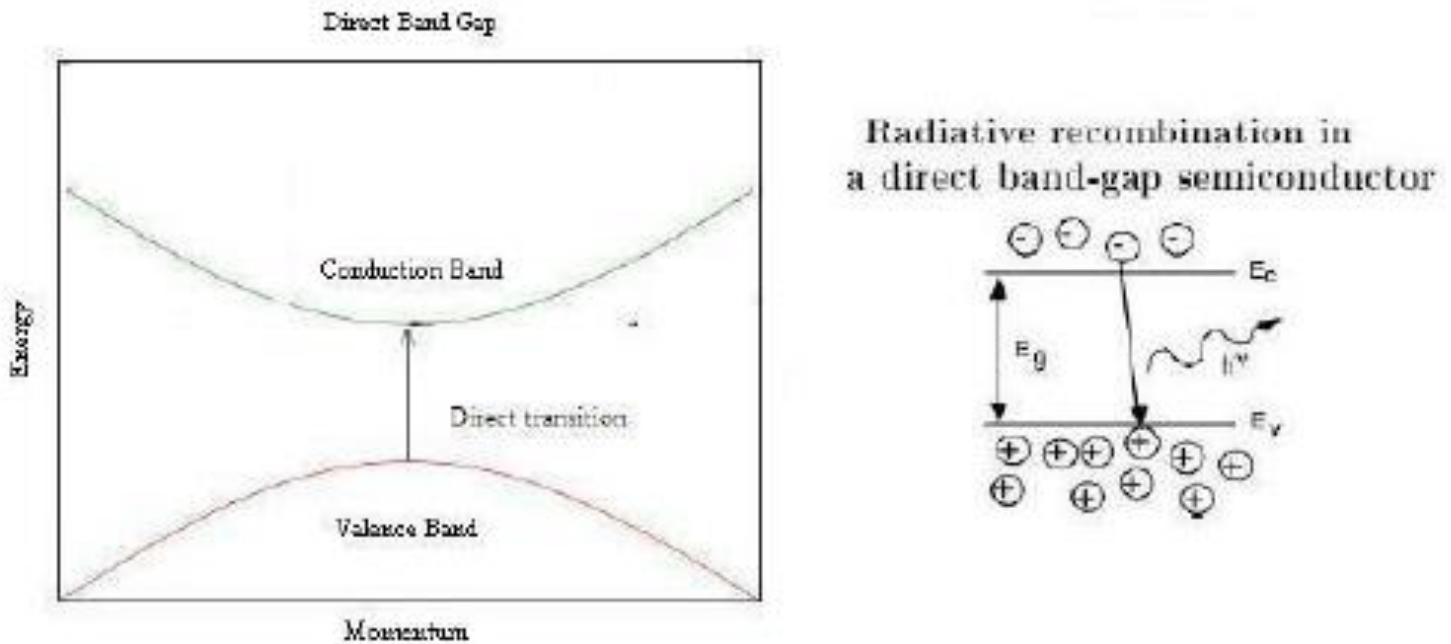


Figure 2: Direct Bandgap and Direct Recombination

In the indirect band gap materials, the minimum energy in the conduction band is shifted by a k-vector relative to the valence band. The k-vector difference represents a difference in momentum. Due to this difference in momentum, the probability of direct electron-hole recombination is less. In these materials, additional dopants (impurities) are added which form very shallow donor states. These donor states capture the free electrons locally; provides the necessary momentum shift for recombination. These donor states serve as the recombination centers. This is called Indirect (non-radiative) Recombination.

Figure 3 shows the E-k plot of an indirect band gap material and an example of how Nitrogen serves as a recombination center in GaAsP. In this case it creates a donor state, when SiC is doped with Al, it recombination takes place through an acceptor level. The indirect recombination should satisfy both conservation energy, and momentum. Thus besides a photon emission, phonon emission or absorption has to take place. GaP is an example of an indirect band-gap material.

The wavelength of the light emitted, and hence the color, depends on the band gap energy of the materials forming the p-n junction.

The emitted photon energy is approximately equal to the band gap energy of the semiconductor. The following equation relates the wavelength and the energy band gap.

$$h\nu = E_g$$

$$hc/\lambda = E_g$$

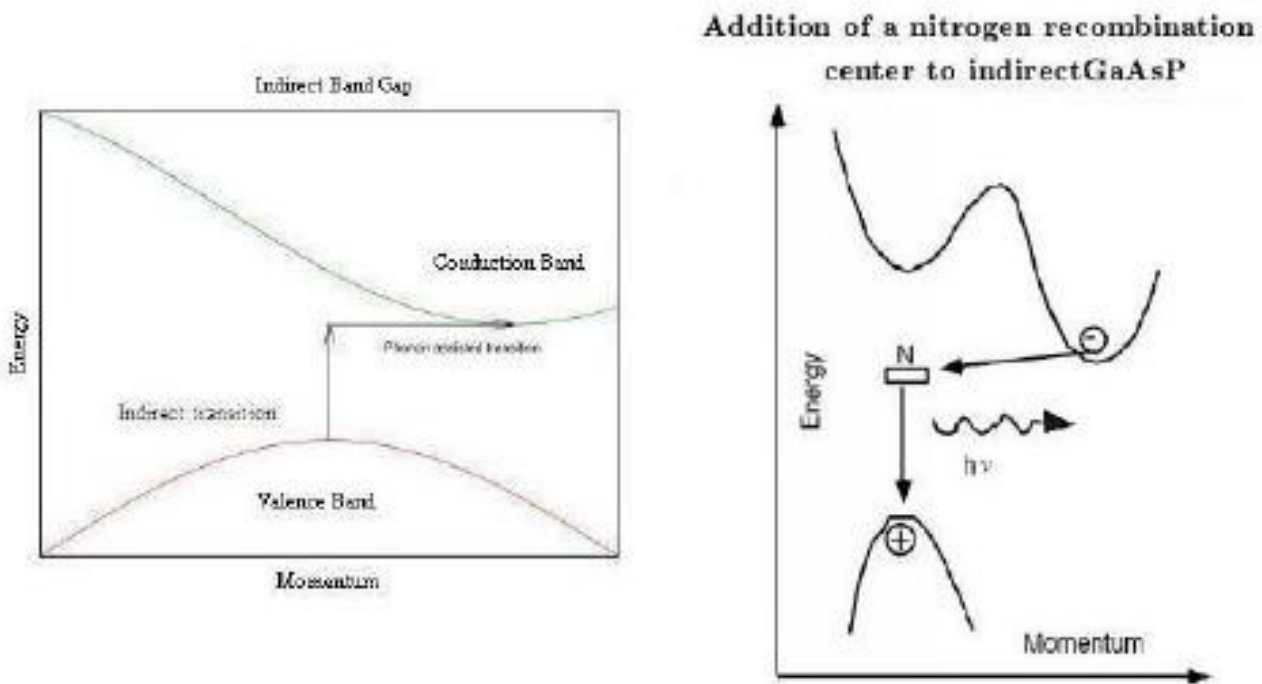


Figure 3: Indirect Bandgap and NonRadiative recombination

- (C) How many free electrons in the cubic centimeter of pure copper if it has density of 8.96 gm/cm^3 and molecular mass of 63.54 gm/mole where each copper atom share one free electron? [$N_A = 6.023 \times 10^{23} \text{ atom/mole}$] **(6 marks)**

$$\rho = 8.96 \text{ g/cm}^3$$

$$M = 63.54 \text{ g/mol}$$

$$N_A = 6.02 \times 10^{23} \text{ atom/mol}$$

$$N = 1 \text{ free electron per atom}$$

$$n = N N_A \rho / M$$

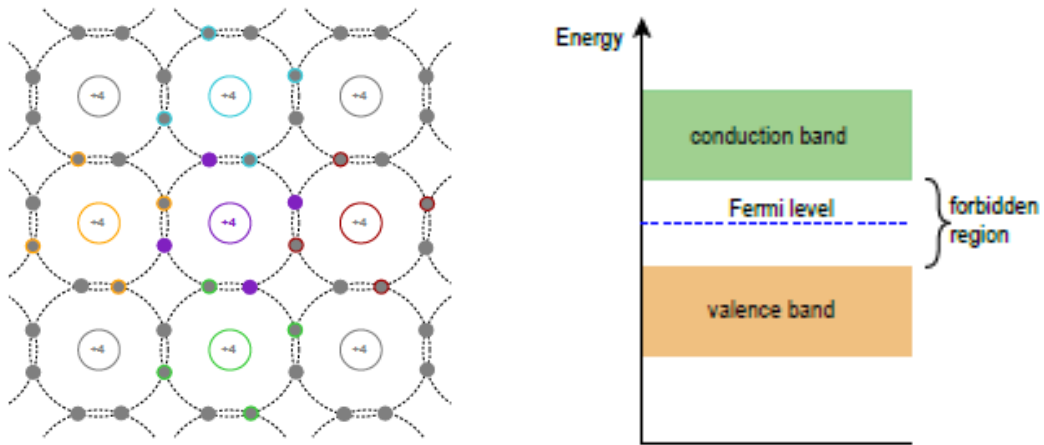
$$= (1) (6.02 \times 10^{23}) (8.96) / (63.54)$$

$$= 8.49 \times 10^{22} \text{ free electrons / cm}^3$$

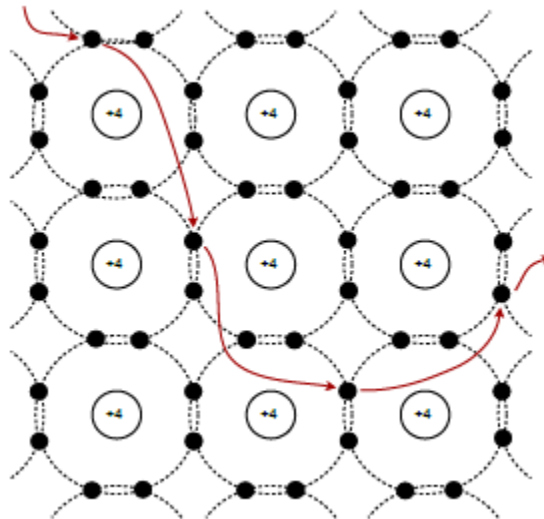
Question (2) (18 marks)

- (A) What is meant by intrinsic semiconductors? Discuss the effect of thermal energy on the electric conduction within such materials? **(6 marks)**

We used silicon in the preceding example on purpose. The fact that it has a half filled valence shell with four electrons puts it in a special place. As is, it's neither a great conductor nor a superior insulator. With some attention to detail, it will become a semiconductor. Silicon is not the only material that can be used for semiconductors. In fact, many of the earliest semiconductors were made from germanium and currently we make semiconductors from other materials. Silicon, however, remains the source of most semiconductors today.



Without any external energy applied (i.e., isolated and at absolute zero), the crystal lattice is stable and there is no electron movement through the crystal. As we add thermal energy, it is possible for valence electrons to jump up to the conduction band. At this point, the electron can “wander” through the crystal in the manner depicted in Figure 1.11



(B) At room temperature of 20 °C, silicon is found to have 1.45×10^{10} electrons/cm³. How many free electrons per each atom of silicon if its density is 2.33 gm/cm³ and its molar mass is 28.09 gm/mole? **(6 marks)**

$$\rho = 2.33 \text{ g/cm}^3$$

$$M = 28.09 \text{ g/mol}$$

$$N_A = 6.02 \times 10^{23} \text{ atom/mol}$$

$$n = 1.45 \times 10^{10} \text{ atom/cm}^3$$

$$n = N N_A \rho / M$$

$$N = n M / N_A \rho$$

$$= (1.45 \times 10^{10}) (28.09) / (6.02 \times 10^{23}) (2.33)$$

$$= 2.9 \times 10^{-13} \text{ free electrons / atom}$$

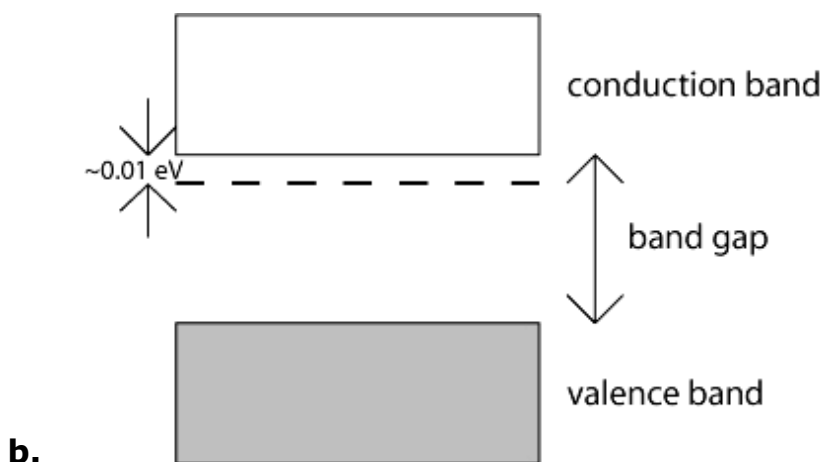
(C) Explain the different methods of doping in order to modify the electric conduction in semiconducting materials? **(6 marks)**

In most pure semiconductors, at room temperature, the concentration of charge carriers is much lower than for a metallic conductor. For example, The number of thermally excited electrons in silicon (Si), at 298 K, is 1.5×10^{10} electrons per cm^3 . In gallium arsenide (GaAs) the population is only 1.1×10^6 electrons per cm^3 . This may be compared with the number density of free electrons in a typical metal, which is of the order of 10^{28} electrons per cm^3 .

Given these numbers of charge carriers within semiconductors, it is no surprise that, when they are extremely pure, silicon and other semiconductors have high electrical resistivities, and therefore low electrical conductivities. This problem can be overcome by doping a semiconducting material with impurity atoms. Even very small controlled additions of impurity atoms at the 0.0001% level can make very large differences to the conductivity of a semiconductor. Electrical conductivity of semiconductors can be increased by two different types of doping which will be described as follows:

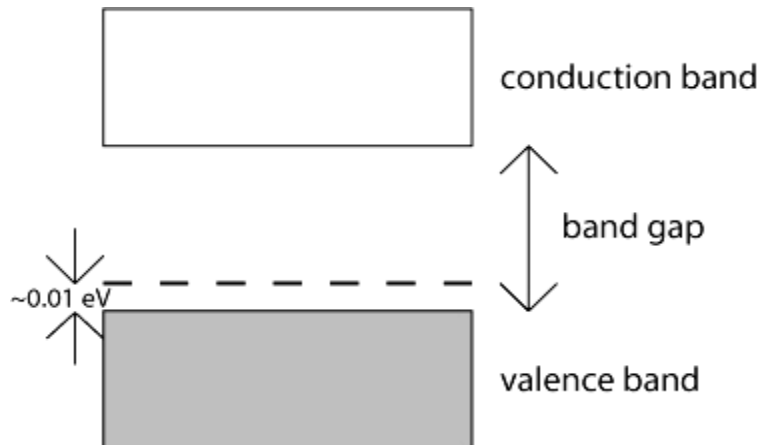
a. n-type semiconductors

In this case, a very small number of atoms of group V elements such as arsenic (As) are added to the silicon (Si) crystal as substitutional atoms in the lattice. Arsenic atoms have five valence electrons while silicon atoms has only four valence electrons so, the fifth electrons of arsenic are bound only weakly to their parent impurity atoms (the bonding energies are of the order of 0.01 eV), This is often represented schematically in band diagrams by the addition of 'donor levels' just below the bottom of the conduction band.



p-type semiconductors

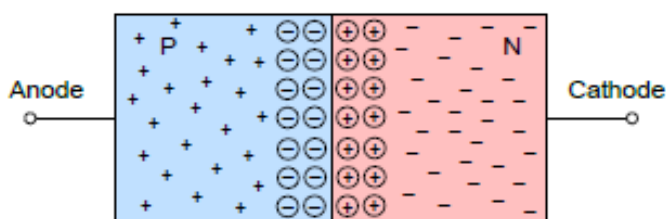
In this case, a very small number of atoms of group III elements such as gallium (Ga) are added to the silicon (Si) crystal as substitutional atoms in the lattice. Gallium atoms have three valence electrons while silicon (Si) atoms has only four valence electrons so, this case results in presence of vacancies called holes in the electron structure of the crystal. This is often represented schematically in band diagrams by the addition of 'acceptor levels' just above the highest valence band



Question (3) (24 marks)

(A) Discuss the construction and operation idea of the diode and explain its function in case of forward and reverse biased connection? **(6 marks)**

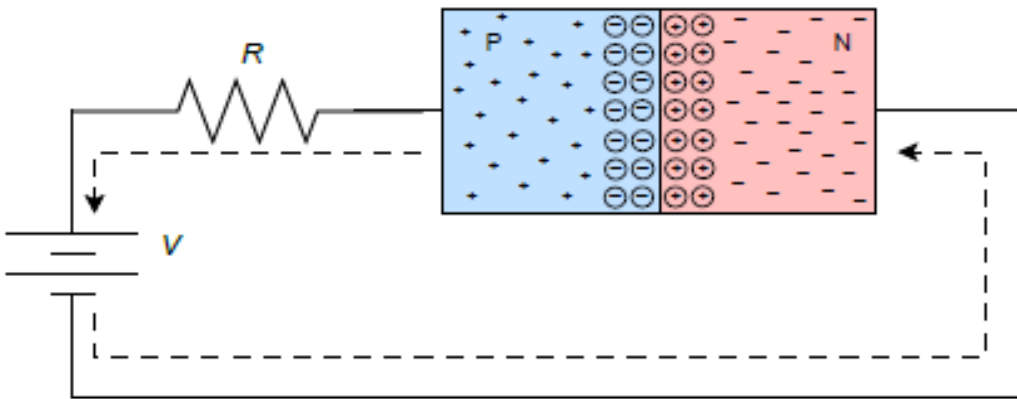
If we were to create a region of N material abutting a region of P material in a single crystal, an interesting situation occurs. Assuming the crystal is not at absolute zero, the thermal energy in the system will cause some of the free electrons in the N material to “fall” into the excess holes of the adjoining P material. This will create a region that is devoid of charge carriers (remember, electrons are the majority charge carrier in N material while holes are the majority charge carrier in P material). In other words, the area where the N and P materials abut is depleted of available electrons and holes, and thus we refer to it as a depletion region. This is depicted in Figure 2.1. The excess electrons of the N material are denoted by minus signs while the excess holes of the P material are denoted with plus signs. At the interface, the free electrons have recombined with holes. When an electron recombines, it leaves behind a positive ion in the N material (shown here as a circled plus sign) and produces a negative ion in the P material (shown as a circled minus sign).



Forward--Bias

The dotted line of Figure 2.3 shows the direction of electron flow (opposite the direction of conventional flow). First, electrons flow from the negative terminal of the battery toward the N material. In N material, the majority carriers are electrons and it is easy for these electrons to move through the N material. Upon entering the depletion region, if the supplied potential is high enough, the electrons can diffuse into the P material where there are a large number of lower energy holes. From here, the electrons can migrate through to the positive terminal of the source, completing the circuit (the resistor has been added to limit maximum current flow). The “trick” here is to assure that the supplied potential is large enough to overcome the effect of the depletion region. That is, a certain voltage will be dropped across the depletion region in order to achieve current flow. This required potential is called the barrier potential or forward voltage drop. The precise value depends on the material used.

For silicon devices the barrier potential is usually estimated at around 0.7 volts. For germanium devices it is closer to 0.3 volts while LEDs may exhibit barrier potentials in the vicinity of 1.5 to 3 volts, partly depending on the color.



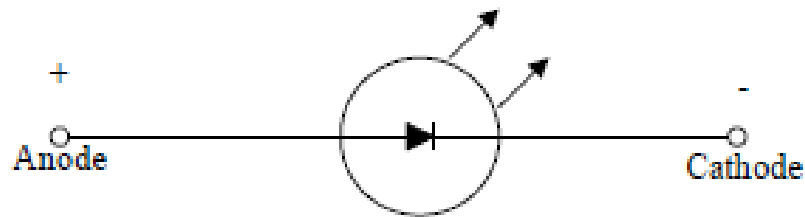
Reverse--Bias

If the voltage source polarity is reversed in Figure 2.3, the behavior of the PN junction is altered radically. In this case, the electrons in the N material will be drawn toward the positive terminal of the source while the P material holes will be drawn toward the negative terminal, creating a small, short-lived current. This has the effect of widening the depletion region and once it reaches the supplied potential, the flow of current ceases. In essence, we have increased the size of the energy hill. Further increases in the source voltage only serve to make the situation worse. The depletion region simply expands to fill the void, so to speak. Ideally, the PN junction acts like an open circuit with an applied reverse-bias voltage. This asymmetry in response to a supplied potential turns out to be extraordinarily useful. Perhaps the simplest of all semiconductor devices is the diode. In its basic form a diode is just a PN junction. It is a device that will allow current to pass easily in one direction but prevent current flow in the opposite direction.

(B) What is the importance of light emitting diodes? By using the necessary diagrams, explain its components and working? **(6 marks)**

LED

- Similar to diodes, LEDs are current-dependent devices.
- LED brightness is controlled by controlling current through LED.
- Too little current through LED LED remains OFF.
- Small current through LED dimly lit LED.
- Large current through LED brightly lit LED.
- Too much current through LED LED is destroyed.
- A resistor placed in series with LED accomplishes current control

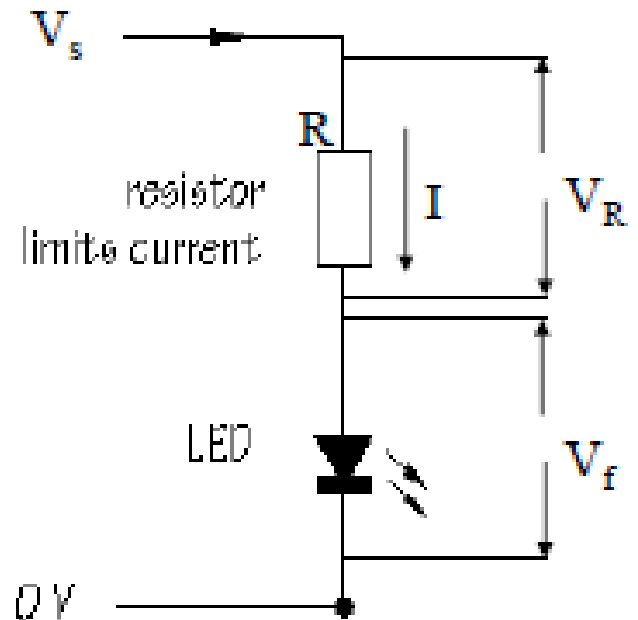


LED symbol

- Let V_s be the supply voltage.
- Let V_f be the required forward bias voltage for the LED.
- Let I be the desired current flow through LED.
- Then, the current limiting resistance R is sized as follow:

$$V_R = V_s - V_f$$

$$R = \frac{V_R}{I} = \frac{V_s - V_f}{I}$$



- If R is chosen smaller than the above value, a larger current will flow through the LED.
- LEDs can handle only limited current (varies from 20mA to 100mA).
 - If current through LED is larger than the maximum allowed value, than the LED will be damaged.

How LED Works

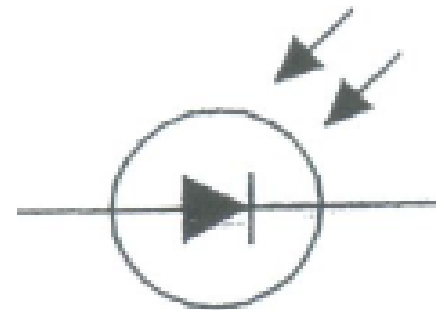
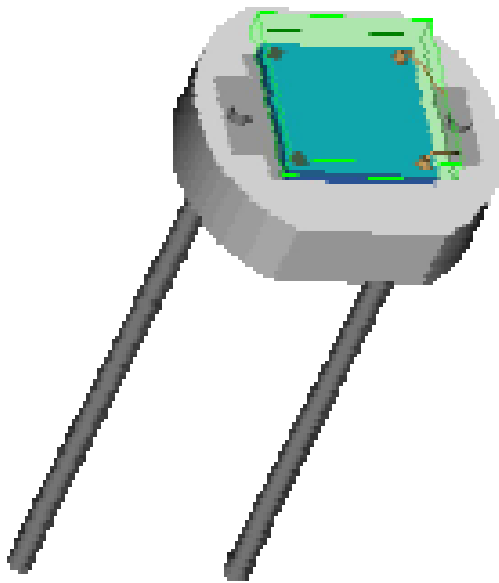
- The light-emitting section of an LED is made by joining n-type and p-type semiconductors together to form a pn junction.
- When the pn junction is forward-biased, electrons in the n side are excited across the pn junction and into the p side, where they combine with holes.
- As the electrons combine with the holes, photons are emitted.
- The pn-junction section of an LED is encased in an epoxy shell that is doped with light scattering particles to diffuse light and make the LED appear brighter.
- Often a reflector placed beneath the semiconductor is used to direct the light upward.

(C) How can doped semiconducting materials be used in the construction of photodiodes or photosensors? Give some examples for daily applications? **(6 marks)**

Photodiode

- Photodiode is a 2 lead semiconductor device that transforms light energy to electric current.
- Suppose anode and cathode of a photodiode are wired to a current meter.
 - When photodiode is placed in dark, the current meter displays zero current flow.
 - When the photodiode is exposed to light, it acts as a current source, causing current flow from cathode to anode of photodiode through the current meter.
- Photodiodes have very linear light v/s current characteristics.
 - Commonly used as light meters in cameras.
- Photodiodes often have built-in lenses and optical filters.
- Response time of a photodiode slows with increasing surface area.
- Photodiodes are more sensitive than photoresistor.

Symbol



Symbol

How Photodiode Works

- Photodiode: A thin n-type semiconductor sandwiched with a thicker p-type semiconductor.
- N-side is cathode, p-side is anode.
- Upon illumination, a # of photons pass from the n-side and into the p-side of photodiode.
 - Some photons making it into p-side collide with bound electrons within p semiconductor, ejecting them and creating holes.
 - If these collisions are close to the pn interface, the ejected electrons cross the junction, yielding extra electrons on the n-side and extra holes on the p-side.
 - Segregation of +ve and -ve charges leads to a potential difference across the pn-junction.
 - When a wire is connected between the cathode and anode, a conventionally positive current flow from the anode to cathode .

(D) Discuss in details the photoelectric phenomenon? If the photoelectric effect in some metal begins at 6×10^{14} Hz. Find the work function of emission of electrons from this metal? Find the frequency of incident light which ejects electrons that are fully retarded by a reverse potential of 3 V? [$h = 6.6 \times 10^{-34}$ J.s , $c = 3 \times 10^8$ m/s , $m = 9.1 \times 10^{-31}$ Kg] **(6 marks)**

$$\nu_0 = 6 \times 10^{14} \text{ Hz.}$$

$$W = h \nu_0$$

$$= 6.6 \times 10^{-34} \times 6 \times 10^{14} = 3.96 \times 10^{-19} \text{ J}$$

$$V_o = 3 \text{ V}$$

$$h \nu = h \nu_0 + e V_o$$

$$6.6 \times 10^{-34} \nu = 6.6 \times 10^{-34} \times 6 \times 10^{14} + 1.6 \times 10^{-19} \times 3$$

$$\nu = 1.33 \times 10^{15} \text{ Hz}$$

GOOD LUCK

Dr. Hytham Abdelghany