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Semiconductors and Optoelectronic devices

For students of the 3 LMD Physics of materials

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Semiconductors and Optoelectronic devices

Preface

This document represents courses in optoelectronic for undergraduate students 3LMD Material Physics.

For understanding the characteristics and operation optoelectronic devices, it is essential to have a thorough knowledge of the physics of the semiconductor material.

The document is divided into five parts:

Part I covers the study of semiconductors and the pn junction, which is the necessary basic for the optoelectronic devices; in this part we will study pure and doped semiconductors, and derive the thermal-equilibrium concentrations of electrons and holes in a semiconductor as a function of the Fermi energy level and the concentration of dopant atoms added to the semiconductor. Most optoelectronic devices contain at least one junction between p-type and n-type semiconductor regions. Optoelectronic device characteristics and operation are intimately connected to these pn junctions, so considerable attention is devoted initially to this basic device.

Part II presents the simple optoelectronic device which is the light emitting diode (LED), this later is essentially a pn junction diode in which an electron-hole pair recombination results in the emission of a photon following an electric current caused by an applied electric field.

In Part III, a solar cell as a pn junction device with no voltage directly applied across the junction is presented. The solar cell converts photon power into electrical power and delivered to a load. These devices have long been used for the power supply of satellites and space vehicles, and also as the power supply to some calculators. We will first consider the simple pn junction solar cell with uniform generation of excess carriers. We will also discuss briefly heterojunction solar cells.

The fourth part presents an overview of semiconductor laser diodes.

The last part is a study of a photodiode, which is a pn junction diode operated with an applied reverse-biased voltage.

In the end, we hope that this document will be useful for students, and for more information, they might consult the references mentioned at the end of this document.

I. Fundamental notions of semiconductor physics

Semiconductors and devices based on them are in every aspect of modern life, from a simple electronic game to personal computer and mobile phones. Semiconductors contribute to life perhaps like no other manmade materials. Electronic devices such as: diodes, bipolar junction transistors, and field effect transistors drive modern electronic technology. Optoelectronic devices such as laser diodes, modulators, and detectors drive the optical networks. The expanding world of semiconductors brings new challenges and opportunities, where new semiconductors appear and new physical phenomena need to be studied as structures become ever smaller toward the nanometer scale.

I. Fundamental notions of semiconductor physics

Introduction:

In this chapter we develop a basic understanding of the properties of intrinsic and extrinsic semiconductors. Initial studies on semiconductors were carried out in single material systems based on Si, Ge, and C. Compound semiconductors such as GaAs are also commonly used. Then it was realized if semiconductors could be combined as a heterostructure, this later would yield very interesting properties. Semiconductor heterostructures are now widely used in electronics and optoelectronics. Heterostructures are primarily used to confine electrons and holes and to produce low dimensional electronic systems. These low dimensional systems, including quantum wells, quantum wires, and quantum dots have density of states and other electronic properties which make them attractive for many applications.

Although the most of discussions and examples will be based on Si, but they can apply to Ge and compound semiconductors such as GaAs, InP, and others.

Intrinsic Silicon is an ideal perfect crystal that has no impurities or crystal defects such as dislocations and grain boundaries. The crystal consists of Si atoms perfectly bonded to each other in the diamond structure.

I.1. Generalities

A semiconductor is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator, where the resistivity varies from 10^{-3} to 10^{4} Ω.cm (or more). Electrical conduction takes place by electrons and holes, or preferably by one or another type of carrier. A semiconductor can be either pure in which case it is called ″intrinsic″, or doped by impurities (which make it possible to control its resistivity) in which case it is called ″extrinsic″. If we take, for example, Silicon pure enough and we add an atom of Boron or Phosphorus for every 10^5 atoms of silicon, its resistivity decreases from 10^3 to approximately 10^{-2} Ω.cm. Table (I.1) gives examples of semiconductor materials and compounds and the position of these elements in the Mendeleev periodic table of elements.

Columns		**Semiconductor**
IV		Ge, Si
III-V	Binary	GaAs, GaP, GaSb, InAs, InP, InSb
	Ternary	$Al_xGa_{1-x}As$, $GaAs_yP_{1-y}$
	Quaternary	$Al_xGa_{1-x}As_yP_{1-y}$
II-VI	Binary	CdS, HgTe, CdTe, ZnTe, ZnS
	Ternary	$Cd_xHg_{1-x}Te$

Table I.1. Examples of semiconductors.

I.2. Column IV semiconductors (Si and Ge) – diamond structure

The electrons of an isolated atom take a discrete energy level and each level of energy can accommodate a limited number of electrons. This number is equal to $2n^2$ where n corresponds to the level number (layer) starting from the core. The electrons are distributed into first occupying the levels closest to the nucleus (which corresponds to the minimum energy).

In the case of Silicon, which has an atomic number Z equal to 14, there will be 2 electrons on the first layer (complete), 8 on the second (also complete) and 4 on the last which is not full, since it can accomodate up to 18 electrons. Figure (I.1.a) gives a representation of energy levels and their occupying electrons . This representation is simplified in figure (I.1.b) by considering only the four ″peripheral″ electrons of the outer layer (which will participate in the bonds between atoms).

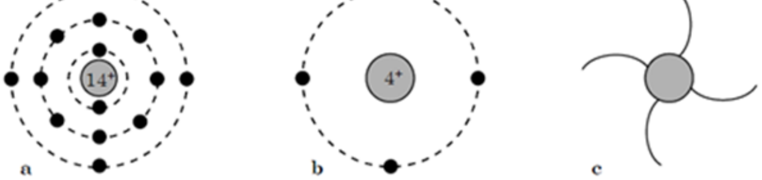


Figure I.1. Representations of the Silicon atom showing: a. Energy levels and their occupying electrons. b. The last level of energy. c. The four possible covalent bonds.

A chemical element has a great stability when it has eight electrons on its outer orbital (structure of rare gases), which is not the case for the isolated silicon atom. During the formation of the crystal, the silicon atom will “gain” four electrons by forming covalent bonds, which correspond to “share” of its peripheral electrons with the neighboring atoms. Thus, the silicon atom, which associates with four other silicon atoms, “will see” eight electrons on its last orbital. Such association is illustrated in figure (I.2). If no bond is broken (for example at 0 K), there are no electrons free, and therefore the crystal is insulating.

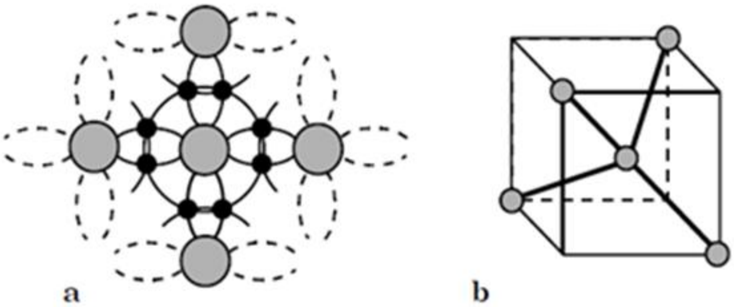


Figure I.2. Representation of the Silicon atom association with its four neighbors: a. In plane projection. b. In three dimensions.

The cubic system, in which silicon, germanium (as well as C, Sn) crystallize is the diamond lattice consisting of interfere of two face-centered cubic lattices (offset with a quarter of the main diagonal of the cube).

I.3. Energy Bands

The electrons of an isolated atom take discrete energy levels (figure (I.3)), which are made up of levels (or sub-levels); but when we bring two atoms together, these levels (or sub-levels) will split. By extending this reasoning to N atoms, this “degeneration” reveals bands of permitted energy, which can “interpenetrate” and separate again when the inter-atomic distance decreases (see Fig. (I.3)), giving forbidden energy bands, of width E_G (″Gap″). Table (I.2) gives some examples of forbidden band width as well as inter-atomic distances.

atom	**E G (eV)**	**type of materials**	**d (Å)**
C (Carbone)	5,5	Insulator	3,567
Si (Silicon)	1,1	semiconductor	5,431
Ge (Germanium)	0,7	semiconductor	5,646
Sn (Tin)	0	conductor	6,489

Table II.2. Example of the gap values and the inter-atomic distance ("the lattice constant″ = edge of the lattice cube "a" = (4 /√3)× distance to nearest neighbor).

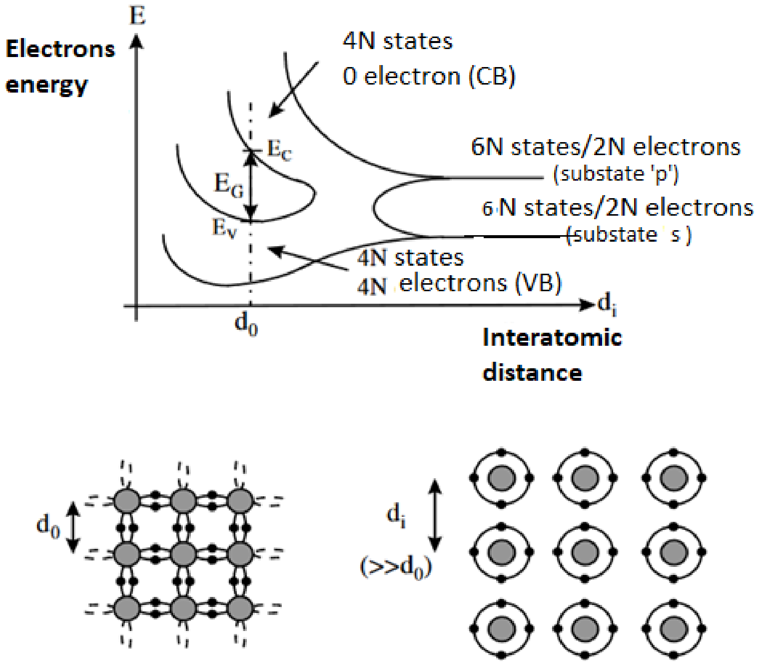


Figure I.3. Appearance of valence, conduction and forbidden band with the decrease in inter-atomic distance for a material of the column IV, when N identical atoms are brought together.

Figure (I.3) illustrates the case of group IV semiconductors (Silicon for example): the upper band is called ″Conduction Band″ and, at 0 K, contains no electrons unlike the lower band, called the ″Valence Band″, which contains 4N electrons (which is the last full band). Between these two bands, there is an area with E_G width (in J or eV) prohibited to electrons and called ″ Forbidden Band ″ or ″Gap″. The fact that these two bands (CB or VB) are completely empty or full implies that electrical conduction cannot exist. For a temperature different from 0 K, an electron from the VB can receive enough energy to pass into the CB (a ″hole″ appears in the VB) and makes the electrical conduction possible. The material is no longer insulating; but the more E_G will be greater plus the number of ″carriers free″ (electrons in the CB or holes in the VB) will be weak, and the more the material will be insulating.

I.4. Direct and indirect gap

The curves $E_{C,V}\,(\vec{k})$ also called "dispersion relations", where k is the wave vector associated to the electron (momentum $\vec{p} = m\vec{v} = \hbar\vec{k}$), reveal two types of semiconductors: the first type is the direct gap semiconductor; where the bottom of the conduction band E_C, and the top of the valence band E_V occur at the same value of $\vec{k}$,. The other semiconductor type is called SC with an indirect gap (see figure I.4).

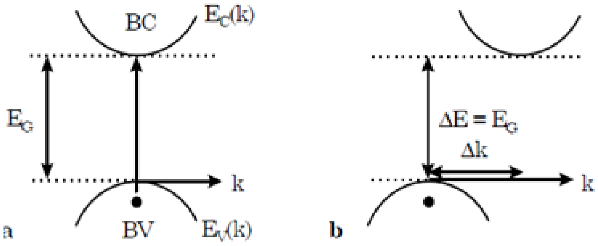


Figure II.4.a. Direct gap semiconductor. b. Indirect gap semiconductor.

The nature of the gap plays a fundamental role in the interaction of the semiconductor with an electromagnetic radiation (in particular light), and therefore in the functioning of optoelectronics components. We can notice that, in a SC with a direct gap, an electron from the top of the VB which acquires energy E_G passes into the CB without a change in the momentum ($\Delta p = \hbar\Delta k = 0$) which is not the case in an indirect gap SC.

I.5. Conduction by electrons or holes

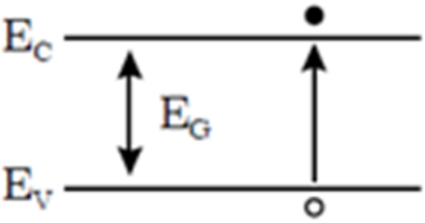


Figure I.5. Transition of an electron from the VB to the CB.

We can break a valence bond if we provide sufficient energy (thermal or light): one or more electrons, which engaged in these bonds, are extracted. In the energy band model used, the one or more electrons pass from the valence band to a state located in the conduction band (at a level depending to the energy supply): the electron is "free" (it no longer participates in a crystalline bond) and on the other hand, it can, participate in electrical conduction, see figure (I.5). It behaves like "almost-free" particle in the semiconductor because it is subject to the influence of lattice. We represent this "almost-free" particle (electron) by a free "almost-particle" and assigning it an "effective" mass m_n different from the mass m_0 ($0.91\text{x}10^{-30}$ kg) of the free electron in vacuum.

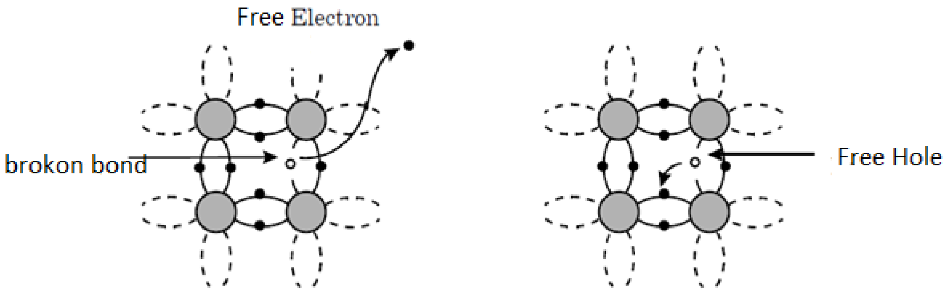


Figure I.6. Free electron and free hole appearance during a covalent bond broken.

At the same time as a free electron appears in the conduction band (becoming free by breaking a bond), a hole (empty place) appears in the valence band (corresponding to an unsecured bond) which can be occupied by another electron of the VB (participant previously to another covalent bond). This phenomenon is illustrated in figure (II.9). At this empty place (called hole) is assigned a positive charge +q (its movement will be opposite to that of electrons when an electric field is applied). The valence band being always almost full (of N-1 valence electrons), the study of the movement of particles in this band will be simplified by only considering the movement of the hole to which we will assign an effective mass m_h.

Holes and electrons constitute the intrinsic free carriers, whose number depends on temperature. The electrical neutrality of the material requires that the holes and electrons have identical numbers (ni and pi).

For pure silicon at 300 K, we measure: ni = pi = $1.5\text{x}10^{10}$ cm^{-3}. This number is very low if we compare it to the number of atoms.

For pure silicon at 300 K, the mobilities are: $\mu_n = 12{,}10^{6}.\text{m}^2\text{V}^{-1}\text{s}^{-1}$ and $\mu_h = 5{,}10^{6}.\text{m}^2\text{V}^{-1}\text{s}^{-1}$.

The intrinsic conductivity of the material $\sigma = q\ (ni.\mu_n + pi.\mu_p)$ is very low.

I.6 Density of states:

We can calculate the number of “places” available (occupied or not) by electrons (in the CB) and holes (in the VB). This “density of states” is obtained for example for electrons (in the CB) by writing:

$n_C(E)dE$ = number of states (m^{-3}) in the interval of energy E, E + dE

$$\boldsymbol{n_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_n}{\hbar^2}\right)^{3/2}(E - E_c)^{1/2}} \qquad \textbf{Eq. (I.1)}$$

Likewise, for holes in the valence band, we obtain as density of states:

$$\boldsymbol{n_v(E) = \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2}(E_v - E\ \ )^{1/2}} \qquad \textbf{Eq. (I.2)}$$

I.7. Undoped and doped semiconductors.

I.7.1. Undoped (intrinsic) semiconductors

A semiconductor is said intrinsic when the crystal is not doped (voluntarily or not) by impurities that can change the concentration of free carriers. For a temperature different from 0 K, electrons can become “free” which means, it can pass from the valence band to the conduction band, where their concentration is denoted n. These electrons leave holes in the BV (with a concentration noted p) which are also free to move. The concentrations of n and p are equal. For this particular case, we define an intrinsic concentration n_i (equal to the concentrations n and p) for which we will show later being given by the relation:

$$n = p = n_i(T) = AT^{3/2}\exp\left(-\frac{E_G}{2KT}\right) \qquad \textbf{Eq. (I.3)}$$

where A is a specific constant of the material.

Equation (I.3), illustrated in figures (I.7.a) for silicon, germanium and GaAs. The figure reflects that the more temperature increases the more thermal energy increases, and as a result, more electrons cross the forbidden band and hence their density increases. But for semiconductors with a higher gap (E_G), the energy that electrons acquire becomes important. This remark implies that a wide gap material has better temperature stability which makes it interesting for power electronics.

Figure I.7 a or b shows that as a first approximation $\ln(n_i)$ as a function of (1/T) is a straight line of a (– EG/2k) slope which gives the possibility to deduce experimentally EG.

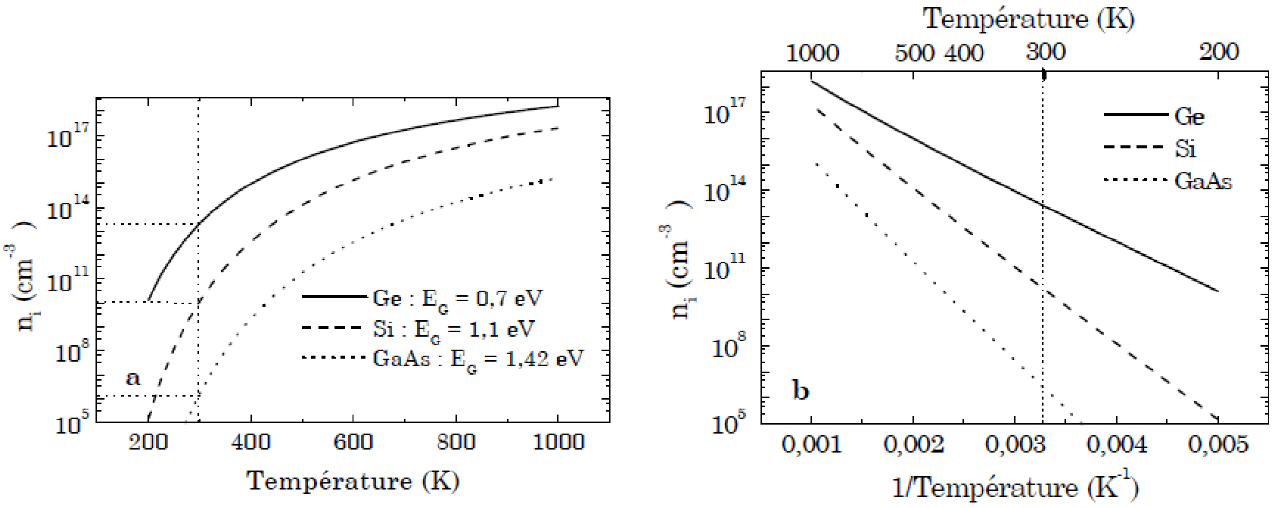


Figure I.7. Evolution of the intrinsic concentration in semi-log representation for silicon, germanium and GaAs: a. Dependence on temperature. b. Dependence on the inverse of temperature.

I.7.2. Doped semiconductors (extrinsic)

The introduction of certain impurities into a semiconductor material makes it possible to modify the number of free carriers, to choose the type of conduction (by electrons or by holes) and to control the conductivity.

I.7.2.1 n-type semiconductor

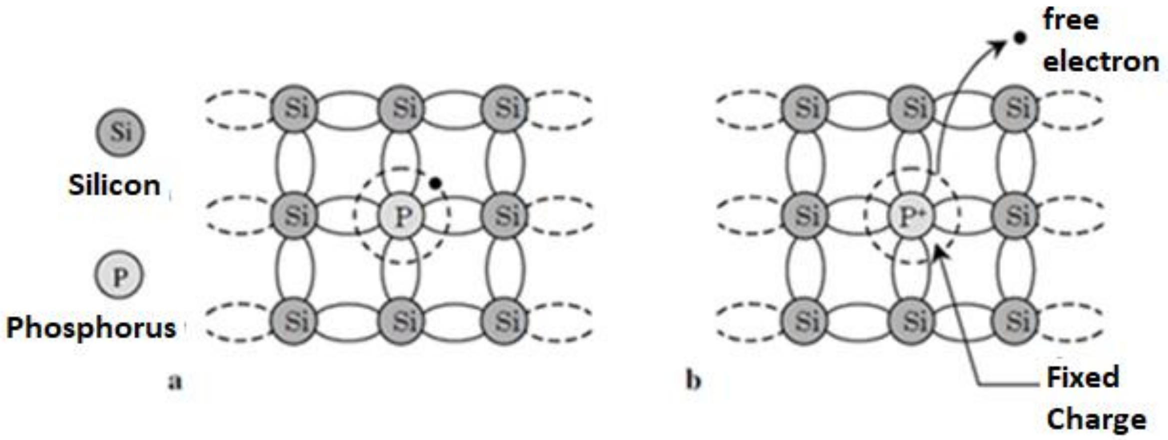


Figure I.8. Silicon doped with phosphorus: a. T = 0 K, b. T≠ 0 K.

For **n-type semiconductors**, atoms (or impurities) of donor (electron) type have been introduced (generally in small quantities) to favor conduction by electrons rather than by holes. The atoms can be from column V if the semiconductor is from the IV column. Figure (I.8.) gives the example of silicon doped with phosphorus which has five electrons in the outer orbital.

Each four neighboring silicon atoms share one electron with the phosphorus atom, which itself shares four of its five peripheral electrons. A low energy (0.04 eV), for example, due to a temperature different from 0 K, can '**release**' the fifth electron of the phosphorus atom (figure (I.8.b)) which then finds itself ionized positively (fixed charge).

This phenomenon corresponds to the appearance of an energy level E_D in the forbidden band (with E_C - E_D = 0.04 eV), shown in figure (I.9). Donor atoms are gradually ionized with the increase in temperature and from of approximately 50 K all impurities are ionized. The concentration n_0 in electrons (called concentration of **majority** carriers) will then be equal to the concentration of doping N_D ($n_0 = N_D >> ni >> p_0$ concentration of holes, minorities) as long as the intrinsic behavior of the material does not take over (equation (I.3)) if the temperature is greater than 500 K the electron concentration temperature dependent will re-appear.

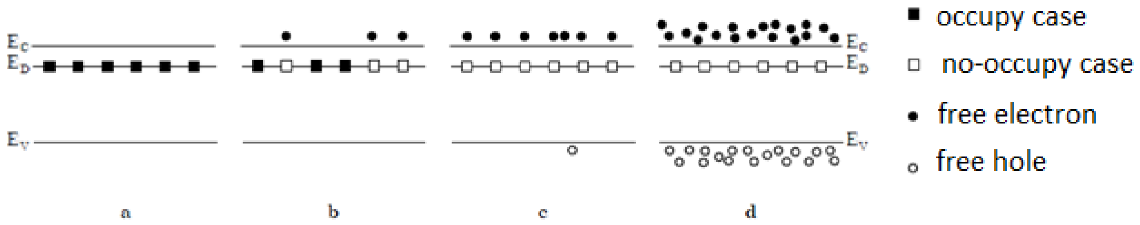


Figure I.9 Band diagrams showing the energy level of states type donor and their occupation. a. T0 = 0 K, $n_0 = p_0 = 0$, b. 0 < T1 < 50 K, impurities ionize, c. 50 K < T2 < 500 K, $n_0 \approx N_D >> n_i(T2) >> p_0$, and d. T3 > 500 K, n0 ≈ p0 ≈ ni(T3).

I.7.2.2 p-type semiconductor

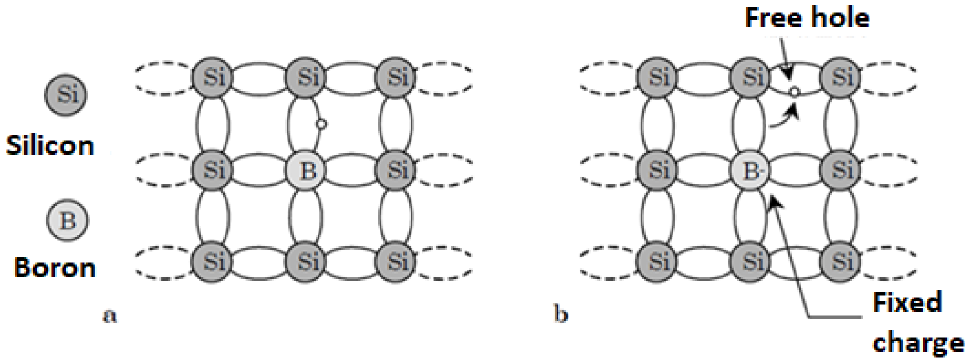


Figure I.10. Silicon doped with Boron: a. T = 0 K, b. T≠ 0 K.

In this case, the impurities are electron acceptor type which corresponds to the atoms of column III for a semiconductor made up of atoms from column IV. Figure (I.10) gives an overview of what happens to a silicon crystal into which boron atoms have been introduced.

The association with its four neighbors gives the boron atom seven electrons on the external orbital, which is insufficient to make it stable and it is then tempted to steal one by one close neighbor who himself can take one from one of his neighbors and so on.

For this, a minimum input of energy is required which can be provided by the thermal vibrations of the crystal; boron finds itself negatively ionized (fixed charge) and we witness a movement of a hole (free) from atom to atom. The concentration of holes p_0 (majority carriers) is equal to the N_A doping concentration ($p_0 = N_A >> ni >> n_0$). From a temperature of the order of 50 K; the intrinsic character becomes dominant again beyond approximately 500 K (equation (I.3)).

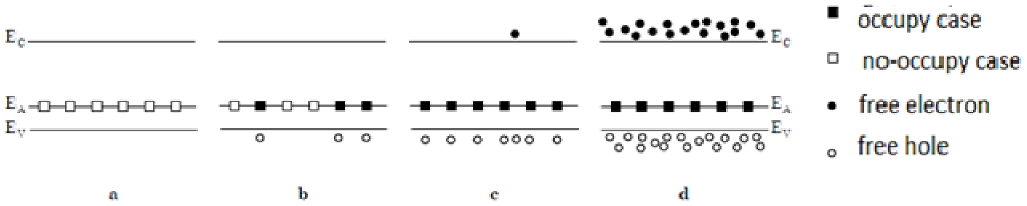


Figure I.11. Band diagrams showing the energy level of type states acceptor and their occupation: a. T0 = 0K, $n_0 = p_0 = 0$, b. 0 < T1 < 50 K, the impurities ionize, c. 50 K < T2 < 500K, $p_0 = N_A >> n_i(T2) >> n_0$, and d. T3 > 500 K, $n_0 \approx p_0 \approx ni(T3)$.

I.7.3. Compensated semiconductor

Doping (or even deep) impurities of different types can compensate each other, partially or totally. The semiconductor will have the type of the dominant impurity. If we arrive to compensate perfectly ($N_A = N_D$), we then obtain an intrinsic semiconductor by compensation (...although it contains doping impurities).

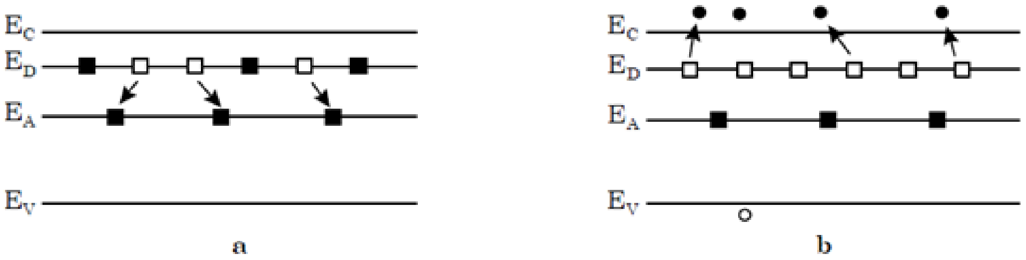


Figure I.12. Band diagram of a partially compensated n-type semiconductor ($N_A < N_D$): a. T0 = 0K, b. T1 > 50 K: the equivalent doping (at ambient temperature) is ($N_D - N_A$) =n_0.

Remarks:

The minimum doping depends on the refinement of the material; for example, in silicon residual boron concentrations of approximately 10^{13} atoms per cm^3 are observed, so the intrinsic silicon at room temperature (where ni (10^{10} cm^{-3}) is very difficult to obtain. On the other hand, certain (metallic) impurities or defects in the crystal lattice give energy levels closer to the middle of the forbidden band which is of little interest to doping level but is likely to modify the recombination properties; it is said that these '**deep**' levels constitute '**recombination centers'.**

We also remind that during any transition between energy levels, laws of the energy and momentum conservation must be applied and the momentum associated with a photon:

$$p_{ph} = mc = \frac{mc^2}{c} = \frac{E_{ph}}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} = \hbar k_{ph} \qquad \textbf{(Eq. I.4)}$$

I.8. Semiconductors in equilibrium

I.8.1. Concentration of free charges

We consider that a semiconductor is not degenerate, i.e. the Fermi level remains in the forbidden band at equilibrium, the concentration of the free electrons n_0 in the conduction band:

$$n_0 = N_c \exp\left(-\frac{E_c - E_f}{kT}\right) \qquad \textbf{Eq. (I.5)}$$

Where $N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$

N_C (cm^{-3}) is the equivalent density of states in the conduction band.

The concentration of the free holes n_0 in the conduction band:

$$p_0 = N_v \exp\left(-\frac{E_f - E_v}{kT}\right) \qquad \textbf{Eq. (I.6)}$$

where $N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$

N_v (cm^{-3}) is the equivalent density of states in the valance band.

I.8.1.1. Mass law:

By multiplying the electron density by the hole density (equations (I.5) and (I.6)) we obtains a result independent of the position of the Fermi level (and therefore of doping). This law is called "law of mass action":

$$p_0.n_0 = N_v N_c \exp\left(-\frac{E_c - E_v}{kT}\right) = N_v N_c \exp\left(-\frac{E_G}{kT}\right) \qquad \textbf{Eq. (I.7)}$$

In an intrinsic semiconductor the concentrations of free carriers are equal to the intrinsic concentration of carriers ni what makes it possible to write:

$$n_i = p_0 = n_0 = N_c \exp\left(-\frac{E_c - E_{fi}}{kT}\right) \qquad \textbf{Eq. (I.8)}$$

With the equation (I.7), we can write:

$$p_0.n_0 = N_v N_c \exp\left(-\frac{E_G}{kT}\right) = n_i^2(T) \qquad \textbf{Eq. (I.9)}$$

This result makes it possible to present the intrinsic concentration of carriers in the form (already indicated: equation (I.3)):

$$n_i = \sqrt{N_v N_c} \exp\left(-\frac{E_G}{2kT}\right) \propto T^{3/2} \exp\left(-\frac{E_G}{kT}\right) \qquad \textbf{Eq. (I.10)}$$

Because $N_{c,v} \propto \left(m_{e,h} T\right)^{3/2}$

We also express the Fermi level as a function of N_C and N_V by equaling ni and n_0 or p_0.

$$N_c \exp\left(-\frac{E_c-E_{fi}}{kT}\right) = \sqrt{N_v N_c}\exp\left(-\frac{E_c-E_v}{2kT}\right)$$

$$E_{Fi} = \frac{E_C+E_v}{2} - \frac{kT}{2}\ln\left(\frac{N_c}{N_v}\right) = E_i - \frac{kT}{2}\ln\left(\frac{N_c}{N_v}\right) \simeq E_i \qquad \textbf{Eq. (I.11)}$$

Where E_i is the middle of the forbidden band. $E_i = \frac{E_C+E_v}{2}$

We express the density n_0 as a function of ni by using the equation (I.5):

$$n_0 = N_c \exp\left(-\frac{E_c-E_{fi}}{kT}\right)\exp\left(-\frac{E_{fi}-E_f}{kT}\right) = n_i(T)\exp\left(-\frac{E_{fi}-E_f}{kT}\right) \qquad \textbf{Eq. (I.12)}$$

The density p_0 as a function of ni:

$$p_0 = N_v \exp\left(\frac{E_v-E_{fi}}{kT}\right)\exp\left(\frac{E_{fi}-E_f}{kT}\right) = n_i(T)\exp\left(\frac{E_{fi}-E_f}{kT}\right) = \frac{n_i(T)^2}{n_0} \qquad \textbf{Eq. (I.13)}$$

I.9. Study of non-equilibrium semiconductors

I.9.1. Definition of a non-equilibrium semiconductor

In a semiconductor material and in the absence of an electric field, the overall current created by the free electrons and holes is zero. When the semiconductor is subjected to an external electric field ($E \neq 0$) its behavior is completely different. Indeed, the movement of electrons and holes under the effect of the electric field generates an electric current.

So, under the effect of the electric field:

- The free electron undergoes an electric force of the form;

$$\vec{F} = -q\vec{E} = m_e \frac{d\overrightarrow{v_e}}{dt} \qquad \textbf{Eq. (I.14)}$$

(m_e: is the effective mass of the free electron)

- The speed of the electron is given by; $\overrightarrow{v_e} = -\frac{q\tau}{m_e}\vec{E} = -\mu_n\vec{E}$ **Eq. (I.15)**

μ_n is electronic mobility; τ is the average time between two successive collisions.

I.9.2. Calculation of current densities in nonequilibrium semiconductors

I.9.2.1. Calculation of conduction current densities (mobility of charge carriers)

The current density created by the electrons is given by the relation:

$$\overrightarrow{J_e} = +n\ q\ \overrightarrow{v_e} \qquad \textbf{Eq. (I.16)}$$

With: n the electron density

The current density is also written as a function of the conductivity σ_e and the electric field $\vec{E}$:

$$\overrightarrow{J_n} = n\ q\mu_n\ \vec{E} = \sigma_e\vec{E} \qquad \textbf{Eq. (I.17)}$$

It results from the relationships **Eq. (I.16)** and **Eq. (I.17)** :

$$\sigma_e = nq\ \mu_n \qquad \textbf{Eq. (I.18)}$$

And from the equation **Eq. (I.15),** we can write: $\frac{q\tau}{m_e} = \mu_n$

So : $\sigma_e = nq\ ^2\frac{\tau}{m_e}$ **Eq. (I.19)**

- In the same way, the current density created by the moving holes is written:

$$\overrightarrow{J_h} = p\ q\mu_p\ \vec{E} = \sigma_{hp}\vec{E} \qquad \textbf{Eq. (I.20)}$$

With: $\sigma_p = pq\ \mu_p = pq\ ^2\frac{\tau}{m_h}$ **Eq. (I.21)**

m_h: is the effective mass of the free hole.

The total conductivity (σ) is the sum of the two conductivities, of electrons ($\sigma_n)$) and of holes ($\sigma_p)$:

$$\sigma = \sigma_e + \sigma_p = n\ q\mu_n + pq\ \mu_p = q(n\ \mu_n + p\ \mu_p) \qquad \textbf{Eq. (I.22)}$$

In the case of an intrinsic semiconductor ($n=p=n_i$), the conductivity becomes:

$$\sigma = \sigma_n + \sigma_p = q\ n_i(\ \mu_n +\ \mu_p) \qquad \textbf{Eq. (I.23)}$$

I.9.2.2. Calculation of diffusion current density

The appearance of a carrier gradient in a material (in the case of a semiconductor non-homogeneous or during local excitation...) generates a flow of these carriers in the direction inverse of the gradient. Indeed, in a place where the concentration of carriers is very high, the interaction between the carriers is very large and the energy density is greater in this place than where the concentration of carriers is lower. To establish balance, carriers will “broadcast”.

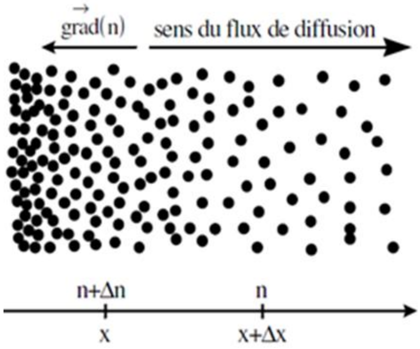


Figure I.13. The electrons concentration gradient generates a diffusion of these electrons towards the least concentrated area.

If we take the case of electrons (figure (I.13) in one dimension), the flow of carriers ($m^{-2}s^{-1}$) is given by Fick's law **Eq. (I.24)**:

$$\begin{cases} \overrightarrow{j_{Dn}} = (-q)\overrightarrow{flux\ n_n} = qD_n\overrightarrow{grad}(n) \\ \overrightarrow{j_{Dp}} = (q)\overrightarrow{flux\ p_p} = -qD_p\overrightarrow{grad}(p) \end{cases} \quad \textbf{Eq. (I.24)}$$

D_n and D_p are the diffusion constants of electrons and holes respectively.

The diffusion current in one dimension is written by (**Eq. (I.25)**):

$$\begin{cases} j_{\boldsymbol{Dn}} = qD_n\frac{dn}{dx} \\ j_{\boldsymbol{Dp}} = -qD_p\frac{dp}{dx} \end{cases} \quad \textbf{Eq. (I.25)}$$

Finally, the total diffusion current density (j_D) is the sum of the diffusion current densities created by electrons and holes:

$$j_{\boldsymbol{D}} = j_{\boldsymbol{Dn}} + j_{\boldsymbol{Dn}} = qD_n\overrightarrow{grad}(n) - qD_p\overrightarrow{grad}(p) \quad \textbf{Eq. (I.26)}$$

In the presence of an electric field ($\vec{E}$), the current densities are:

The current densities created by electrons:

$$\vec{J_n} = n\, q\mu_n\, \vec{E} + qD_n\overrightarrow{grad}(n) \qquad \textbf{Eq. (I.27)}$$

The current densities created by holes:

$$\vec{J_p} = p\, q\mu_p\, \vec{E} - qD_p\overrightarrow{grad}(p) \qquad \textbf{Eq. (I.28)}$$

I.9.3. Optical properties of a semiconductor

I.9.3.1. Spontaneous emission in a semiconductor

A semiconductor, at room temperature, is an insulator because its valence band is full while the conduction band is empty. If enough energy is transmitted to an electron, it passes from the valence band to the conduction band, leaving a hole in the valence band. The entire semiconductor is then no longer stable but excited. This instability is transient because the electron will come down by recombining with a hole. But during this recombination, the electron gives up energy whose nature can be radiative. If it is radiative, then there is emission of a photon. Figure (I.14).

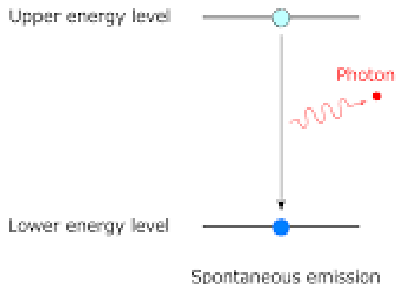


Figure I.14 Principle of spontaneous emission between two energy levels

I.9.3.2. Optical absorption in a semiconductor

Optical absorption occurs if a phonon transmits enough energy to an electron, this later move to a higher energy level. In the case of a semiconductor, the movement of the electron takes place from the valance band to the conduction band. This movement leads to the appearance of a hole in the valence band (figure I.15).

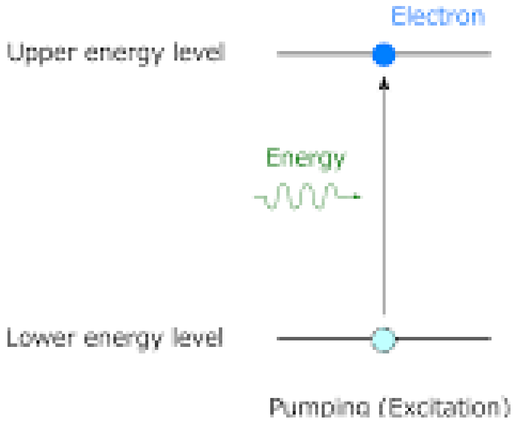


Figure (I.15) optical absorption of a photon in a semiconductor and creation of an electron-hole pair

I.10. Generation-Recombination Phenomenon

g' and r' are respectively be the number of charge carriers created per unit of volume and unit of time (cm^{-3}s^{-1}) and the number of charge carriers that disappear per unit of volume and time (cm-3s- 1).

The number of charge carriers created per unit of volume and unit of time g results on the one hand from spontaneous generation due to thermal agitation g_{th} called thermal generation rate and on the other hand from excitation by an external source (g) such as; optical excitation, particle irradiation, electric field, etc.

The number of charge carriers created per unit of volume and unit of time g is written:

$$g' = g + g_{th}$$ **Eq. (I.29)**

The number of charge carriers r' depends on the processes governing the recombination of excess charge carriers; it is a parameter specific to the material.

The variation in the density of charge carriers per unit of volume and unit of time is due to the generation – recombination processes produced under the effect of external excitation and thermal agitation, then:

$$\left(\frac{dn}{dt}\right)_{gr} = g' - r' = g + g_{th} - r' \qquad \textbf{Eq. (I.29)}$$

With : g : is the generation rate specific to external excitation.

g_{th} and r’: are material specific parameters at a given temperature

We pose: $r = r' - g_{th}$

This relationship represents the balance between recombination and thermal generation. R is a material-specific parameter, it represents the recombination rate.

The variation of the density of charge carriers per unit of volume and unit of time becomes:

$$\left(\frac{dn}{dt}\right)_{gr} = g - r \qquad \textbf{Eq. (I.30)}$$

I.11. Study of PN junctions

I.11.1 Definition of PN junctions

A PN junction is formed by the juxtaposition of a P-type doped semiconductor (called anode) and a N-type doped semiconductor (called cathode), both of them are from the same semiconductor single crystal (figure I.16). When these two types of semiconductors are brought into contact, a transient electrical regime is established on either side of the junction, followed by a permanent regime. A single junction forms a diode.

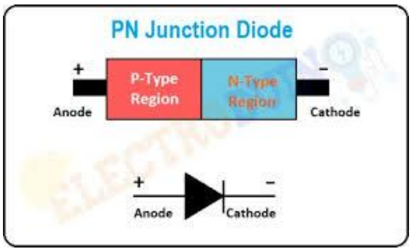


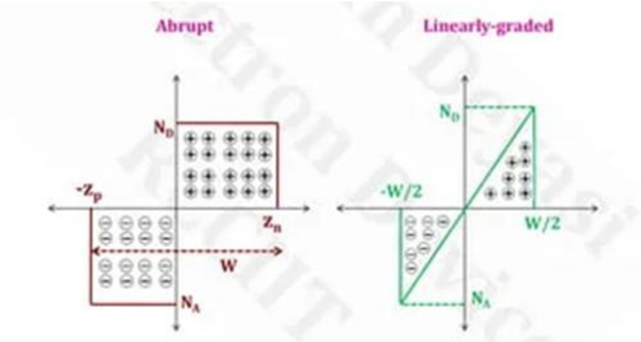
Figure I.16 PN junction

I.11.1.1. Abrupt PN junction:

In an abrupt junction, the concentration of impurities varies abruptly from the P-type doped region to the N-type doped region, i.e the Nd–Na difference passes abruptly at x = 0 from a negative value in the type P doped region to a positive value in the type N doped region, see figure (I.17.a).

I.11.1.2. Gradual junction:

In a graded junction, the impurity concentration is an x-dependent function around the contact region. That is to say, the difference (Nd–Na) depends on x between Xp and Xn, see figure (I.17.b). case of a linear dependence.



(a) **(b)**

Figure I.17 Evolution of the difference (Nd – Na); a) abrupt and b) gradual junctions.

I.11.2. Study of a non-polarized abrupt PN junction at equilibrium

I.11.2.1. The ideal pn junction:

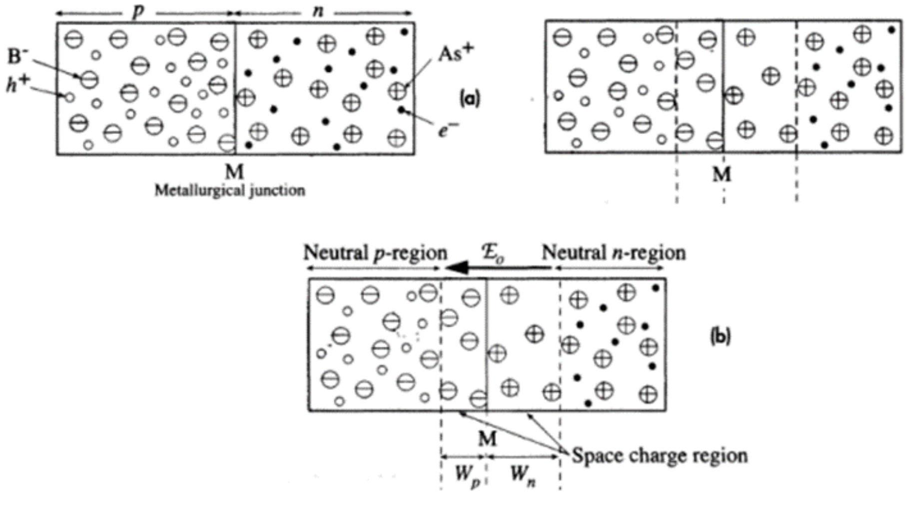


Figure I.18 PN junction

When two p-type and n-type semiconductors are brought into contact, holes, predominantly in the p-type region, diffuse towards the n-type region. It is the same for electrons, in the other direction (figure I.18-a). The diffusion of free carries on either side of the junction reveals a space charge resulting from the presence of ionized donors and acceptors, whose charges are no longer fully compensated by those of the free carriers.
An electric field is then established in the vicinity of the metallurgical junction which opposes the diffusion of the majority carriers. Thermodynamic equilibrium is established when the electric force, resulting from the appearance of the field, balances the diffusion force associated with the concentration gradients of free carriers.

I.11.2.2. Space charge

In order to simplify the writing, we will call Nd the excess of donors in the n-type region, Nd= $(Nd-Na)_n$ and Na the excess of acceptors in the p-type region, Na= $(Na-Nd)_p$.
The densities of free carriers in each of the regions are then given by:

$$\left.\begin{array}{ll} n_n=N_d & p_n=n_i^2/N_d \\ n_p=n_i^2/N_a & p_p=N_a \end{array}\right\} \quad n_p.p_p=n_i^2 \qquad \textbf{Eq. (I.31)}$$

By assuming all donors and acceptors are ionized, the space charge in each region of the junction is written:

$$\rho(x) = q[N_d - N_a + p(x) - n(x)] \qquad \textbf{Eq. (I.32)}$$

Due to the presence of the electric field, the diffusion-recombination of carriers is limited to the vicinity of the metallurgical junction. Far from the junction, the free carrier densities are given by expressions (**I.31**) and the semiconductor is neutral, ρ(x) = 0.

The space charge is shown in figure (I.19): on the n side the charge is positive because it results from the presence of ionized Nd donors; on the p side the negative charge results from the presence of the ionized Na acceptors. It should be noted that, since space charge results from recombination of electron-hole pairs, the total quantity of charge developed in each of the regions are equal.

Due to the presence of an intense electric field in the space charge region, the density of free carriers in this region is negligible. The actual space charge is shown in figure (I.19)

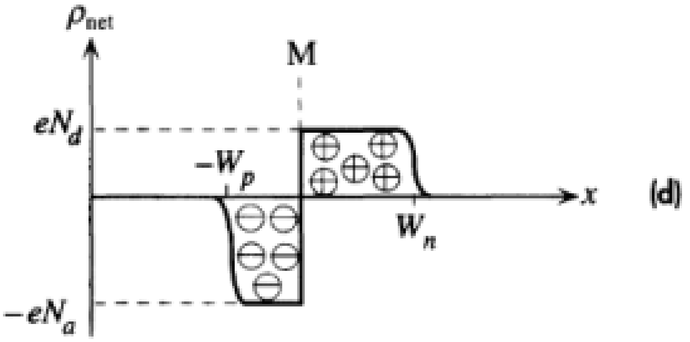


Figure I.19 The space charge

The charge density is written:

$$\left.\begin{array}{lll} \rho(x)=0 & \text{for } x<x_p & \text{and } x>x_n \\ \rho(x)=-qN_a & \text{for} & x_p<x<0 \\ \rho(x)=qN_d & for & 0<x<x_n \end{array}\right\} \quad \textbf{Eq. (I.33)}$$

I.11.2.3. Diffusion voltage

The presence of a space charge results in the existence of an electric field and a variation in potential. The potential varies from a value Vp in the p-type neutral region, to a value Vn in the n-type neutral region (Fig. I.20). The potential difference between these two regions constitutes a potential barrier which is called diffusion voltage, due to the fact that it is the barrier which balances the diffusion forces. $V_d = V_n - V_p$

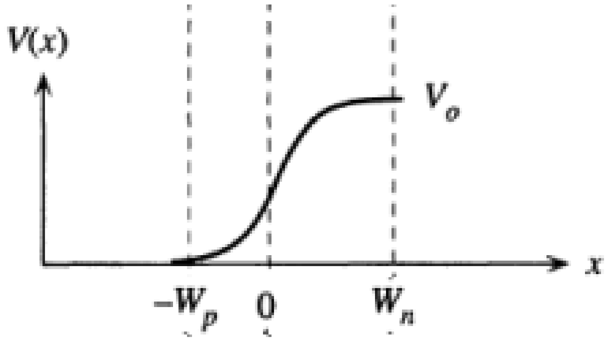


Figure I.20 Diffusion voltage

We can calculate the voltage V_d by writing that the Fermi level is the same throughout the structure. The electron densities in each region are written

$$n_n = N_c e^{-(E_{cn}-E_F)}/_{kT}$$ **Eq. (I.34)**

$$n_p = N_c e^{-(E_{cp}-E_F)/kT}$$ **Eq. (I.35)**

Which can write: $E_{cp} - E_{cn} = kTln\frac{n_n}{n_p} = kTln\frac{N_d N_a}{n_i^2}$ **Eq. (I.36)**

The energy difference E_{cp}-E_{cn} is the difference in potential energy of the electrons between the p-type region and the n-type region. Indeed, the electrons and holes participating in conduction being located at the ends of the bands, their kinetic energy is zero since the group speed is zero (extremum of the energy function) and all their energy is potential.

The diffusion voltage is therefore given by the expression:

$$V_d = \frac{kT}{q}\ln\frac{N_d N_a}{n_i^2}$$ **Eq. (I.37)**

For dopings used in practice and taking into account the values of ni at room temperature, the values of Vd are respectively of the order of 0.7 V and 0.35 V in silicon and germanium junctions respectively.

I.11.2.4 Potential and Electric field in the space charge region

To obtain the potential and electric field, it is sufficient to integrate the Poisson equation with the charge density given by equations (I.31):

$$\frac{d^2V}{d^2x} = -\frac{\rho(x)}{\varepsilon}$$ **Eq. (I.38)**

For $x_p<x<0$ the Poisson equation is written:

$$\frac{d^2V}{d^2x} = \frac{qN_a}{\varepsilon} \qquad d\left(\frac{dv}{dx}\right) = \frac{qN_a}{\varepsilon}dx \qquad \left(\frac{dv}{dx}\right) = \frac{qN_a}{\varepsilon}x + A$$

By integrating twice with the conditions E = 0 and V=Vp at x= xp we obtain:

$$-E = \frac{dv}{dx}$$

$$\frac{dV}{dx} = \frac{qN_a}{\varepsilon}(x - x_p)$$

$$V = \frac{qN_a}{2\varepsilon}(x - x_p)^2 + V_p \qquad \textbf{Eq. (I.39)}$$

For $0<x< x_n$ the Poisson equation is written:

$$\frac{d^2V}{d^2x} = -\frac{qN_d}{\varepsilon}$$

By integrating twice with the conditions E = 0 and V=Vn at $x= x_n$ we obtain:

$$\frac{dV}{dx} = \frac{-qN_d}{\varepsilon}(x - x_n)$$

$$V = -\frac{qN_d}{2\varepsilon}(x - x_n)^2 + V_n \qquad \textbf{Eq. (I.40)}$$

The electric field is directed along x and given by E = − dV/dx

For $x_p<x<0$ $$E = -\frac{qN_a}{\varepsilon}(x - x_p) \qquad \textbf{Eq. (I.41)}$$

For $0<x< x_n$ $$E = \frac{qN_d}{\varepsilon}(x - x_n) \qquad \textbf{Eq. (I.42)}$$

The variations of the electric potential and field are represented in figures (I.21.a and b).

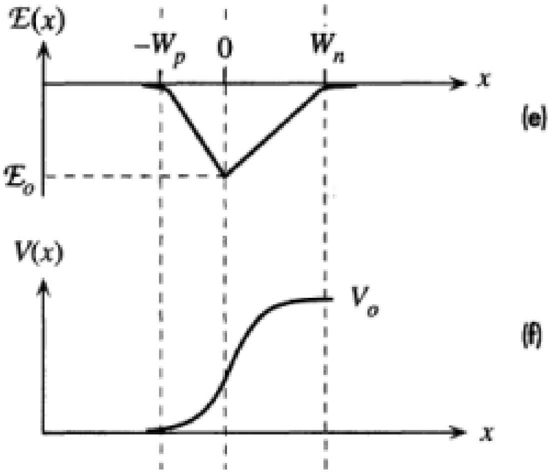


Figure I.21. The electric field and potential in the space charge region

I.11.2.5. Width of space charge area

The continuity at x = 0, of the normal component of the displacement vector D=εE, makes it possible to establish a relationship between x_n and x_p.

Let us write $\varepsilon E_{0+} = \varepsilon E_{0-}$

$$qN_a x_p = -qN_d x_n$$

We put $w_p = |x_p| = -x_p$ and $w_n = |x_n| = x_n$

$$N_a w_p = N_d w_n \qquad \textbf{Eq. (I.43)}$$

We obtain the expression for the width of the space charge zone by writing the continuity of the potential at x = 0.

$$\frac{qN_a}{2\varepsilon}(x_p)^2 + V_p = -\frac{qN_d}{2\varepsilon}(x_n)^2 + V_n$$

So: $V_d = V_n - V_p = \frac{q}{2\varepsilon}(N_a {w^2}_{p+} N_d {w^2}_n)$ **Eq. (I.44)**

Using the relation (I.34), this expression is written in one of the following forms:

$$V_d = \frac{qN_d}{2\varepsilon} {w^2}_n (1 + \frac{N_d}{N_a}) = \frac{qN_a}{2\varepsilon} {w^2}_p (1 + \frac{N_a}{N_d}) \qquad \textbf{Eq. (I.45)}$$

Which gives for Wn and Wp the expressions:

$$w_n^2 = \frac{2\varepsilon}{qN_d} \; \frac{1}{1+{}^{N_d}/_{N_a}} V_d \qquad w_n = \sqrt{\frac{2\varepsilon}{qN_d} \; \frac{1}{1+{}^{N_d}/_{N_a}} V_d} = \sqrt{\frac{2\varepsilon N_a}{qN_d} \; \frac{v_d}{N_a+N_d}} \qquad \textbf{Eq. (I.46.a)}$$

$$w_p^2 = \frac{2\varepsilon}{qN_a} \; \frac{1}{1+{}^{N_a}/_{N_d}} V_d \qquad w_p = \sqrt{\frac{2\varepsilon}{qN_a} \; \frac{1}{1+{}^{N_a}/_{N_d}} V_d} = \sqrt{\frac{2\varepsilon N_d}{qN_a} \; \frac{v_d}{N_a+N_d}} \qquad \textbf{Eq. (I.46.b)}$$

$$\boldsymbol{w = w_n + w_p} = \sqrt{\frac{2\varepsilon v_d}{q(N_a+N_d)} \left(\frac{N_a}{N_d} + \frac{N_d}{N_a}\right)} \qquad \textbf{Eq. (I.47)}$$

I.11.2.6. Polarized abrupt junction

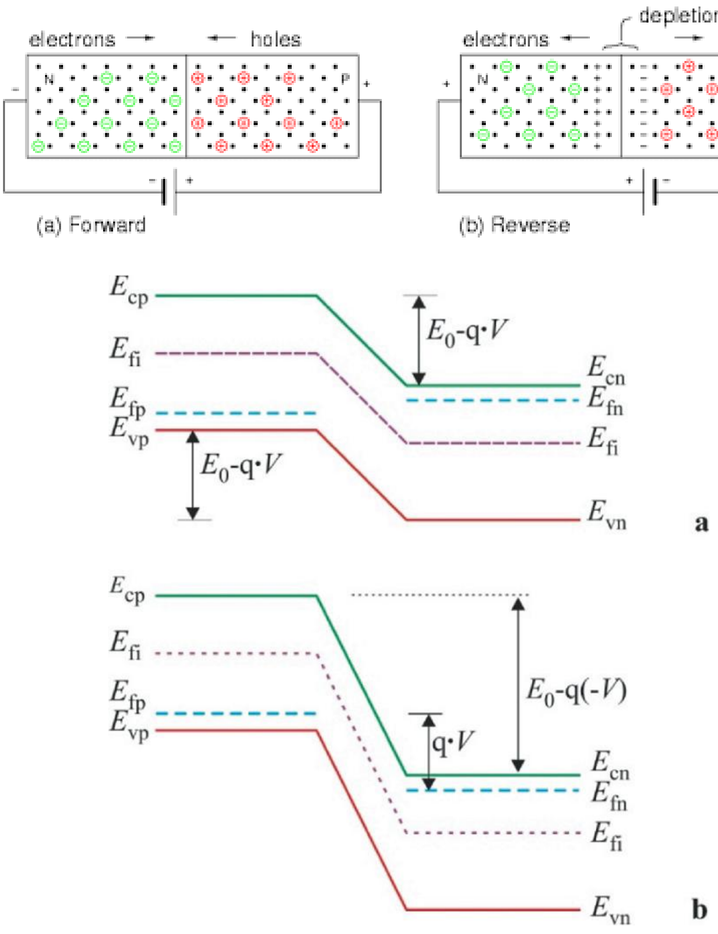


Figure I.22. Polarized abrupt junction

When the junction is polarized, the potential barrier is modified and consequently the diffusion of carriers from one region to another.

When the bias voltage V is positive, the potential difference between regions n and p at the junction becomes Vn− Vp= Vd−V (Fig. I.21b) and the height of the potential barrier becomes (Vd−V) (Fig. I.21.c). It is enough to observe the shift in Fermi levels in the neutral regions to explain this modification. The difference in Fermi levels in the neutral regions is the applied potential difference. Valence band and conduction band are positioned in the neutral regions with respect to the Fermi level depending on the doping. The potential barrier is no longer sufficient to stop the diffusion of carriers; electrons diffuse from region n to region p, and holes from region p to region n. The diode is forward biased, forward current flows from region p to region n.

When the bias voltage V is negative, the potential difference across the space charge zone is increased, Vn− Vp=Vd+ V (Fig. I.21-d), and the height of the potential barrier becomes (Vd+ V) (Fig. I.21.e). The balance between the conduction current and the diffusion current is broken but this time in favor of the conduction current. The diffusion of the majority carriers is blocked, only the minority carriers which reach the space charge zone pass into the opposite region, propelled by the electric field. The diode is reverse biased, the reverse current flows from region n to region p. Due to the differences in densities between the majority carriers and the minority carriers, the reverse current is considerably lower than the forward current.

I.11.2.6.1 I(V) properties in a polarized pn junction

A voltage applied to a pn junction will disturb the balance between the diffusion current and the conduction current of the electrons and holes.

a. Under forward bias, the applied voltage reduces the electrostatic potential barrier across the deletion region (Fig. I.22.a).

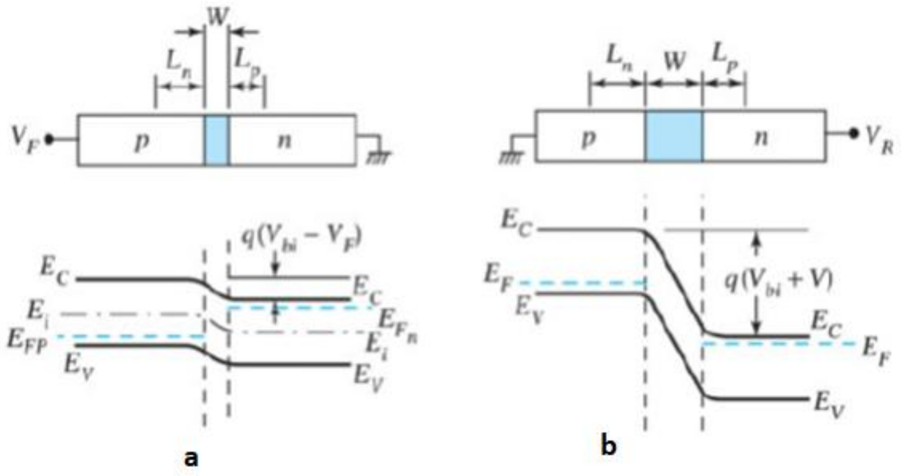


Figure I.22. The depletion zone, and band energy diagram. (a) Direct polarization. (b) Indirect polarization

The electrons, at a high energy level in the conduction band on the (n) side, have enough energy to overcome the reduced barrier and diffuse from the n side to the P.

Similarly, holes in the valence band on the p side diffuse towards the valence band on the n side.

Therefore, injections of minority charge carriers occur, that is, electrons are injected into the p side, while holes are injected into the n side.

Under indirect polarization

The applied indirect voltage increases the electrostatic potential barrier across the depletion region (Fig. I.22b). This significantly reduces diffusion currents.

For the conduction current, it is almost the same despite the change in potential barrier. Because the concentrations of the minority electrons or holes in the p or n side are low, the conduction current mainly depends on the number of minority carriers.

In the following paragraph, we consider the ideal properties (voltage – current); i.e. we did not take the phenomena of generation, recombination and other effects.

$$V_d = \frac{kT}{q}\ln\frac{p_{p0}n_{n0}}{n_i^2} = \frac{kT}{q}\ln\frac{n_{n0}}{n_{p0}} \qquad\qquad p_{p0}n_{p0} = n_i^2$$

We can write:

$$n_{n0} = n_{p0}e^{qv_d/kT} \qquad \textbf{Eq. (I.48)}$$

$$p_{p0} = p_{n0}e^{qv_d/kT} \qquad \textbf{Eq. (I.49)}$$

Under an applied polarization, we can write:

$$n_n = n_p e^{q(v_d-v)/kT} \qquad \textbf{Eq. (I.50)}$$

n_n and n_p are the densities of non-equilibrium electrons in the vicinity of the depletion zone in regions n and p respectively, with V positive for direct polarization and negative for indirect polarization. For a weak injection condition, the density of the injected minority charge carriers is low compared to the density of the majority charge carriers so we can write: $n_n \approx n_{n0}$. We replace equation (**(I.48)** in equation **Eq. (I.50)**:

$$n_{p0}e^{qv_d/kT} = n_p e^{q(v_d-v)/kT} \quad \Longrightarrow \quad n_p = n_{p0}e^{qv/kT}$$

$$n_p - n_{p0} = n_{p0}(e^{qv/kT} - 1) \qquad \textbf{Eq. (I.51)}$$

In the same way we find:

$$p_n = p_{n0}e^{qv/kT} \qquad \textbf{Eq. (I.52)}$$

$$p_{n-}p_{n0} = p_{n0}(e^{qv}/_{kT} - 1)$$ **Eq. (I.53)**

In a junction where the diffusion length of minority charge carriers is very small compared to the length of zones n and p, the hole current in region n and the electron current in region p are given respectively by:

$$j_p(x) = \frac{qD_p p_{n0}}{L_p}\left(e^{qv}/_{kT} - 1\right)$$ **Eq. (I.54)**

$$j_n(x) = \frac{qD_n n_{p0}}{L_n}\left(e^{qv}/_{kT} - 1\right)$$ **Eq. (I.55)**

With: $L_n = \sqrt{D_n \tau_n}$ is the electron diffusion length in zone p, Dn is the electron diffusion constant.

$L_p = \sqrt{D_p \tau_p}$ is the hole diffusion length in zone n, Dp is the hole diffusion constant.

The total current is (figure I.23):

$$j = j_p(x_n) + j_n(-x_p) = j_s\left(e^{qv}/_{kT} - 1\right)$$ **Eq. (I.56)**

j_s is the saturation current:

$$j_s = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}$$ **Eq. (I.57)**

E can use the Einstein equation:

$$D_n = (\frac{kT}{q})\mu_n \quad and \quad D_p = (\frac{kT}{q})\mu_p$$ **Eq. (I.58)**

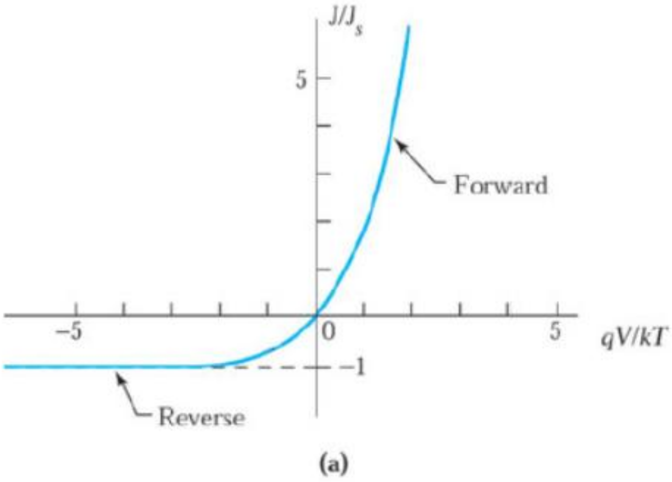


Figure I.23. The total current

LIGHT EMITTING DIODES (LED)

II.1 LED principles

A light emitting diode (LED) is essentially a pn junction diode typically made from a direct band gap semiconductor for example GaAs, in which the Electron-hole pair (EHP) recombination results in the emission of a photon. The emitted photon energy hν is approximately equal to the band gap energy Eg.

$$\lambda(nm) = \frac{hc}{E_g(eV)} = \frac{1240}{E_g(eV)} \qquad \textbf{Eq. (II.1)}$$

Figure II.1.a shows the energy band diagram of an unbiased pn+ junction device in which the n-side is more heavily doped than the p-side.

The Fermi level E_F is uniform through the device, which is a requirement of equilibrium with no applied bias; $E_{Fn} = E_{Fp}$. The depletion region extends mainly into the p-side.

There is a potential energy (PE) barrier (qVo) from Ec on the n-side to Ec on the p-side where Vo is the built-in voltage.

The potential energy (PE) barrier eVo prevents the diffusion of electrons from the n-side to the p-side.

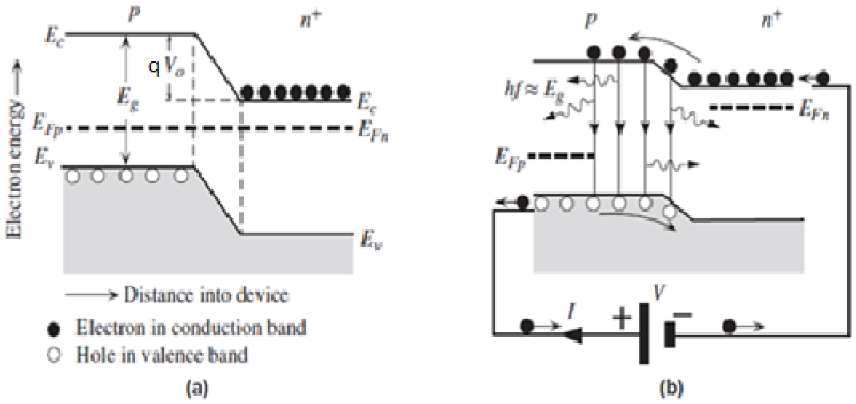


Figure II.1 Energy band diagram of a pn (heavily n-type doped) junction. (a) No bias voltage. The p-layer is usually thin. (b) With forward bias V. Direct recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission. The Fermi levels are separated and $E_{Fn} - E_{Fp} = qV$.

When a forward bias V is applied, the built-in potential Vo is reduced to Vo − V, which then allows the electrons from the n+-side to diffuse, that is, become injected, into the p-side as depicted in Figure II.1.b.

The hole injection component from p into the n+-side is much smaller than the electron injection component from the n+-side to the p-side. The recombination of injected electrons in the depletion region and within a volume extending over the electron diffusion length L_e in the p-side leads to photon emission. The phenomenon of light emission from the Electron Hole Pairs recombination as a result of minority carrier injection is called injection electroluminescence.

Due to the statistical nature of the recombination process between electrons and holes, the emitted photons are in random directions; they result from spontaneous recombination processes between electrons and holes. Such spontaneous direct recombination processes result in spontaneous photon emission. The emitted photon has an energy that is roughly equal to the band gap that is $h\nu \approx E_g$.

The LED structure has to be such that the emitted photons can escape the device without being reabsorbed by the semiconductor material. This means the p-side has to be sufficiently narrow or we have to use heterostructure devices as discussed below.

One very simple LED structure is shown in figure II.2. First a doped semiconductor n type layer is grown on suitable substrate (GaAs or GaP). The substrate is essentially a sufficient thick crystal that serves as mechanical support for the pn junction device and can be of different crystal. The pn^+ junction is formed by growing another layer but doped p-type. Those photons that are emitted toward the n-side become either absorbed or reflected back at the substrate interface.

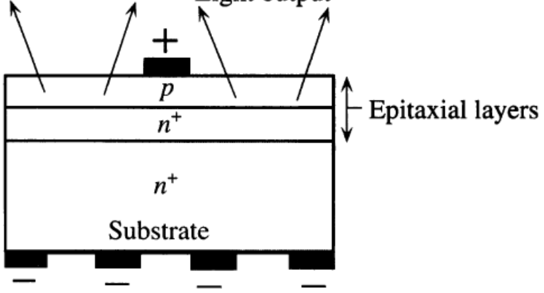


Figure II.2 Schematic illustration of one possible LED device structure. First an n+ layer is grown on a substrate; A thin p layer is then grown on the first layer.

If the layer and the substrate have different crystal lattice parameters, then there is mismatch between the two crystals structures. This causes lattice strain in the LED layer and hence leads to crystal defects. Such crystal defects encourage radiation less EHP recombination. For example, one of the AlGaAs alloys is a direct band gap semiconductor that has a band gap in the red emission region. It can be grown on GaAs substrates with excellent lattice match which results in high-efficiency LED devices.

II.2 LED materials and structures

There are various direct band gap semiconductor materials that can be readily doped to make commercial pn junction LEDs which emit radiation in the red and infrared range of wavelengths. III–V ternary alloys based on alloying GaAs and GaP and denoted as $GaAs_{1-y}P_y$ represent an important class of commercial semiconductor materials that covers the visible spectrum. In this compound, As and P atoms from Group V are distributed randomly at normal As sites in the GaAs crystal structure.

When $y < 0.45$, the alloy $GaAs_{1-y}P_y$ is a direct band gap semiconductor and hence the EHP recombination process is direct as shown in Figure II.3a. The rate of recombination is directly proportional to the product of electron and hole concentrations.

The emitted wavelengths range from about 630 nm, red, for $y = 0.45$ ($GaAs_{0.55}P_{0.45}$) to 870 nm for $y = 0$ (GaAs).

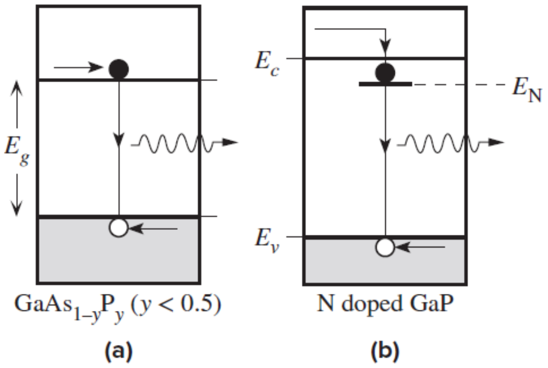
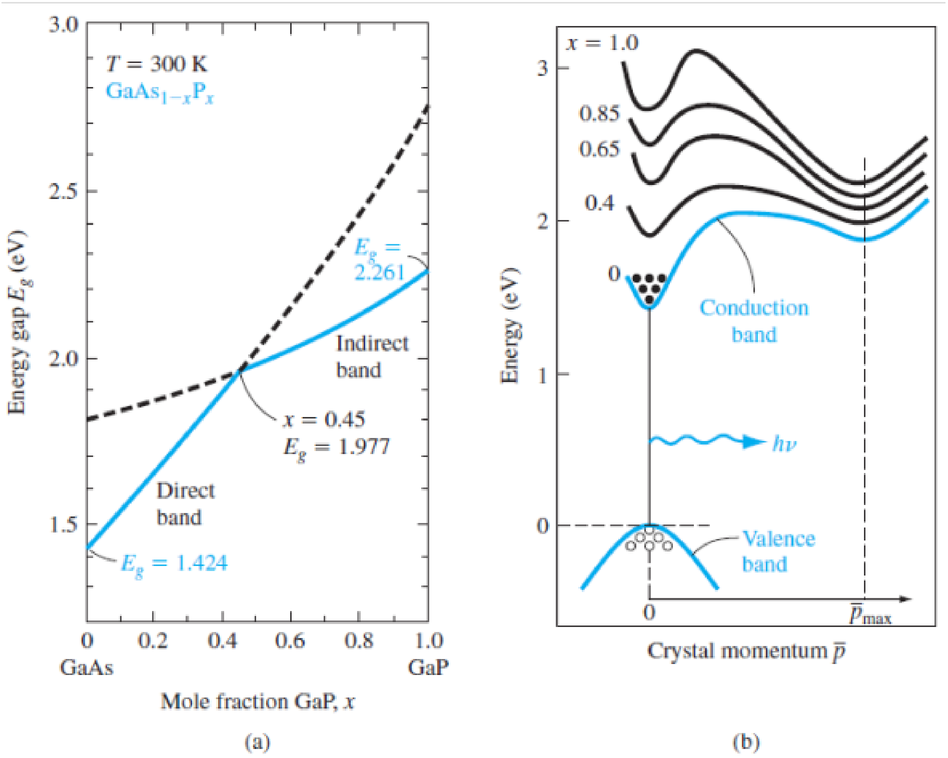


Figure II.3 GaAs1-yPy LED ; (a) Direct band gap for y<0.5, (b) Indirect band gap fory≥0.5

$GaAs_{1-y}P_y$ alloys (which include GaP) with $y > 0.5$ are indirect band gap semiconductors. The EHP recombination processes occur through recombination centers and involve lattice vibrations rather than photon emission.

The figure below shows the change in the gap from direct to indirect with the mole fraction y of phosphorus:



(a) (b)

Figure II.4 (a) Band gap energy of $\mathrm{GaAs_{1\text{-}y}P_y}$ as a function of mole fraction y (b) E versus k diagram of $\mathrm{GaAs_{1\text{-}y}P_y}$ for various values of y.

However, if we add isoelectronic impurities or dopants such as nitrogen (in the same Group V as P) into the semiconductor crystal, then these N atoms substitute for P atoms. Since N and P have the same valency, N atoms substituting for P atoms form the same number of bonds and do not act as donors or acceptors. The electronic cores of N and P, however, are different. The positive nucleus of N is less shielded by electrons compared with that of the P atom. This means that a conduction electron in the neighborhood of an N atom will be attracted and may become captured at this site. N atoms therefore introduce localized energy levels, or electron traps, E_N near the conduction band (CB) edge as depicted in Figure II.3.b. When a conduction electron is captured at E_N, it can attract a hole (in the valence band) in its vicinity by Coulombic attraction and eventually recombine with it directly and emit a photon. The emitted photon energy is only slightly less than Eg as E_N is typically close to Ec, e.g., Eg = 2.26 eV for GaP and E_N is 0.05–0.15 eV below Ec. As the recombination process depends on N doping, it is not as efficient as direct recombination. Thus, the efficiency of LEDs from N-doped indirect bandgap $\mathrm{GaAs_{1-y}P_y}$ semiconductors is less than those from direct band gap compositions. Nitrogen-doped indirect band gap $\mathrm{GaAs_{1-y}P_y}$ alloys are widely used in inexpensive green, yellow, and orange LEDs.

II.3 Heterojunction high-intensity LEDs

A pn junction between two differently doped semiconductors that are of the same material, that is, the same bandgap Eg, is called a homojunction. A junction between two different bandgap semiconductors is called a heterojunction. A semiconductor device structure that has junctions between different bandgap materials is called a heterostructure device.

LED constructions for increasing the intensity of the output light make use of the double heterostructure. Figure II.5.a shows a double-heterostructure (DH) device based on two junctions between different semiconductor materials with different bandgaps. In this case the semiconductors are AlGaAs with Eg ≈ 2 eV and GaAs with Eg ≈ 1.4 eV. The double heterostructure in Figure II.5.a has an n^+p heterojunction between n+-AlGaAs and p-GaAs. There is another heterojunction between p-GaAs and p-AlGaAs. The p-GaAs region is a thin layer, typically a fraction of a micron, and it is lightly doped.

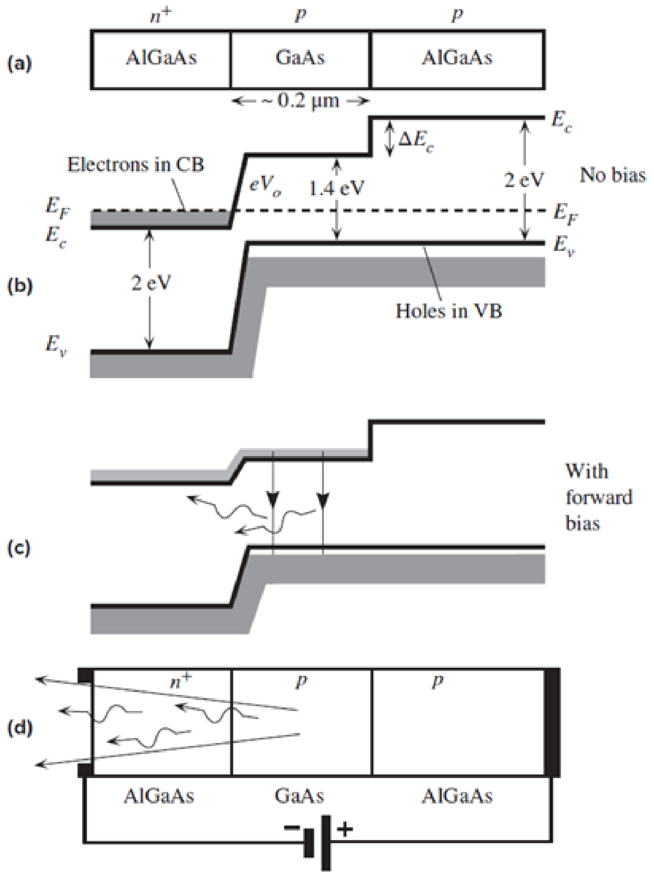


Figure II.5 (a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs). (b) A simplified energy band diagram with exaggerated features. E_F must be uniform. (c) Forward-biased simplified energy band diagram. (d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

The simplified energy band diagram for the whole device in the absence of an applied voltage is shown in Figure II.5.b. The Fermi level EF is continuous throughout the whole structure. There is a potential energy barrier eVo for electrons in the CB of n+-AlGaAs against diffusion into p-GaAs. There is a bandgap change at the junction between p-GaAs and p-AlGaAs which results in a step change ΔEc in Ec between the two conduction bands of p-GaAs and p-AlGaAs. This ΔEc is effectively a potential energy barrier that prevents any electrons in the CB in p-GaAs passing to the CB of p-AlGaAs. (There is also a step change ΔEv in Ev, but this is small and is not shown.)

When a forward bias is applied, most of this voltage drops between the n+-AlGaAs and p-GaAs and reduces the potential energy barrier eVo, just as in the normal pn junction. This allows electrons in the CB of n+-AlGaAs to be injected into p-GaAs as shown in Figure II.5.c. These electrons, however, are confined to the CB of p-GaAs since there is a barrier ΔEc between p-GaAs and p-AlGaAs. The wide bandgap AlGaAs layer therefore acts as a confining layer that restrict injected electrons to the p-GaAs layer. The recombination of injected electrons and the holes in this p-GaAs layer results in spontaneous photon emission.

The radiative recombination and photon generation takes place in the p-GaAs layer, which is called the active layer. Since the bandgap (2 eV) of AlGaAs is greater than GaAs, the emitted photons do not get reabsorbed as they escape the active region and can reach the surface of the device as depicted in Figure II.5.d. Since light is also not absorbed in p-AlGaAs, it can be reflected to increase the light output.

The holes lost by recombination with electrons in the p-GaAs layer are readily replenished by p-AlGaAs, connected to the positive terminal. Further, notice that the potential energy barrier against hole injection from p-GaAs into n+-AlGaAs is quite large, compared to the homojunction case, which suppresses the flow of holes away from p-GaAs into n+-AlGaAs.

II.4 LED Efficiency

Once electron–hole pairs are formed, there are several possible processes by which the electrons and holes can recombine. Some recombination processes may result in photon emission from direct band gap materials, whereas other recombination processes in the same material may not

II.4.1 Internal Quantum Efficiency

The quantum efficiency is defined as the ratio of the radiative recombination rate to the total recombination rate for all processes. We can write:

$$\eta_i = \frac{R_r}{R_r + R_{nr}} \qquad \textbf{Eq. (II.2)}$$

where η_q is the quantum efficiency, Rr is the radiative recombination rate, and R is the total recombination rate of the excess carriers.

Recombination rates are expressed as a function of lifetimes by the relationships:

$$R = {}^{-\Delta n}/_{\tau_r}\,, \qquad R_{nr} = {}^{-\Delta \mathrm{n}}/_{\tau_{nr}}$$

where τ_{nr} is the nonradiative lifetime and τ_r is the radiative lifetime. We can write the quantum efficiency in terms of lifetimes as:

$$\eta_i = \frac{\tau_r}{\tau_{nr} + \tau_r} \qquad \textbf{Eq. (II.3)}$$

For a direct gap material, the nonradiative lifetimes must be large than radiative lifetimes: $\tau_{nr} \ll \tau_r$; thus, the probability of a nonradiative recombination is small compared to the radiative recombination and quantum efficiency $\eta_i \approx 1$.

II.4.2 Optical Efficiency

Not all photons created at the junction emitted from the semiconductor. The optical efficiency is ηo is defined as the ratio of the number of photons emitted outside the diode to the number of photons created at the junction.

Once a photon has been produced in the semiconductor, there are three loss mechanisms the photon may encounter: photon absorption within the semiconductor, Fresnel loss, and critical angle loss.

Figure II.6 shows a pn junction LED. Photons can be emitted in any direction. Since the emitted photon energy must be hν ≥ Eg, these emitted photons can be reabsorbed within the semiconductor material. The majority of photons will actually be emitted away from the surface and reabsorbed in the semiconductor.

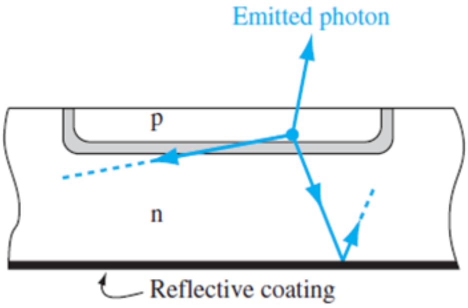


Figure II.6 | Schematic of photon emission at the pn junction of an LED.

Photons must be emitted from the semiconductor into air; thus, the photons must be transmitted across a dielectric interface. Figure II.7 shows the incident, reflected, and transmitted waves. The parameter n_2 is the index of refraction for the semiconductor and n_1 is the index of refraction for air. The reflection coefficient is:

$$\Gamma = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$ **Eq. (II.4)**

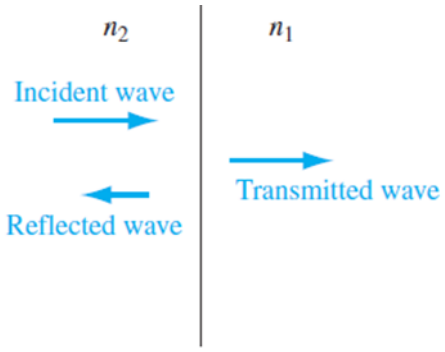


Figure II.7 Schematic of incident, reflected, and transmitted photons at a dielectric interface.

Photons incident on the semiconductor–air interface at an angle are refracted as shown in Figure II.8. If the photons are incident on the interface at an angle greater than the critical angle θ_c, the photons experience total internal reflection. The critical angle is determined from Snell's law and is given by **Eq. (II.5)**:

$\theta c = \sin -1n1n2$ **Eq. (II.5)**

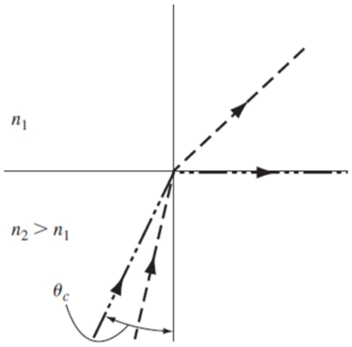


Figure II.8 Schematic showing refraction and total internal reflection at the critical angle at a dielectric interface.

The optical efficiency is given by the following relationship:

$$\eta_o = \frac{1}{4}\left(\frac{n_1}{n_2}\right)^2 \left(1 - \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2\right)$$ **Eq. (II.6)**

For emission into the air ($n_1 = 1$), the optical efficiency is:

$$\eta_o = \frac{1}{4n^2{}_2}\left(1-\left(\frac{n_{2-}1}{n_2+1}\right)^2\right) \approx \frac{1}{n(n+1)^2} \quad \textbf{Eq. (II.7)}$$

Example to calculate η_O:

For a diode with a refractive index of n = 3.5, we obtain ηo≈ 1%.

The optical efficiency is improved by covering the diode with a transparent plastic material, the n_p index of which is greater than that of air.

$$\eta_o = \frac{1}{4}\left(\frac{n_p}{n_2}\right)^2\left(1-\left(\frac{n_{2-}n_p}{n_2+n_p}\right)^2\right) \quad \textbf{Eq. (II.8)}$$

Example: for n_2=3.5 and n_p≈ 1.5 the optical efficiency at the semiconductor-plastic interface is ηo≈ 4%.

We also limit losses due to the angle of incidence by making the plastic in the form of a hemispherical dome so that the photons are incident on the interface with θ=90°.

The transmission coefficient at this interface is given by:

$$T = 1 - R = 1 - \left(\frac{(1-n_p)}{(1+n_p)}\right)^2 \quad \textbf{Eq. (II.9)}$$

For the previous example T= 96%.

II.4.3 External Quantum Efficiency

The external quantum efficiency (η_e) is defined as the ratio of the number of photons emitted by the diode to the number of carriers crossing the junction. In other words, this recovery is given by:

$$\eta_e = \eta_i\, \eta_o \quad \textbf{Eq. (II.10)}$$

II.4.4 Overall Efficiency

Overall efficiency is defined as the ratio of light power emitted, to the electrical power absorbed:

$$\eta = {}^{w_{op}}/_{w_{el}} \qquad \textbf{Eq. (II.11)}$$

If the number of photons emitted per second is N_{ph} and if the energy of each of these photons assumed to be identical, is hυ, the light power emitted is:

$$w_{op} = N_{ph}\, h\nu \qquad \textbf{Eq. (II.12)}$$

The absorbed electrical power is given by the product VxI, where V is the voltage applied to the diode and I the current delivered. I is the quantity of charges which cross the junction per second, $I = N_{el}\, q$, thus $w_{el} = N_{el}\, eV$.

The overall efficient is therefore written:

$$\eta = \frac{N_{ph}}{N_{el}} = \eta_e \frac{h\nu}{qV} \qquad \textbf{Eq. (II.13)}$$

The energy of the emitted radiation is close to the gap, hν=E_g on the other hand the voltage V is partly lost in the series resistance of the diode, so that the efficiency is written:

$$\eta = \eta_e \quad \frac{{}^{E_g}/_{q}}{r_s I + V_d} \qquad \textbf{Eq. (II.14)}$$

II.5. Light spectrum

Light spectrum as a function of wavelength and energy. The figure includes the relative response of the human eye

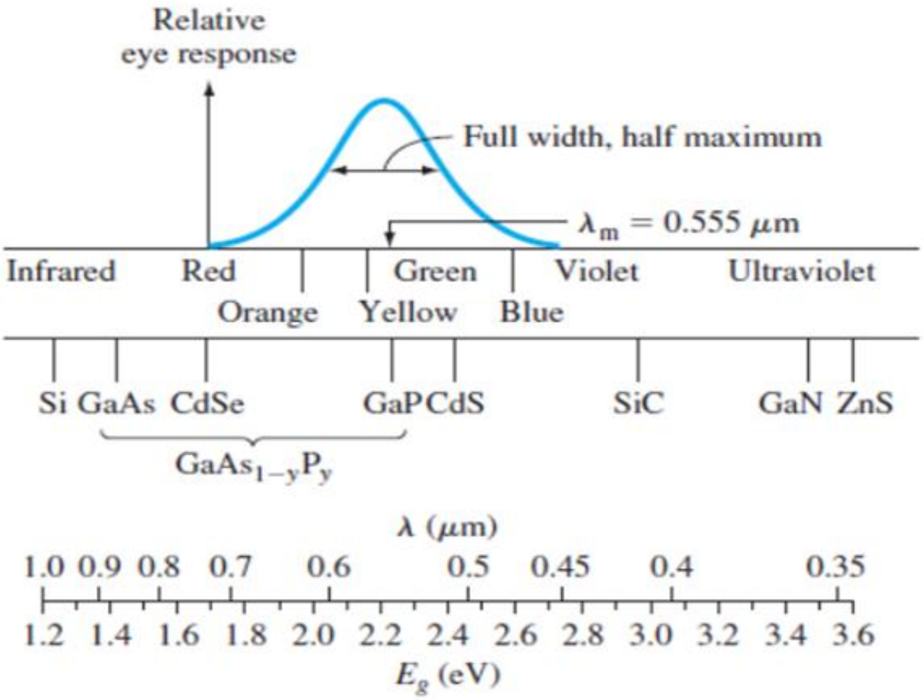


Figure II.9 | Light spectrum versus wavelength and energy. Figure includes relative response of the human eye.

SOLAR CELLS

III Solar cells

III.1 Photovoltaic device principles

A solar cell is an optoelectronic device based on a pn junction, it operates without external voltage. The solar cell converts photon energy into electrical energy and delivers this energy to a charge. These optoelectronic devices have long been used to power satellites and space vehicles, as well as the power supply of certain calculators, we will first consider the simple pn junction solar cell with uniform generation of excess carriers. We will also discuss briefly the heterojunction.

A simplified schematic diagram of a typical solar cell is shown in Figure III.1. Consider a pn junction with a very narrow and more heavily doped n-region.

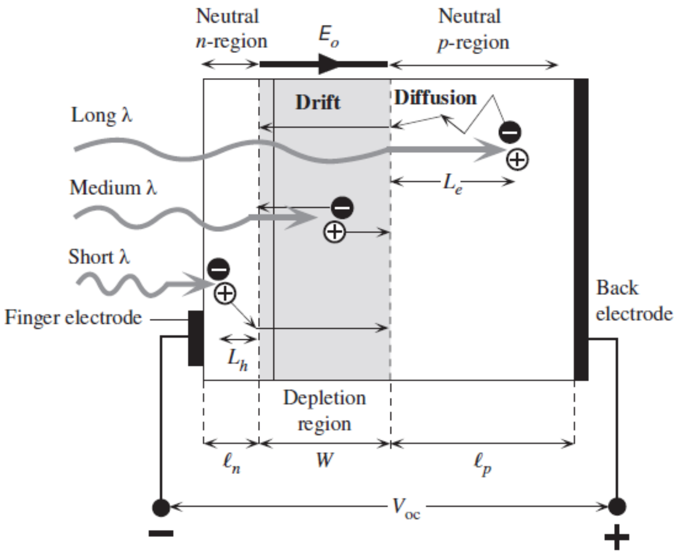


Figure III.1 basic principle of operation of the solar cell (exaggerated features to highlight principles). The built-in field change upon illumination

The illumination is through the thin n-side. The depletion region (W) or the space charge layer (SCL) extends primarily into the p-side. There is a built-in field Eo in this depletion layer. The electrodes attached to the n-side must allow illumination to enter the device and at the same time result in a small series resistance. They are deposited on the n-side to form an array of finger electrodes on the surface as depicted in Figure III.2. A thin antireflection coating on the surface reduces reflections and allows more light to enter the device.

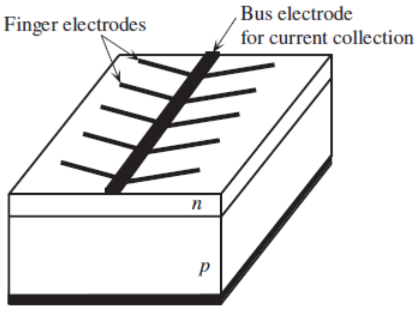


Figure III.2 Finger electrodes on the surface of a solar cell reduce the series resistance.

As the n-side is very narrow, most of the photons are absorbed within the depletion region (W) and within the neutral p-side (ℓp), These photons photogenerate electron-hole pairs (EHPs) in these regions. EHPs photogenerated in the depletion region are immediately separated by the built-in field E_o which drifts them apart. The electron drifts and reaches the neutral n-side, it makes this region negative by an amount of charge −q.

Similarly, the hole drifts and reaches the neutral p-side and thereby makes this side positive. Consequently, a net open circuit voltage develops between the terminals of the device with the p-side positive with respect to the n-side.

The EHPs photogenerated by **long-wavelength** photons that are absorbed in the neutral **p-side** diffuse around in this region as there is no electric field. If the recombination lifetime of the electron is τ_e, it diffuses a mean distance $\boldsymbol{L_e = \sqrt{D_e \tau_e}}$ where D_e is its diffusion coefficient in the p-side. Those **electrons** within a distance $\mathbf{L_e}$ to the depletion region can readily diffuse and reach this region so they become drifted by Eo to the n-side as shown in Figure III.1 it is swept over to the n-side by Eo to give an **additional negative charge** there. Consequently, only those EHPs photogenerated within the minority carrier diffusion length Le to the depletion layer can contribute to the photovoltaic effect. Again, the importance of the built-in field Eo is apparent.

Holes left behind in the p-side contribute a net positive charge to this region.

Those photogenerated EHPs further away from the depletion region than L_e are lost by recombination. It is therefore important to have the minority carrier diffusion length L_e be as long as possible. It is therefore important to have the minority carrier diffusion length Le be as long as possible.

The same ideas also apply to EHPs photogenerated by short wavelength photons absorbed in the n-side. Those holes photogenerated within a diffusion length L_h can reach the depletion layer and become swept across to the p-side.

EHPs photogenerated by energetic photons absorbed in the n-side near the surface region or outside the diffusion length Lh to the depletion layer are lost by recombination as the lifetime in the n-side is generally very short (due to heavy doping). The n-side is therefore made very thin, typically less than 0.2 μm. Indeed, the length ℓn of the n-side may be shorter than the hole diffusion length Lh. The EHPs photogenerated very near the surface of the n-side, however, disappear by recombination due to various surface defects acting as recombination centers as discussed below.

III.2 pn junction solar cell in shorted circuit

The photogeneration of EHPs that contributes to the photovoltaic effect therefore occurs in a volume covering $L_h + W + L_e$. If the terminals of the device are shorted, as in Figure III.3, then the photogenerated electrons that are drifted into the n-side can flow through the external circuit to neutralize the photogenerated holes that have drifted into the p-side. This current due to the flow of the photogenerated carriers is called the photocurrent.

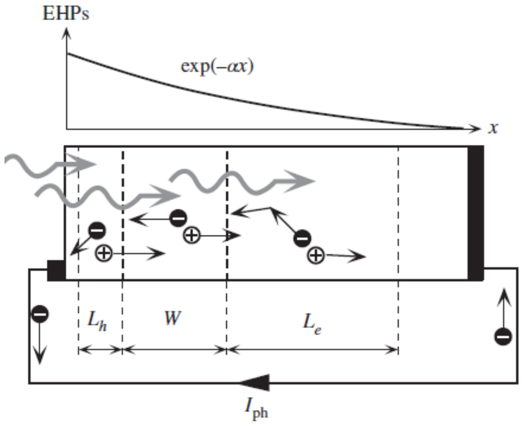


Figure III.3 An np junction solar cell in short circuit. Photogenerated carriers within the volume $L_h + W + L_e$ give rise to a photocurrent Iph. The variation in the photogenerated EHP concentration with distance is also shown where α is the absorption coefficient at the wavelength of interest

III.3 pn junction solar cell in open circuit

Under a steady-state operation, there can be no net current through an opencircuit solar cell. This means the photocurrent inside the device due to the flow of photogenerated carriers must be exactly balanced by a flow of carriers in the opposite direction. The latter carriers are minority carriers that become injected by the appearance of the photovoltaic voltage across the pn junction as in a normal diode. This is not shown in Figure III.1.

III.4 Solar cell connected to an external load R

Consider an ideal pn junction photovoltaic device connected to a resistive load R as shown in Figure III.4.a. Note that I and V in the figure define the convention for the direction of positive current and positive voltage. If the load is a short circuit, then the only current in the circuit is that generated by the incident light. This is the photocurrent Iph shown in Figure III.4.b which depends on the number of EHPs photogenerated within the volume enclosing the depletion region (W) and the diffusion lengths to the depletion region (Figure III.3).

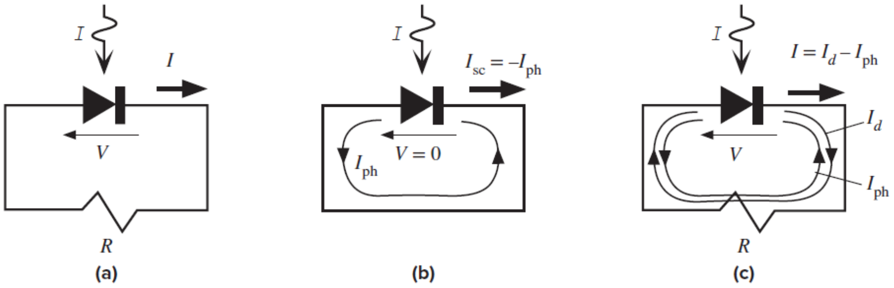


Figure III.4 (a) The solar cell connected to an external load R and the convention for the definitions of positive voltage and positive current. (b) The solar cell in short circuit. The current is the photocurrent Iph. (c) The solar cell driving an external load R. There is a voltage V and current I in the circuit

If **I** is the light intensity, then **the short circuit current** is :

$$I_{sc} = -I_{ph} = -KI \qquad \textbf{(Eq. III.1)}$$

where K is a constant that depends on the particular device. The photocurrent does not depend on the voltage across the pn junction because there is always some internal field to drift the photogenerated EHP. We exclude the secondary effect of the voltage modulating the width of the depletion region. The photocurrent I_{ph} therefore flows even when there is not a voltage across the device.

If R is not a short circuit, then a positive voltage V appears across the pn junction as a result of the current passing through it as shown in Figure III.4.c. This voltage reduces the built-in potential of the pn junction and hence leads to minority carrier injection and diffusion just as it would in a normal diode. Thus, in addition to Iph there is also a forward diode current Id in the circuit as shown in Figure III.4c which arises from the voltage developed across R. Since Id is due to the normal pn junction behavior, it is given by the diode characteristics,

$$I_d = I_s \left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right] \qquad \textbf{(Eq. III.2)}$$

where I_s is the “reverse saturation current” and η is the ideality factor ($\eta = 1-2$). In an open circuit, the net current is zero. This means that the photocurrent I_{ph} develops just enough photovoltaic voltage Voc to generate a diode current $I_d = I_{ph}$. Thus the total current through the solar cell, as shown in Figure III4.c, is:

$$I = I_{ph} + I_s \left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right] \qquad \textbf{(Eq. III.3)}$$

The overall I–V characteristics of a typical Si solar cell are shown in Figure III.5. It can be seen that it corresponds to the normal dark characteristics being shifted down by the photocurrent I_{ph}, which depends on the light intensity I. The open circuit output voltage Voc, of the solar cell is given by the point where the I–V curvecuts the V axis (I = 0). It is apparent that although it depends on the light intensity, its value typically lies in the range 0.5–0.7 V.

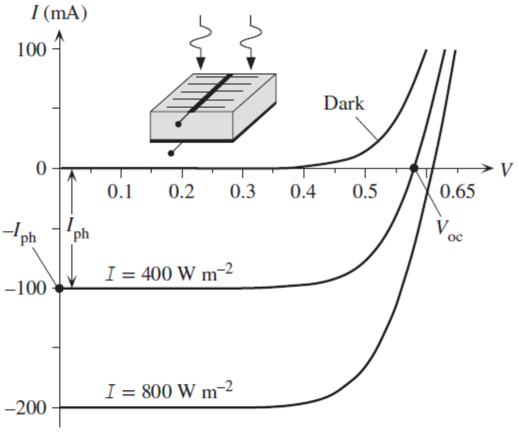


Figure III.5 Typical I–V characteristics of a Si solar cell. The short circuit current is Iph and the open circuit voltage is Voc. The I–V curves for positive current require an external bias voltage. Photovoltaic operation is always in the negative current region

Equation below gives the I–V characteristics of the solar cell. When the solar cell is connected to a load as in Figure III.6.a, the load has the same voltage as the solar cell and carries the same current. But the current I through R is now in the opposite direction to the convention that current flows from high to low potential. Thus, as shown in Figure III.6.a,

$$I = \frac{V}{R} \qquad \textbf{(Eq. III.4)}$$

The actual current I′ and voltage V′ in the circuit must satisfy both the I–V characteristics of the solar cell, Equation **(Eq. III.3)**, and that of the load, Equation **(Eq. III.4)**.

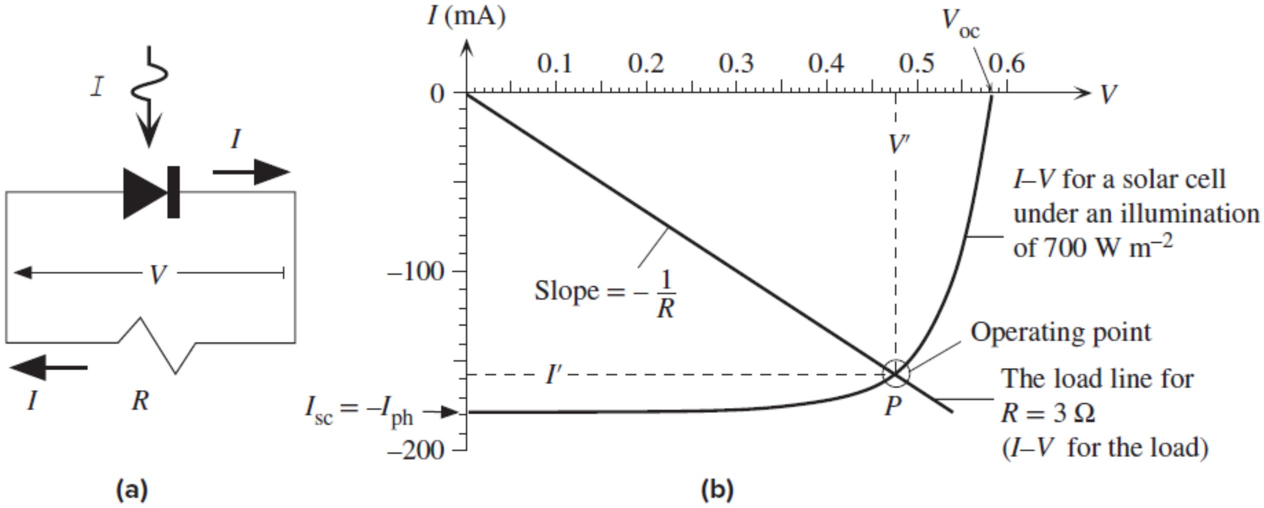


Figure III.6.(a) When a solar cell drives a load R, R has the same voltage as the solar cell but the current through it is in the opposite direction to the convention that current flows from high to low potential. (b) The current I′ and voltage V′ in the circuit of (a) can be found from a load line construction. Point P is the operating point (I′, V′). The load line is for R = 3 Ω.

We can find I′ and V′ by solving these two equations simultaneously or using a load line construction. The I–V characteristic of the load in Equation (Eq. III.4) is a straight line with a negative slope −1⁄R. This is called the load line and is shown in Figure III.6. b along with the I–V characteristics of the solar cell under a given intensity of illumination. The load line cuts the solar cell characteristic at P where the load and the solar cell have the same current and voltage I′ and V′. Point P therefore satisfies both Equations (Eq. III.3) and (Eq. III.4) and thus represents the operating point of the circuit.

The power delivered to the load is Pout = I′V′, which is the area of the rectangle bound by the I and V axes and the dashed lines shown in Figure III.6.b.
Maximum power is delivered to the load when this rectangular area is maximized (by changing R or the intensity of illumination), when I′ = Im and V′ = Vm. Since the maximum possible current is Isc and the maximum possible voltage is Voc, $I_{sc}V_{oc}$ represents the desirable goal in power delivery for a given solar cell. Therefore, it makes sense to compare the maximum power output ImVm with IscVoc. The fill factor FF, which is a figure of merit for the solar cell, is defined as:

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \qquad \textbf{(Eq. III. 5)}$$

The FF is a measure of the closeness of the solar cell I–V curve to the rectangular shape (the ideal shape). It is clearly advantageous to have the FF as close to unity as possible, but the exponential pn junction properties prevent this. Typically, FF values are in the range 70–85 percent and depend on the device material and structure.

Laser diode – LD

IV. Laser diode – LD

Historically, the laser adventure began in 1917 when Einstein discovered the existence of the process of stimulated emission, that is to say the emission of a photon controlled by another photon. In July 1960 Maiman produced the first LASER (Light Amplification by Stimulated Emission of Radiation) using the levels of the Cr3+ ion in Al2O3, the ruby laser. From then on, much research was developed and different types of lasers, solid, gas, dye, were produced. In 1958 Aigrain put forward the hypothesis of the use of semiconductors to obtain the laser effect, the first laser was produced with GaAs in 1962.

IV.1 Principle of operation

IV.1.1 Spontaneous emission and stimulated emission

An electron can be excited from an energy level E1 to a higher energy level E2 by the absorption of a photon $h\nu=E_2-E_1$ (Fig. IV.1). When this electron returns to the equilibrium state (E1), it will emit a photon. There are two essential processes for this broadcast:

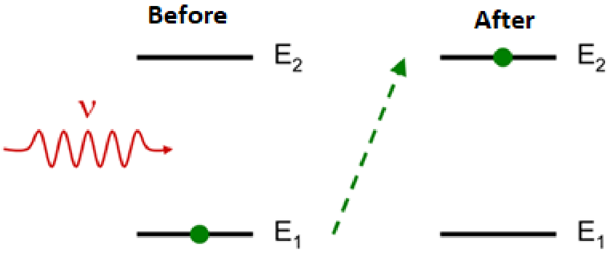


Figure IV. 1. An electron can be excited from an energy level E1 to a higher energy level E2 by the absorption of a photon hν

IV.1.1.1. Spontaneous emission

In a spontaneous emission, the electron descends in energy from level E2 to E1 and emits a photon of energy hν. The transition is only spontaneous if the energy state E1 is not already occupied by another electron (fig IV.2).

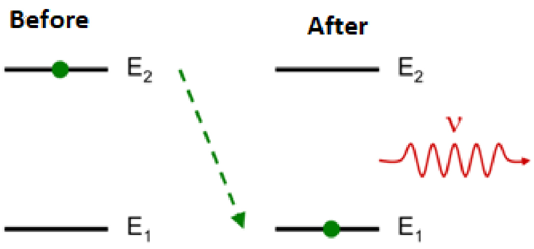


Figure IV.2. Spontaneous emission

IV.1.1.2. Stimulated emission

An incident photon of energy hν=E2-E1 stimulates an emission process; it induces the passage of the electron from level E2 to level E1. The emitted photon is in phase with the incident photon, it goes in the same direction and it has the same frequency, it must also have the energy E2-E1 (fig. IV.3).

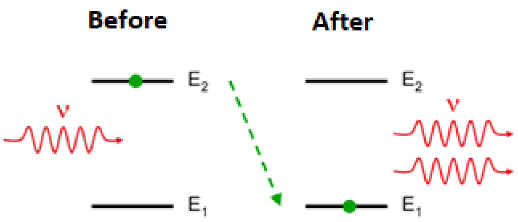


Figure IV.3. Stimulated emission

To obtain stimulated emission (Figure IV.3) it is necessary that:

- The incident photon must not be absorbed by an electron at level E1.
- For light amplification, the majority of atoms must be at level 2; if this is not the case the incident photon will be absorbed by an atom at level E1.
- When the population of level E2 is greater than that of level E, we say that we have an inverse population.

IV.2. Laser principle

Stimulated emission is the basis of the laser, since from an incident photon we will obtain two photons at the output. The latter are symmetrical: the same frequency, direction and phase, which gives the laser effect.

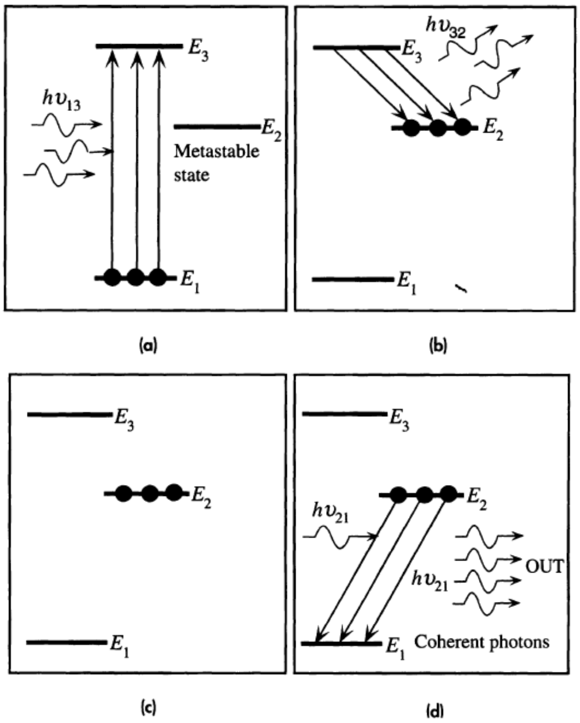


Figure IV.4 Laser principle

a. The electrons in the ground state are excited at the E3 level with an incident photon of energy $h\nu_{13}$=E3-E1; This is the pumping procedure. In this case it is optical pumping since the excitation is made by a photon

b. the excited atoms at the E3 level decline towards the metastable E2 level by emitting a photon or a vibration of the lattice: $h\nu_{32}$=E3-E2.

C. Since the atoms at level E2 are metastable, we will have an inverse population between E2 and E.

d. An incident photon with energy hν21=E2-E1 can cause stimulated emission. The photons emitted by stimulation can themselves cause the stimulated emission of other photons. This leads to an avalanche of coherent photons emitted.

IV.3. HeNe laser

The figure below shows a schematic of a HeNe laser, which produces a red laser of wavelength 632.8nm. It consists of a glass tube containing a mixture of He and Ne gases. The Ne atoms give the laser rays, and the He atoms play the role of pumping by collision with the Ne atoms.

The He atoms are excited by high voltage. The edges of the tube are covered by fully reflective (99.9%) and partially reflective (98.5%) mirrors to obtain a reflective cavity. The pumping procedure is carried out by the collision between He and Ne atoms.

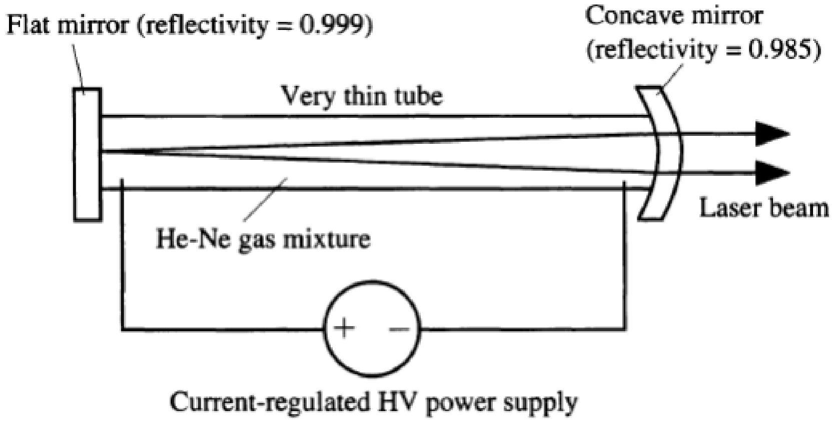


Figure IV. 5. Schematic illustration of th HeNe laser

IV.4. Spectrum of a laser

The rays coming out of the laser are not really a single well-defined wavelength, but they cover a range of wavelengths with a central peak; This is the Doppler effect:

The Doppler effect is the shift in frequency of a wave (mechanical, acoustic, electromagnetic or of another nature) observed between measurements at transmission and reception. When the atoms are moving towards an observer, the latter sees that the gas of the atoms moves with a maximum frequency ν_2 given with the following formula:

$$\nu_2 = \nu_0 \left(1 + \frac{v_x}{c}\right) \qquad \textbf{Eq. (IV.1)}$$

With: v_x is the relative speed of the atoms compared to an observer.

C: is the speed of light.

ν_0 is the central peak frequency

When the gas of atoms moves away from the observer with a minimum frequency ν_1:

$$\nu_1 = \nu_0 \left(1 - \frac{v_x}{c}\right) \qquad \textbf{Eq. (IV.2)}$$

As the atoms are in random motion, the frequencies or wavelengths of the rays emitted from a laser have a width: $\Delta\nu=\nu_2-\nu_1$

There are other phenomena that broaden the spectrum of a laser but we do not discuss them in this course.

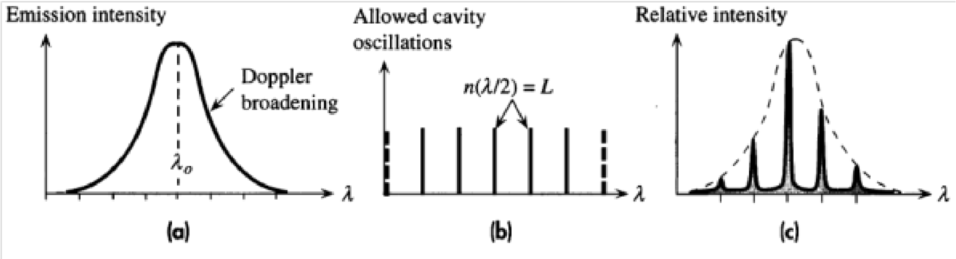


Figure VI. 6 a. Doppler- broadened emission versus wavelength characteristics of the lasing medium. b. Allowed oscillations and their wavelengths with the optical cavity. C. The output spectrum is determined by satisfying (a) and (b) simultaneously.

The mirrors at the end of the laser cause the waves to be reflected inside the cavity; they move in opposite directions. As the waves of a laser are in phase, they interfere in a constructive way and we will obtain standing waves. In other words, part of the energy of this wave is harnessed by the 99% reflecting mirror to obtain 1% output.

Only standing waves with certain wavelengths can be maintained in the optical cavity. Any standing wave in the cavity must have a half-wavelength λ /2 suitable for the length of the cavity L, or:

$$n\left(\frac{\lambda}{2}\right) = L$$

n is an integer, called the standing wave mode number.

Each standing wave in the cavity (laser tube) satisfying the previous equation is called cavity mode. Figure 3.43 shows the spectrum of a laser, the spectrum is broad with peaks at certain wavelengths corresponding to the cavity modes existing with the Dopller effect.

IV.5. Semiconductor laser

The laser diode, like the LED, uses a forward-biased p-n junction to inject electrons and holes to generate light.

In the case of semiconductors, the problem is significantly different. While in conventional lasers the electronic states are localized and discrete energy levels, in semiconductors the energy levels are grouped in permitted bands where their distribution is quasi-continuous. The population inversion condition between two discrete levels, (N2>N1) must be expressed here between the valence band and the conduction band.

The laser effect occurs here between the states at the bottom of the conduction band, where the electrons injected into this band thermalize, and the states at the top of the valence band where the holes created in this band thermalize.

All laser diodes are practically double heterostructures. The figure below shows the case of a GaAs laser; where we have two junctions between GaAs and AlGaAs. The AlGaAs gap is of the order of 2 eV and the GaAs gap is 1.4 eV. The GaAs (p) layer is thin, it is between 0.1-0.2 µm, it is the active layer where the stimulated emission will take place. The AlGaAs(n) and AlGaAs(p) zones are heavily doped in a way to have degenerate semiconductors, i.e. the Fermi levels are located in the permitted bands.

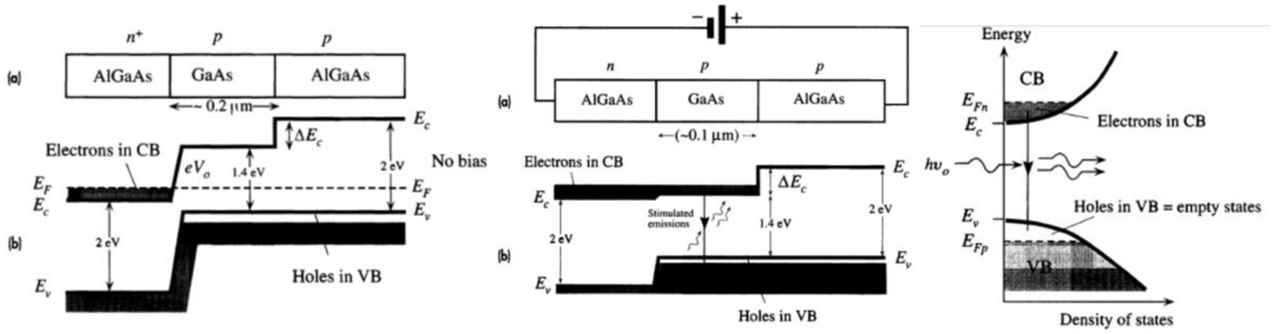


Figure IV.7. (a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AIGaAs). (b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the p-GaAs layer, the active layer. (c) The density of states and energy distribution of electrons and holes in the conduction and valence bands in the active layer.

V. Photodiode

V. Photodiode

V.1 Photodiode principle

A photodiode is a pn junction diode operated with an applied reverse-biased voltage. We will initially consider a long diode in which excess carriers are generated uniformly throughout the semiconductor device.

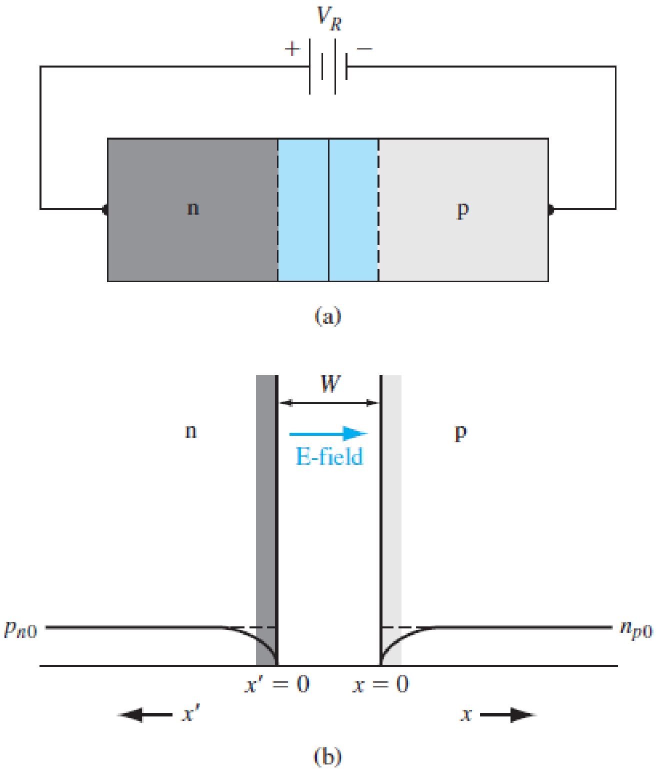


Figure V.1 (a) A reverse-biased pn junction.

(b) Minority carrier concentration in the reverse-biased pn junction.

Figure V.1.a. shows the reverse biased diode and Figure V.1.b shows the minority carrier distribution in the reverse-biased junction prior to photon illumination.

Let G_L be the generation rate of excess carriers. The excess carriers generated within the space charge region are swept out of the depletion region very quickly by the electric field; the electrons are swept into the n region and the holes into the p region. The photon-generated current density from the space charge region is given by:

$$J_{L1} = q\int G_L dx \qquad \textbf{Eq. (V.1)}$$

where the integral is over the space charge region width. If GL is constant throughout the space charge volume, then:

$$J_{L1} = qG_LW \qquad \textbf{Eq. (V.2)}$$

Where W is the space charge width. We may note that J_{L1} is in the reverse-biased direction through the pn junction. This component of photocurrent responds very quickly to the photon illumination and is known as the prompt photocurrent.

The speed of the photodiode is limited by the carrier transport through the space charge region.

V.2 Photocurrents in a "long" reverse-biased pn junction

Excess carriers are also generated within the neutral n and p regions of the diode. The excess minority carrier electron distribution in the p region is found from the ambipolar transport equation, which is:

$$D_n \frac{\partial^2(\delta n_p)}{\partial x^2} + G_L - \frac{\delta n_p}{\tau_{n0}} = \frac{\partial(\delta n_p)}{\partial t} \qquad \textbf{Eq. (V.3)}$$

We will assume that the E-field is zero in the neutral regions. In steady state, $\frac{\partial(\delta n_p)}{\partial t} = 0$, so that Equation (V.3) can be written as:

$$\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = -\frac{G_L}{D_n} \qquad \textbf{Eq. (V.4)}$$

Where $L_n^2 = D_n\tau_{n0}$

The solution to Equation (V.4) can be found as the sum of the homogeneous and particular solutions. The homogeneous solution is found from the equation:

$$\frac{d^2(\delta n_{ph})}{dx^2} - \frac{\delta n_{ph}}{L_n^2} = 0 \qquad \textbf{Eq. (V.5)}$$

where δn_{ph} is the homogeneous solution and is given by

$$\delta n_{ph} = Ae^{-x/Ln} + Be^{x/Ln} \qquad (x \geq 0) \qquad \textbf{Eq. (V.6)}$$

One boundary condition is that δn_{ph} must remain finite, which implies that B = 0 for the "long" diode.

The particular solution is found from:

$$-\frac{\delta n_{pp}}{L_n^2} = -\frac{G_L}{D_n}$$ **Eq. (V.7)**

which yields:

$$\delta n_{pp} = \frac{G_L L_n^2}{D_n} = \frac{G_L D_n \tau_{n0}}{D_n} = G_L \tau_{n0}$$ **Eq. (V.8)**

The total steady-state solution for the excess minority carrier electron concentration in the p region is then:

$$\delta n_p = Ae^{-x/Ln} + G_L \tau_{n0}$$ **Eq.(V. 9)**

The total electron concentration is zero at x = 0 for the reverse-biased junction. The excess electron concentration x = 0 is then:

$$\delta n_p(x = 0) = -n_{p0}$$ **Eq. (V. 10)**

Using the boundary condition from Equation (V. 10), the electron concentration given by Equation (V. 9) becomes: $\delta n_p = G_L \tau_{n0} - (G_L \tau_{n0} + n_{p0})e^{-x/L_n}$ **Eq. (V. 11)**

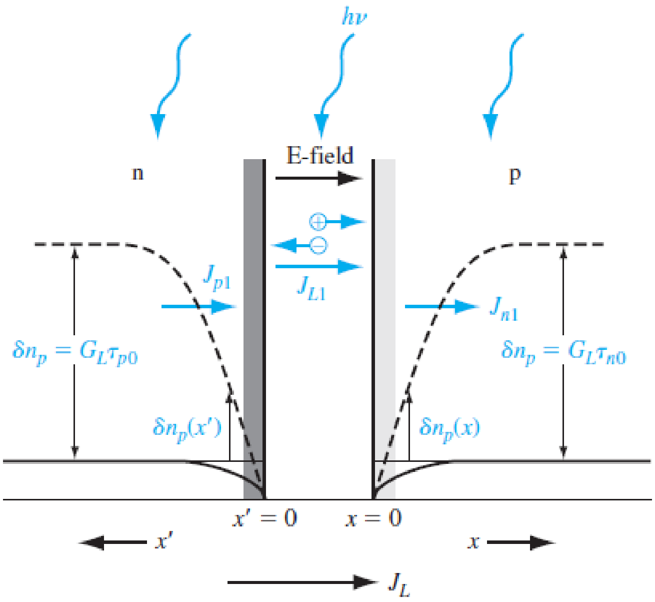


Figure V.2 Steady-state, photoinduced minority carrier concentrations and photocurrents in a "long" reverse-biased pn junction

We can find the excess minority carrier hole concentration in the n region using the same type of analysis. Using the x' notation shown in Figure V.2, we can write

$$\delta p_n = G_L \tau_{p0} - (G_L \tau_{p0} + p_{n0}) e^{-x'/L_p} \qquad \textbf{Eq. (V. 12)}$$

Equations (V. 12) and (V. 11) are plotted in Figure V.2. We may note that the steady-state values far from the space charge region are the same as were given previously.

V.3 The diffusion current

The gradient in the minority carrier concentrations will produce diffusion currents in the pn junction. The diffusion current density at x =0 due to minority carrier electrons is :

$$J_{n1} = qD_n \frac{d(\delta n_p)}{dx}\bigg|_{x=0} = qD_n \frac{d}{dx}\left[G_L \tau_{n0} - \left(G_L \tau_{n0} + n_{p0}\right) e^{-x/L_n}\right]\bigg|_{x=0}$$

$$= \frac{qD_n}{L_n}(G_L \tau_{n0} + n_{p0}) \qquad \textbf{Eq.(V. 13)}$$

Equation (V.13) can be written as:

$$J_{n1} = qG_L L_n + \frac{qD_n}{L_n} n_{p0} \qquad \textbf{Eq. (V.14)}$$

The first term in Equation (V.40) is the steady-state photocurrent density while the second term is the ideal reverse saturation current density due to the minority carrier electrons.

The diffusion current density (in the x direction) at x= 0 due to the minority carrier holes is

$$J_{p1} = qG_L L_p + \frac{qD_p}{L_p} p_{n0} \qquad \textbf{Eq. (V. 15)}$$

Similarly, the first term is the steady-state photocurrent density and the second term is the ideal reverse saturation current density.

The total steady-state diode photocurrent density for the long diode is now

$$J_L = qG_L W + qG_L L_n + qG_L L_p = q\left(W + L_n + L_p\right) G_L \qquad \textbf{Eq. (V.16)}$$

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