Chapter 6
OPTEOELECTRONIC DEVICES

6.1 Optical Effects in Semiconductors

The interaction between electromagnetic radiation and material especially semiconductors has produced an area of interest called optoelectronics. The interaction is based on photon exchange of energy with electrons and atoms. Usually we call this radiation light although its wavelength may not be in the visible region of the spectrum. Devices whose operation depends on this interaction are called optoelectronic devices. Among these devices we have two classes of concern here. One is called photodetectors. These are devices in which one of their properties (e.g. electrical conductivity) changes with light, hence can be used to detect or sense light (for example), they are called detectors or sensors. Upon detecting light some circuitry may produce action according to the light signal. Detectors can also be used to sense physical quantities other than light such as pressure, temperature and chemicals. Another class of optoelectronic devices deal with power, i.e., to obtain electrical power for example from absorbed light. This power could be used in lighting or in driving motors etc. Such devices include for example solar cells. Other devices are sources of light such as LEDs and lasers. Other devices include display devices. Others include transmitting media are related devices such as optical fibers and optical modulators.

6.2 Photoconductor

In this case, conductivity is dependent on light. We have seen that in the absence of external effects, thermal equilibrium prevails in which n_o and p_o are constant values at a constant temperature. When light falls on a semiconductor many effects happen. If light photons have energy $h\upsilon \geq E_g$, they will liberate electrons from the covalent bonds and, hence, generate electron-hole pairs in excess of values set by thermal equilibrium. Thus, excess electron and hole densities are produced. We call the rate at which such photons are absorbed per unit volume g_L, which is equal to the rate at which excess electron-hole pairs are generated per unit volume.

We also know that an electron-hole pair has a limited lifetime due to the process of recombination. We call the electron density under light $n_o + \delta n$ and the hole density under light $n_o + \delta p$. Considering that the liberation of an excess electron gives rise to an excess hole, $\delta n = \delta p$. We may define the rate of recombination $\delta n / \tau_r$, which is the same as $\delta p / \tau_r$, where τ_r is the recombination lifetime. The rate of decay being proportional to the instantaneous density automatically means that the solution as a function of time must be an exponential decay because

$$\frac{d}{dt} e^{-\alpha t} = -\alpha e^{-\alpha t}$$

Thus, an equation in the form

$$\frac{dx}{dt} = -\alpha x \qquad (6\text{-}1)$$

has a solution

$$x(t) = x_i e^{-\alpha t} \qquad (6\text{-}2)$$

where x_i is the initial value of x, i.e., at $t = 0$, which is the value at the start of the decay. Writing the rate of recombination as proportional to the instantaneous density is common in many physical situations such as radioactivity.

The rate of recombination may be expressed alternatively as in the case of chemical reactions as the product of densities of the reactants, i.e., rnp where r is a constant called coefficient of recombination. The net rate of increase of electron density $\frac{dn}{dt}$ is equal to $\frac{d\delta n}{dt}$, since $n = n_o + \delta n$, and n_o is a constant. Calling the thermal rate of generation g_o and that under light g_L and the rate of recombination rnp, and noting that $\delta n = \delta p$,

$$\frac{dn}{dt} = \frac{d\delta n}{dt} = g_o + g_L - rnp \qquad (6\text{-}3)$$

$$= g_o + g_L - r(n_o + \delta n)(p_o + \delta p)$$

$$= g_o + g_L - rn_o p_o - r(n_o + p_o)\delta n$$

$$= g_L - \frac{\delta n}{\tau_r} \qquad (6\text{-}4)$$

Where $$\tau_r = \frac{1}{r(n_o + p_o)} \qquad (6\text{-}5)$$

We have neglected term in δn^2 for small signals, and taken $g_o = rn_o p_o$ and $\delta n = \delta p$. Eqn. (6-4) -called the rate equation - describes the detailed balance between two opposite processes, namely, generation and recombination of electron-hole pairs and τ_r is called the excess carrier lifetime. At steady state, $\frac{d\delta n}{dt} = 0$, for which $\delta n = \Delta n$ (steady state) and is given for the case $n_o > p_o$ by

$$\Delta n = g_L \tau_r = g_L \frac{1}{r(n_o + p_o)} = g_L \frac{1}{rn_o} \qquad (6\text{-}6)$$

We note that this situation is similar to that of the balance between birth rate and death rate, when the two processes totally balance out (zero population growth). This does not mean $\Delta n = 0$, but it means that the rate of change $\frac{d\delta n}{dt}$ is 0.

We should also note that the excess electron density at steady state is constant, but such electrons will not be the same ones, since electrons on an individual basis keep shuffling up and down the forbidden band through the processes of generation and recombination.

For an n-type semiconductor and from eqn. (6-6), we see that the excess carrier lifetime is $1/rn_o$, which is determined by the majority carriers (in this case, electrons). We can solve eqn. (6-4) (first order differential equation) by proposing two solutions. One is called the steady state solution (also called the particular integral) the other is called the transient solution (also called the complementary function), which is exponential as before. Thus,

$$\delta n(t) = \Delta n + Be^{-t/\tau_r}$$

where B is a constant to be determined by initial conditions. At $t = 0$, $\delta n = 0$
Thus, $B = -\Delta n$. Eqn. (6-6), then reduces to

$$\delta n(t) = \Delta n\left(1 - e^{-t/\tau_r}\right) \qquad (6\text{-}7)$$

we note that Δn is a final steady state value given by setting $t = \infty$. This equation represents a light signal of constant amplitude applied as a step function. At $t = 0^-$ (just before $t = 0$), there is no light, whereas at $t = 0^+$ (just after $t = 0$) there is light. This abrupt change in light intensity cannot be followed

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instantly by the semiconductor, but a gradual build up of excess carriers takes place toward the final steady state value Δn. This situation is very similar to the charging of capacitor. The time constant τ_r in this case is similar in form to CR in the charging of a capacitor of an RC circuit, for which a dc step function V_{BB} is applied. The voltage across changing the capacitor is given by

$$V_c(t) = V_{BB}\left(1 - e^{-t/CR}\right) \qquad (6\text{-}8)$$

From eqn. (2-37) we have at steady state under light $\sigma = \sigma_o + \Delta\sigma_L$ where

$$\Delta\sigma_L = |q|\left(\mu_n + \mu_p\right)\Delta n \qquad (6\text{-}9)$$

From eqn. (6-6), eqn. (6-9) becomes

$$\Delta\sigma_L = |q|\left(\mu_n + \mu_p\right)\tau_r g_L \qquad (6\text{-}10)$$

We see that $\Delta\sigma_L$ is proportional to g_L. Thus, $\Delta\sigma_L$ (called photoconductivity) is a measure of the absorbed light intensity, hence, the device can be used to detect and measure this light intensity. The time constant τ_r should be small for the photoconductor to follow fast variations in light intensity, but should be long enough to make photoconductivity (change in conductivity due to light) appreciable. We have assumed in this analysis that the light intensity is of a small enough level for δn to be small. In other situation we have to calculate directly the value of the conductance (or resistance) under light and in the dark. The decrease of resistance due to light makes photoconductors particularly suited in many civilian and military applications, such as remote sensing, reconnaissance, missile tracking, night vision, fire alarm, intrusion detection and security.

Ex. 6.1

Assume a pulse of light falls on a photoconductor show the effect of increasing and decreasing τ_r

Solution

From eqn. (6-7) we define rise time t_r as the interval which the photoconductor takes to reach 90% of its final value from an initial value of 10%. It can be shown (Prob. 6.1) that

$$t_r = 2.2\tau_r \qquad (6\text{-}11)$$

We see that if τ_r is small the photoconductor will be able to follow fast variations in changes of light intensity with time but the response (Δn) will be small (low sensitivity). Whereas for large τ_r the steady state value Δn is large (high sensitivity), but the photoconductor cannot then follow fast variations in input signal with time.

Ex. 6.2

Obtain the frequency response of a photoconductor for which the input light varies sinusoidally.

Solution

From eqn. (6-4), and using the phasor concepts of ac circuits, we may write $\phi = \phi_{max} e^{j\omega t}$. This leads to $g_L = g_{L_{max}} e^{j\omega t}$. Inserting this phasor input into eqn. (6-4), we expect a phasor output $\delta n = \delta n_{max} e^{(j\omega t + \theta)}$

Thus,

$$j\omega \delta n_{max} e^{j(\omega t+\theta)} = g_{L_{max}} e^{j\omega t} - \frac{\delta n_{max} e^{j(\omega t+\theta)}}{\tau_r} \qquad (6\text{-}12)$$

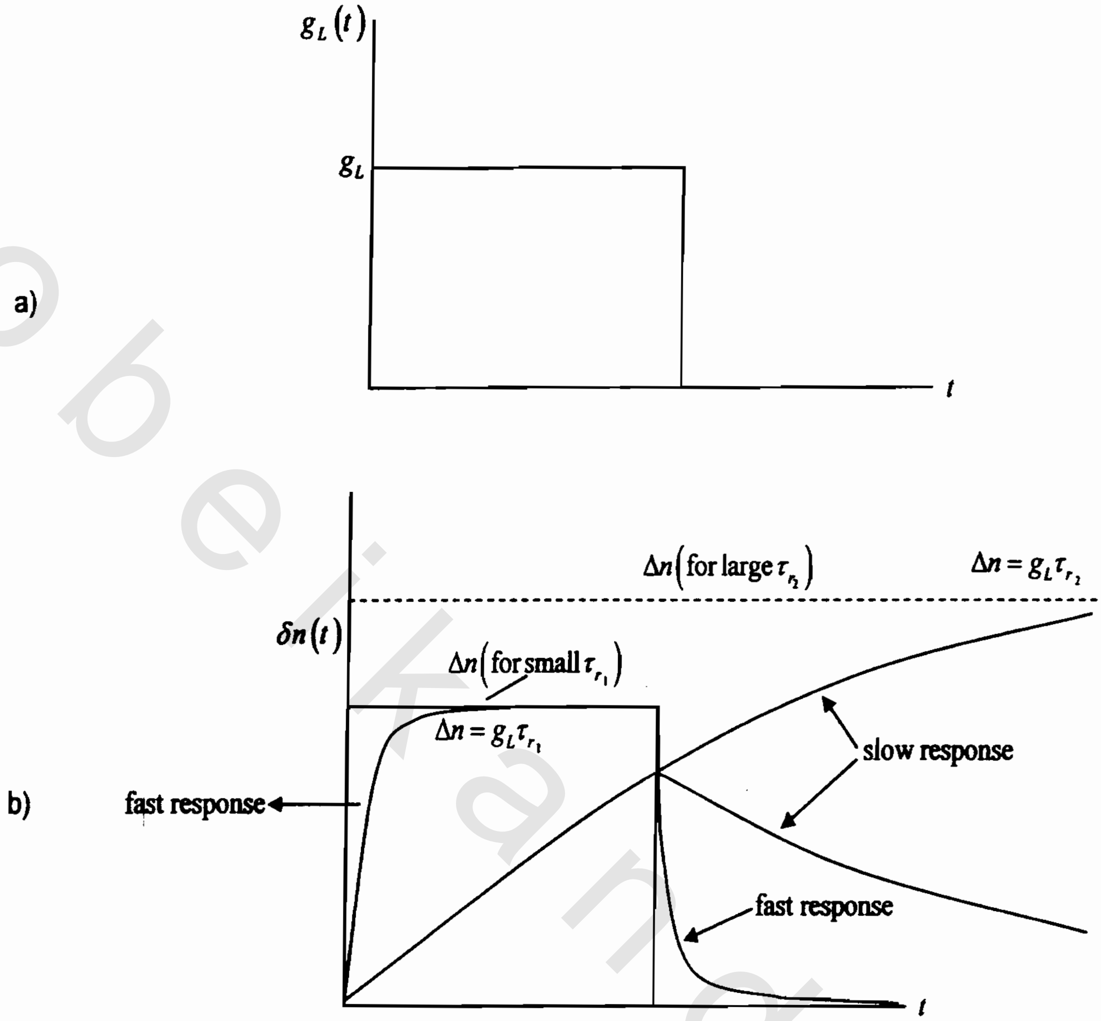

Fig. (6.1) Effect of τ_r on the transient response of a photoconductor
a) light pulse b) response

$$\left(j\omega + \frac{1}{\tau_r}\right)\delta n_{max} e^{j(\omega t+\theta)} = g_{L_{max}} e^{j\omega t}$$

Thus,

$$\delta n_{max} e^{j\theta} = \frac{g_{L_{max}}}{\left(j\omega + \frac{1}{\tau_r}\right)} \tag{6-13}$$

From phasor theory

$$|\delta n_{max}| = \frac{g_{L_{max}}}{\sqrt{\omega^2 + \frac{1}{\tau_r^2}}} = \frac{g_{L_{max}} \tau_r}{\sqrt{\omega^2 \tau_r^2 + 1}} \tag{6-14}$$

$$\theta = -\arctan \omega\tau_r \tag{6-15}$$

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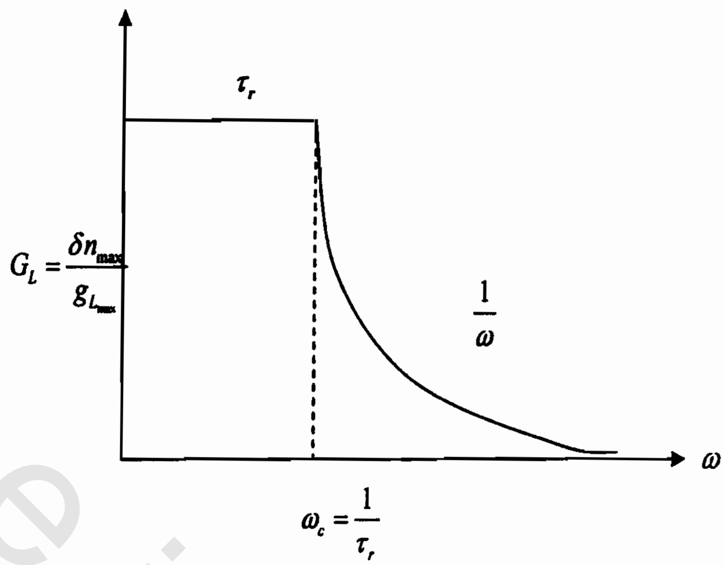

Fig. (6.2) Frequency response of a photoconductor

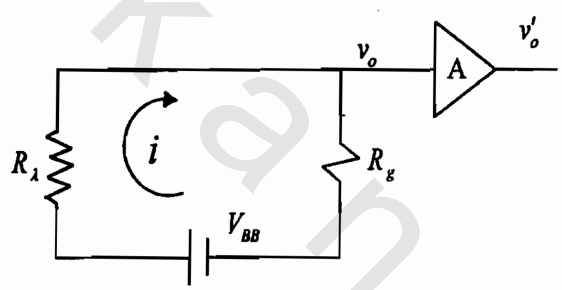

Fig. (6.3) Bias circuit for a photoconductor

For $\omega\tau_r << 1$, eqn. (6-14) reduces to

$$\delta n_{max} = g_{L_{max}} \tau_r \quad (6\text{-}16)$$

We define the photoconductive gain G_L as

$$G_L = \frac{\delta n_{max}}{g_{L_{max}}} \quad (6\text{-}17)$$

For low frequency

$$G_L = \tau_r \quad (6\text{-}18)$$

This expression is similar to eqn (6-6). It is called the dc or low frequency response.

For $\omega\tau_r >> 1$

$$\delta n_{max} = \frac{g_{L_{max}}}{\omega} \quad (6\text{-}19)$$

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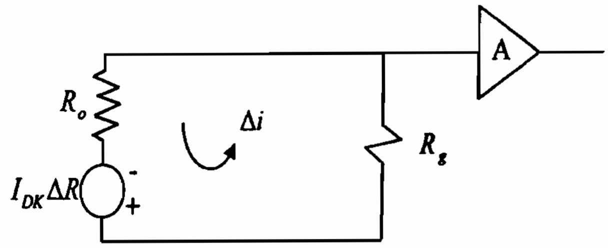

Fig. (6.4) An equivalent circuit for a photoconductor

This shows that the response decreases with frequency. The value of $\omega_c = 1/\tau_r$ is a critical value similar to the cutoff frequency of a LPF. If the chopping radian frequency of light ω (not υ of the photons) is less than ω_c, the output δn_{max} (and lence $\Delta\sigma_{max}$) is independent of ω and has maximum value. For $\omega > \omega_c$ the output rolls off, and the photoconductor loses its responsivity to light. We define the bandwidth of the photoconductor BW by

$$BW = \frac{\omega_c}{2\pi} = \frac{1}{2\pi\tau_r} \qquad (6\text{-}20)$$

It is the range of frequencies up to which the response remains flat (frequency-independent) and after which the photoconductive gain ($\delta n_{max} / g_{L_{max}}$) rolls off.

We note that

$$BW\tau_r = 1/2\pi \qquad (6\text{-}21)$$

Since τ_r is the flat part of the frequency response (Fig. 6.1) we see that $G_L BW$ (gain bandwidth product) is constant, i.e., increasing gain reduces BW and vice versa.

It is advantageous to decrease τ_r to increase the bandwidth and to make the photoconductor able to follow fast variations in the input light intensity levels. However, making τ_r too small reduces the output according to eqn. (6-17). A compromise is usually made. Fig. (6.1) shows the responsivity as a function of ω. This relation is called the frequency (or rather than the angular frequency) response of a photoconductor.

Ex. 6.3

Obtain an expression for photoresistance, and responsivity in a series circuit and hence develop an equivalent circuit, for a small signal of light.

Solution

$$i = \frac{V_{BB}}{R_\lambda + R_g} \qquad (6\text{-}22)$$

$$R_\lambda = R_{DK} + \Delta R \qquad (6\text{-}23)$$

$$i = \frac{V_{BB}}{R_{DK} + \Delta R + R_g} = \frac{V_{BB}}{(R_{DK} + R_g)} \frac{1}{\left(1 + \frac{\Delta R}{R_{DK} + R_g}\right)} \qquad (6\text{-}24)$$

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If $\frac{\Delta R}{R_{DK}+R_g} << 1$, using the binomial approximation

$$i = \frac{V_{BB}}{I_{DK}+R_g}\left[1-\frac{\Delta R}{R_{DK}+R_g}\right] \tag{6-25}$$

$$= I_{DK}\left(1-\frac{\Delta R}{R_{DK}+R_g}\right) \tag{6-26}$$

$$= I_{DK}+\Delta i \tag{6-27}$$

Where I_{Dk} is the bias current in the dark and Δi_L is the photocurrent given by

$$\Delta i = \frac{-I_{DK}\Delta R}{R_{DK}+R_g} \tag{6-28}$$

Thus we deduce a small signal equivalent circuit (Fig. 6.4) where

$$v_o = \frac{I_D \Delta R}{R_g + R_{DK}} R_g \tag{6-29}$$

We define the responsivity $\Re$ in this case as

$$\Re = \frac{I_{DK}\Delta R}{g_L} \tag{6-30}$$

Since the resistance is given by

$$R = \frac{\ell}{\sigma A} \tag{6-31}$$

$$\Delta R = \frac{-\ell}{\sigma^2 A}\Delta\sigma \tag{6-32}$$

$$\Delta\sigma = |q|(\mu_n+\mu_p)\Delta n \tag{6-33}$$

$$\Delta n = g_L \tau \tag{6-33}$$

$$\frac{\Delta R}{R_o} = -\frac{\Delta\sigma}{\sigma_o} \tag{6-35}$$

$$\Delta R = \frac{-\ell}{\sigma_o^2 A}|q|(\mu_n+\mu_p)\Delta n \tag{6-36}$$

$$|\Delta R| = K g_L \tau_r \tag{6-37}$$

where K is a constant given by

$$K = \frac{\ell}{\sigma_o^2 A}|q|(\mu_n+\mu_p) \tag{6-38}$$

Then

$$\Re = K\tau_r \tag{6-39}$$

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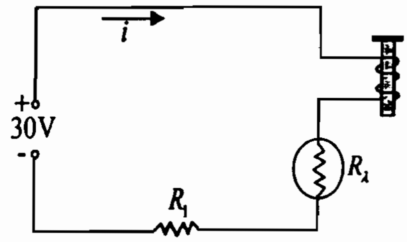

Fig. (6.5) Relay control by a photoconductive cell

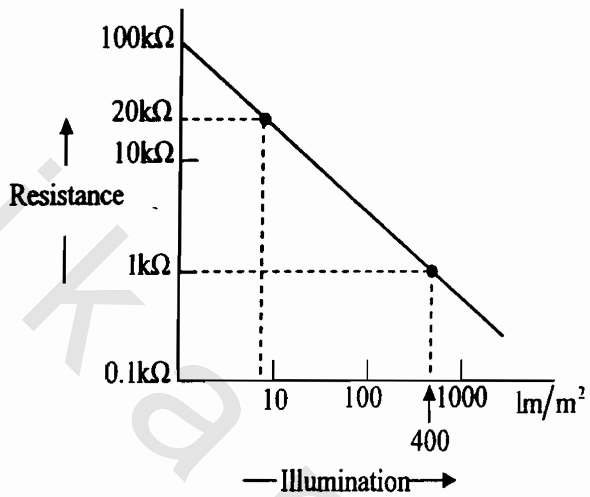

Fig. (6.6) Illumination characteristic for a photoconductive cell

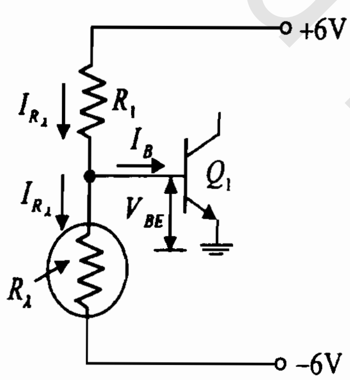

Fig. (6.7) A circuit to switch transistor off when a photoconductive cell is illuminated

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Ex. 6.4

A relay is to be controlled by a photoconductive cell with the characteristic shown in Fig. (6.5). The relay is to be supplied with $10\,\mathrm{mA}$ from a 30-V supply when the cell is illuminated with about $400\ \mathrm{lumens/m^2}$. It is required to be deenergized when dark. Sketch a suitable circuit and calculate the required series resistance and the level of the dark current.

Solution

The circuit is shown in Fig. (6-5). A series resistor R_1 is included to limit the current

The current is

$$I = \frac{30\mathrm{V}}{R_1 + R_\lambda}$$

or

$$R_1 = \frac{30}{I} - R_\lambda$$

From (Fig. 6.6) the cell resistance R_λ at $400\,\mathrm{lm/m^2} \approx 1k\Omega$:

$$R_1 = \frac{30\mathrm{V}}{10\mathrm{mA}} - 1\mathrm{k\Omega} = 2\mathrm{k\Omega}$$

and the cell dark resistance $R_{Dk} \approx 100k\Omega$ (from. Fig. 6.6)

$$I_{DK}\ \text{(Dark current)} \approx \frac{30\mathrm{V}}{2\mathrm{k\Omega} + 100\mathrm{k\Omega}} \approx 0.3\mathrm{mA}$$

Ex. 6.5

An *npn* transistor is to be biased on when photoconductive cell is dark, and off when it is illuminated. The supply voltage is $\pm 6\mathrm{V}$, and the transistor base current is to be $200\mu\mathrm{A}$ when on. If the photoconductive cell has the characteristic shown in Fig. (6.6). Design a suitable circuit.

Solution

The circuit is as shown in Fig. (6.7). When dark the cell resistance is high, and the transistor base is to be biased above its grounded emitter. When illuminated, the base voltage is to be below ground level.

From Fig. (6.6), the cell dark resistance $R_{Dk} \approx 100k\Omega$.

When the transistor is on when the cell is dark.

Cell voltage in the dark $V_D = 6\mathrm{V} + V_{BE} = 6.7\mathrm{V}$ (for a silicon transistor)

Dark cell current $I_{DK} = \dfrac{6.7\mathrm{V}}{100\mathrm{k\Omega}} = 67\mu\mathrm{A}$

The current through R_1 is

$$I_{R_1} = I_{DK} + I_B = 67\mu\mathrm{A} + 200\mu\mathrm{A} = 267\mu\mathrm{A}$$

$$V_{R_1}\ \text{(voltage across } R_1) = 6\mathrm{V} - V_{BE} = 5.3\mathrm{V}$$

$$R_1 = \frac{5.3\mathrm{V}}{267\mu\mathrm{A}} \approx 20\mathrm{k\Omega}$$

When the transistor is off, the transistor is to be at or below zero volts.

$V_{R_1} \approx 6\text{V}$

$$I_{R_1} = \frac{6\text{V}}{20\text{k}\Omega} = 300\mu\text{A}$$

Since $I_B \neq 0$, the cell current is $I_{R_1} = 300\mu\text{A}$, and cell voltage $\approx 6\text{V}$

Cell resistance under light $R_\lambda = \dfrac{6\text{V}}{300\mu\text{A}} = 20\text{k}\Omega$

Therefore, Q_1 will be off when the cell resistance is $20\text{k}\Omega$ or less, i.e., when the illumination level is above approximately $7\ \text{lm/m}^2$.

6.3 Reverse Current in a pn Junction

The reverse current in the transition region is composed of carriers being swept by the local built-in electric field. This current must be supplied by minority carriers (holes in the n-side and electrons in the p-side), being swept by the local electric field inside the transition region. In the depletion region, very few carriers exist anyway, and the reverse current becomes limited by this supply of minority carriers diffusing toward the junction (neglecting recombination and generation inside the depletion region). Since the reverse current depends on the rate of collection of carriers diffusing toward the junction rather than how fast they are swept, this current becomes insensitive to the barrier height. We call this current the saturation current (also known as the leakage current) I_o.

If we consider a volume of an n-type material of area A and the hole diffusion length L_p, the rate of thermal generation of holes within this volume is $AL_p g_o$. From the discussion associated with eqn. (1-51).

$$g_o = rn_o p_o = \frac{n_o}{\tau_{n_o}} = \frac{p_o}{\tau_{p_o}} \tag{6-40}$$

We make the following definitions

$$\tau_{n_o} = \frac{1}{rp_o} \tag{6-41}$$

$$\tau_{p_o} = \frac{1}{rn_o} \tag{6-42}$$

where τ_{n_o} and τ_{p_o} represent decay times for the electron and hole populations respectively at thermal equilibrium. We note that the excess carrier life time is related to the decay times at thermal equilibrium by

$$\frac{1}{\tau_r} = \frac{1}{\tau_{n_o}} + \frac{1}{\tau_{p_o}} \tag{6-43}$$

$$\tau_r = \frac{\tau_{n_o}\tau_{p_o}}{\tau_{n_o} + \tau_{p_o}} \tag{6-44}$$

This is in harmony with eqn. (6-5). Thus,

$$\tau_r = \frac{1}{r(n_o + p_o)} = \frac{\tau_{n_o}\tau_{p_o}}{\tau_{n_o} + \tau_{p_o}} \tag{6-45}$$

which is in agreement with eqn. (6-43). This expression is similar to two resistance in parallel. The smaller of the two determines the net resistance. We must differentiate between τ_{n_o} and τ_{p_o} and the excess carrier lifetime τ_r. We note that for an n-type material

$$\tau_r = \tau_{p_o} \tag{6-46}$$

and for a p-type material

$$\tau_r = \tau_{n_o} \tag{6-47}$$

The rate of recombination at thermal equilibrium is not to be confused with the excess carrier recombination rate $\frac{\delta p}{\tau_r}$.

Now, the rate of thermal generation of holes G_{op} within L_p is given by

$$G_{op} = AL_p \frac{p_{n_o}}{\tau_{p_o}} \tag{6-48}$$

Assume that each thermally generated hole diffuses out of the volume before recombination takes place, the result is hole saturation current I_{o_p}. For an n-material, $n_o > p_o$, and then $\tau_{p_o} < \tau_{n_o}$ .Hence, τ_r is equal to the thermal equilibrium decay time of the minority (which is holes) $\tau_{r_p} = \tau_{p_o}$, i.e., recombination is determined by the minority carriers. Since.

$$L_p = \sqrt{D_p \tau_{p_o}} \tag{6-49}$$

$$L_n = \sqrt{D_n \tau_{n_o}} \tag{6-50}$$

$$I_{op} = |q| AL_p \frac{p_{n_o}}{\tau_{p_o}} = \frac{|q| AD_p}{L_p} p_{n_o} \tag{6-51}$$

Similarly,

$$I_{on} = |q| AL_n \frac{n_{p_o}}{\tau_{n_o}} = \frac{|q| AD_n}{L_n} n_{p_o} \tag{6-52}$$

We note that τ_{r_p} is the recombination lifetime for the n-material predetermined by the minority carriers (which are holes) and τ_{r_n} is the recombination lifetime for the p-material predetermined by minority carriers (which are electrons). The emphasis on minority carriers renders the pn junction and related devices: minority carrier limited. The minority carriers rather than the majority carriers play the central role in the performance of the device. In such devices, the dominant current mechanism is diffusion. In resistors and related devices, the dominant current mechanism is drift, hence called majority limited devices.

The total saturation current I_o is given by

$$I_o = I_{o_p} + I_{o_n}$$

$$= |q| A \left(L_p \frac{p_{n_o}}{\tau_{r_p}} + L_n \frac{n_{p_o}}{\tau_{r_n}} \right) \tag{6-53}$$

$$= |q| A n_i^2 \left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right) \tag{6-54}$$

Note that I_o is a very sensitive function of temperature because of n_i^2 (Ex. 6.6)

To recapitulate, the reverse current in the transition region results from the collection of minority carriers thermally generated within a diffusion length away from the junction, and is dependent of the bias voltage. This current is small because the number of holes and electrons diffusing into the junction is small and is independent of the barrier height.

Ex. 6.6

Show how temperature affects the reverse current I_o

Solution

From eqns. (6-54) and (2-26)

$$I_o = |q| A A_o T^3 e^{-E_g/KT}\left(\frac{D_p}{L_p N_D}+\frac{D_n}{L_n N_A}\right) \qquad (6\text{-}55)$$

Thus,

$$\ell n I_o = \ell n\left(|q| A A_o\right) + 3\ell n T - \frac{E_g}{kT} \qquad (6\text{-}56)$$

Differentiating both sides,

$$\frac{dI_o}{I_o} = \frac{3\Delta T}{T} + \frac{E_g}{2kT^2}\Delta T \qquad (6\text{-}57)$$

$$\frac{1}{I_o}\frac{dI_o}{dT} = \frac{3}{T} + \frac{1}{2}\frac{V_g}{TV_{th}} \qquad (6\text{-}58)$$

At room temperature and with $V_g = 1\text{V}$ for silicon eqn. (6-58) yields

$$\frac{1}{I_o}\frac{dI_o}{dT} = \frac{3}{300} + \frac{1}{2}\frac{1}{300\times 0.025} = 0.08^o C^{-1}$$

Thus,

$$\frac{\Delta I_o}{I_o} = 0.08\Delta T \qquad (6\text{-}59)$$

For $\Delta T = 1^o C, I_o$ will increase by 8%. This shows how fast I_o increases with temperature.

6.3 Photovoltaic Effect

When light of energy $h\upsilon \geq E_g$ falls on a pn junction more bonds are broken. Thus, more carriers enhance the reverse current due to light. This is called photovoltaic effect. We define g_L as the rate of generation of electron hole pairs due to light per unit volume. In this case we may calculate the increase in reverse current due to light I_L by calculating the rate of excess holes and excess electrons reaching the boundaries of the transition region. Once they get there they are swept away by the built-in electric field, hence increasing the reverse current. The reverse current due to thermal generation I_o -however- is not affected by light. Increasing the level of illumination increases the photocurrent I_L. Thus the reverse current I_r given by

$$I_r = I_o + I_L \qquad (6\text{-}60)$$

where I_o is given by eqn. (6-50) and I_L is given by

$$I_L = |q| A\left(L_n + L_p\right) g_L \qquad (6\text{-}61)$$

where g_L is the rate of absorption of photons per unit volume per unit time or the rate of generation of electron hole pairs due to light per unit volume.

We may now write the I-V characteristics of a pn junction under light as

$$I = I_o e^{V/V_{th}} - I_r \qquad (5\text{-}62)$$

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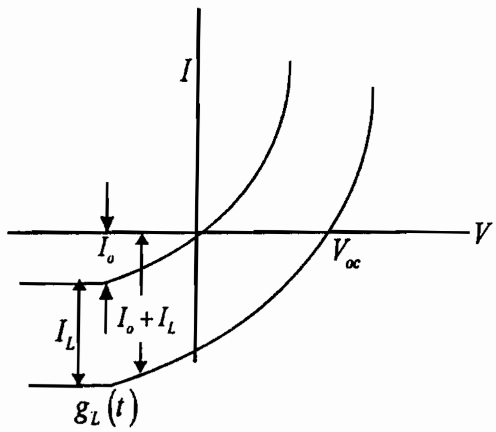

Fig. (6.8) IV characteristics of a pn junction under light

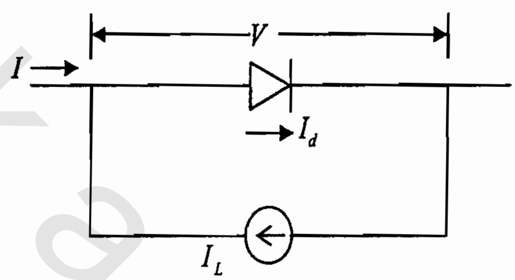

Fig. (6.9) Equivalent circuit of a pn junction under light

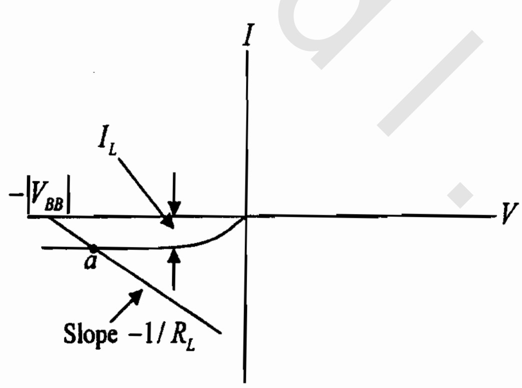

Fig. (6.10) Load line in a photodiode

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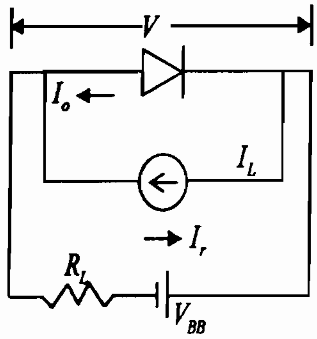

Fig. (6.11) Equivalent circuit of a photodiode

where the first term is the forward current which is not affected by light and the second term is given by eqn. (6-61). Thus

$$I = I_o\left(e^{V/V_{th}} - 1\right) - I_L = I_d - I_L \qquad (6\text{-}63)$$

where I_d is the ideal diode current. Thus, the IV characteristic of a pn junction is shifted by I_L (Fig. 6.8). We note that for $I = 0$ we have an open circuit voltage V_{oc} given by

$$I_L = I_o\left(e^{V_{oc}/V_{th}} - 1\right) \qquad (6\text{-}64)$$

$$e^{V_{oc}/V_{th}} = \frac{I_o + I_L}{I_o} = 1 + \frac{I_L}{I_o} \qquad (6\text{-}65)$$

$$V_{oc} = V_{th}\ln\left[1 + \frac{I_L}{I_o}\right] \qquad (6\text{-}66)$$

If we have a short circuit, the short circuit current $I_{sc} = -I_L$. This characteristic can be represented by an equivalent circuit (Fig. 6.9) in which a current source I_L is connected in parallel with an ideal diode.

We may now verify that under short circuit condition $(V = 0)$ $I_{sc} = -I_L$ and under open circuit condition we have V_{oc} given by eqn. (6-66). In this case charges accumulate such that the p-region - where holes of the photocurrent accumulate become positively charged and the n-region - where electrons accumulate - becomes negatively charged. This voltage is measurable by a voltmeter, since it implies a shift in the Fermi level, and hence, is an external voltage, as if an external voltage due to light is applied.

In the characteristics we have two regions. In the reverse bias, the saturation current increases by I_L, which indicates the amount of absorbed light. Thus, this device may be used as a photodetector, called photodiode, or it can be used to measure the intensity of light. The bias point can be obtained by drawing a load line from point - $|V_{BB}|$ on the abscissa (Fig. 6.10). The equivalent circuit (Fig. 6.11) depicts this situation.

In the forward direction, a load resistance R_L is connected in parallel with the photodiode. The load line is drawn from the origin since there is no battery (Fig. 6.12). The equivalent circuit is shown in Fig. (6.13). We call this device a solar cell (or solar battery) since it can supply power to the resistance. In fact this power comes from the conversion of light to electricity. Without light no power can be dissipated in the resistance. The question that arises now is how to extract maximum power from a solar cell.
Consider the typical illumination characteristics of a photodiode as shown in Fig. (6.14). When dark $I_r = I_{DK} = I_o \approx 20\mu A$ and $|V_r| = 2V$. We define the static dark resistance R_{SDk} as

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a)

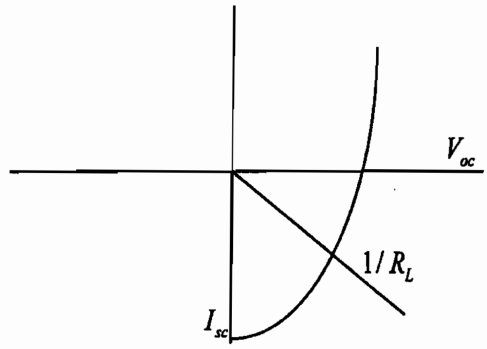

Fig. (6.12) Load line in solar cell

b)

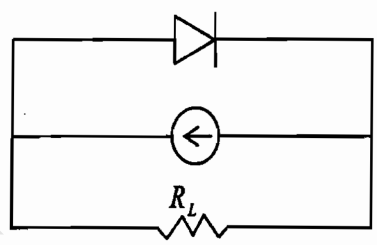

Fig. (6.13) Solar battery
a) characteristic b) equivalent circuit

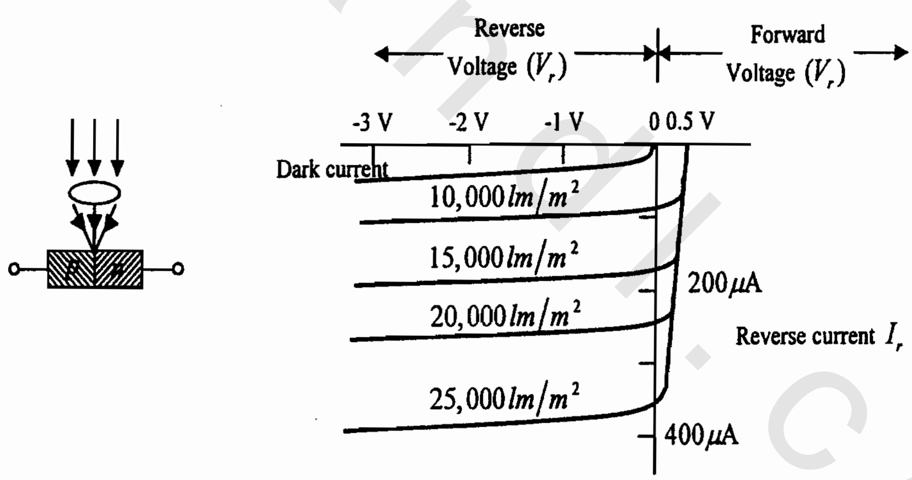

Fig. (6.14) Illumination characteristics of a photodiode

$$R_{SDK} = \frac{|V_r|}{I_r} \approx \frac{2V}{20\mu A} = 100k\Omega$$

When illuminated with $25,000\, lm/m^2$

$$I_r \approx 375\mu A$$

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a)

b)

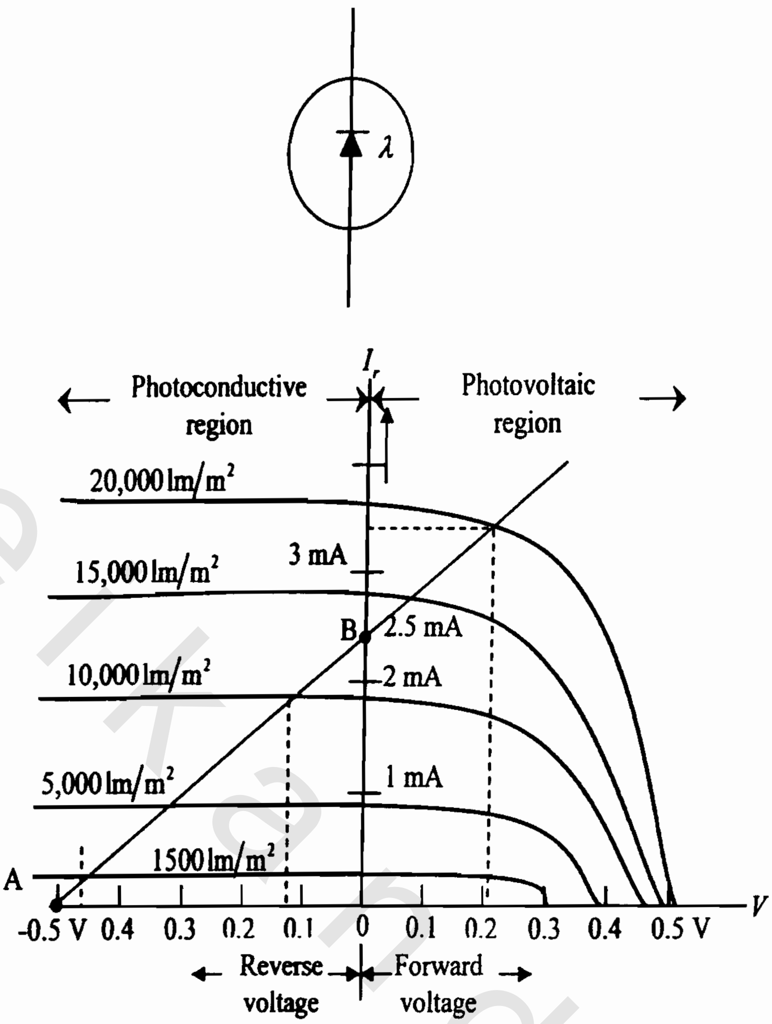

Fig. (6.15) Symbol and typical illumination characteristics for a silicon photodiode
a) photodiode symbol b) illumination characteristics

We also find the static resistance under light R_{SL}

and $$R_{SL} \approx \frac{2V}{375\mu A} = 5.3k\Omega$$

The static resistance has thus changed by a factor of approximately 20, and it is seen that the photodiode under reverse bias is said to be in a photoconductive mode.

When the reverse-bias voltage across a photodiode is removed, minority charge carriers will continue to be swept across the junction, while the diode is illuminated. This has the effect of increasing the number of holes accumulating in the p-side and the number of electrons accumulating in the n-side. But the barrier potential is negative on the p-side and positive on the n-side, and was produced by holes flowing from p to n and electrons from n to p. Therefore, the minority carrier flow tends to reduce the barrier potential as if an external forward biased were applied. When an external circuit is connected across the diode terminals, the minority carriers will return to their original side via the external circuit. The electrons which crossed the junction from p to n will now flow out through the n-terminal and into the p-terminal. Similarly, the holes generated in the n-material cross the junction and flow out through the p-terminal and

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into the n-material. This means that the device is behaving as a battery (source) with the n-side being the negative terminal and the p-side the positive terminal. In fact, a voltage can be measured across the photodiode terminals being, positive on the p-side and negative on the n-side. This photovoltage represents a shift in Fermi level, thus it can be measured by a voltameter. In short a photodiode can behave as a source of power or as a detector of light, depending on the biasing condition.

Typical silicon photodiode illumination characteristics (plotted in the first and second quadrants for convenience) are shown in Fig. (6.15). When the device operates with a reverse voltage applied, it functions as a photoconductive device. When operating without the reverse voltage, it operates as a photovoltaic device in the positive voltage direction. The circuit symbol for the device is also shown in Fig. (6.15).

Ex. 6.7

A photodiode with the illumination characteristics shown in Fig. (6.15) is connected in series with a 200Ω resistance and 0.5V supply. The supply polarity reverse biases the device. Draw the dc load line for the circuit and determine the diode currents and voltages at (1500), (10,000) and (20,000) lm/m^2 illumination.

Solution

The circuit is as shown in Fig. (6.16). In the dark the diode current $I_d = I_{rDK} = I_o$. If I_o is negligible.

$$|V_{BB}| = I_o R_1 + |V_d|$$

$$V_d = V_{BB} = -0.5\text{V}$$

Plot point A on Fig. (6.15) at $I_d = 0$ and $V_d = -0.5\text{V}$

When $V_d = 0, V_{R_1} = V_{BB}$

$$I_d = \frac{V_{R_1}}{R_1} = \frac{-0.5\text{V}}{200\Omega} = 2.5\text{mA}$$

Plot point B at $I_d = -2.5\text{mA}$ and $V_d = 0\text{V}$

Draw the dc load line through point A and B (Fig. 6.15).

From the load line,

At $1500\,\text{lm/m}^2, I_r \approx -0.2\text{mA}$ and $V_d \approx -0.45\text{mA}$

At $10{,}000\,\text{lm/m}^2, I_r \approx -1.9\text{mA}$ and $V_d \approx -0.12\text{mA}$

At $20.000\,\text{lm/m}^2, I_r \approx -3.6\text{mA}$ and $V_d \approx +0.22\text{mA}$

Note that the polarity of V_d changed from negative to positive at the highest level of illumination.

6.4 Solar Battery

At V_{oc} the power delivered to R_L is zero since the current is zero. At I_{sc} the voltage is zero, hence the power is also zero. The power becomes maximum in between (Fig. 6.17). Empirically, we may find the Q point for maximum power, i.e., matching condition, by constructing a rectangle whose sides are V_{oc} and I_{sc}. The diagonal of this rectangle is the load line for maximum power from which we can obtain R_L for matching condition.

Alternatively we may obtain the condition of matching by differentiating the expression for power (Prob. 6.15).

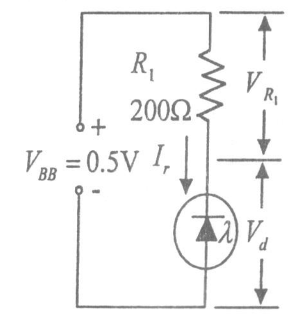

Fig. (6.16) Photodiode with load resistance

a)

b)

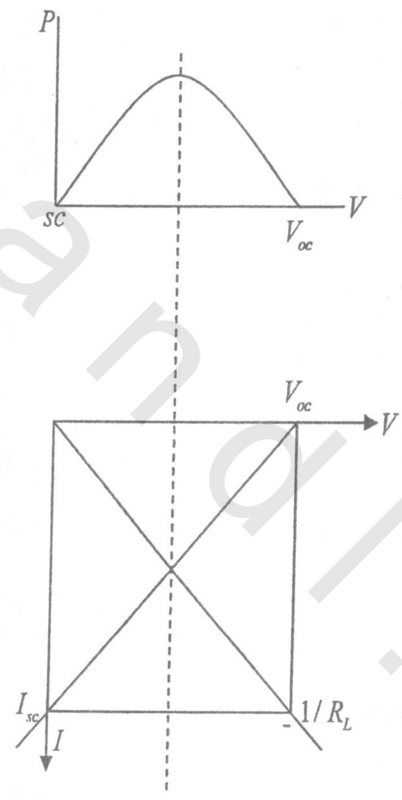

Fig. (6.17) Power delivered by a solar cell

a) characteristic b) matching condition in approximation

$$\begin{aligned} P &= VI \\ &= V\left[I_o\left(e^{V/V_{th}}-1\right)-I_L\right] \end{aligned} \quad (6\text{-}67)$$

Solar cells are usually connected in series to enlarge the voltage and the rows are connected in parallel to enlarge the current. Solar cells are used to convert solar energy into electricity in desolate areas, in military applications and in space, where satellite energy is obtained directly from the sun. Household electricity may also be obtained from solar panels on rooftops of buildings. The initial cost may be high but the running cost is minimal. Solar energy is considered one of cheap alternative sources of energy, called renewable energy sources.

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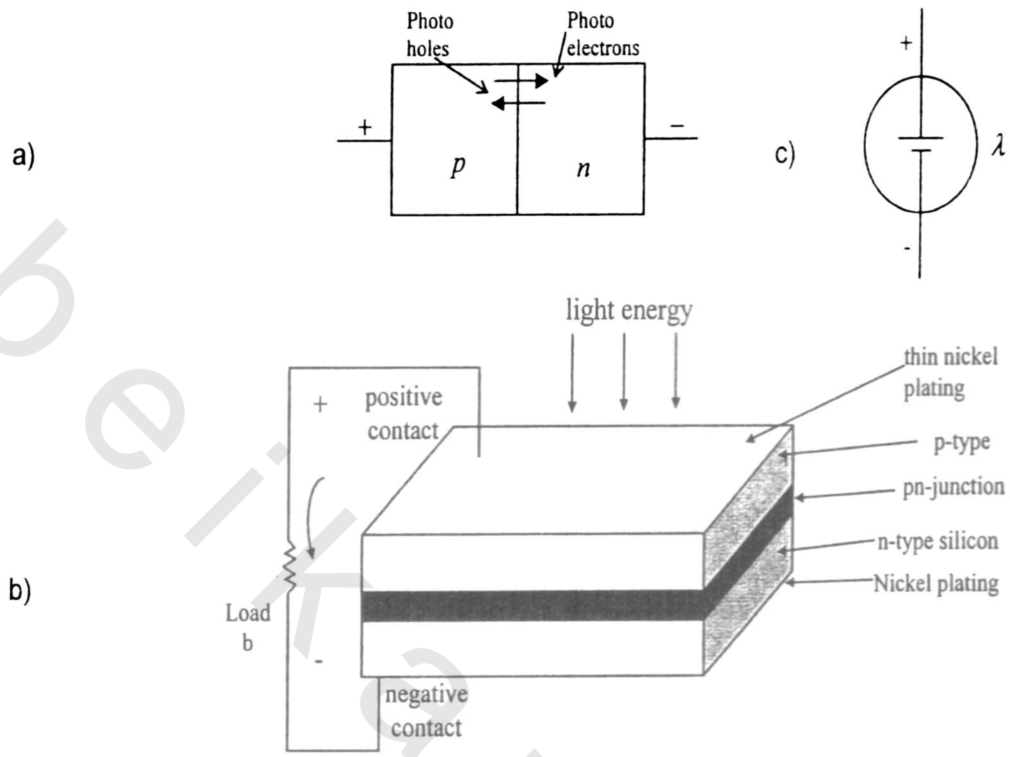

Fig. (6.18) Solar cell
a) polarity b) cross section c) symbol

Among other such sources are wind, tidal waves, water heads. The world is investing in research on alternative energy sources due to the limited resources of deposit (fossil) fuels in anticipation of an overall depletion of such fuels. Also, renewable energy sources are nonpolluting (environment-friendly) and are permanently available and free. If they do not completely satisfy the current demand they can at least offset some of the growing pressure on the consumption of deposit fuels whose cost is on the rise. Intensive research is also underway for developing ways to store and use solar energy day and night through fuel cells.

The construction and cross section of a typical power solar cell for use as an energy converter are shown in Fig. (6.18). The surface layer of p-type material is extremely thin so that light can penetrate to the junction. The nickel-plated ring around the p-type material is the positive output terminal, and the plating at the bottom of the n-type is the negative output terminal. The circuit symbol normally used for a photovoltaic device is also shown in Fig. (6.18).

Typical output characteristics of a power photocell are shown in Fig. (6.19). Consider the device characteristic when the incident illumination is $100\,\mathrm{mW/cm^2}$. If the cell is short circuited, the output current is $50\,\mathrm{mA}$. Since the cell voltage is zero, the output power is zero. If the cell is open circuited, the output current is zero. Therefore, the output power is again zero. For maximum output power the device must be operated at the knee of the characteristic.

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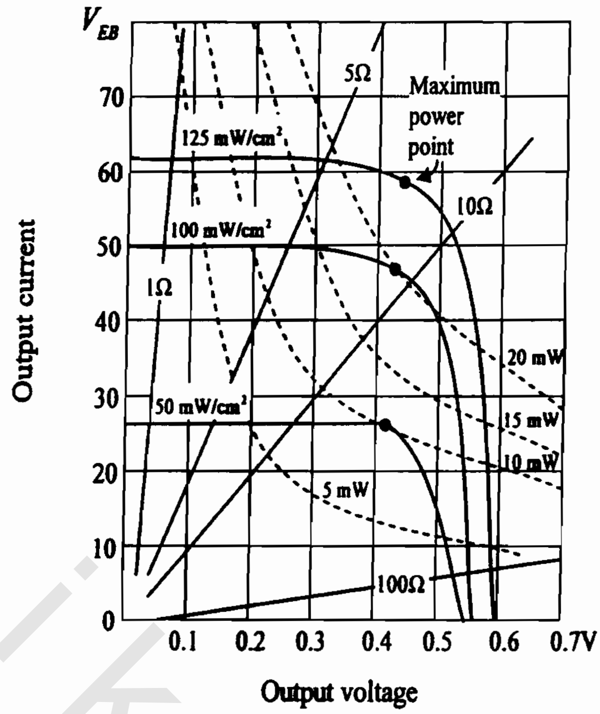

Fig. (6.19) Typical output characteristics of a power photocell for use as a solar cell converter

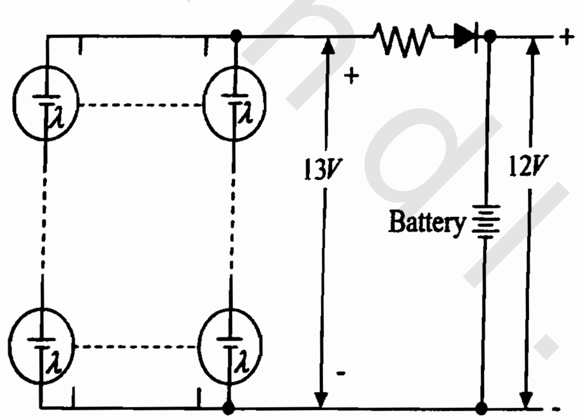

Fig. (6.20) Array of solar cells connected as a battery charger

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Ex. 6.8

An earth satellite has 12V batteries which supply a continuous current of 0.5 A. Solar cells with the characteristics shown in Fig. (6.19) are employed to keep the batteries charged. If the illumination from the sun for 12 hours in every 24 is $125\ \text{mW/cm}^2$, determine approximately the total number of cells required.

Solution

The circuit for the solar cell battery charger is shown in Fig. (6.20). The cells must be connected in series to provide the required output voltage, and groups of series-connected cells must be connected in parallel to produce the necessary current.

For maximum output power, each device should be operated at approximately 0.45 V and 57 mA from Fig. (6.19). Allowing for the voltage drop across the rectifier, a maximum output of approximately 13 V is required.

$$\text{Number of series-connected cells} = \frac{\text{output voltage}}{\text{cell voltage}} = \frac{13\ \text{V}}{0.45\ \text{V}} \approx 29$$

The charge taken from the batteries over a 24-hour period is 24 hours X 0.5 A or 12 ampere-hours. Therefore, the charge delivered by solar cells must be 12 ampere-hours.

The solar cells deliver current only while they are illuminated, i.e., for 12 hours in every 24. Thus, the necessary charging current from the solar cells is 12 ampere-hours/12 hours, or 1 A.

$$\text{Total number of groups of cells in parallel} = \frac{\text{output current}}{\text{cell current}} = \frac{1\ \text{A}}{57\ \text{mA}} \approx 18$$

The total number of cells required is

(number in parallel) X (number in series) =18X29 = 522

6.5 Phototransistor

A phototransistor is similar to an ordinary bipolar transistor, except that no base terminal is provided. Instead of a base current, the input to the transistor is provided in the form of light. Consider an ordinary transistor with its base terminal open circuited (Fig. 6.21).

Since

$$I_C = \beta I_B + (\beta+1) I_{C_o} \qquad (6\text{-}68)$$

$$I_B = 0$$

$$I_C = (\beta+1) I_{cBo} \qquad (6\text{-}69)$$

But at low values of current $\alpha = 0$, $\beta = 0$ so $I_C = I_E = I_{C_o} = I_{cBo}$ when the base is open circuit.

In the case of the photodiode, it was shown that the reverse saturation current was increased by the light energy incident on the junction. Similarly, in the phototransistor I_{CBO} increases when the collector-base junction is illuminated It will be I_{CBO_L}. When I_{CBO_L} is increased $\alpha > 0$, $\beta > 0$, the collector current under light $I_{C_L} = I_{E_L} = \left[(\beta+1) I_{CBO_L}\right]$ is also increased. Therefore, for a given amount of illumination on a very small area, the phototransistor provides a much larger output current than that available from a photodiode; i.e., the phototransistor is the more sensitive of the two. The circuit symbol and typical output characteristics of the phototransistor are shown in Fig. (6.22)

Ex. 6.9

A phototransistor having the characteristics shown in Fig. (6.22) has a supply of 20 V and a collector load resistance of $2\text{k}\Omega$, Determine the output voltage when the illumination level is (a) zero, (b) 20 mW/cm^2, and (c) 40 mW/cm^2

Solution

The load line is drawn in the usual way. (Fig. 6.22)

When $I_C = 0,\ V_{CE} = V_{CC}$

Plot point A at $I_C = 0,\ V_{CE} = 20\text{ V}$.

When $V_{CE} = 0,\ I_C = V_{CC}/R_L = 20\text{V}/2\text{k}\Omega = 10\text{mA}$.

Plot point B at $V_{CE} = 0,\ I_C = 10\text{mA}$

Draw the dc load line through points A and B.

From the intersections of the load line and the characteristics,

At illumination level =0 the output voltage $\approx V_{CE} = 20\text{V}$.

At illumination level $= 20\,\text{mW/cm}^2$, the output voltage $\approx 12.5\text{V}$

At illumination level $= 40\,\text{mW/cm}^2$, the output voltage $\approx 4\text{V}$

6.6 Light Emitting Diode (LED)

Charge carrier recombination takes place at a pn-junction as electrons cross from the n-side and recombine with holes on the p-side. Free electrons are in the conduction band of energy levels while holes are in the valence band. Therefore, electrons are at a higher energy level than holes, and some of this energy is given up in the forms of heat and light when recombination takes place. If the semiconductor material is translucent, the light will be emitted and the junction becomes a light source, i.e., a light-emitting diode (LED). A cross section view of a typical LED is shown in Fig. (6.23). Recently a new class of LED are manufactured using organic materials (OLED), which consume less power and are less costly than LEDs made from semiconductors such as GaAs or GaAsP.

LED operation can be easily understood using Fig. (6.24) for a forward biased pn junction. Electrons injected from the conduction band of the n-side to the p-side will fall down from the conduction band of the p-side to the valence band of the p-side onto energy vacancy (recombination with a hole) thus emitting energy. The electrons will exit the valence band of the p-side into the metal wire and then get pumped by the battery and fed again to the n-side and so on. Thus, electrons merely convert the battery power into emitted light plus heat losses.

Fig. (6.25a) shows the LED circuit symbol (the arrow directions indicate emitted light) and the arrangement of a typical seven-segment LED numerical display (Fig. 6.25b). Any desired numeral from 0 to 9 can be displayed by passing current through the appropriate segments.

Light-emitting diodes are usually switched on and off by means of a transistor circuit like the one illustrated in Fig. (6.26). The voltage drop across the LED is typically 1.2 V, and the transistor saturation voltage is approximately 0.2 V (i.e., for low I_C levels). Resistor R_2 is necessary to limit the current through the LED to the desired level. Ex. (6.10) shows how to design such a circuit.

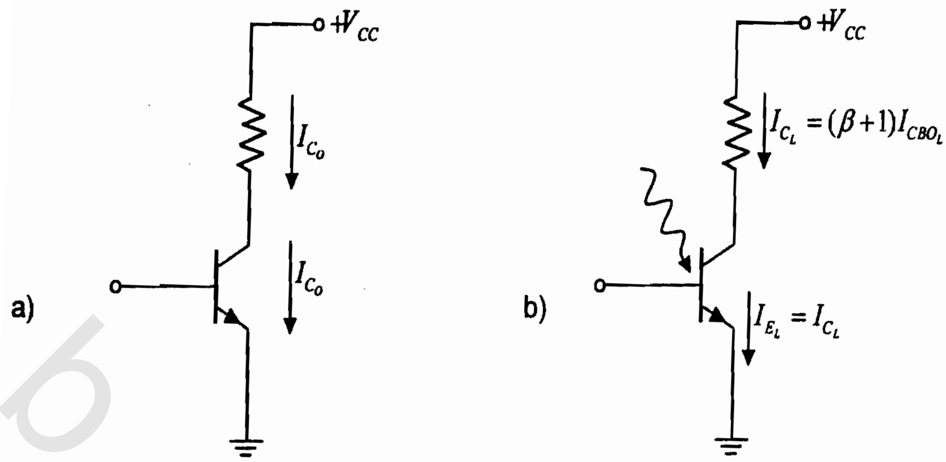

Fig. (6.21) Current in a transistor with its base open circuited
a) in the dark b) under light

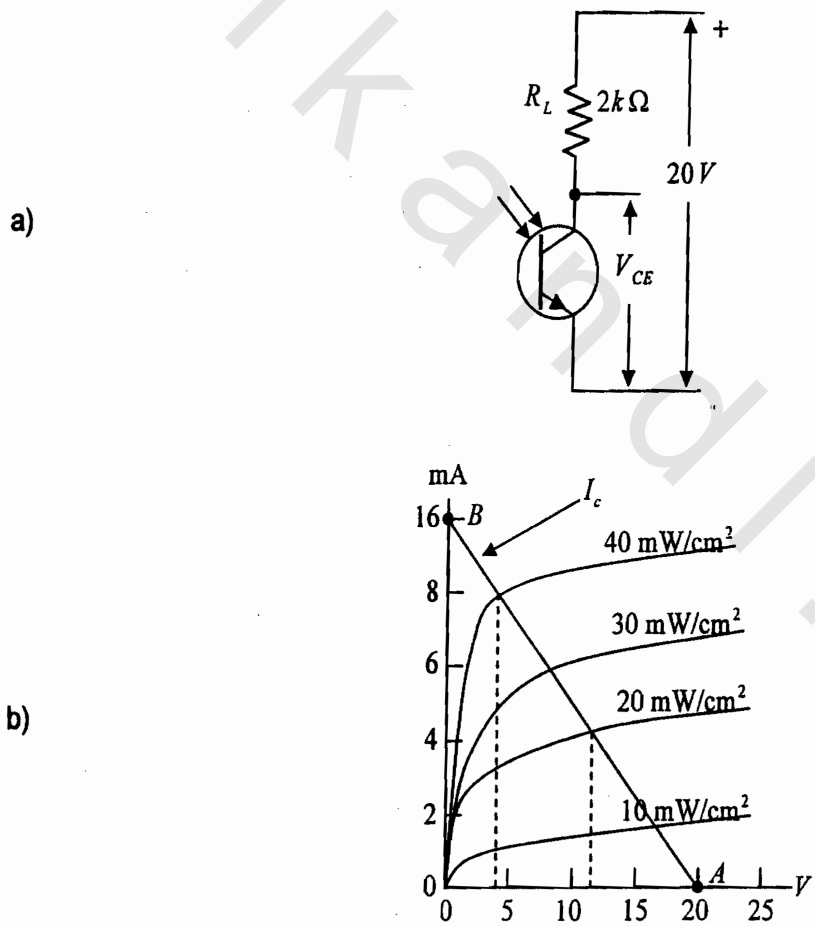

Fig. (6.22) Phototransistor
a) circuit b) characteristics and load line

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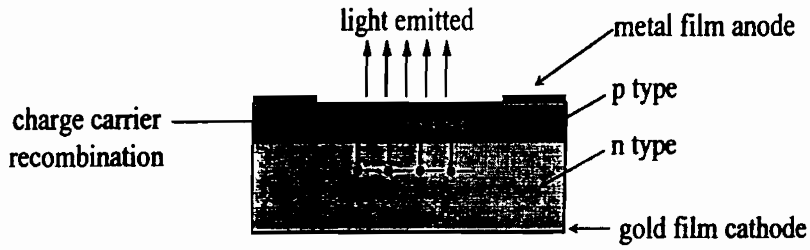

Fig. (6.23) Cross section of a light emitting diode

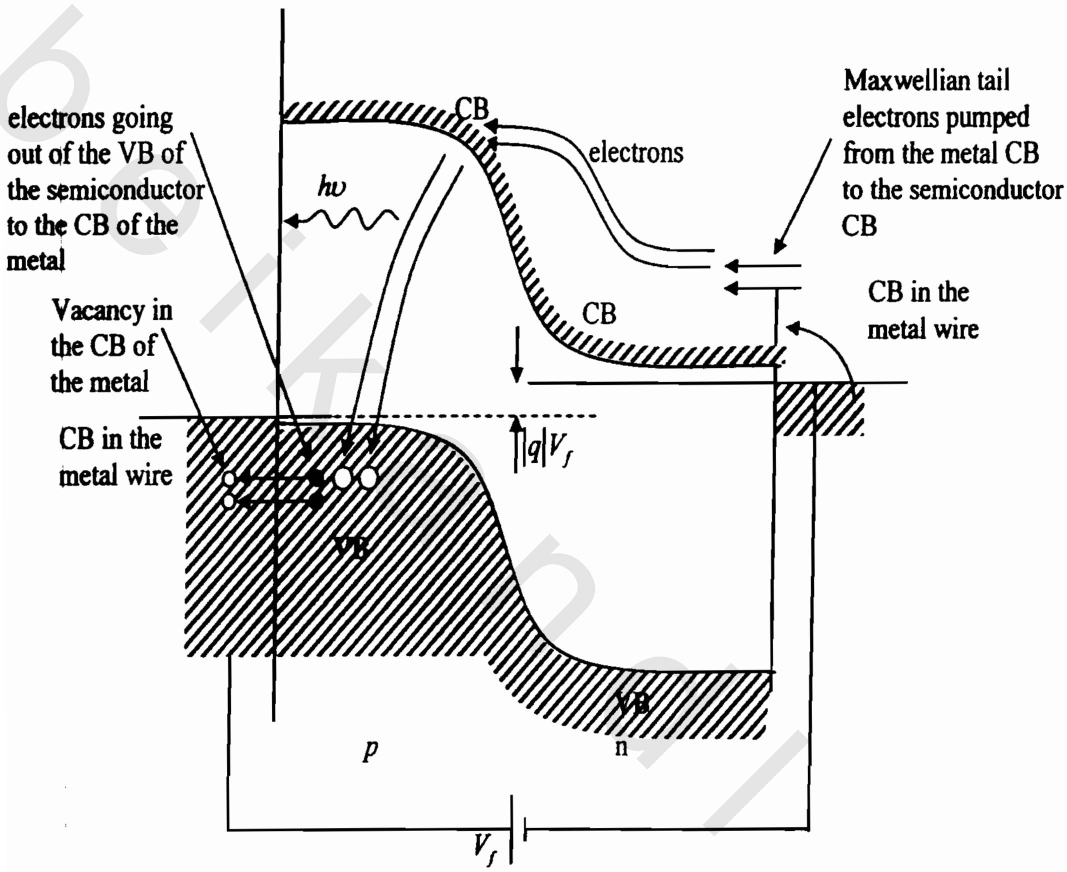

Fig. (6.24) LED operation

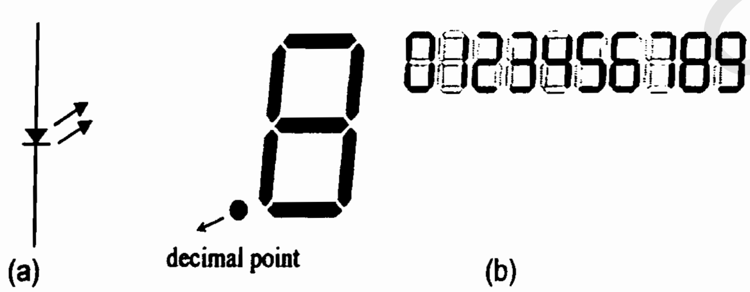

Fig. (6.25) LEDs in a seven segment display
a) symbol b) seven-segment display

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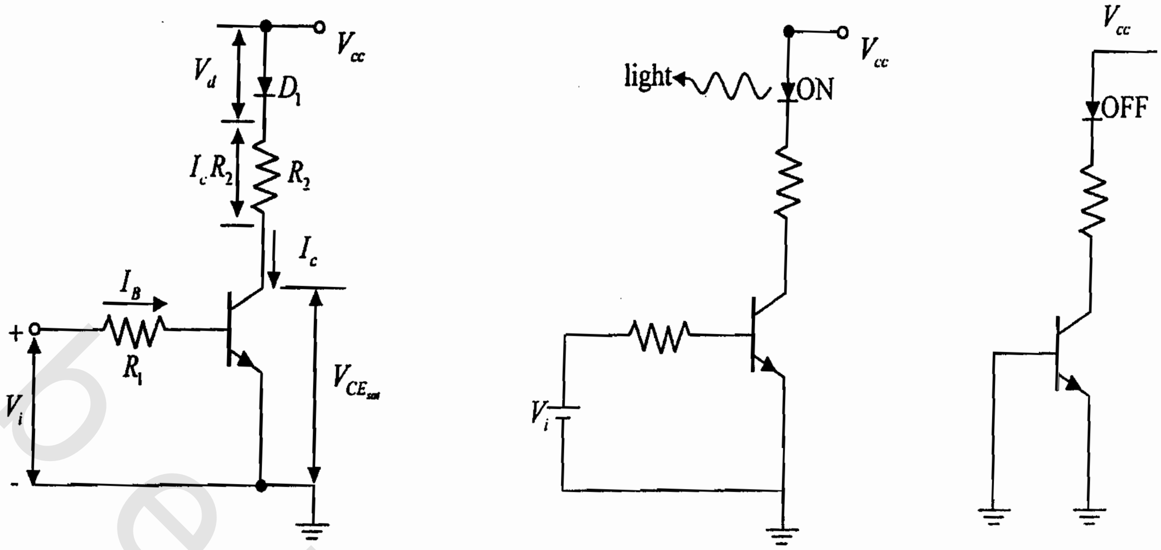

Fig. (6.26) LED and transistor switch
a) basic circuit   b) LED on   c) LED off

Ex. 6.10

The LED shown in Fig. (6.26) is to have a current of approximately 10mA passed through it when the transistor is on. The supply voltage is $V_{CC} = 9\text{V}$, and the input voltage is $V_i = 7\text{V}$. Calculate the required values of R_1 and R_2, Take $\beta = 100$

Solution

$$V_{CC} = V_d + I_C R_2 + V_{CE(sat)}$$

$$R_2 = \frac{V_{CC} - V_d - V_{CE(sat)}}{I_C}$$

$$= \frac{9\text{V-1.2V-0.2V}}{10\text{mA}}$$

$$= 760\Omega$$

I_C becomes

$$\frac{9\text{V-1.2V-0.2V}}{680\Omega} = 11.2\text{mA}$$

For $\beta = 100$

$$I_B = \frac{11.2\text{mA}}{100} = 112\mu\text{A}$$

$$V_i = I_B R_1 + V_{BE}$$

$$R_1 = \frac{V_i - V_{BE}}{I_B} = \frac{7\text{V} - 0.7\text{V}}{112\mu\text{A}}$$

$$\approx 56k\Omega$$

6.7 Liquid Crystal Display (LCD)

A liquid-crystal cell consists of a layer of liquid-crystal material sandwiched between glass sheets a high transparent metal film electrodes deposited on the inside faces (Fig. 6.27). With both glass sheets transparent, the cell is known as a transmittive-type cell. When only one glass sheet is transparent and the other has a reflective coating, the cell is termed reflective type.

The molecules in ordinary liquids normally have random orientations. In liquid crystals the molecules are normally oriented in a definite crystal pattern. When an electric field is applied to the liquid crystal, the molecules, which are approximately cigar shaped, tend to change their alignment randomly perpendicular to the field. Thus charge carriers flowing through the liquid disrupt the initial molecular alignment and cause a turbulence within the liquid. This is illustrated in Fig. (6.28). When not activated, the liquid crystal is transparent. When activated, the molecular turbulence causes the light to be scattered in all directions so that the activated areas appear bright. This phenomenon is known as dynamic scattering.

When not activated, the transmittive-type cell will simply transmit rear or edge lighting through the cell in straight lines. In this condition the cell will not appear bright. When activated, the incident light is diffusely scattered forward, as shown in Fig. (6.29a), and the cell appears quite bright even under high-intensity ambient light conditions. The reflective-cell operates from light incident on its front surface. When not activated, light is reflected in the usual way from the mirror surface, and the cell does not appear bright. When activated the dynamic scattering phenomenon occurs, and the cell appears quite bright (Fig. 6.29b). Transmittive cells are usually used in PC displays particularly in back lit laptops.

The field effect LCD is constructed similarly to the dynamic scattering type, with the exception that two thin polarizing optical filters are placed at the surface of each glass sheet. The liquid-crystal material employed is known as twisted nematic (TN) type, and it actually twists the light through as molecules themselves are twisted when the cell is not energized. This twisting allows the light to pass through the polarizing filters. Thus, in the case of a transmittive-type cell, the unenergized cell can let light through. When energized, the cell molecules straighten up and light is blocked.

Since liquid-crystal cells are light reflectors or transmitters rather than light generators, they consume very small amounts of energy. The only energy required by the cell is that needed to activate the liquid crystal. The total current flow through four small seven segment displays is typically about $25\ \mu A$ for dynamic scattering cells and $300\ \mu A$ for field effect cells. However, the LCD requires an ac voltage supply, either in the form of a sine wave or a square wave. This is because a continuous direct current flow produces a plating of the cell electrodes, which could damage the device. Repeatedly reversing the current avoids this problem.

Fig. (6.30) illustrates the square wave drive method for liquid-crystal cells. The back plane, which is one terminal common to all cells, is supplied with a square wave. A similar square wave is applied to each of the other terminals. These square waves are either in-phase or in antiphase with the back plane square wave. Those cells with waveforms in the back plane waveform (cell e and f in Fig. (6.30) have no voltage developed across them (both terminals of the segment are at the same potential); therefore, they are off. The cells with square waves antiphase with the back plane input have an ac voltage developed across them double the peak of each square wave, and the normally light cell appears dark.

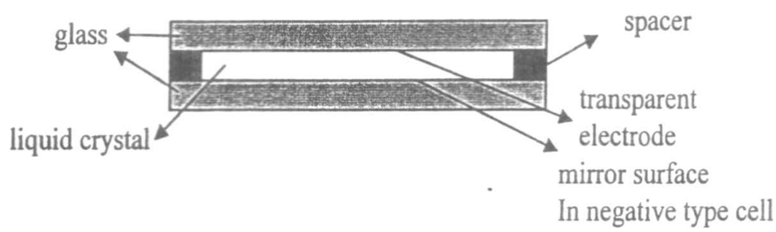

Fig. (6.27) LCD cell

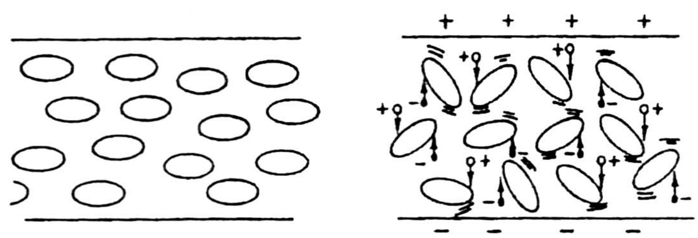

Fig. (6.28) Molecules in a liquid crystal

a) molecules are arranged when no current flows (dark)

b) when current flows (activated) alignment is disrupted causing turbulence (bright)

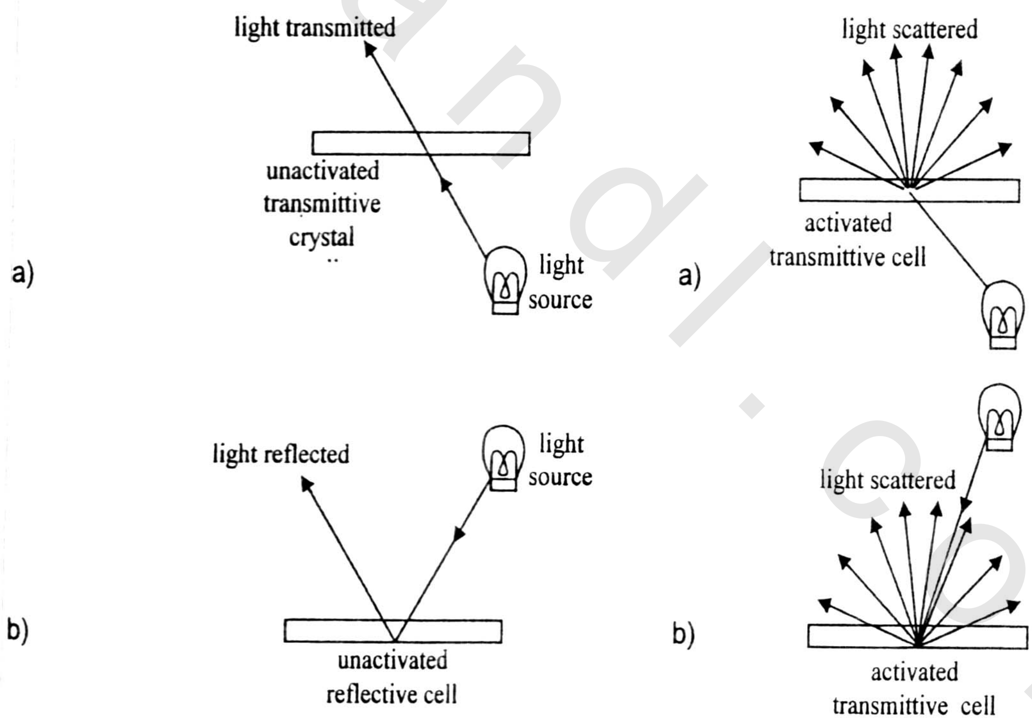

Fig. (6.29) Operation of liquid-crystal cells.

a) transmittive type b) reflective type

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Unlike LED displays, which are usually quite small, liquid-crystal displays can be fabricated in almost any convenient size. The maximum power consumed for. a typical LCD used in electronics equipment is around $20\,\mu W$ per segment, or $140\,\mu W$ per numeral when all seven segments are energized. Comparing this to about $400\,mW$ per numeral for a LED display (including series resistors), the major advantage of liquid-crystal devices becomes obvious. Perhaps the major disadvantage of the LCD is its decay time of $150\,ms$ (or more). This is very slow compared to the rise and fall times of LED's. In fact, the human eye can sometimes observe the fading out of LCD segments switching off. At low temperatures the response time is considerably increased.

6.8 Laser Diode

Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation". A laser emits radiation of essentially one wavelength (or a very narrow band of wavelengths). This means that the light has a single color (monochromatic); i.e., it is not a combination of several colors. Laser light is referred to as coherent light as opposed to light made up of a wide band of wavelengths, which is termed incoherent. The unique property of light generated by a laser is that the emission is in the form of a very narrow beam without significant divergence. The beam of light contains sufficient energy to weld metals or operate surgically.

The source of light in LED is the energy emitted by electrons which recombine with holes (at a lower energy level). In the case of an LED, the light is incoherent; i.e., it is made up of a wide spectrum of wavelengths. In a semiconductor laser electrons in the conduction band are injected from n-side to p-side by forward bias. A condition of population inversion must be created so that electrons in the conduction of the p-side find plenty of empty levels below in the valence band of the p-side.

Photons emitted are reflected back and forth by the mirror surfaces of the pn devices and stimulate further electrons to fall coherently from the conduction band of the p-side to the valence band of the p side. The reflection back and forward continues thousands of times, and the photons increase in number as they cause other similar photons to be emitted. This activity of reflection and generation of increasing numbers of photons amounts to amplification of the initially emitted photons. The beam of laser light emerges through the partially reflective end of the junction (Fig. 6.31).

To achieve population inversion, semiconductor laser is made up of degenerate materials i.e., highly doped pn junction. (Fig. 6.32a). The bands under forward bias are shown (Fig. 6.32b). The key to laser action is this state of population inversion, i.e. the state when electrons exist abundantly in a high level below which there are plenty of empty levels. In this case electrons are stimulated to fall collectively, thus, emitting coherent (in phase) light. Bouncing back and forth due to polished surfaces in the laser medium - where population inversion is constantly recreated - the light beam is amplified. When let pass it is a highly powered narrow and coherent well defined beam.

Population inversion at a junction is best described by the use of quasi Fermi levels. Because the material is degenerate when the junction is forward biased and considerable current flows electrons find themselves in a population inversion state (Fig. 6.32). Because $F_n - F_p > E_g$ where F_n and F_p are quasi Fermi levels for electrons and holes respectively, we find that the emitted photons which have energy $h\nu_g = E_g$ cannot be reabsorbed, which minimizes losses in a semiconductor laser, and this is a merit for this type of laser.

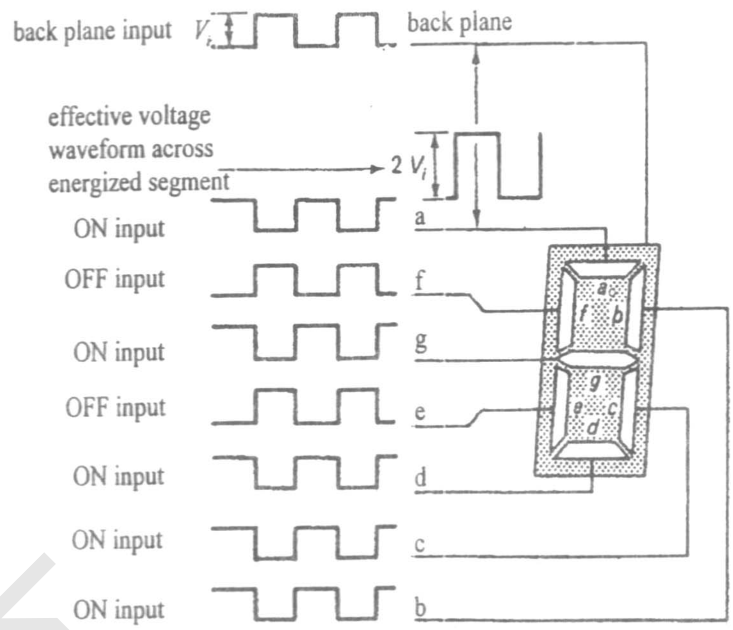

Fig. (6.30) Square wave drive for LCD

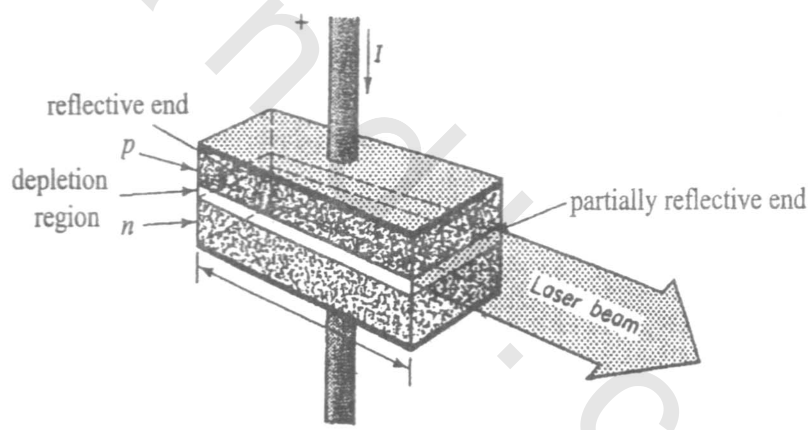

Fig. (6.31) Basic construction of a laser diode

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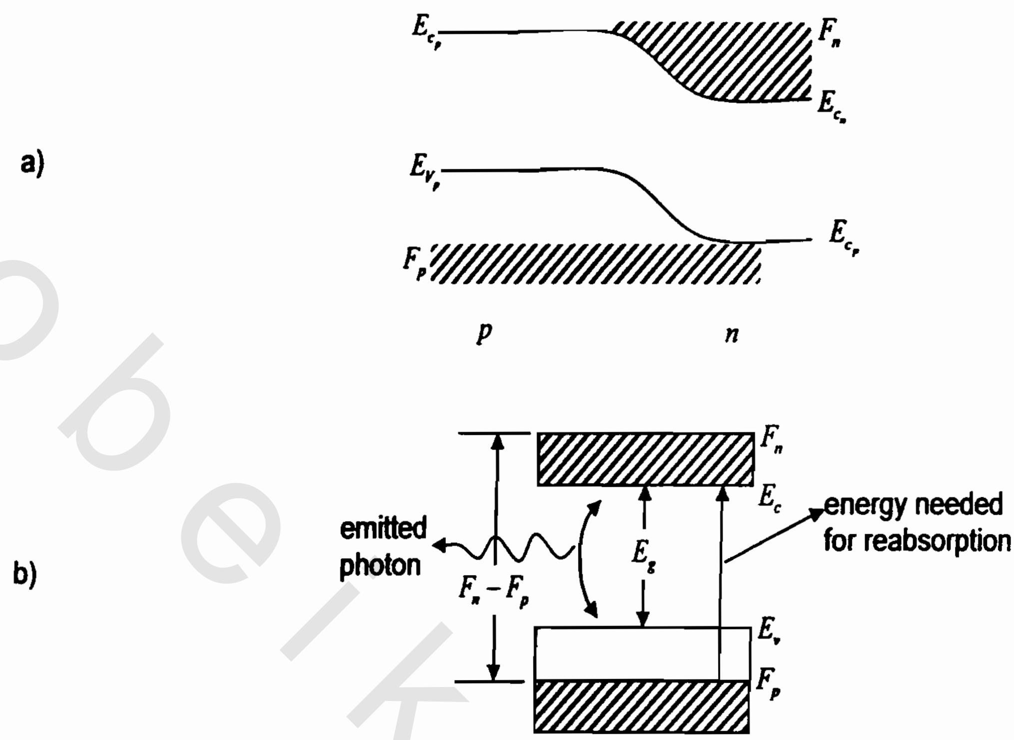

Fig. (6.32) pn junction laser
a) population inversion b) no reabsorption

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Problems

1- Verify eqn. (6-9) then show that $t_r = \frac{0.34}{BW}$

2- Assume, 10^3 electron-hole pairs/cm^3 are created optically every microsecond in a Si sample, $n_o = 10^{14} cm^{-3}$ and $\tau_r = 2\mu s$. Calculate the excess electron and hole concentrations, hence the total electron and hole concentrations.

3- In the above problem calculate the quasi Fermi levels for electrons and holes under light. Compare with E_{F_i} at equilibrium.

4- a) A 0.46μm thick sample of *GaAs* is illuminated with monochromatic light of $h\upsilon = 2eV$. The absorption coefficient is $5\times10^4 cm^{-1}$. The power incident on the sample is 10mW. Calculate the total energy absorbed by the sample per second. The bandgap of *GaAs* is 1.43eV.

b) Find the rate of excess thermal energy given up by the electrons to the lattice before recombination.

c) Find the rate of photons given off from recombination, assuming one emitted photon per recombining electron-hole pair.

d) Calculate the rate of electron-hole pair generation under light

5- a) A sample of *GaAs* of volume $1cm^3$ is doped with 10^{15} acceptor atoms/cm^3, n_i for $GaAs = 10^7 cm^3$. If 10^{14} electron hole pairs are generated per cm^3 per second and the excess carrier recombination time $\tau_r = 10^{-8} s$, calculate the steady state concentration and photoconductivity change %, $\mu_n = 8500 cm^2/Vs$ and $\mu_p = 400 cm^2/Vs$.

b) Sketch the change of concentration as a function of time if a square wave illumination is applied at a frequency of 50kHz, $h\upsilon = 1.43eV$.

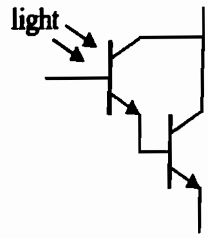
c) Defining the majority as holes and the minority as electrons in this case, calculate the percentage photoconductivity and show that they both have the same excess carrier lifetime.

6- Analyze photodarlington circuit shown.

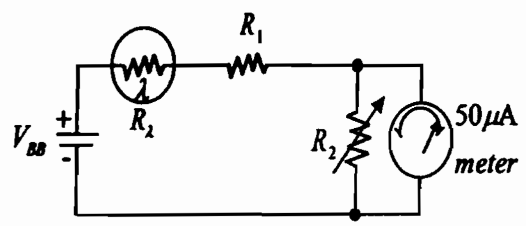
7- A pnp transistor is to be biased on when the level of illumination on a photoconductive cell is greater than $100 lm/m^2$ and off when dark. The supply voltage available is ±5 V, and the transistor collector current is to be 10 mA when on. If the transistor has a β of 50 and the photoconductive cell has the characteristics shown in Fig. (6.6), design a suitable circuit.

8- The light meter shown has the following components: $R_1 = 13.8k\Omega$, $R_2 = 390\Omega$ and meter resistance $R_m = 390\Omega$. The photoconductive cell has the characteristics in Fig. (6.6). Calculate the meter indication when the illumination level is (a) $400 lm/m^2$; (b) $7 lm/m^2$. Take $V_{BB} = 1.5V$.

9- A photodiode with the characteristics shown in Fig. (6.15) is connected in series with 0.4V supply and 100Ω resistance. Determine the static resistance offered by the photodiode at 15,000 lm/m^2, 10,000 lm/m^2, and 5000 lm/m^2.



Prob. (6.6)



Prob. (6.8)

10- A telephone system uses 6V rechargeable batteries which supply an average current of 50 mA. The batteries are recharged from an array of solar cells which each has the characteristics shown in Fig. (6.15). The average level of sunshine is $50\ mW/cm^2$ for 12 hours of each 24-hour period. Calculate the number of solar cells required, and determine how they should be connected.

11- The roof of a house has an area of $200\ m^2$ and is covered with solar cells which are each $2\ cm \times 2\ cm$. If the cells have the output characteristics shown in Fig. (6.15), determine how they should be connected to provide an voltage of approximately 220 V for average daytime illumination of $100\ mW/cm^2$, for If 12 hours illumination in every 24 hours, calculate the kilowatthours generated by the solar cells each day.

12- A phototransistor operating from a 25 V supply has the output, characteristics (Fig. 6.22) if V_{CE} is to be 10 V when the illumination level is $30\ mW/cm^2$, determine the value of load resistance that should be used.

13- A phototransistor with the characteristics shown in Fig. (6-22) is connected in series with a relay coil which has a resistance of $1\ k\Omega$. The coil current is to be 8 mA when the illumination level is $40\ mW/cm^2$. Determine the required supply voltage level, and estimate the coil current when the illumination falls to $10\ mW/cm^2$.

14- Design a circuit which ensures that street lights are turned off in daytime and turned on at night.

15- Analyze the circuit of Fig. (6.30) showing which segment is ON and which is OFF.

16- Obtain exact expression for maximum power and load resistance in a solar cell. Calculate these values for a) Maximum current of 50mA, b) Maximum voltage of 0.5V. Assume $I_o = 20\mu A$, use the characteristics of Fig. (6.15). Compare with the approximate method for matched condition.

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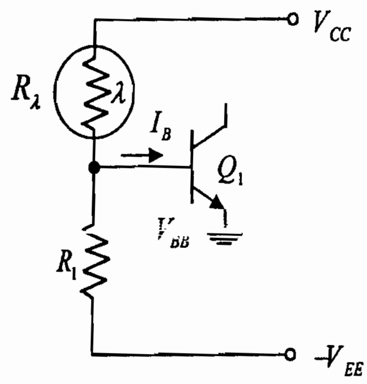

Prob. (6.17)

17- Analyze the circuit shown with the same data as in Ex. 6.5

18- Design an intruder detection circuit.

19- Design a 7 segment display drive using LEDs.

20- Obtain an expression for charge accumulated in p-side and n-side of an open circuit photoconductive cell and locate the positions of quasi Fermi levels in the cell.

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