Lecture 15: Optoelectronic devices: Introduction

Contents

1 Optical absorption

Opto electronic devices are based on the interaction of light with matter, typically semiconductors. Classic examples of these devices include the solid state semiconductor laser, light emitting diodes, photodetectors, and solar cells. In these devices, light or electromagnetic (EM) radiation is absorbed by the semiconductor and converted into electrical signals (electron-hole pairs) or electrical signals are converted to EM radiation (typically in the IR-Vis-UV range). To understand the working of these devices it is essentially to look at light - semiconductor interaction.

Consider light of wavelength, λ, incident on a semiconductor with band gap E_g. The energy of the radiation E is given by $\dfrac{hc}{\lambda}$. Based on the relation between E and E_g there can be two conditions.

1. $E < E_g$ - semiconductor is transparent, though there could be scattering at the interfaces.
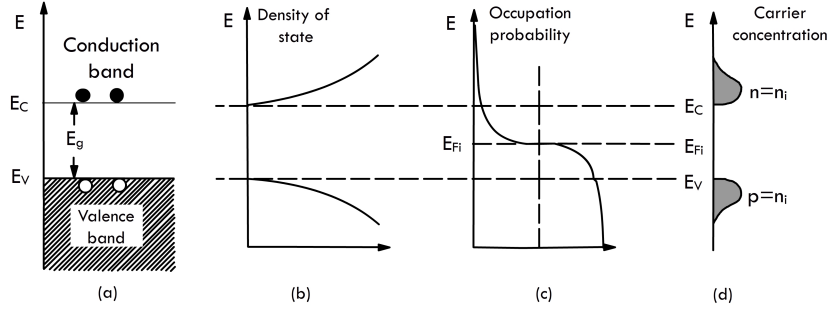
Figure 1: (a) Energy band diagram for a semiconductor showing the valence and conduction band edges. (b) The density of states monotonically increases from the band edges (c) Occupation probability of electrons and holes in the CB and VB, calculated with respect to the intrinsic Fermi function (d) Product of (b) and (c) gives the concentration of electrons in CB and holes in the VB. Adapted from *Physics of semiconductor devices - S.M. Sze.*

    2. $E > E_g$ - semiconductor is opaque and the radiation gets absorbed. Typically, this absorption produces electrons in the conduction band and holes in the valence band.

Light absorption occurs for photon energies larger than E_g, in *direct band gap semiconductors*. For indirect band gap semiconductors, absorption is usually small, unless the photon energy is larger than the direct gap value. The electrons and holes that are produced are unstable and lose energy to the lattice, i.e.*thermalize*, and move to the valence and conduction band edges. This can be understood by looking at the occupation probability ($f(E).g(E)$) which is maximum close to the band edges, summarized in figure 1.

  If light of energy E greater than E_g is incident on a semiconductor then the excess energy $(E - E_g)$ is lost to the lattice vibrations as heat (*thermalization*). The optical absorption process is summarized in figure 2. Let I_0 be the intensity of the incident radiation. The units of intensity are usually Wm^{-2} or $Jm^{-2}s^{-1}$. This is related to the photon flux (Γ_{ph}) and the energy of the radiation (hv) by

$$I_0 = \Gamma_{ph} (hv) \tag{1}$$

1.1 Absorption coefficient

The absorption of the photons is proportional to the thickness, for one dimensional absorption with the radiation perpendicular to the surface. If $I(x)$ is the intensity of the radiation at some depth x within the semiconductor,
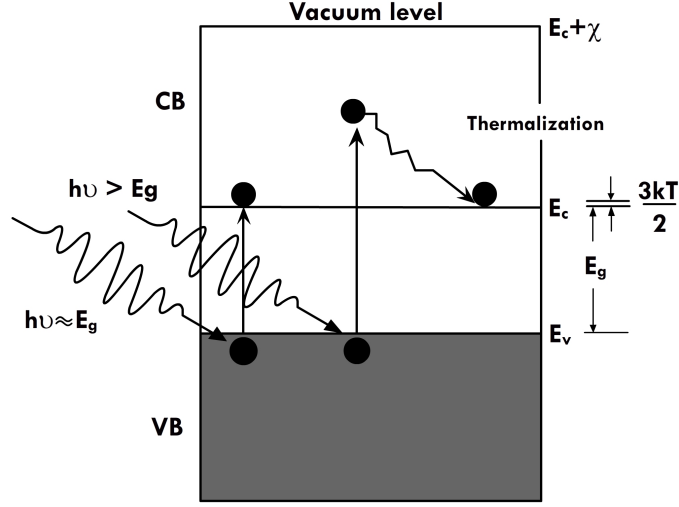
Figure 2: Optical absorption process in a semiconductor. Photons of energy equal to and greater than the band gap cause excitation of electrons. Higher energy electrons thermalize to the band edges. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

then the change in intensity for an incremental change in distance (δx) is given by

$$
\begin{aligned}
\delta I &= -\alpha \ \delta x \\
I(x) &= I_0 \ \exp(-\alpha x)
\end{aligned}
\tag{2}
$$

This is shown schematically in figure 3. This is called the **Beer-Lambert law** where α is the absorption coefficient, with units m^{-1}. According to equation 2 the intensity reduces exponentially as the depth within the semiconductor increases. Given that the energy does not change, elastic scattering, this means that the photon flux reduces with distance. The maximum flux is at the surface. It is possible to define a *penetration depth* equal to $\frac{1}{\alpha}$. At this distance $I(x) = \frac{I_0}{e}$, i.e. the incident flux reduces by e.

The absorption coefficient, α, is a function of the wavelength (energy) of the photon. When the photon energy is less than the band gap, the absorption is really small, while for energies above the band gap, photon absorption creates electron-hole pairs. This depends on the density of states distribution in the valence and conduction band, as shown in figure 4.

The optical absorption coefficient also depends on whether the semiconductor has a direct or indirect band gap. The dependence of α on photon
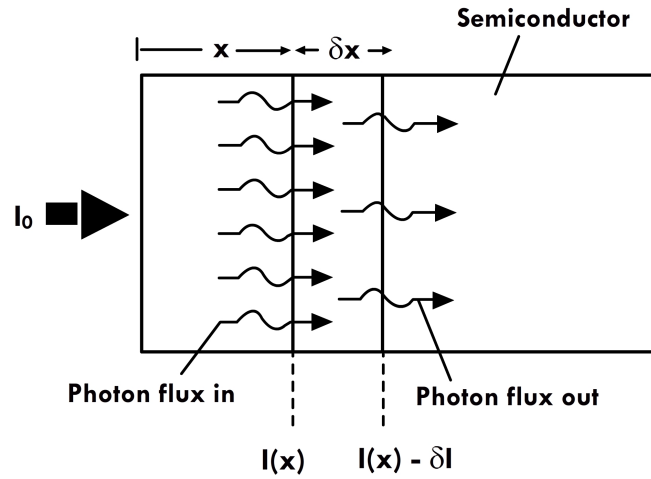
Figure 3: Intensity drop with depth inside a semiconductor, due to absorption. There is an exponential decrease in intensity as depth increases. Adapted from *Principles of Electronic Materials - S.O. Kasap.*
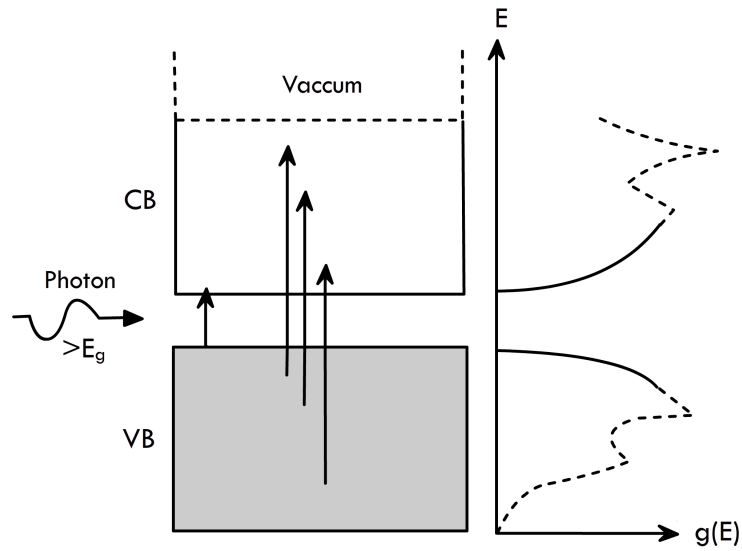

Figure 4: Electron-hole pair creation by optical absorption. The concentration is proportional to the number of available states, given by the density of states function. Adapted from *Principles of Electronic Materials - S.O. Kasap.*
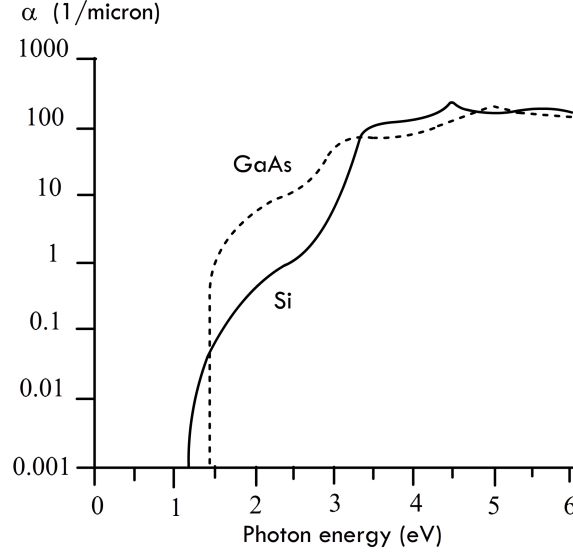
Figure 5: Absorption coefficient vs. photon energy for Si and GaAs. Si has a gradual rise in α beyond its band gap since it is an indirect band gap semiconductor, while the rise in α is sharper for GaAs (direct E_g). Adapted from *Principles of Electronic Materials - S.O. Kasap.*

energy is compared for Si and GaAs, in figure 5. When $h\upsilon$ is less than E_g the absorption is negligible. When $h\upsilon$ is equal to E_g in a direct band gap semiconductor absorption takes place from VB edge to CB edge. Since the DOS states at the band edges are small the value of α is also small. But when photon energy increases even slightly above E_g (e.g. $k_B T$ above E_g), there is a rapid increases in the number of available states and α increases rapidly. This is seen in figure 5 for GaAs where there is rapid increase in α at 1.43 eV, corresponding to the band gap. Beyond E_g, the actual shape of the absorption coefficient curve depends on the shape of the DOS. For an indirect band gap semiconductor, like Si, absorption occurs when there is a lattice vibration (phonon) assisting the photon absorption. So the absorption coefficient increases less slowly above E_g, compared to GaAs.

2   Optical recombination

Optical absorption results in the production of electron-hole pairs. These electron - hole pairs then recombine to produce photons. For a direct band gap semiconductor, the photon energy is equal to E_g, while for an indirect
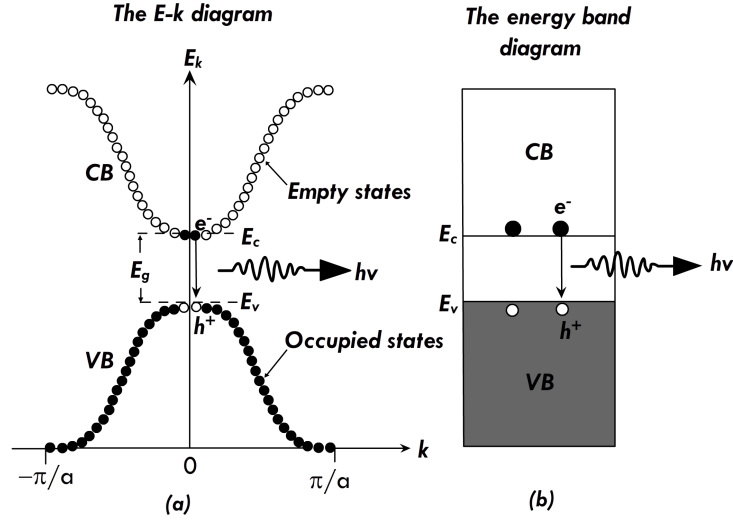
Figure 6: Recombination in GaAs shown using (a) *E vs. k* diagram (b)a schematic energy band diagram. The transition give rise to photons of energy equal to E_g. For GaAs, this photon lies in the infra red region. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

band gap semiconductor recombination is usually mediated by a recombination center. The recombination in GaAs is shown in figure 6. The recombination in Si, mediated by a recombination center, is shown in figure 7. Recombination can also occur through defect states located in the band gap. These are usually *localized* states. Defect states located close to the band edges (valence or conduction) are called *shallow states* and aid in optical recombination. On the other hand, defect states located close to the center of the band gap are called *deep states* and cause indirect recombination with preferential release of heat rather than light.

3 Recombination and carrier lifetime

Consider a n-type semiconductor at room temperature with a dopant concentration (N_D) of 5×10^{16} cm^{-3}. For Si, with n_i of 10^{10} cm^{-3}, this gives a hole concentration (p) of 2×10^3 cm^{-3}. The electron concentration (n) equals N_D since the dopants are fully ionized. This sample is now uniformly illuminated with light ($> E_g$) to create excess carriers (electrons and holes), as shown in figure 8. Let $\Delta n = \Delta p$ be the excess carriers. In *weak illumination*, $\Delta n \ll n$ i.e. the excess concentration is negligible compared to the
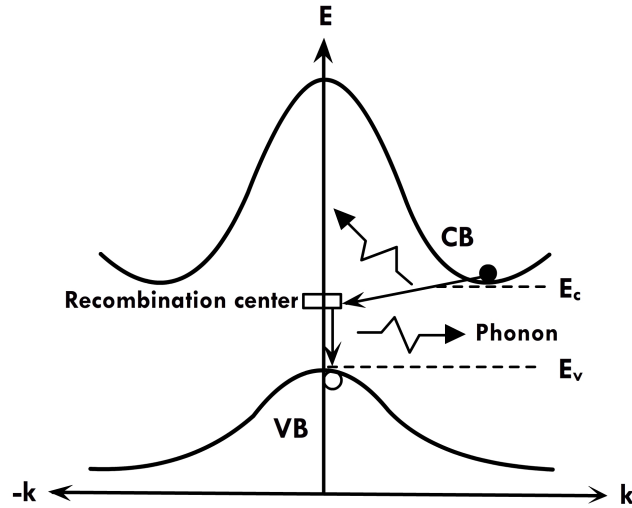
Figure 7: Indirect recombination in Si mediated by a recombination center. Since there is a change in electron wavevector, k, this process involves the lattice vibrations in Si, i.e. phonons. Adapted from *Principles of Electronic Materials - S.O. Kasap.*
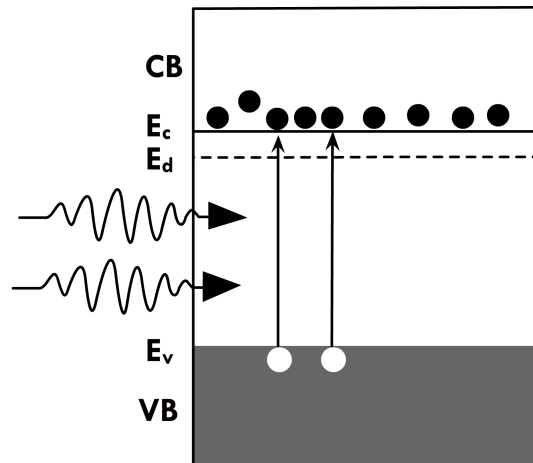

Figure 8: Weak illumination in Si. This happens when the number of electron-hole pairs created is smaller than the dopant concentration. In this scenario only the minority carrier concentration is significantly affected, while changes in majority carrier concentration can be ignored. Adapted from *Principles of Electronic Materials - S.O. Kasap.*
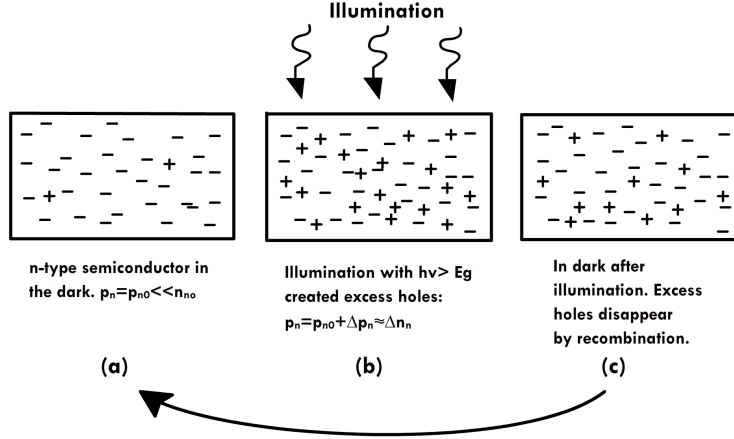
Figure 9: Carrier generation (a) equilibrium (b) during illumination and (c) once the light is turned off. After a certain time interval (determined by minority carrier lifetime) the system returns to state (a). Adapted from *Principles of Electronic Materials - S.O. Kasap.*

majority carrier concentration. There is only a significant change in the minority carrier concentration. In the presence of light, with a non-equilibrium carrier concentration, $np \neq n_i^2$, the law of mass action is *not* valid. The new electron and hole concentration, under weak illumination, are given by

$$
\begin{aligned}
n &= N_D + \Delta n \approx N_D \\
p &= \frac{n_i^2}{N_d} + \Delta p \approx \Delta p
\end{aligned}
\tag{3}
$$

Consider a particular example, $\Delta n = \Delta p = 5 \times 10^{14} \ cm^{-3}$. Then, the new electron concentration, per equation 3, is $5.05 \times 10^{16} \ cm^{-3}$. This is a change of only 1%. On the other hand, the new hole concentration is $5 \times 10^{14} \ cm^{-3}$, or a change of approximately 10^{13} %. The conclusion is that weak illumination leads to a drastic increase in minority carrier concentration. When the illumination is turned off, these excess carriers recombine and the original carrier concentration is obtained, as shown in figure 9. The time required for the system to return to equilibrium is given by the minority carrier lifetime, τ_h. τ_h defines the average time the hole exists in the valence band before the electron from the conduction band recombines with it. Similarly, for a p type semiconductor it is possible to define a minority carrier lifetime for electrons, τ_e, to exist in the conduction band before recombination. If G_{ph} is the rate of generation of carriers, then it is possible to write a general equation relating
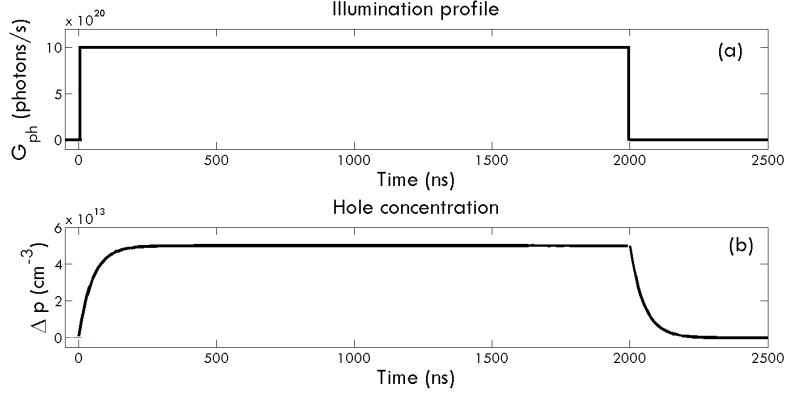
Figure 10: (a) Uniform illumination of a n-semiconductor for a fixed time. (b) The minority carrier concentration before, during, and after illumination is plotted. This is a case of weak illumination so that changes in the electron concentration can be ignored. In this example illumination time is orders of magnitude higher than the recombination time. The plot is generated in MATLAB.

this to the excess carrier concentration (Δp) and the carrier lifetime (τ_h)

$$\frac{d\Delta p}{dt} = G_{ph} - \frac{\Delta p}{\tau_h} \qquad (4)$$

The first term on the right hand side refers to generation of new carriers and the second terms represents the loss of the new carriers due to recombination. At steady state the rate of change of carrier concentration is zero. This means that the generation rate is equal to the recombination rate.

3.1 Photo response time

Consider n-doped Si with dopant concentration of 5×10^{16} cm^{-3}, that is uniformly illuminated with light for a certain duration, after which it is turned off. The material is at room temperature and the photon flux is 10^{21} cm^{-3} s^{-1} and the minority (hole) carrier lifetime is (τ_h) 50 ns. The illumination profile is shown schematically in figure 10(a). When, initially, there is no light, the minority carrier concentration is given by p_{n0}, the equilibrium hole concentration, which is very small compared to N_D and n_i. For this particular example, p_0 is 2×10^3 cm^{-3}. If G_{ph} is the photon flux impinging on the semiconductor, and if the process is 100% efficient, it produces G_{ph} electron-hole pairs. Under conditions of weak uniform illumination, the change in electron

concentration can be neglected, while the hole concentration (i.e. the minority concentration) change is substantial.

Let the time when illumination is turned on be set as the origin, i.e. $t = 0$. Then, by solving equation 4, it is possible to write an expression for the hole concentration as a function of time, using the initial condition that at $t = 0$, $\Delta p_n = 0$. This gives the hole concentration during illumination as

$$\Delta p_n(t) = \tau_h G_{ph} \left[1 - \exp(-\frac{t}{\tau_{ph}}) \right] \tag{5}$$

where τ_h is the hole lifetime (minority carrier lifetime). At steady state, rate of change of hole concentration is zero, so that using equation 4, $\Delta p_n = G_{ph}\tau_h$. This is reached after a time $t > \tau_h$. After steady state is reached, the illumination is switched off at time $t_{off} \gg \tau_h$, as shown in figure 10(a). The excess hole concentration starts to reduce and this can be obtained by solving equation 4 with $G_{ph} = 0$. This gives

$$\Delta p_n(t') = \tau_h G_{ph} \exp(-\frac{t'}{\tau_h})$$
$$t' = t - t_{\text{off}} \tag{6}$$

Once the light is turned off the excess carrier concentration decreases exponentially towards the original value. The change in hole concentration, as a function of time, is shown in figure 10(b). There is a rapid increase to the equilibrium concentration and then when the light is turned off the value quickly reduces back to equilibrium. This increase and decrease is controlled by the carrier lifetime, τ_h. Smaller the value of τ_h, faster is the return to p_{n0}, i.e. the equilibrium situation. A similar set of equations and solutions can be written for a p-type semiconductor under weak illumination, where the minority carriers are electrons. The system is controlled by the electron lifetime, τ_e.

4   Continuity equation

Carrier concentration during uniform illumination is a specific example of a more general case of light illumination on a semiconductor. Typically, illumination occurs at or close to the surface, where excess carriers are generated. As depth increases, the carrier generation also decreases. But excess carriers generated at the surface diffuse into the material due to the presence of a concentration gradient. When an external field is applied the electric field that is setup can also affect carrier motion. This is summarized in figure 11.
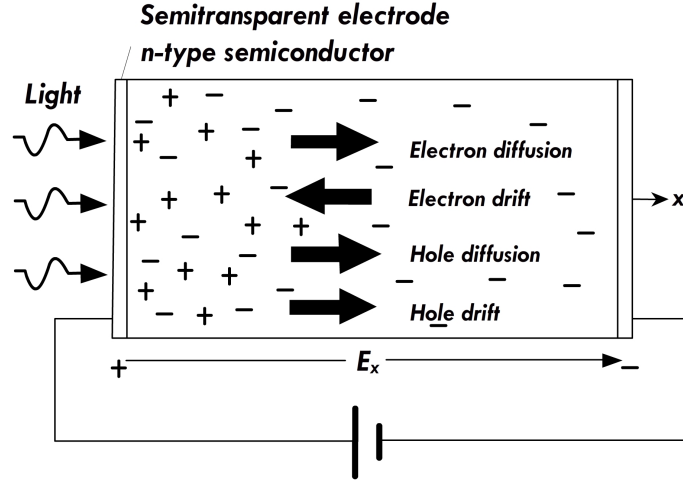
Figure 11: Illumination at the surface creates excess carriers and there is a diffusion current into the bulk. There is also a drift current due to the applied external field. In this figure, electron drift and diffusion are in opposite directions, while hole drift and diffusion are in the same direction. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

It is possible to write equations for total electron and hole current (J_e and J_h), taking both drift and diffusion into account.

$$
\begin{aligned}
J_e &= ne\mu_e E_x \ + \ eD_e\frac{dn}{dx} \\
J_h &= pe\mu_h E_x \ - \ eD_h\frac{dp}{dx}
\end{aligned}
\tag{7}
$$

D_e and D_h are the diffusion coefficients, which are in turn related to the drift mobilities, μ_e and μ_h by the **Einstein relation**

$$
\frac{D_e}{\mu_e} \ = \ \frac{D_h}{\mu_h} \ = \ \frac{k_B T}{e}
\tag{8}
$$

Equation 7 is similar to the Fick's first law of diffusion equation except that there is also a drift term along with the diffusion term. J_e and J_h are currents at steady state, similar to a steady state flux.

Similar, to Fick's second law, which is an example of non-steady state diffusion, it is possible to write a generalized equation for excess carriers in the case of non-uniform illumination. Consider an elemental volume in a semiconductor, as shown in figure 12. Hole motion is along the positive x direction so that it uniform across the cross section. Within this elemental
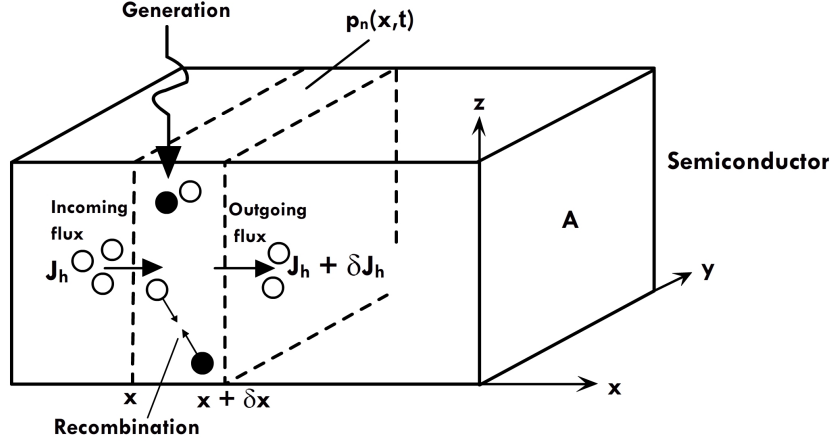
Figure 12: Derivation of the continuity equation showing various possible processes in a semiconductor. A small elemental volume is considered. The flux through this volume can be due to diffusion and drift current. Under weak illumination changes in majority carrier concentration can be ignored and only generation and recombination of minority carriers need to be considered. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

volume, the net change in hole concentration is due to a change in a flux (due to diffusion or drift), holes lost due to recombination, and holes created by illumination. This can be represented mathematically by a **continuity equation**. This is written as

$$\boxed{\frac{\partial p_n}{\partial t} \;=\; -\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right) \;-\; \frac{\Delta p_n}{\tau_h} \;+\; G_{ph}}$$

(9)

If there is no flux of holes equation 9 becomes the same as equation 4, uniform illumination.

Under steady state conditions with surface illumination, equation 9 becomes

$$\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right) \;=\; -\frac{\Delta p_n}{\tau_h}$$

(10)

If we take the electrical field to be small, so that drift current can be ignored, then equation 7 can be used to write the above equation as

$$\frac{d^2 \Delta p_n}{dx^2} \;=\; \frac{\Delta p_n}{L_h^2}$$

(11)

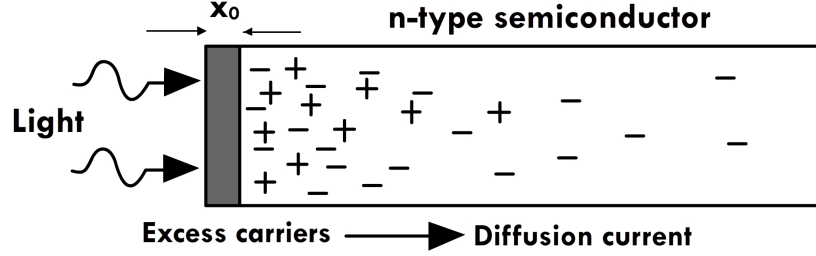where L_h is called the *diffusion length* and is given by $\sqrt{D_h\,\tau_h}$.

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Figure 13: Weak illumination at the surface creates excess holes that diffuse into the bulk. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

4.1   Weak illumination at the surface

Consider the situation weak illumination at the surface, with negligible absorption at the depth, as shown in figure 13. Light is incident at the surface of the semiconductor creating electron-hole pairs. With increase in depth, light intensity decreases (Beer-Lambert law, equation 2) so that the carrier generation also decreases. The rapidity of this decreases depends on the *penetration depth*, which is inversely related to the absorption coefficient for that wavelength. To simply this dependence, it is possible to consider a certain depth x_0 within which carrier generation occurs and there is no generation within the bulk of the semiconductor.

Ignoring electrical field variation within the semiconductor, the hole concentration for this system can be obtained by solving equation 11. This gives the solution for excess holes, as a function of distance to be

$$\Delta p_n(x) \;=\; \Delta p_n(0)\,\exp(-\frac{x}{L_h}) \tag{12}$$

where $\Delta p_n(0)$ is the excess hole concentration at the surface. This can be calculated from the photon flux, G_{ph}, and also the width of the region where electron-hole pairs are generated (x_0).

$$\Delta p_n(0) \;=\; x_0 G_{ph}\sqrt{\frac{\tau_h}{D_h}} \tag{13}$$

It is possible to write a similar equation for the excess electron concentration, as a function of depth, by

$$\Delta n_n(x) \;=\; \Delta n_n(0)\,\exp(-\frac{x}{L_e})$$
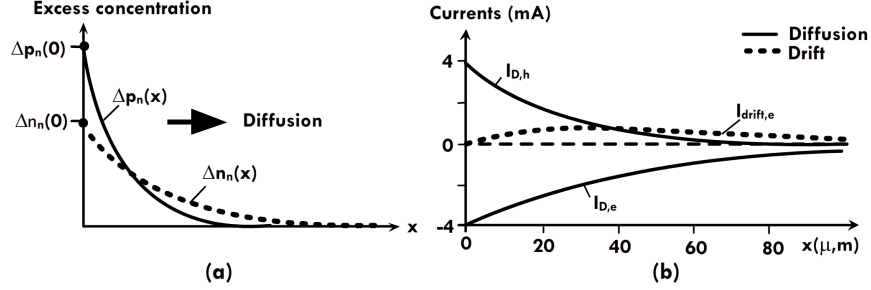$$\Delta n_n(0) \;=\; x_0 G_{ph}\sqrt{\frac{\tau_e}{D_e}} \tag{14}$$

Figure 14: (a) Excess concentration and (b) diffusion current as a function of depth for weak surface illumination. There is an electron and hole diffusion current due to movement of carriers to the bulk. In the absence of any external field this diffusion current is balanced by a drift current. Adapted from *Principles of Electronic Materials - S.O. Kasap.*

Taking the ratio of the two terms gives

$$\frac{\Delta p_n(0)}{\Delta n_n(0)} \;=\; \sqrt{\frac{D_e}{D_h}} \tag{15}$$

For Si, this ratio is higher than 1. This is because diffusion coefficients are directly related to carrier mobilities, given by equation 8, and electron mobilities are higher than hole mobilities in Si. Again, this is because the electron effective mass in Si in the conduction band is smaller than the hole effective mass in the valence band.

For weak illumination, the change the bulk concentration due to the excess electrons created can be neglected. The decrease in the hole concentration as we penetrate within the bulk of the semiconductor leads to a hole diffusion current. This is given by

$$J_h \;=\; -eD_h \frac{dp_n(x)}{dx} \;=\; \frac{eD_h}{L_h}\Delta p_n(0)\exp(-\frac{x}{L_h}) \tag{16}$$

The electron diffusion current is given by

$$J_e \;=\; -eD_e \frac{dn_n(x)}{dx} \;=\; \frac{eD_e}{L_e}\Delta n_n(0)\exp(-\frac{x}{L_e}) \tag{17}$$

The excess carriers and the diffusion currents are plotted in figure 14. In an open circuit the total current in the semiconductor is zero. So that

$$J_{drift,e} \;=\; -J_{D,h} \;-\; J_{D,e} \tag{18}$$

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This drift current arises because the diffusion currents due to electrons and holes are different. The magnitude of the drift current increases with depth until the bulk concentrations are reached, as shown in figure 14. Weak illumination at the surface is a particularly useful case for analyzing the effect of light absorption in a semiconductor. Practical situations lead to more complicated applications of the continuity equation. This is important to calculate emitted intensities in light emitting diodes and light absorption and carrier generation in solar cells and photodetectors.