For this **pn-junction**, if its cross-sectional area is A and the incident photons generate G electron-hole pairs per second per unit volume (ehp/s/cm^3), and if L_e and L_h are the respective minority diffusion lengths in the **p- and n-regions**, then the resulting photocurrent from the **n-to the p-region** is

$$I_{PC} = qAG(W + L_e + L_h),$$

Let the optical power incident on one side of the **pn-photodiode** be P_I. If R_p is the power reflection coefficient at the air-semiconductor interface, the power transmitted at the interface is $(1 - R_p)\ P_I$. The transmitted power through the photodiode is:

$$P_{\text{tr}} = (1 - R_p)P_I \exp(-\alpha W),$$

where α is the absorption coefficient and W is the thickness of the depletion or active region of the photodetector. Therefore, the power absorbed in the photodiode is

$$P_{\text{abs}} = (1 - R_p)P_I - P_{\text{tr}} = (1 - R_p)P_I[1 - \exp(-\alpha W)].$$

From equation above, we find that the mean number of photons absorbed per unit time, or *photon absorption rate*, is $P_{abs}/(hf_0)$.

If *a* photon is absorbed, *an* electron-hole pair is generated. Therefore, the number of electron-hole pairs generated per unit time is:

$$\frac{N_{PC}}{T} = \frac{P_{\text{abs}}}{hf_0}.$$

Therefore, quantum efficiency (η) can be write as:

$$\eta = \frac{P_{\text{abs}}\zeta}{P_I} = (1 - R_p)\zeta[1 - \exp(-\alpha W)].$$

The quantum efficiency is equal to a product of:

1. The power transmission coefficient at the air‑semiconductor interface, 1-R_p;
2. The photons absorbed in the active region of thickness W, given by the term 1-exp(-αW);
3. The fraction of photocarriers ζ that reach the device terminal and contribute to the measured photocurrent.

Example:

If the incident optical signal on a pn photodiode is at a wavelength of 550 nm, its absorption coefficient α = 10^4 cm^{-1}, width of the active region W= 3 μ m, and optical power 1 nW, calculate (a) the photon incidence rate, (b) the photon absorption rate, and, (c) the quantum efficiency. Assume R_p = 0 and ζ = 0.9.

Solution:

(a) The energy of a photon is:

$$E_{ph} = \frac{hc}{\lambda_0} = 3.6 \times 10^{-19} \text{ J.}$$

The photon incidence rate is given by:

$$R_{\text{incident}} = \frac{P_I}{E_{ph}} = \frac{1 \times 10^{-9} \text{ W}}{3.6 \times 10^{-19}} \text{photons/s}$$
$$= 2.77 \times 10^9 \text{ photons/s.}$$

(b) With R_p = 0, the photon absorption rate is:

$$R_{\text{abs}} = R_{\text{incident}}[1 - \exp(-\alpha W)]$$
$$= 2.77 \times 10^9 \times [1 - \exp(-10^4 \times 3 \times 10^{-4})] \text{ photons/s}$$
$$= 2.63 \times 10^9 \text{ photons/s.}$$

(c) The quantum efficiency is given by:

$$\eta = (1 - R_p)\zeta[1 - \exp(-\alpha W)]$$
$$= 0.9 \times (1 - \exp(-10^4 \times 3 \times 10^{-4}))$$
$$= 0.855.$$

Responsivity or Photoresponse

The responsivity or photoresponse (sometimes also called *sensitivity*) is a measure of the ability of the photodetector to convert optical power into an electrical current or voltage. It depends on the wavelength of the incident radiation, the type of photoresponsive (or active) material in the detector, and the structure and operating conditions of the photodetector. It is defined as

$$R = \frac{I_{PC}}{P_I},$$

where I_{PC} is the photocurrent and P_I is the input optical power.

The photocurrent, in turn, depends on the absorption characteristics of the active (photoresponsive) material on the photodetector and the quantum efficiency. In a photodetector, the intrinsic quantum efficiency is the number of ehps generated per incident photon. In the ideal case, the quantum efficiency, which is a measure of the number of photogenerated ehps per incident photon, is 1 or 100%, that is, each photon of appropriate energy (equal to or greater than the energy band gap E_g of the active semiconductor material) generates one ehp.

For a pn photodiode, we find

$$R = \frac{\eta q}{hf_0}.$$

If we insert the numerical values for q, c, and h and with $f_0 = c/\lambda_0$, the equation above can be rewritten as:

$$R(\text{A/W}) = \eta \frac{\lambda_0(\mu\text{m})}{1.24}.$$

Note that the responsivity is proportional to both the quantum efficiency η and the free-space wavelength λ_0.

<u>Example:</u>

In a GaAs photodiode, if the quantum efficiency η = 0.9, band-gap energy E_g = 1.42 eV, and operating (free-space) wavelength = 1.1 μm, calculate (a) the responsivity R and (b) the cutoff wavelength λ_{co}.

<u>Solution:</u>

(a) The responsivity R is given by:

$$R = \eta \frac{\lambda_0(\mu\text{m})}{1.24} \text{ A/W}$$
$$= \frac{0.9 \times 1.1}{1.24} \text{A/W} = 0.9 \text{ A/W}.$$

(b) The cutoff wavelength is given by:

$$\lambda_{co} = \frac{1.2}{E_g(\text{eV})}\mu\text{m}$$
$$= \frac{1.2}{1.42}\ \mu\text{m} = 0.873\ \mu\text{m}.$$

Example 5.3

Consider radiation of wavelength λ = 700 nm incident on a photodetector whose measured responsivity is 0.4 A/W. What is its quantum efficiency at this wavelength? If the wavelength is reduced to 500 nm, what is the new QE assuming that the responsivity is the same?

Solution:

- Using responsivity equation:

$$R(\text{A/W}) = \eta\frac{\lambda_0(\mu\text{m})}{1.24}.$$

$$0.4\ \text{A/W} = \eta\frac{\lambda_0(\mu\text{m})}{1.24} \Rightarrow \eta = \frac{0.4 \times 1.24}{0.7} = 0.7086(\simeq 71\%).$$

- For λ_0 = 500 nm, the new QE is:

$$\eta = 0.7086 \times \frac{0.5}{0.7} = 0.506(\simeq 51\%).$$

Photodetector Design Rules

To improve the quantum efficiency, we should minimize light reflections (R_p term) from the semiconductor surface or maximize the light transmitted into the semiconductor. For this, we can use an antireflection coating to achieve better light transmittance. If the light is incident from air (refractive index n_{air}) into the semiconductor (refractive index n_{sc}), then we should choose a material whose refractive index n_{AR} (refractive index of antireflection coating) is given by:

$$n_{\text{AR}} = \sqrt{n_{\text{air}} n_{\text{sc}}}.$$

If we use a quarter-wavelength antireflection coating of a transparent material with a refractive index n_{AR} , then the thickness t_{AR} which causes minimum reflection of the incoming radiation is given by:

$$t_{AR} = \frac{\lambda}{4n_{AR}},$$

where λ is the free-space wavelength of the incident light onto the antireflection coating.

Example:

If we use a silicon photodetector to detect red light at 680 nm, and refractive index of air (n_{air}) = 1, refractive index of silicon (n_{Si}) = 3.6, determine the refractive index and thickness of the antireflection coating.

Solution:

The required antireflection coating should have a refractive in:

$$n_{AR} = \sqrt{n_{air} n_{Si}} = 1.9$$

The thickness should be:

$$t_{AR} = \lambda/(4n_{AR}) = 680\ \text{nm}/(4 \times 1.9) \simeq 90\ \text{nm}.$$

At 680 nm, the refractive index of silicon nitride (Si_3N_4)~2 and that of silicon dioxide (SiO_2)~1.5. Therefore, Si_3N_4 would be a good choice for the antireflection coating.