PHOTODETECTOR

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Photodetectors

Optical signal generally is **weakened** and distorted when it emerges from the end of the fiber, **the photodetector must meet following strict performance requirements.**

- ❑A **high sensitivity** to the emission wavelength range of the received light signal
- ❑A **minimum** addition of **noise** to the signal
- ❑A **fast response** speed to handle the desired data rate
- ❑Be **insensitive** to **temperature** variations
- ❑Be **compatible** with the physical dimensions of the **fiber**
- ❑Have a **Reasonable cost** compared to other system components
- ❑Have a long **operating lifetime**

Photodetectors

Some important parameters while discussing photodetectors:

Quantum Efficiency

It is the ratio of primary electron-hole pairs created by incident photon to the photon incident on the diode material.

Detector Responsivity

*This is the ratio of output current to input optical power. Hence this is the efficiency of the device.

Spectral Response Range

This is the range of wavelengths over which the device will operate.

Noise Characteristics

The level of noise produced in the device is critical to its operation at low levels of input light.

Response Time

This is a measure of how quickly the detector can respond to variations in the input light intensity.

Physical Principles of Photodiodes

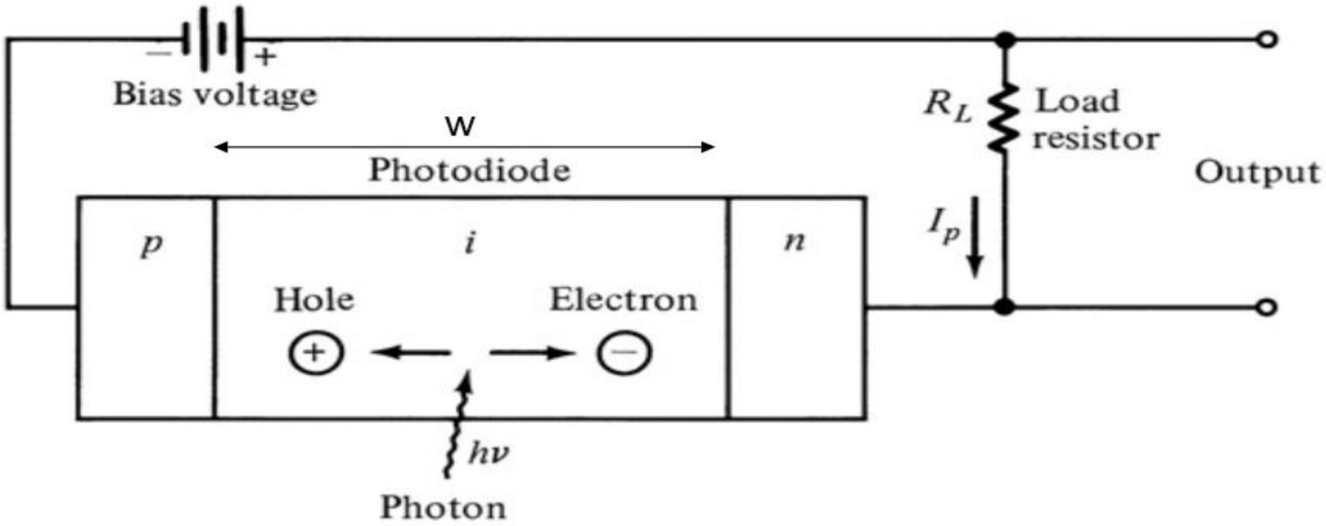
The Pin Photodetector

The **device structure** consists of **p and n** semiconductor regions separated by a very **lightly n-doped intrinsic (i) region.**

In **normal operation** a reverse-bias voltage is applied across the device so that **no free electrons or holes** exist in the **intrinsic region**.

Incident photon having energy **greater than or equal** to the **bandgap energy** of the semiconductor material, **give up its energy** and **excite an electron** from the valence band to the conduction band

pin Photodetector



The high electric field present in the depletion region causes photo-generated carriers to Separate and be collected across the reverse –biased junction. This give rise to a current Flow in an external circuit, known as **photocurrent**.

The Pin Photodetector

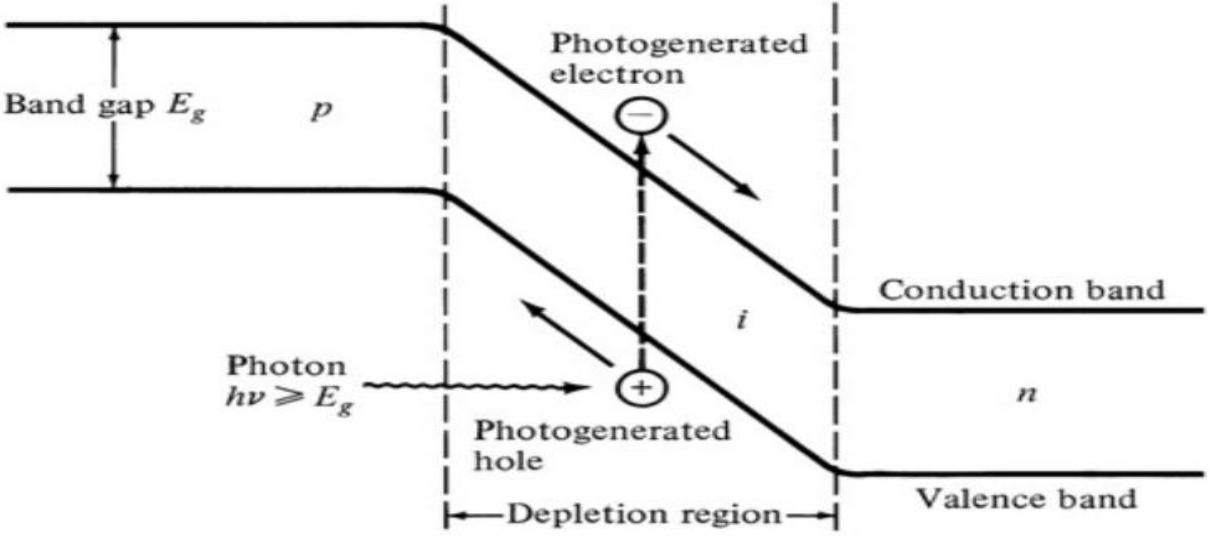
Photocarriers:

Incident photon, generates free (mobile) **electron-hole pairs in the intrinsic region**. These charge carriers are known as **photocarriers**, since they are generated by a photon.

Photocurrent:

The electric field across the device causes the **photocarriers to be swept out of the intrinsic region**, thereby giving rise to a **current flow in an external circuit**. This current flow is known as the **photocurrent**.

Energy-Band diagram for a *pin* photodiode



The Pin Photodetector

An incident photon is able to boost an electron to the conduction band only if it has an energy that is greater than or equal to the bandgap energy

****Beyond a certain wavelength, the light will not be absorbed by the material since the wavelength of a photon is inversely proportional to its energy**

Thus, a particular semiconductor material can be used only over a limited wavelength range.

The upper wavelength λ_c cutoff is determined by the band-gap energy E_g of the material.

$$\lambda_c = \frac{hc}{E_g}$$

continued

- As the charge carriers flow through the material some of them recombine and disappear.
- The charge carriers move a distance L_n ot L_p for electrons and holes before recombining. This distance is known as diffusion length
- The time it take to recombine is its life time τ_n or τ_p respectively.

$$L_n = D_n \tau_n \quad \text{and} \quad L_p = D_p \tau_p$$

- Where D_n and D_p are the diffusion coefficients for electrons and holes respectively.

Photo current

- As a photon flux penetrates through the semiconductor, it will be absorbed.
- If P_{in} is the optical power falling on the photo detector at x=0 and P(x) is the power level at a distance x into the material then the incremental change be given as

$$dP(x) = -\alpha_s(\lambda)P(x)dx$$

where $\alpha_s(\lambda)$ is the photon absorption coefficient at a wavelength λ. So that

$$P(x) = P_{in}\exp(-\alpha_s x)$$

Photocurrent

- Optical power absorbed, $P(x)$ in the depletion region can be written in terms of incident optical power, P_0 :

$$P(x) = P_0(1 - e^{-\alpha_s(\lambda)x}) \qquad [6\text{-}1]$$

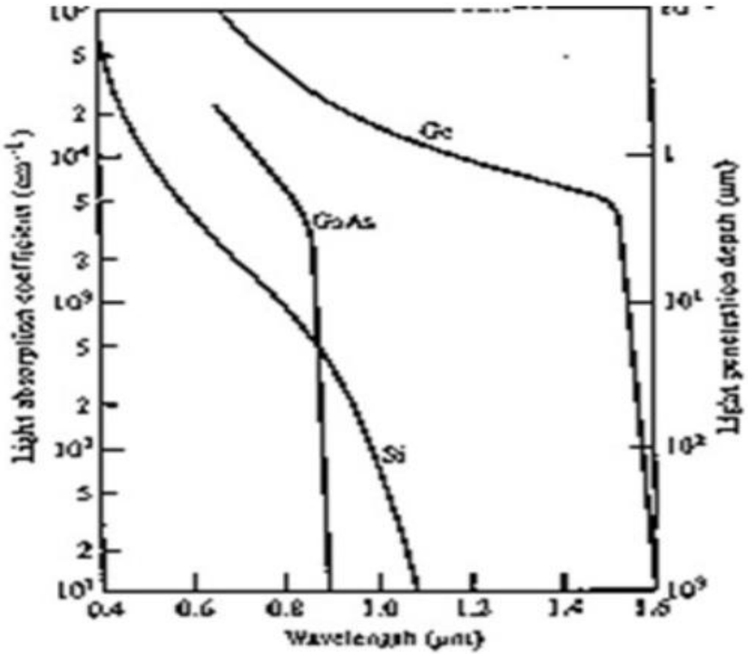
- Absorption coefficient $\alpha_s(\lambda)$ strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

$$\lambda_c(\mu\text{m}) = \frac{1.24}{E_g(\text{eV})} \qquad [6\text{-}2]$$

- Taking entrance face reflectivity into consideration, the absorbed power in the width of depletion region, w, becomes:

$$(1-R_f)P(w) = P_0(1-e^{-\alpha_s(\lambda)w})(1-R_f)$$

Optical Absorption Coefficient



Responsivity

- The primary photocurrent resulting from absorption is:

$$\boxed{I_p = \frac{q}{h\nu} P_0 (1 - e^{-\alpha_s(\lambda) w})(1 - R_f)}$$ [6-3]

- Quantum Efficiency:

$$\eta = \frac{\text{\# of electron - hole photogenerated pairs}}{\text{\# of incident photons}}$$

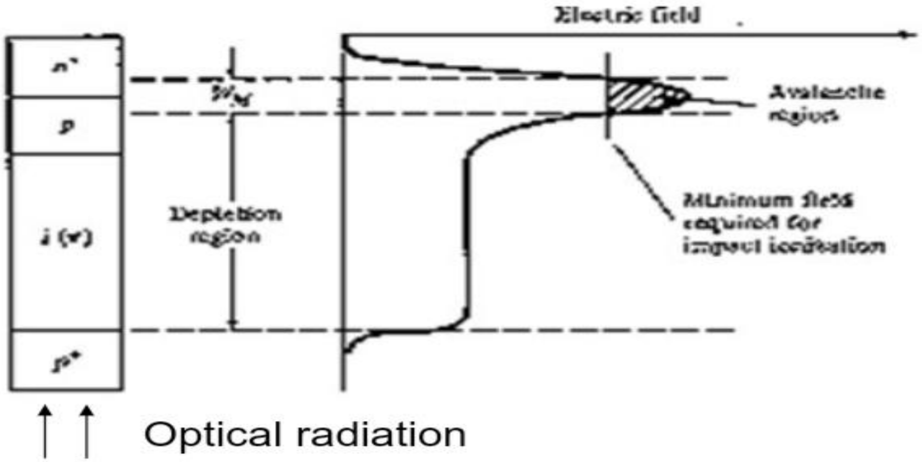
$$\boxed{\eta = \frac{I_P / q}{P_0 / h\nu}}$$ [6-4]

- **Responsivity:**

$$\boxed{\Re = \frac{I_P}{P_0} = \frac{\eta q}{h\nu} \quad [\mathrm{A/W}]}$$ [6-5]

Avalanche Photodiode (APD)

APDs internally multiply the primary photocurrent before it enters to following circuitry. In order to carrier multiplication take place, the photogenerated carriers must traverse along a high field region. In this region, photogenerated electrons and holes gain enough energy to ionize bound electrons in VB upon colliding with them. This multiplication is known as **impact ionization**. The newly created carriers in the presence of high electric field result in more ionization called **avalanche effect**.



Reach-Through APD structure (RAPD) showing the electric fields in depletion region and multiplication region.

Responsivity of APD

- The multiplication factor (current gain) M for all carriers generated in the photodiode is defined as:

$$M = \frac{I_M}{I_p} \qquad [6\text{-}6]$$

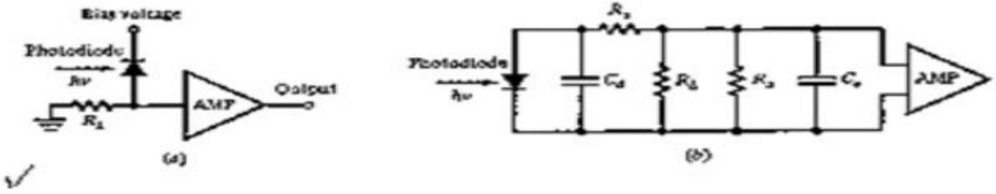
- Where I_M is the average value of the total multiplied output current & I_P is the primary photocurrent.

- The responsivity of APD can be calculated by considering the current gain as:

$$\boxed{\Re_{\mathrm{APD}} = \frac{\eta q}{h\nu} M = \Re_0 M} \qquad [6\text{-}7]$$

Photodetector Noise & S/N

- Detection of weak optical signal requires that the photodetector and its following amplification circuitry be optimized for a desired signal-to-noise ratio.
- It is the noise current which determines the minimum optical power level that can be detected. This minimum detectable optical power defines the **sensitivity** of photodetector. That is the optical power that generates a photocurrent with the amplitude equal to that of the total noise current (*S/N=1*)



$$\frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

Signal Calculation

- Consider the modulated optical power signal *P(t)* falls on the photodetector with the form of:

$$P(t) = P_0[1 + ms(t)] \qquad [6\text{-}8]$$

- Where *s(t)* is message electrical signal and *m* is modulation index. Therefore the primary photocurrent is (for pin photodiode $M=1$):

$$i_{\mathrm{ph}} = \frac{\eta q}{h\nu} MP(t) = I_P[\text{DC value}] + i_p(t)[\text{AC current}] \qquad [6\text{-}9]$$

- The root mean square signal current is then:

$$\langle i_s{}^2 \rangle = \langle i_p{}^2 \rangle M^2 = \sigma_s{}^2 \qquad [6\text{-}9]$$

$$\langle i_p{}^2 \rangle = \sigma_p{}^2 = \frac{m^2 I_P^2}{2} \quad \text{for sinusoidal signal} \qquad [6\text{-}10]$$

Noise calculation (2)

- The total rms photodetector noise current is:

$$\boxed{\begin{aligned}\langle i_N{}^2\rangle = \sigma_N{}^2 &= \langle i_Q{}^2\rangle + \langle i_{DB}{}^2\rangle + \langle i_{DS}{}^2\rangle \\ &= 2q(I_P + I_D)BM^2F(M) + 2qI_LB\end{aligned}}$$

[6-14]

- The thermal noise of amplifier connected to the photodetector is:

$$\langle i_T{}^2\rangle = \sigma_T{}^2 = \frac{4k_BTB}{R_L}$$

[6-15]

R_L input resistance of amplifier, and $k_B = 1.38\times10^{-23}$ JK $^{-1}$ is Boltzmann cte.

S/N Calculation

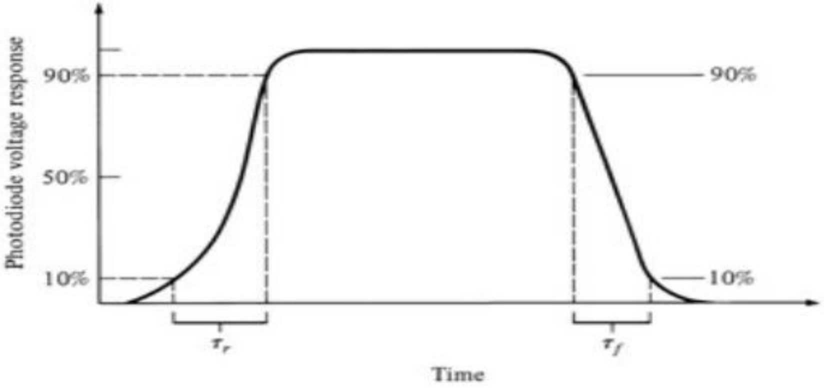
- Having obtained the signal and total noise, the signal-to-noise-ratio can be written as:

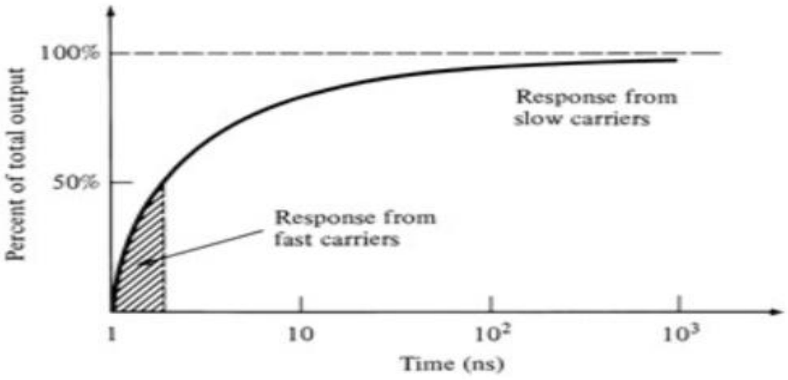
$$\boxed{\frac{S}{N}=\frac{\left\langle i_P{}^2\right\rangle M^2}{2q(I_P+I_D)BM^2F(M)+2qI_LB+4k_BTB/R_L}} \qquad [6\text{-}16]$$

- Since the noise figure *F(M)* increases with M, there always exists an optimum value of *M* that maximizes the S/N. For sinusoidally modulated signal with *m=1* and $F(M)\approx M^x$:

$$M_{\mathrm{opt}}^{x+2}=\frac{2qI_L+4k_BT/R_L}{xq(I_P+I_D)} \qquad [6\text{-}17]$$

Photodiode response to optical pulse





Typical response time of the photodiode that is not fully depleted

Various optical responses of photodetectors: Trade-off between quantum efficiency & response time

- To achieve a high quantum efficiency, the depletion layer width must be larger than $1/\alpha_s$ (the inverse of the absorption coefficient), so that most of the light will be absorbed. At the same time with large width, the capacitance is small and *RC* time constant getting smaller, leading to faster response, but wide width results in larger transit time in the depletion region. Therefore there is a trade-off between width and QE. It is shown that the best is:

$$1/\alpha_s \leq w \leq 2/\alpha_s$$