Optical Receivers

Theory and Operation

PHOTODETECTORS

Photo Detectors

- Optical receivers convert optical signal (light) to electrical signal (current/voltage)
  - Hence referred ‘O/E Converter’
- Photodetector is the fundamental element of optical receiver, followed by amplifiers and signal conditioning circuitry

Photodetector Requirements

- Good sensitivity (responsivity) at the desired wavelength and poor responsivity elsewhere → wavelength selectivity
- Fast response time → high bandwidth
- Compatible physical dimensions
- Low noise
- Insensitive to temperature variations
- Long operating life and reasonable cost

Types of photo detectors

- There are several photodetector types:
  - Photodiodes, Phototransistors, Photon multipliers, Photo-resistors etc,

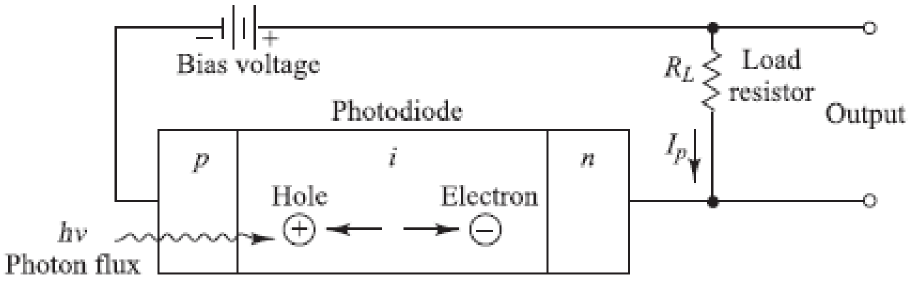
Photodiodes

- Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems
- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain
- Avalanche Photo Diode (*APD*)
  - An internal gain of M due to self multiplication
- Photodiodes are sufficiently *reverse biased* during normal operation → no current flow, the intrinsic region is fully depleted of carriers

Physical Principles of Photodiodes

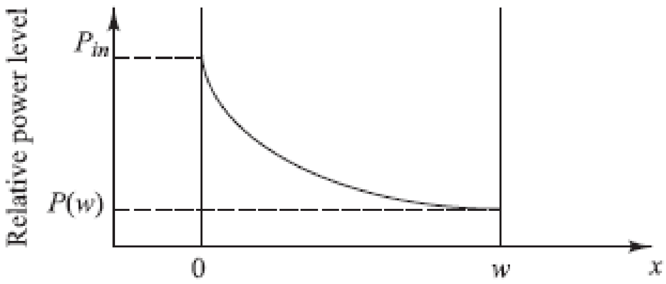
- As a photon flux Φ penetrates into a semiconductor, it will be absorbed as it progresses through the material.
- If $\alpha_s(\lambda)$ is the photon absorption coefficient at a wavelength λ, the *power level at a distance x into the material* is

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



Absorbed photons trigger *photocurrent* I_p in the external circuitry

Photocurrent ∝ Incident Light Power



Examples of Photon Absorption

Example 6.1 If the absorption coefficient of $In_{0.53}Ga_{0.47}As$ is 0.8 μm^{-1} at 1550 nm, what is the penetration depth at which $P(x)/P_{in} = 1/e = 0.368$?

Solution: From Eq. (6.1),

$$\frac{P(x)}{P_{in}} = \exp(-\alpha_s x) = \exp[(-0.8)x] = 0.368$$

Therefore

$$-0.8\,x = \ln 0.368 = -0.9997$$

which yields $x = 1.25\ \mu m$.

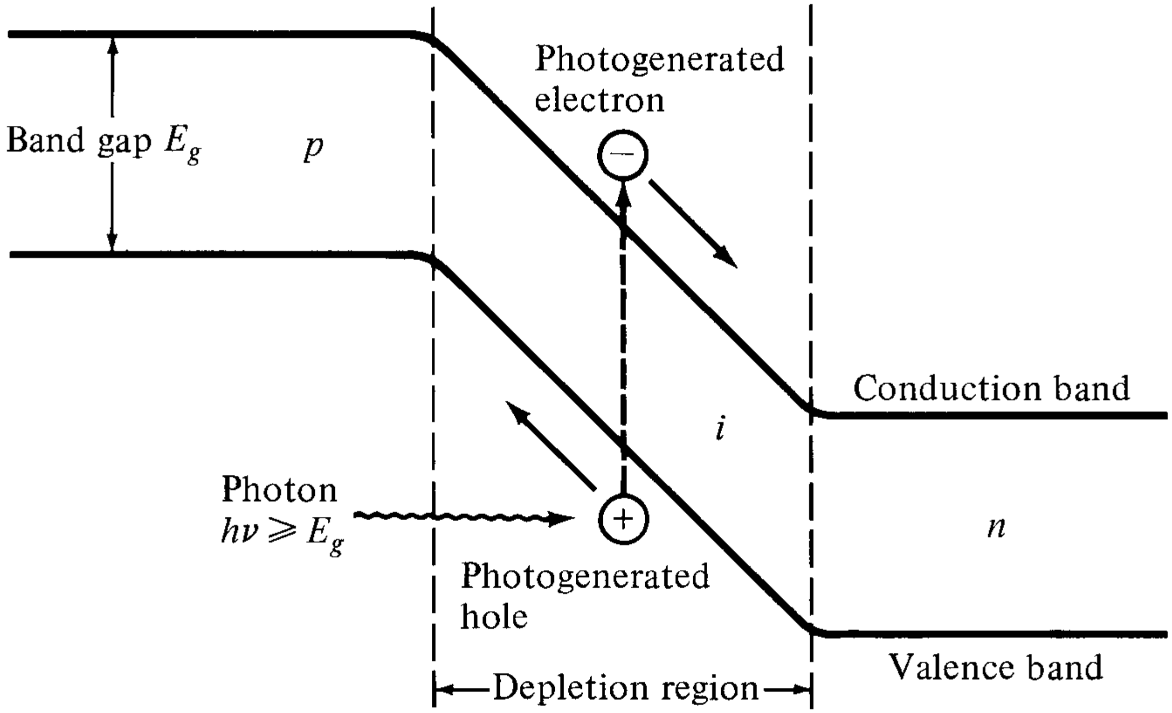
Example 6.2 A high-speed $In_{0.53}Ga_{0.47}As$ *pin* photodetector is made with a depletion layer thickness of 0.15 μm. What percent of incident photons are absorbed in this photodetector at 1310 nm if the absorption coefficient is 1.5 μm^{-1} at this wavelength?

Solution: From Eq. (6.1), the optical power level at $x = 0.15\ \mu m$ relative to the incident power level is

$$\frac{P(0.15)}{P_{in}} = \exp(-\alpha_s x) = \exp[(-1.5)0.15] = 0.80$$

Therefore only 20 percent of the incident photons are absorbed.

pin energy-band diagram



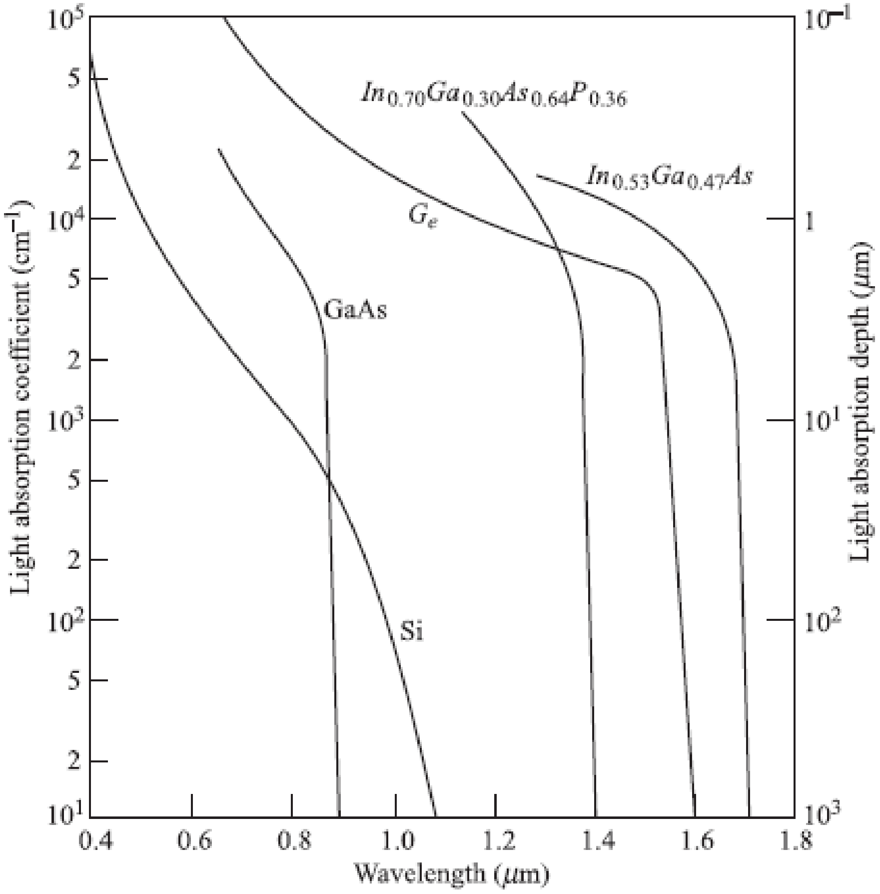
$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \ \mu\text{m}$$

Cut off wavelength depends on the band gap energy

Light Absorption Coefficient

- The upper wavelength cutoff is determined by the bandgap energy E_g of the material.

- At the lower-wavelength end, the photo response cuts off as a result of the very large values of α_s.



Power Absorbed and Photo Current

- If the depletion region has a width w, then the total power absorbed in the distance w is

$$P_{\text{absorbed}}(w) = \int_0^w \alpha_s P_{in} \exp(-\alpha_s x)\, dx = P_{in}(1 - e^{-\alpha_s w})$$

- If we take into account a reflectivity Rf at the entrance face of the photodiode, then the primary photocurrent Ip resulting from the power absorption

$$I_p = \frac{q}{h\nu} P_{in}(1 - e^{-\alpha_s w})(1 - R_f)$$

Quantum Efficiency

- The *quantum efficiency* η is the number of the electron–hole carrier pairs generated per incident–absorbed photon of energy $h\nu$ and is given by

$$\eta = \frac{\text{number of electron–hole pairs generated}}{\text{number of incident–absorbed photons}} = \frac{I_p / q}{P_{in} / h\nu}$$

I_p is the photocurrent generated by a steady-state optical power P_{in} incident on the photodetector.

Responsivity ($\Re$)

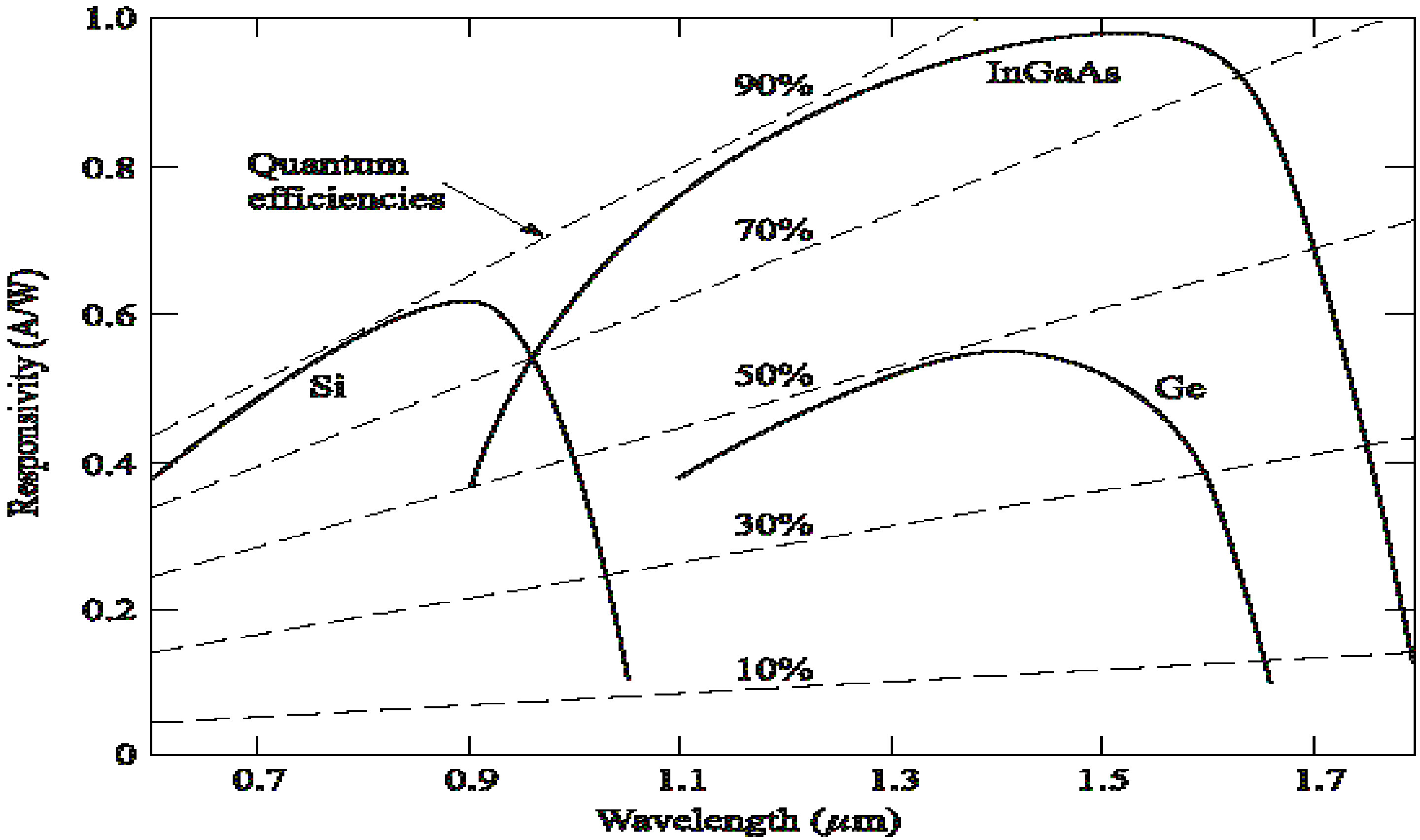
Quantum Efficiency (η)

= number of e-h pairs generated / number of incident photons

$$\eta = \frac{I_p / q}{P_0 / h\nu} \rightarrow \boxed{\Re = \frac{I_p}{P_o} = \frac{\eta q}{h\nu} = \frac{\eta\lambda}{1.24}} \quad \text{mA/mW}$$

Responsivity

$$\Re = \eta\lambda / 1.24$$



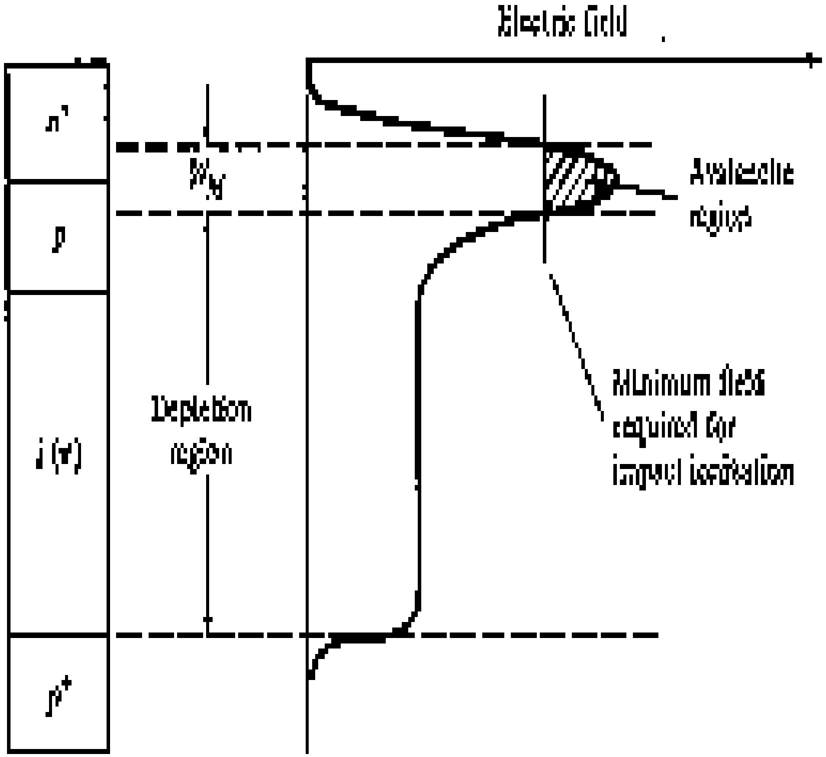
When λ<< λ_c absorption is low
When λ > λ_c; no absorption

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \ \mu\text{m}$$

Avalanche Photodiode (APD)

- APD has an internal gain obtained by having a *high electric field* that energizes photo-generated electrons and holes
- These electrons and holes ionize bound electrons in the valence band upon colliding with them
- This mechanism is known as *impact ionization*
- The newly generated electrons and holes are also accelerated by the high electric field and they gain enough energy to cause further impact ionization
- This phenomena is called the avalanche effect

Structure of APD



Responsivity of APD

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

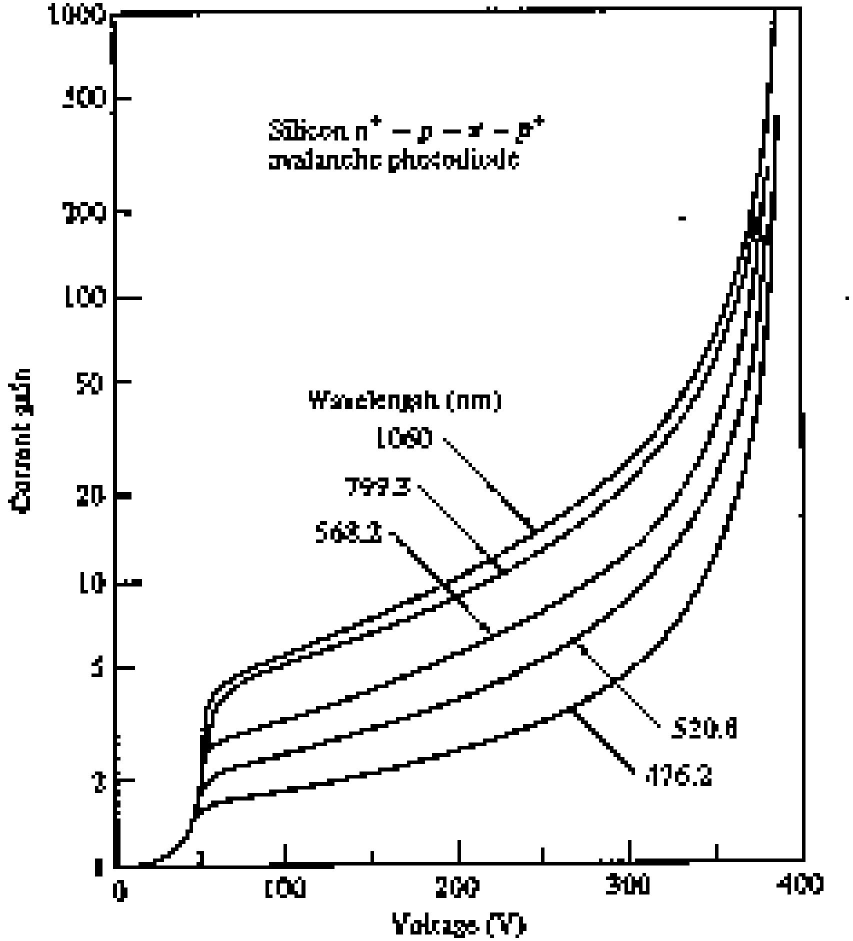
$$M = \frac{I_M}{I_p} \qquad [6\text{-}6]$$

- 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:

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

Current gain (M) vs. Voltage for different optical wavelengths



APD Vs PIN

- APD has high gain due to self multiplying mechanism, used in high end systems
- The tradeoff is the ‘excess noise’ due to random nature of the self multiplying process.
- APD’s need high reverse bias voltage (Ex: 40 V)
- Therefore costly and need additional circuitry

Photodetector Noise

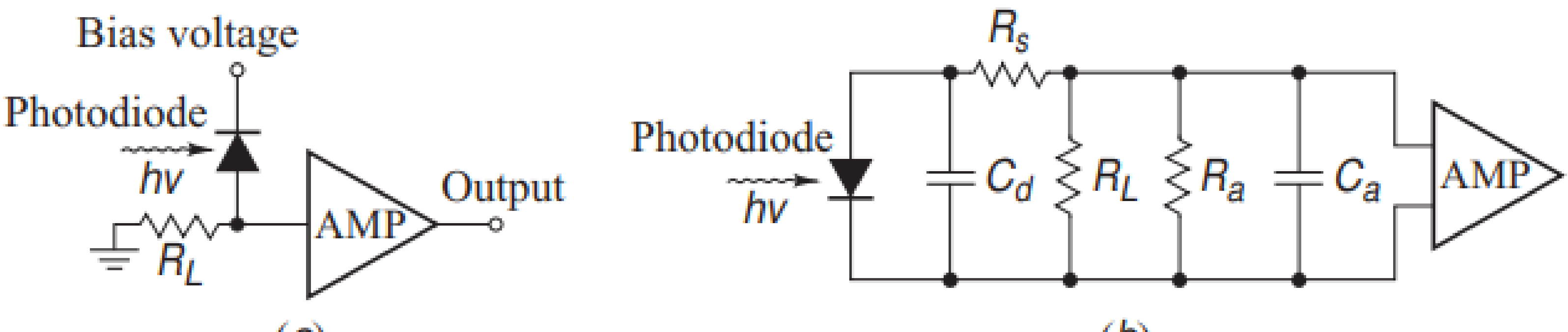
- In fiber optic communication systems, the photodiode is generally required to detect very weak optical signals.
- Detection of weak optical signals requires that the photodetector and its amplification circuitry be optimized to maintain a given signal-to-noise ratio.
- The power signal-to-noise ratio S/N (also designated by SNR) at the output of an optical receiver is defined by

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

SNR Can NOT be improved by amplification

The sensitivity of a photo detector in an optical fiber communication system is describable in terms of the minimum detectable optical power. This is the optical power necessary to produce a photocurrent of the same magnitude

Simple model of a photo detector receiver, and its equivalent circuit



(b)

$$i_{\mathrm{ph}}(t) = \frac{\eta q}{h\nu} P(t)$$

For *pin* photodiodes the mean-square signal current $\langle i_s^2 \rangle$ is

$$\langle i_s^2 \rangle = \sigma_{s,\ pin}^2 = \langle i_p^2(t) \rangle$$

avalanche photodetectors,

$$\langle i_s^2 \rangle = \sigma_{s,\ \mathrm{APD}}^2 = \langle i_p^2(t) \rangle M^2$$

Notation: Detector Current

- The direct current value is denoted by, I_P ; capital main entry and capital suffix.
- The time varying (either randomly or periodically) current with a zero mean is denoted by, i_p small main entry and small suffix.
- Therefore, the total current *Ip* is the sum of the DC component I_P and the AC component i_p .

$$\boxed{I_P = I_p + i_p}$$

$$\left\langle i_p^2 \right\rangle = \mathrm{Lim}_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} i_p^2(t)\,dt$$

Quantum (Shot Noise)

Due optical power fluctuation because light is made up of discrete number of photons

$$\boxed{\left\langle i_Q^2 \right\rangle = 2qI_p BM^2 F(M)}$$

$F(M)$: APD Noise Figure

$F(M) \sim= M^x \; (0 \leq x \leq 1)$

I_p: Mean Detected Current

B = Bandwidth

Dark/Leakage Current Noise

There will be some (dark and leakage) current without any incident light. This current generates two types of noise

Bulk Dark Current Noise $$\boxed{\left\langle i_{DB}^{2} \right\rangle = 2qI_D BM^2 F(M)}$$

I_D: Dark Current

Surface Leakage Current Noise

$$\left\langle i_{DS}^{2} \right\rangle = 2qI_L B$$

(not multiplied by M)

I_L: Leakage Current

Photo detector noise current

photodetector noise current $\left\langle i_N^2 \right\rangle$ can be written as

$$\left\langle i_N^2 \right\rangle = \sigma_N^2 = \left\langle i_{\text{shot}}^2 \right\rangle + \left\langle i_{DB}^2 \right\rangle + \left\langle i_{DS}^2 \right\rangle = \sigma_{\text{shot}}^2 + \sigma_{DB}^2 + \sigma_{DS}^2$$

$$= 2q(I_p + I_D)M^2 F(M)B_e + 2qI_L B_e$$

Thermal Noise

The photodetector load resistor R_L contributes to thermal (Johnson) noise current

$$\boxed{\left\langle i_T^2 \right\rangle = 4K_B TB / R_L}$$

K_B: Boltzmann's constant = 1.38054 X $10^{(-23)}$ J/K
T is the absolute Temperature

- Quantum and Thermal are the important noise mechanisms in all optical receivers
- RIN (Relative Intensity Noise) will also appear in analog links

Signal to Noise Ratio

Detected current = AC (i_p) + DC (I_p)

Signal Power = $<i_p{}^2>M^2$

$$SNR = \frac{\left\langle i_p^2 \right\rangle M^2}{2q(I_p + I_D)M^2F(M)B + 2qI_LB + 4k_BTB/R_L}$$

Typically not all the noise terms will have equal weight. Often the average signal current is much larger than the leakage and dark currents

$$\boxed{\frac{S}{N} = \frac{\left\langle i_p^2 \right\rangle M^2}{2qI_pM^2F(M)B_e + 4k_BTB_e/R_L}}$$

Limiting Cases for SNR

- When the optical signal power is relatively high, then the shot noise power is much greater than the thermal noise power. In this case the SNR is called *shot-noise limited* or *quantum noise limited*.
- When the optical signal power is low, then thermal noise usually dominates over the shot noise. In this case the SNR is referred to as being *thermal-noise limited*.

The optimum gain at the maximum signal-to-noise ratio can be found by differentiating

$$M_{\mathrm{opt}}^{x+2} - \frac{2qI_L + 4k_B T / R_L}{xq(I_p + I_D)}$$

Limiting Cases of SNR

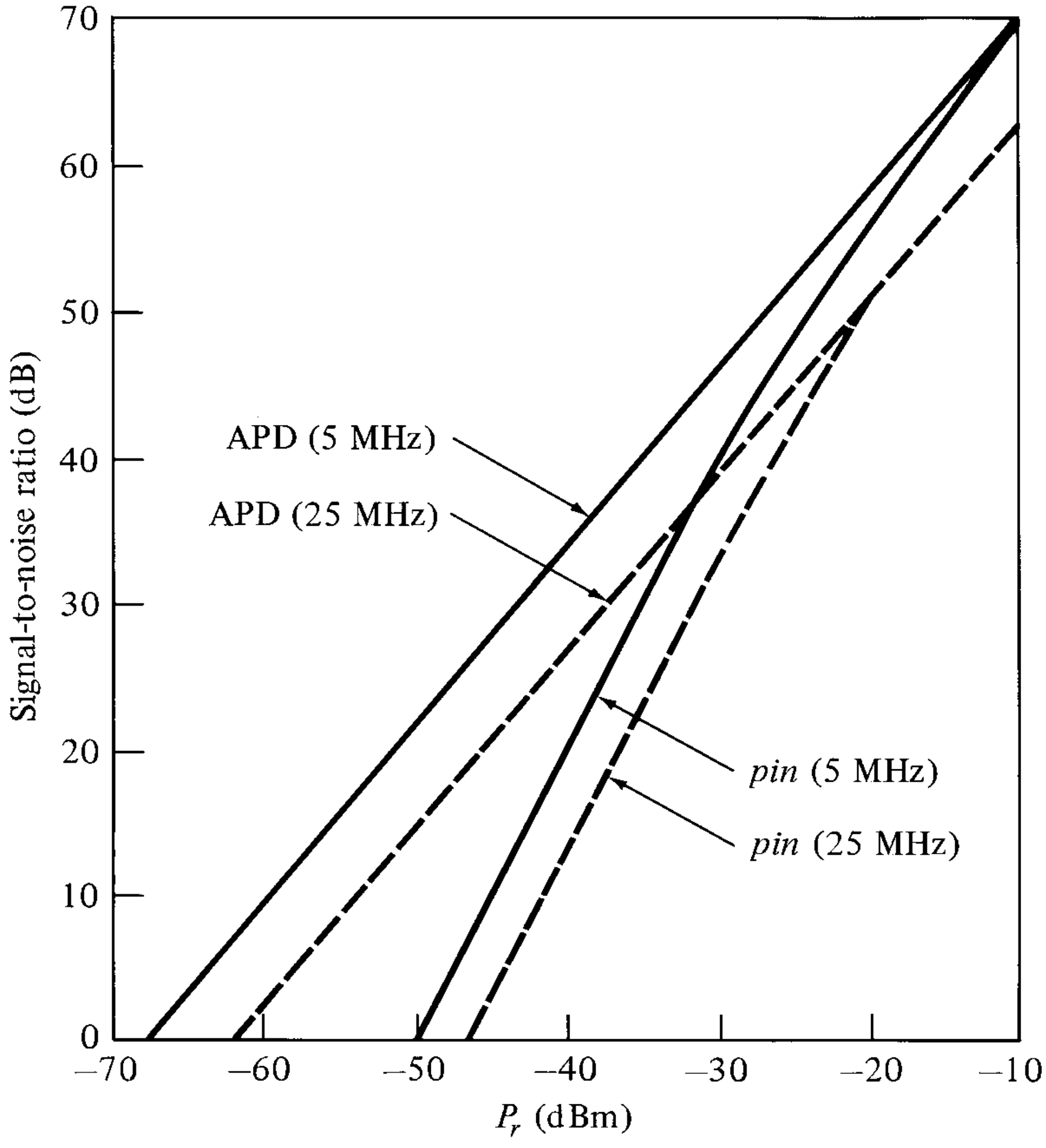
In the shot current limited case the SNR is:

$$SNR = \frac{\langle i_p^2 \rangle}{2q(I_p)F(M)B}$$

For analog links, there will be *RIN (Relative Intensity Noise)* as well

$$SNR = \frac{\langle i_p^2 \rangle M^2}{\left[2q(I_p + I_D)M^2F(M) + 4k_BT/R_L + (RIN)I_p^2\right]B}$$

SNR vs. Received Power



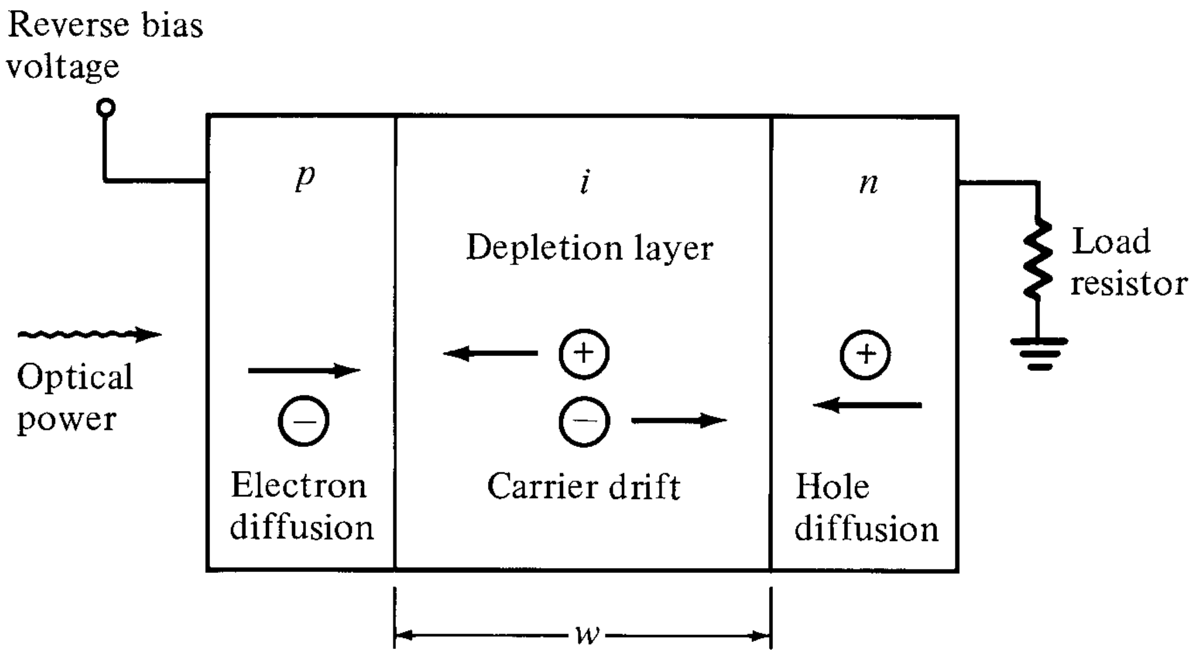
Noise-Equivalent Power

- The sensitivity of a photodetector is describable in terms of the *minimum detectable optical power* to have SNR = 1.
- This optical power is the *noise equivalent power or NEP*.
- Example: Consider the thermal-noise limited case for a *pin* photodiode. Then $\mathrm{SNR} = \mathcal{R}^2 P^2 / (4 k_B T B_e / R_L)$

To find the NEP, set the SNR = 1 and solve for P:

$$\mathrm{NEP} = \frac{P_{\min}}{\sqrt{B_e}} = \sqrt{4 k_B T / R_L} / \mathcal{R}$$

Fig. 6-10: Reverse-biased *pin* photodiode



Depletion Layer Photocurrent

$$J_{\mathrm{tot}} = J_{\mathrm{dr}} + J_{\mathrm{diff}}$$

$$J_{\mathrm{dr}} = \frac{I_p}{A} = q\Phi_0 (1 - e^{-\alpha_s W})$$

$$\Phi_0 = \frac{P_{in}(1 - R_f)}{Ah\nu}$$

$$J_{\mathrm{tot}} = q\Phi_0 \left(1 - \frac{e^{-\alpha_s W}}{1 + \alpha_s L_p} \right) + q p_{n0} \frac{D_p}{L_p}$$

Receiver Response Time

Response time depends on

- The transit time of the photocarriers in the depletion region.
- The diffusion time of the photocarriers generated outside the depletion region.
- The RC time constant of the photodiode and its associated circuit
- The photodiode parameters responsible for these three factors are the absorption coefficient as, the depletion region width w, the photodiode junction and package capacitances, the amplifi er capacitance, the detector load resistance, the amplifi er input resistance, and the photodiode series resistance. The photodiode series resistance is generally only a few ohms and can be neglected in comparison with the large load resistance and the amplifi er input resistance

$$t_d = \frac{w}{v_d}$$

Fig. 6-11: Rise and fall times

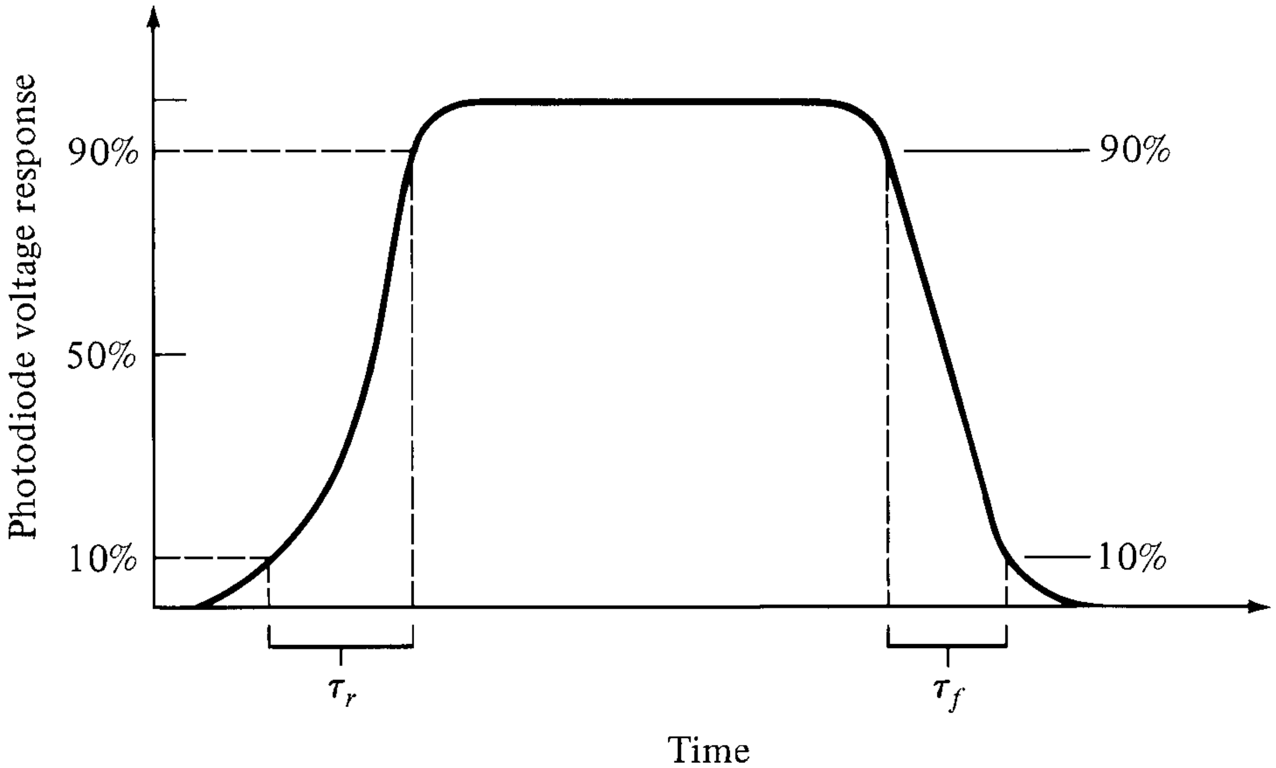


Fig. 6-12: Photodiode not fully depleted

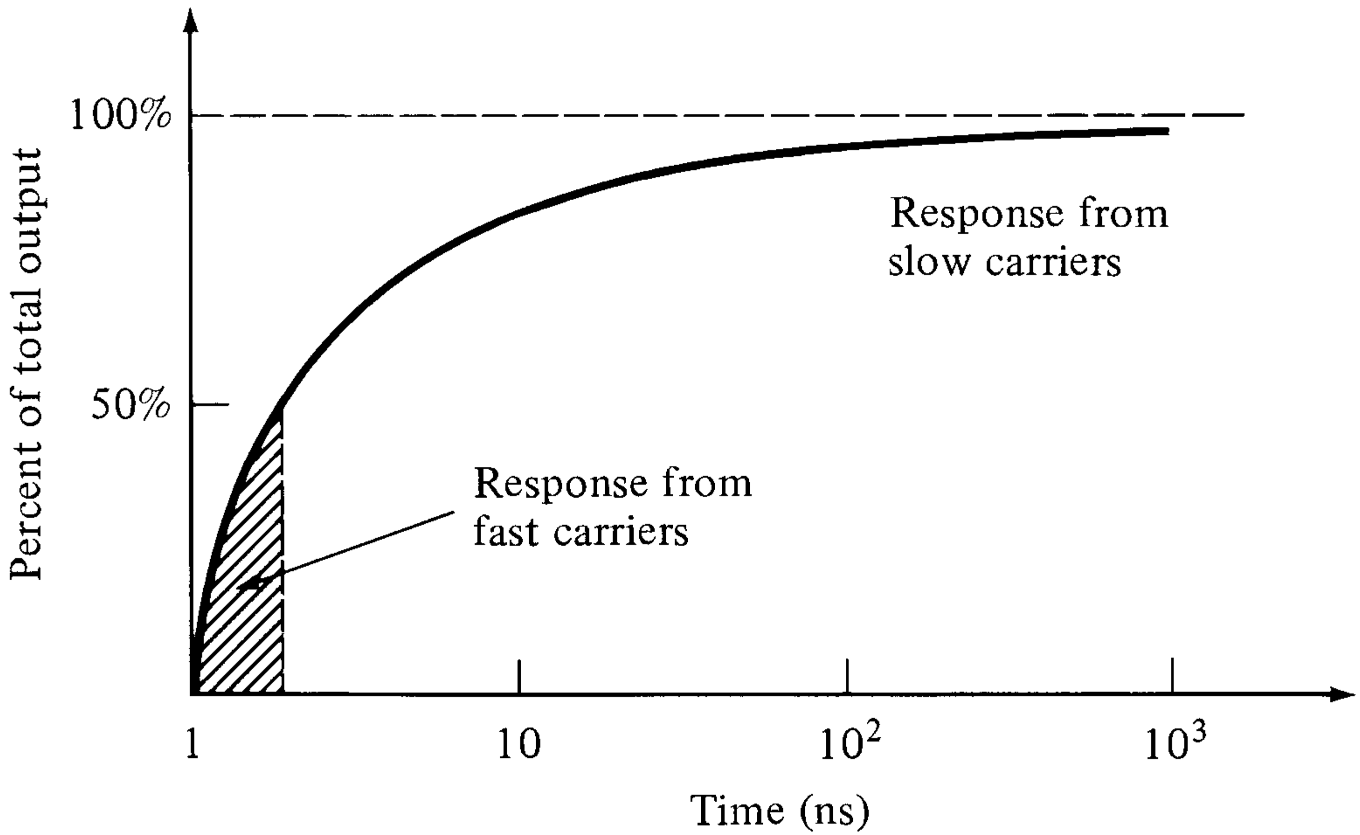
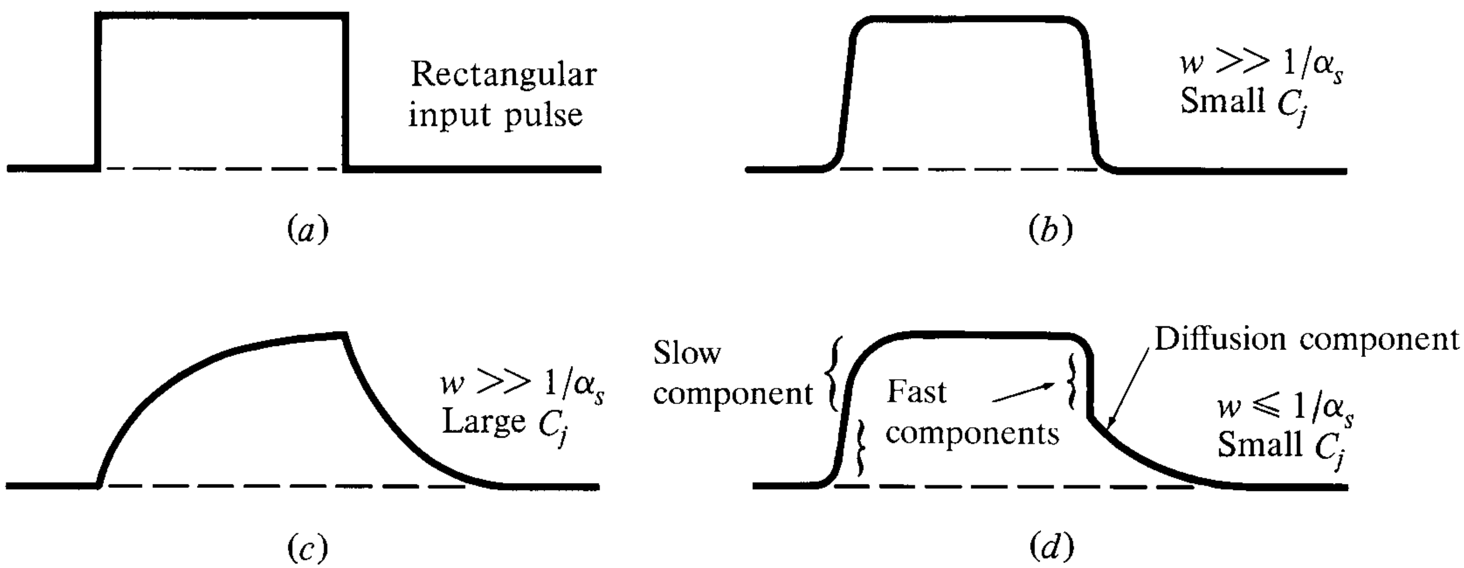


Fig. 6-13: Various pulse responses



If RT is the combination of the load and amplifier input resistances and CT is the sum of the photodiode and amplifier capacitances, the detector behaves approximately like a simple RC low-pass filter with a passband given by

$$B_c = \frac{1}{2\pi R_T C_T}$$