Chapter 6

Photodetectors

Content

- Physical Principles of Photodiodes
- *pin*, APD
- Photodetectors characteristics (Quantum efficiency, Responsivity, S/N)
- Noise in Photodetector Circuits
- Photodiode Response Time
- Photodiodes structures

Photodetectors

- These are **Opto-electric devices** i.e. to convert the optical signal back into electrical impulses.

- The light detectors are commonly made up of semiconductor material.

- When the light strikes the light detector a current is produced in the external circuit proportional to the intensity of the incident light.

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.

Photodetectors

Types of Light Detectors

- PIN Photodiode
- Avalanche Photodiode

PIN photodiode

InGaAs avalanche photodiode

Photodetectors

Photodetector materials

Operating Wavelength Ranges for Several Different Photodetector Materials

Material	Energy gap, eV	λ_{cutoff}, nm	Wavelength range, nm
Silicon	1.17	1060	400–1060
Germanium	0.775	1600	600–1600
GaAs	1.424	870	650–870
InGaAs	0.73	1700	900–1700
InGaAsP	0.75–1.35	1650–920	800–1650

InGaAs is used most commonly for both long-wavelength pin and avalanche photodiodes

Physical Principles of Photodiodes

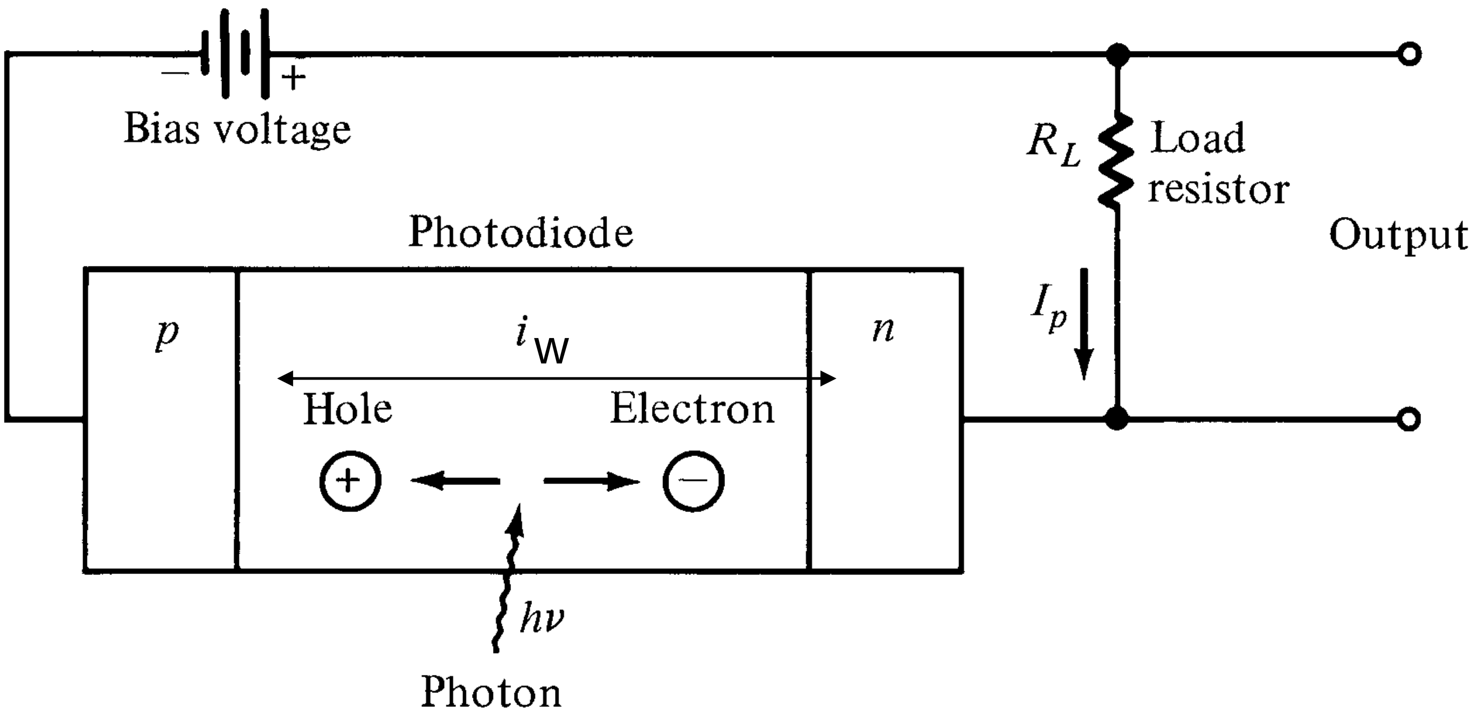
The Pin Photodetector

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 gives rise to a current flow in an external circuit, known as **photocurrent**.

The Pin Photodetector

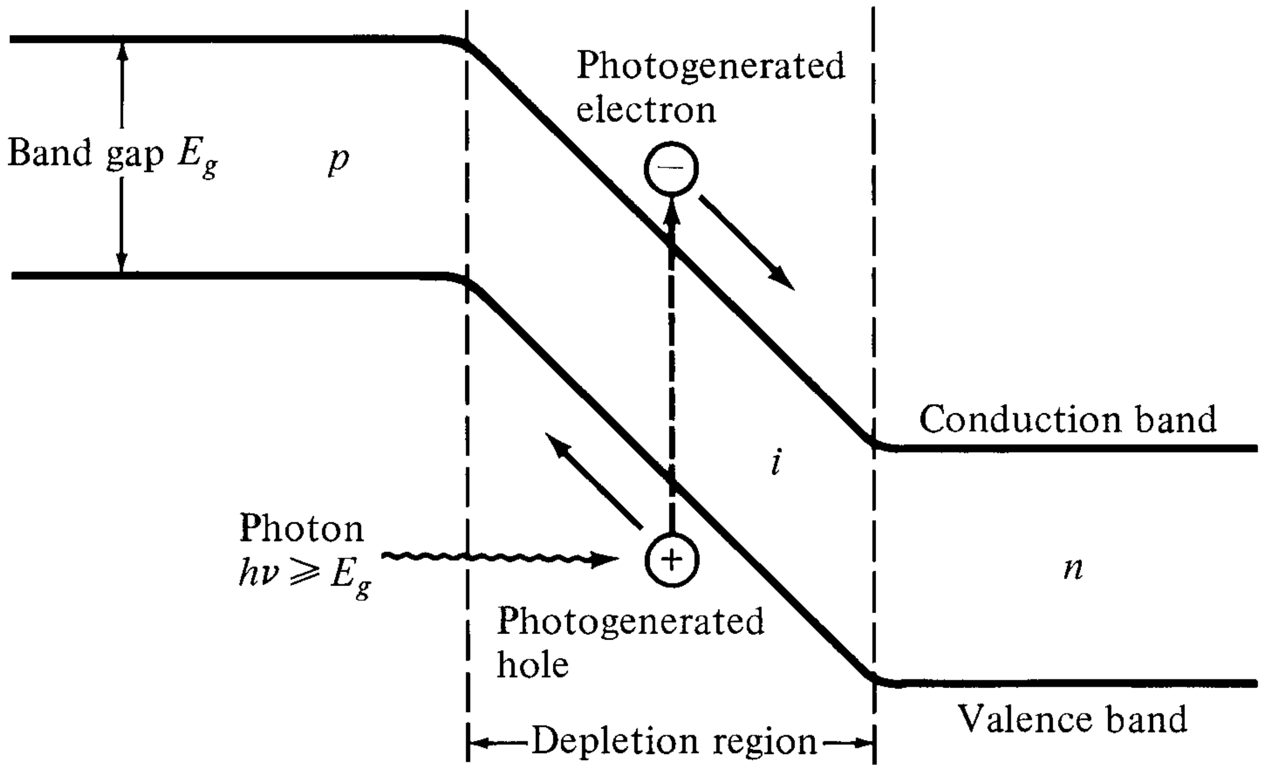
Photocarriers:

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 <u>wavelength of a photon is inversely proportional to its energy</u>**

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.

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

- As the charge carriers flow through the material some of them recombine and disappear.
- The charge carriers move a distance L_n or 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.

$$L_n = (D_n \tau_n)^{1/2} \quad \text{and} \quad L_p = (D_p \tau_p)^{1/2}$$

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

Photocurrent

- 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_{in} :

$$P(x) = P_{in}(1 - e^{-\alpha_s(\lambda)x})$$

[6-1]

- 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:

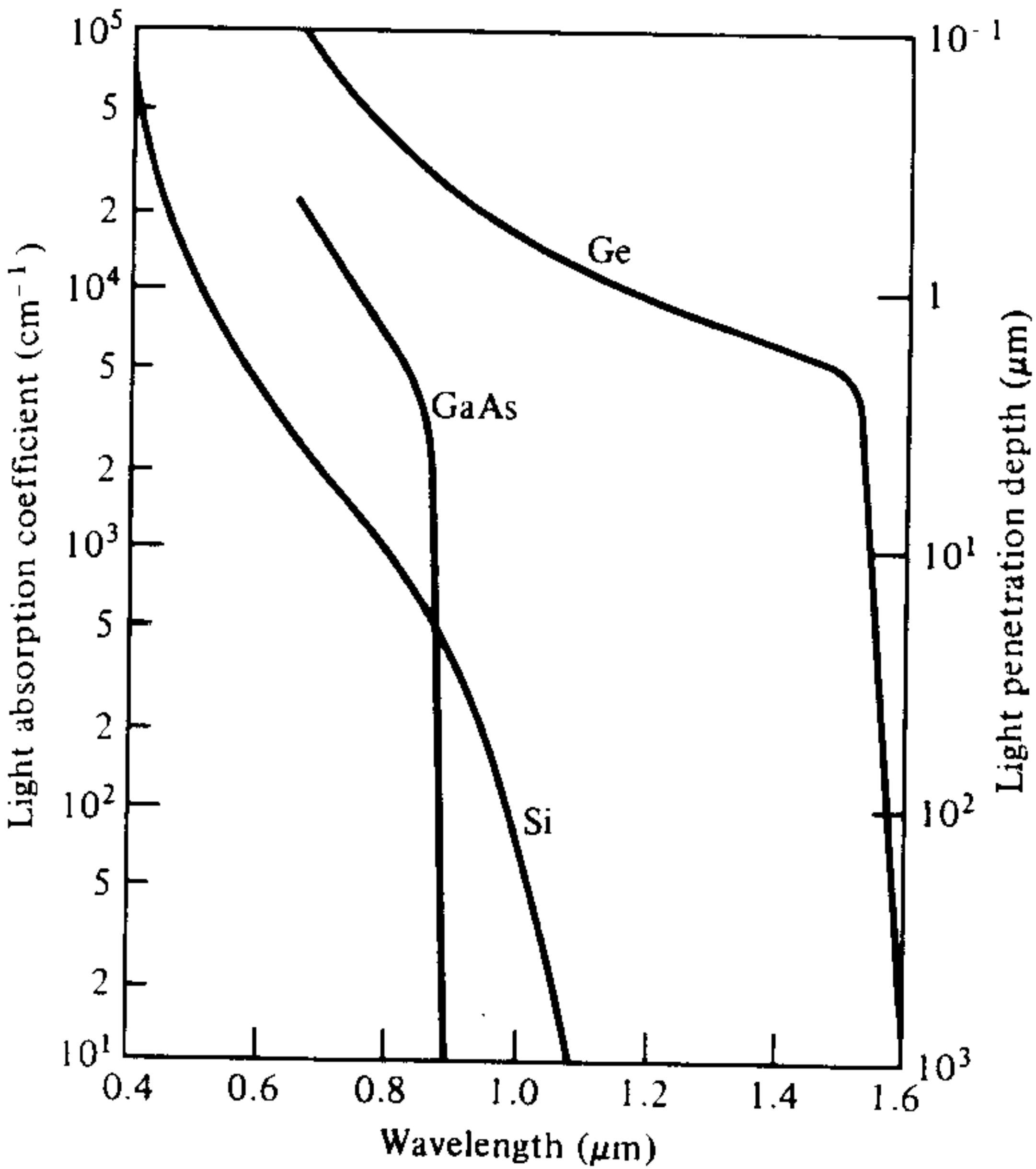
$$\lambda_c(\mu\text{m}) = \frac{1.24}{E_g(\text{eV})}$$

[6-2]

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

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

Optical Absorption Coefficient



Responsivity

- The primary photocurrent resulting from absorption is:

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

- Quantum Efficiency:

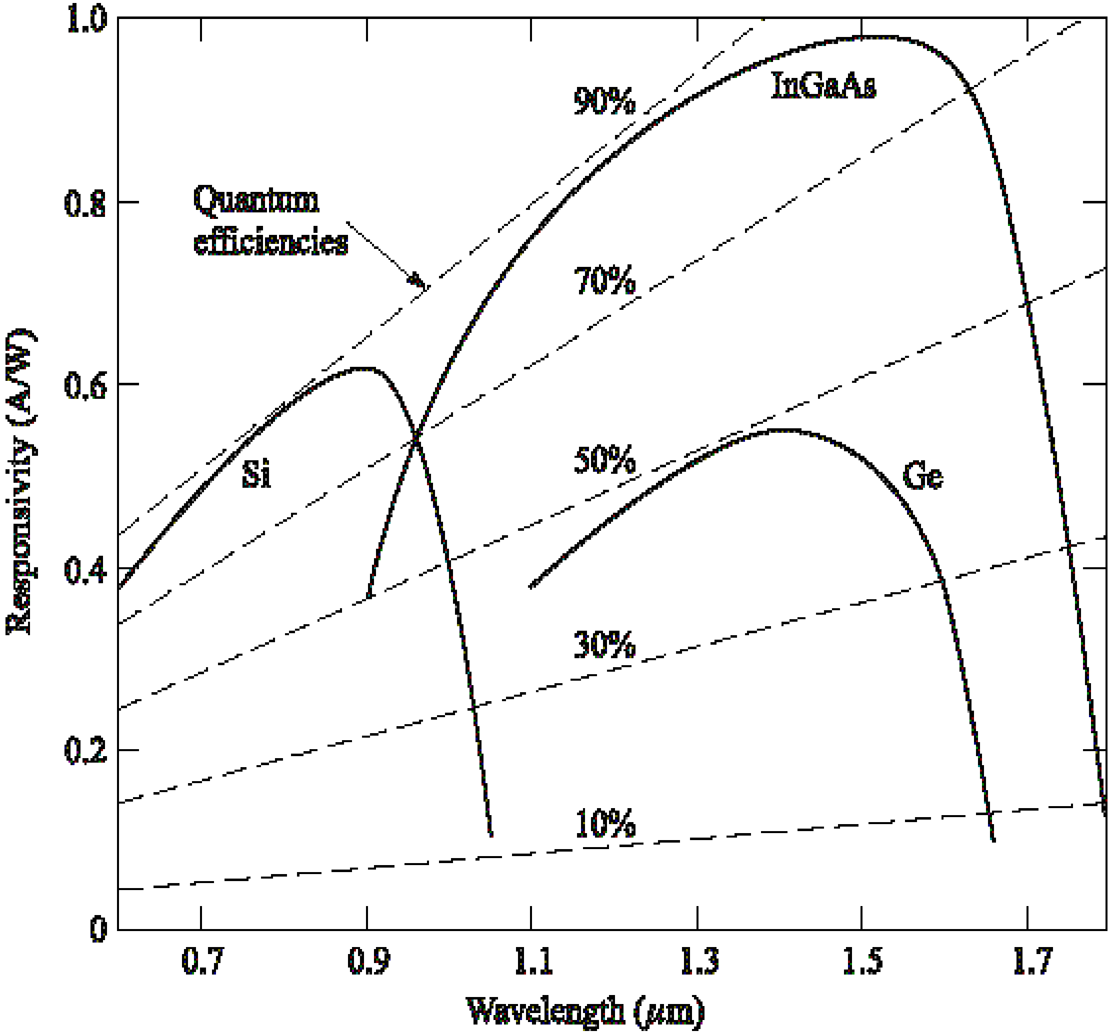
$$\eta = \frac{\text{\# of electron - hole photogenerated pairs}}{\text{\# of incident photons}}$$

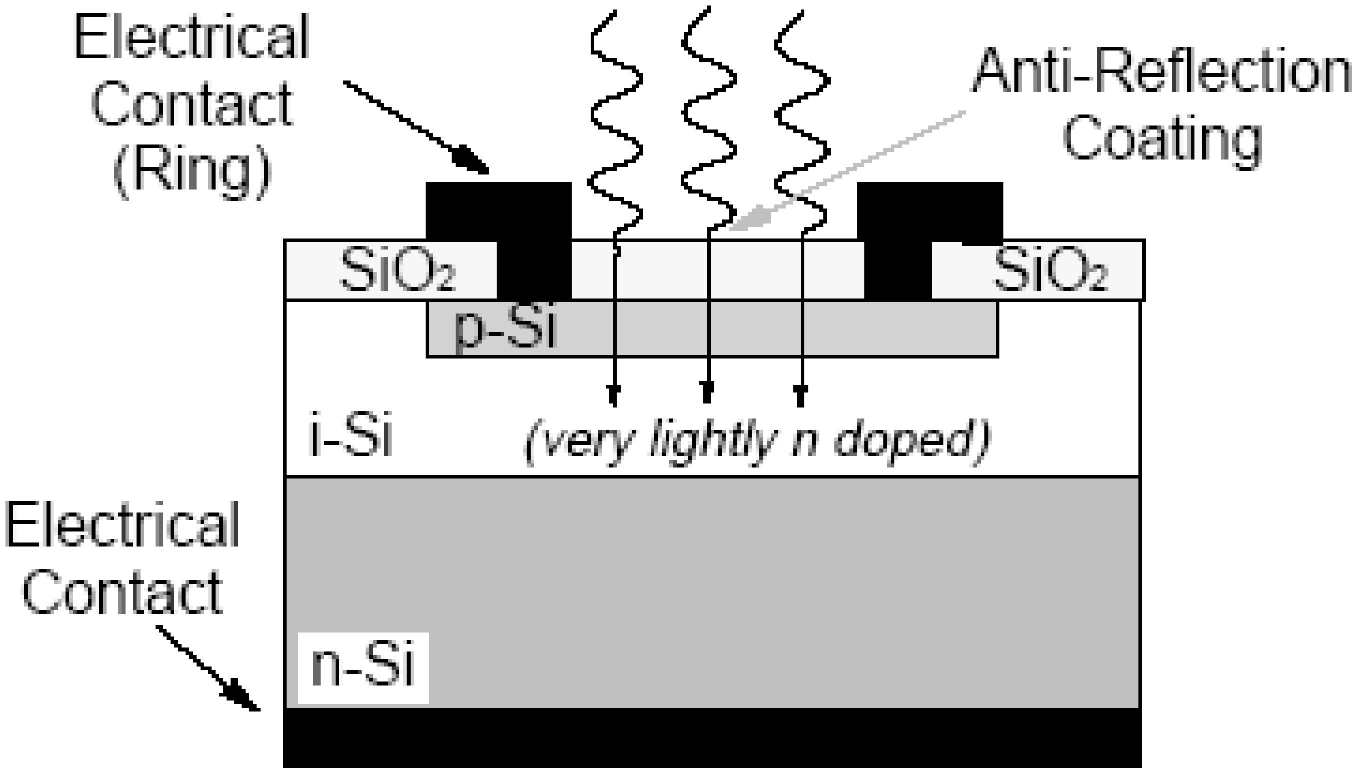
$$\eta = \frac{I_P / q}{P_{in} / h\nu}$$ [6-4]

- **Responsivity:**

$$\Re = \frac{I_P}{P_{in}} = \frac{\eta q}{h\nu} \quad [\text{A/W}]$$ [6-5]

Responsivity vs. wavelength





Typical Silicon P-I-N Diode Schematic

The Pin Photodetector

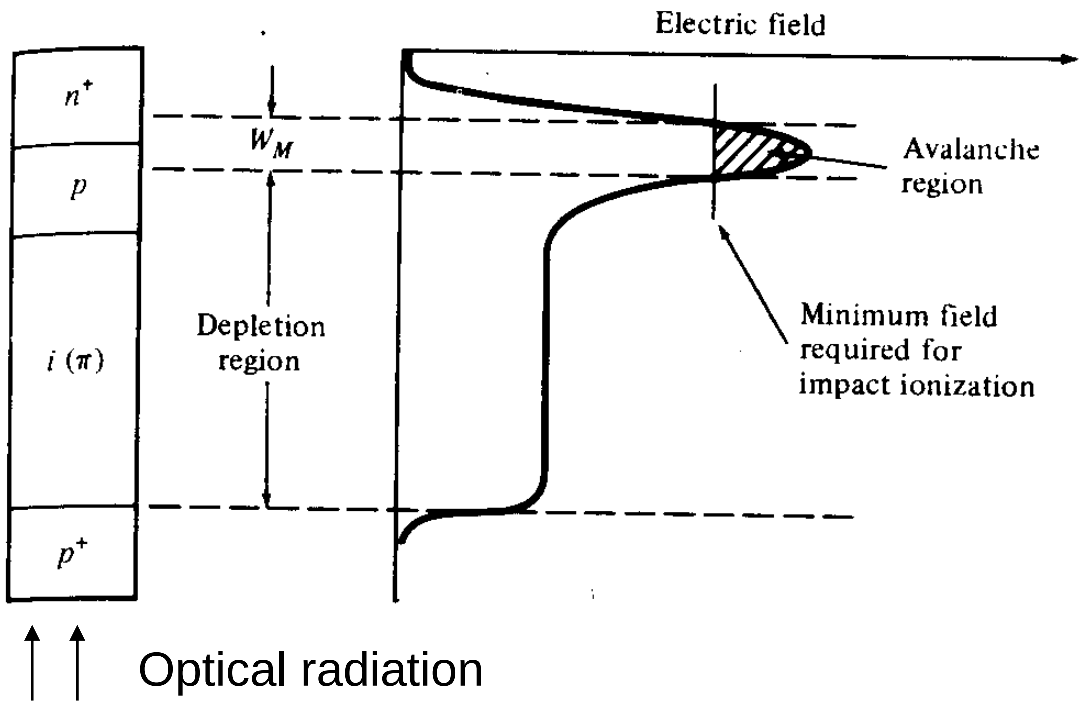
Generic Operating Parameters of an InGaAs pin Photodiode

Parameter	Symbol	Unit	Value Range
Wavelength range	λ	nm	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.75–0.95
Dark current	I_D	nA	0.5–2.0
Rise time	τ_r	ns	0.05–0.5
Bandwidth	B	GHz	1–2
Bias voltage	V_B	V	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.

Avalanche Photodiodes

Ionization rate

The average number of electron-hole pairs created by a carrier per unit distance traveled is called the **ionization rate.**

Most materials exhibit different electron ionization rates α and hole ionization rates β.

The ratio $k = \beta / \alpha$ of the two ionization rates is a measure of the photodetector performance.

Only silicon has a **significant difference** between electron and hole ionization rates.

Responsivity of APD

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

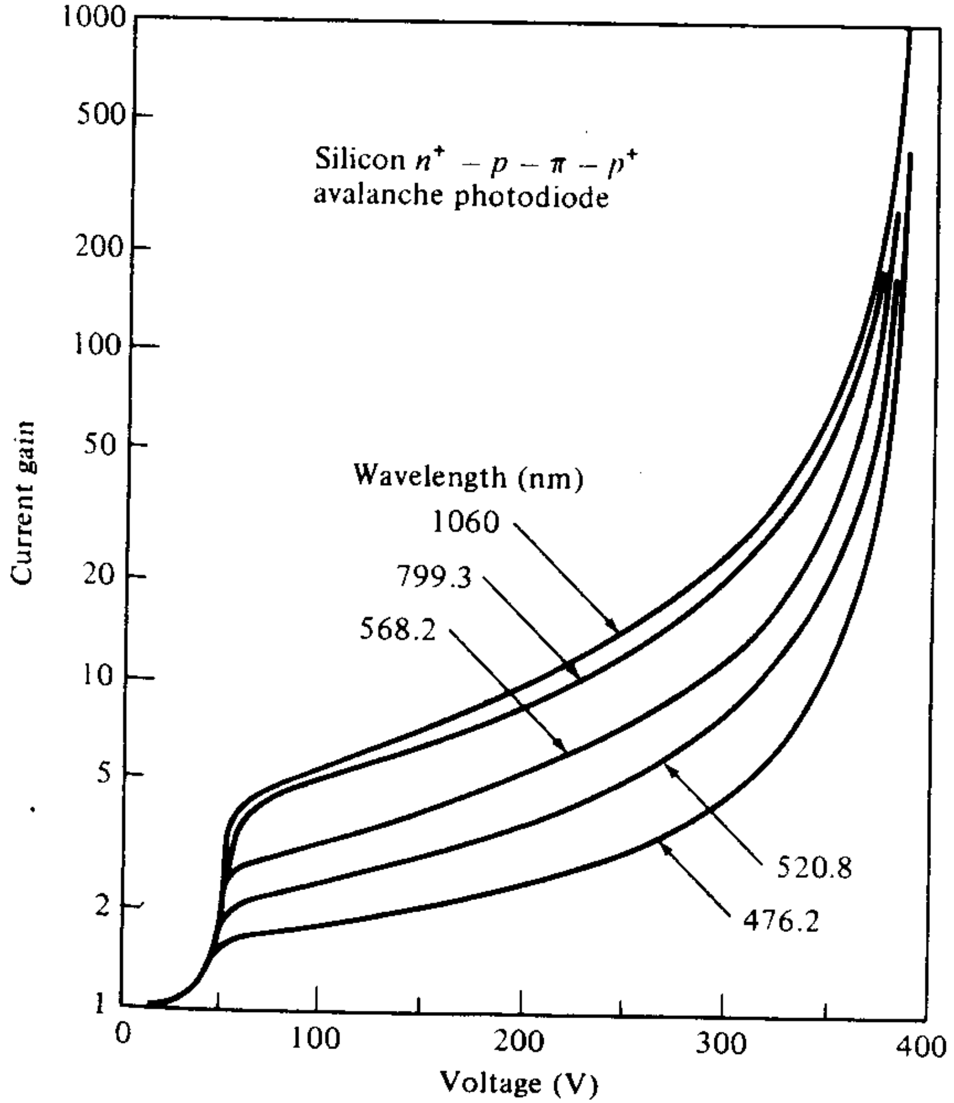
$$M = \frac{I_M}{I_p} \qquad [6\text{-}6]$$

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

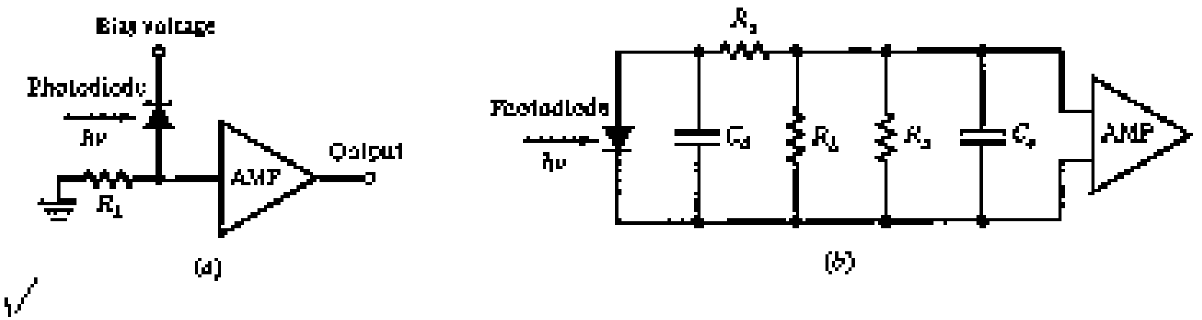


Generic Operating Parameters of an InGaAs Avalanche Photodiode

Parameter	Symbol	Unit	Value Range
Wavelength range	λ	nm	1100–1700
Avalanche gain	M	—	10–40
Dark current	I_D	nA	10–50 at $M = 10$
Rise time	τ_r	ns	0.1–0.5
Gain–bandwidth	MB	GHz	20–250
Bias voltage	V_B	V	20–30

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:

$$P(t) = P_0[1 + ms(t)]$$ [6-8]

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

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

- The mean square signal current is then:

[6-9]

Signal Power

$$\langle i_s{}^2 \rangle = \langle i_p{}^2 \rangle M^2 = \sigma_s{}^2$$

Signal Component

$$\langle i_p{}^2 \rangle = \sigma_p{}^2 = \frac{m^2 I_P^2}{2}$$

For sinusoidally varying signal $s(t)$ of modulation index m

[6-10]

Noise Sources in Photodetecors

- The principal noises associated with photodetectors are :

  1- Quantum (Shot) noise: arises from statistical nature of the production and collection of photo-generated electrons upon optical illumination. It has been shown that the statistics follow a Poisson process.

  2- Dark current noise: is the current that continues to flow through the bias circuit in the absence of the light. This is the combination of **bulk dark current**, which is due to thermally generated e and h in the *pn* junction, and the **surface dark current**, due to surface defects, bias voltage and surface area.
- Surface dark current is also known as surface leakage current. It depends on surface defects, cleanliness, bias voltage and surface area. The surface currnt can be reduced by using the guard rings so that the surface current should not flow through the load resistor
- In order to calculate the total noise present in photodetector, we should sum up the root mean square of each noise current by assuming that those are uncorrelated.

Total photodetector noise current=quantum noise current +bulk dark current noise + surface current noise

Noise calculation (1)

- **Quantum noise current** (lower limit on the sensitivity):

$$\langle i_{shot}{}^2 \rangle = \sigma_{shot}{}^2 = 2qI_P BM^2 F(M) \qquad [6\text{-}13]$$

B: Bandwidth, $F(M)$ is the noise figure and generally is

$$F(M) \approx M^x \quad 0 \le x \le 1.0$$

Note that for *pin* photodiode

$$M^2 F(M) = 1$$

- **Bulk dark current noise:**

$$\langle i_{DB}{}^2 \rangle = \sigma_{DB}^2 = 2qI_D BM^2 F(M) \qquad [6\text{-}14]$$

I_D is primary (unmultiplied) bulk dark current.

- **Surface dark current noise:** I_L is the surface leakage current.

$$\langle i_{DS}{}^2 \rangle = \sigma_{DS}^2 = 2qI_L B \qquad [6\text{-}15]$$

Noise calculation (2)

- Since the dark current and the signal current are totally uncorrelated so the total ms photodetector noise current is:

$$\langle i_N{}^2 \rangle = \sigma_N{}^2 = \langle i_Q{}^2 \rangle + \langle i_{DB}{}^2 \rangle + \langle i_{DS}{}^2 \rangle$$
$$= 2q(I_P + I_D)BM^2F(M) + 2qI_LB \qquad [6\text{-}16]$$

- The thermal noise of amplifier connected to the photodetector is: [Assumption: amplifier input impedance is much greater than the load resistor]

$$\langle i_T{}^2 \rangle = \sigma_T{}^2 = \frac{4k_BTB}{R_L} \qquad k_B = 1.38 \times 10^{-23}\ \mathrm{JK}^{-1} \qquad [6\text{-}17]$$

R_L is the input resistance of amplifier, and k_B is Boltzmann’s constant.

S/N Calculation

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

$$\frac{S}{N} = \frac{\langle i_P{}^2 \rangle M^2}{2q(I_P + I_D)BM^2 F(M) + 2qI_L B + 4k_B TB / R_L} \quad [6\text{-}18]$$

- 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 :

$$F(M) \approx M^x$$

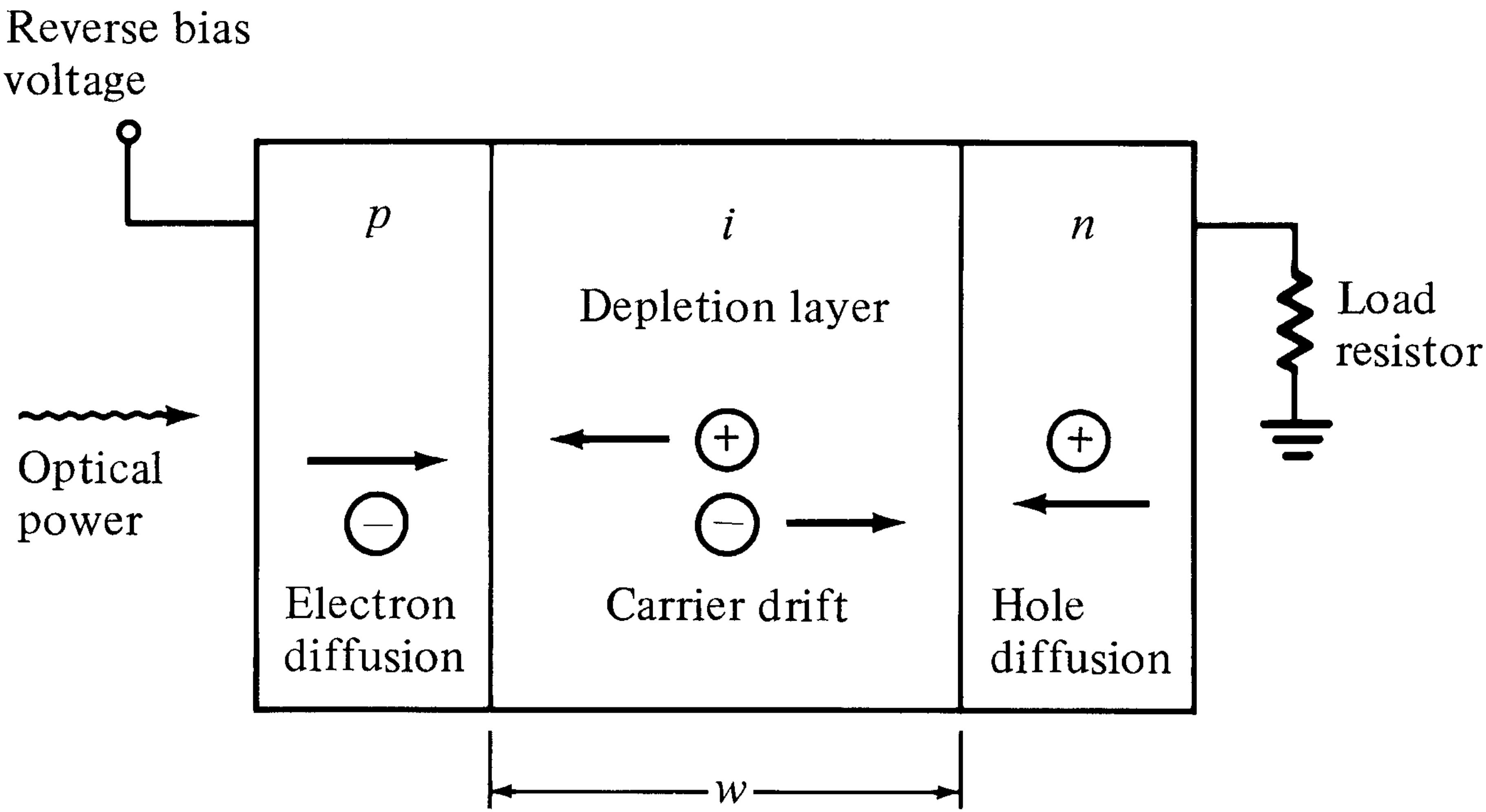
$$M_{\mathrm{opt}}^{x+2} = \frac{2qI_L + 4k_B T / R_L}{xq(I_P + I_D)} \quad [6\text{-}19]$$

Detector Response Time

The response time of <u>photodiode</u> together with its <u>output circuit</u> depends mainly on the following three factors:

1. **The transit time of the photocarriers in the depletion region.**
2. **The diffusion time of the photocarriers generated outside the depletion region.**
3. **The RC time constant of the photodiode and its associated circuit.**

Reverse-biased pin photodiode



Schematic representation of a reversed biased pin photodiode

Depletion Layer Photocurrent

- Under steady state the total current flowing through the depletion layer is $J_{total} = J_{dr} + J_{diff}$

- *J_{dr} is the drift current from the carriers inside the depletion region*
- J_{diff} is the current due to the carriers generated outside the depletion region (in n or p side) and diffuses into the reverse bias region. The drift current density is

$$J_{dr} = \frac{I_p}{A} = q\Phi_o\left(1 - e^{-\alpha_s w}\right)$$

where

$$\Phi_o = \frac{P_{in}\left(1 - R_f\right)}{Ah\nu}$$

Depletion Layer Photocurrent

- The surface p layer of a pin photodiode is normally very thin. The diffusion current is mainly due to the holes diffusion from bulk n region. The hole diffusion in the material can be determined by the one dimensional diffusion equation

$$D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} + G(x) = 0$$

- Where D_p is the hole diffusion constant, p_n is the hole concentration in the n-type material, τ_p is the excess hole life time, p_{no} is the equilibrium hole density, and $G(x)$ is the electron-hole generation rate.

Depletion Layer Photocurrent

Diffusion current:

- Solving the diffusion equation using the electron hole generation rate

$$G(x) = \Phi_0 \alpha_s e^{-\alpha_s x}$$

- The diffusion current density is given as

$$J_{diff} = q\Phi_0 \frac{\alpha_s L_p}{1+\alpha_s L_p} e^{-\alpha_s x} + q p_{n0} \frac{D_p}{L_p}$$

- The total current density can be written as

$$J_{tot} = q\Phi_0 \left[1 - \frac{e^{-\alpha_s x}}{1+\alpha_s L_p} \right] + q p_{n0} \frac{D_p}{L_p}$$

Photodetector Response Time

- The response time of a photo detector with its output circuit depends mainly on the following three factors:

1- The transit time of the photo carriers in the depletion region. The transit time t_d depends on the carrier drift velocity v_d and the depletion layer width *w*, and is given by:

$$t_d = \frac{w}{v_d} \qquad [6\text{-}27]$$

2- Diffusion time of photocarriers outside depletion region.

3- *RC* time constant of the circuit. The circuit after the photodetector acts like *RC* low pass filter with a passband given by:

$$B = \frac{1}{2\pi R_T C_T} \qquad [6\text{-}29]$$

$$R_T = R_s \parallel R_L \text{ and } C_T = C_a + C_d$$

Detector Response Time

The photodiode parameters responsible for these three factors (transient time, diffusion time, RC time constant) are:

1. **Absorption coefficient α**
2. **Depletion region width**
3. Photodiode **junction** and package **capacitance**
4. Amplifier capacitance
5. Detector load resistor
6. Amplifier input resistance
7. Photodiode series resistance

Detector Response Time

The **diffusion processes** are **slow** compared with the **drift of carriers** in the high field region.

To have a high speed photodiode:

•Photocarriers should be **generated** in the depletion region or close to the depletion region.

•Diffusion times should be **less than or equal** to the **carrier drift times**.

The **effect of long diffusion times** can be seen by considering the **photodiode response time.**

Detector Response Time

Response time is described by the **rise time** and the **fall time** of the **detector output** when the detector is illuminated by the step input of optical radiation.

The rise time is typically measured from the 10 to 90 percent points of the leading edge of the output pulse.

For **Fully depleted photodiodes** the **rise time** and the **fall time** are generally the **same**. They can be **different at low bias** levels where the **photodiode is not fully depleted**.

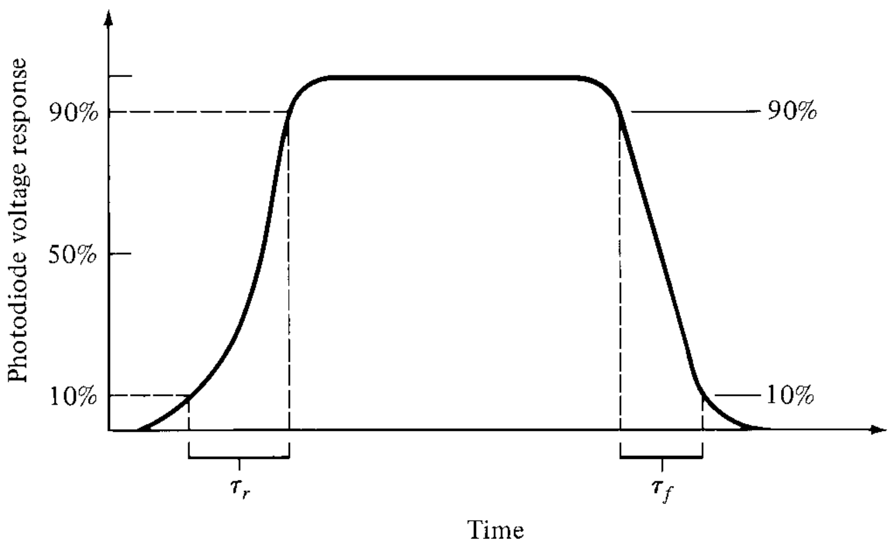
Fast carriers

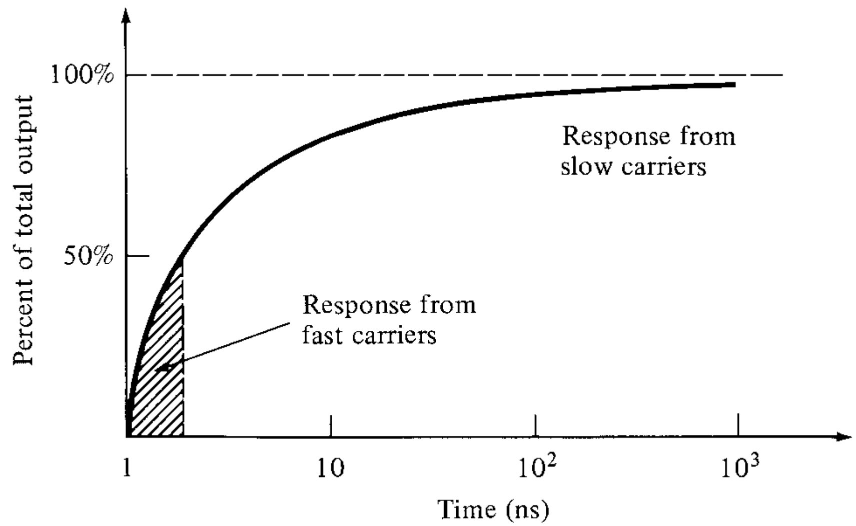
Charge carriers produced **in the depletion** region are separated and collected **quickly**.

Slow carriers

Electron hole pairs generated **in the n and p regions** must slowly diffuse to the depletion region before they can be separated and collected.

Photodiode response to optical pulse

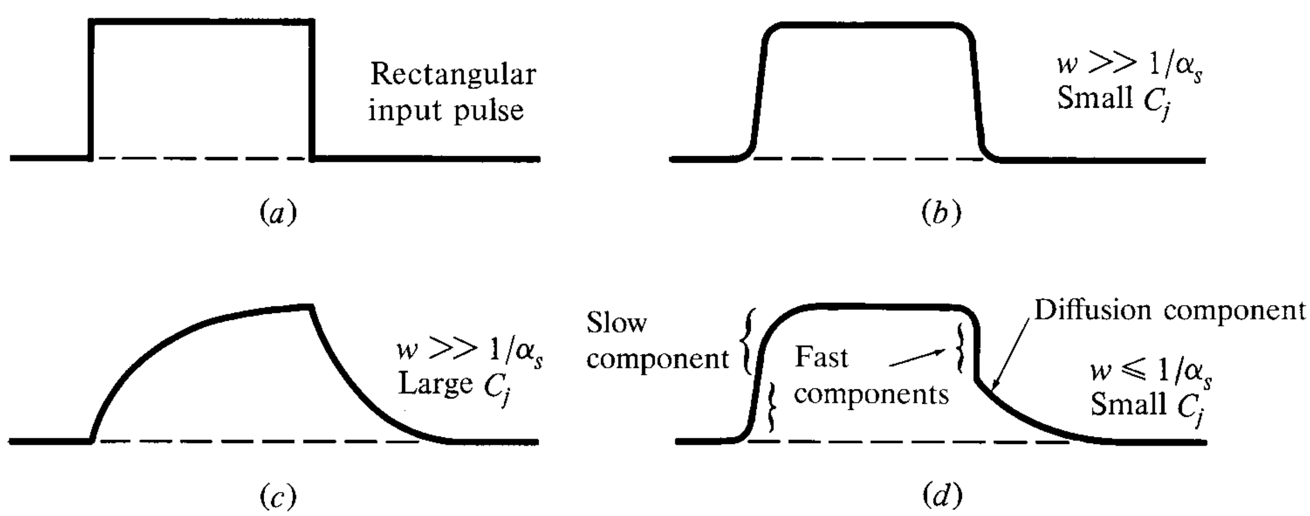




Typical response time of the photodiode that is not fully depleted

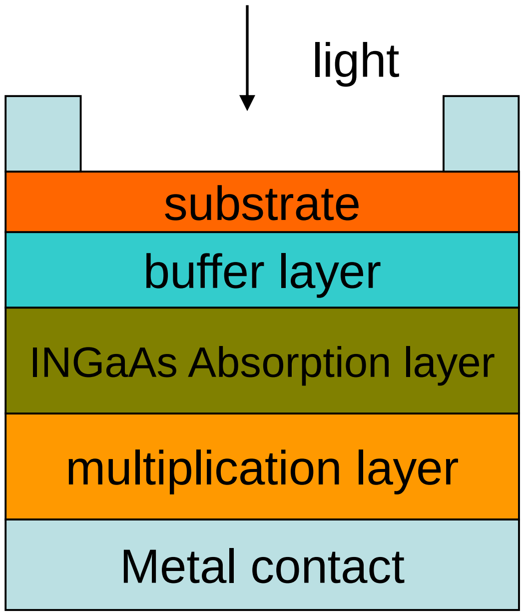
Various optical responses of photodetectors: Trade-off between quantum efficiency & response time

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



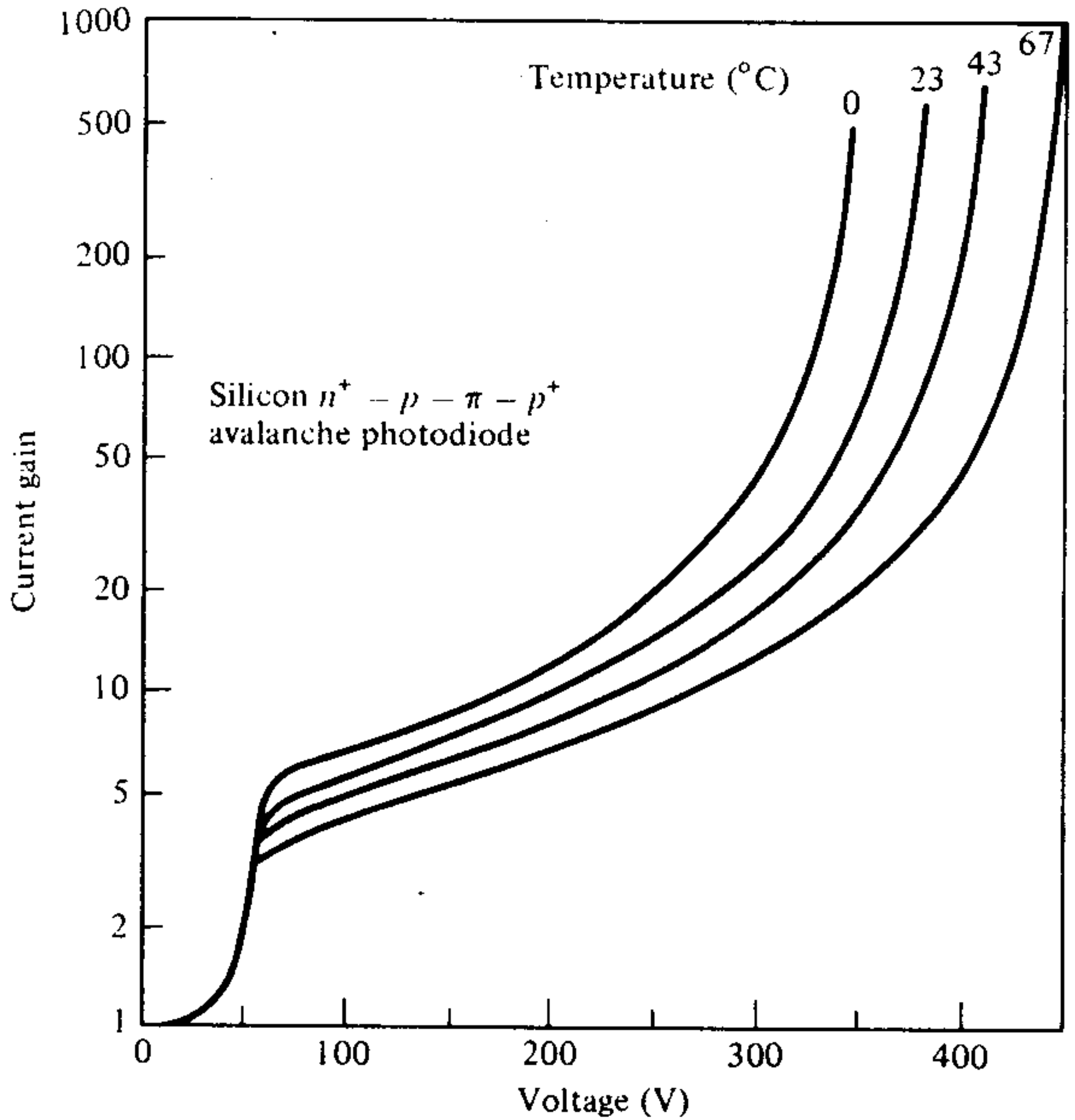
Structures for InGaAs APDs

- Separate-absorption-and multiplication (SAM) APD



- InGaAs APD superlattice structure (The multiplication region is composed of several layers of InAlGaAs quantum wells separated by InAlAs barrier layers.

Temperature effect on avalanche gain



Comparison of photodetectors

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Bandwidth	B	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

TABLE 6-2
Generic operating parameters of Si, Ge, and InGaAs avalanche photodiodes

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Avalanche gain	M	—	20–400	50–200	10–40
Dark current	I_D	nA	0.1–1	50–500	10–50 @ $M = 10$
Rise time	τ_r	ns	0.1–2	0.5–0.8	0.1–0.5
Gain · bandwidth	$M \cdot B$	GHz	100–400	2–10	20–250
Bias voltage	V_B	V	150–400	20–40	20–30