PIN Photodiode

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CONTENT

Physical Principles of PIN Photodetector

Photodetectors characteristics (Quantum efficiency, Responsivity, S/N)

Noise in Photodetector Circuits

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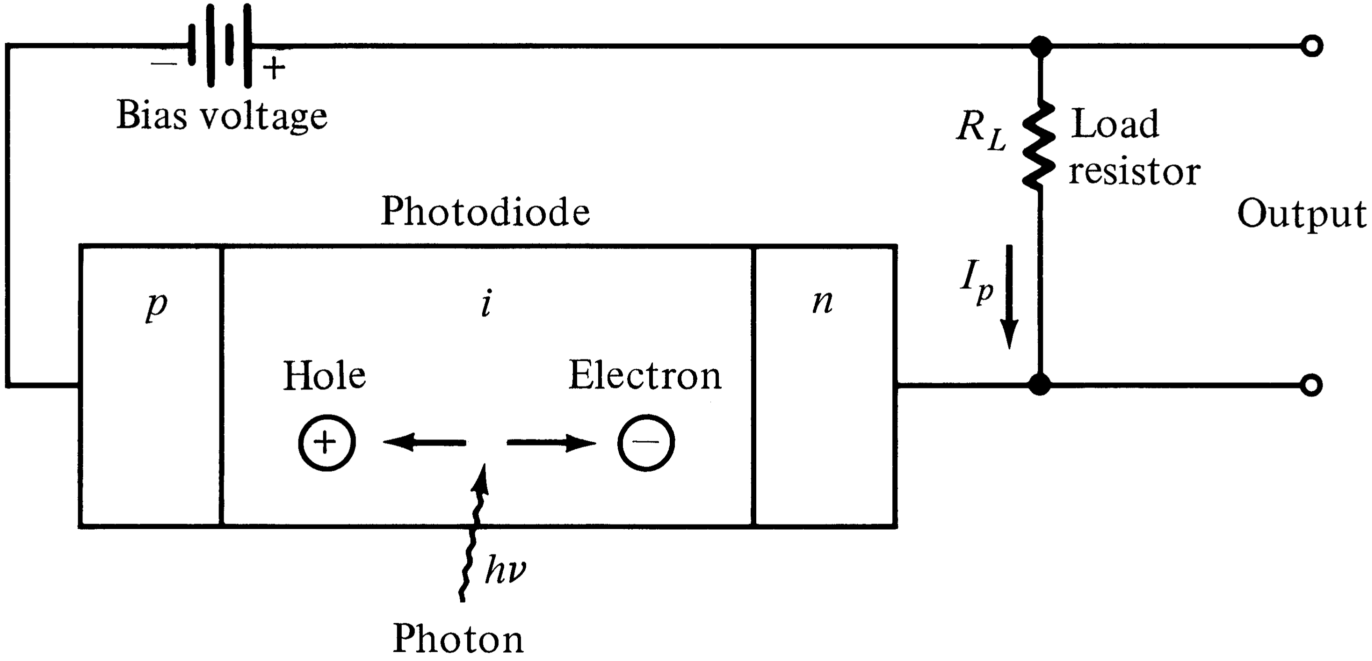
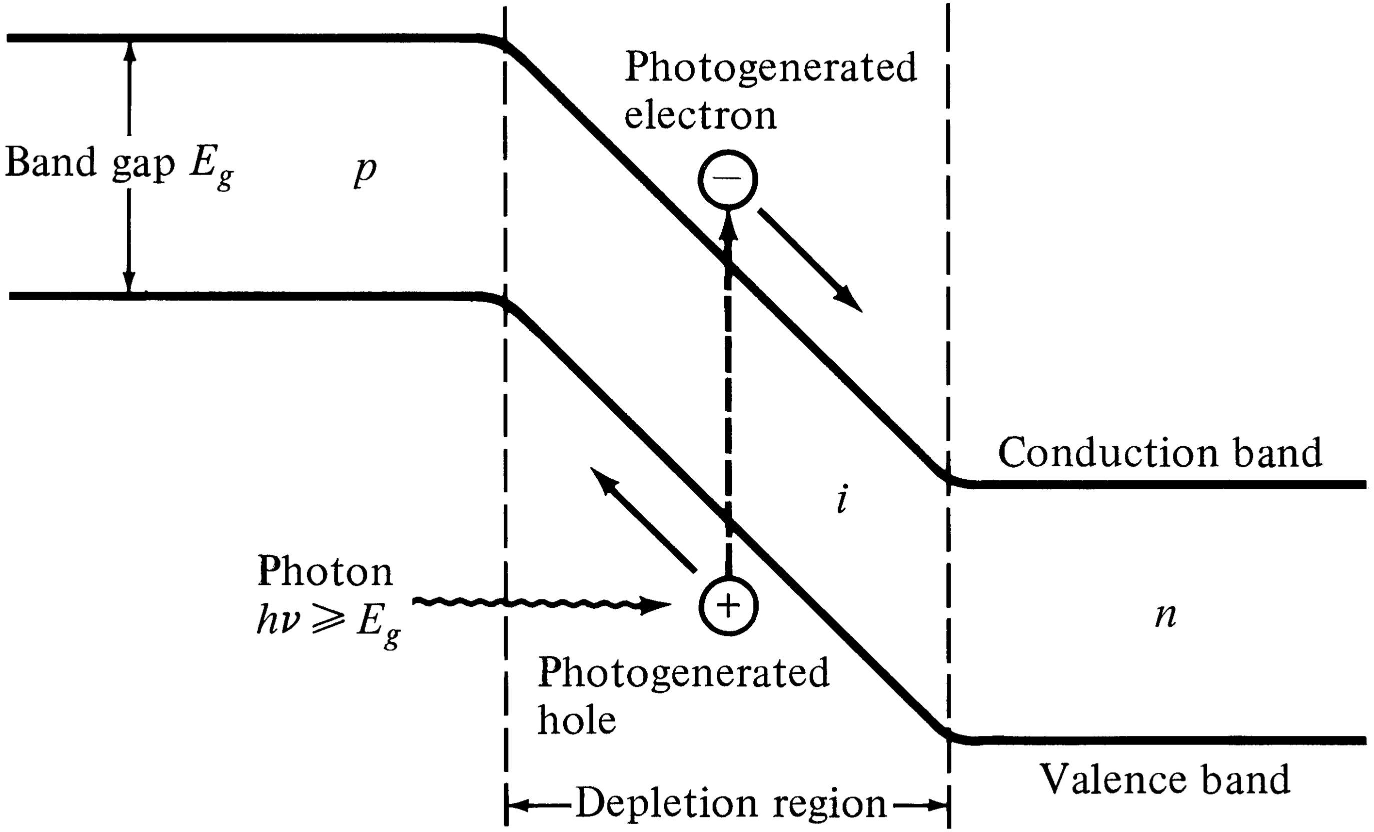
PIN PHOTODETECTOR



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.

ENERGY-BAND DIAGRAM FOR A PIN PHOTODIODE



PHOTOCURRENT

Optical power absorbed, in the depletion region can be written in terms of incident optical power:

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

Absorption coefficient strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

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

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

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

RESPONSIVITY ($\Re$)

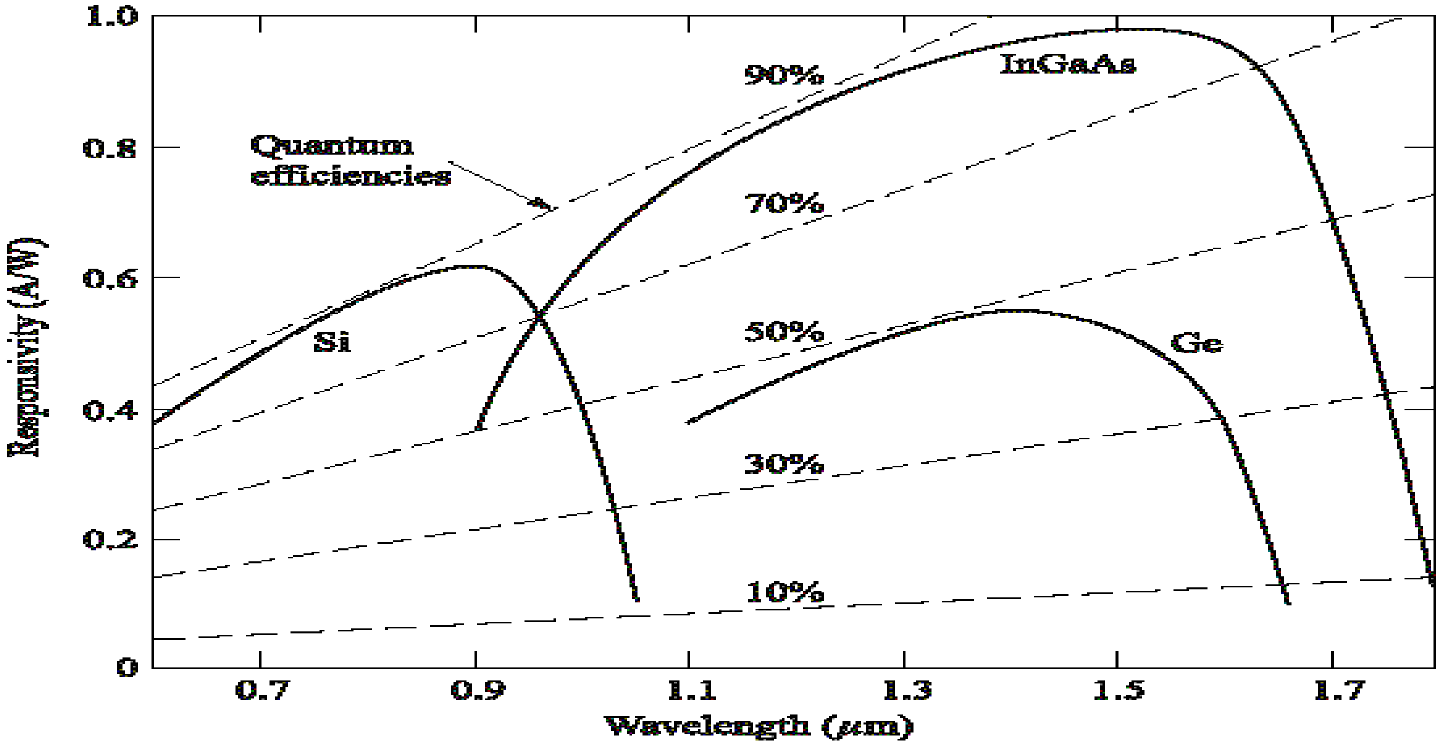
Quantum Efficiency (η) = number of e-h pairs generated / number of incident photons

$$\eta = \frac{I_p / q}{P_0 / h\nu} \qquad \longrightarrow$$

Responsivity measures the input-output gain of a detector system. In the specific case of a photodetector, responsivity measures the electrical output per optical input.

$$\Re = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} \quad \text{mA/mW}$$

RESPONSIVITY



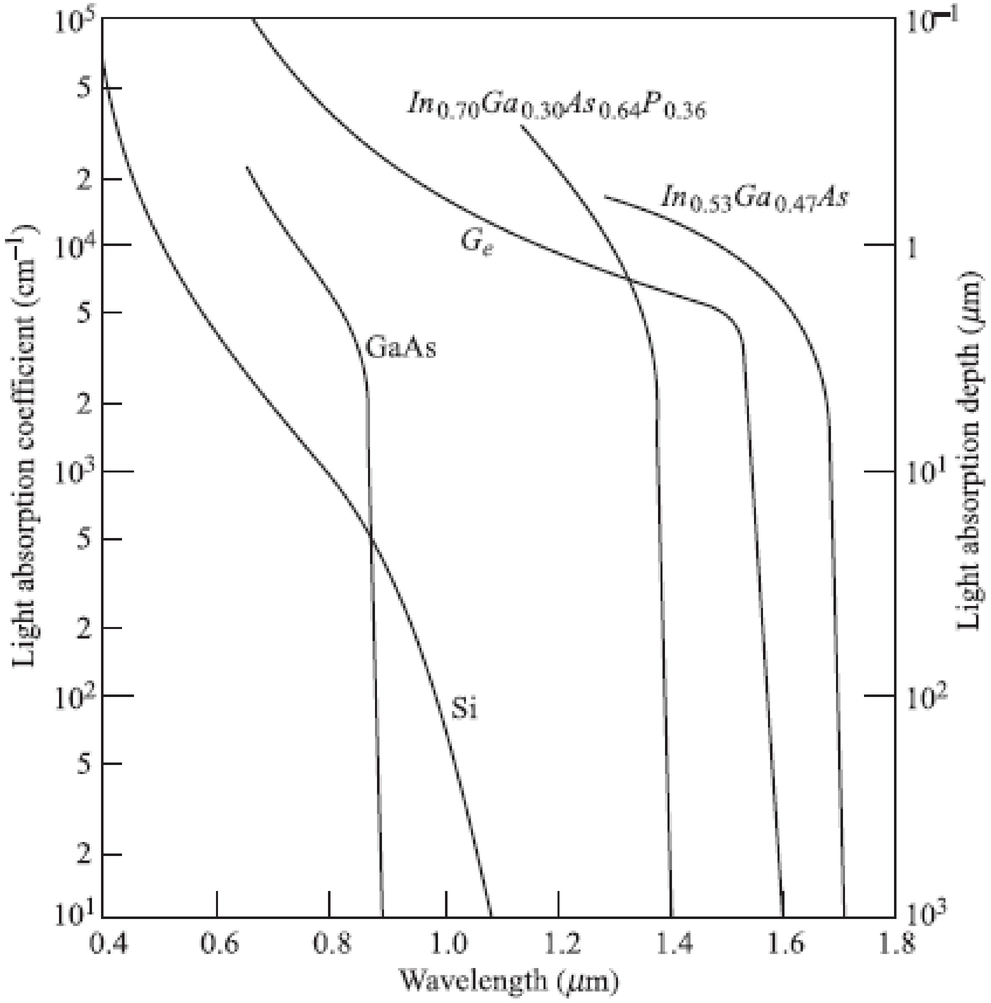
When $\lambda << \lambda_c$ absorption is low
When $\lambda > \lambda_{c;}$ no absorption

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

LIGHT ABSORPTION COEFFICIENT

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

At lower-wavelength end, the photo response diminishes due to low absorption (very large values of αs).



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

QUANTUM (SHOT NOISE)

Quantum noise arises due optical power fluctuation because light is made up of discrete number of photons

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

F(M): APD Noise Figure F(M) ~= Mx (0 ≤ x ≤ 1)
I_p: Mean Detected Current
B = Bandwidth
q: Charge of an electron

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

$$\left\langle i_{DB}^2 \right\rangle = 2qI_D BM^2 F(M)$$

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

THERMAL NOISE

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

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

K_B: Boltzmann's constant = 1.38054 X 10(−23) J/K
T is the absolute Temperature

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

SIGNAL TO NOISE RATIO

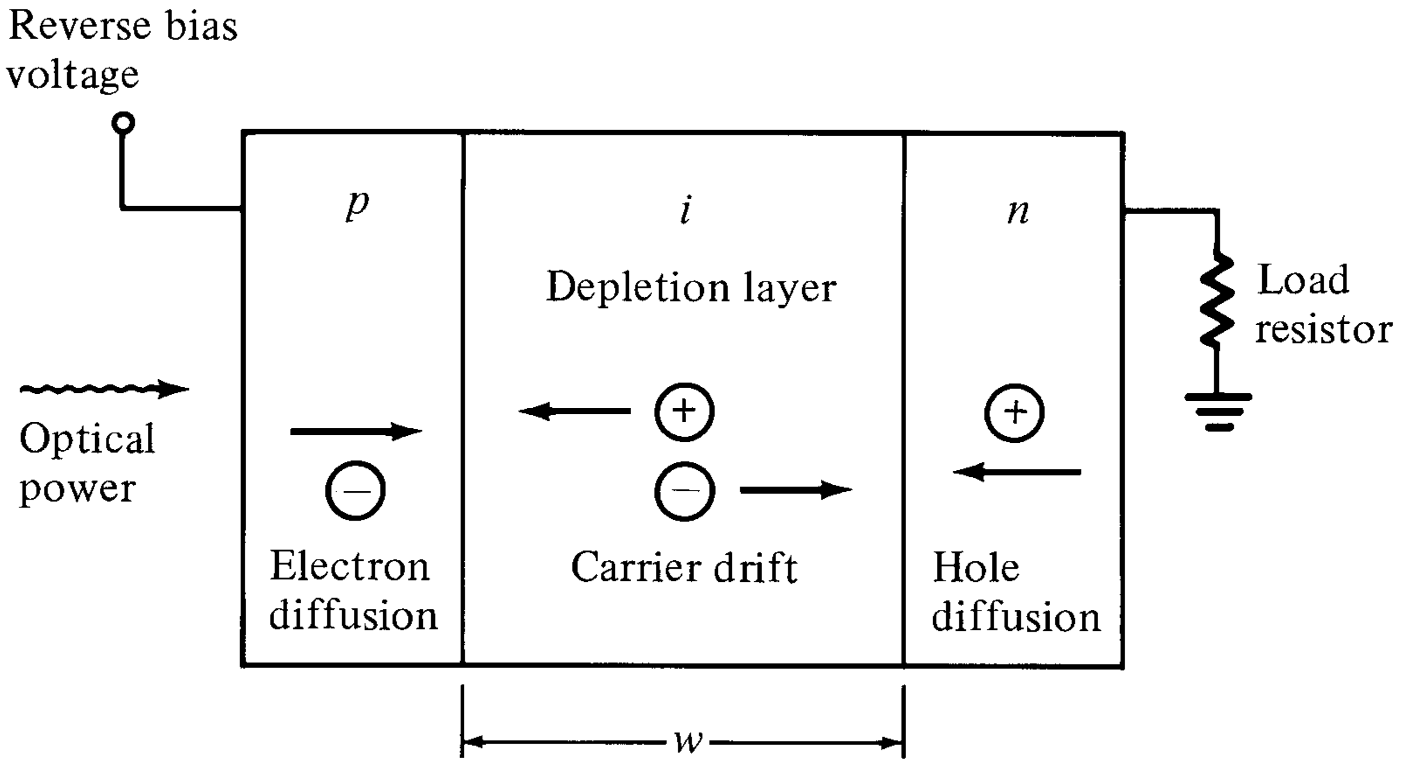
Detected current = AC (i_p) + DC (I_p)

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

$$SNR = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_L B + 4k_B TB / R_L}$$

Typically not all the noise terms will have equal weight. Often thermal and quantum noise are the most significant.

RESPONSE TIME IN *PIN* PHOTODIODE

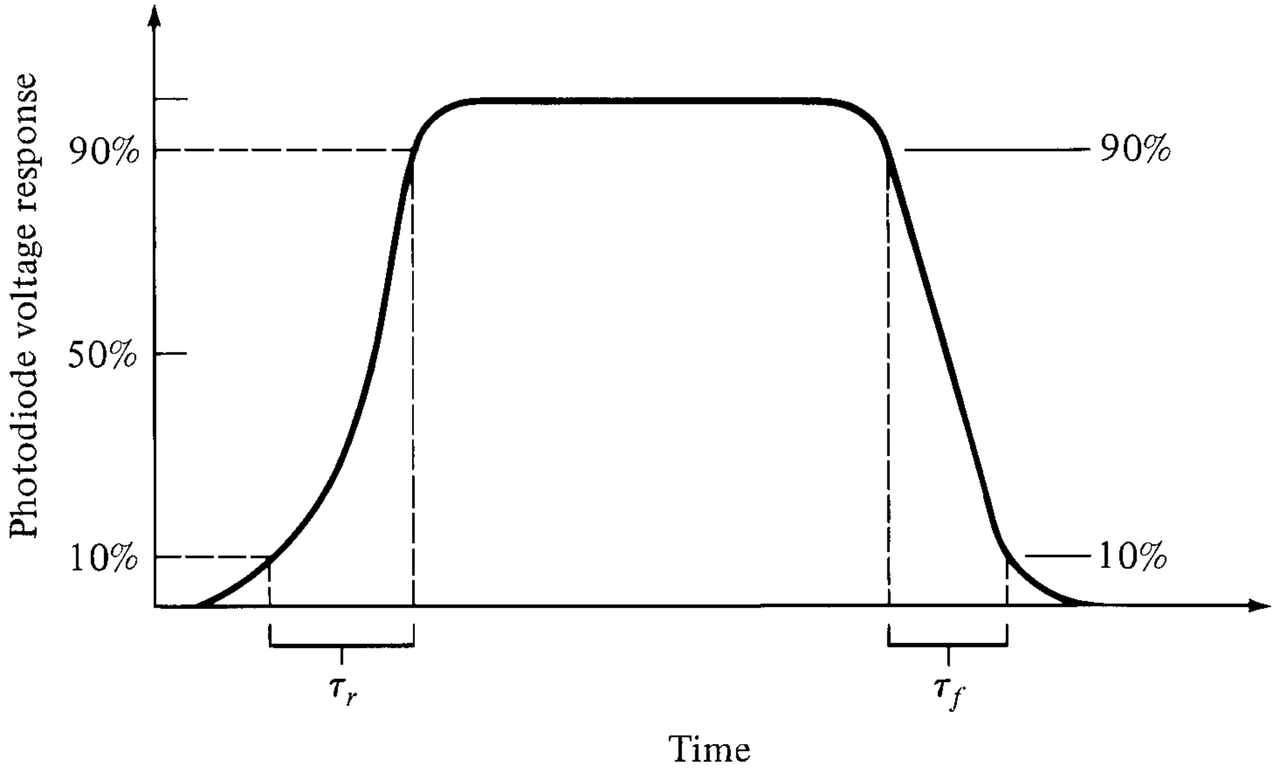


Transit time, t_d and carrier drift velocity v_d are related by

$$t_d = w / v_d$$

For a high speed Si PD, $t_d = 0.1$ ns

RISE AND FALL TIMES



Photodiode has uneven rise and fall times depending on:

1. Absorption coefficient $\alpha_s(\lambda)$ and
2. Junction Capacitance C_j

$$C_j = \varepsilon_o \varepsilon_r A / w$$

JUNCTION CAPACITANCE

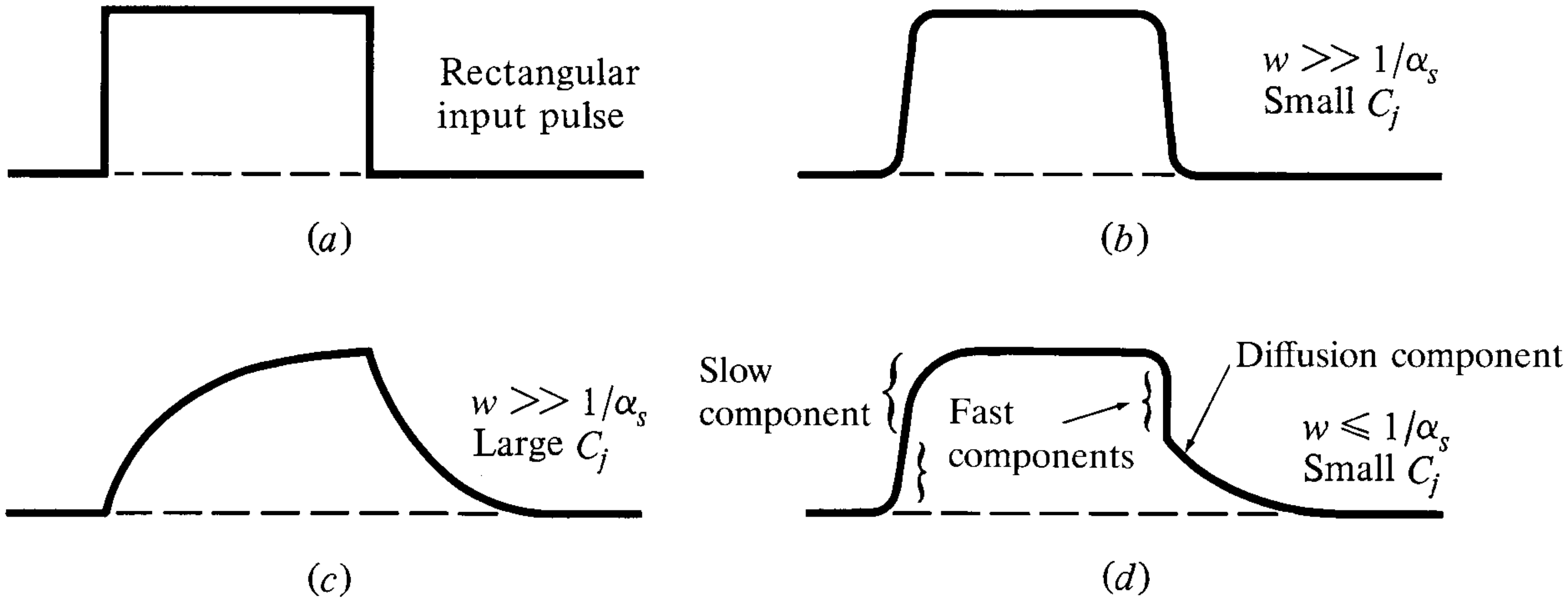
$$C_j = \varepsilon_o \varepsilon_r A / w$$

ε_o = 8.8542 x 10(−12) F/m; free space permittivity
ε_r = the semiconductor dielectric constant
A = the diffusion layer (photo sensitive) area
w = width of the depletion layer

Large area photo detectors have large junction capacitance hence small bandwidth (low speed)

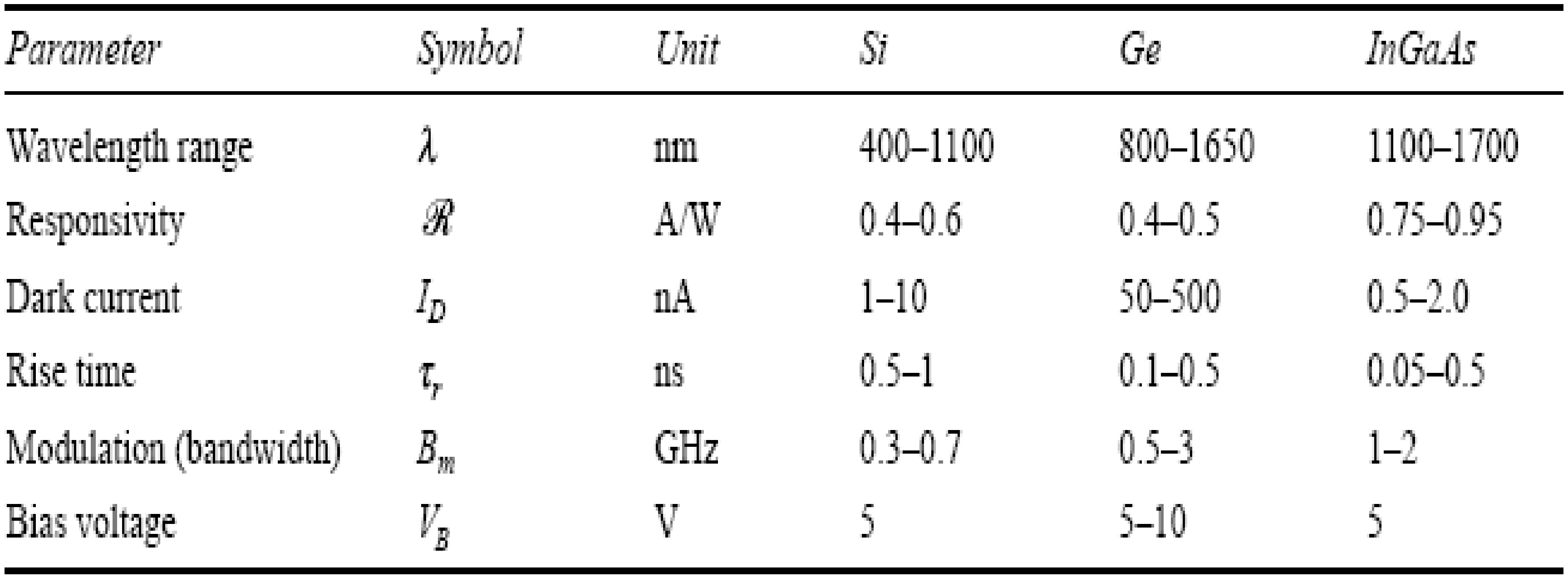
→ A concern in free space optical receivers

VARIOUS PULSE RESPONSES



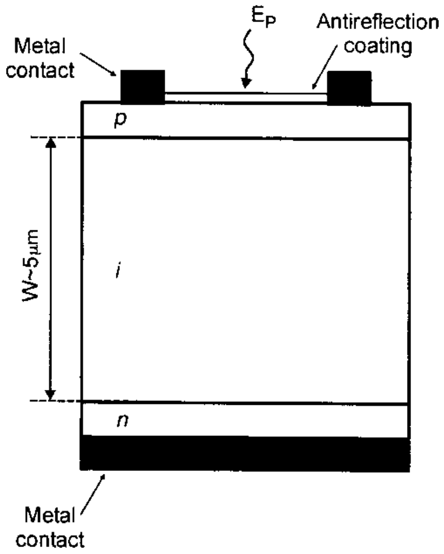
Pulse response is a complex function of absorption coefficient and junction capacitance

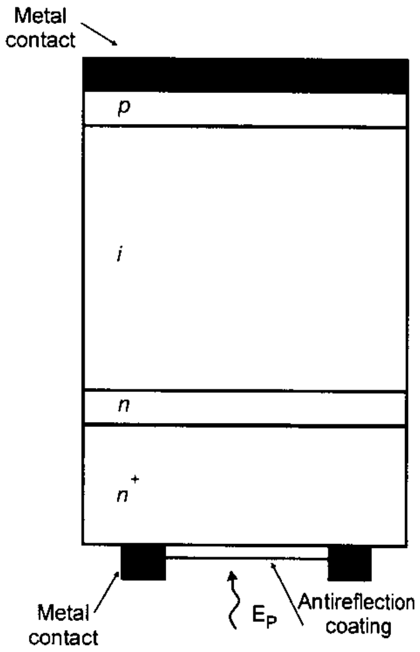
COMPARISONS OF *PIN* PHOTODIODES



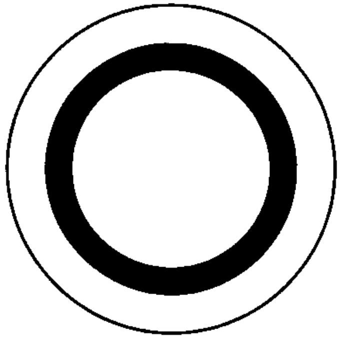
Parameter	*Symbol*	*Unit*	*Si*	*Ge*	*InGaAs*
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Modulation (bandwidth)	B_m	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5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

BASIC PIN PHOTODIODE STRUCTURE



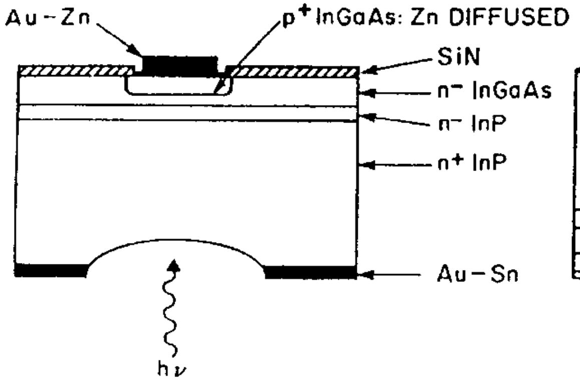


Rear Illuminated Photodiode

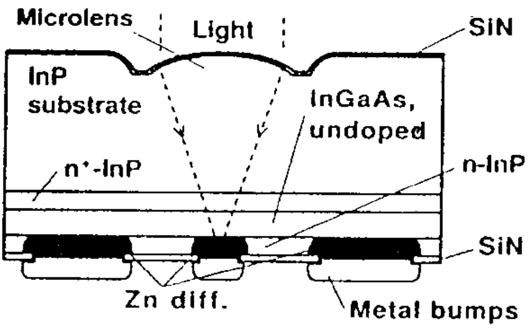


Front Illuminated Photodiode

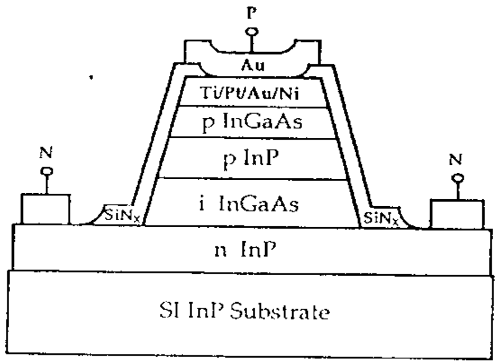
PIN DIODE STRUCTURES



Diffused Type
(Makiuchi et al. 1990)



Diffused Type
(Dupis et al 1986)



Etched Mesa Structure
(Wey et al. 1991)

Diffused structures tend to have lower dark current than mesa etched structures although they are more difficult to integrate with electronic devices because an additional high temperature processing step is required.

ANY QUERIES??

THANK YOU