Chapter 11: Optical Receivers

- Photodiode (光电二极管)
- Performance Evaluation
- Receivers (接收器)

Receivers in fiber optic networks

Receivers: detects & converts optical signal to electrical one

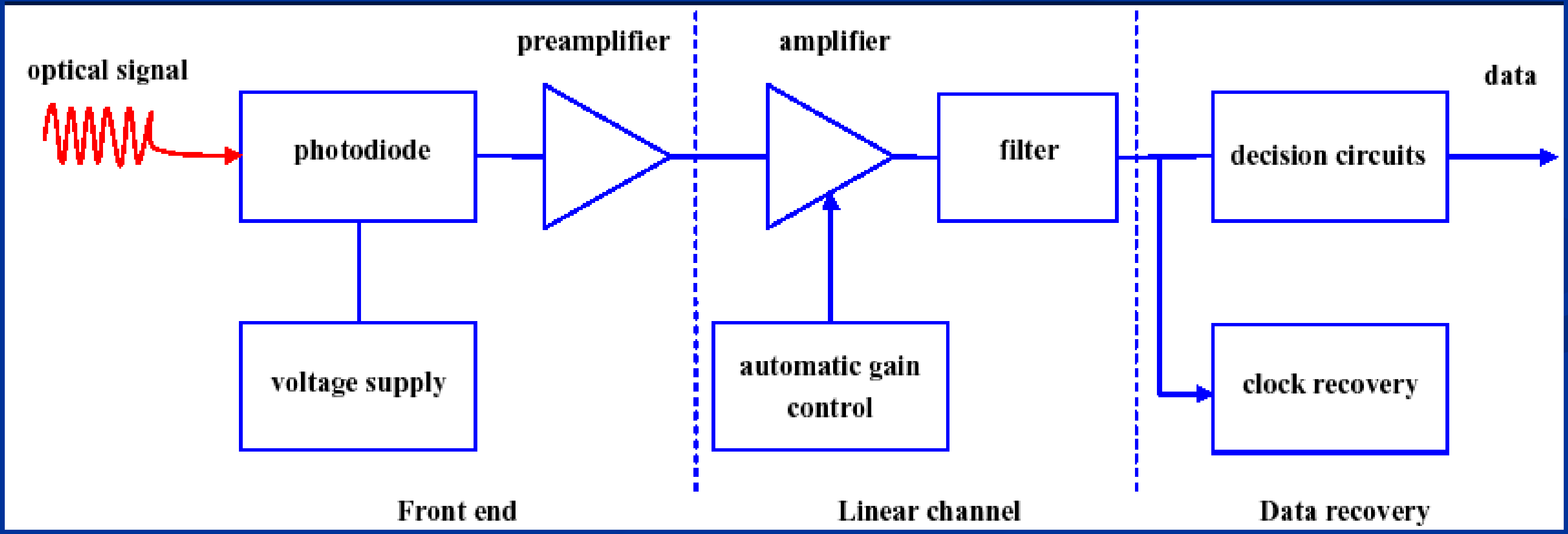
- Main component: **photo detector**
  - pn diode
  - p-i-n diode
  - Avalanche photodiode (APD)
  - MSM photodetector
- Key issues for photo detector
  - Responsivity
  - Sensitivity to achieve a particular BER
  - Noise
- Performance Evaluation

Classification of detectors

- **Classifying detectors by mechanism of response to incident light**
  - Detectors of photons
  - Detectors of heat
- **Semiconductor detectors**
  - Electron-hole pairs created by excitation with incident light
  - Two types of semiconductor diodes
    - Bulk semiconductor -- light dependent resistor
    - Junction diode – p-n diode, pin diode, phototransistor
- **Photoemissive detectors**
  - Electrons ejected from a photosensitive material on irradiation by light
  - photomultiplier tube
- **Thermal detectors**
  - Heating effect of light raising the temperature of the irradiated material
  - With the subsequent change in its electric properties
  - Thermopile, pyroelectric detector

Desirable properties of photodetectors

- High sensitivity or detectability at operating wavelength
- Fast response or high bandwidth
- Low noise
- High reliability and long operating life
- Reasonable cost
- Compatible physical dimensions
- Insensitive to temperature variations



Semiconductor detectors

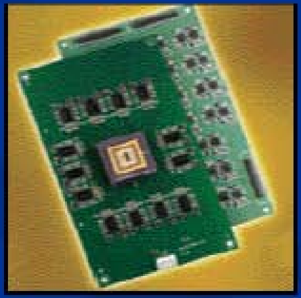
- Typical photodetector structures:
  - p-n junction photodiode
  - Positive intrinsic negative (p-i-n, PIN) photodiode
  - Avalanche photodiode (APD)
  - Metal-semiconductor-metal (MSM) photodetector
- The common properties of semiconductor photodetectors:
  - High reliability and low cost
  - High performance (for 1.3 and 1.55 μm wavelength, InGaAs PIN photodetectors; for wavelength < 1 μm, Si photodetectors generally)

Some models of photodiodes

Detector-Amplifier Hybrids & Receiver Modules

Silicon PIN photodiodes

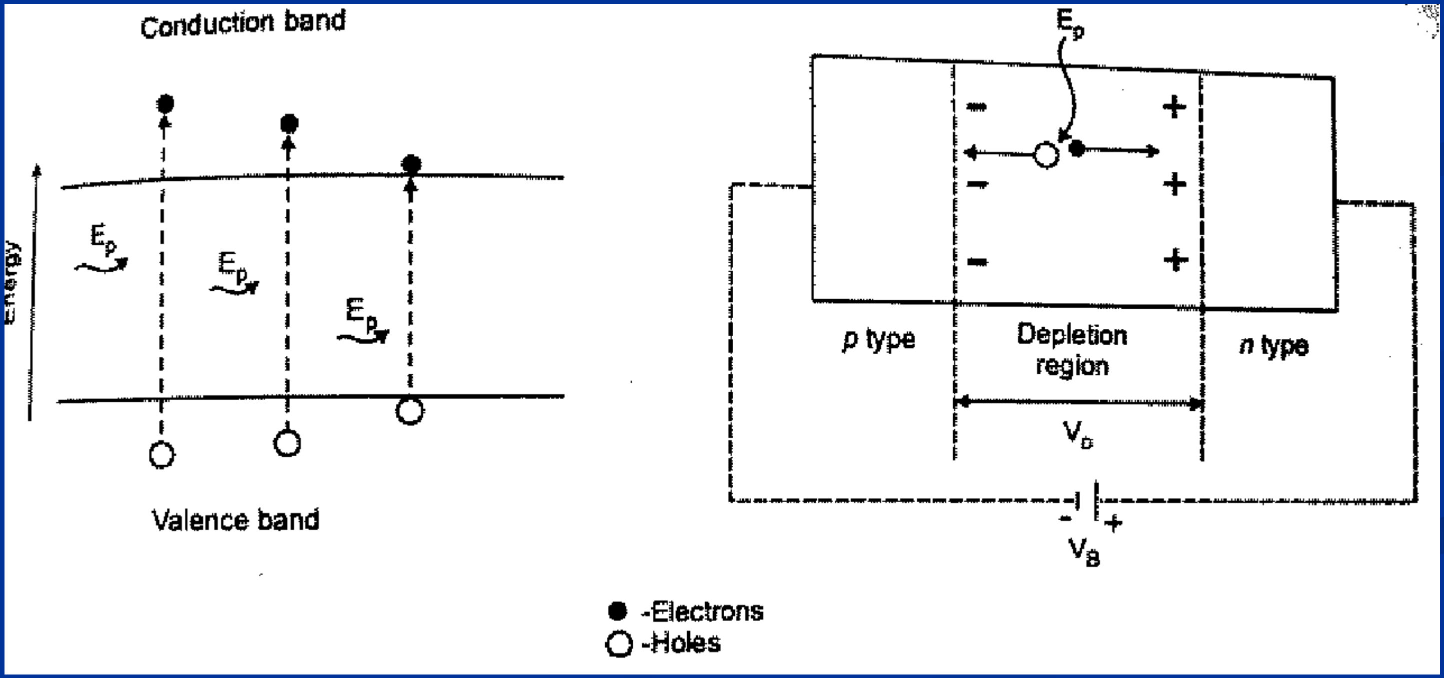
Near IR photodiodes



Photodiode array

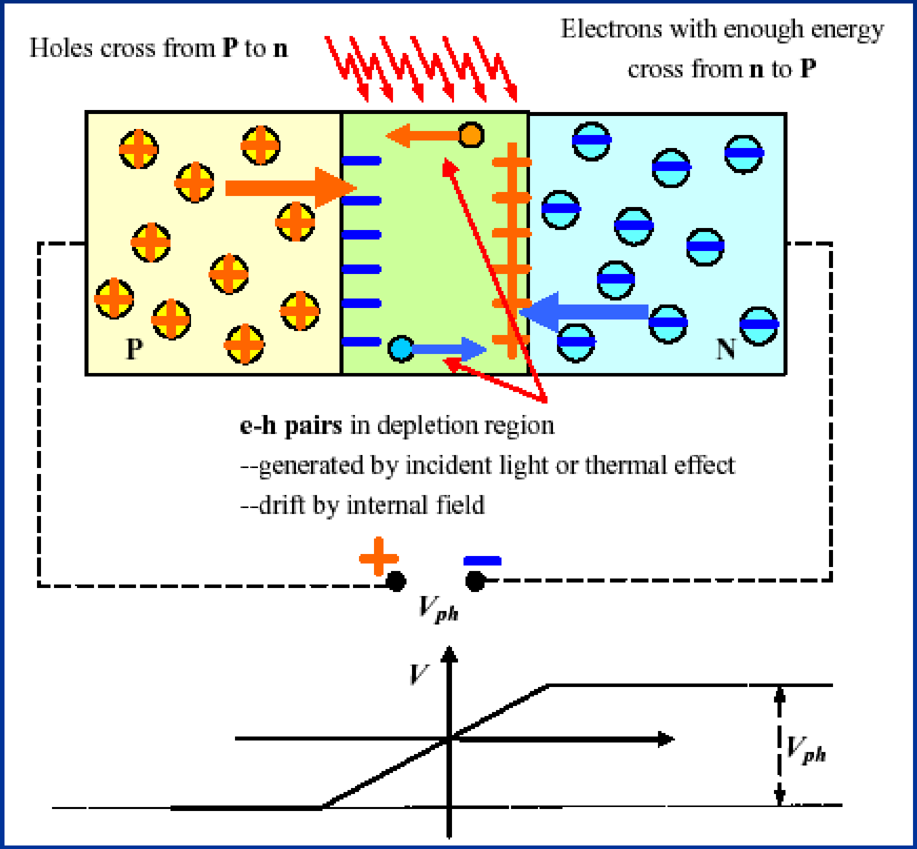
Principle of Photodiodes

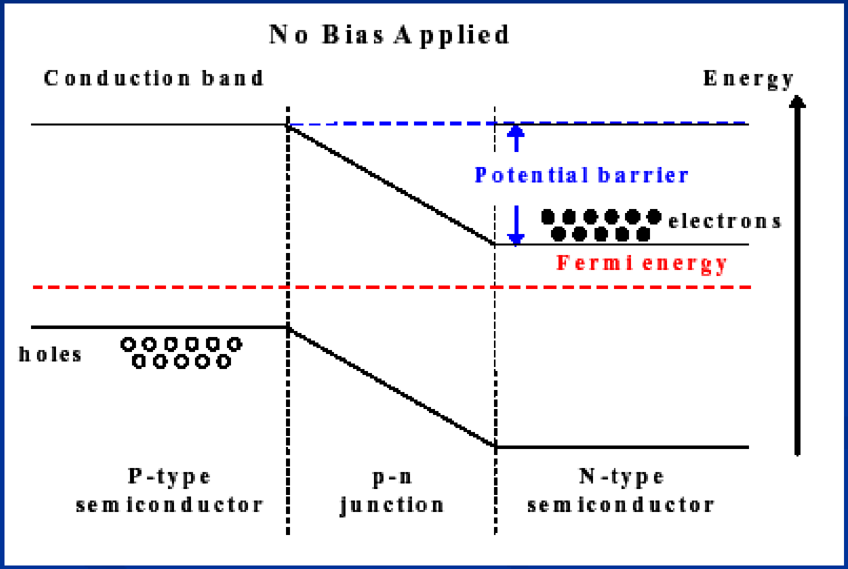
- Photon energy absorbed by an electron to overcome energy gap and become a free electron.
- External photons (light) strikes the semiconductor and separates the electrons and holes. The flow of these free charge carriers produces current. External voltage (reverse bias) enhances this effect.



Photovoltaic and photoconductive modes

Photovoltaic mode -- no bias applied





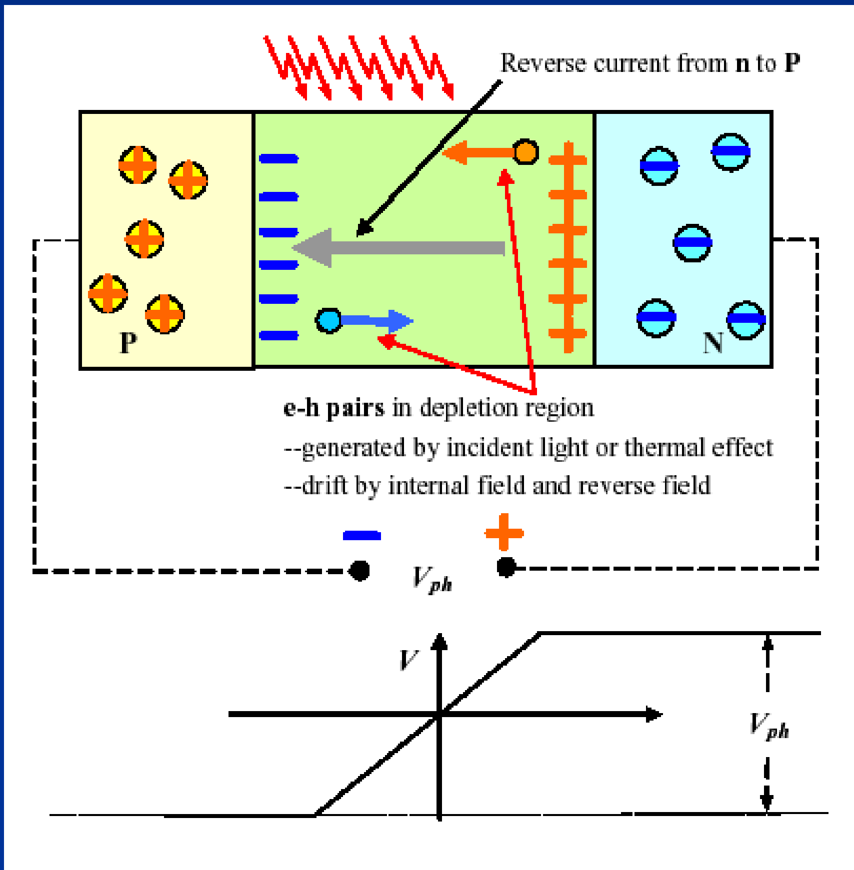
- Electrons diffusing across boundary to fill holes
- A built-in field and potential created
- diffusion = drift

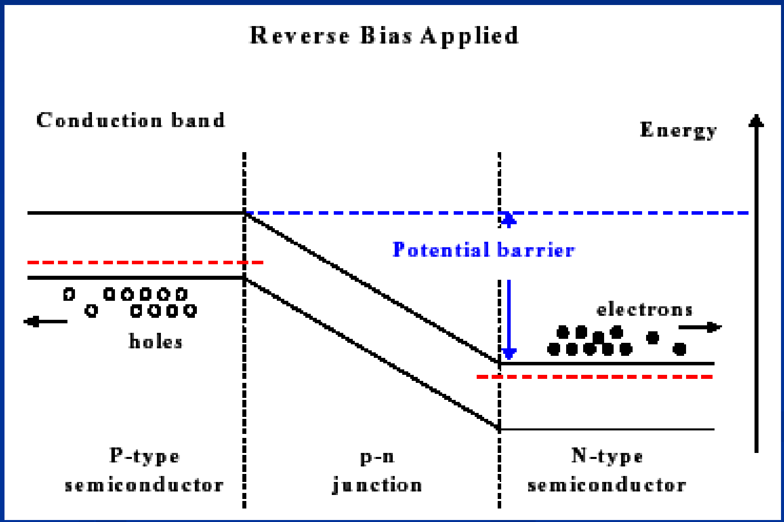
- Output voltage is nonlinear function of incident light power
- e-h pairs are pulled to respective contacts under internal field
- Speed of response depends on diode thickness (generally slow)
- Absence of a leakage current provides low noise

Photovoltaic and photoconductive modes

Photovconductive mode -- reverse bias applied

Normal operation situation of photodiodes





- The bias voltage drop across the depletion region
- Weak voltage either on p- or n-region
- Wider depletion region
- Minority carriers can move freely with the field

p-n junction photodiodes

- **The advantages of reverse biasing**
  - Quickly separating and removing the generated electron-hole pairs to form photocurrent in the deplete region are fast $\rightarrow$ photocurrent (drift current)
    - Drift current (a fast process)
    - Diffusion current (a relatively slow process and weak) -- the electron-hole pairs generated in p- or n-region, separated slowly and inefficiently
    - Separation time << recombination time of electrons and holes
  - Reducing dark current
- **The advantages of the photoconductive mode**
  - Improving linearity of photodiodes
    $\rightarrow I_p \propto P_0$ (output signal proportion to the incident power)
  - A higher response speed and efficiency of operation than photovoltaic mode
    - wider depletion layer and higher electric field
    - immediate separation of electron-hole pair (reduced transit time)
  - Reducing dark current
  - The photon generated current as the measured output signal (not the voltage dropped across the diode as photovoltaic mode)
  - Reducing probability of secondary absorption

Input-output characteristic

- Definition of responsivity:

  $R(A/W) = I_p / P$ → $I_p = RP$

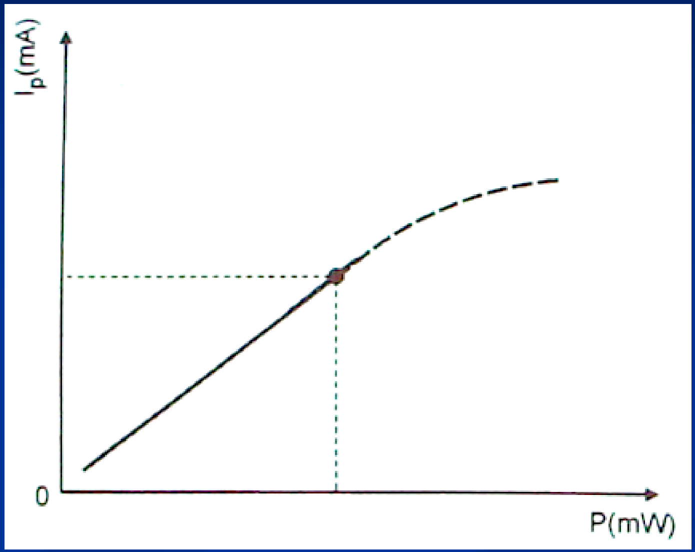
- Responsivity vs. wavelength:

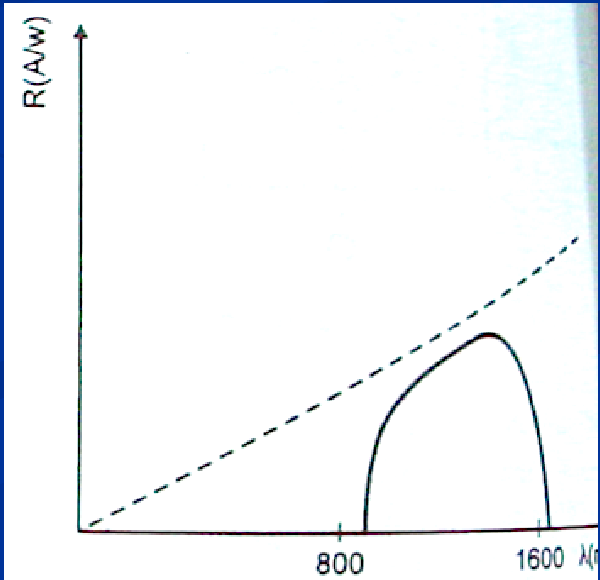
  $I_p = N_e e / t$ $P = N_p E_p / t$ $\eta = N_e / N_p$

  $$R = (N_e / N_p)(e / E_p) = \eta(e\lambda / hc)$$
  $$= (\eta / 1248)\lambda(nm)$$

  The longer the wavelength, the grater the amount of current produced from the same amount of light power.

- Short and long cutoff wavelengths:
  - Long wavelength: the photodiode can only detect $\lambda < \lambda_c = hc / E_g$
  - Short wavelength: strike electrons at the valence band far from the energy-gap edge





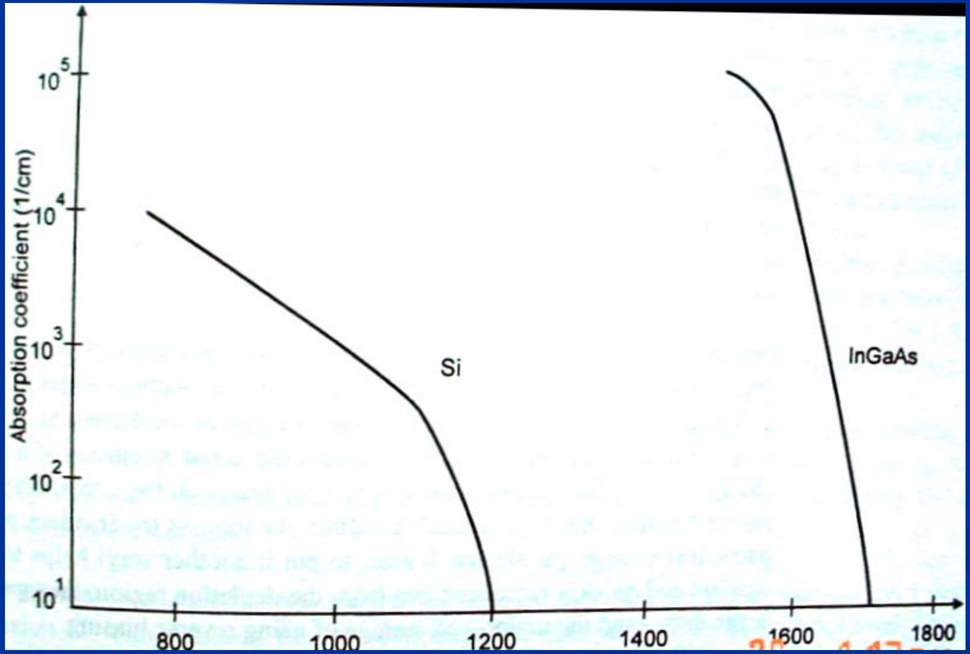
Input-output characteristic

- Quantum efficiency

$$P_{abs} = P_{in}[1 - \exp(-\alpha_{abs} w)]$$

$$\eta = P_{abs} / P_{in} = 1 - \exp(-\alpha_{abs} w)$$

For a given absorption coefficient, a wider (thicker) depletion region results in a higher quantum efficiency.



The width of the depletion region is determined by the reverse voltage ($w \sim V^{1/2}$)

Bandwidth

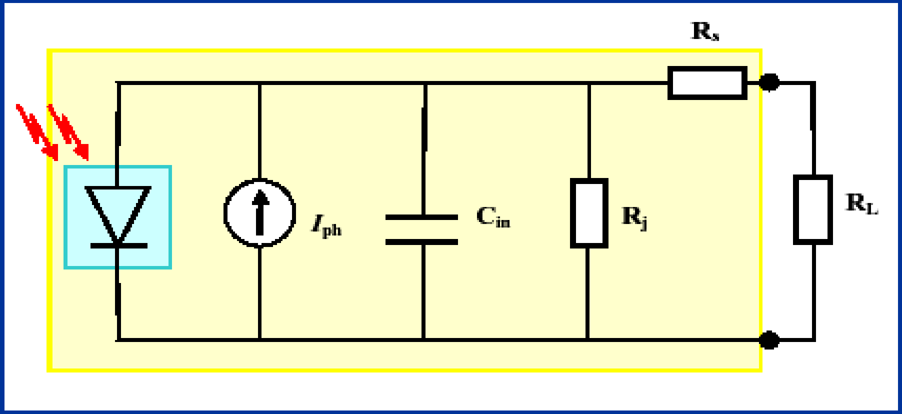
- Bandwidth determined by transmit time and time constant:

Transit time: $\tau_{tr} = w / v_{sat}$ (~100ps)

Time constant induced by a capacitor: $\tau_{RC} = (R_s + R_L)C_{in} \approx R_L C_{in}$ (50-100ps)

$$BW_{PD} = 1/[2\pi(\tau_{tr} + \tau_{RC})] = 1/[2\pi(\frac{w}{v_{sat}} + R_L \frac{\varepsilon A}{w})]$$

$$w_{opt} = \sqrt{v_{sat} R_L \varepsilon A}$$



equivalent circuit of a p-n photondiode

R_j: junction resistance -- resistance of photodiode's depletion region (high, ~ MΩ)

R_s: series resistance – electrical contact resistance between depletion region and load circuit (~ several Ω)

R_j and R_s forming internal resistance of photodiode

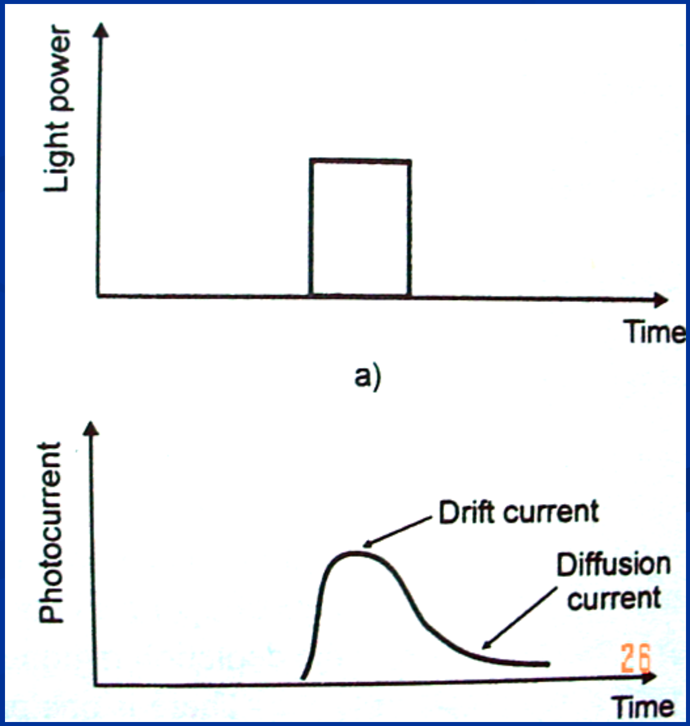
C_{in}: inherent capacitance $C_{in} = \varepsilon A / w$

How to increase bandwidth:

- Tuning the reversal-bias voltage?
- Reducing the load resistance?

Trade-off relationship

- Trade-off between power and bandwidth :
  - The power efficiency is proportional to the thickness of the depletion region.
  - The bandwidth is at its maximum when the thickness of the depletion region is optimal.
- Active area: (several μm ~ several hundred μm)
  - From the power standpoint, the area should be large.
  - From the bandwidth standpoint, the area should be small.
- The bandwidth is limited by the diffusion photocurrent since the p and n regions are much wider than the depletion region



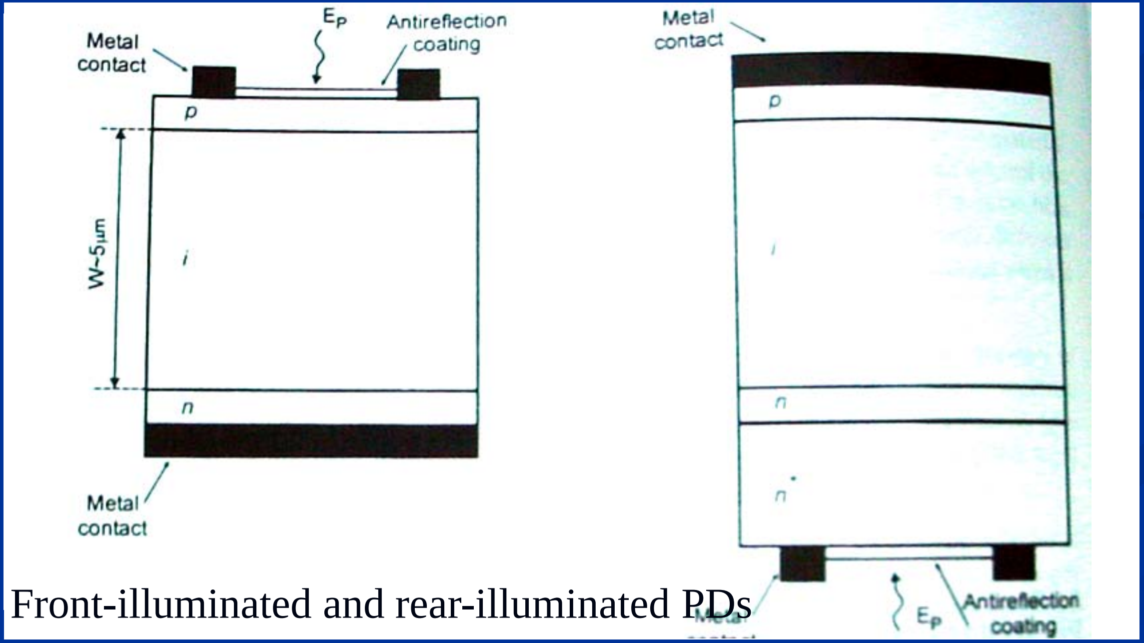
How to increase the width of a depletion region without manipulating unnecessarily the value of the reverse-bias voltage?

Positive intrinsic negative (p-i-n) photodiode

p-i-n diode ---- a variation on standard pn-diode

Structure

- Inserting an thick intrinsic layer (i-layer, pure or slightly doped) the p-n junction
- i-layer acts as depletion layer
- Reducing the thickness of *p*- and *n*-type layer
- Higher bandgap materials for *p*- and *n*-type layers



Front-illuminated and rear-illuminated PDs

p-i-n Photodiode

- Depletion width (W)
  - ~ 20-50 µm for Si, Ge (τ_{tr} > 200 ps)
  - ~ 3-5 µm for InGaAs (τ_{tr} ~10 ps)

$$BW_{PD} = 1/2\pi\tau_{tr}$$

p-i-n photodiode

- Properties and advantages
  - Both the power and bandwidth efficiencies are high
  - Reducing the dark current
  - The diffusion current is very small
  - The reverse-bias voltage is very small (generally 5V)

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4-1.1	0.8-1.8	1.0-1.7
Responsivity	R	A/W	0.4-0.6	0.5-0.7	0.6-0.9
Quantum efficiency	η	%	75-90	50-55	60-70
Dark current	I_d	nA	1-10	50-500	1-20
Rise time	T_r	ns	0.5-1	0.1-0.5	0.02-0.5
Bandwidth	$\Delta\upsilon$	GHz	0.3-0.6	0.5-3	1-10
Bias voltage	V_b	V	50-100	6-10	5-6

Avalanche photodiodes (APDs)

A special PIN PD with very high sensitivity

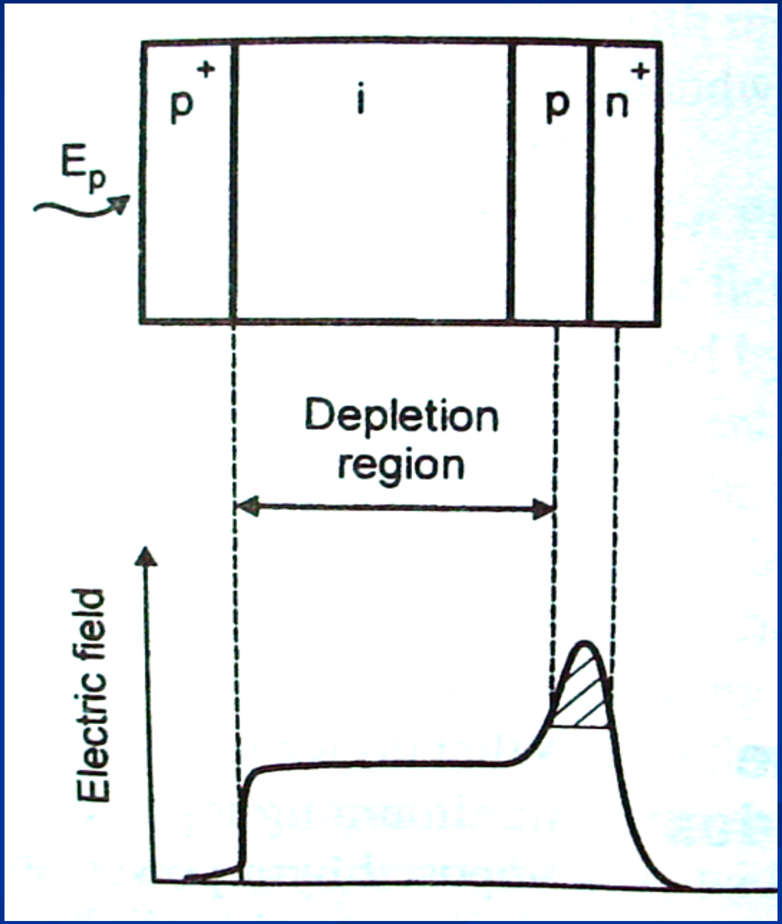
- High reverse bias ~20V
- Electrons or holes are accelerated to gain energy
- e or h strike neutral atoms producing secondary e or h (impact ionization)

  → avalanche effect
- One photon →10-100 e-h pairs
- Quantum efficiency > 1
- Multiplication: (M= 10 ~ 500)

$$R_{APD} = MR_{p-i-n}$$

- Gain-bandwidth product:

$$M \times BW = 1/2\pi\tau_e \qquad \tau_e = k_A\tau_{tr}$$



Si: 500GHz (500x1 GHz), InGaAs: 120GHz (40x3 GHz)

Characteristics of common APDs

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4 - 1.1	0.8 - 1.8	1.0 - 1.7
Responsivity	R_{APD}	A/W	80 - 130	3 - 30	5 - 20
APD gain	M		100 - 500	50 - 200	10 - 40
k-factor	k_A		0.02 - 0.05	0.7 - 1.0	0.5 - 0.7
Dark current	I_d	nA	0.1 - 1	50 - 500	1 - 5
Rise time	T_r	ns	0.1 - 2	0.5 - 0.8	0.1 - 0.5
Bandwidth	$\Delta\upsilon$	GHz	0.2 - 1	0.4 - 0.7	1 - 10
Bias voltage	V_b	V	200 - 250	20 - 40	20 - 30

- **Higher responsivity but more noise (require large bias)**
- Reduced **bandwidth (generation and collection of secondary electro-hole pair take additional time)**

Comparison of PIN and APD

Positive Intrinsic Negative (PIN)

- preferred element in most receivers
- operating at a standard power supply (typically 5 ~ 15 V)

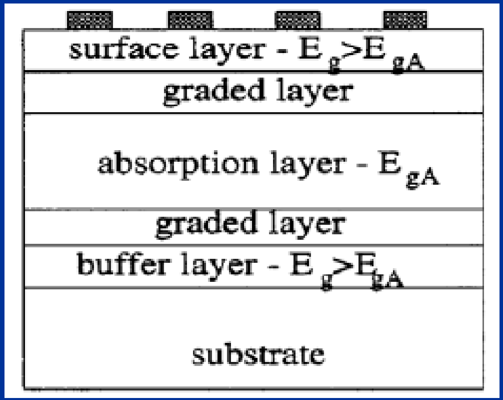
Avalanche Photo Diode (APD)

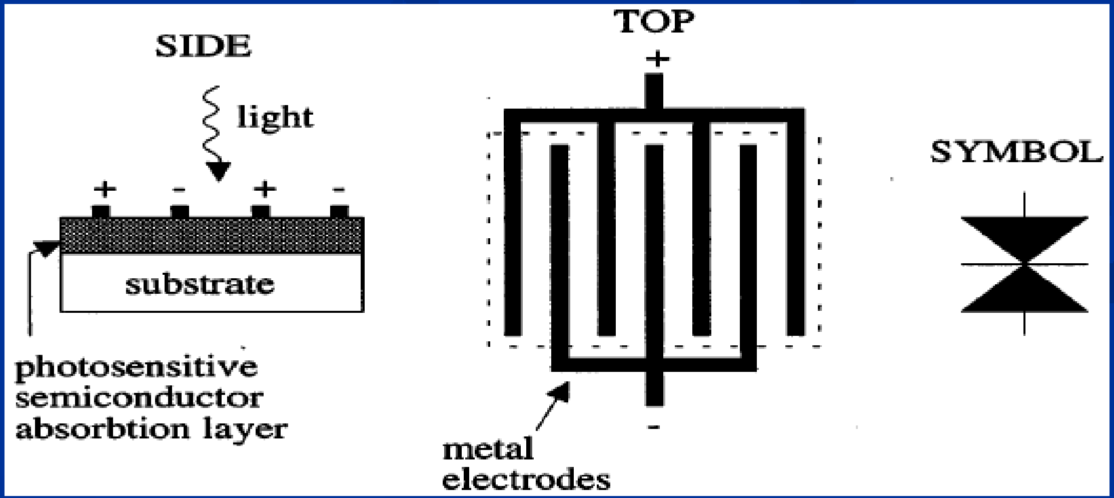
---- usually found in long haul communications links

- Showing much better sensitivity (normally 5 to 10 dB more sensitivity than PIN)
- Increasing noise and parasitic capacitance
- Cannot be used on a 5V printed circuit board
- Requiring a stable power supply
- Higher cost

Metal-semiconductor-metal (MSM) detectors

- An absorption layer sandwiched between two metals -- forming a Schottkey barrier at each metal-semiconductor interface
- Simplest MSM requires fingers, absorption layer and a substrate – forming two Schottky diodes on top of a semiconductor layer
- This barrier preventing electron flow from metal to semiconductor, but generated electron-hole pairs flowing toward the metal contact
- For the practical reason, the two metal contacts made on the same (top) side absorbing layer using interdigited electrodes with a finger spacing of about 1 μm
- Inherently low parasitic capacitance allowing high-speed operation (up to 300 GHz)
- Easy fabricated and integrated





Noise in photodiodes

- Shot noise:
  - Deviation of actual number of electrons from the average

$$i_s = \sqrt{2eI_P^* BW_{PD}} \qquad i_{sN}(A/\sqrt{\text{Hz}}) = i_s / \sqrt{BW_{PD}} = \sqrt{2eI_P^*}$$

- Thermal noise:
  - The deviations of an instantaneous number of electrons from their average value because of temperature change

$$i_t = \sqrt{(4k_B T / R_L) BW_{PD}} \qquad i_{tN}(A/\sqrt{Hz}) = i_t / \sqrt{BW_{PD}} = \sqrt{4k_B T / R_L}$$

- Dark current noise
  - Dark current is the current flows in a photodiode devoid of input light

$$i_d = \sqrt{2eI_d^* BW_{PD}} \qquad i_{dN}(A/\sqrt{\text{Hz}}) = i_d / \sqrt{BW_{PD}} = \sqrt{2eI_d^*}$$

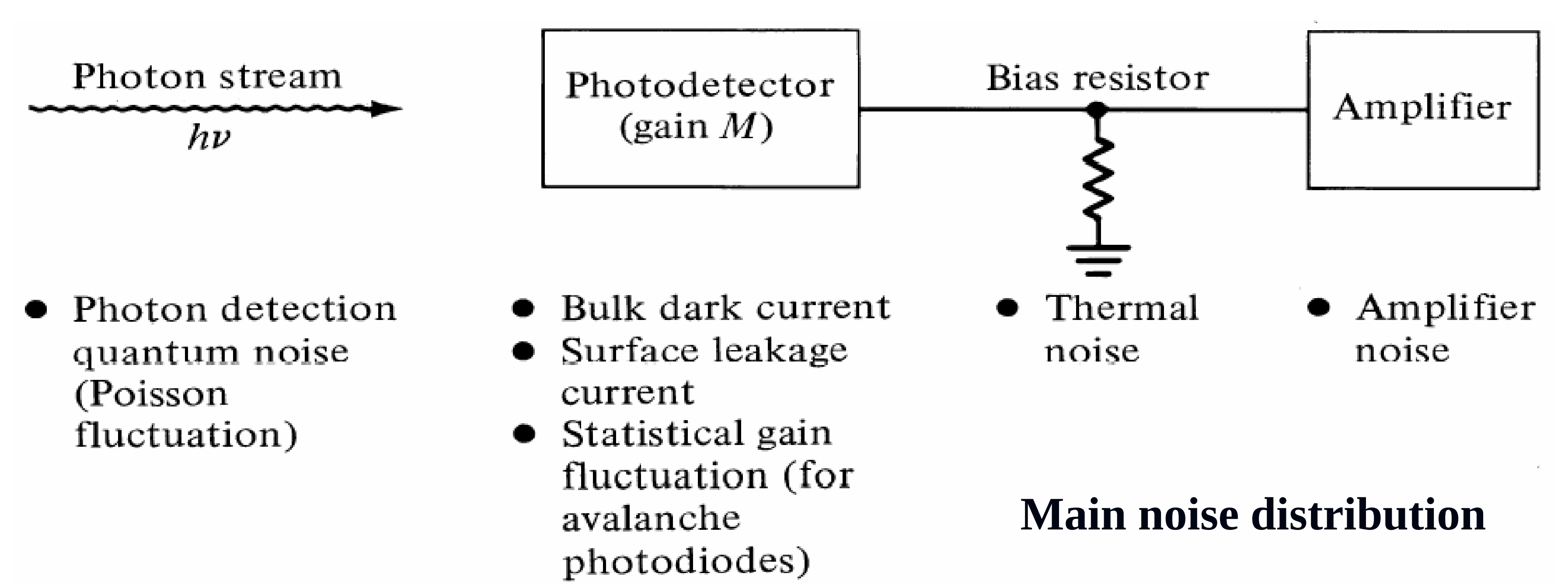
- 1/f noise
  - Noise is not f independent (white noise), α=2, β=1-1.5 , f=modulation freq. (Operation freq.)

$$i_{1/fN}(A/\sqrt{\text{Hz}}) = i_{1/f} / \sqrt{BW_{PD}} = (K_{1/f} I^{\alpha}) / f^{\beta}$$

RMS of total noise current: $i_{noise} = \sqrt{i_s^2 + i_t^2 + i_d^2 + i_{1/f}^2}$

Performance evaluation

- Noise measurements:
  - Signal-to-noise ratio (SNR)
  - Noise-equivalent power (NEP)
  - Detectivity
  - Bit-error rate (BER)



Main noise distribution

Signal-to-noise ratio (SNR)

The ratio of the total signal power to the total noise power

SNR = signal power / noise power

showing how much higher the signal level is than the level of the noise.

$$SNR_{p-i-n} = \frac{R^2 P^{*2}}{i_{noise}^2}, \quad SNR_{APD} = \frac{M^2 R^2 P^{*2}}{[2eM^2 F_s RP + 4k_B T / R_L] BW_{PD}}$$

Where $I_P^* = RP^*$: average photocurrent, R_L: load resistance, k_B: the Boltzmann constant, F_S: excess noise factor, M: multiplication factor, BW_{PD}: bandwidth, R: responsivity.

- p-i-n photodiode
  - Thermal noise dominates $SNR_{p-i-n} = R^2 P^2 R_L / (4k_B T BW_{PD})$
- APD
  - Impact ionization increases shot noise
  - SNR raised by multiplication factor, M, in thermal-noise limit.

Noise-equivalent power (NEP)

The minimum signal power leading to SNR = 1

- RMS (root mean square) of the optical power that yields SNR = 1
- Expressed in terms of noise equivalent optical power (the noise of optical receivers or of an entire transmission system).

- Determining the weakest optical signal can be detected in the presence of noise
- Usually given in NEP per unit of bandwidth

$$NEP(W) = \frac{i_{noise}}{R}, \qquad NEP_{norm}(W/\sqrt{\mathrm{Hz}}) = \frac{NEP}{\sqrt{BW_{PD}}}$$

- Increasing with increasing frequency
- Wavelength dependent
- Tradeoff between bandwidth and NEP

Detectivity

- Inversely proportion to NEP (not a crucial parameter)
- Various definitions

(1) $D = \sqrt{D_A(BW)/NEP}$ (2) 1/NEP

D_A: the photosensitive area of a PD

Bit-error rate (BER)

BER ---- the ratio of the number of bits received incorrectly (errors) divided by the total number of bits received, representing error probability per bit.

$$BER = \frac{1}{2}\left[P(1|0) + P(0|1)\right]$$

$$P(1|0) = 0.5\,erfc\left[(I_1 - I_{th})/i_1\sqrt{2}\right]$$

$$P(0|1) = 0.5\,erfc\left[(I_{th} - I_0)/i_0\sqrt{2}\right]$$

Where P(1/0) and P(0/1) are the probabilities that decides 1 when bit 0 is received actually and vice versa respectively. ***erfc*** : complementary error function.

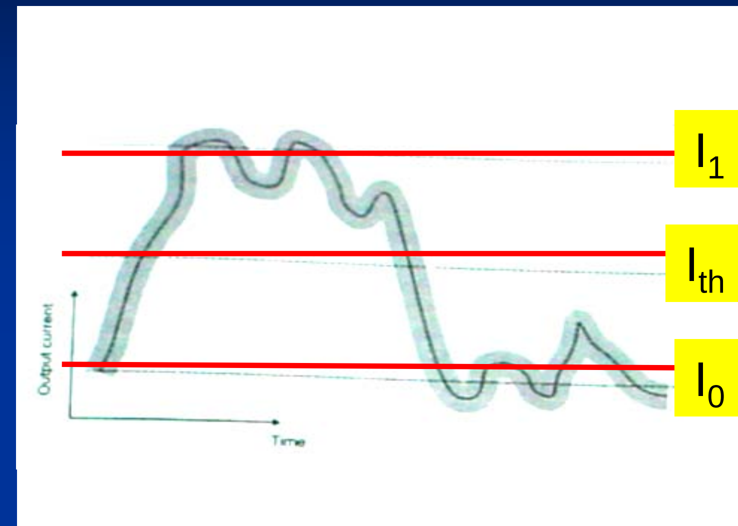
- Providing an overall score for the performance of a system, but little help on why performance might be below expectations
- Note: BER testing logical problems as well as parametric ones
- Modern fiber-optical communication systems: BER $<10^{-12}$

Sensitivity: minimum optical power a photodiode can detect at a given bit-error rate

Bit-error rate (BER)

An optimized threshold current (I_{th}) leads to a minimum BER and yields BER_{min} when:

$$\frac{(I_1 - I_{th})}{i_1} = \frac{(I_{th} - I_0)}{i_0} \equiv Q$$



Then

$$BER_{min} = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}}$$

I_0: average value of bit-0 current, I_1: average value of bit-1 current; i_1 and i_0 are the corresponding variance of current representing bit 1 and 0.

Q-parameter known as digital Signal-to-Noise Ratio (SNR)

$$Q = \frac{I_1 - I_0}{i_1 + i_0}$$

Q > 6 required for a BER of < 10^{-9}; Q > 7 provided for a BER of < 10^{-12}

Minimum received power

For a given BER, the minimum optical power required (an average optical power in bit 1 and bit 0) is

$$P_{\min} = (P_1 + P_0)/2 = \frac{Q}{R\left[eQ(BW_{PD}) + i_t\right]}$$

or

$$BER_{\min} = \frac{\frac{1}{2}erfc\,(2RP_{\min})}{\sqrt{4eRP_{\min}BW_{PD} + \frac{4k_BT}{R_L}BW_{PD}} + \sqrt{\frac{4k_BT}{R_L}BW_{PD}}}$$

Quantum limit and sensitivity

The minimum number of photons required to detect a bit at a given BER

$$BER = 0.5e^{-N_P}$$

for an ideal detector (no thermal noise, no dark current, $\eta = 1$)

The sensitivity of receiver (in power, dBm)

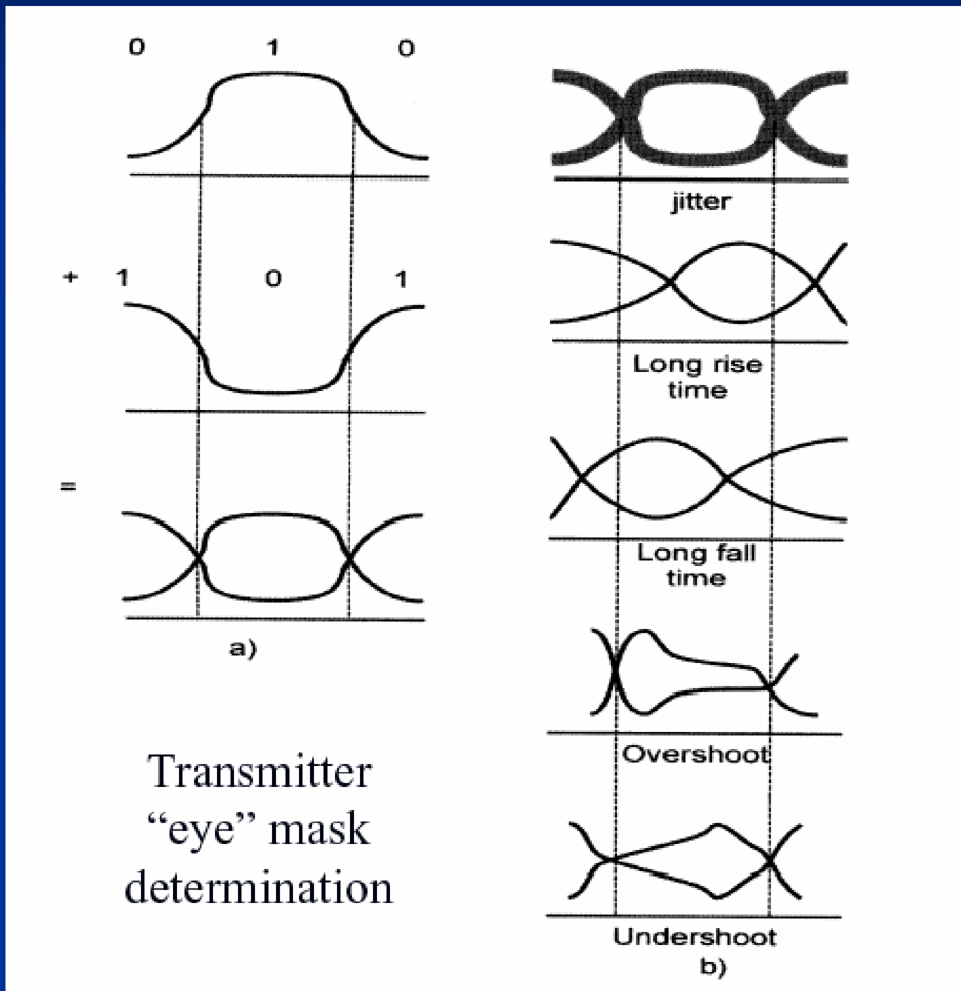
$$\overline{P}_{rec} = N_P h\upsilon B$$

B: bit rate, N_p: average number of photons in an optical pulse.

e.g. $N_p \sim 26$ for BER < 10^{-12} → every pulse containing 26 photons at least to achieve BER < 10^{-12}.

Eye diagrams

Eye Diagrams

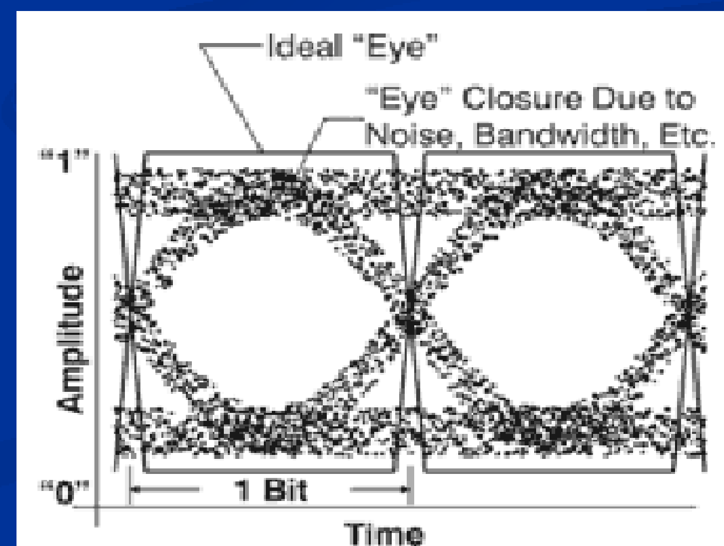


Computer Simulation of a distorted eye diagram

Eye Pattern:

A diagram that shows the proper function of a digital system. The "openness" of the eye (partial closure) relates to the BER that can be achieved.

a very successful way of quickly and intuitively assessing the quality of a digital signal.



Performance evaluation

The errors generated in photodiodes will influence the performance of a receiver strongly!

Criterion to judge the performance of receivers (or systems)

---- judged on their ability to pass bits faithfully, and without error

The minimum optical power can be detect by a receiver versus the data rate (in order to achieve a particular BER < 10^{-9} typically).

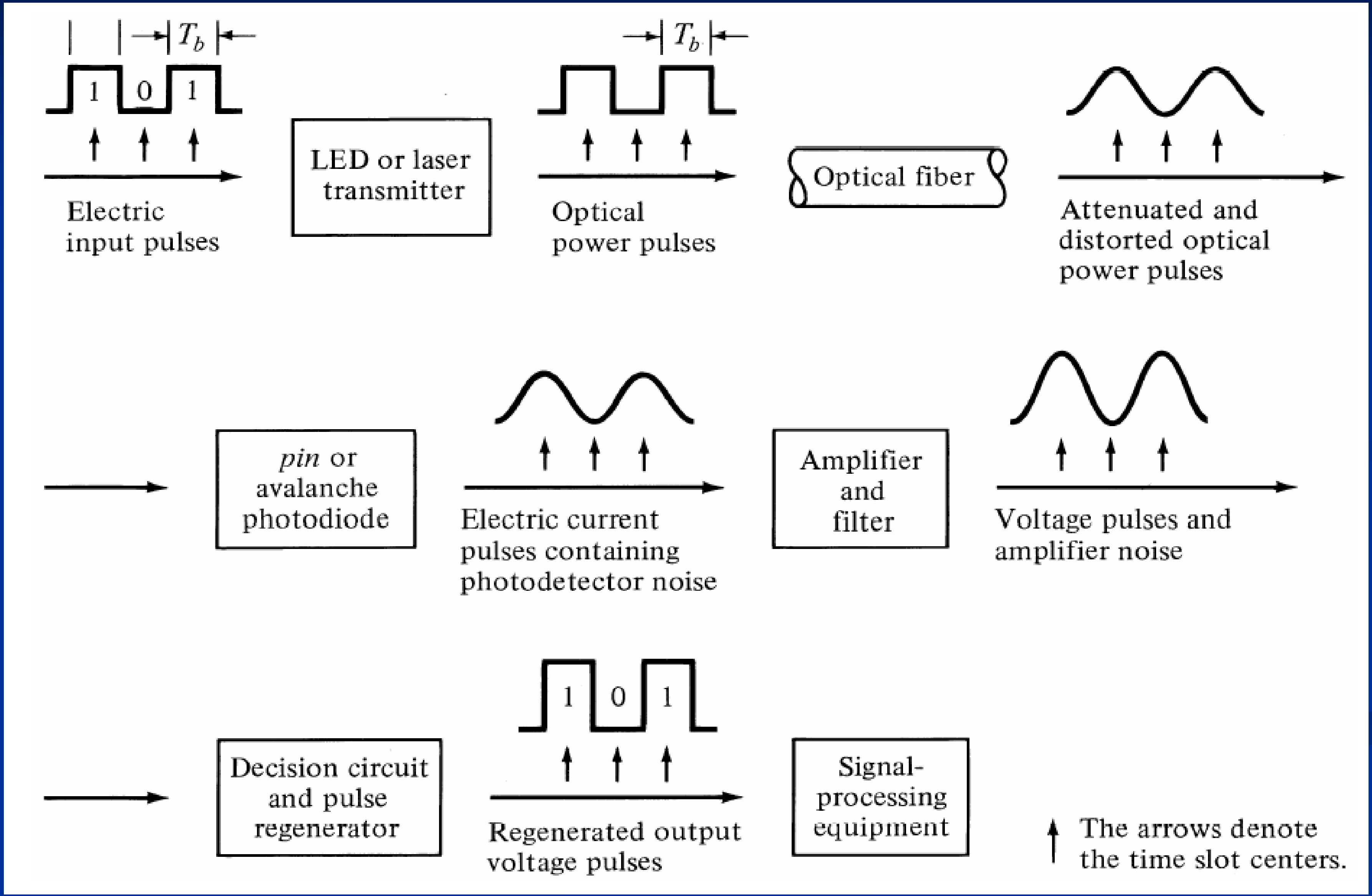
The BER delivered to the users for intensity modulation

- The received optical signal power
- The noise in the receiver (shot and thermal noise most significant in a receiver)
- The processing bandwidth

Summary

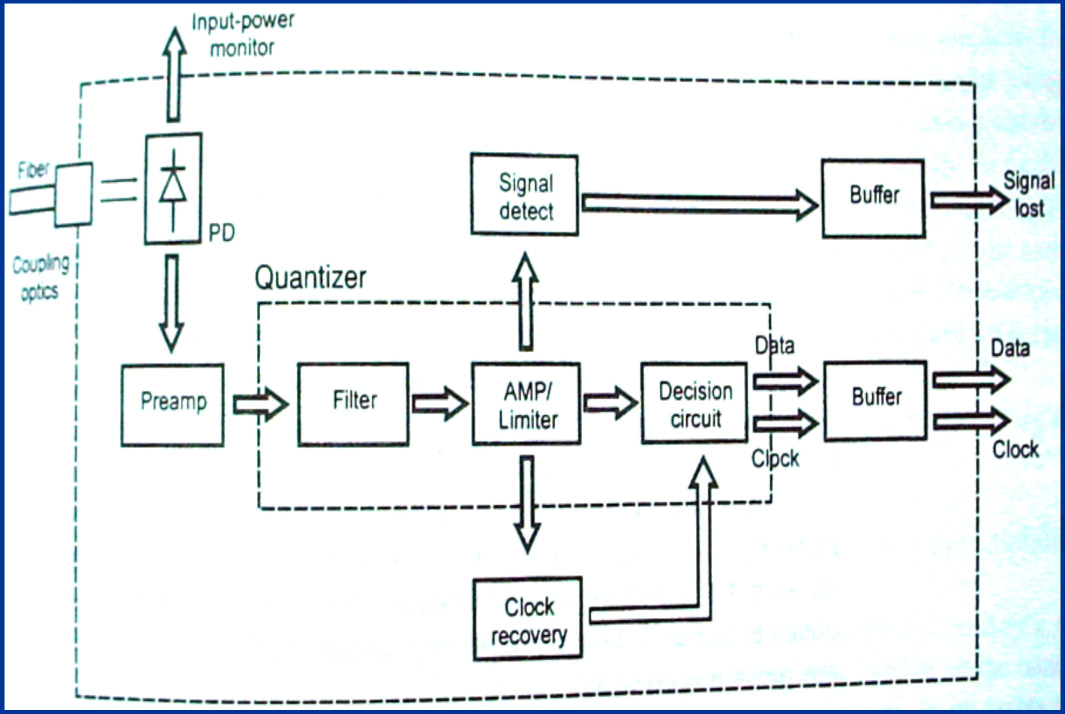
- Mixture between materials gives different bandgaps
- InGaAs are commonly used in detectors (1.55 μm)
- p-i-n photodiode commonly use InGaAs & InP
- APD is used at limited optical power

Signal path through an optical link

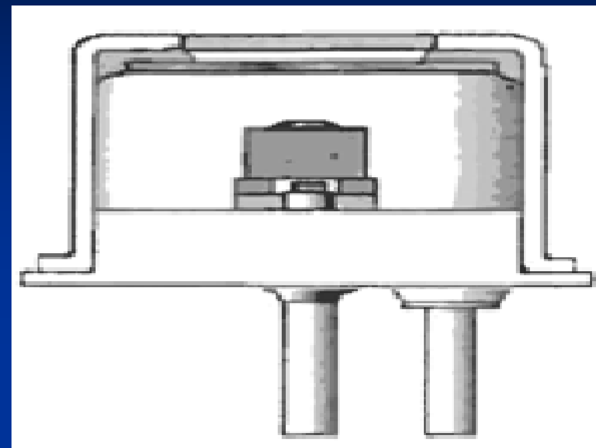


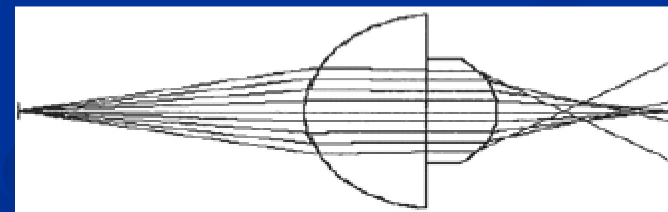
Receiver unit

- Two main functions of the receiver:
  - Optical to electrical conversion
  - Transmitted data recovery
- Main parts:
  - Optical front end: convert light into electric voltage of the required amplitude
  - Quantizer: a noise filter, a power amplifier/limiter, and a decision circuit
  - Buffers: transfer a logical signal from the input to the output unchanged
  - Clock recovery: extract timing information from the data stream

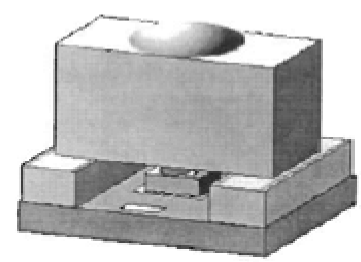


Receiver module





Ray trace model of a TO lens focusing the light on the detector area.



Receiver micromodule.

p-i-n diode, Si lens, and pre-amplifier

Homework

- 11.5, 11.23, 11.48, 11.52