# OPTICAL DETECTORS

# Optical Detectors

- **Purpose: To convert the received optical signal into an electrical signal.**

**Requirements For Detector**

- **HIGH SENSITIVITY** (at operating wave lengths) at normal op. temp (300 K) 0.85µm/1.1 µm/ 1.3 µm

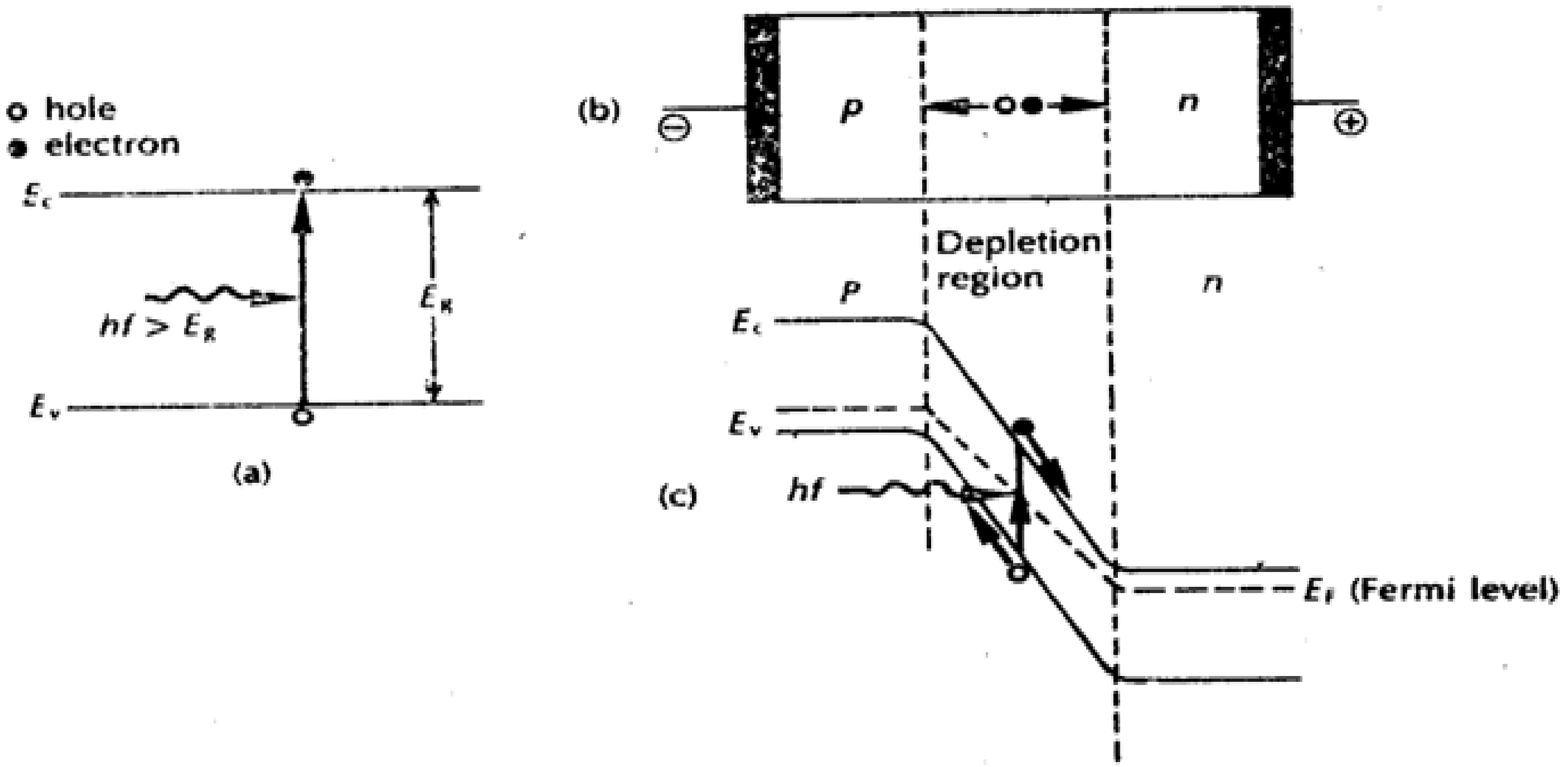
- **HIGH FIDELITY** (Linear response over a wide range for analog transmission)

- **High quantum efficiency**
- **Short response time**. (To obtain suitable BW)
- **Minimum Noise** (introduced by detector)

# Optical Detectors (Contd.)

- **Stability of performance characteristics** (independent of change in ambient conditions).
- **Small size**. (for efficient coupling to fiber and easy packaging )
- **Low bias voltages.**
- **High reliability**
- **Low cost**

# OPTICAL DETECTION -PRINCIPLE



Operation of the *p–n* photodiode: (a) photogeneration of an electron–hole pair in an intrinsic semiconductor; (b) the structure of the reverse biased *p–n* junction illustrating carrier drift in the depletion region; (c) the energy band diagram of the reverse biased *p–n* junction showing photo-generation and the subsequent separation of an electron–hole pair.

# OPTICAL DETECTION -PRINCIPLE

- A Photon incident in or near depletion region which has energy, **hf > Eg** will excite an electron from valence band into conduction band.

- This process creates an electron – hole (carrier) pair.

- Carrier pairs so generated are separated and swept under the influence of electric field. This is known as **displacement current** (in excess of any reverse leakage current)

# Optical Detection-Principle

- Note: Wider depletion layer (DL) is required for incident light to be absorbed for max. carrier-pair generation.

- However long carrier drift times in DL restrict speed of operation, and hence trade off between sensitivity & response

# Absorption coefficient($\alpha_0$)

- The absorption of photons in a photo diode to produce carrier pairs and thus a photo current, is dependant on the absorption coefficient, $\alpha_0$ of the light in the semiconductor(used to fabricate the device).
- Ip (Photo Current)=$P_0 e(1-r)\ [1-e^{-\alpha_0 d}]/hf$
- $P_o$ = Optical power (of incident light)

# Absorption coefficient($\alpha_0$)

- e- charge of an electron
- r- Fresnel Coefficient (at semiconductor air interface)
- d= width of absorption region.
- Note: Abs. Coefft. is strongly dependant on λ. This is due to differing band gap energies of semiconductor photodiode materials at 300 K (Si/Ge/ GaAs/ GaSb/ InAs)

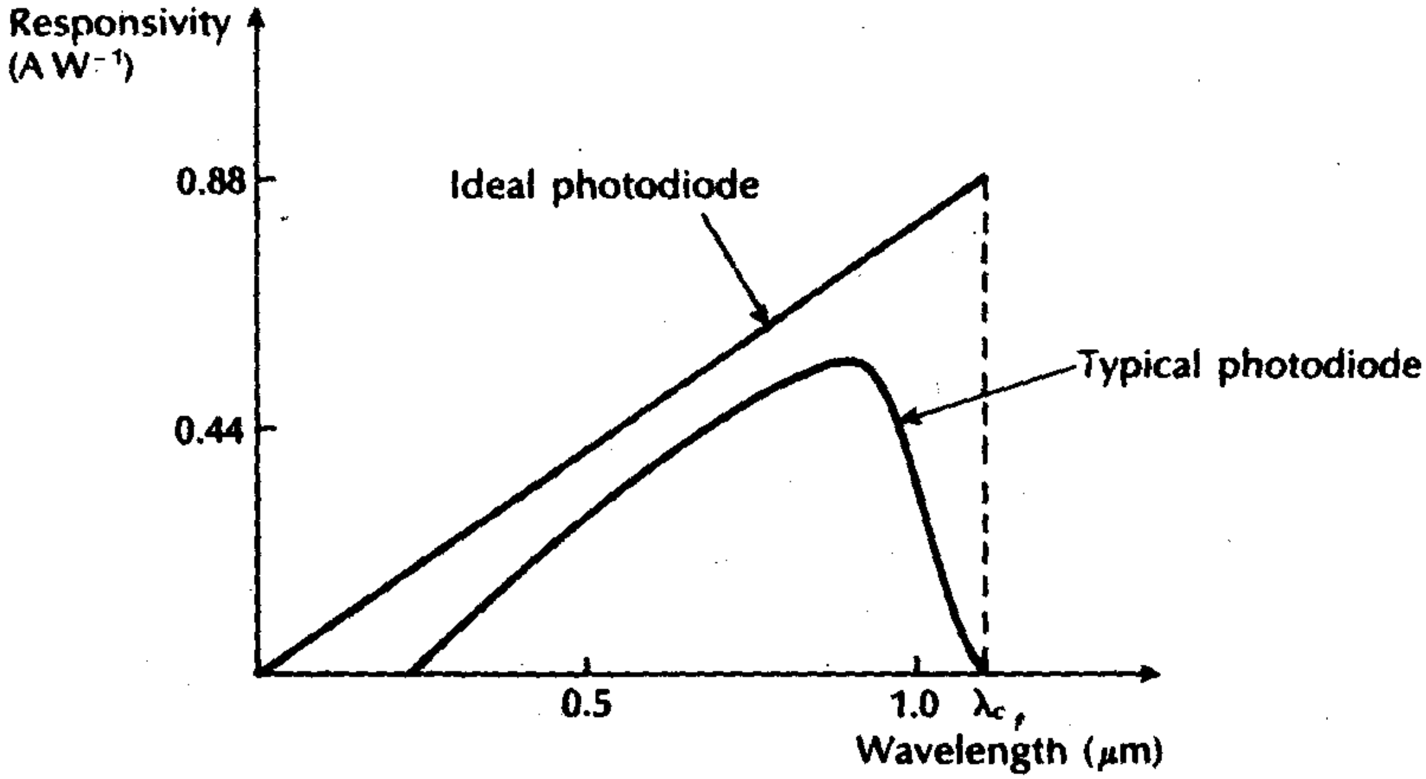
# Responsivity (R) of a photo detector

- **R= Ip/Po** ($AW^{-1}$)
- $I_p$= o/p photocurrent (amp)
- $P_o$=Incident optical power (watts)
- R gives the transfer characteristics of the detector (photo current per unit incident optical power).
- rp, the incident photon rate =$P_o$/hf = no. of photons /sec

# Responsivity (R) of a photo detector

- But $r_e = \eta\ r_p$ $[\eta = r_e / r_p] = \frac{\text{No.of electrons collected}}{\text{No.of incident photons}}$
- $r_e = \eta\ P_o / hf$
- Photocurrent (output ),$Ip = \eta\ P_o\ e/hf = (r_e * e)$
- $R = Ip/P_{0=}\ \eta e/hf$
- $c = f\lambda$ $f = c/\lambda$
- $R = \eta e/hc/\lambda = \eta e\lambda/hc$
- $R\ \alpha\ \eta$ (at a specific $\lambda$ )

# Responsivity (R) of a photo detector



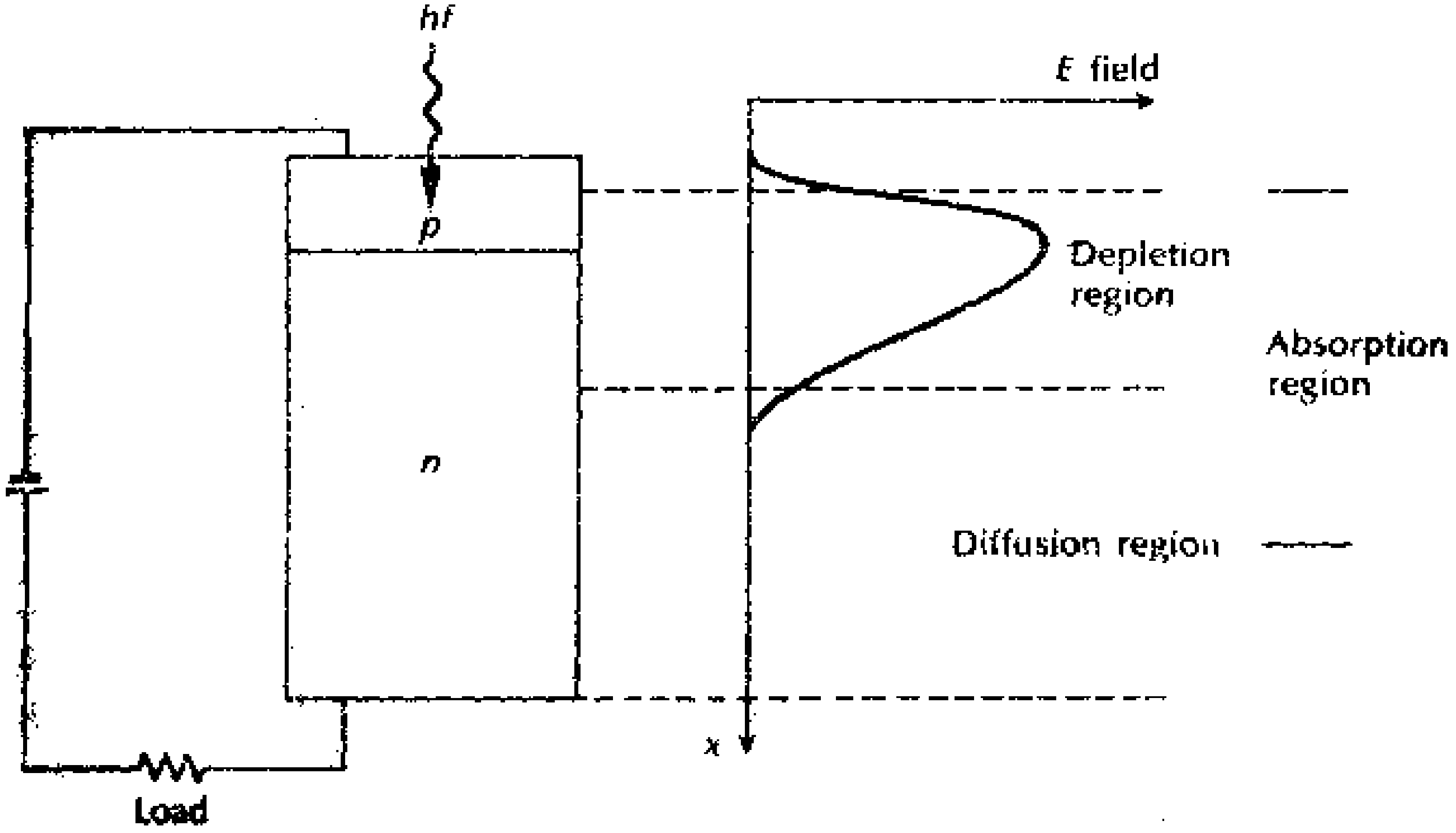
# Long wavelength cut-off

- In intrinsic absorption process the energy of incident photons should be greater than or equal to bandgap energy (Eg) of the material of photodetector .
- $hf \geq Eg$ or $hc/\lambda \geq Eg$ or
- $\lambda c$ =Long λ cutoff point (threshold for detection) = $hc/Eg$

# Long wavelength cut-off (contd.)

- This is the longest wavelength of light to give photodetection.
- Note: The expression $\lambda c = hc / Eg$ is applicable to intrinsic semiconductors (photodetectors).
- Extrinsic photodetectors are not currently used in OFC.

# Reverse bias P-N Photodiode



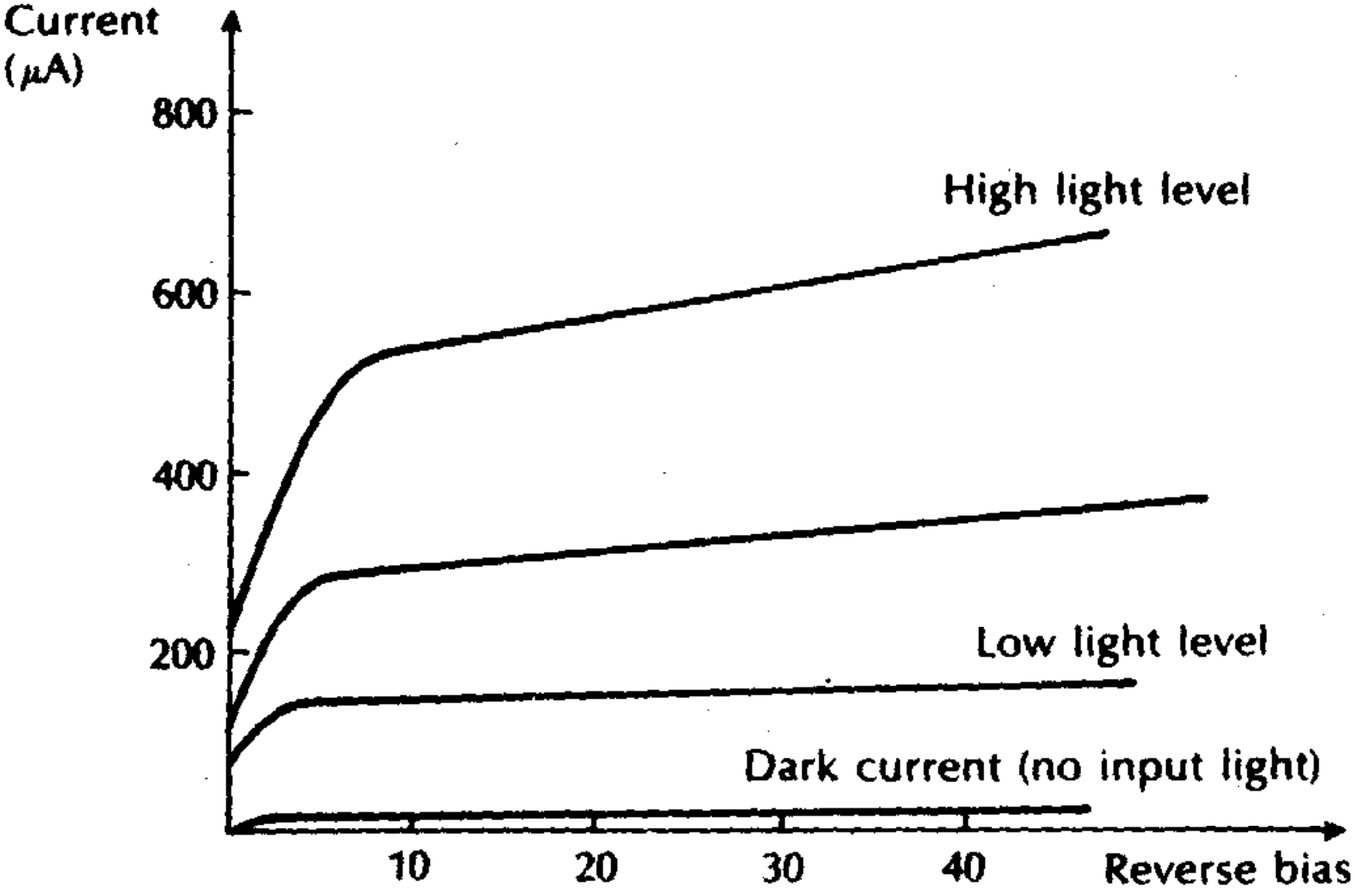
# Reverse bias P-N Photoiode(contd.)

- Width of depletion region is dependant upon doping level.
- Photons are absorbed in depletion as well as diffusion regions.
- Absorption region's dimension depends on energy of incident photons & material of photodiode.
- Electron–Hole pairs are generated in both depletion & diffusion regions.

# Reverse bias P-N Photo diode (contd.)

- **Diffusion is very slow compared to Drift. This limits response of photodiode.**
- Photons should be absorbed in depletion region(≈ 1 to 3 μm)
- Output increases with light level.
- Note: Lower the doping, wider is the depletion layer.

# Typical P-N Photodiode o/p characteristics

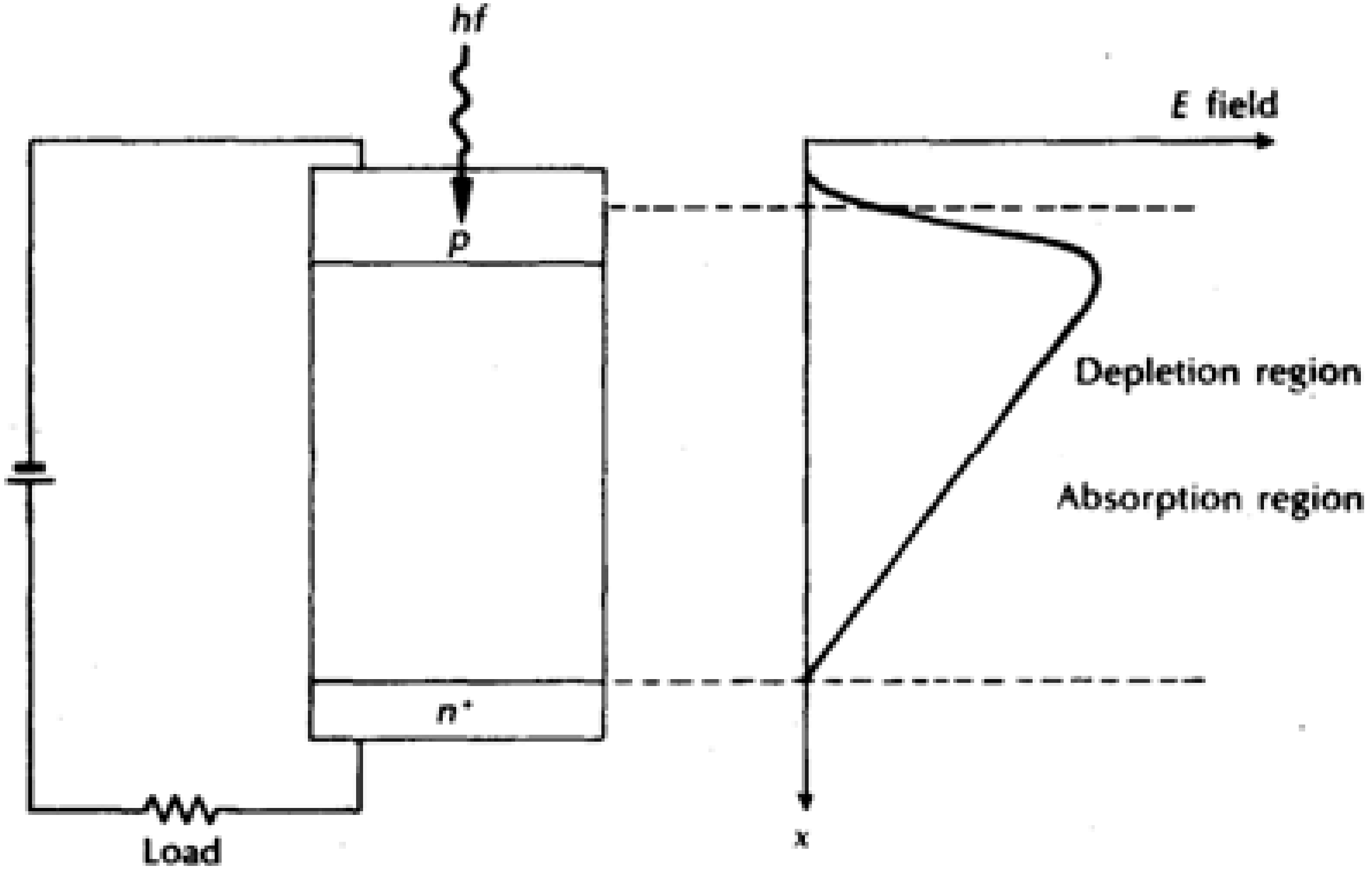


# Typical P-N Photodiode o/p characteristics (contd.)

**Dark current**

- Dark current arises from surface leakage currents as well as generation-recombination currents in the depletion region in the absence of illumination.
- It may be noted that current o/p is higher for higher light level input to photodiode.

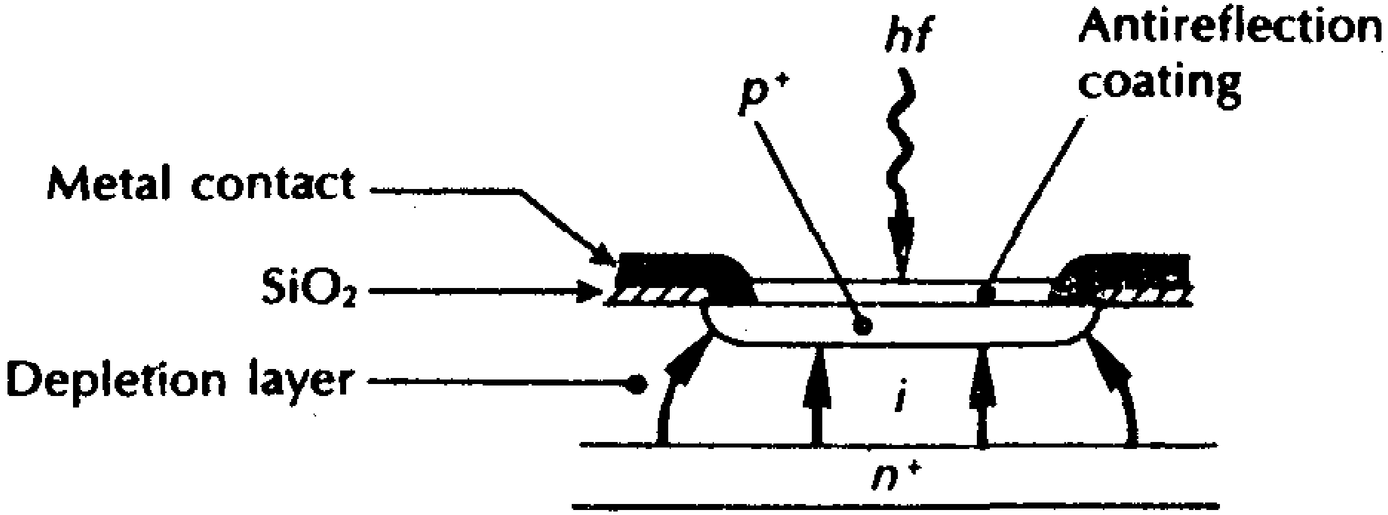
# P-I-N Photodiode



# P-I-N Photodiode (contd.)

- A wider depletion layer region is necessary (longer λ)
- All the absorption takes place in the depletion region.
- Front illuminated photodiode has a fast response time(<1n sec) and low dark current (1nA). η = 85% w=20-50 µm (wavelength=0.8 to 0.9 µm)
- Side illuminated has a larger absorption width (=500µm).wavelength=1.09 µm

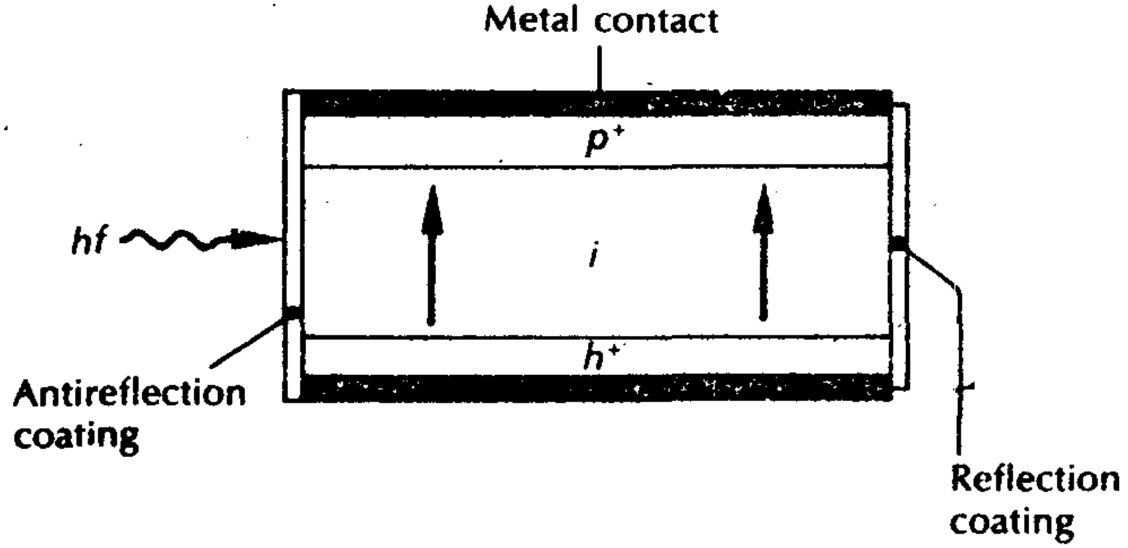
# Front illuminated Silicon p-i-n photodiode



Depletion region : 20 to 50 μm for quantum η = 85%

- Simplest structure – light entry thr' upper $p^+$ layer
- **Quantum η is high and dark current is low (1n amp)**
- **Device has fast response time (< 1ns)**

# **side illuminated p-i-n photodiode**.

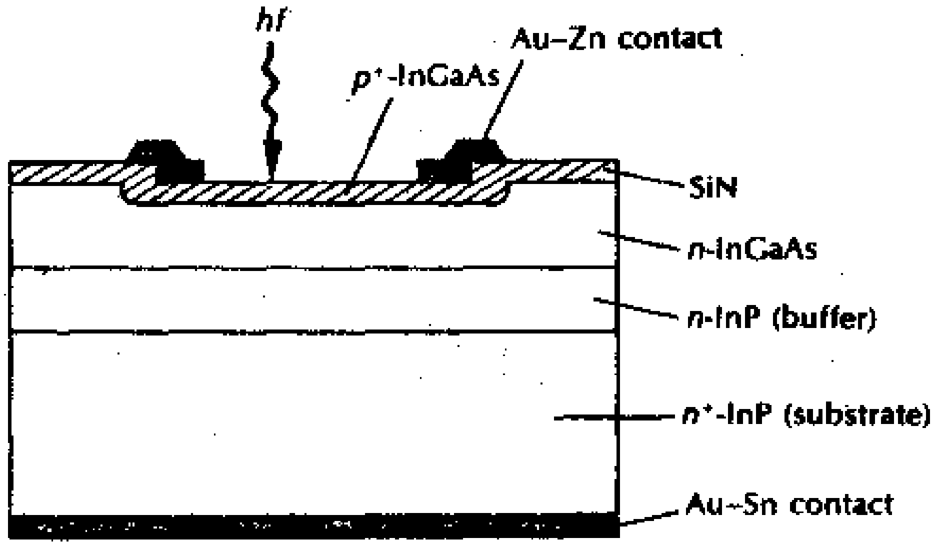


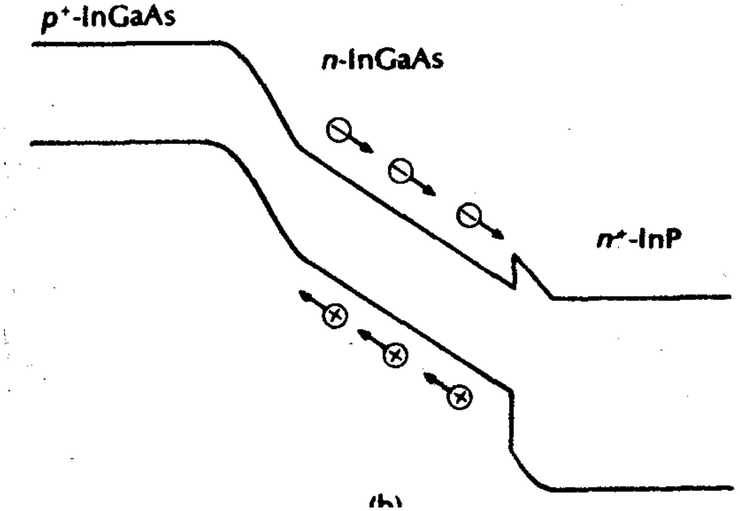
Light is injected parallel to junction plane.

This exhibits large absorption width (=500µm)

This device is sensitive at wavelength of 1.09µm, where absorption coeff. is relatively small.

# Planar lnGaAs p-i-n photodiode

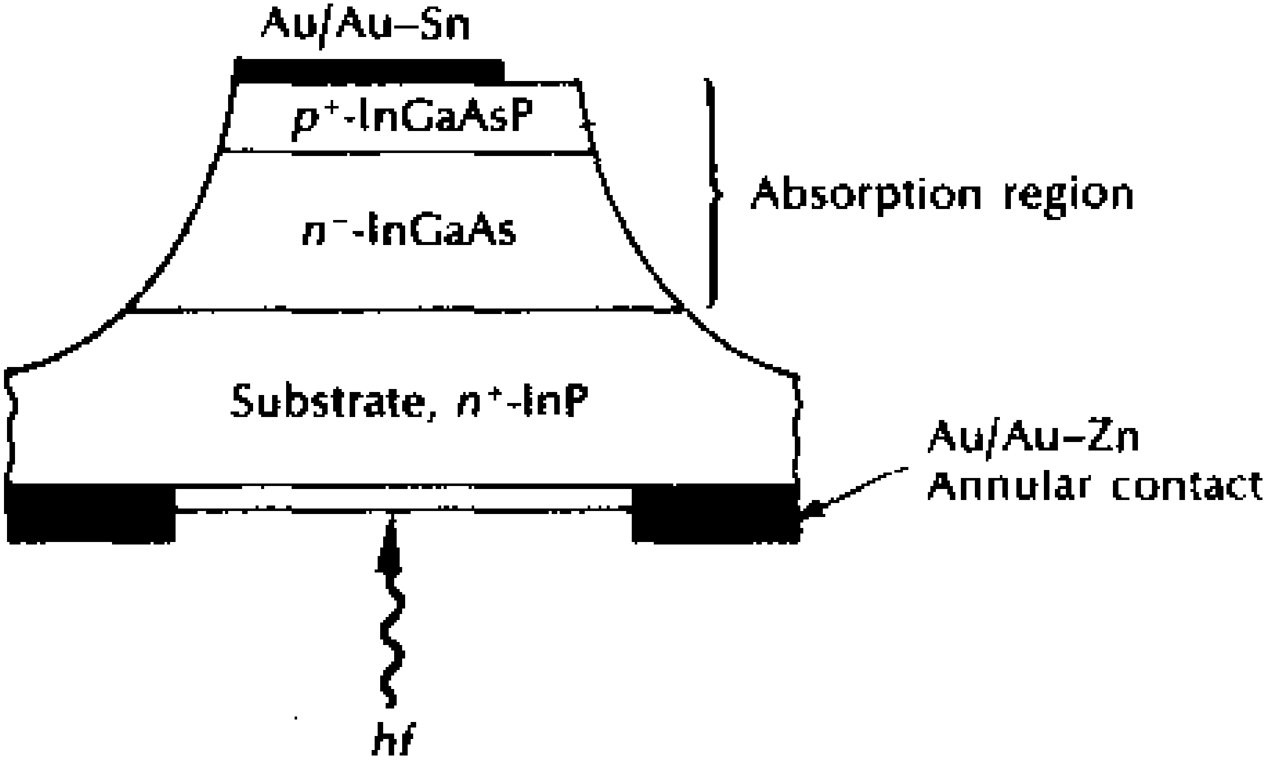




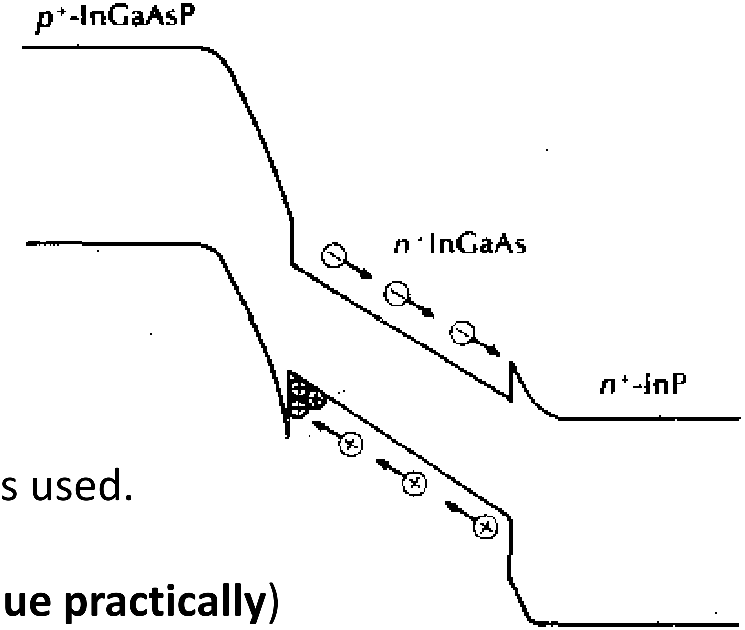
Fabricated as **mesa structure** which reduces parasitic capacitances.

Charge trapping at interface causes limitation in response time .

**Hetrojunction structure improves quantum η. Such devices can be produced with low capacitance** (< 0.1 pF)



**Quantum η = 75 to 100%**
**Dark current < 1nA**



In both devices low doping is used.
BW ≈ 15 GHz (theoretical)
**BW = 1 to 2 GHz (typical value practically**)

# Speed of response (Photodiode)

**Factors limiting the speed of response**

- A) Drift time of carriers thr' depletion region .
- $T(\text{drift}) = \dfrac{w}{v_d}$
- Transit time (When w=10µm)=0.1 n sec.
- Diffusion time of carriers (generated outside w)
- $T_{diff} = \dfrac{d^2}{2Dc}$ d= distance

  Dc= minority carrier diffusion coefft.
- T diff (holes)=40nsec. tdiff (electrons) =8 n sec [d=10µm silicon]

# Speed of response (contd.)

- **Time constant due to cap of photodiode with its load.**
- Jn Cap $C_j = \frac{\varepsilon_s A}{\omega}$ $\varepsilon_s =$ Permitivity of SC.
- A-Diode Jn area

  $\omega$-width of dep. layer
- $C_d$ (cap. of photodiode)= $C_j$+ cap of leads/packaging.
- Cd must be minimised in order to reduce RC time constant which limits the detector response time and Bandwidth.

# Speed of response (contd.)

- $B_m$ (max 3db BW) = $\dfrac{1}{2\Pi\, t_{driftt}} = \dfrac{1}{2\Pi\, w/\upsilon d}$
- = $\upsilon d/2\Pi\, w$ (assuming cj=0)

(assuming no carriers are generated outside the depletion region)

- Max. response time of the device=1/Bm

# Response of photodiode (Contd.)

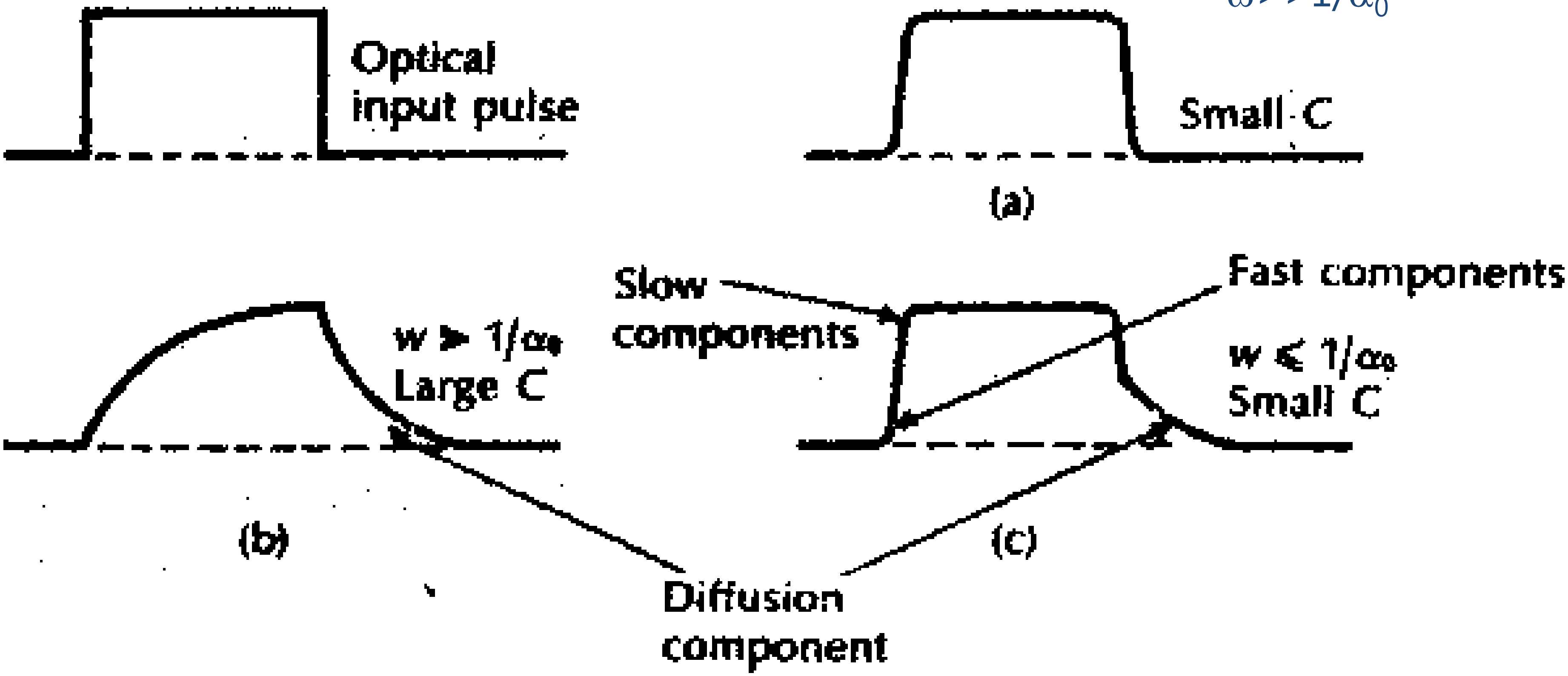
- **For higher quantum η, w >>1/ $\alpha_0$ so that most of the incident light will be absorbed**.

- Fig A : Response of photodiode with the above condition and small capacitance (negligible diffusion outside depletion region).
- Fig B: (**Large C**) Speed of response becomes limited by the RC time constant (R-Load Res.)
- Fig C**:( w< 1/ $\alpha_0$ )** and (**small C** ) dep. layer is narrow. Carriers are created by absorption outside the dep. region. o/p pulse displays a long tail caused by the diffusion component.

- Devices with **thin dep. layer** have a tendency to exhibit distinctive **fast response** and **slow response components**. The fast response is from absorption in the thin dep. layer.

# Response of photodiode (Contd.)

$\omega >> 1/\alpha_0$



# Noise in photodiodes

- Random current and voltage fluctuations occur at o/p both, in the presence and absence of an optical signal.
- Dark Current (Id) : O/P photocurrent in the absence of an opt. input signal.
- RMS value of shot noise

$$\text{current } (\overline{i_s^2})^{1/2} = (2eBI)^{1/2}$$

**Shot noise** is a type of electronic noise which originates from the discrete nature of electric charge. The term also applies to photon counting in optical devices, where shot noise is associated with the particle nature of light.

# Noise in photodiodes (Contd.)

- where $\overline{i_s^2}$ = mean square current variation
- B = Rx Bandwidth
- I = Detector average current.
- Noise performance is assessed using the following
  - Noise Eqvt. Power (NEP)
  - Detectivity (D)
  - Specific Detectivity (D*)

# Noise in photodiodes (Contd.)

- **NEP**: It is the incident opt power at a particular λ required to produce a photo current equal to RMS noise current within a unit bandwidth (B=1Hz)

From $I_p = \eta P_0 e/hf$ or $P_0 = I_p hf/\eta e$

Or

$P_o = I_P hc/\eta e\lambda$, using A and putting

$I_P = (\overline{i_s^{\,2}})^{1/2}$

Ip=(2eBI)1/2,where I = Ip + Id,

$$I_p = 2eB(I_p + I_d)^{1/2}$$

(Ip>>Id) Ip=2eB

Hence, **NEP = Po = 2hc/ ηλ**

# Noise in photodiodes (contd.)

- When Ip << $I_d$ (dark current)
- Then Ip = $[2e\,(I_p + I_d)\,B]^{1/2} = [2eI_d\,B]^{½}$
- Ip = $[2eI_d\,\mathbf{B}]1/2$ When B=1Hz
- NEP = $P_0 = \dfrac{hcI_p}{\eta e\lambda} = \dfrac{hc(2eI_d)^{1/2}}{\eta e\lambda}$
- Detectivity (D) = 1/NEP = $\dfrac{\eta e\lambda}{hc(2eI_d)^{1/2}}$

# Noise in photodiodes (Contd.)

- **Specific Detectivity (D)** : The area (A) of Photo detector is taken into account. This is necessary when background radiation and thermal generation rather than surface conduction are the major causes of dark current .

- $$D^* = D \times A^{1/2} = \frac{\eta e \lambda}{hc\,(2eI_d)^{1/2}} \times (A^{1/2})$$

$$= \frac{\eta e \lambda}{hc(2eI_d/A)^{1/2}} \qquad \text{[when B=1Hz]}$$

**$D^*$ (over BW=B) = $D\,(A \times B)^{1/2}$**

**IT IS A PARAMETER WHICH INCORPORATE THE AREA OF PHOTODETECTOR ‘A’ IN ORDER TO TAKE ACCOUNT OF THE EFFECT OF THIS FACTOR ON THE AMPLITUDE OF DEVICE DARK CURRENT.**

# Noise (contd.)

- **Thermal Noise** : This is the spontaneous fluctuation due to thermal interaction between the free electrons and vibrating ions in a conducting medium (especially prevalent in resistors at room temp.)

- Thermal noise current $\overline{i_t^2} = \frac{4KTB}{R}$

- where K is Boltzmann's Constant
  B-Post Detection (elect) BW
  R- Resistor in optical Rx

# Noise (contd.)

- **Dark Current Noise**

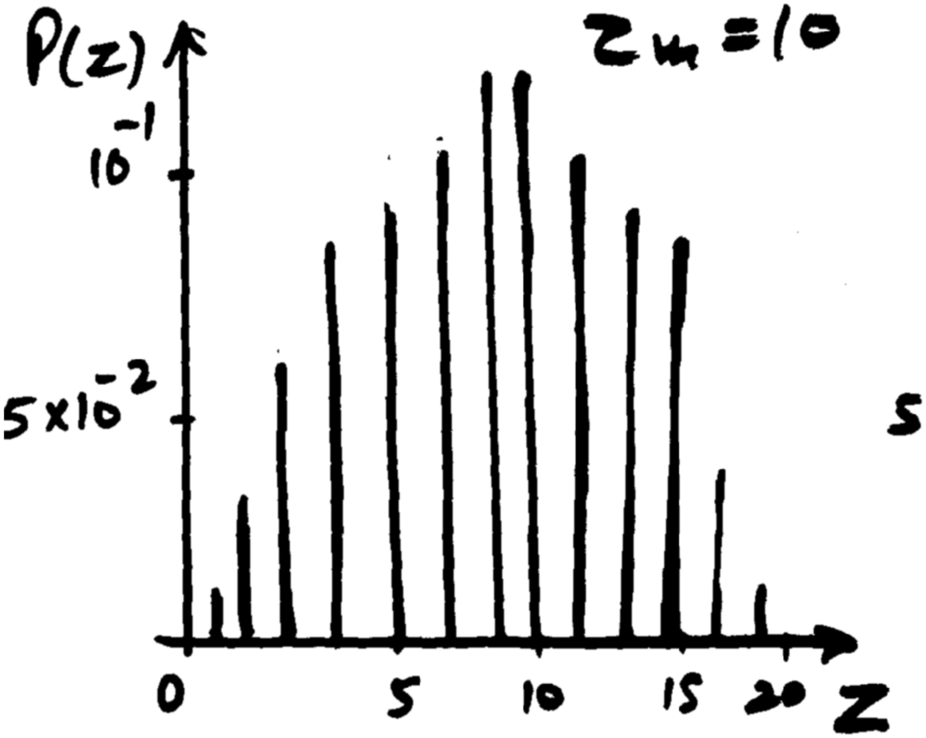
$$_{i(d)}{}^{2} = 2eBI_d$$

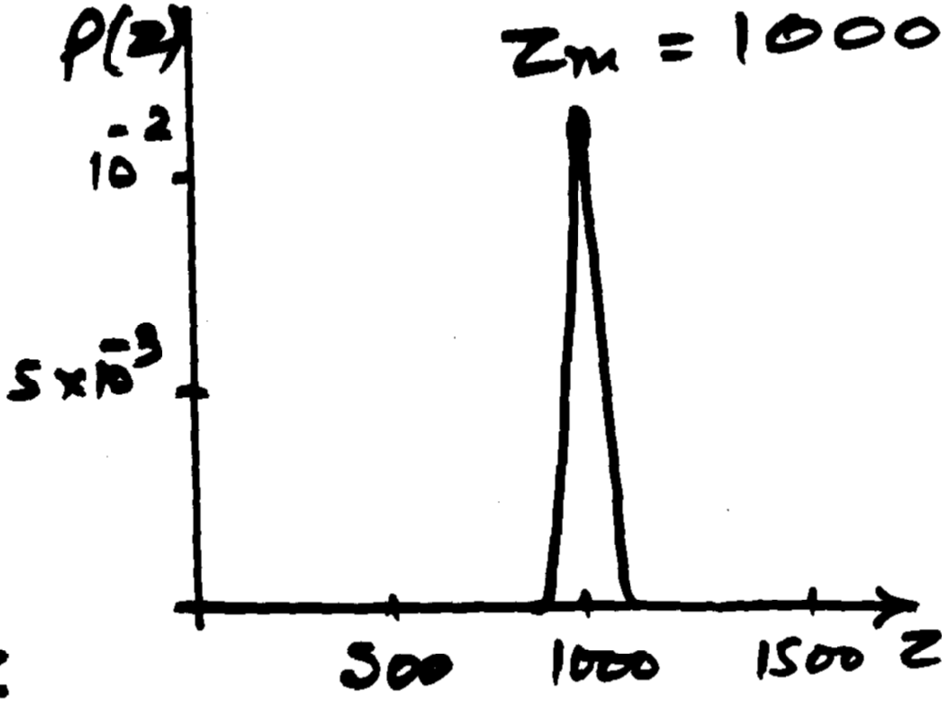
- Dark current can be reduced by careful design and fabrication of the detector.
- **Quantum Noise**
- E=hf (energy of a photon)
- At optical frequencies , hf >KT, therefore the quantum behavior of E.M. radiation must be taken into account .

# Noise (Contd.)

- $P(z) = \frac{z_m e^{-zm}}{\lfloor z}$ Where $z_m$ = Variation of prop. distribution
- P(z) =Prop of detecting z photons in time period
- Zm= mean =Variance (Poisson Distribution)
- $\eta = \frac{r_e \text{ (electron rate)}}{r_p \text{ (incident photon rate)}}$
- or $r_e = \eta r_p = \eta \frac{P_o t}{hf}$
- No. of electrons generated in time is equal to avg. no of photons detected over this time period.
- $Zm = \frac{\eta P_o}{hf} t$

# Poisson Dist for Zm = 10 & Zm = 1000





This represents the detection process for monochromatic coherent light.

# APD Design

- **Desirable Features**

- Carrier multiplication should take place uniformly across the whole area illuminated by the incident radiation.

- The peak field where avalanche multiplication will occur should be confined to a very thin layer.

- The avalanche should be initiated by carriers with higher ionization coefficient, otherwise BW will be less & noise factor will be increased.

- High quality material should be used (to prevent premature avalanche)

# APD Design (Contd.)

- Quantum η should be high
- Dark currents should be low.
- (Note: Higher dark currents are due to small energy band gap and edge/surface defects)
- Noise Factor should be low
- Speed of response should be high.

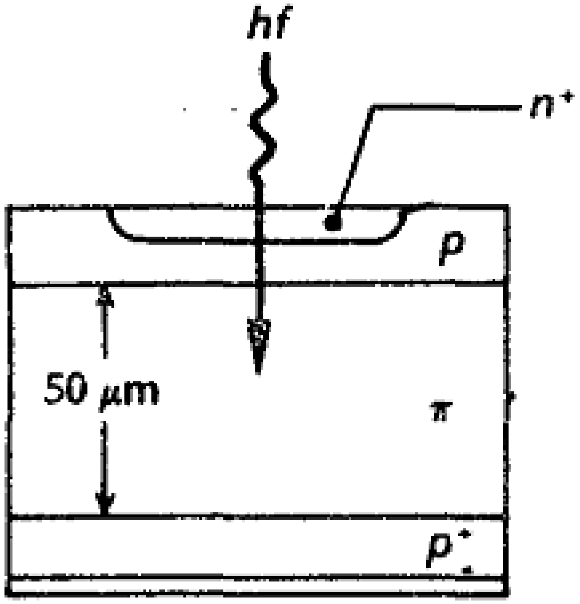
# APD Design (contd.)

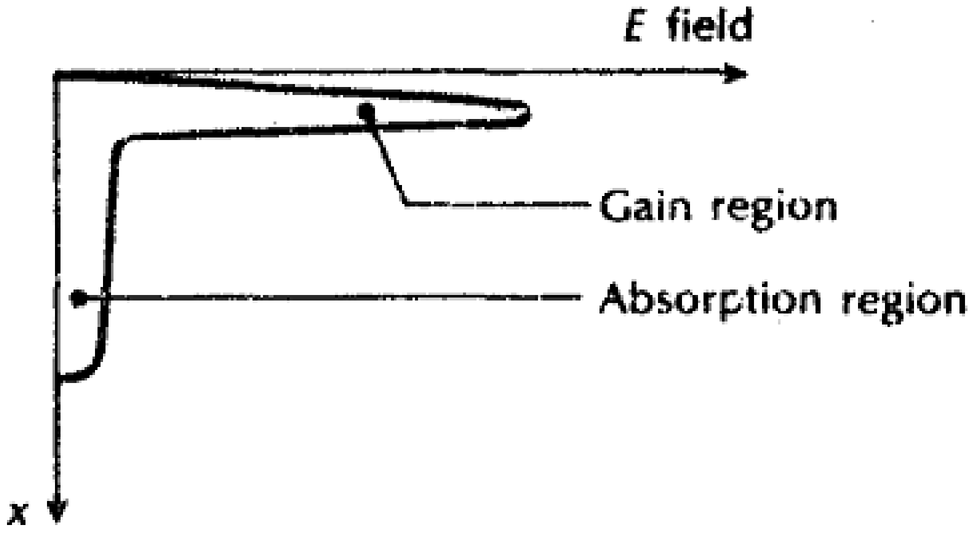
- Note: (The speed of response of a photodiode is limited by the time it takes the photo-generated carriers to takes the photo-generated carriers to drift across the depletion region)

- The system design should take into account various impairments (modal noise, dispersion, feedback, cross talk and non-linearities in fiber.)

# Silicon Reach Through APD(RAPD)

- For min noise, the elect field at avalanche breakdown must be as low as possible and impact ionisation should be initiated by electrons.
- RAPD Consist of $p^+$ -Π –p-$n^+$ Layers
- Avalanche multiplication takes place in relatively narrow place centered on p-$n^+$ junction.





# Silicon Reachthrough APD(RAPD)

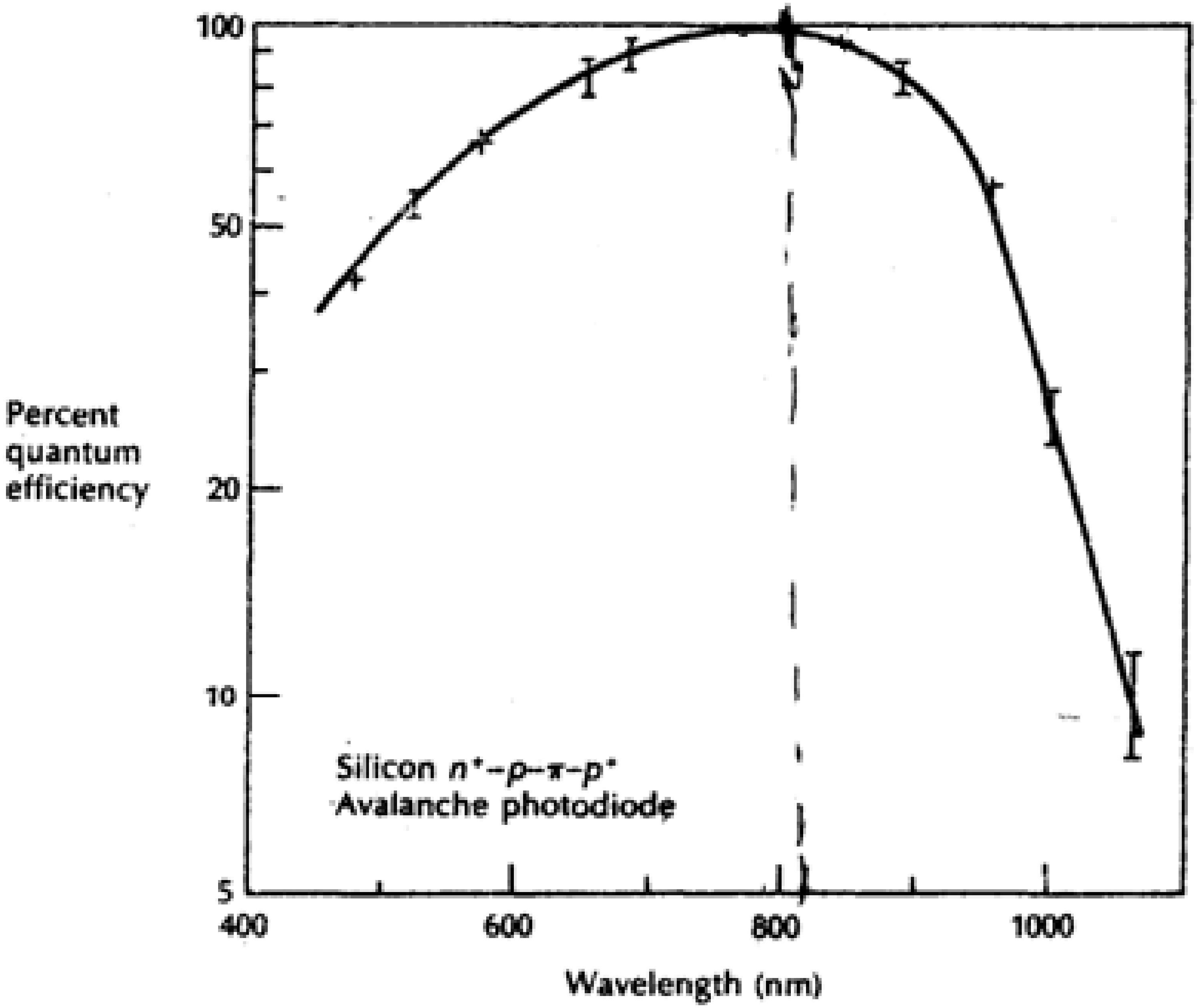
- Reverse Bias depletion layer widens until it reaches through to lightly doped Π region

Field in Πregion is much lower than at p-n$^+$jn.

But still it is high enough ($2*10^4$ V/cm).

- This limits the transit time and ensures a fast response (0.5 n sec.)
- At 0.825 µm wavelength, Quant η =100%
- Low dark currents!

# Quantum Efficiency Vs Wavelength Silicon RAPD



# Quantum Efficiency Vs Wavelength Silicon RAPD

- Quantum = 100% at 0.825 µm(λ)
- Dark Currents for this photodiode are low and depend only slightly on bias voltage.