Optical Detectors

- **PURPOSE: TO CONVERT THE RECEIVED OPTICAL SIGNAL INTO AN ELECTRICAL SIGNAL.**

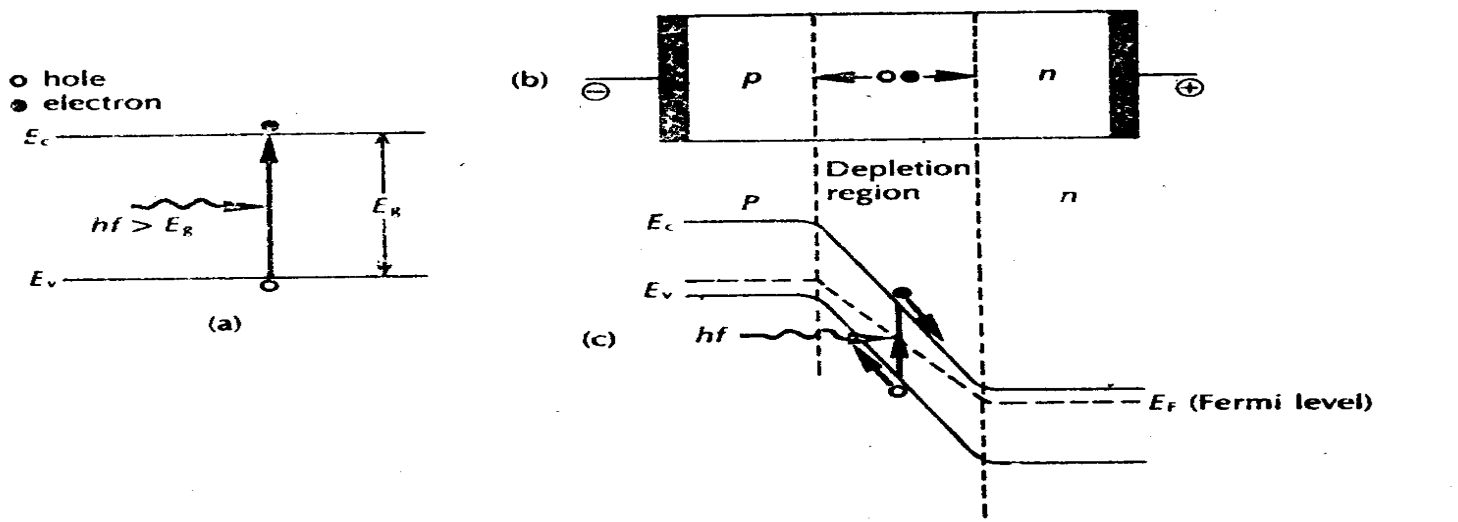
Requirements For Detector

- **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**. (FOR 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



[redacted] 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, **$hf \geq E_g$** 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)

Opt. Detection-Principle (contd)

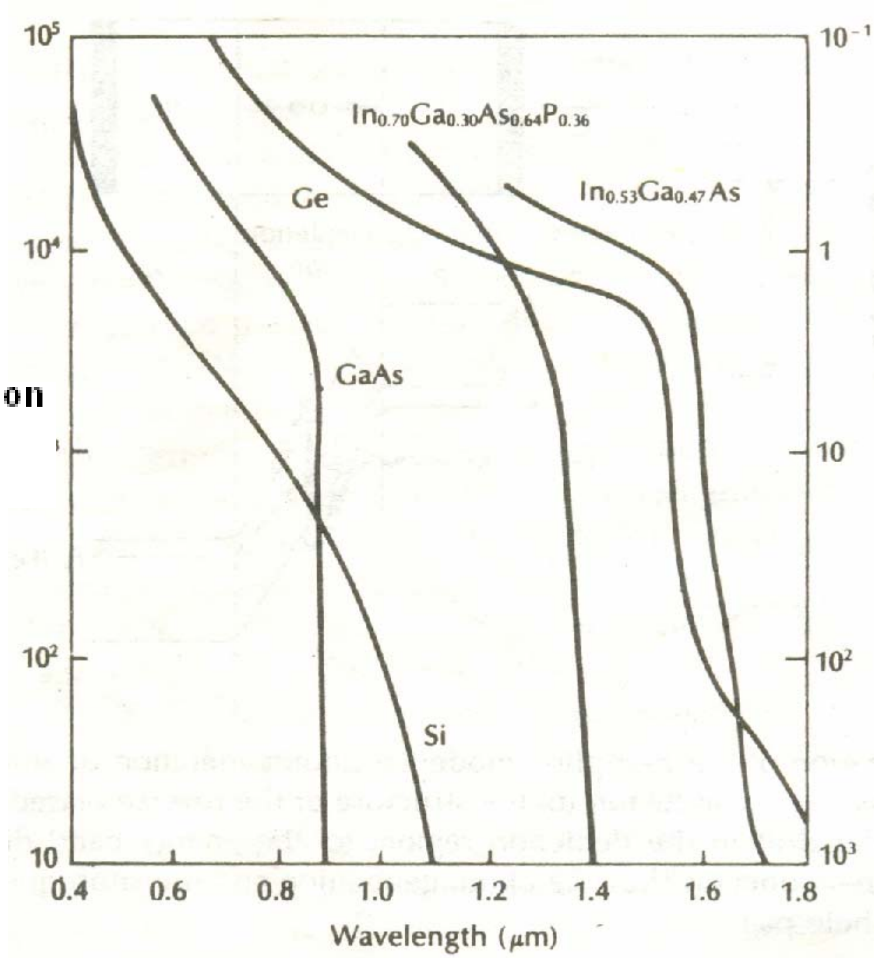
- Note: Wider depletion layer (DL) is required for incident light to be absorbed for max. carrier-pair generation.

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

Absorption coefficient(α_0)

- The absorption of photons in a photo diode to produce carrier pairs and thus a photo current, is dependant on the absorption coefficient, α_0 of the light in the semiconductor (used to fabricate the device)
- Ip (Photo Current)=$P_0 e(1-r)\ [1-e^{-\alpha_0 d}]/hf$
- Po = Optical power (of incident light)

Optical absorption coefficient (cm-1)



Light Penetration depth (um)

Optical absorption curves for some common semiconductor: photodiode materials (silicon,germanium, gallium,arsenide,indium gallium arsenide,indium gallium arsenide phosphide)

Band gaps for some semiconductor Photodiode materials at 300k

		Bandgap(ev) at 300k
	INDIRECT	DIRECT
Si	1.14	4.10
Ge	0.67	0.81
GaAs	-	1.43
InAs	-	0.35
InP	-	1.35
GaSb	-	0.73
InGaAs	-	0.75
GaAs Sb	-	1.15

Absorption coefficient(α_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)

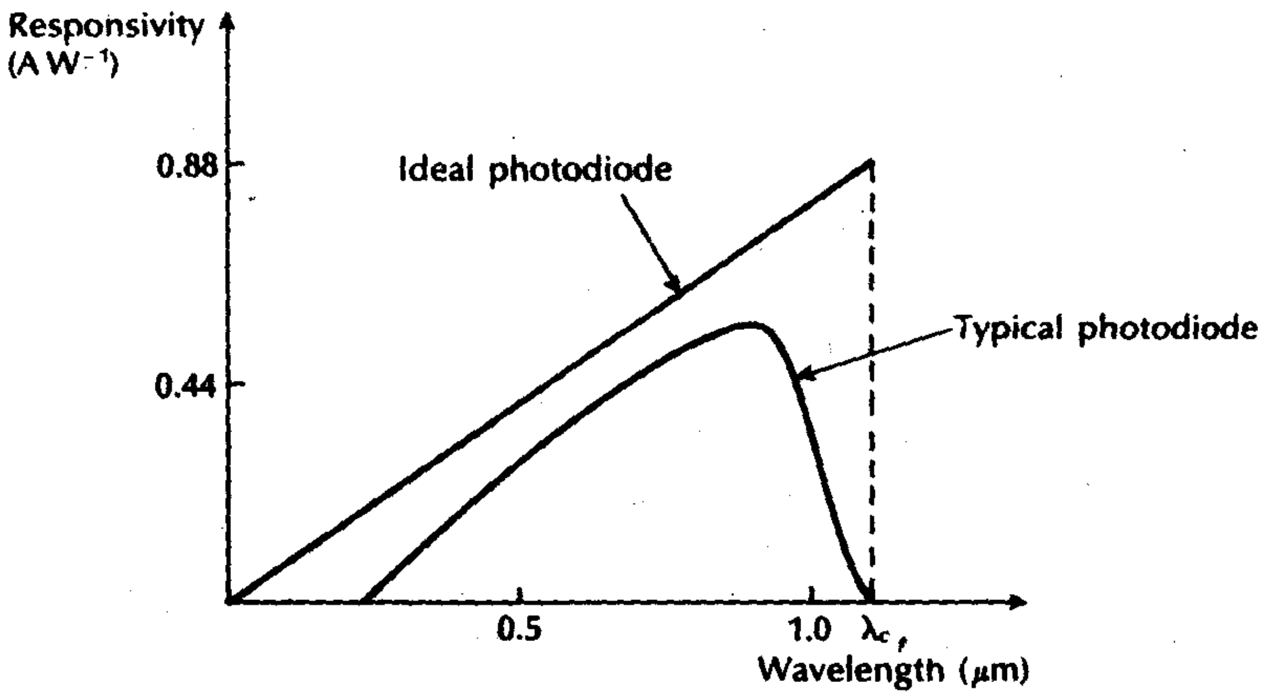
Responsivity (R) of a photo detector

- **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 $r_e = \eta\, r_p$ $[\eta = r_e/r_p]$ $= \dfrac{\text{No.of electrons collected}}{\text{No.of incident photons}}$
- $r_e = \eta\, P_o/hf$
- 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 λ)

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 $\lambda c \leq hc/Eg$
- **λc =Long λ cutoff (threshold for detection) = hc /Eg**

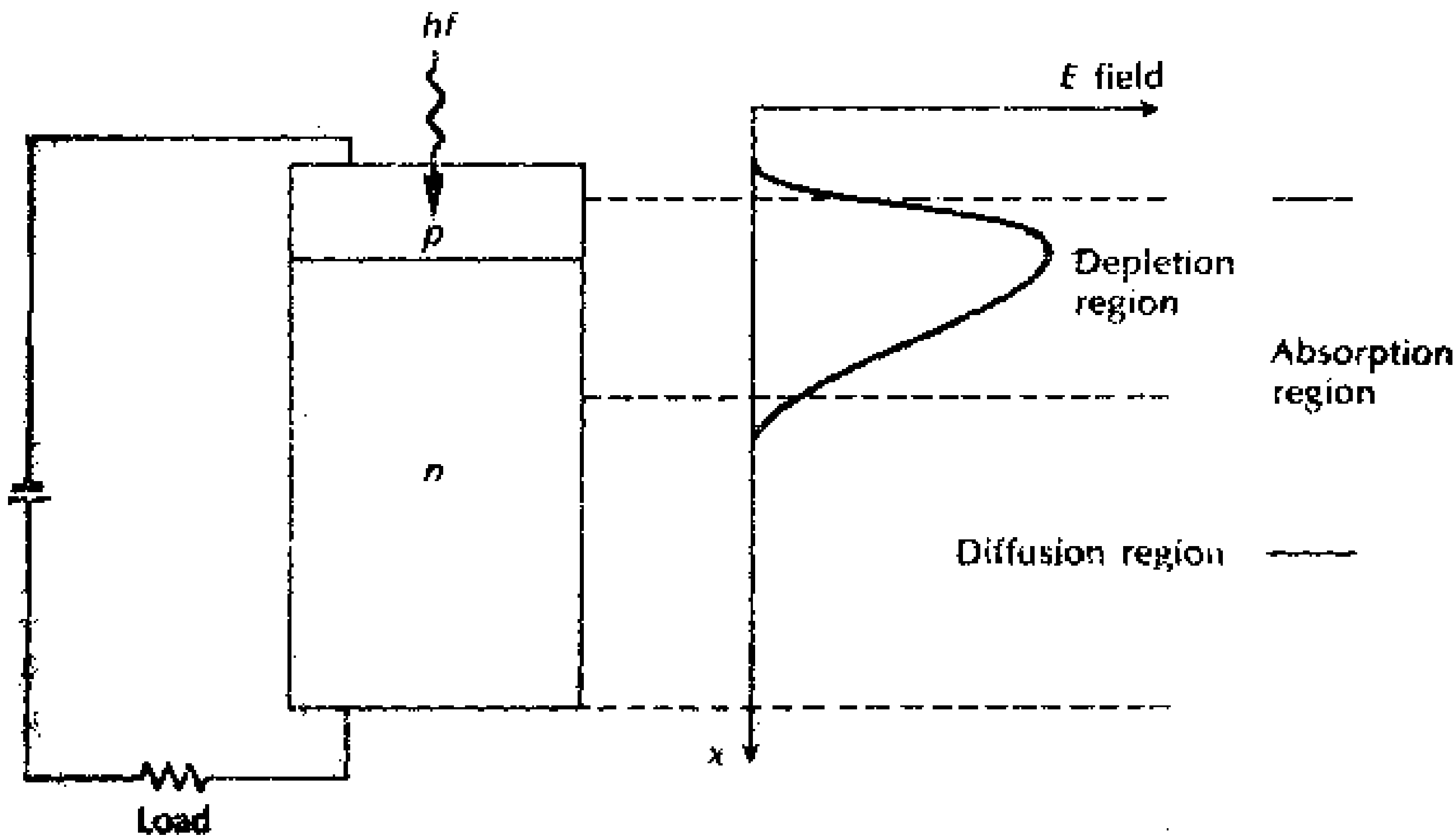
Long wavelength cut-off (contd.)

- This is the longest wavelength of light to give photo detection.
- The cut-off wavelength is 1.06 μm for Si and 1.6 μm for Ge.

Note

- Extrinsic photo detectors are not currently used in OFC.

Reverse bias P-N Photodiode



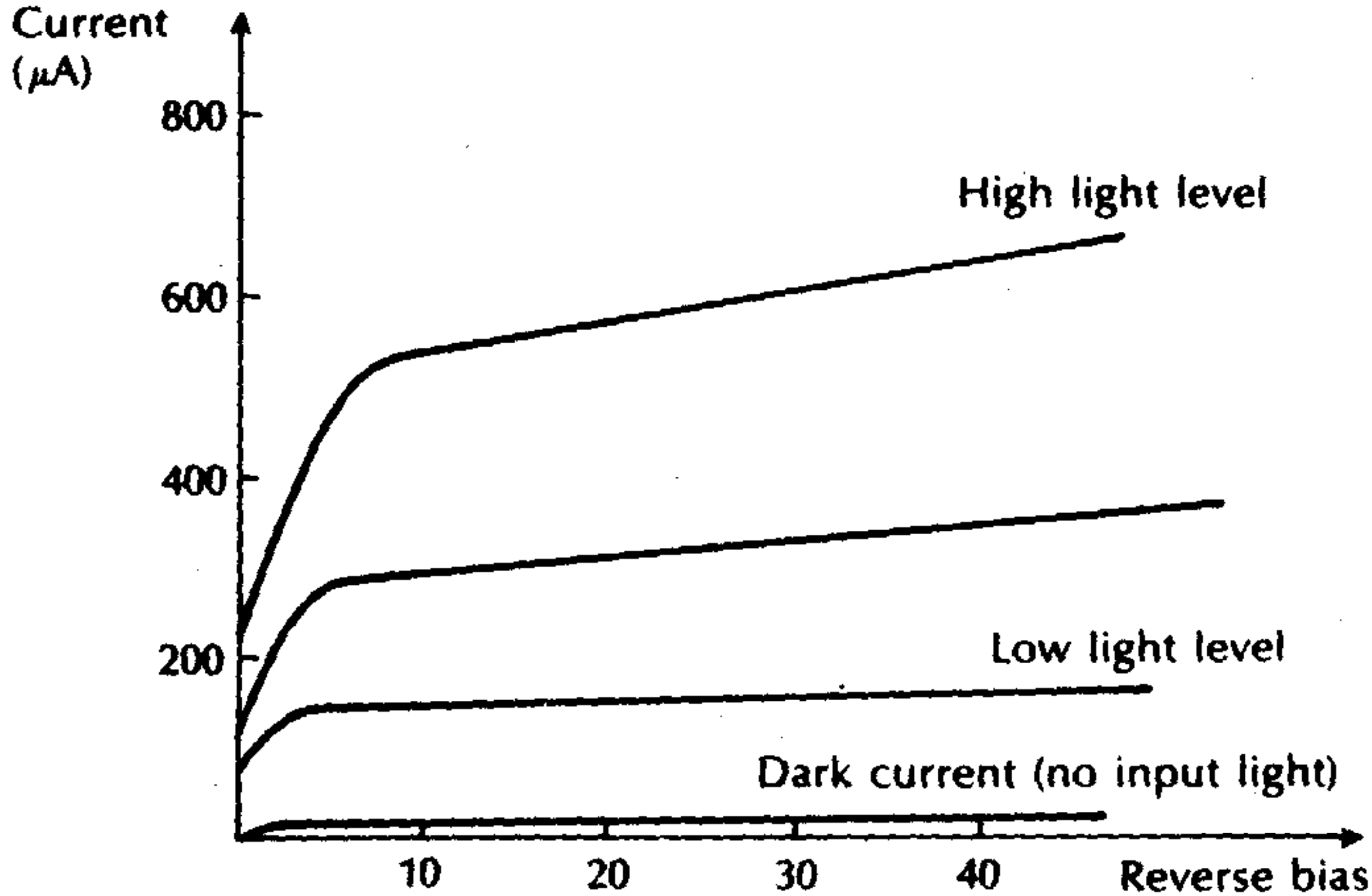
Reverse bias P-N Photodiode

- 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

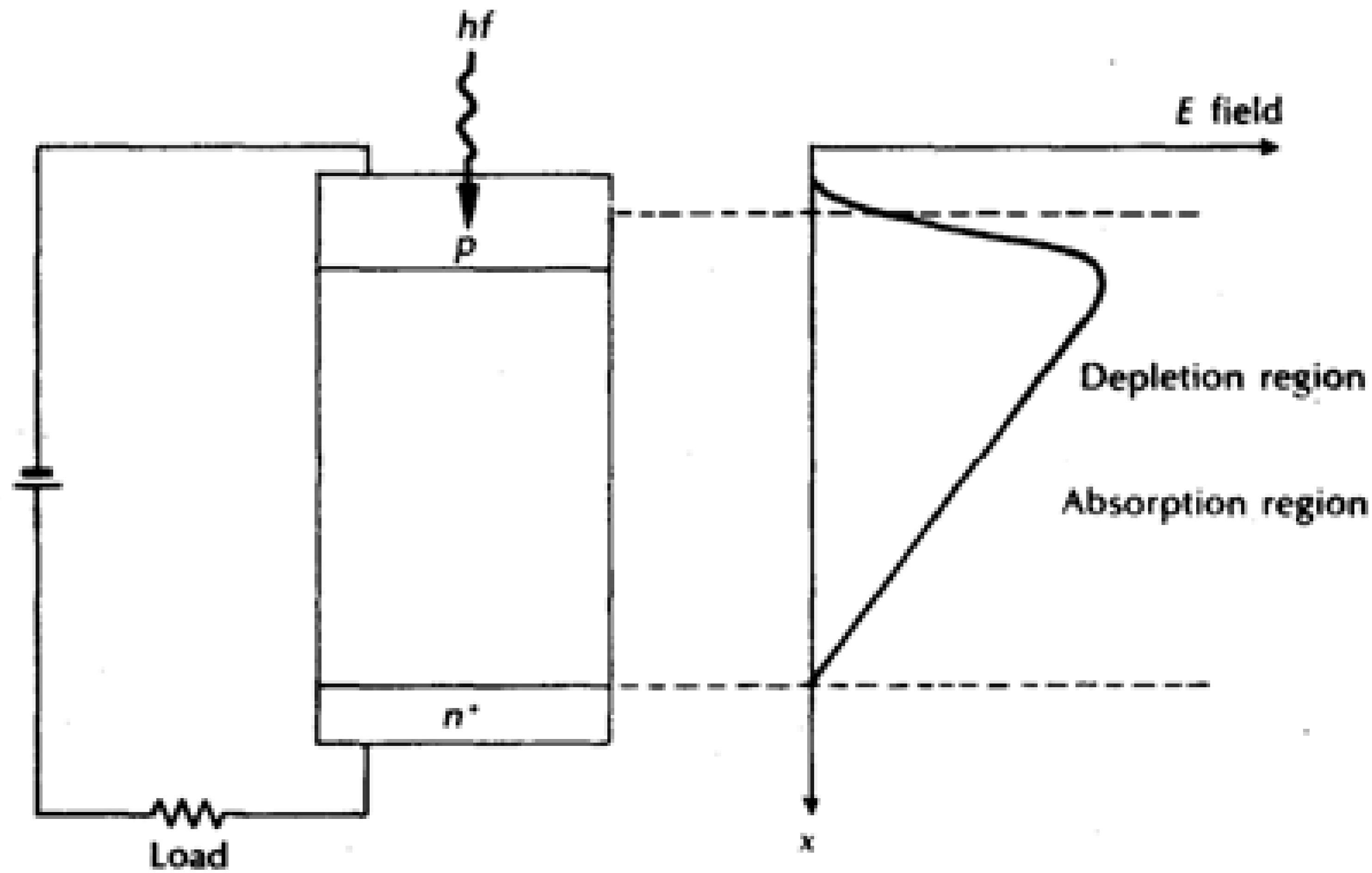


Typical P-N Photodiode o/p characteristics (contd.)

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.)

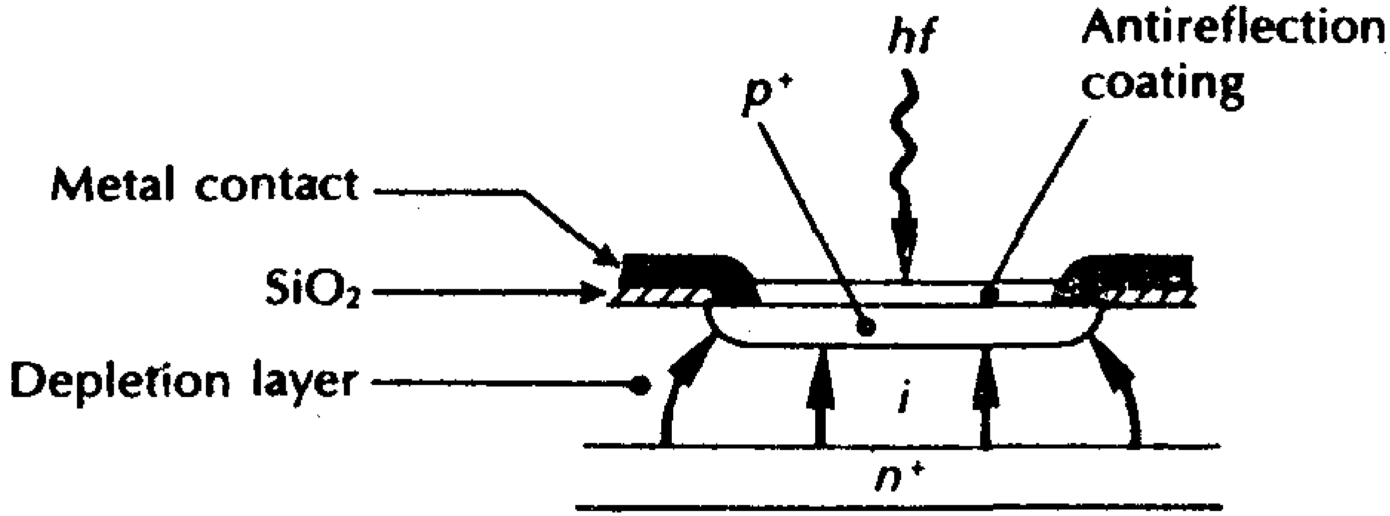
- **P-I-N STRUCTURE :** **Highly doped n type (n+) layer with lightly doped n type (intrinsic) and p type on the other end.**

- A wider depletion layer region is necessary (longer λ)
- **All the absorption takes place in the depletion region**.

P-I-N Photodiode (contd.)

- 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 (=500 μm) at wavelength=1.09 μm

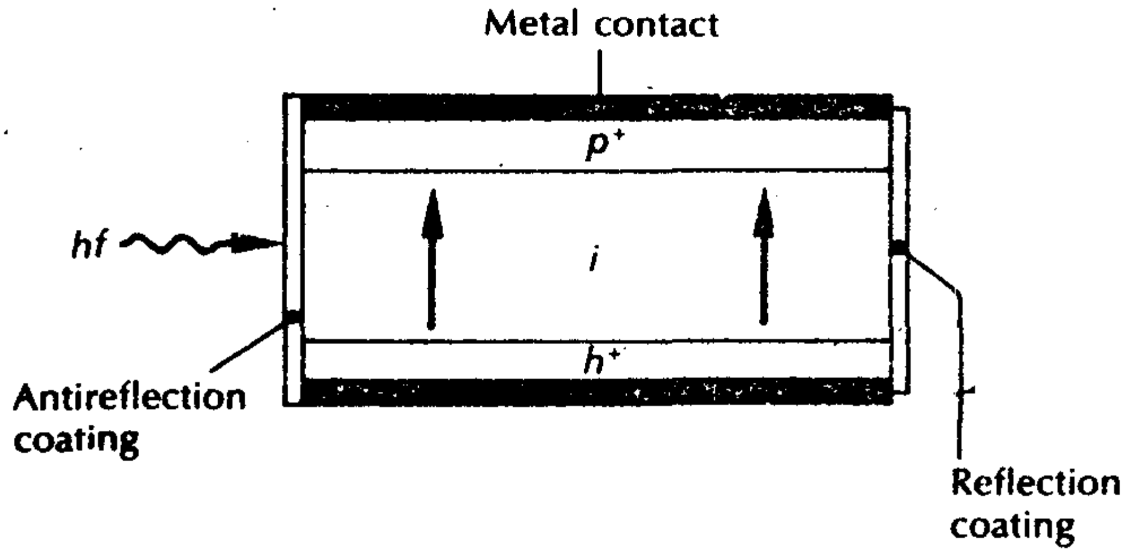
Front illuminated Silicon p-i-n photodiode



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.

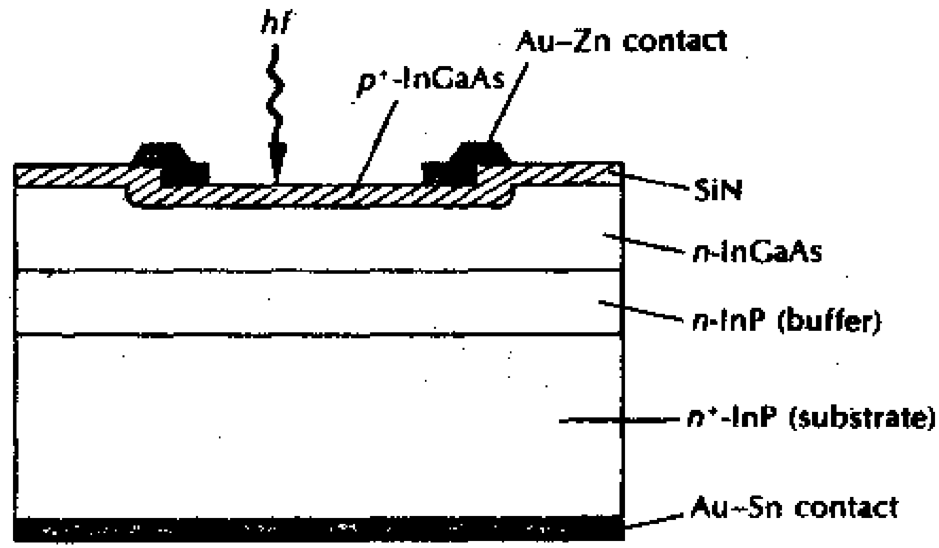


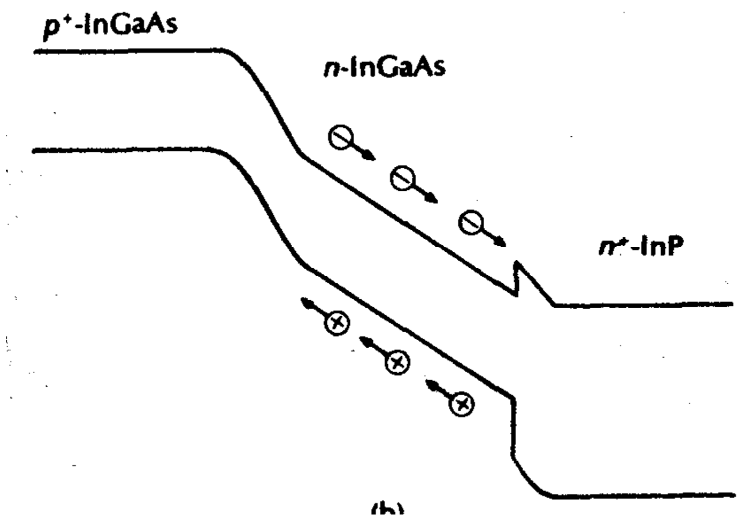
Light is injected parallel to junction plane.

This exhibits large absorption width (=500 μm)

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

Planar lnGaAs p-i-n photodiode-Top entry



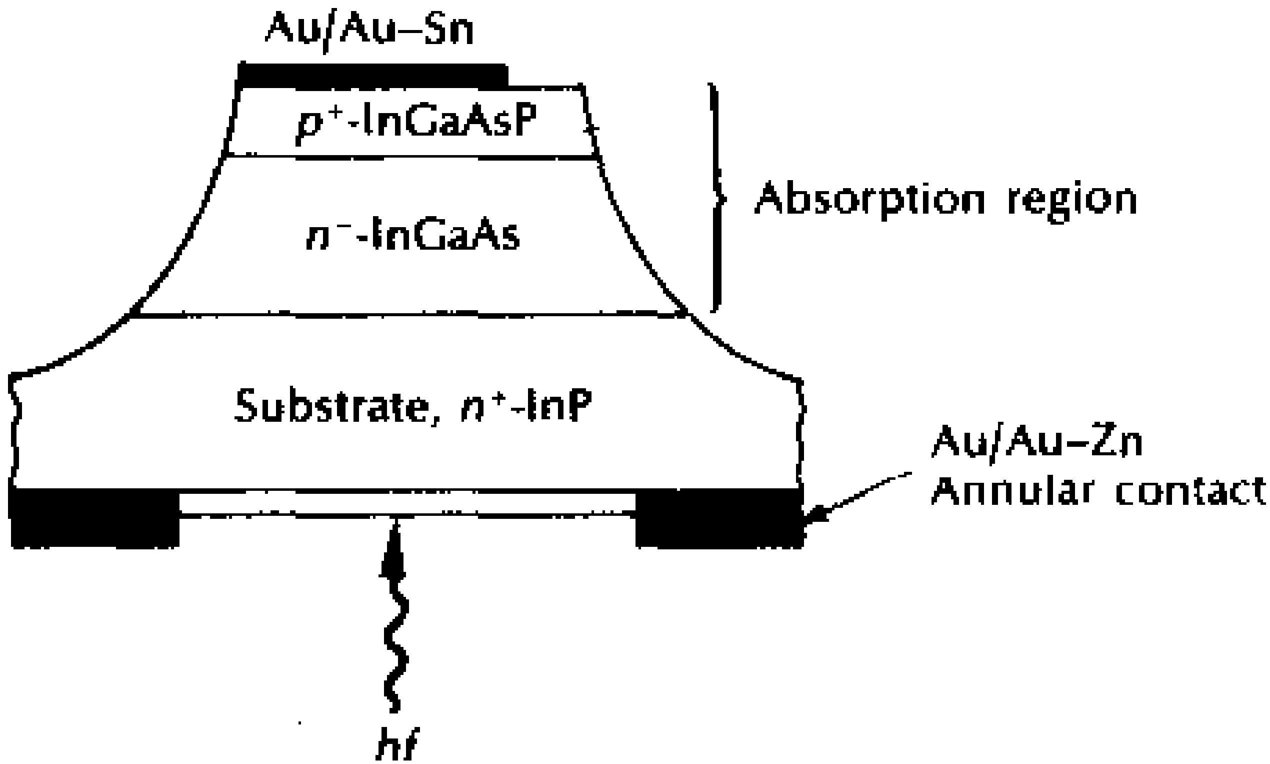


SUBSTRATE ENTRY –P-I-N PHOTODIODE

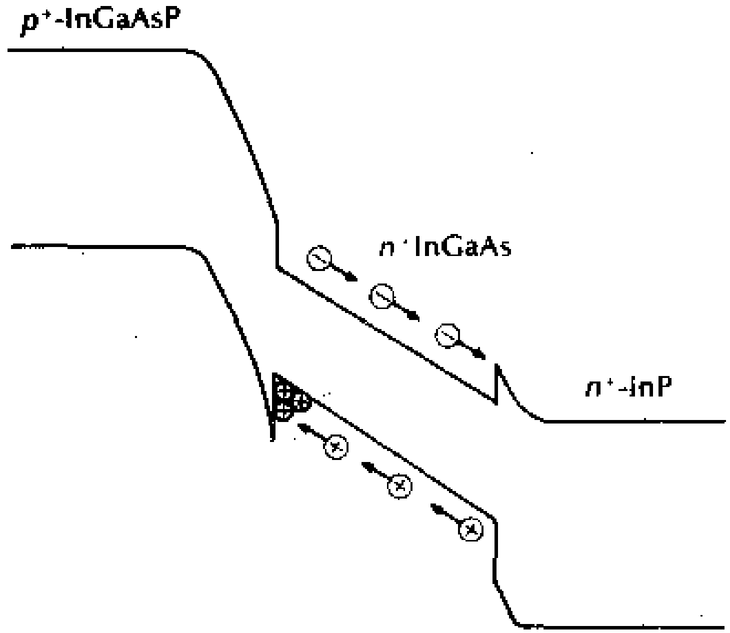
-Fabricated as **mesa structure** which reduces parasitic capacitances.

-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 .
- $t(drift) = \frac{w}{v_d}$
- Transit time (when w=10 μm) = 0.1 n sec.
- Diffusion time of carriers (generated outside w)
- $t_{diff} = \frac{d^2}{2Dc}$ d= distance
  Dc= minority carrier diffusion coefft.
- ``t diff (holes)=40 nsec. tdiff (electrons) =8 nsec [d=10μm in silicon]

Speed of response (contd.)

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

  ω-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) $= \dfrac{1}{2\pi t_{drift}} = \dfrac{1}{2\pi w/\upsilon d}$

  $= \upsilon d / 2\pi w$

  (assuming cj=0, and 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/ α_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.)

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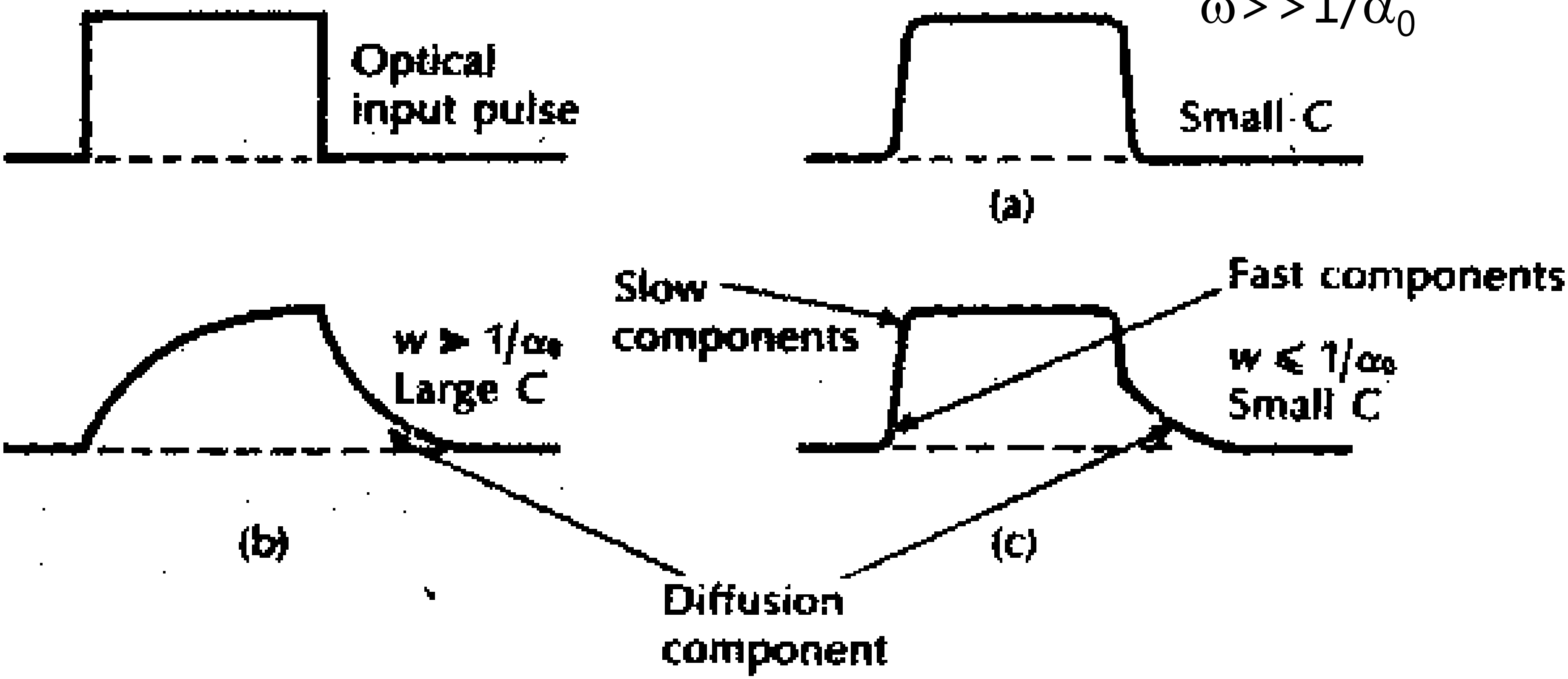
Response of photodiode (Contd)

- Fig C**:(w< 1/ α_0)** and (**small C**) **<u>Dep. layer is narrow</u>.**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 in the presence as well as absence of an optical signal.
- **Dark Current (Id) : O/P photocurrent in the absence of an opt. input signal.**
- RMS value of shot noise *current*

$$(\overline{i_s^2})^{1/2} = (2eB\overline{I})^{1/2}$$

(A)

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**

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

Or $P_o = I_P hc/\eta e\lambda$,

using $\overline{A}$ and putting $I_P = (\overline{i_s^2})^{1/2}$

$Ip = (2eB\overline{I})^{1/2}$ where $I = Ip + Id$, $Ip = [2eB(Ip + Id)]^{1/2}$

when $(Ip \gg Id)$, $Ip = 2eB$

NEP=Po=2eB.h c / (ηeλ) = 2hc/ ηλ

Noise in photodiodes (contd.)

- When $I_p << I_d$ (dark current)
- Then $I_p = [2e(I_p + I_d)B]^{1/2} = [2eI_d B]^{½}$
- $I_p = [2eI_d]^{1/2}$ When B=1 Hz

- **NEP**$= P_0 = \frac{hcI_p}{\eta e\lambda} = \frac{hc(2eI_d)^{1/2}}{\eta e\lambda}$
- **Detectivity (D) = 1/NEP** $= \frac{\boldsymbol{\eta e\lambda}}{\mathbf{hc(2eI_d)^{1/2}}}$

Noise in photodiodes (Contd.)

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

- $D^* = DA^{1/2} = \dfrac{\eta e \lambda}{hc(2eI_d)^{1/2}} \quad (A^{1/2})$

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

D^*(over BW=B) =D(AB)$^{1/2}$

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 Receiver

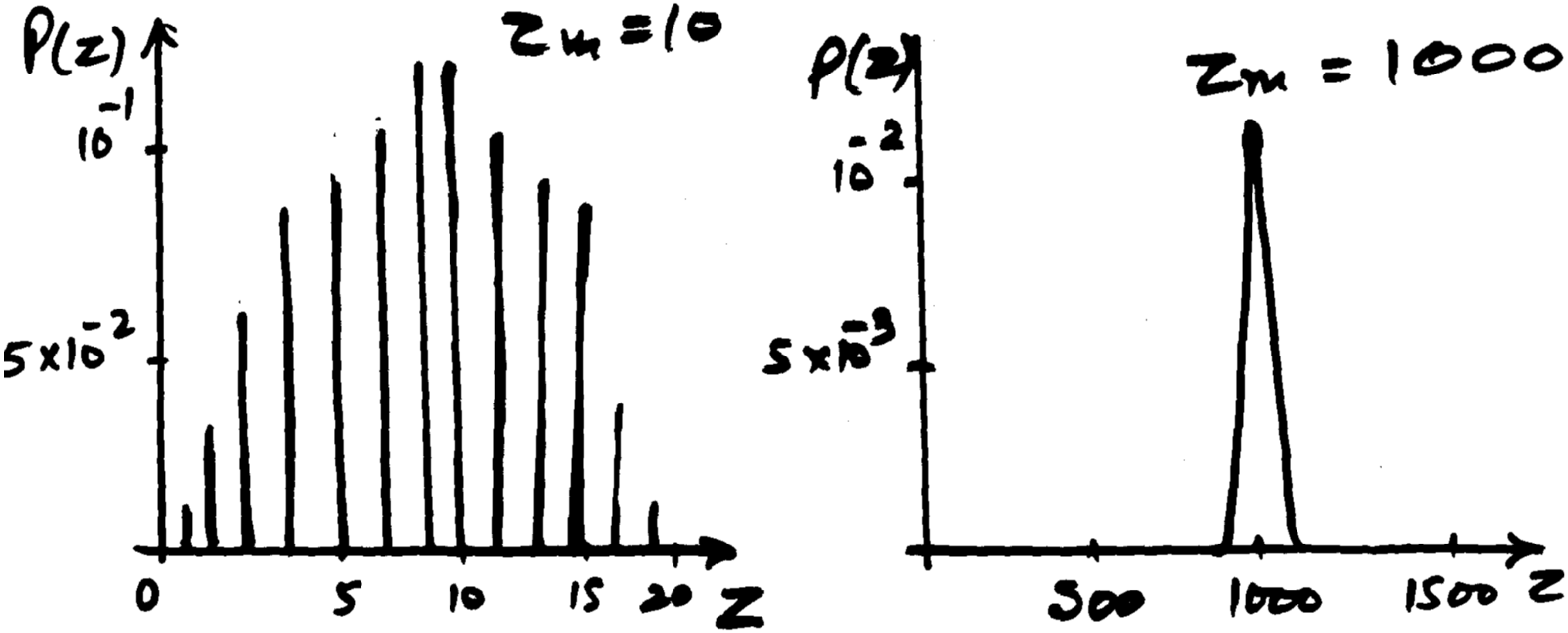
Noise (contd.)

- **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 behaviour of e.m. radiation must be taken into account as quantum fluctuations dominate over thermal fluctuations.

Noise (Contd.)

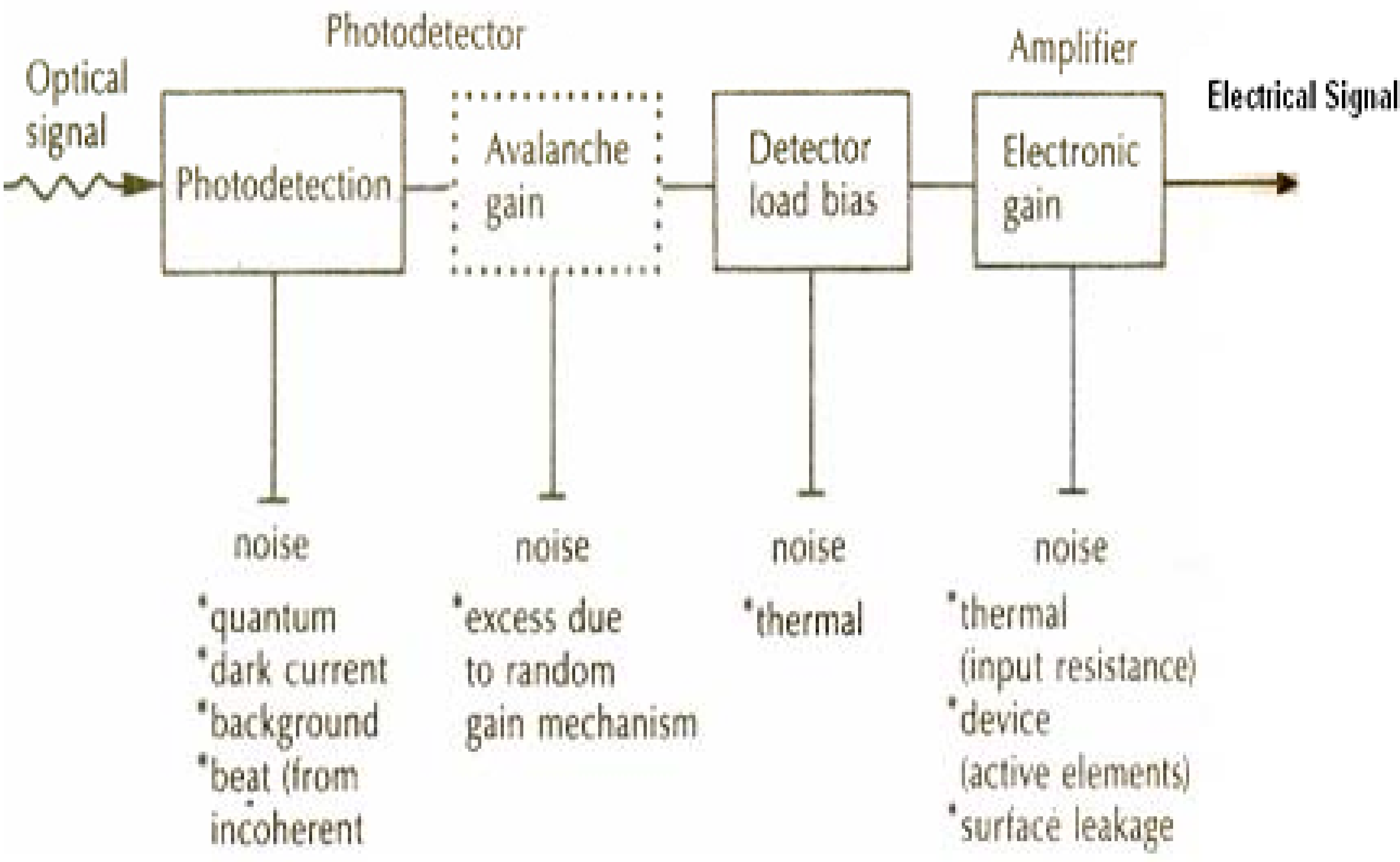
- $P(z) = \frac{z_m^{\,z}\, e^{-zm}}{\llcorner z}$ Where z_m = Variance of prop. distribution
- P(z) =Prob of detecting z photons in time period t
- Zm= mean =Variance (Poisson Distribution)
- $\eta = \frac{r_e \text{ (electron rate)}}{r_p \text{ (incident photon rate)}}$
- or $r_e = \eta\, r_p = \eta \frac{P_o}{hf}$
- No. of electrons generated in time t 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.

NOISE IN OPT. RECEIVER



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

APD

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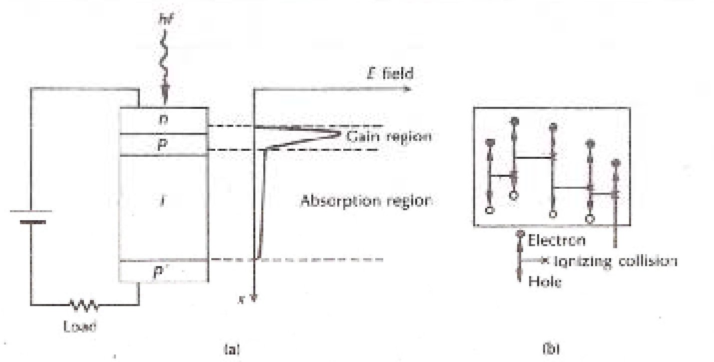

(a) Avalanche photodiode showing high electric field (gain) region. (b) Carrier pair multiplication in the gain region.

APD

- More sophisticated structure than p-i-n Photodiode so as to create a high electric field.
- Most of the photons are absorbed in the Depletion region .
- There is another high field region in which holes and electrons acquire sufficient energy to excite new electron-hole pairs.(IMPACT IONISATION)

APD (contd)

- High Reverse Bias required (50-400V)
- Carrier multiplication factors upto 10^4 can be obtained using defect free materials
- **MICROPLASMAS(** small ares with lower BD voltage than the remainder of the junction) must be reduced thr better fabrication and defect free materials.
- Rise time: 150-200 ps, Fall time: 1ns
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SILICON APD(with guard ring)

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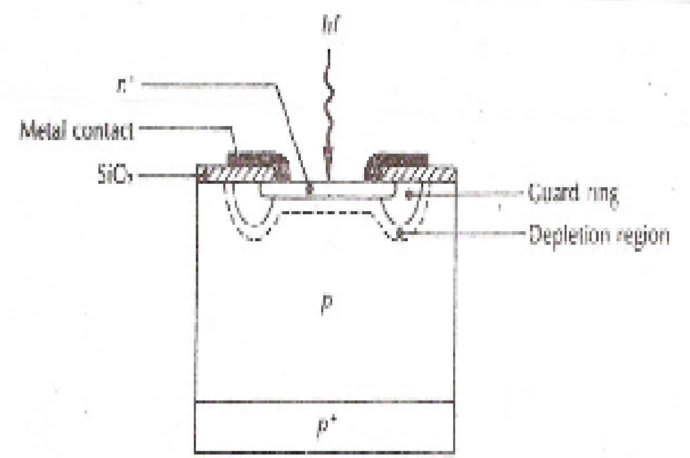


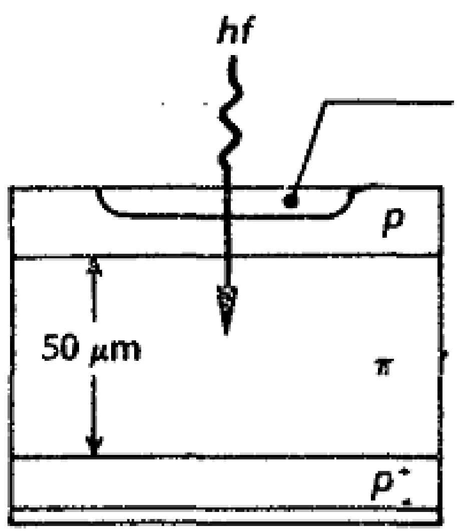
Structure of a silicon avalanche photodiode with guard ring.

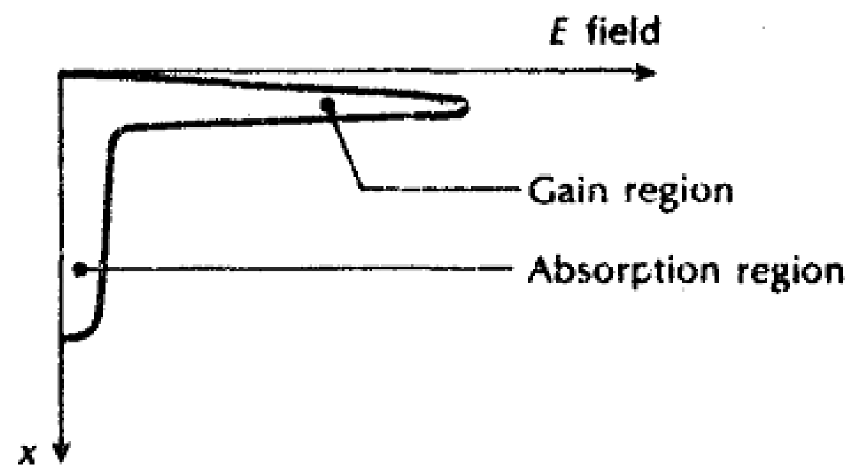
SILICON APD

- Guard Ring structure eliminates excessive leakage at junction edges.
- When elect field is high, all carriers drift .
- At low gain, transit time and RC time constant dominate .
- At high gain, Avalanche build up time dominates (BW decreases with increasing gain)

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 consists of p^+ -Π –p-n^+ layers
- Avalanche multiplication takes place in relatively narrow place centered on p-n^+ junction.





Silicon Reach Through APD(RAPD)

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

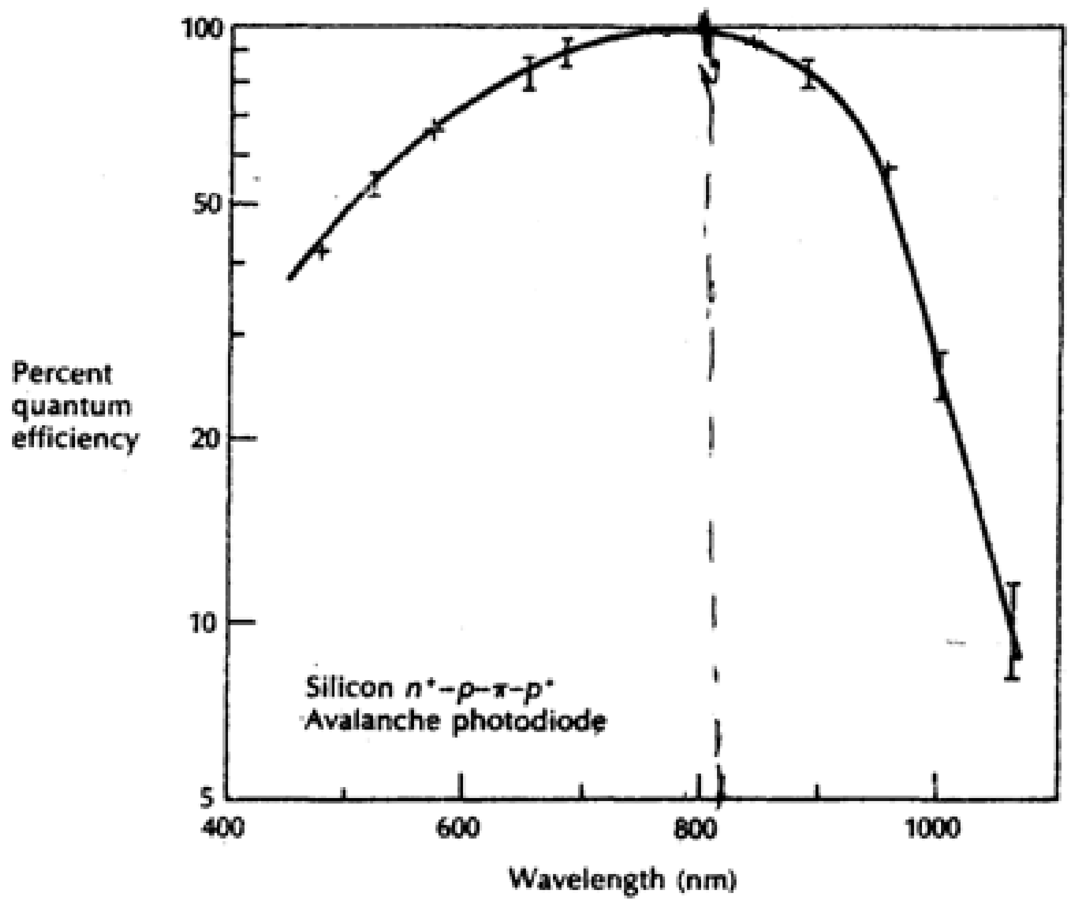
Field in Π region is much lower than at p-n^+junction, but still it is high enough ($2*10^4$ V/cm) .This limits the transit time and ensures a fast response (0.5 n sec.)

- At 0.825 μm wavelength, Quant η =100%
- Dark currents are low.

RAPD (contd)

- Normally RAPD is operated in fully depleted mode
- Light enters the device thr p + region and is absorbed in the π material
- Upon being absorbed, photon gives up its energy, thereby creating electron-hole pairs
- The electrons drift thr π region in the pn+ junction, where high electric field exists
- Carrier multiplication takes place in this high-field region.

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.

Multiplication Factor(M) –APD

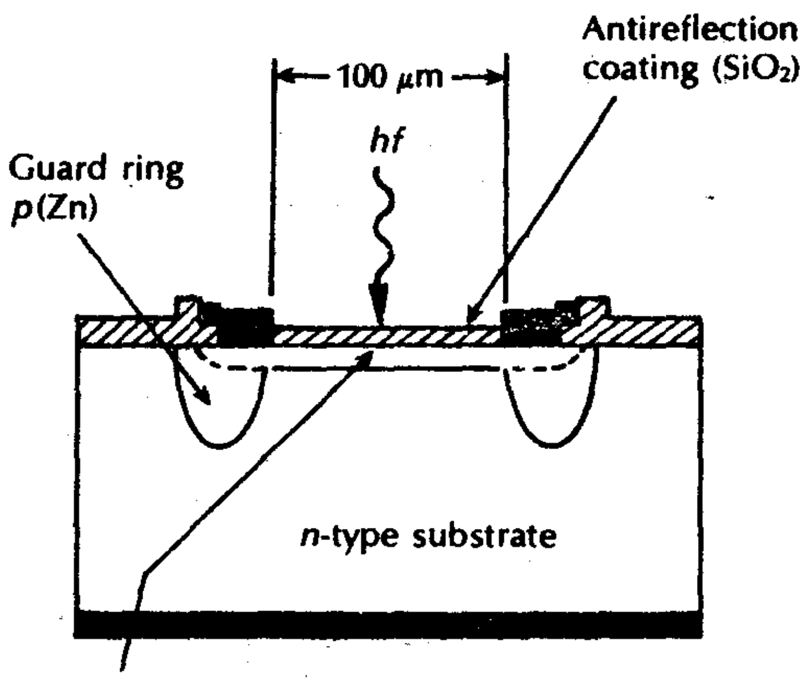
- M is a measure of the internal gain provided by the APD.
- $M = I / I_p$
- Where I- Total O/P current at the operating voltage (where carrier multiplication occurs)
- I_p - Initial or primary photo current (i.e. before carrier multiplication occurs)

Germanium Avalanche Photodiode

- These APD’s can be used over the entire wavelength range (0.8-1.6 μm).
- However ,these APD’s have **higher dark currents** together with **excess noise** than those in silicon APD’s
- These higher dark currents are due to surface effects and excess noise is due to electrons rather than holes initiating the multiplication process.

Germanium Avalanche Photodiode (contd)

- Advantage: Avalanche BD voltage is low (typically 25 v)
- Ge has a higher absorption co-efficient



(a)

- **<u>Ge APD – p^+ n structure</u>**

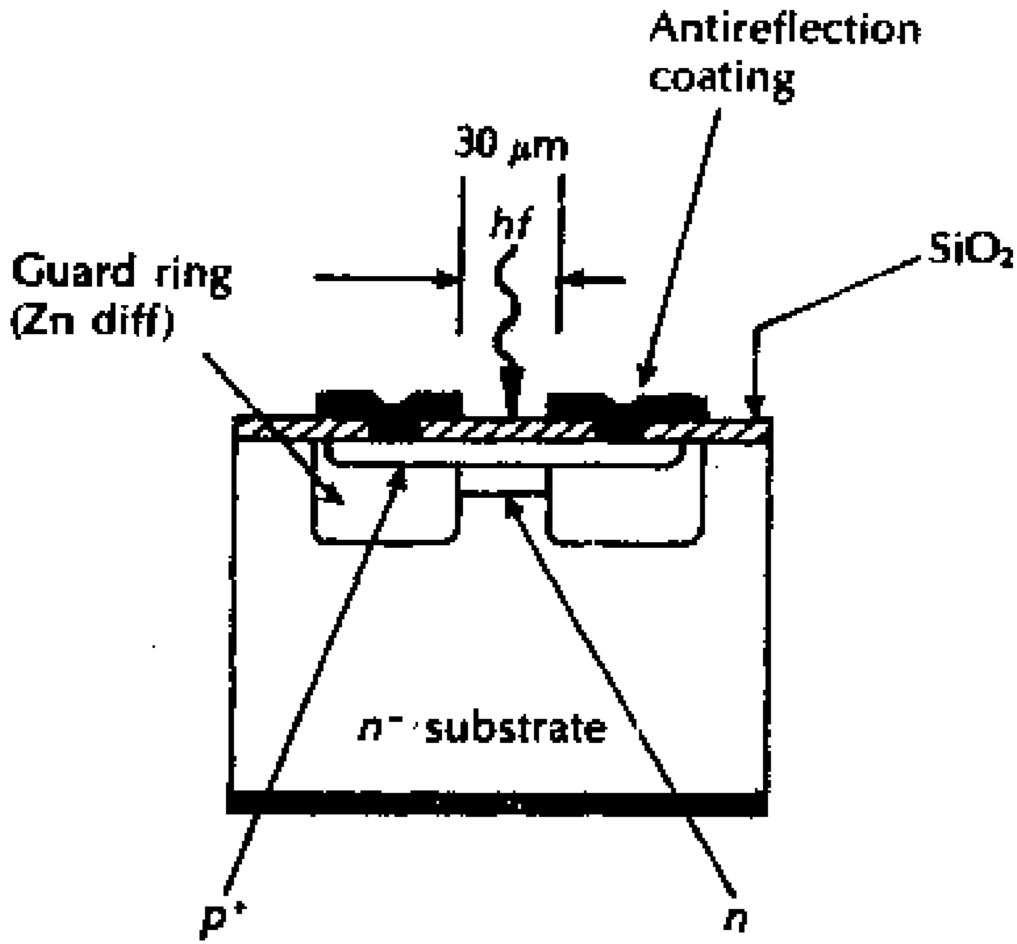
- **Dark current**

  150 to 250 nA 100 µm sensitive area

  5 nA 30 µm sensitive area

- Speed of this structure at 1.5 µm wavelength is poor.(most of abs. outside DL)
- This is overcome by the use of p^+ n n^- structure, also known as Hi –LO structure.

Ge APD-Hi –LO (p^+ nn^-)structure.



Ge APD-Hi –LO ($p^+ nn^-$)structure.

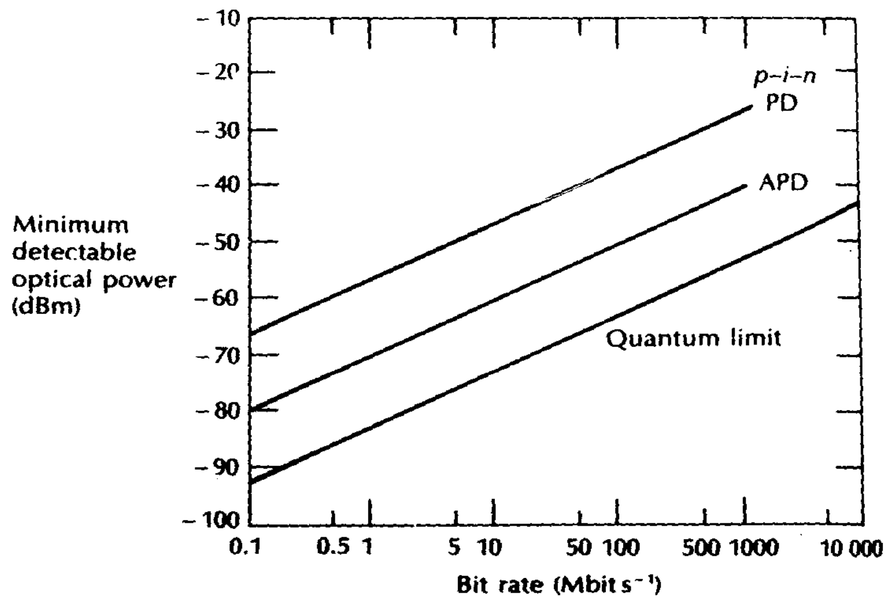
- The above structure resembles the reach thr structure for silicon APD's
- It is called Hi-Lo structure as it combines high bandwidth (700MHz) with low multiplied dark current (33 nA)
- It has good excess noise performance.

Ge APD- Hi-LO ($p^+ nn^-$)structure (contd.)

- **Disadvantage**: Breakdown voltage is higher (85V)

- The Hi-Lo devices are among the highest performing Ge APD’s for longer wavelength operation.

Benefits & Drawbacks-APD



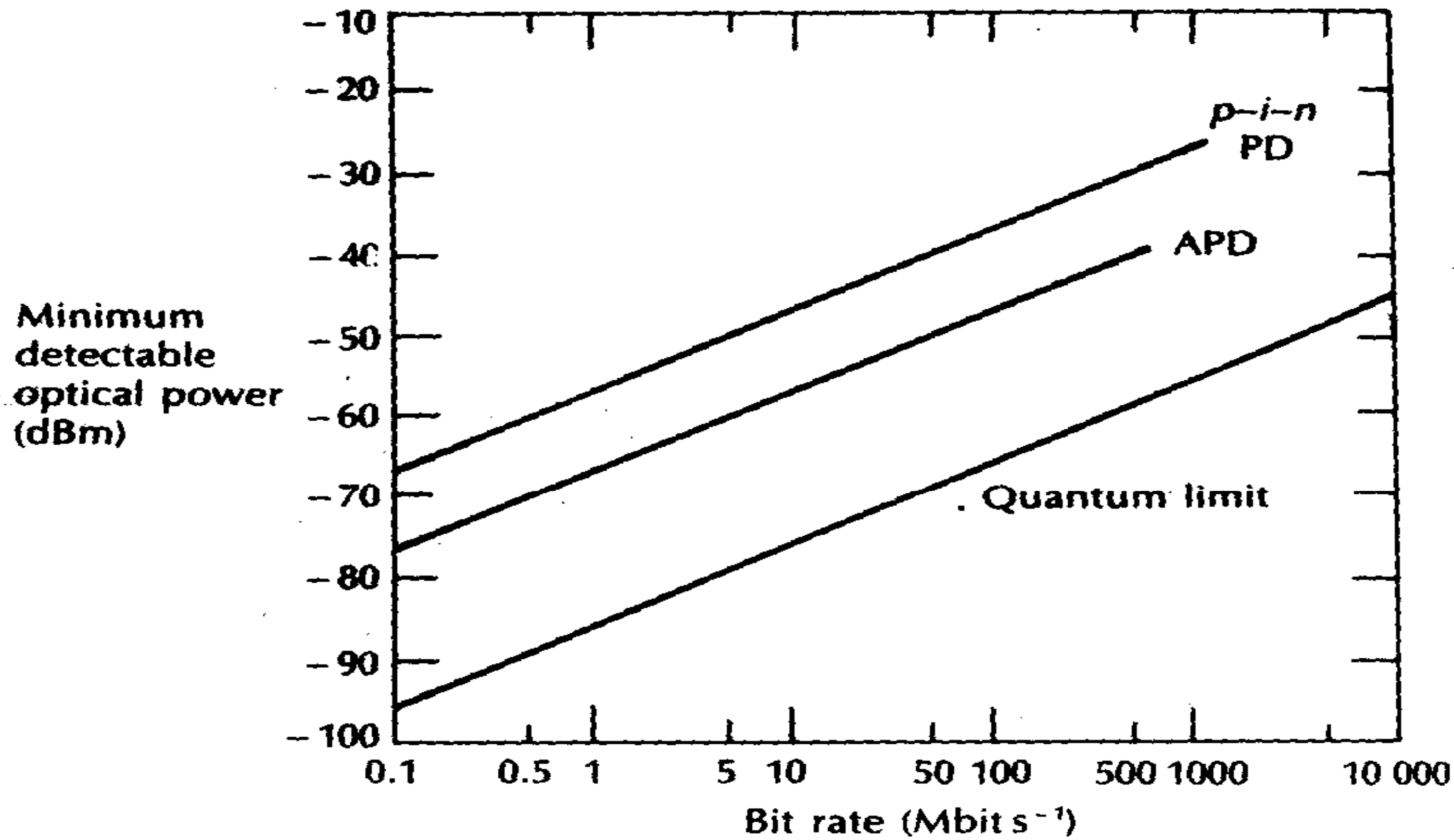
Si Det.

sensitivity at

0.82 µm

Benefits : APD's can detect low light levels

- Increased sensitivity over p-i-n diodes (5 to 15db)
- Wider Dynamic Range (as a result of gain variation with response time & rev. bias)



In GaAs DET at λ=1.55μm

Drawbacks of APD's

- Fabrication difficulty (complex structure)
- Increased cost.
- High bias voltages (50 to 400V)
- Additional Noise (due to random nature of gain mechanism)
- Variation of gain with temp. This requires a temp compensation for stability of operation.