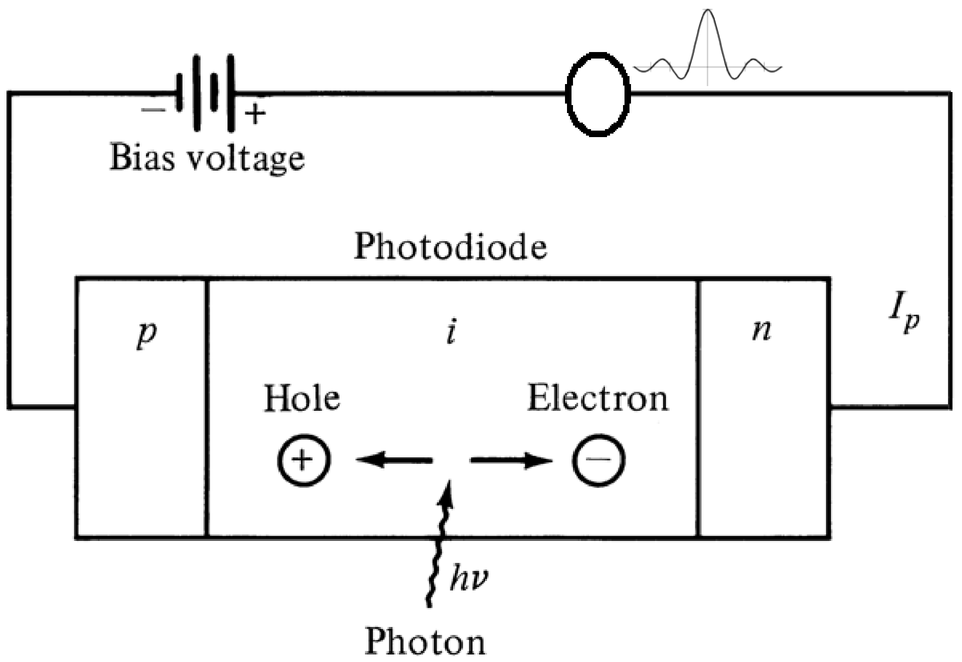
# Topic 25

25. Photo-detectors (1)
    - 25.1 Introduction
    - 25.2 Basic concepts
    - 25.3 Type of photo-detectors
        - 25.4.1 Photoconductors and their characteristics
        - 25.4.2 Photodiodes and their characteristics

# Introduction




- Convert an **optical signal** into an **electrical signal**
  Photo-detector absorbs photons and then generates electrons
  Under applied electric fields, an electrical current is produced
- Photo-detector requires
  (1) high sensitivity and low noise; (2) high efficient conversion;
  (3)Fast response; (4) high reliability

# Basic concepts

- **Quantum efficiency**

$$\eta = \frac{Number\ of\ (e-h)\ generated\ and\ collected}{Number\ of\ incident\ photons} = \frac{I_{ph}/q}{P_0/h\nu}$$

$I_{ph}$: photocurrent; $P_0$: incident optical power

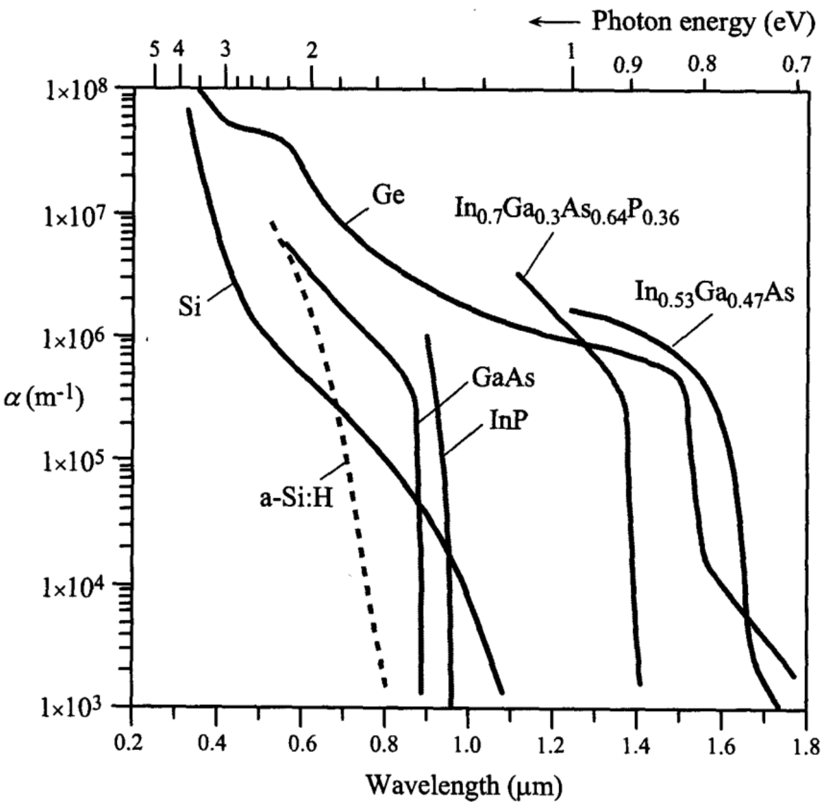
- **Responsivity:**

$$\Re = \frac{Photocurrent\ (\mathrm{A})}{Incident\ Optical\ Power\ (\mathrm{W})} = \frac{I_{ph}}{P_0} = \frac{\eta q}{h\nu} = \frac{\eta\lambda}{1.24}(A/W)$$

- **Quantum efficiency is determined by optical absorption, surface reflectivity and internal quantum efficiency**

  IQE: the number of e-h pairs divided by the number of photons absorbed (normally IQE is very high)

# Absorption Coefficient




- External quantum efficiency is determined by absorption coefficient and the thickness of the absorption region

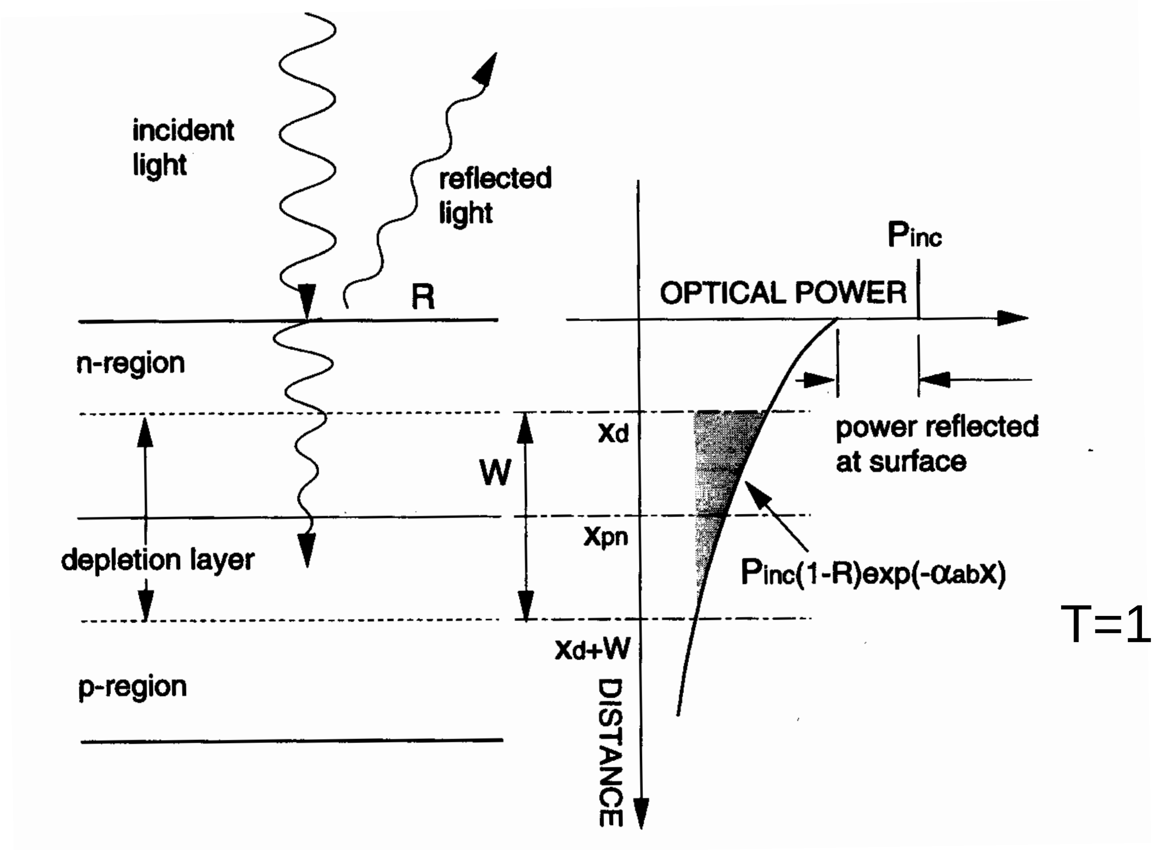
- Optical power absorbed in terms of incident optical power $P_0$

$$\boxed{P(x) = P_0(1 - e^{-\alpha L})}$$

$\alpha$: Absorption coefficient, strongly depending on wavelength. The upper wavelength cutoff is determined by its energy gap

- **For high efficiency need $\alpha L > 1$**

# Reflection and External Quantum Efficiency



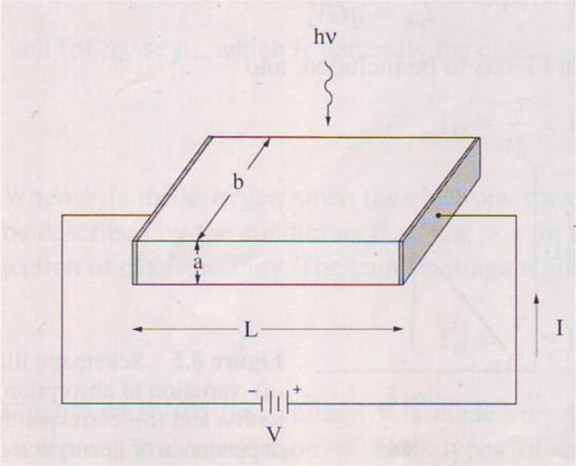

T=1-R

- Reflectivity: $R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$ ~30% of light lost by reflection at the air/semiconductor interface

- The optical power entering the photo-detector: $\boxed{P = P_0(1-R)(1-e^{-\alpha L})}$

# Photo-conductors (i)

1. Structure:
2. Characteristics




Gain $\Gamma$: Recombination rate ($\tau$) and transit time ($t_{tr}$)

Bandwidth: shortest response time

Noise: Johnson and generation-recombination

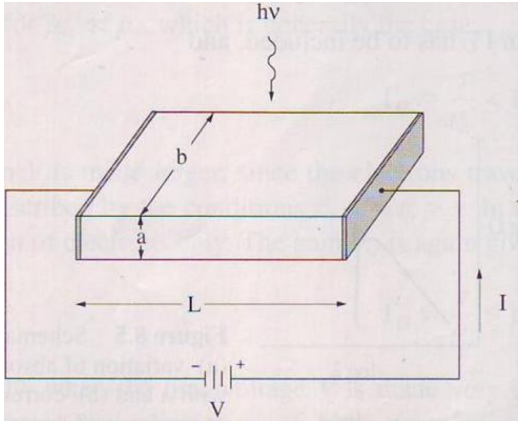
NEP: Noise equivalent power (minimum detectable signal)

Detectivity: 1/NEP

S/N ratio: ratio of signal to noise

# Photo-conductors (ii)

- Photocurrent Gain Γ: $\boxed{\Gamma_G = \dfrac{\tau}{t_{tr}}}$



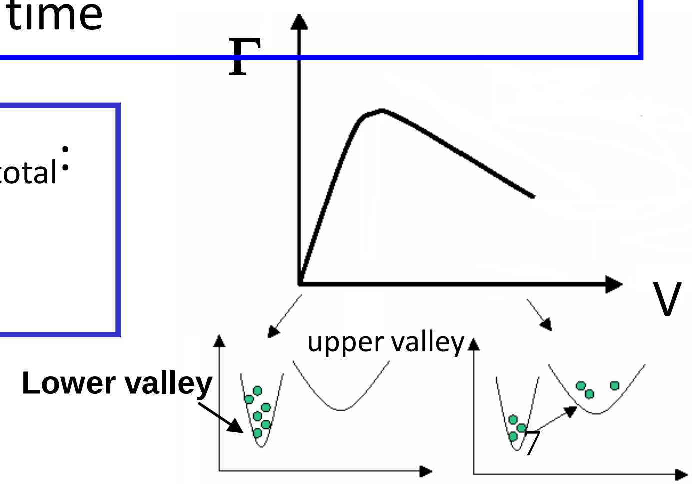

- Bandwidth: determined by transit time
- Transit time: $\boxed{t_{tr} = \dfrac{L}{\upsilon} = \dfrac{L}{\mu E} = \dfrac{L}{\mu \frac{V}{L}} = \dfrac{L^2}{\mu V}}$
- Photocurrent: $\boxed{I_{ph} = q p_{inc} \dfrac{\eta}{h\nu} \Gamma_G = \dfrac{q p \eta}{h\nu} \dfrac{\tau}{t_{tr}}}$

  For ac, extra factor: $\boxed{\dfrac{1}{(1+\omega^2\tau^2)^{1/2}}}$

- Photocurrent: (1) Transit time < recombination time
  (2) Modulated time< response time

- Considering electrons and holes, the total gain $\Gamma_{total}$:

$$\Gamma = \frac{\tau}{t_{tr}} = \frac{\tau}{\boxed{\frac{L^2}{\mu_e V} + \frac{L^2}{\mu_h V}}} = \boxed{\frac{\tau(\mu_e + \mu_h)V}{L^2 \mu_e \mu_h}}$$



# Noise in photo-conductors

Major limit: large dark current and the associated noise

- Johnson (thermal) noise: random motion of carriers (due to $k_BT$) contributing to the dark current

$$\overline{i_j^2} = \frac{4k_B TB}{R_c}$$

2. Generation—recombination noise: fluctuation in the rates of generation and recombination of electron-holes

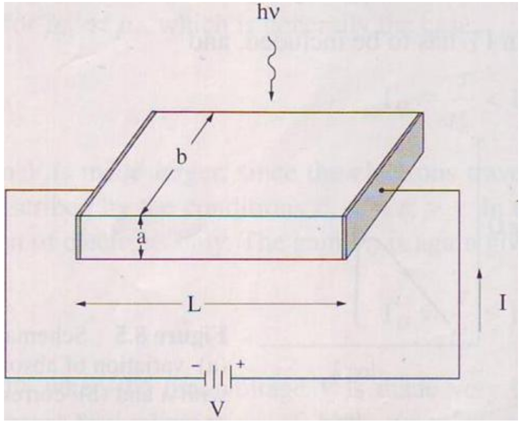
$$\overline{i_{GR}^2} = \frac{4q\Gamma_G I_0 B}{(1+\omega^2\tau^2)}$$

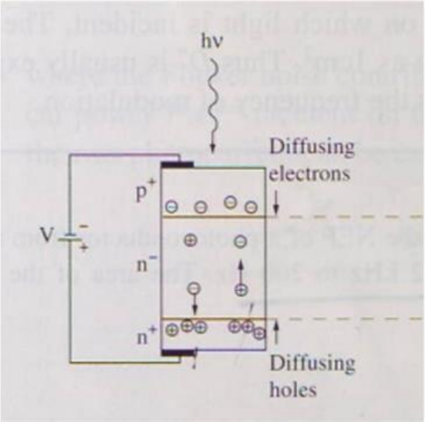
- Noise equivalent power (NEP): **minimum detectable signal,** where signal is equal to noise at a band width of 1 Hz

- Detectivity: 1/NEP

- S/N ratio: $\frac{S}{N} = \frac{\overline{i_{ph}^2}}{\overline{i_J^2} + \overline{i_{GR}^2}}$

# Photodiodes

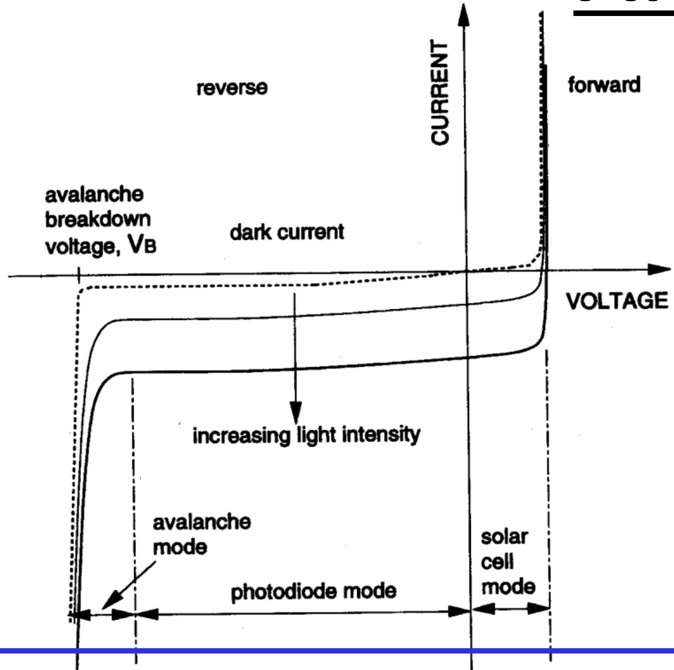



**It would be easy to understand if you understand the difference between a photoconductor and a photodiode**

- **Photoconductors:** single layer, and does not involve p-n junction
- **Junction diodes:** p and n doped layers
  (1) PIN diode
  (2) Avalanche diode

# PIN photodiode




Un-doped i region sandwiched by n and p-doped regions

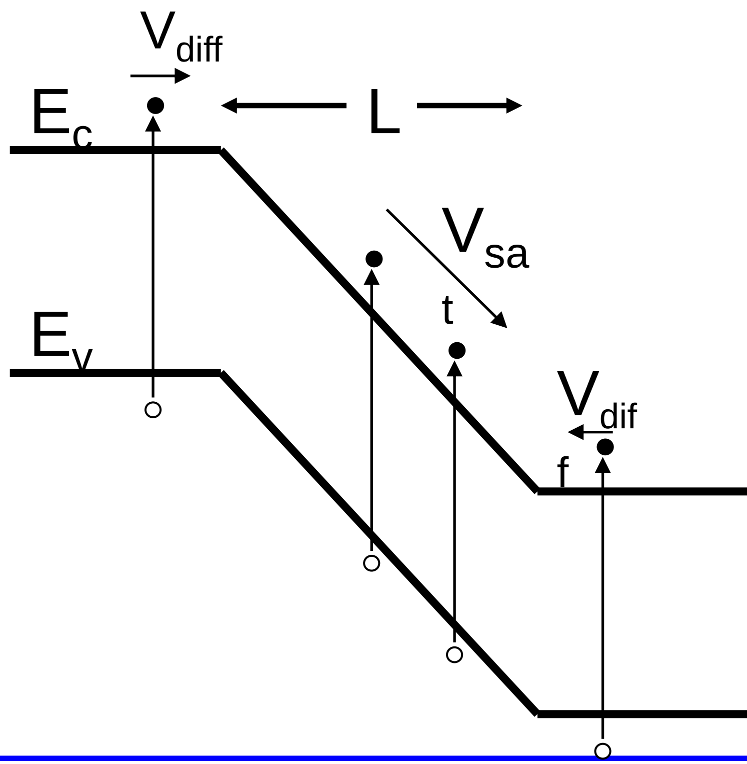
(1) i region: low carrier density and high resistivity
(2) Any applied bias almost across the i-region

- Operation mechanism: like LED in reverse!
- PIN diode with large forward bias is an LED

- **i region**: Determine the transit time, which actually determines **response and thus bandwidth**
- **Reverse bias**: high enough in order to make electron and hole drift at **saturation velocity ($V_{sat}$)** ~$10^5$m/s
- You can reduce i-region thickness in order to reduce transit time.

**PIN is used for the application of a large bandwidth.**

# Photocurrent

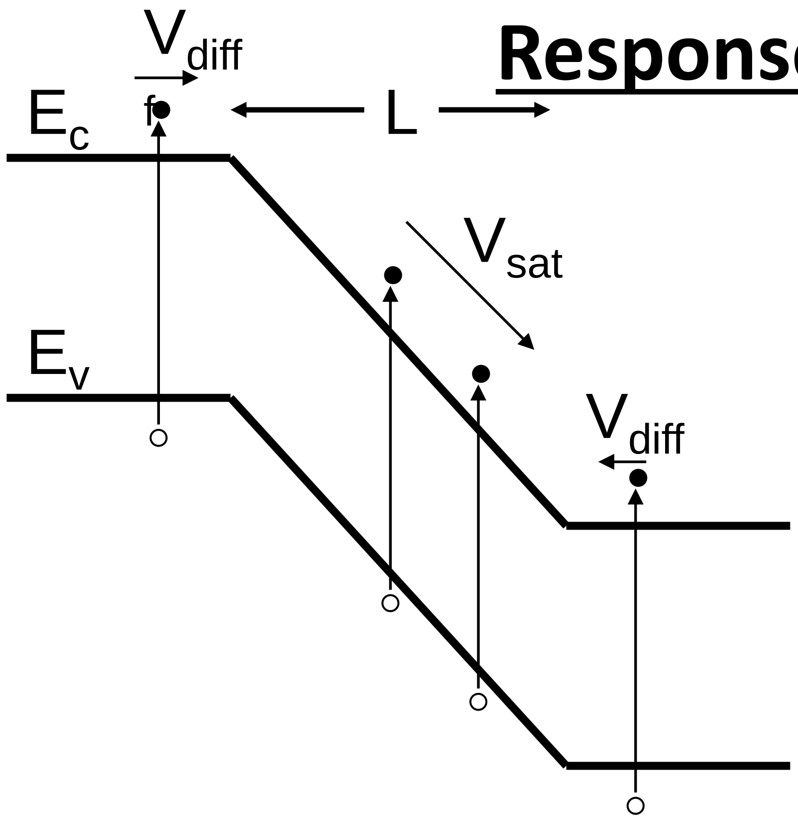


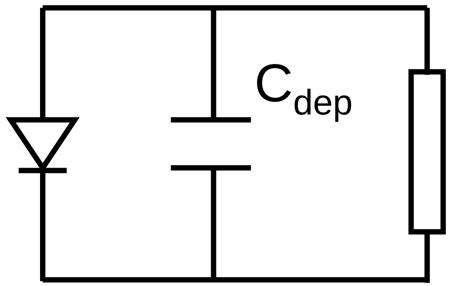

- Further reduce response time and then increase bandwidth:

  (1) Minority carriers in doped regions: diffuse into intrinsic region (**slow**), and needs to be minimised

  (2) Minimise minority diffusion in three ways: (1) junction should be close surface (2) use of different materials; (3)wide i region (also leads to long **transit time, not ideal**);

# Response Time




- Transit Time for carriers across reverse biased diode

  **$t_c = L/V_{sat}$;** $V_{sat}$ ~$10^5$m/s; **L ~μms**

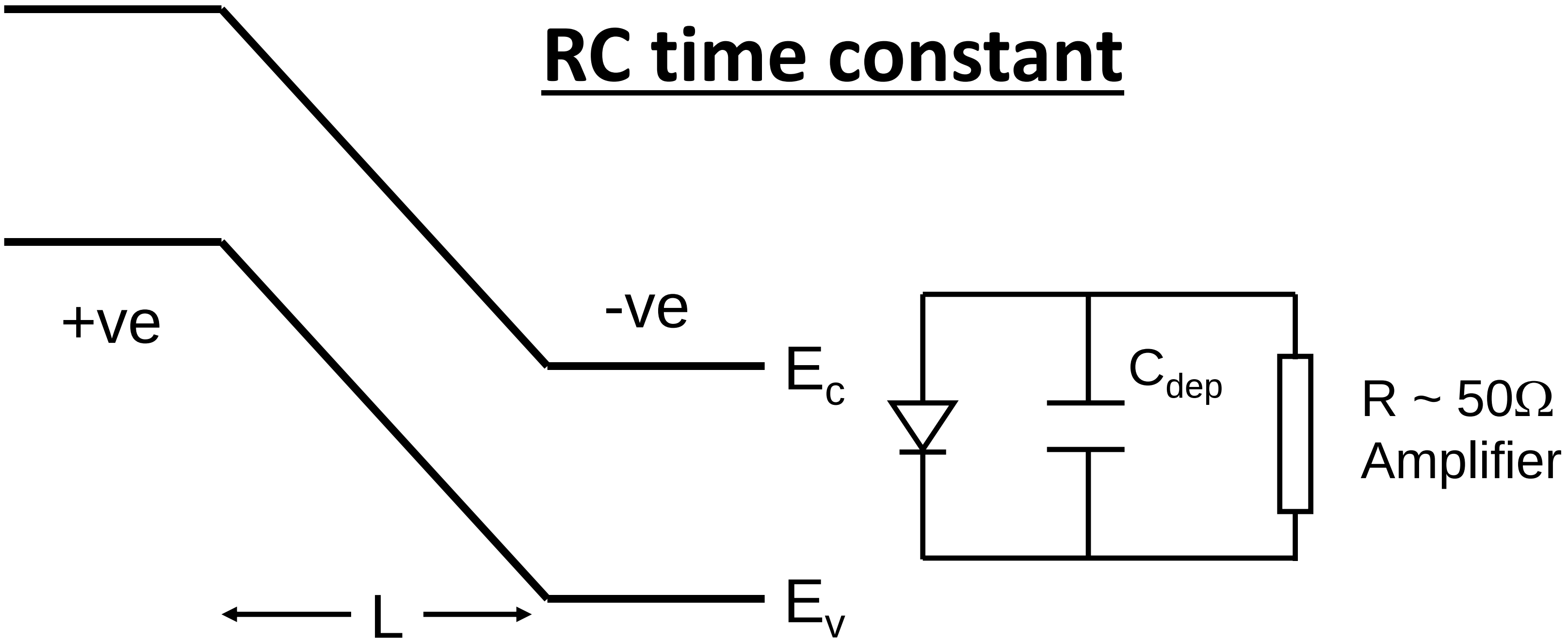
- **Maximum bandwidth:**

  determined by the transit time, giving **~GHz operation (~$1/t_{tr}$)**

- **Need to consider** junction capacitance:

  determined by the capacitor characteristic time, if it is longer than the transit time, giving **(~$1/t_{RC}$)**

# RC time constant




- Need to consider junction capacitance
- Have a reverse bias, separated by a distance L; A is the PIN area

**$C \sim \varepsilon\varepsilon_0 A/L$**

- In order to obtain a short RC time, you need to have small A and long L

**But:** **A small area A** leads to reduced absorption
**A long L** leads to long transit time

# Response Time Example

**Estimate maximum bandwidth:**

Considering InGaAs ($\varepsilon$= 12) photodiode; (1) 10um thick i-region; (2) optical window in a 200um diameter; (3) Saturation velocity = $10^5$ m/s; (4) Driving a preamplifier with 50 $\Omega$ impedance

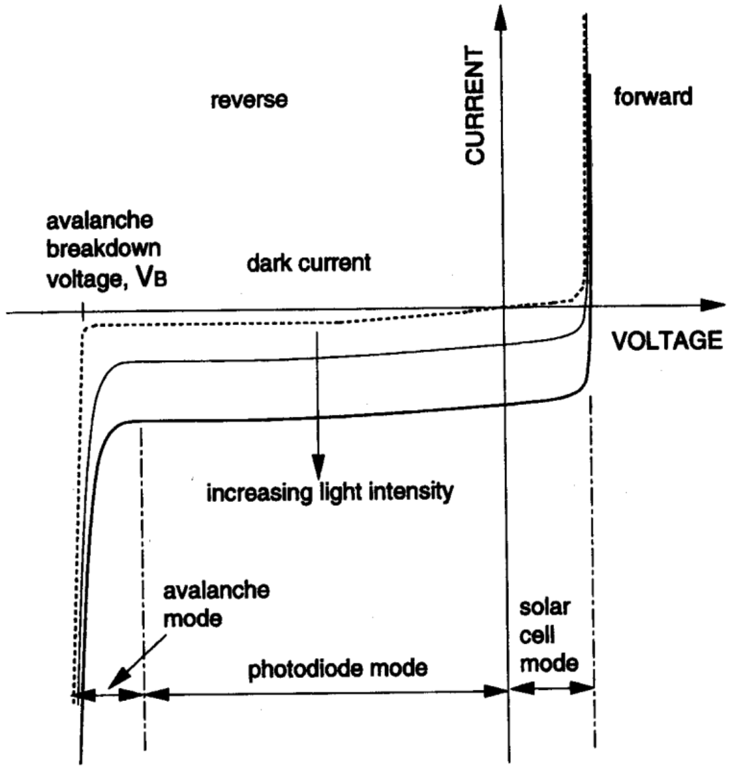
- Transit time = $L/v = 10 \times 10^{-6} / 10^5 = 1 \times 10^{-10}$ s = 0.1ns

- $C = \varepsilon\varepsilon_0 A/L = 12 \times 8.85 \times 10^{-12} \times \pi \times (100 \times 10^{-6})^2 / 10 \times 10^{-6} = 0.33$pF

Therefore, RC = 0.017ns

However, response time of photodiode is limited by carrier capture (transit time) to 0.1ns. f~ 10GHz

# Noise Performance




- **The noise level (dark current)t is very small** (operated under reverse bias)

**PIN is used for the application of a low noise**

- Shot-noise (generation-recombination): small compared with photoconductors

- Johnson noise: dominate, but can be minimised through optimising circuit parameters

# Noise – Quantum and Thermal (i)

**Quantum Noise (Shot Noise)**

(1) Photo-induced carriers are produced randomly when photons are absorbed
(2) Motion of these carriers is also random –

$$\overline{i_{sn}^2} = 2q\bar{I}B_{bw} \Rightarrow \overline{i_{sn}^2} = 2q(I_{ph} + I_d + I_{bg})B_{bw}$$

**Thermal Noise (Johnson Noise)**

Random motion of carriers with a distribution of thermal energy produces a noise in the current and hence a noise voltage over a resistor

White noise $$\overline{i_{jn}^2} = \frac{4k_B T B_{bw}}{R_{eq}}$$

At low frequencies, 1/f noise is important but ignored here

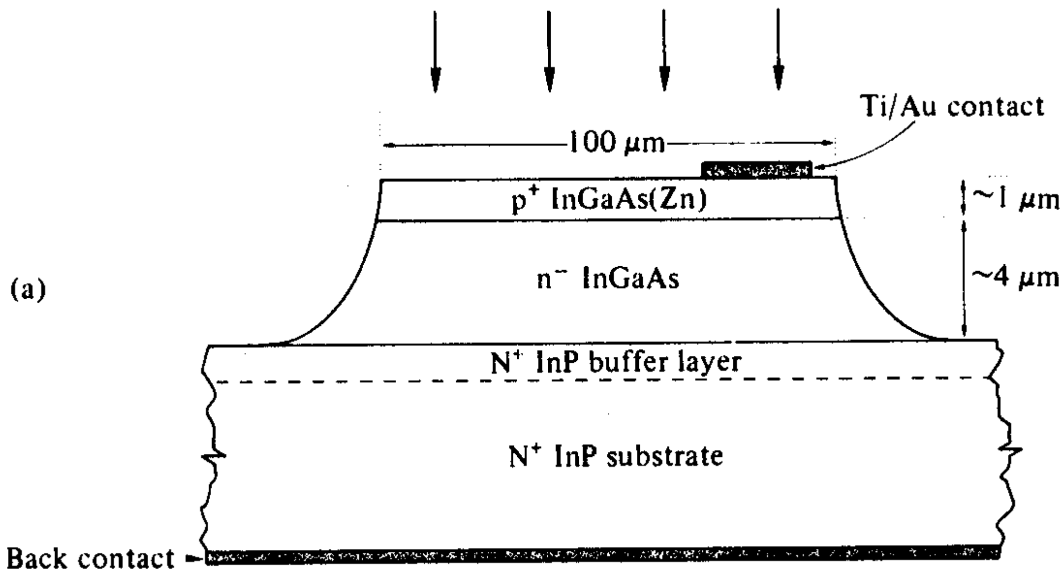
# Signal to Noise (Power) Ratio

$$\frac{S_{rms}^{pp}}{N_{rms}} = \frac{\overline{i_{ph}^{2}}}{(\overline{i_{sn}^{2}} + \overline{i_{jn}^{2}})}$$

•Noise Equivalent Power (NEP): **minimum detectable signal,** often used to characterize responsivity.

•NEP: the input rms optical power per unit Bandwidth at which the photocurrent is equal to the noise current and corresponds to the minimum optical power detectable.

# Examples of Device Structure




**Top entry**

- Diffused thin p doped region (avoids diffusion effects)
- Mesa etched to small size – limit C

$\alpha = 10^6$/m

$\alpha L = 5$ , $\eta_{int} = 99\%$

$T_{tr} = 4x10^{-6} / 10^5 =$ 40ps ~25GHz

# Summary – Topic 25

- A diode in reverse bias
- Efficiency of a photodiode is a function of the external (reflectivity of device) and internal efficiency (thickness of absorption region)
- Frequency response has two limits – transit time needs to be short (small absorption/i-region thickness), and low C (high i-region thickness)
- Noise (NEP) determines the SNR and hence minimum receiver power is required in a lightwave system

# Tutorial Questions

T25.1 Calculate the current gain of a photoconductor

T25.2 Sketch the construction of a pin photodiode and the shape of its band-edge structure when the diode is reverse biased. Describe the principles of photocurrent production and the factors which determine efficiency and speed. Explain how the length of the depletion region must be chosen as a compromise for these important device parameters.

T25.3 What is the effect of elevated temperature on a p-i-n photodetector? What effect will this have on system performance?