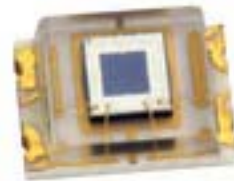


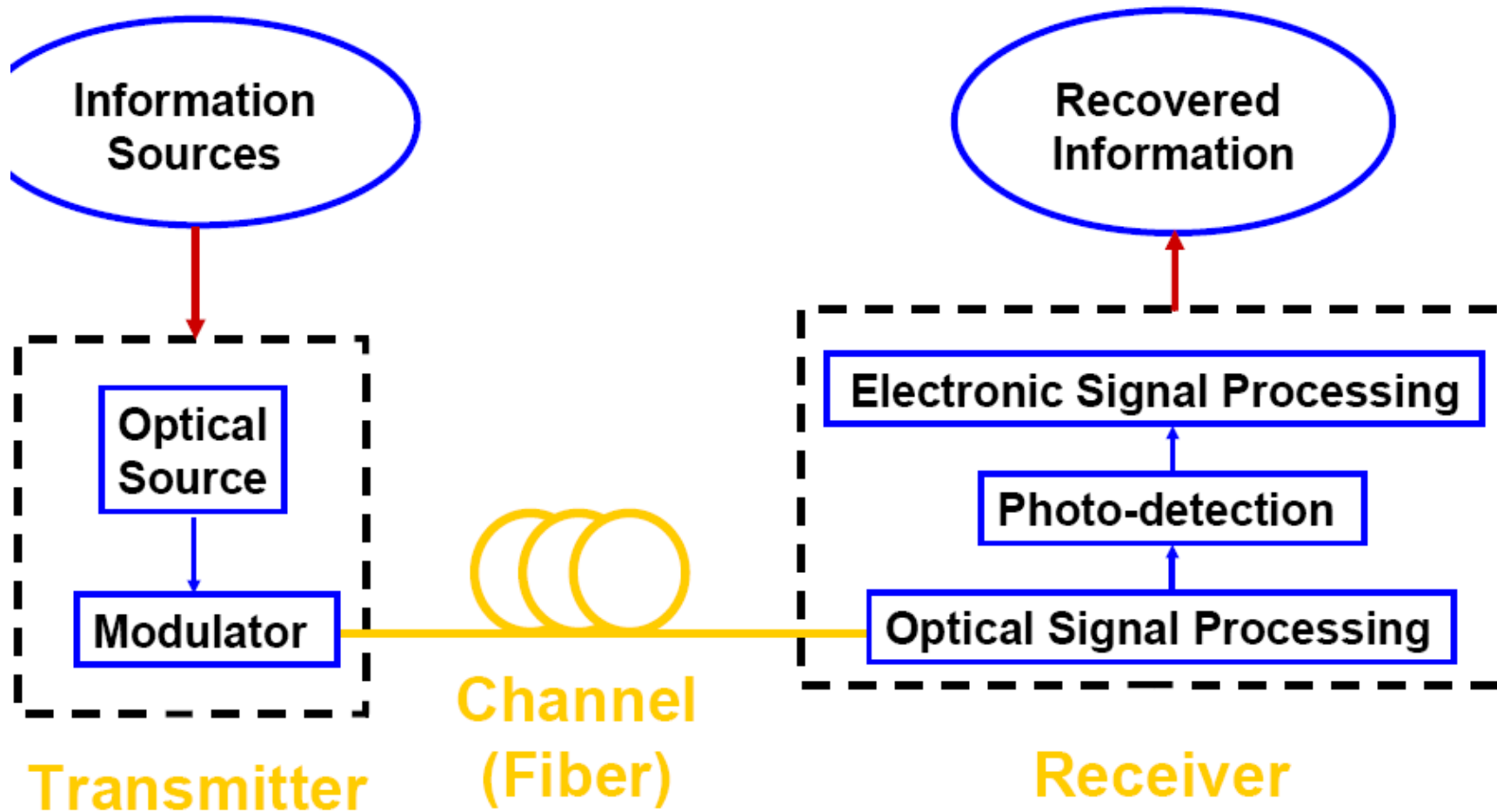
# Photodetectors

## Photodiodes

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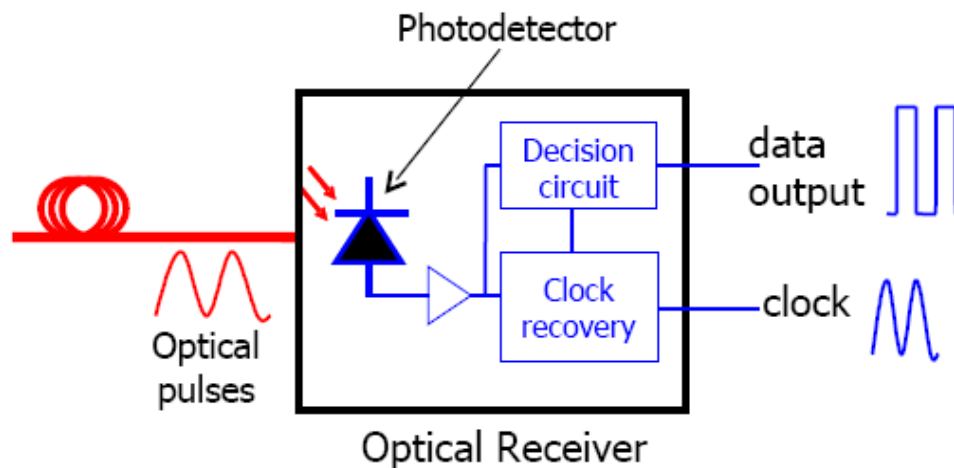


# 1. Introduction



## 4. Photodetector

- ❑ Convert an optical signal into an electrical signal
  - **Photodetectors** made of semiconductor materials **absorb** incident photons and produces electrons
  - If electric field imposed on photodetector an electric current (**photocurrent**) is produced  $\Rightarrow$  **photodiode**



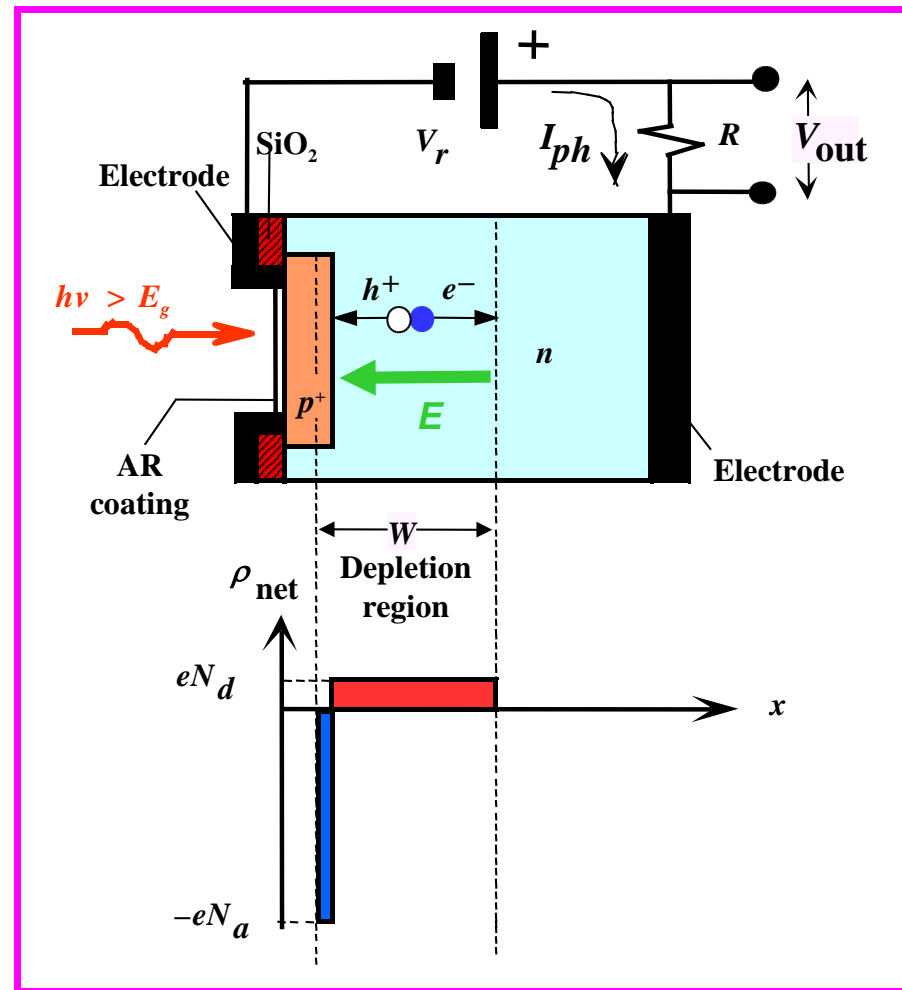
## 4. Photodetector

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- ❑ Basic requirements of a photodetector
  - **Sensitivity** at the required wavelength
  - **Efficient conversion** of photons to electrons
  - **Fast response** to operate at high frequencies
  - **Low noise** for reduced errors
  - **Sufficient area** for efficient coupling to optical fiber
  - **High reliability**
  - **Low cost**

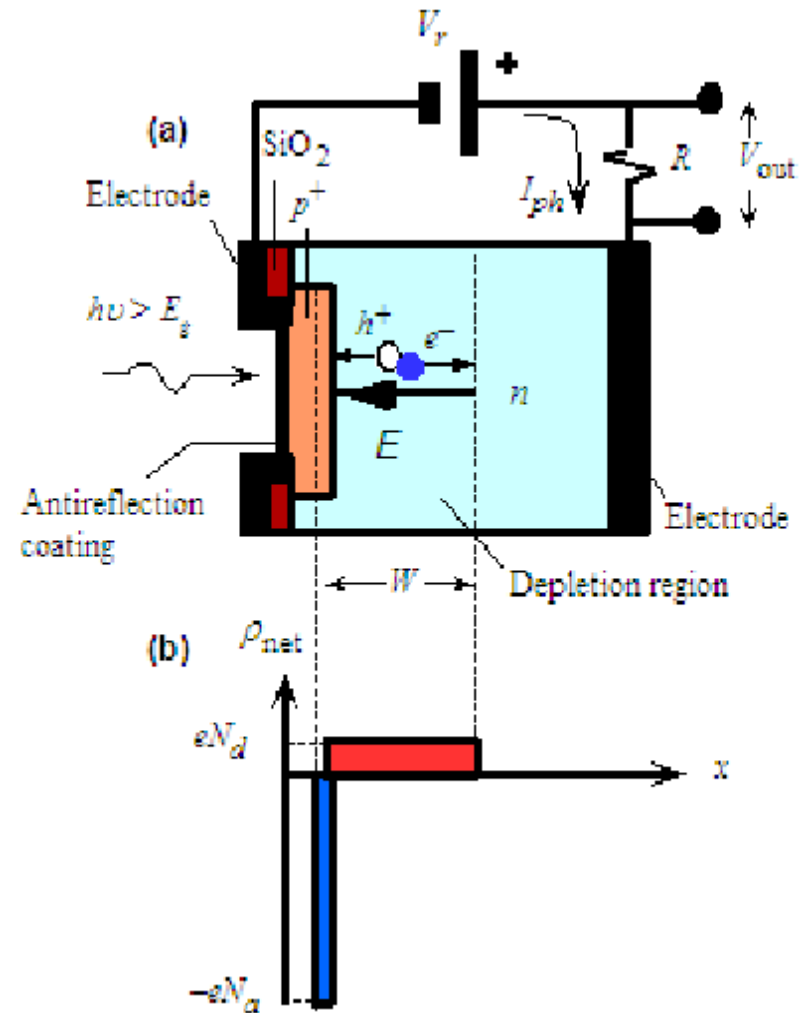
# Photo-detectors: Principle of the P-N junction photo-diode

- ❑ Schematic diagram of a **reverse biased p-n junction photodiode**
  - Photocurrent is depend on number of EHP and drift velocity.
  - The electrode do not inject carriers but allow excess carriers in the sample to leave and become collected by the battery.
- ❑ **Net space charge** across the diode in the depletion region.  $N_d$  and  $N_a$  are the donor and acceptor concentrations in the  $p$  and  $n$  sides.



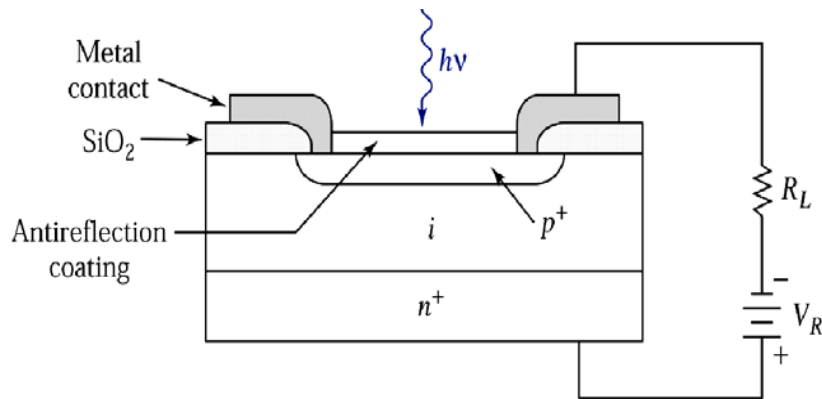
# Principle of *pn* junction photodiode

- (a) **Reversed biased** *pn* junction photodiode.
- Annular electrode to allow photon to enter the device.
  - Anti-reflection coating ( $\text{Si}_3\text{N}_4$ ) to reduce the reflection.
  - The  $p^+$ -side thickness **< 1  $\mu\text{m}$** .
- (b) Net space charge distribution, within SCL.

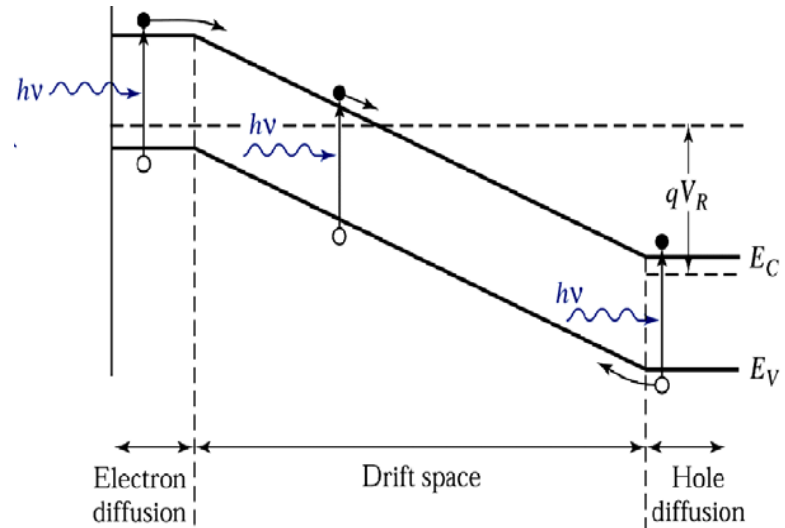


# Photo-detectors: Principle of the p-n junction Photo-diode

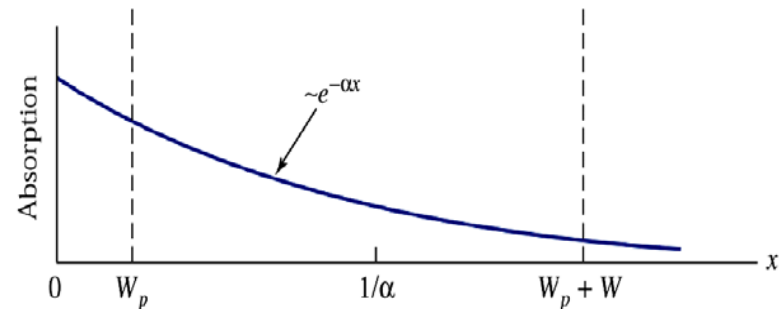
## ❑ Operation of a photo-diode



(a) Cross-section view of a photo-diode



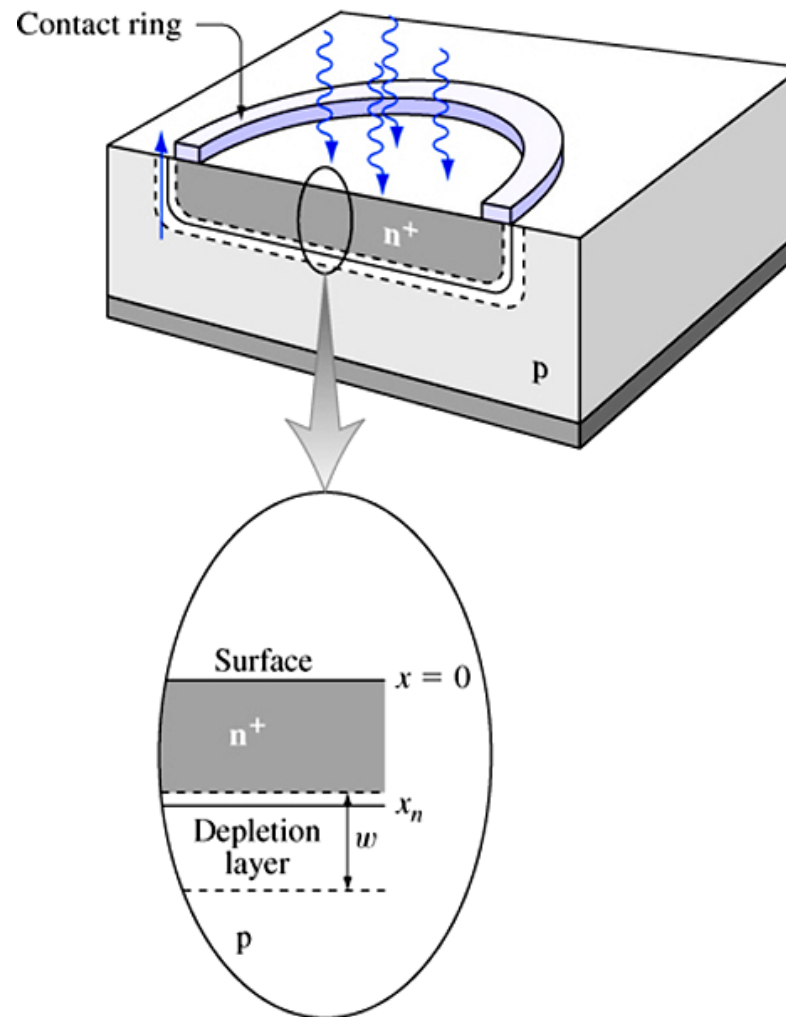
(b) Energy band diagram under reverse bias.



(c) Carrier absorption characteristics.

# Photodetectors: Principle of the p-n junction Photo-diode

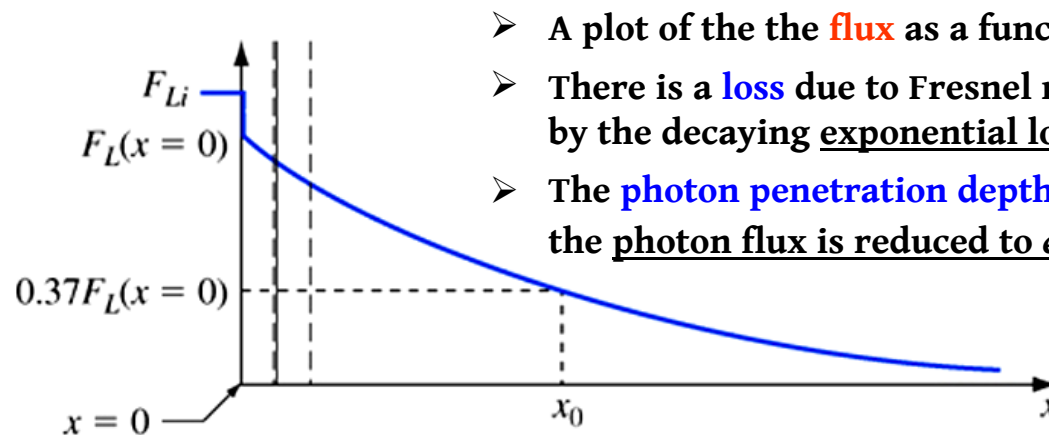
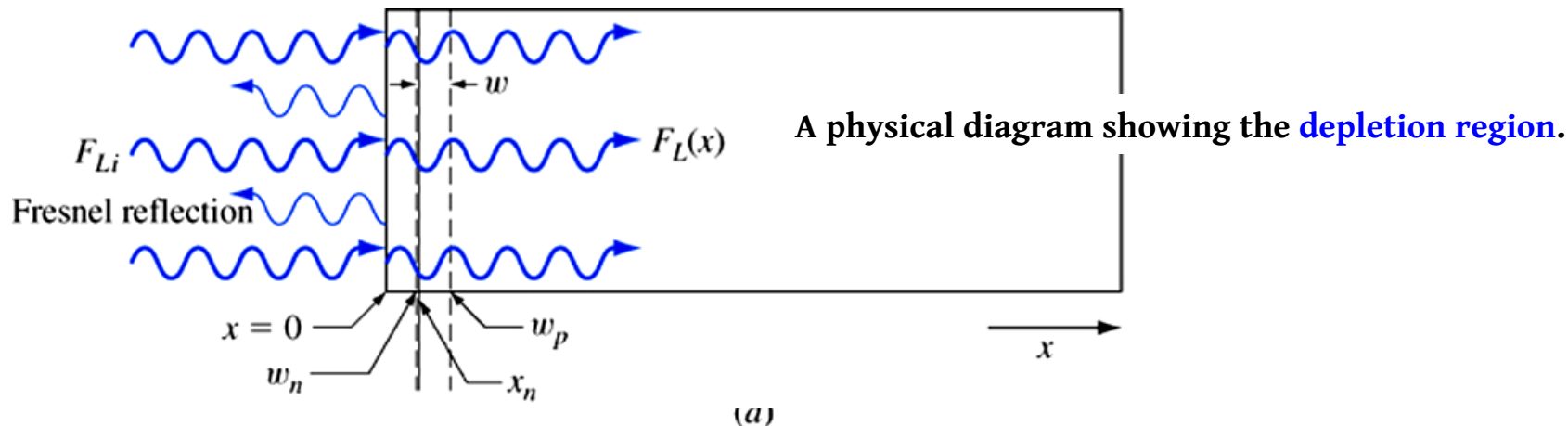
## □ A generic photo-diode





# Photodetectors: Principle of the p-n junction Photo-diode

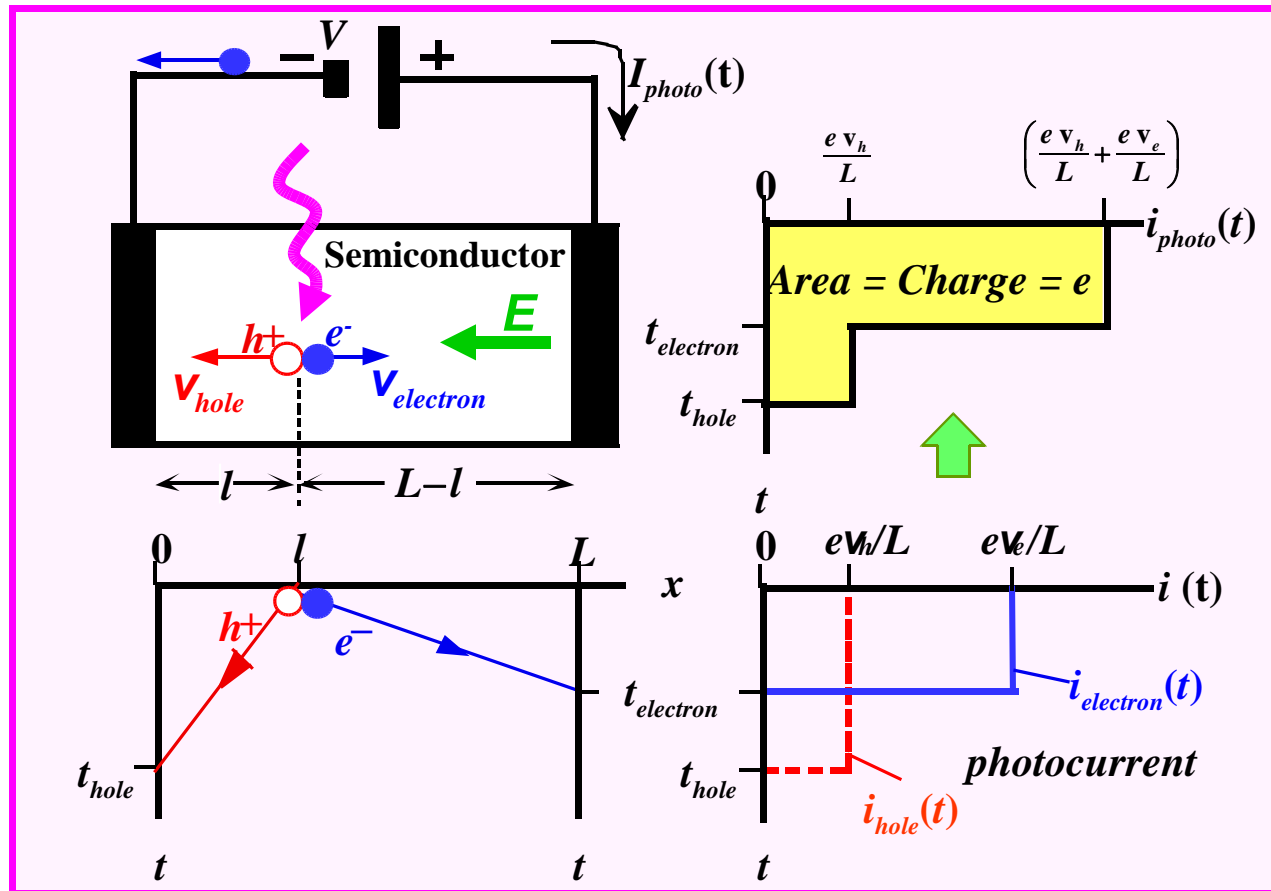
## □ Variation of photon flux with distance.



- A plot of the the **flux** as a function of distance.
- There is a **loss** due to Fresnel reflection **at the surface**, followed by the decaying exponential loss due to absorption.
- The **photon penetration depth**  $x_0$  is defined as the depth at which the photon flux is reduced to  $e^{-1}$  of its surface value.

# Photo-detectors: RAMO's Theorem and External Photo-current

- An EHP is photogenerated at  $x = l$ . The electron and the hole drift in opposite directions with drift velocities  $v_h$  and  $v_e$ .
- The electron arrives at time  $t_{electron} = (L-l)/v_e$  and the hole arrives at time  $t_{hole} = l/v_h$ .



# Photo-detectors: RAMO's Theorem and External Photo-current

- As the electron and hole drift, each generates  $i_{electron}(t)$  and  $i_{hole}(t)$ .
- The total photocurrent is the sum of hole and electron photocurrents each lasting a duration  $t_h$  and  $t_e$  respectively.

$$t_e(t) = \frac{L-l}{v_e} \quad \text{and} \quad t_h(t) = \frac{l}{v_h} \quad \text{Transit time}$$

$$\text{Work done} = e \cdot E dx = V \cdot i_e(t) dt$$

$E = \frac{V}{L} \quad v_e = \frac{dx}{dt}$

$$i_e(t) = \frac{e v_e}{L}; \quad t < t_e \quad i_h(t) = \frac{e v_h}{L}; \quad t < t_h \quad \text{Photocurrent}$$

$$Q_{collected} = \int_0^{t_e} i_e(t) dt + \int_0^{t_h} i_h(t) dt = e \quad \text{The collected charge is not } 2e \text{ but just "one electron".}$$

If a charge  $q$  is being drifted with a velocity  $v_d(t)$  by a field between two biased electrodes separated by  $L$ , the motion of  $q$  generates an external current given by

$$i(t) = \frac{e v_d(t)}{L}; \quad t < t_{transit} \quad \text{Ramo's Theorem}$$

# Photo-detectors: Absorption Coefficient & Photo-diode Materials

- ❑ Absorbed Photon create Electron-Hole Pair.

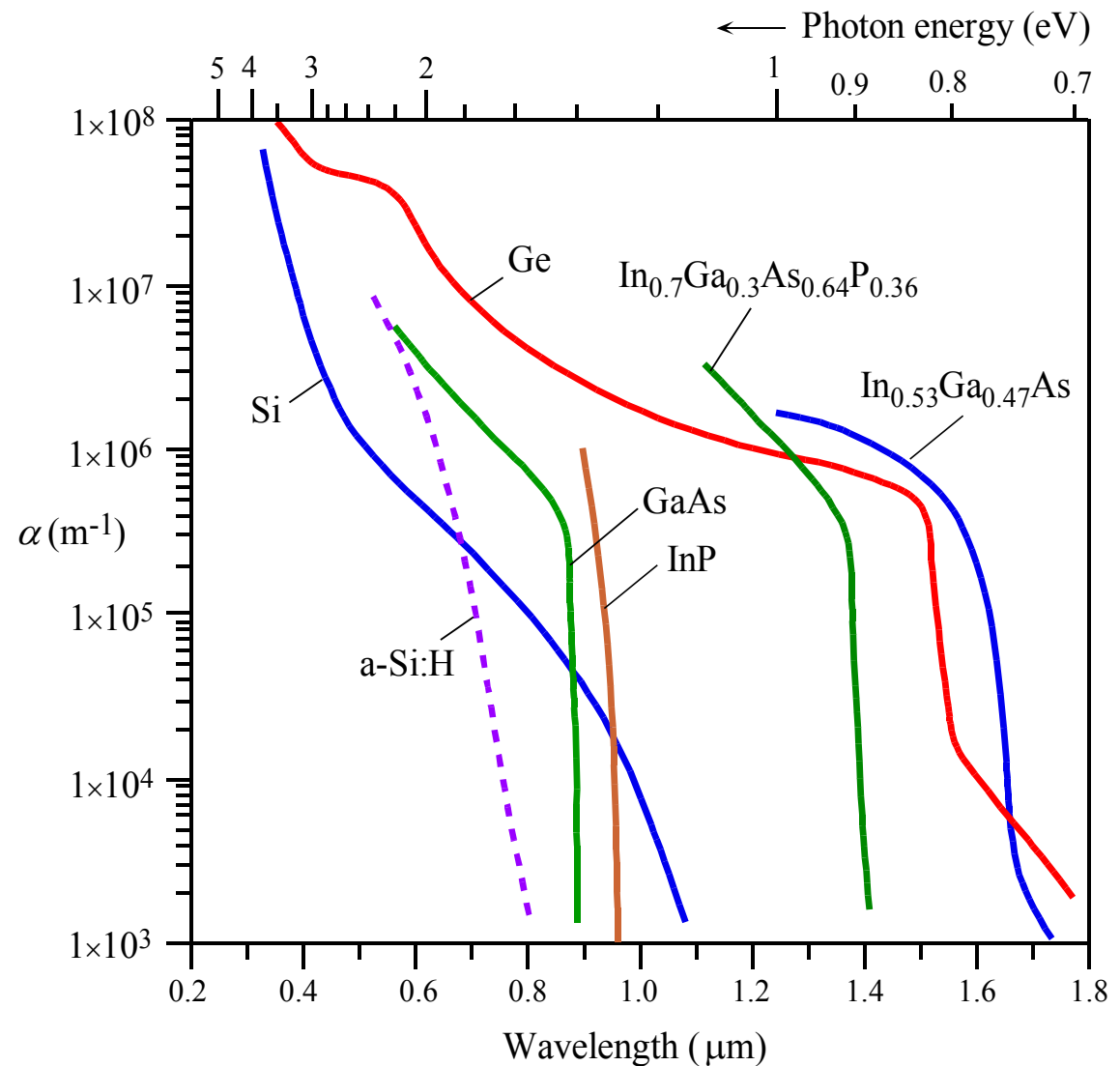
$$\lambda_g [\mu m] = \frac{1.24}{E_g [eV]} \quad \text{Cut-off wavelength vs. Energy bandgap}$$

- ❑ Incident photons become absorbed as they travel in the semiconductor and light intensity decays exponentially with distance into the semiconductor.

$$I(x) = I_0 \cdot e^{-\alpha x} \quad \text{Absorption coefficient}$$

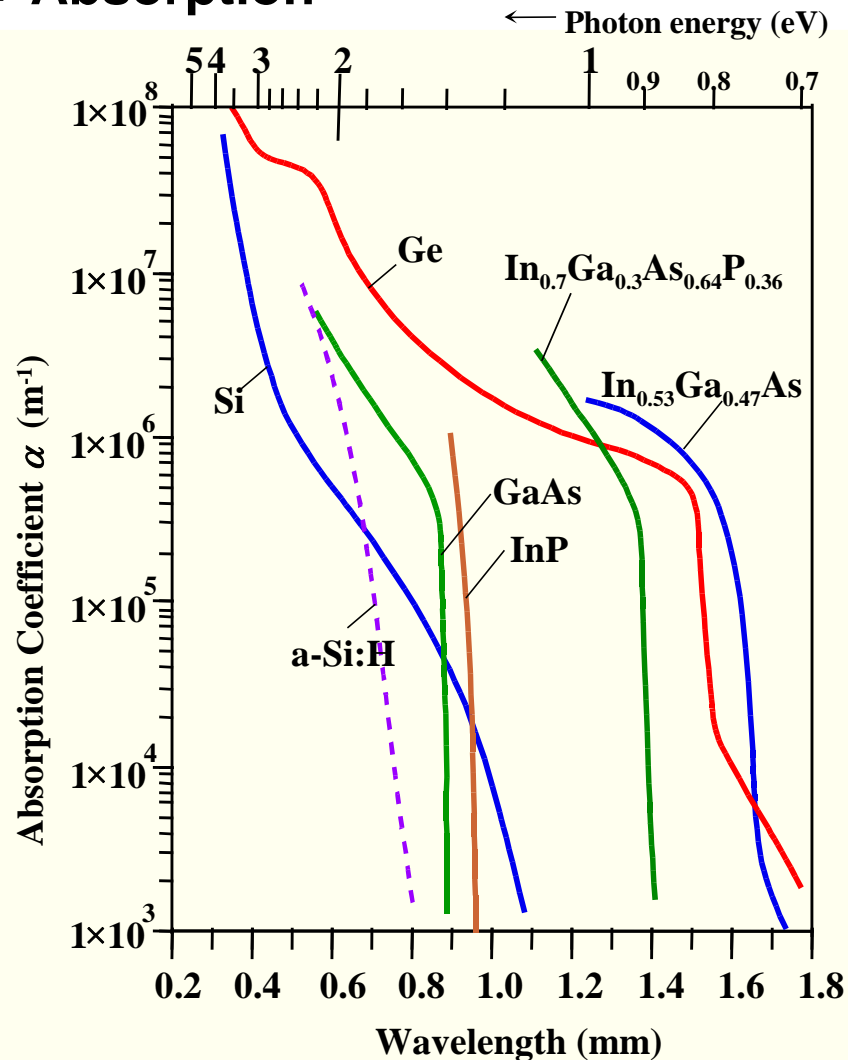
# Absorption Coefficient

- Absorption coefficient  $\alpha$  is a material property.
- Most of the photon absorption (63%) occurs over a distance  $1/\alpha$  (it is called **penetration depth  $\delta$** )

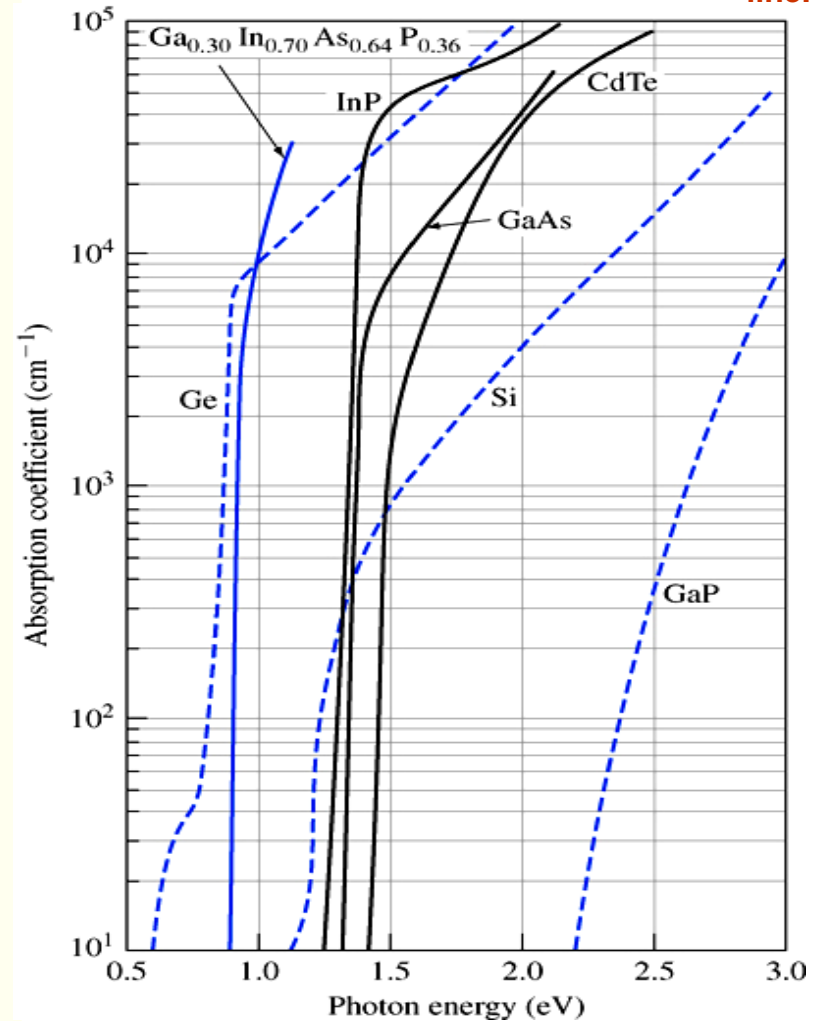


# Photo-detectors: Absorption Coefficient & Photo-diode Materials

## □ Absorption

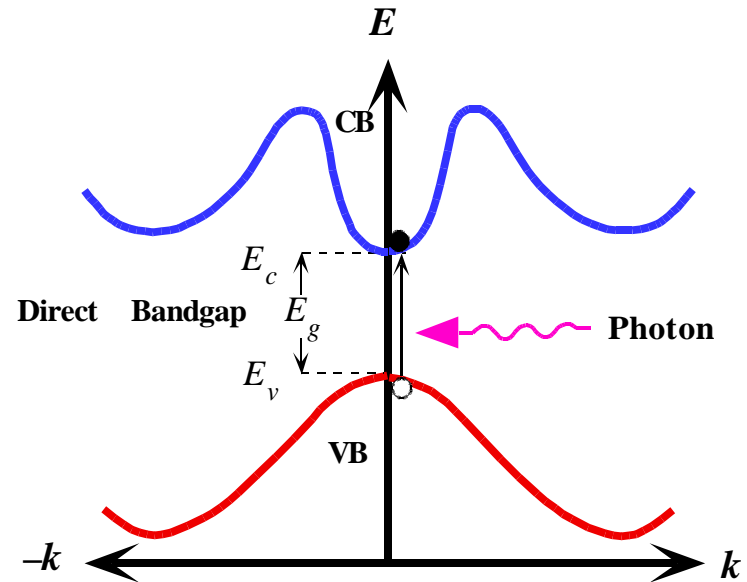


The indirect-gap materials are shown with a broken line.



# Absorption Coefficient

- Direct bandgap semiconductors (GaAs, InAs, InP, GaSb, InGaAs, GaAsSb), the photon absorption **does not require assistant from lattice vibrations**. The photon is absorbed and the electron is excited directly from the VB to CB without a change in its k-vector (crystal momentum  $\hbar k$ ), since photon momentum is very small.



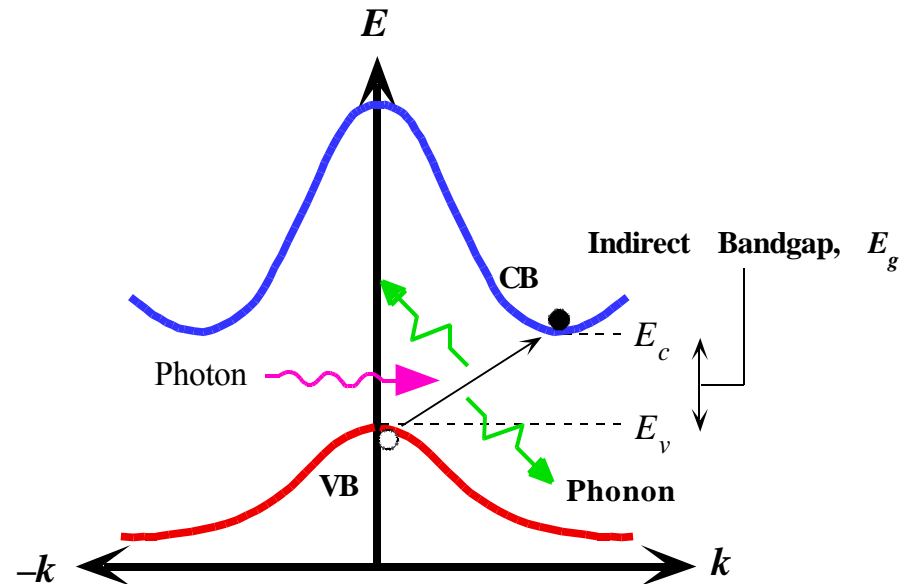
(a) GaAs (Direct bandgap)

$$\hbar k_{CB} - \hbar k_{VB} = \text{photon momentum} \approx 0$$

- Absorption coefficient  $\alpha$  for direct band-gap semiconductors rise sharply with decreasing wavelength from  $\lambda_g$  (GaAs and InP).

# Absorption Coefficient

- Indirect band-gap semiconductors (Si and Ge), the photon absorption **requires assistant from lattice vibrations (phonon)**. If  $K$  is wave vector of lattice wave, then  $\hbar K$  represents the momentum associated with lattice vibration  $\rightarrow \hbar K$  is a **phonon momentum**.



(b) Si (Indirect bandgap)

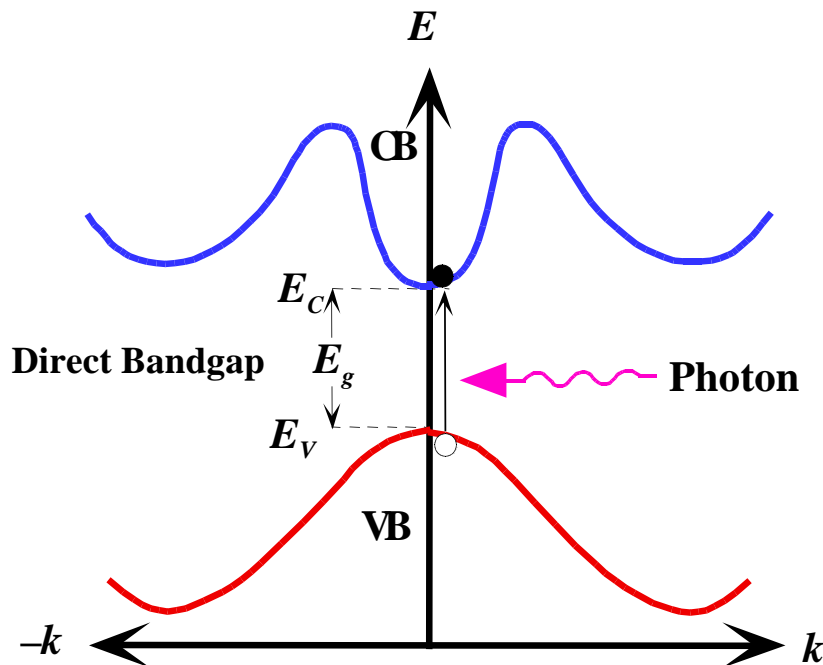
$$\hbar k_{CB} - \hbar k_{VB} = \text{phonon momentum} = \hbar K$$

- Thus the probability of photon absorption is not as high as in a direct transition and the  $\lambda_g$  is not as sharp as for direct band-gap semiconductors.

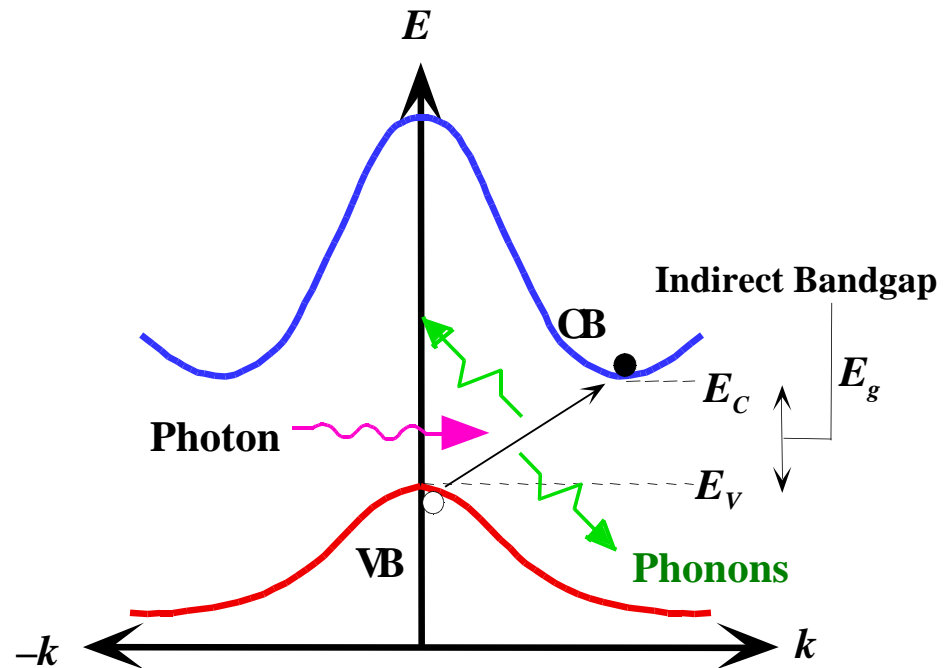


# Photo-detectors: Absorption Coefficient & Photo-diode Materials

Photon absorption in a **direct bandgap** semiconductor.



Photon absorption in an **indirect bandgap** semiconductor



# Photo-detectors: Quantum Efficiency and Responsivity

## ❑ External Quantum Efficiency

$$\eta = \frac{\text{Number of EHP generated and collected}}{\text{Number of incident photons}} = \frac{I_{ph}/e}{P_0/h\nu}$$

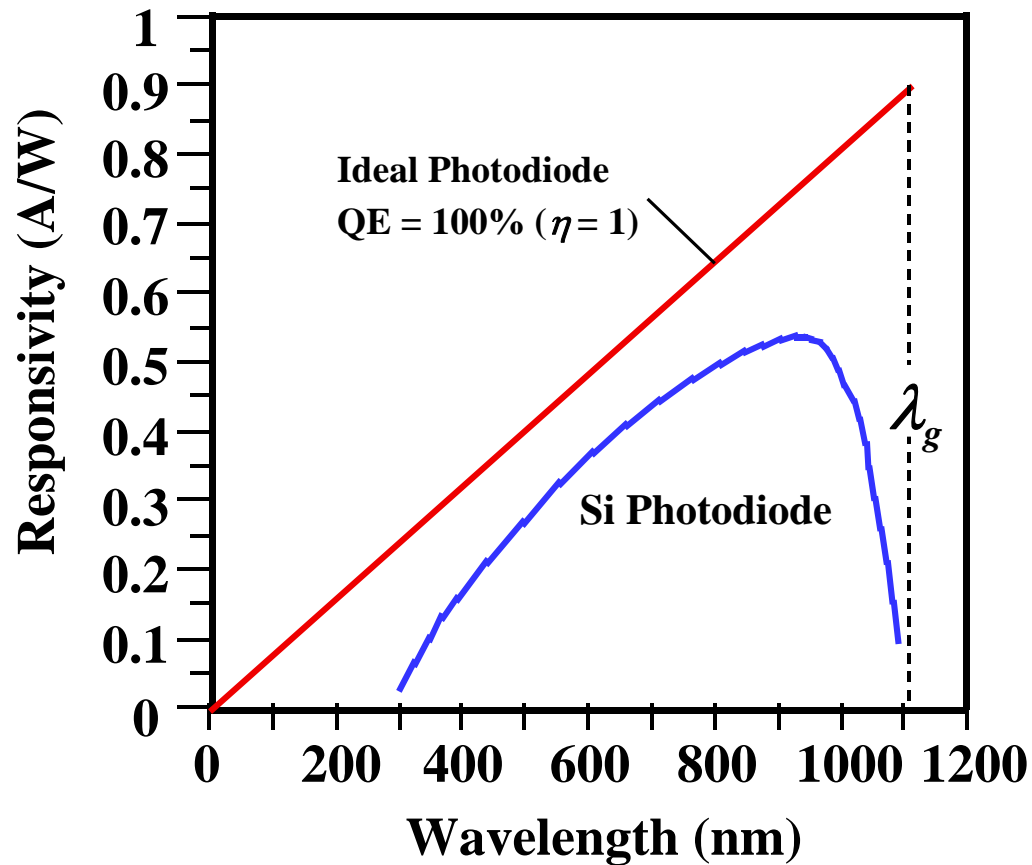
## ❑ Responsivity

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_0}$$

$$R = \eta \frac{e}{h\nu} = \eta \frac{e\lambda}{hc} \quad \text{Spectral Responsivity}$$

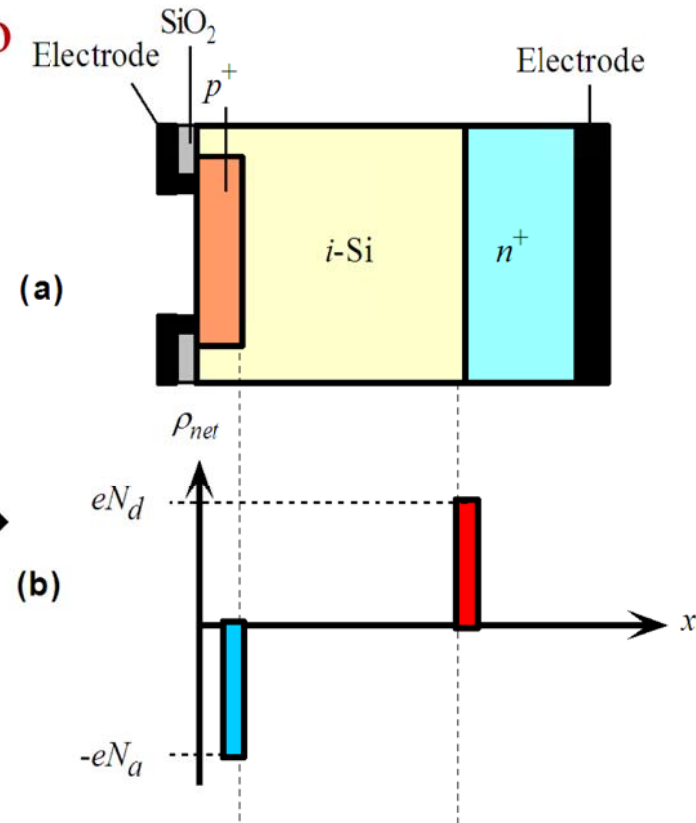
# Photo-detectors

- Responsivity vs. wavelength for a typical *Si* photo-diode



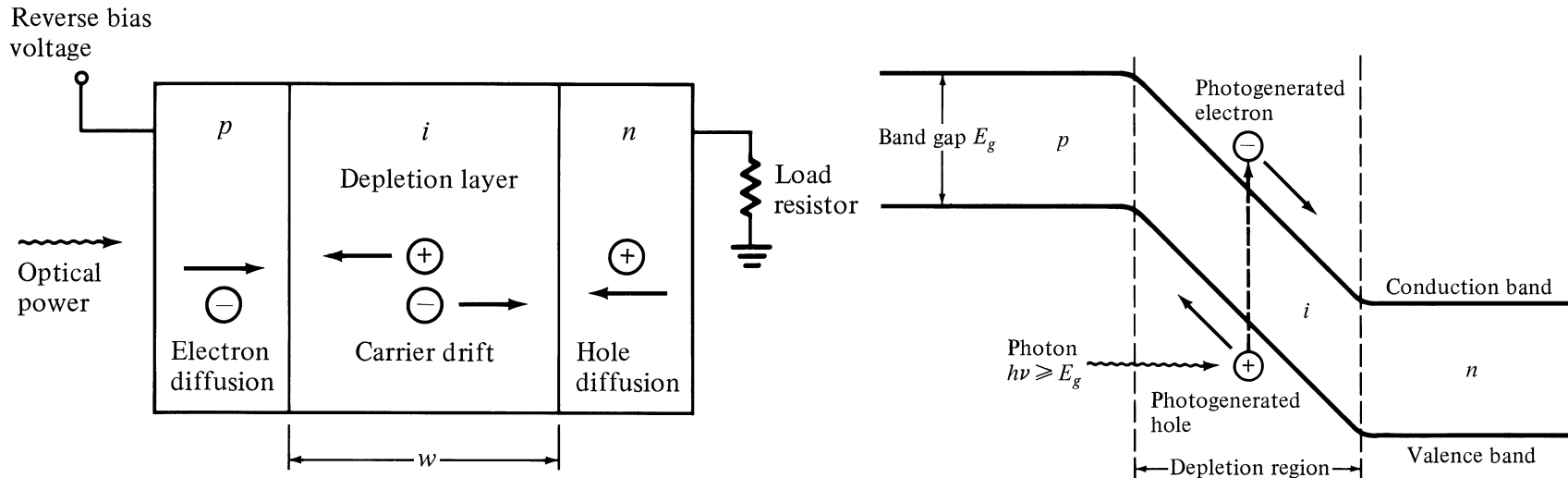
# The *pin* Photo-diode

- The *pn* junction photo-diode has **two drawbacks**:
  - **Depletion layer capacitance** is not sufficiently small to allow photodetection at high modulation frequencies (RC time constant limitation).
  - **Narrow SCL** (at most a few microns) → long wavelengths incident photons are absorbed outside SCL → low QE
- The *pin* photo-diode can significantly reduce these problems.
- Intrinsic layer has less doping and wider region (5 – 50  $\mu\text{m}$ ).

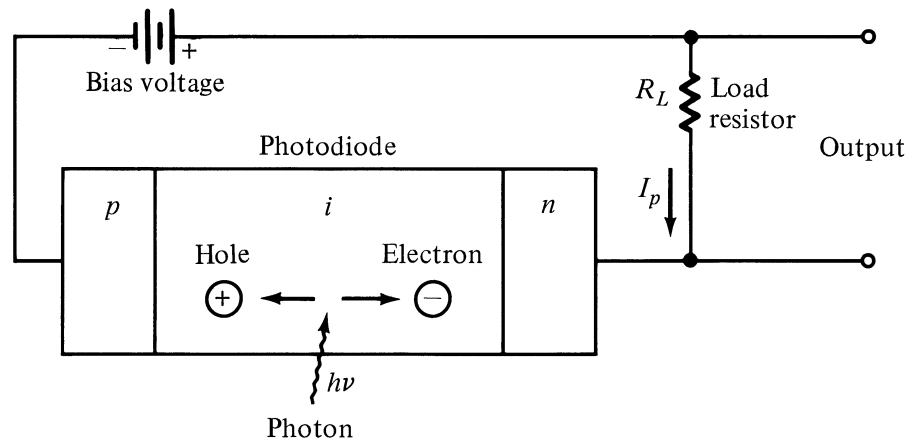


# Photo-detectors: *PIN* Photo-diode

- Reverse-biased *p-i-n* photodiode
- pin* energy-band diagram

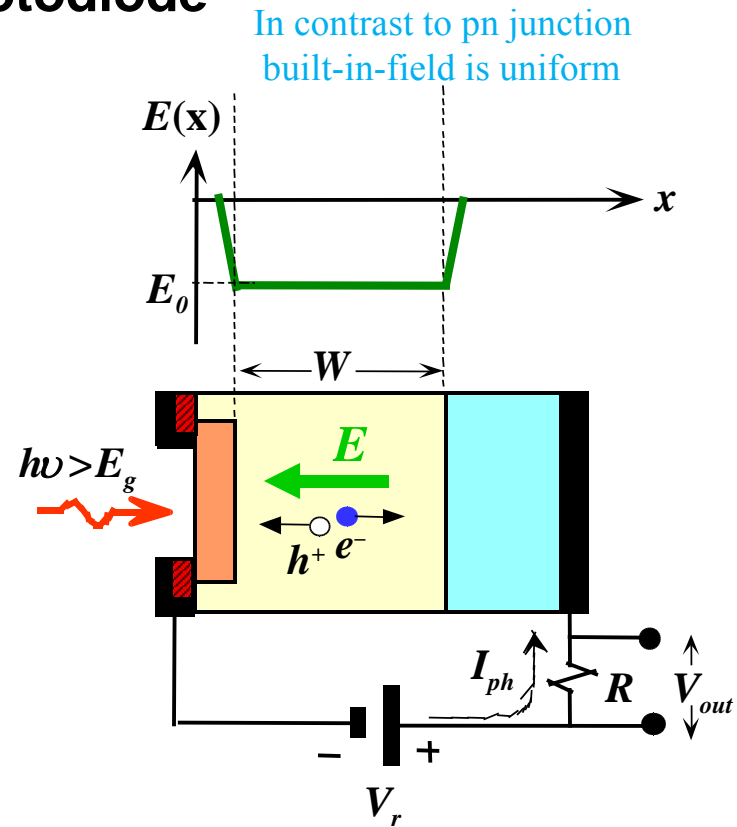
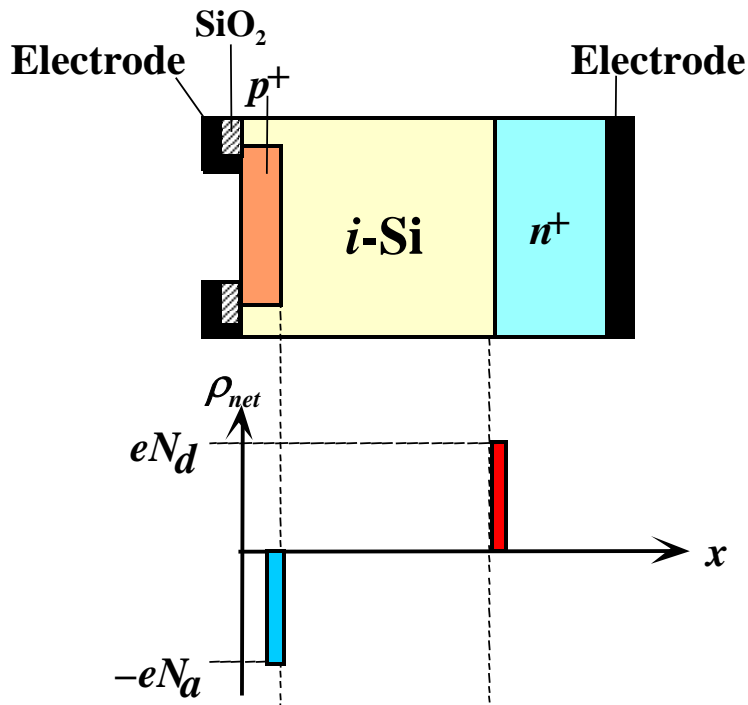


- pin* photodiode circuit



# Photo-detectors: PIN Photo-diode

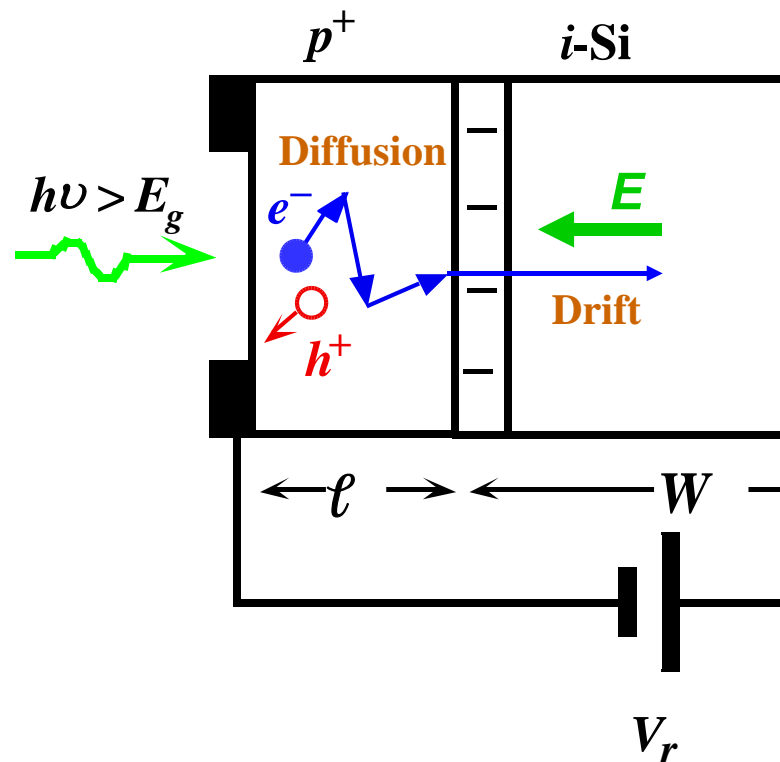
## ❑ Schematic diagram of *pin* photodiode



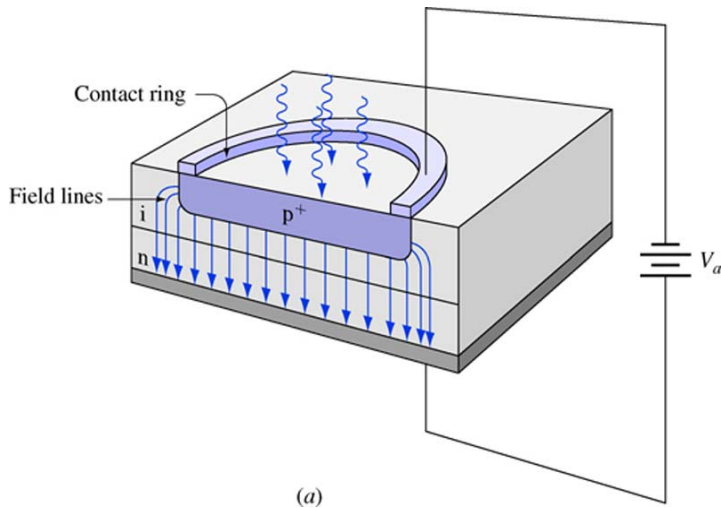
- Small depletion layer capacitance gives high modulation frequencies.
- High Quantum efficiency.

# Photo-detectors: *PIN* Photo-diode

- A reverse biased *pin photodiode* is illuminated with a short wavelength photon that is absorbed very near the surface.
- The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

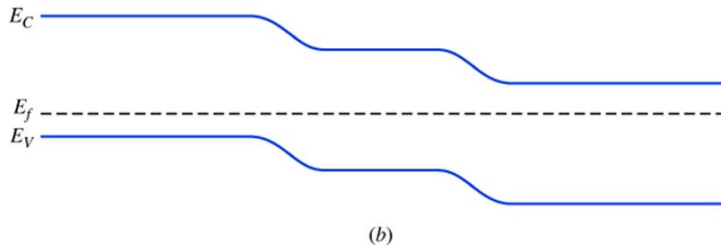


# Photo-detectors: *PIN* Photo-diode

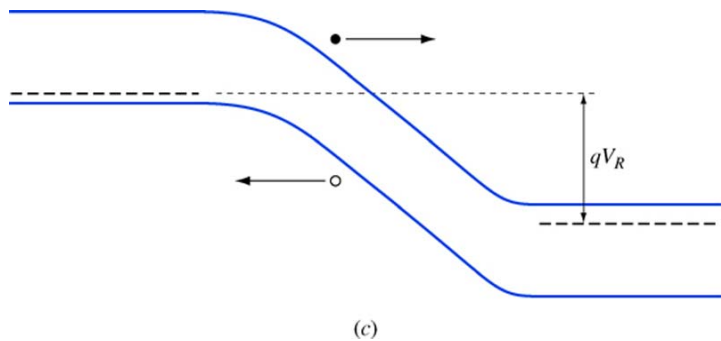


*p-i-n* diode

(a) The structure;



(b) equilibrium energy band diagram;

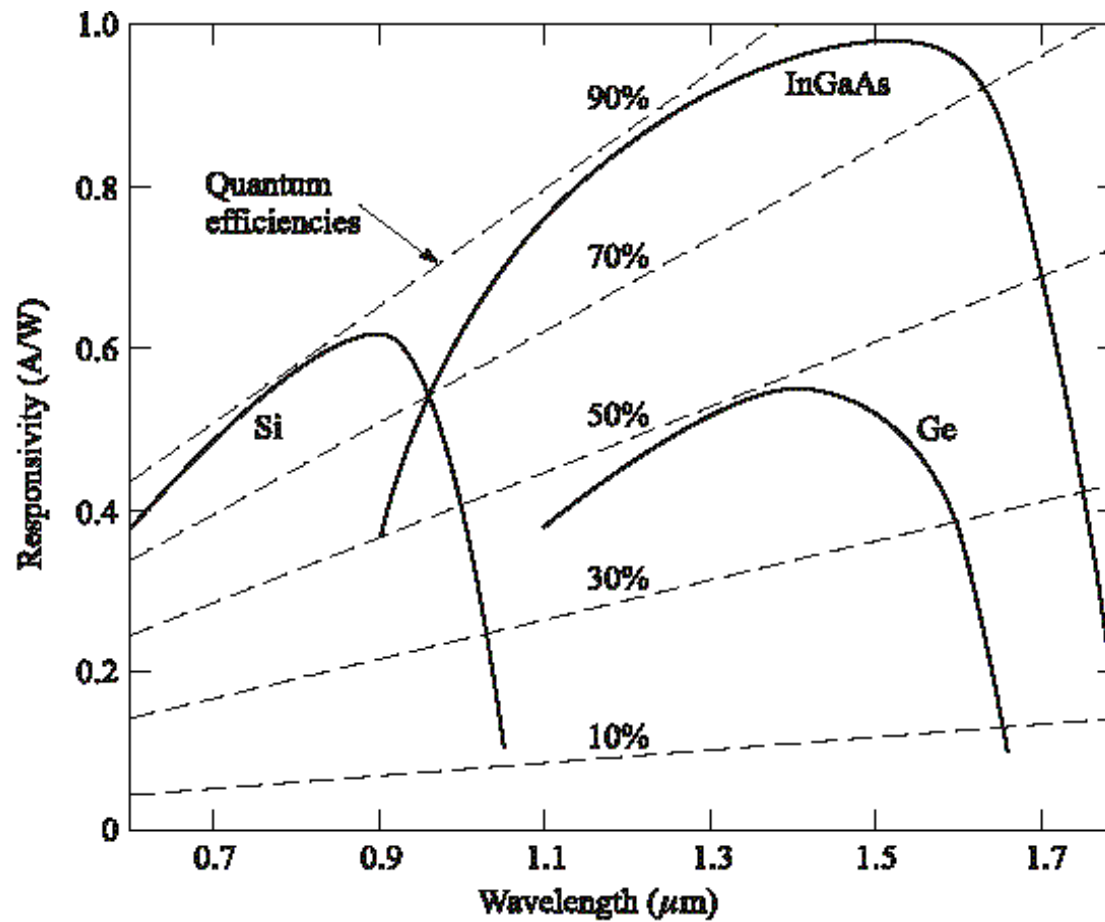


(c) energy band diagram under reverse bias.



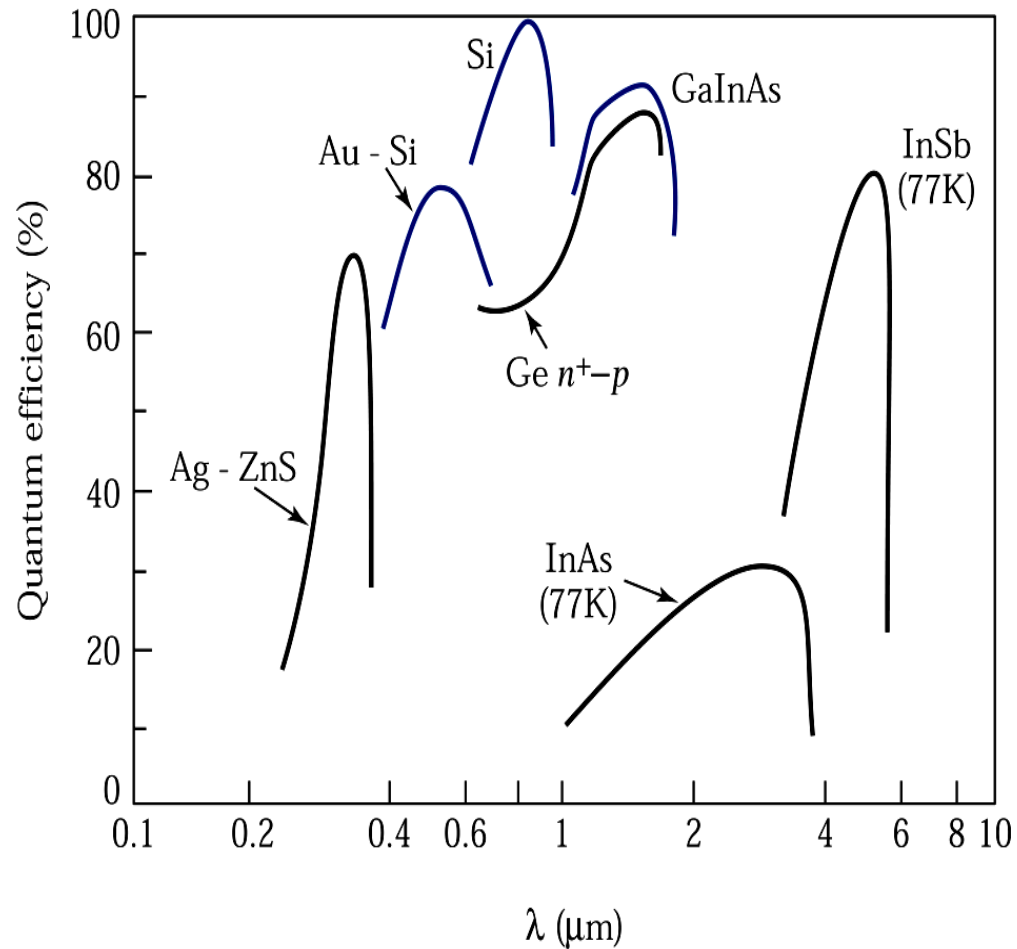
# Photo-detectors: *PIN* Photo-diode

- The responsivity of *PIN* photodiodes



# Photo-detectors: Photo-conductive Detectors and Gain

## Quantum efficiency versus wavelength for various photo-detectors



# Photo-detectors: *PIN* Photo-diode

## ❑ Junction capacitance of *pin*

$$C_{dep} = \frac{\epsilon_0 \epsilon_r A}{W}$$

- Small capacitance: High modulation frequency
- $RC_{dep}$  time constant is  $\sim 50$  psec.

## ❑ Electric field of biased *pin*

$$E = E_0 + \frac{V_r}{W} \approx \frac{V_r}{W}$$

## ❑ Response time

$$t_{drift} = \frac{W}{v_d}$$

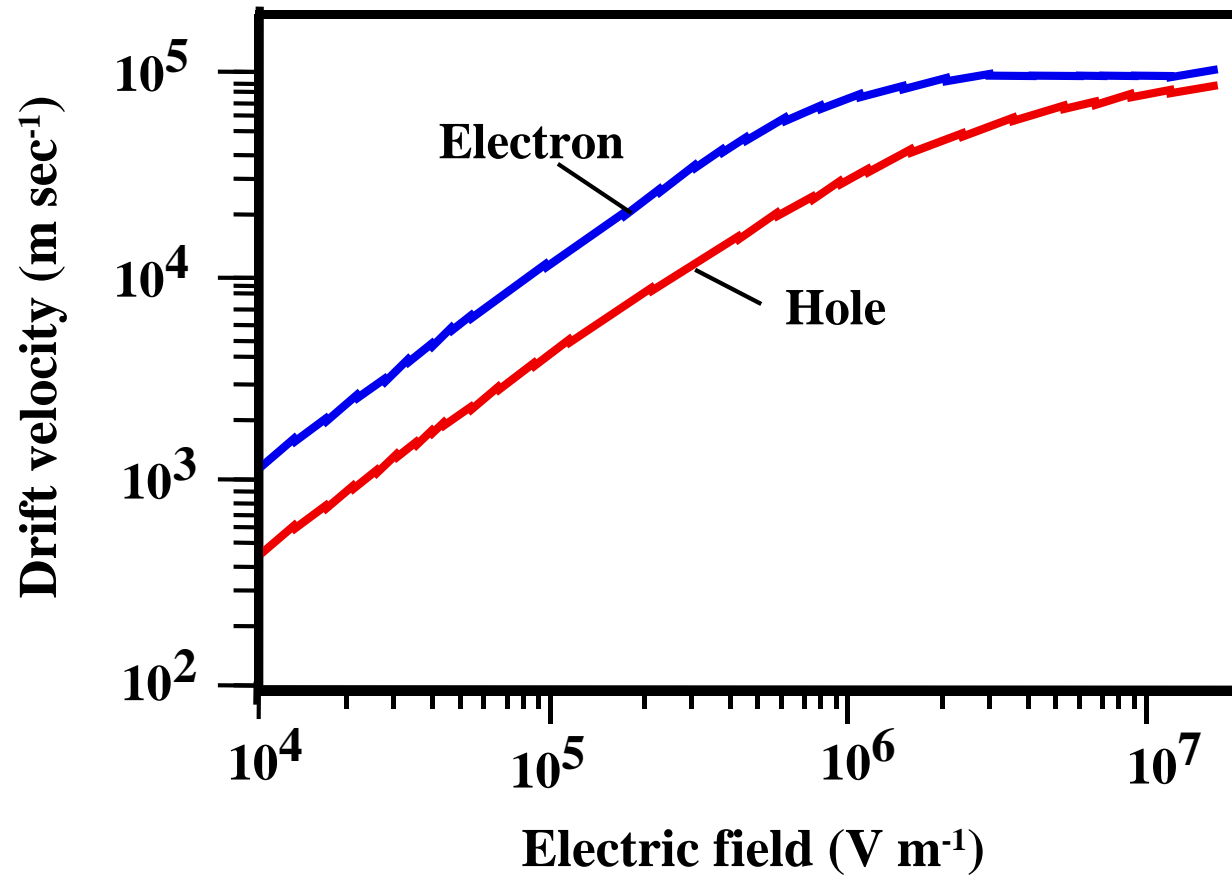
$$v_d = \mu_d E$$

The speed of *pin* photodiodes are invariably limited by the transit time of photogenerated carriers across the *i*-Si layer.

For *i*-Si layer of width  $10 \mu\text{m}$ , the drift time is about is about  $0.1$  nsec.

# Photo-detectors: *PIN* Photo-diode

- ❑ **Drift velocity** vs. electric field for holes and electrons in Silicon.



A Si *pin* photodiode has an *i*-Si layer of width 20  $\mu\text{m}$ . The  $p^+$  layer on the illumination side is very thin (0.1  $\mu\text{m}$ ). The *pin* is reverse biased by a voltage of 100 V and then illuminated with a very short optical pulse of wavelength 900 nm. What is the duration of the photocurrent if absorption occurs over the whole *i*-Si layer?

**Solution** The absorption coefficient at 900 nm is  $\sim 3 \times 10^4 \text{ m}^{-1}$  so that the absorption depth is  $\sim 33 \mu\text{m}$  as apparent in Figure 5.3. We can assume that absorption and hence photogeneration occurs over the entire width  $W$  of the *i*-Si layer. The field in the *i*-Si layer is

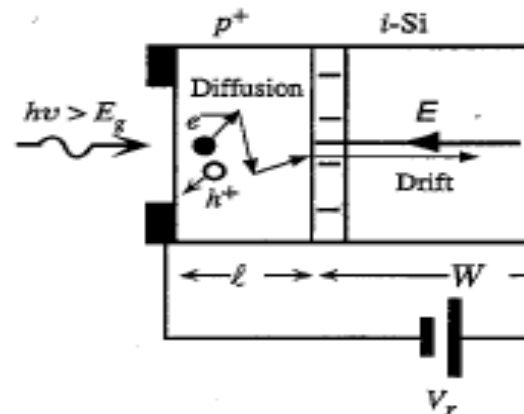
$$E \approx V_r/W = (100 \text{ V})/(20 \times 10^{-6} \text{ m}) = 5 \times 10^6 \text{ V m}^{-1}.$$

At this field the electron drift velocity  $v_e$  is very near its saturation at  $10^5 \text{ m s}^{-1}$ , whereas the hole drift velocity  $v_h$ , is about  $7 \times 10^4 \text{ m s}^{-1}$  as shown in Figure 5.7. Holes are slightly slower than the electrons. The transit time  $t_h$  of holes across the *i*-Si layer is

$$t_h = W/v_h = (20 \times 10^{-6} \text{ m})/(7 \times 10^4 \text{ m s}^{-1}) = 2.86 \times 10^{-10} \text{ s or } 0.3 \text{ ns}.$$

This is the response time of the *pin* as determined by the transit time of the slowest carriers, holes, across the *i*-Si layer. To improve the response time the width of the *i*-Si layer has to be narrowed but this decreases the quantity of absorbed photons and hence reduces the responsivity. There is therefore a trade off between speed and responsivity.

A reverse biased *pin* photodiode is illuminated with a short wavelength photon that is absorbed very near the surface as shown in Figure 5.8. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across. What is the speed of response of this photodiode if the *i*-Si layer is 20  $\mu\text{m}$  and the  $p^+$  layer is 1  $\mu\text{m}$  and the applied voltage is 120 V? The diffusion coefficient ( $D_e$ ) of electrons in the heavily doped  $p^+$  region is approximately  $3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ .



**FIGURE 5.8** A reverse biased *pin* photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

**Solution** There is no electric field in the  $p^+$  side outside the depletion region as shown in Figure 5.8. The photogenerated electrons have to make it across to the  $n^+$  side to give rise to a photocurrent. In the  $p^+$  side, the electrons move by diffusion. In time  $t$ , an electron, on average, diffuses a distance  $\ell$  given by<sup>5</sup>

$$\ell = [2D_e t]^{1/2}$$

The *diffusion time*  $t_{\text{diff}}$  is the time it takes for an electron to diffuse across the  $p^+$  side (of length  $\ell$ ) to reach the depletion layer is

$$t_{\text{diff}} = \ell^2 / (2D_e) = (1 \times 10^{-6} \text{ m})^2 / [2(3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})] = 1.67 \times 10^{-9} \text{ s or } 1.67 \text{ ns.}$$

On the other hand, once the electron reaches the depletion region, it becomes drifted across the width  $W$  of the *i*-Si layer at the saturation drift velocity since the electric field here is  $E = V_r / W = 120 \text{ V} / 20 \mu\text{m} = 6 \times 10^6 \text{ V m}^{-1}$  and at this field the electron drift velocity  $v_e$  saturates at  $10^5 \text{ m s}^{-1}$ . The *drift time* across the *i*-Si layer is

$$t_{\text{drift}} = W / v_e = (20 \times 10^{-6} \text{ m}) / (1 \times 10^5 \text{ m s}^{-1}) = 2.0 \times 10^{-10} \text{ s or } 0.2 \text{ ns.}$$

Thus, the response time of the *pin* to a pulse of short wavelength radiation that is absorbed near the surface is about  $t_{\text{diff}} + t_{\text{drift}}$  or 1.87 ns.

A Si *pin* photodiode has an active light receiving area of diameter 0.4 mm. When radiation of wavelength 700 nm (red light) and intensity  $0.1 \text{ mW cm}^{-2}$  is incident it generates a photocurrent of 56.6 nA. What is the responsivity and QE of the photodiode at 700 nm?

**Solution** The incident light intensity  $I = 0.1 \text{ mW cm}^{-2}$  means that the incident power for conversion is

$$P_o = AI = \pi(0.02 \text{ cm})^2(1 \times 10^{-3} \text{ W cm}^{-2}) = 1.26 \times 10^{-7} \text{ W or } 0.126 \mu\text{W}.$$

The responsivity is

$$R = I_{ph}/P_o = (56.6 \times 10^{-9} \text{ A})/(1.26 \times 10^{-7} \text{ W}) = 0.45 \text{ A W}^{-1}$$

The QE can be found from

$$\eta = R \frac{hc}{e\lambda} = (0.45 \text{ A W}^{-1}) \frac{(6.62 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})}{(1.6 \times 10^{-19} \text{ C})(700 \times 10^{-9} \text{ m})} = 0.80 = 80\%$$

## Example

### Bandgap and photodetection

- (a) Determine the maximum value of the **energy gap** which a semiconductor, used as a photoconductor, can have if it is to be sensitive to yellow light (600 nm).
- (b) A photodetector whose area is  $5 \times 10^{-2} \text{ cm}^2$  is irradiated with yellow light whose intensity is  $20 \text{ mW cm}^{-2}$ . Assuming that each photon generates one electron-hole pair, calculate **the number of pairs generated per second**.

### Solution

- (a) Given,  $\lambda = 600 \text{ nm}$ , we need  $E_{ph} = h\nu = E_g$  so that,  
$$E_g = hc/\lambda = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})/(600 \times 10^{-9} \text{ m}) = 2.07 \text{ eV}$$
- (b)  $Area = 5 \times 10^{-2} \text{ cm}^2$  and  $I_{light} = 20 \times 10^{-3} \text{ W/cm}^2$ .  
The received power is  
$$P = Area \times I_{light} = (5 \times 10^{-2} \text{ cm}^2)(20 \times 10^{-3} \text{ W/cm}^2) = 10^{-3} \text{ W}$$
  
$$N_{ph} = \text{number of photons arriving per second} = P/E_{ph}$$
$$= (10^{-3} \text{ W})/(2.059 \times 1.60218 \times 10^{-19} \text{ J/eV})$$
$$= 2.9787 \times 10^{15} \text{ photons s}^{-1} = 2.9787 \times 10^{15} \text{ EHP s}^{-1}.$$



## Example

### Bandgap and Photodetection

- (c) From the known energy gap of the semiconductor GaAs ( $E_g = 1.42$  eV), calculate the primary **wavelength** of photons emitted from this crystal as a result of electron-hole recombination. Is this wavelength in the visible?
- (d) Will a **silicon photodetector** be sensitive to the radiation from a **GaAs laser**? Why?

### Solution

(c) For GaAs,  $E_g = 1.42$  eV and the corresponding wavelength is  $\lambda = hc / E_g = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1}) / (1.42 \text{ eV} \times 1.6 \times 10^{-19} \text{ J/eV}) = 873 \text{ nm}$  (invisible IR).  $\therefore$  The wavelength of emitted radiation due to EHP recombination is **873 nm**.

(d) For Si,  $E_g = 1.1$  eV and the corresponding cut-off wavelength is  $\lambda_g = hc / E_g = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1}) / (1.1 \text{ eV} \times 1.6 \times 10^{-19} \text{ J/eV}) = \mathbf{1120 \text{ nm}}$

Since the 873 nm wavelength is shorter than the cut-off wavelength of 1120 nm, the Si photodetector can detect the 873 nm radiation (Put differently, the photon energy corresponding to 873 nm, 1.42 eV, is larger than the  $E_g$ , 1.1 eV, of Si which mean that the **Si photodetector can indeed detect the 873 nm radiation**)

## Example

### Absorption coefficient

(a) If  $d$  is the thickness of a photodetector material,  $I_0$  is the intensity of the incoming radiation, the **number of photons absorbed** per unit volume of sample is

$$n_{ph} = \frac{I_0 [1 - \exp(-\alpha \cdot d)]}{d h \nu}$$

### Solution

(a) If  $I_0$  is the intensity of incoming radiation (energy flowing per unit area per second),  $I_0 \exp(-\alpha d)$  is the transmitted intensity through the specimen with thickness  $d$  and thus  $I_0 \exp(-\alpha d)$  is the **“absorbed” intensity**

## Example

(b) What is the **thickness** of a Ge and  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  crystal layer that is needed for absorbing 90% of the incident radiation at  $1.5\ \mu\text{m}$ ?

For Ge,  $\alpha \approx 5.2 \times 10^5\ \text{m}^{-1}$  at  $1.5\ \mu\text{m}$  incident radiation.

For  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,  $\alpha \approx 7.5 \times 10^5\ \text{m}^{-1}$  at  $1.5\ \mu\text{m}$  incident radiation.

(b) For Ge,  $\alpha \approx 5.2 \times 10^5\ \text{m}^{-1}$  at  $1.5\ \mu\text{m}$  incident radiation.

$$\therefore 1 - \exp(-\alpha \cdot d) = 0.9$$

$$d = \frac{1}{\alpha} \ln\left(\frac{1}{1 - 0.9}\right) = \frac{1}{5.2 \times 10^5} \ln\left(\frac{1}{1 - 0.9}\right) = 4.428 \times 10^{-6}\ \text{m} = 4.428\ \mu\text{m}$$

For  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,  $\alpha \approx 7.5 \times 10^5\ \text{m}^{-1}$  at  $1.5\ \mu\text{m}$  incident radiation.

$$d = \frac{1}{7.5 \times 10^5} \ln\left(\frac{1}{1 - 0.9}\right) = 3.07 \times 10^{-6}\ \text{m} = 3.07\ \mu\text{m}$$

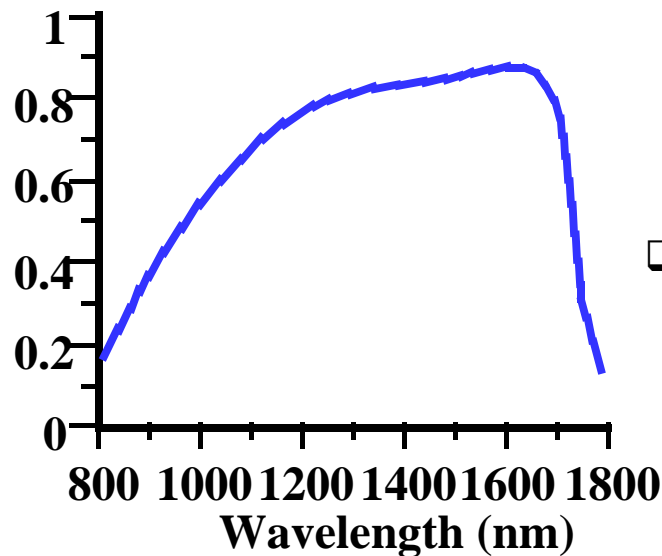
## Example

### InGaAs *pin* Photodiodes

Consider a commercial InGaAs *pin* photodiode whose responsivity is shown below. Its dark current is 5 nA.

- (a) What optical power at a wavelength of 1.55  $\mu\text{m}$  would give a photocurrent that is twice the dark current? What is the QE of the photodetector at 1.55  $\mu\text{m}$ ?
- (b) What would be the photocurrent if the incident power in (a) was at 1.3  $\mu\text{m}$ ? What is the QE at 1.3  $\mu\text{m}$  operation?

Responsivity (A/W)



□ The responsivity of an InGaAs *pin* photodiode

## Solution

- (a) At  $\lambda = 1.55 \times 10^{-6} \text{ m}$ , from the responsivity vs. wavelength curve we have  $R \approx 0.87 \text{ A/W}$ . From the definition of responsivity,

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_0}$$

we have  $P_0 = \frac{I_{ph}}{R} = \frac{2I_{dark}}{R} = \frac{2 \times 5 \times 10^{-9} \text{ (A)}}{0.87 \text{ A/W}} = 11.5 \text{ nW}$

From the definitions of quantum efficiency  $\eta$  and responsivity,

$$R = \eta \frac{e}{h\nu} = \eta \frac{e\lambda}{hc}$$

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{sec})(3 \times 10^8 \text{ m/s})(0.87 \text{ A/W})}{(1.6 \times 10^{-19} \text{ coul})(1.55 \times 10^{-6} \text{ m})} = 0.70 \text{ (70 \%)}$$

Note the following dimensional identities:  $\text{A} = \text{C s}^{-1}$  and  $\text{W} = \text{J s}^{-1}$  so that  $\text{A W}^{-1} = \text{C J}^{-1}$ . Thus, responsivity in terms of **photocurrent per unit incident optical power** is also **charge collected per unit incident energy**.

## Solution

(b) At  $\lambda = 1.3 \times 10^{-6} \text{ m}$ , from the responsivity vs. wavelength curve,  $R = 0.82 \text{ A/W}$ .

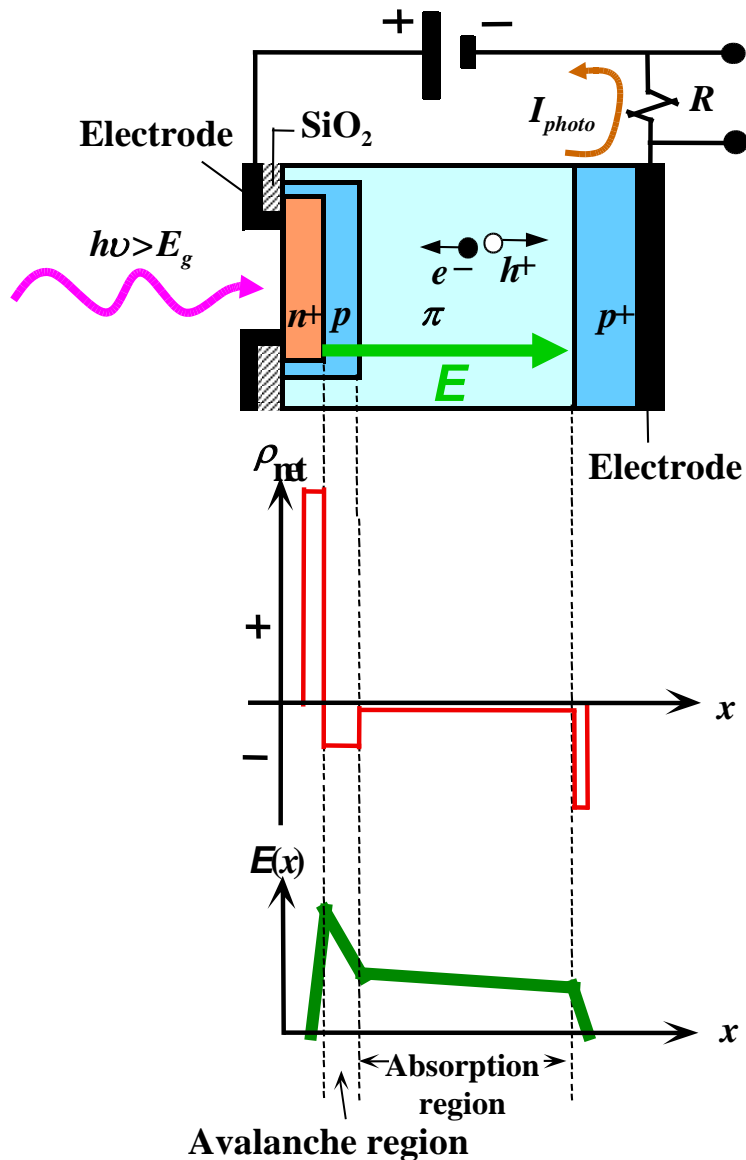
Since  $P_o$  is the same and  $11.5 \text{ nW}$  as in (a),

$$I_{ph} = R \cdot P_o = (0.82 \text{ A/W})(1.15 \text{ nW}) = 9.43 \text{ nA}$$

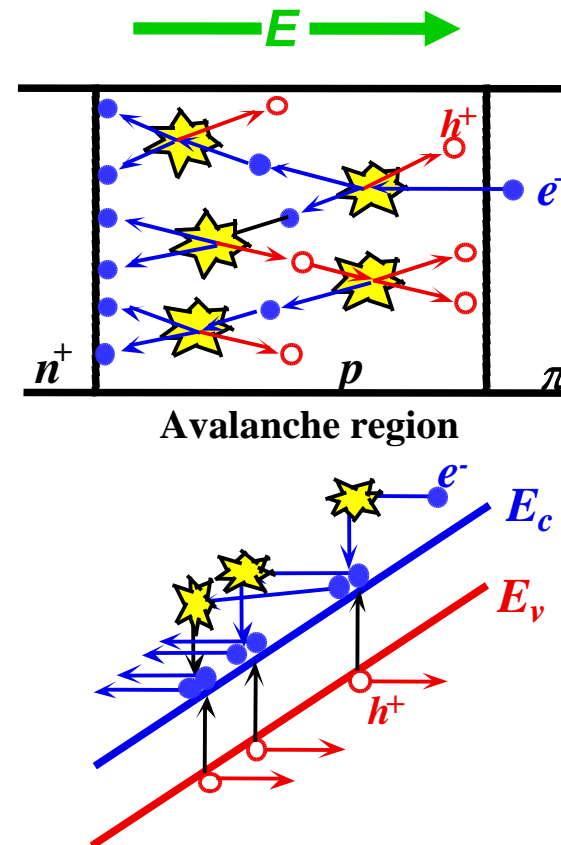
The QE at  $\lambda = 1.3 \text{ }\mu\text{m}$  is

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{sec})(3 \times 10^8 \text{ m/s})(0.82 \text{ A/W})}{(1.6 \times 10^{-19} \text{ coul})(1.3 \times 10^{-6} \text{ m})} \approx 0.78 \text{ (78 \%)}$$

# Photo-detectors: Avalanche Photo-diode (APD)



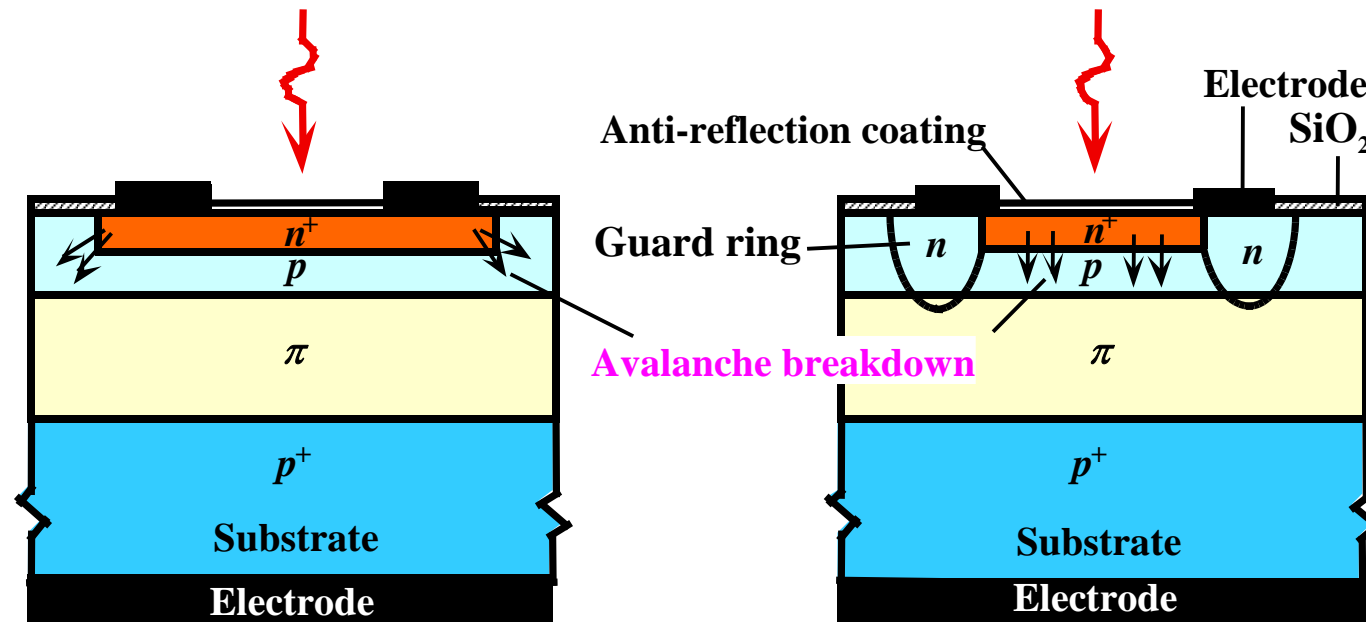
- **Impact ionization** processes resulting **avalanche multiplication**



- Impact of an energetic electron's kinetic energy excites VB electron to the CV.

# Photo detectors: Avalanche Photo-diode (APD)

- Schematic diagram of typical *Si* APD.



*Si* APD structure without a guard ring

More practical *Si* APD

- Breakdown voltage around periphery is higher and avalanche is confined more to illuminated region ( $n^+p$  junction).