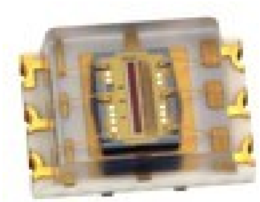
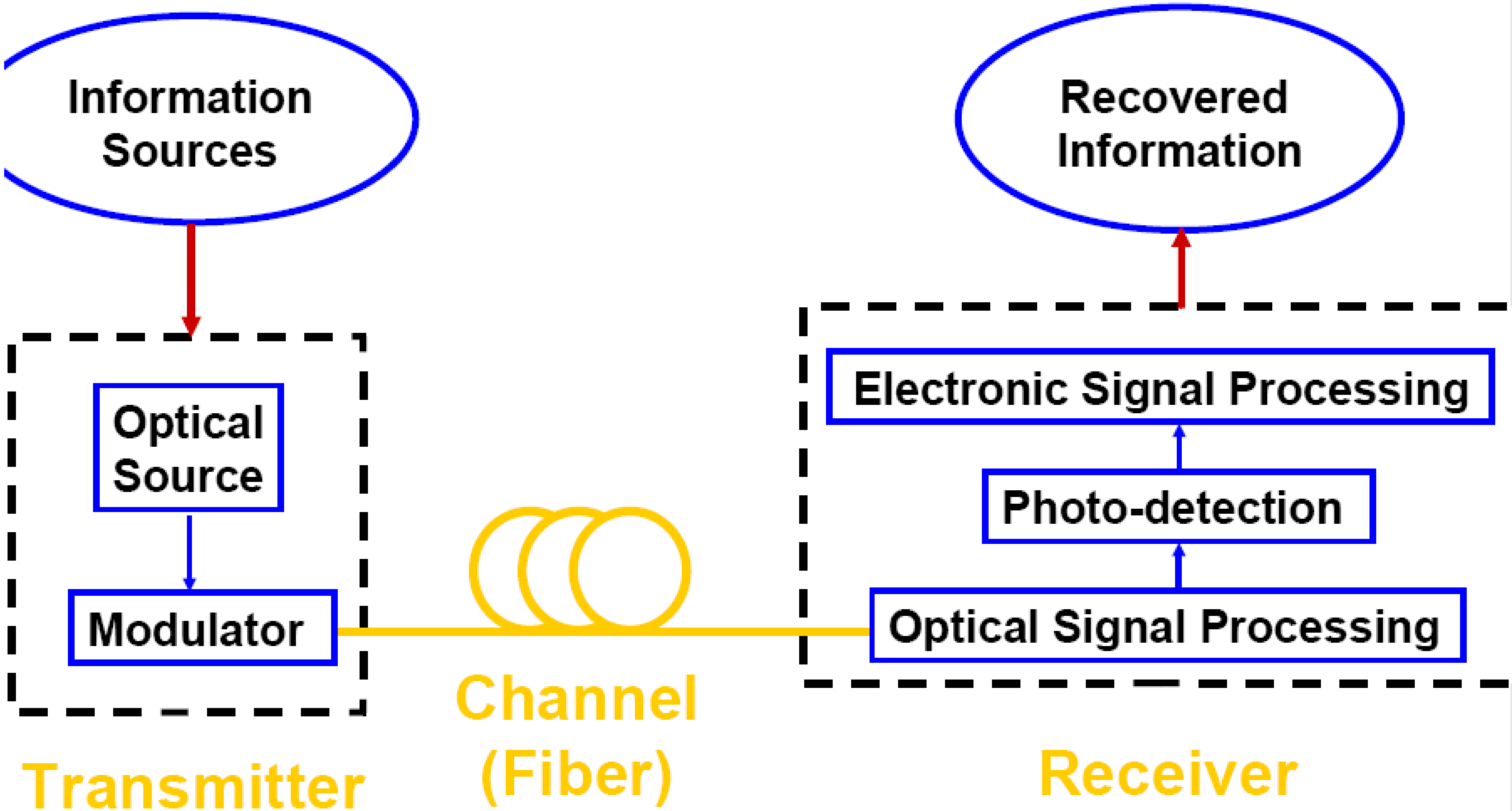
Photodetectors





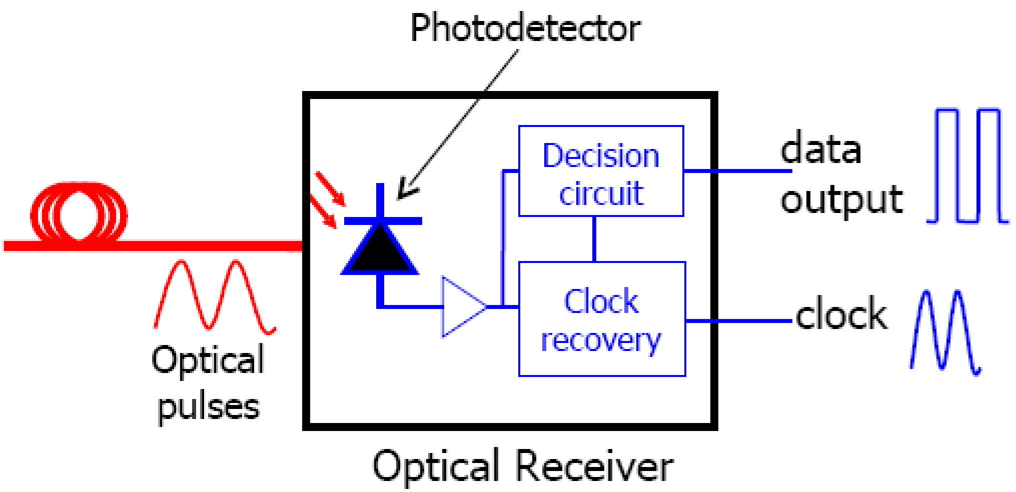


1. Introduction



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 photodector an electric current (photocurrent) is produced ⇒ photodiode



4. Photodetector

- 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

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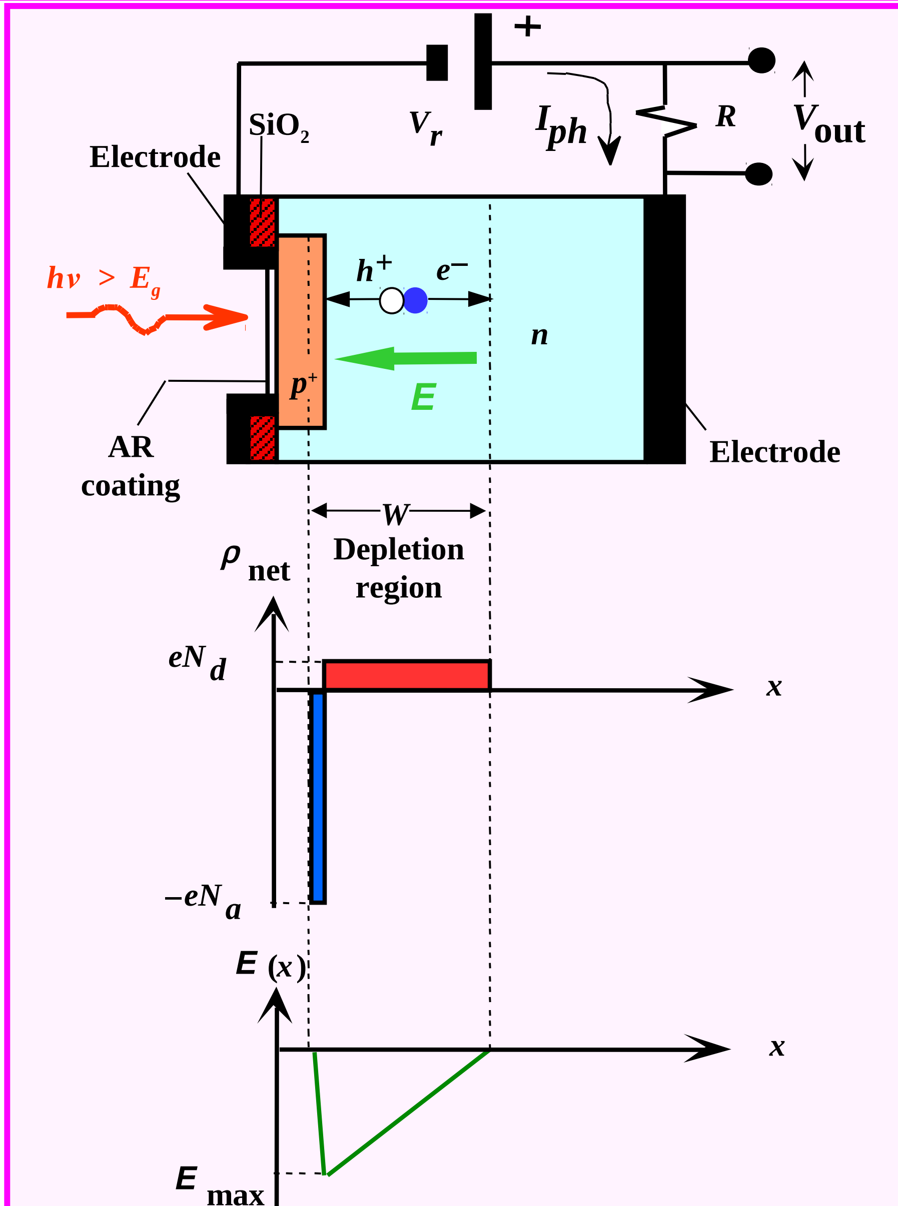
Principle of the p-n junction Photodiode

- ❑ 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.

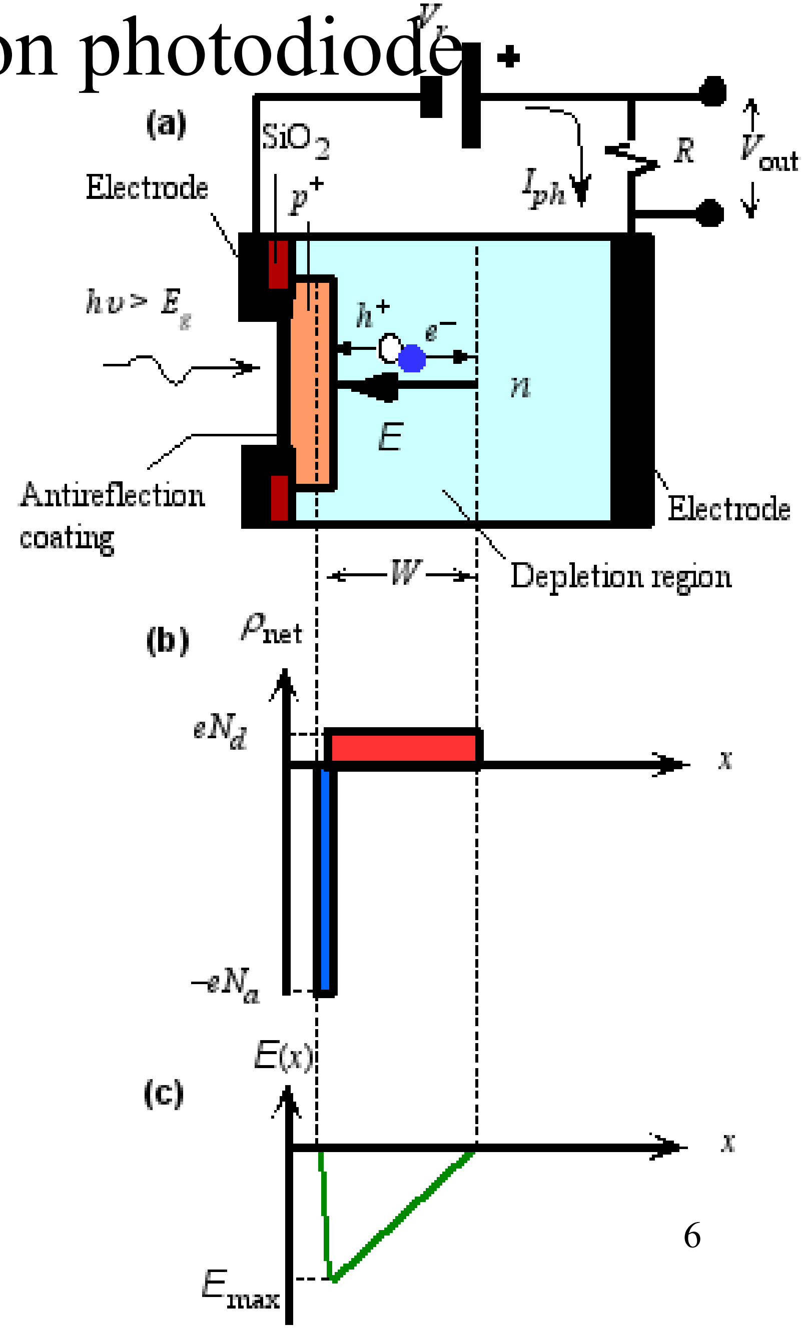
- ❑ Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides.

- ❑ The field in the depletion region.



Principle of *pn* junction photodiode

- (a) Reversed biased $p^{+}n$ junction photodiode.
- Annular electrode to allow photon to enter the device.
- Antireflection coating (Si_3N_4) to reduce the reflection.
- The p^{+}-side thickness < 1 μm.
- (b) Net space charge distribution, within SCL.
- (c) The E field across depletion region.



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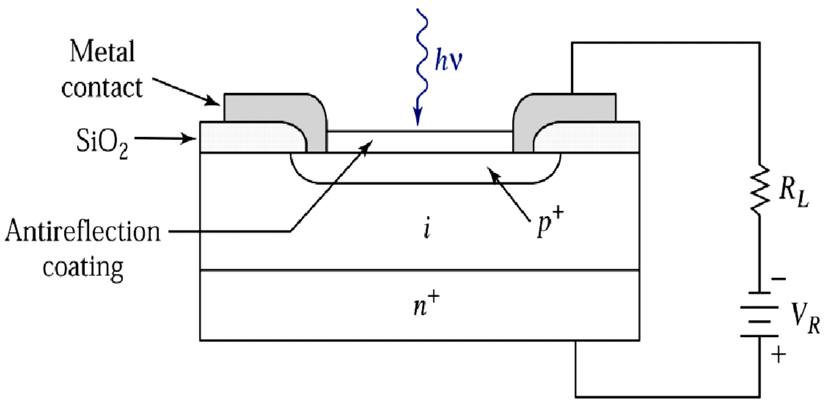
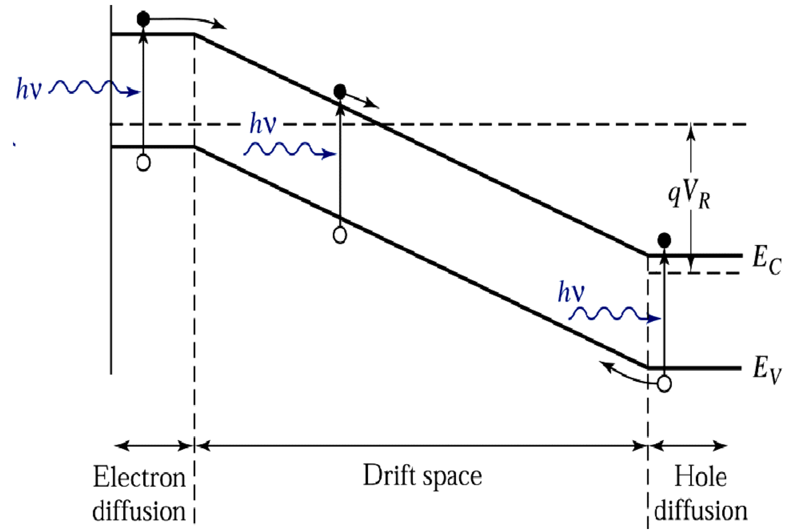
Principle of the p-n junction Photodiode

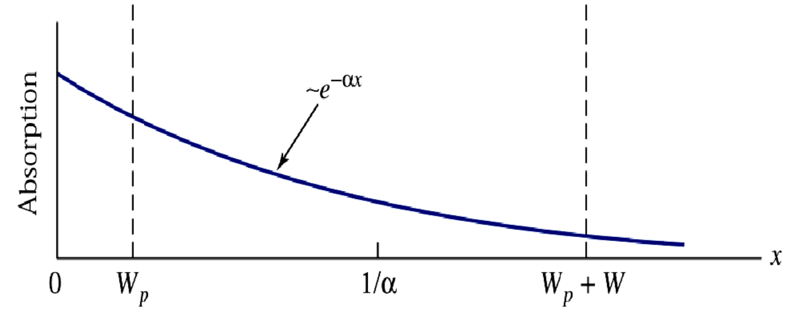
- Operation of a p-i-n photodiode.



(a) Cross-section view of a p-i-n photodiode.



(b) Energy band diagram under reverse bias.



(c) Carrier absorption characteristics.

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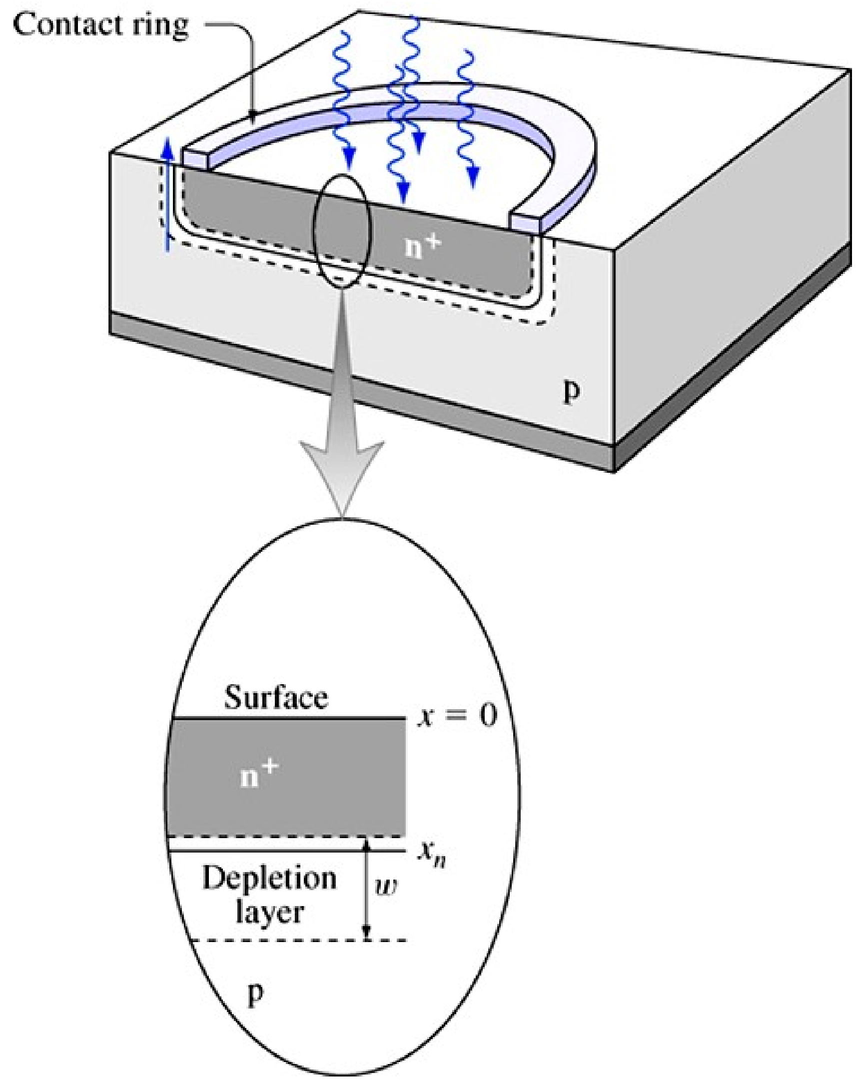
Principle of the p-n junction Photodiode

- A generic photodiode.



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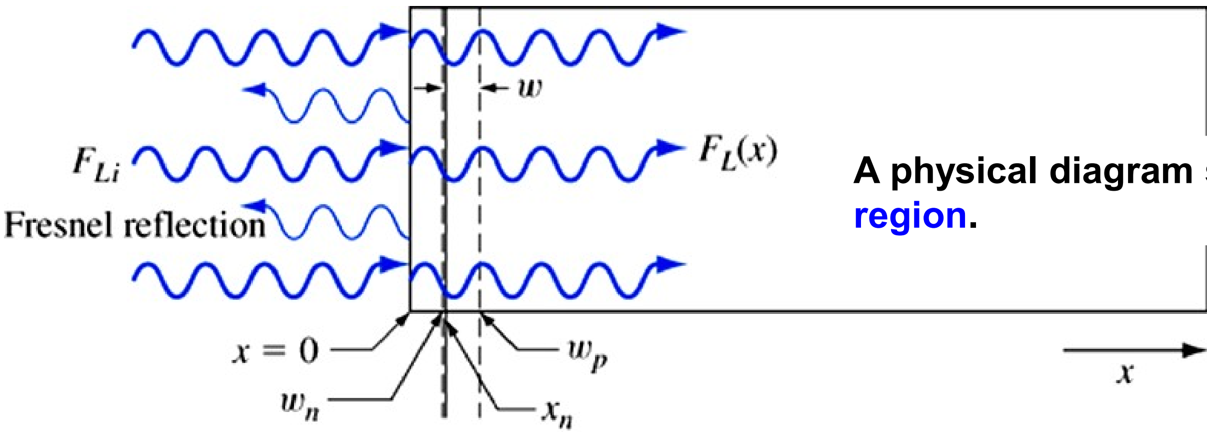
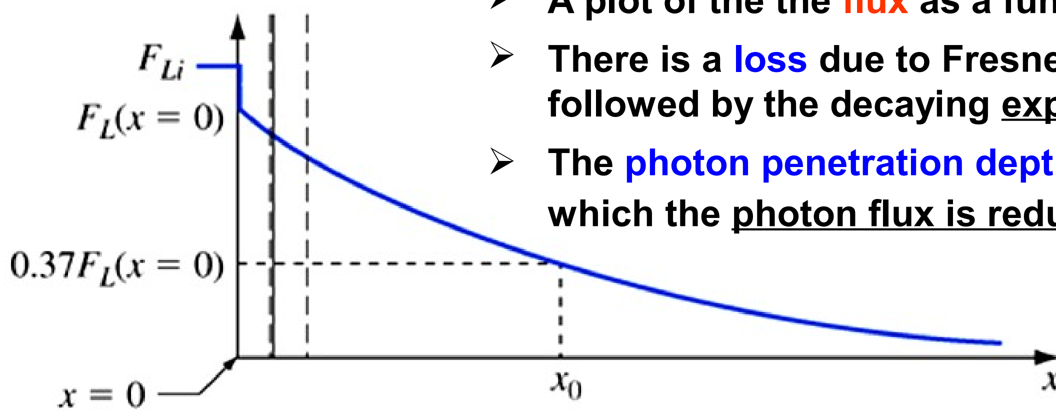
Principle of the p-n junction Photodiode

- ❑ **Variation of photon flux with distance.**



A physical diagram showing the depletion region.



- **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.**

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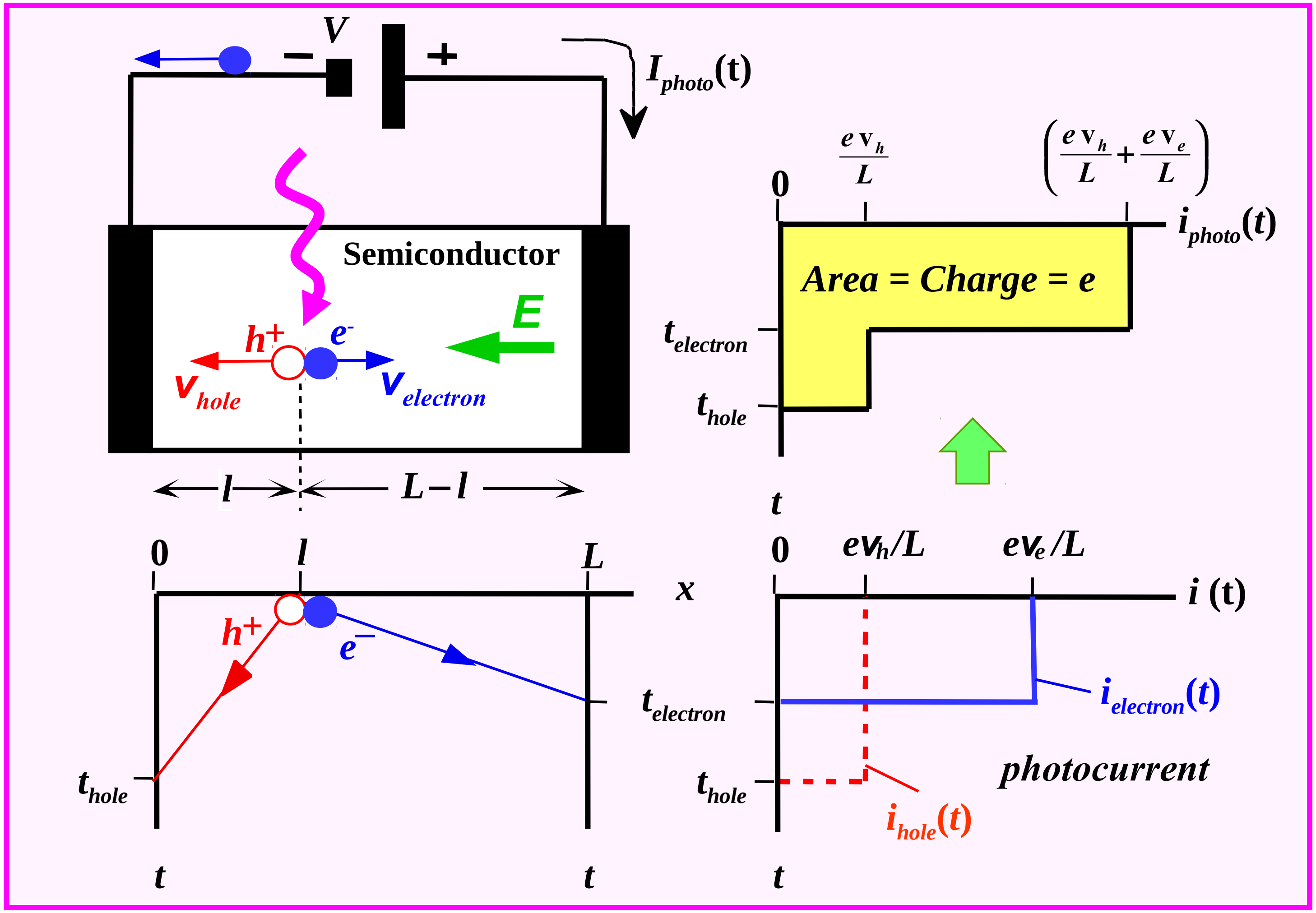
RAMO's Theorem and External Photocurrent

- 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 $t_{hole} = l/v_h$.



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RAMO's Theorem and External Photocurrent

- **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.**

$$t_e(t) = \frac{L-l}{\mathbf{v}_e} \quad and \quad t_h(t) = \frac{l}{\mathbf{v}_h} \qquad \textit{Transit time}$$

$$Work\ done = e \cdot E\,dx = V \cdot i_e(t)\,dt \qquad E = \frac{V}{L} \qquad v_e = \frac{dx}{dt}$$

$$i_e(t) = \frac{e\,\mathrm{v}_e}{L};\quad t < t_e \qquad i_h(t) = \frac{e\,\mathrm{v}_h}{L};\quad t < t_h \qquad \textit{Photocurrent}$$

$$Q_{collected} = \int_0^{t_e} i_e(t)\,dt + \int_0^{t_h} i_h(t)\,dt = e$$

The collected charge is not $2e$ but just "one electron".

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

$$i(t) = \frac{e\,\mathrm{v}_d(t)}{L};\quad t < t_{transit} \qquad \textit{Ramo's Theorem}$$

Photodetectors

Absorption Coefficient and Photodiode Materials

- Absorbed Photon create Electron-Hole Pair.

$$\lambda_g[\mu m] = \frac{1.24}{E_g[eV]}$$

Cut-off wavelength vs. Energy bandgap

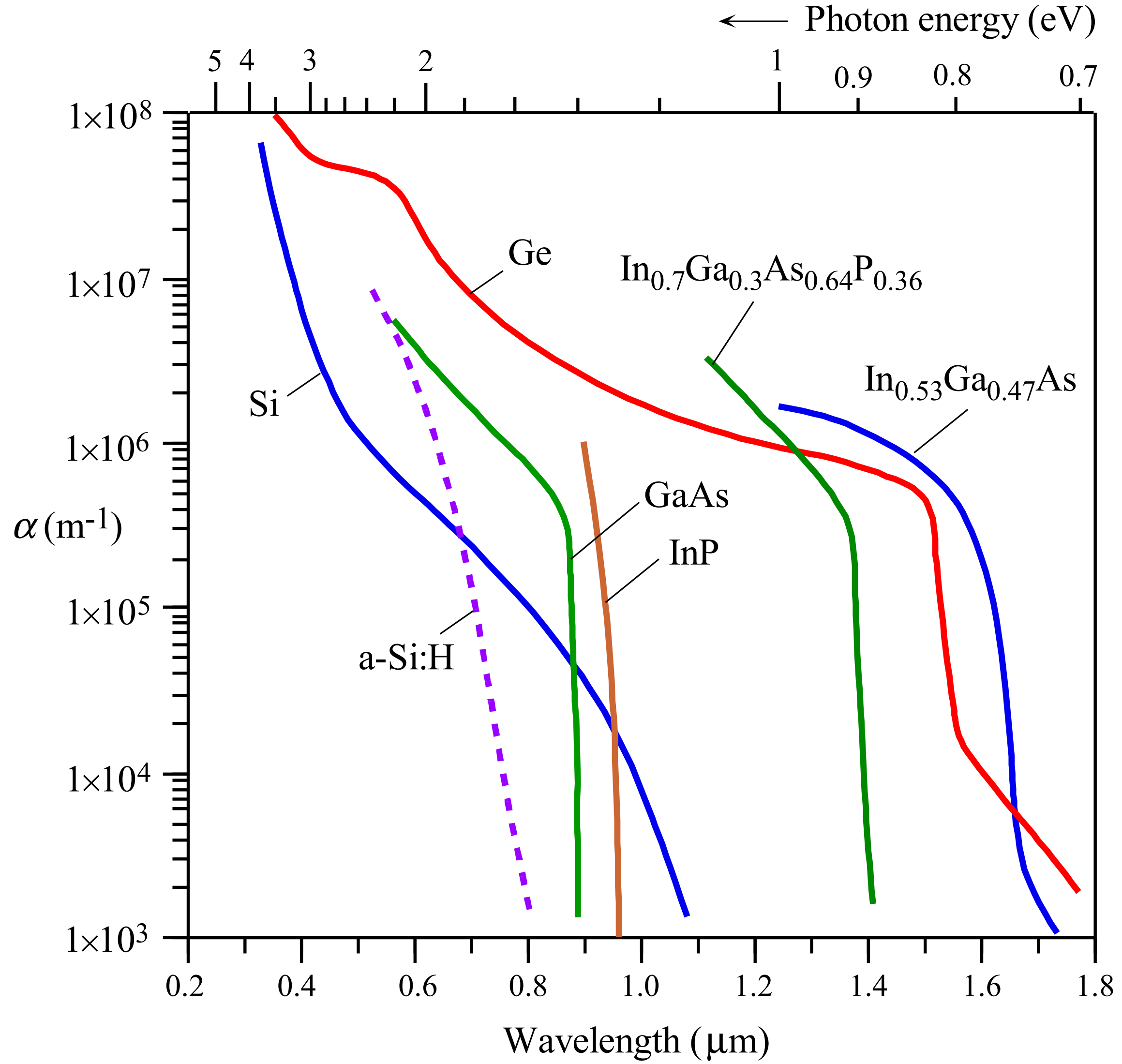
- Incident photons become absorbed as they travel in the semiconductor and <u>light intensity decays exponentially</u> with distance into the semiconductor.

$$I(x) = I_0 \cdot e^{-\alpha x}$$

Absorption coefficient

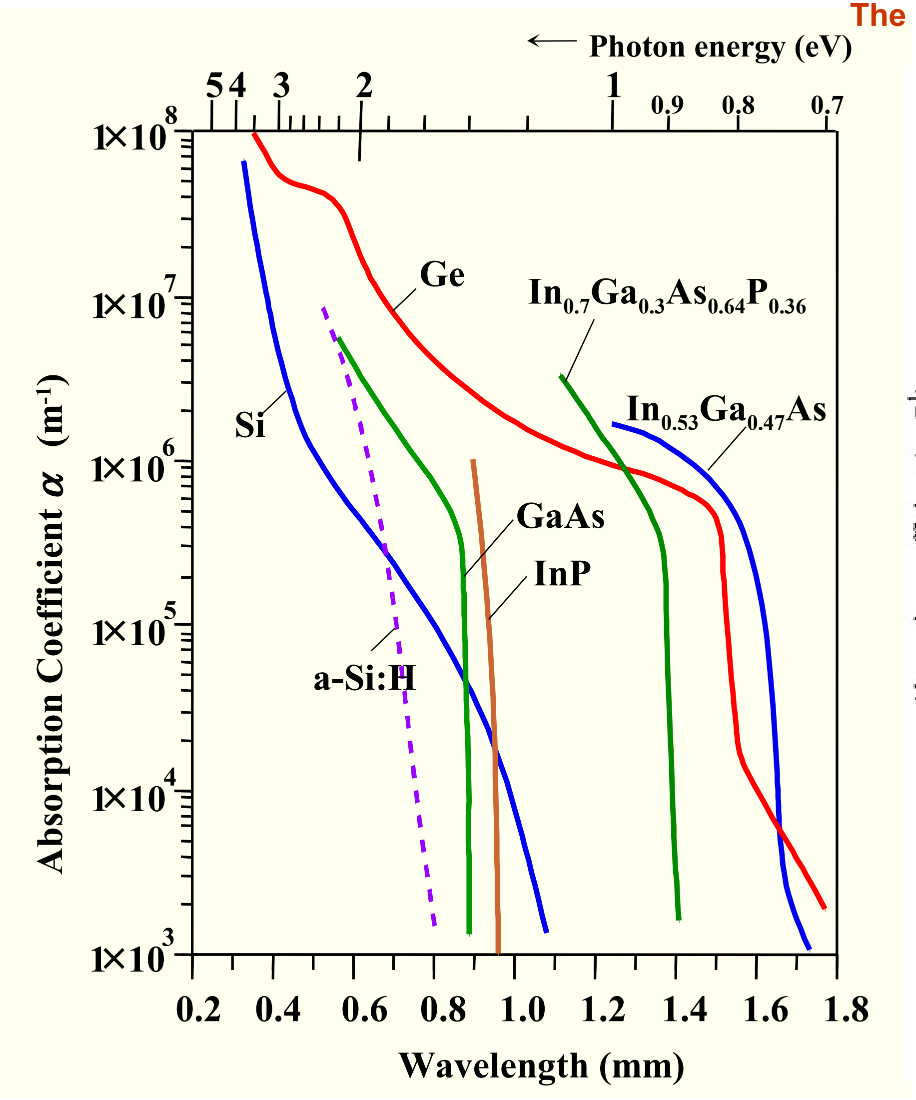
Absorption Coefficient

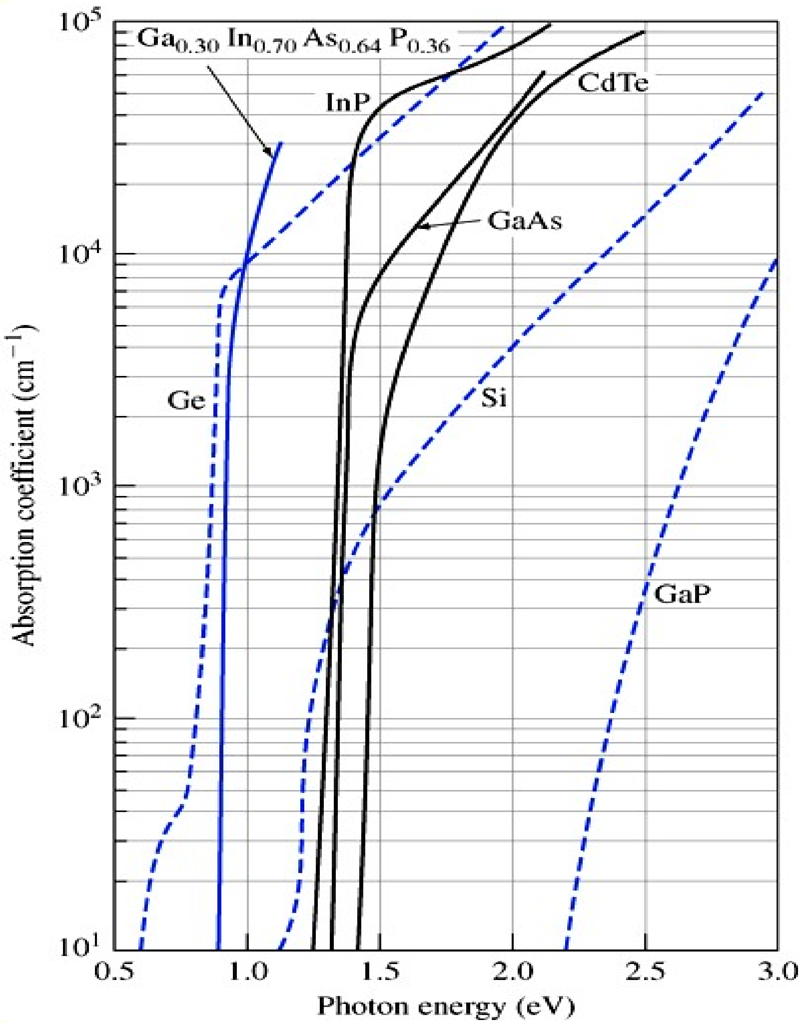
- Absorption coefficient α is a material property.
- Most of the photon absorption (63%) occurs over a distance 1/α (it is called **penetration depth** δ)



❑ Absorption

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

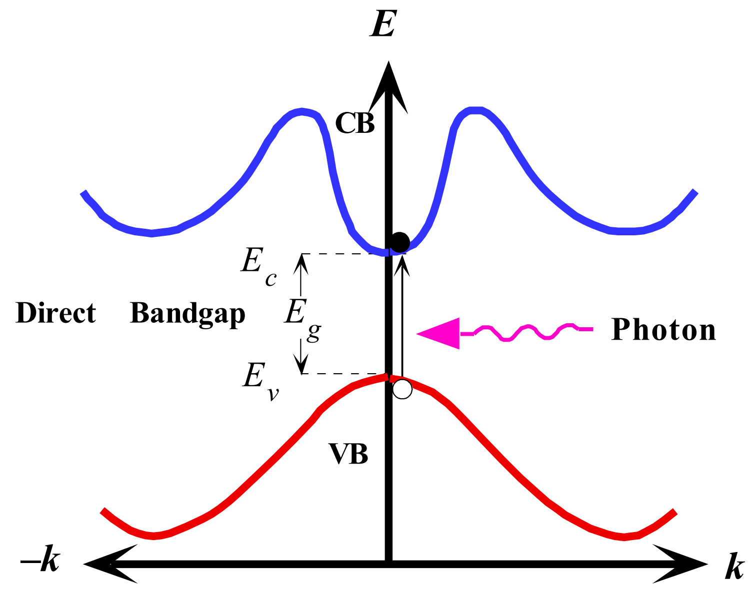




Absorption Coefficient

- 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 ħk), since photon momentum is very small.

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

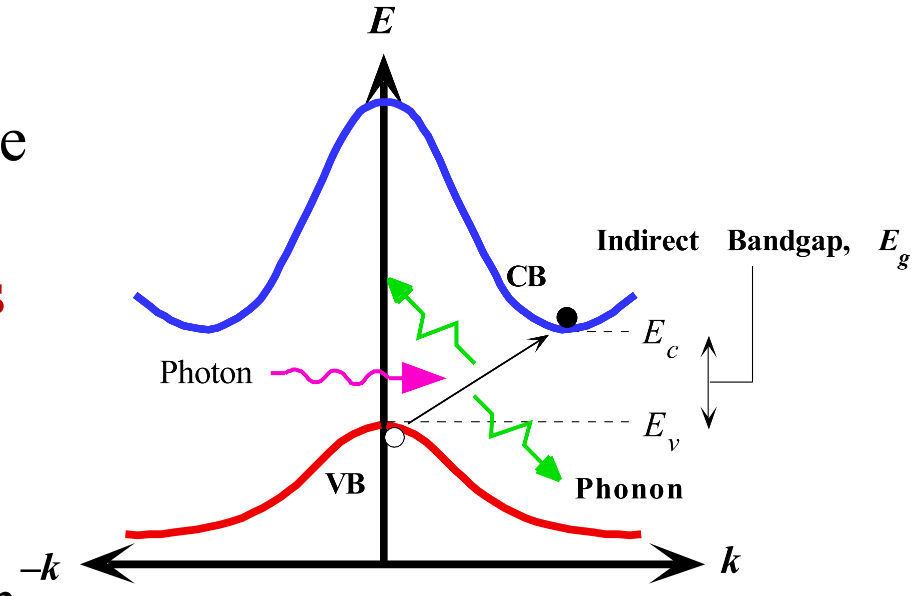


(a) GaAs (Direct bandgap)

- Absorption coefficient α for direct bandgap semiconductors rise sharply with decreasing wavelength from λ_g (GaAs and InP).

Absorption Coefficient

- Indirect bandgap semiconductors (Si and Ge), the photon absorption requires assistant from lattice vibrations (**phonon**). If K is wave vector of lattice wave, then ħK represents the momentum associated with lattice vibration → ħK is a **phonon momentum**.



(b) Si (Indirect bandgap)

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

- Thus the probability of photon absorption is not as high as in a direct transition and the λ_g is not as sharp as for direct bandgap semiconductors.

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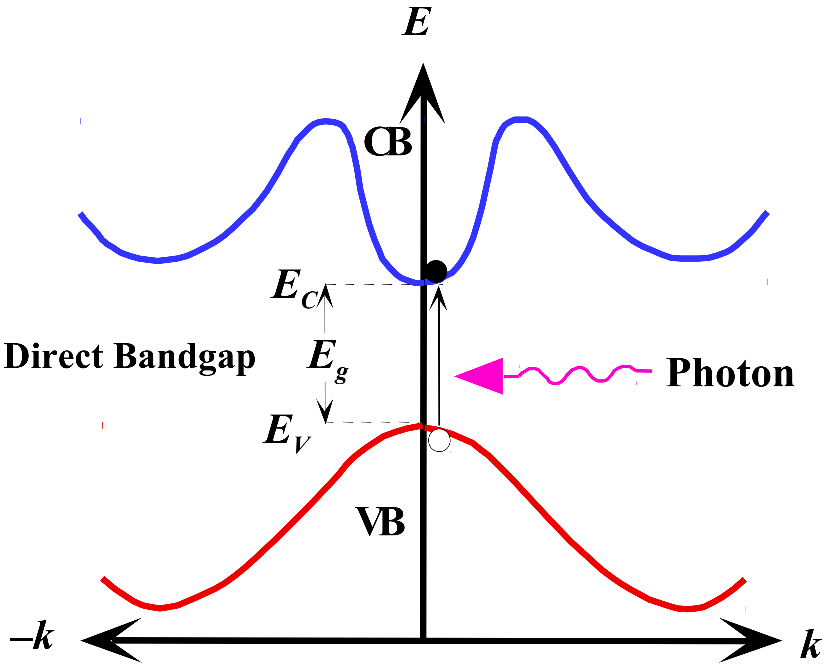
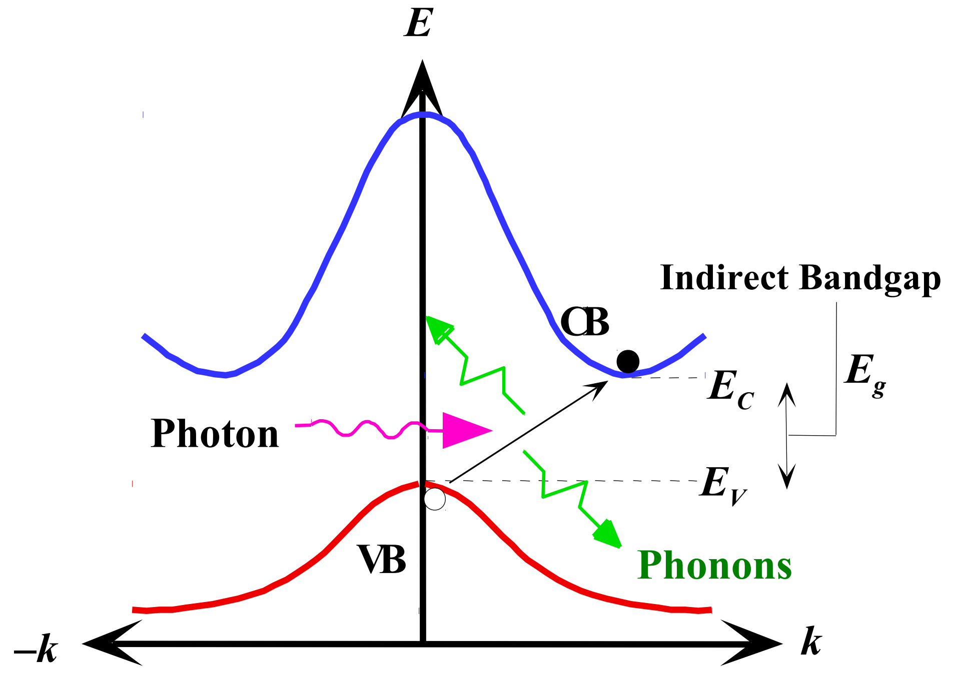
Absorption Coefficient and Photodiode Materials

Photon absorption in a direct bandgap semiconductor.



Photon absorption in an indirect bandgap semiconductor



Quantum Efficiency and Responsivity

- External Quantum Efficiency

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

- Responsivity

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

$$R = \eta\frac{e}{h\nu} = \eta\frac{e\lambda}{h\,c}$$ *Spectral Responsivity*

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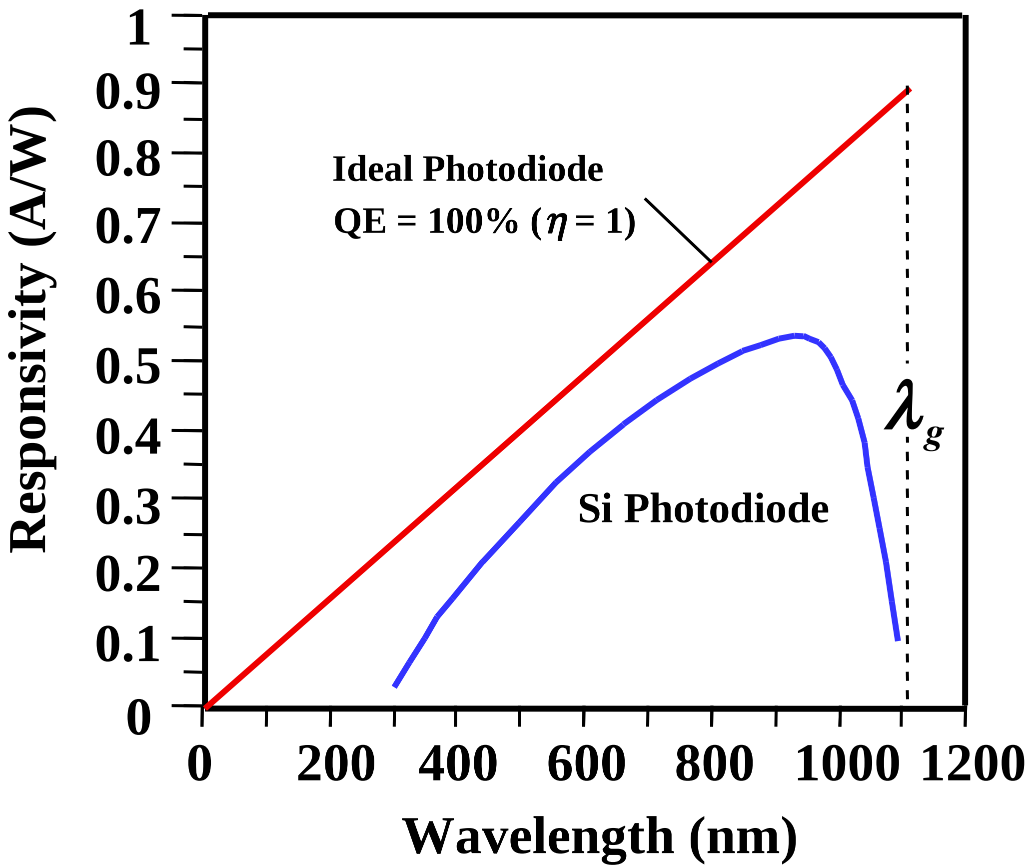
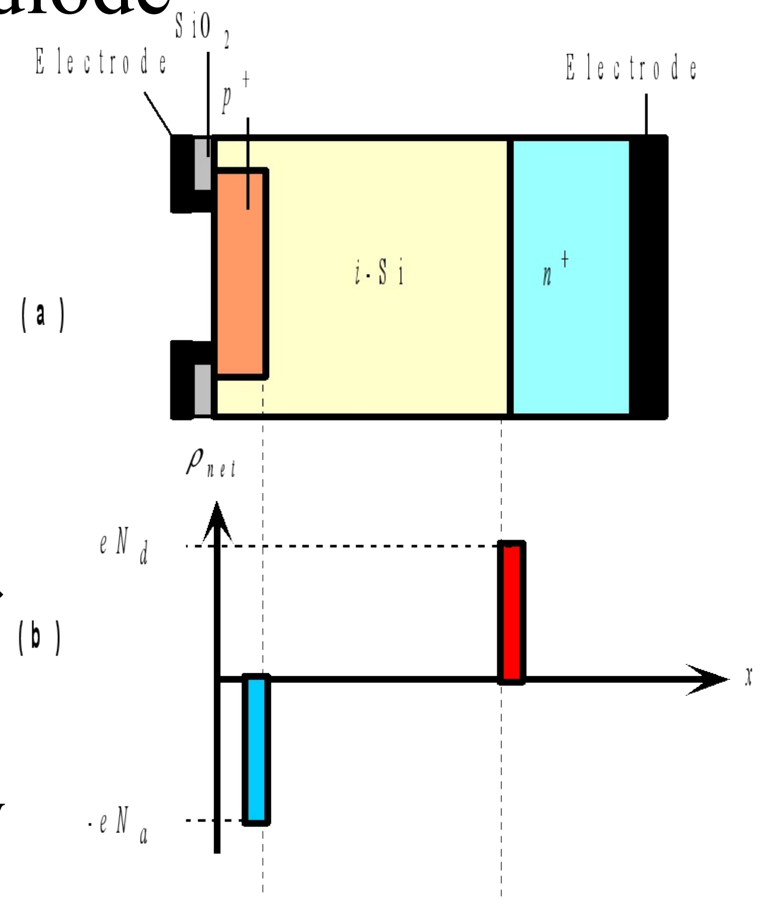
- Responsivity vs. wavelength for a typical *Si* photodiode.



The *pin* Photodiode

- The *pn* junction photodiode 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* photodiode can significantly reduce these problems.



- Intrinsic layer has less doping and wider region (5 – 50 μm).

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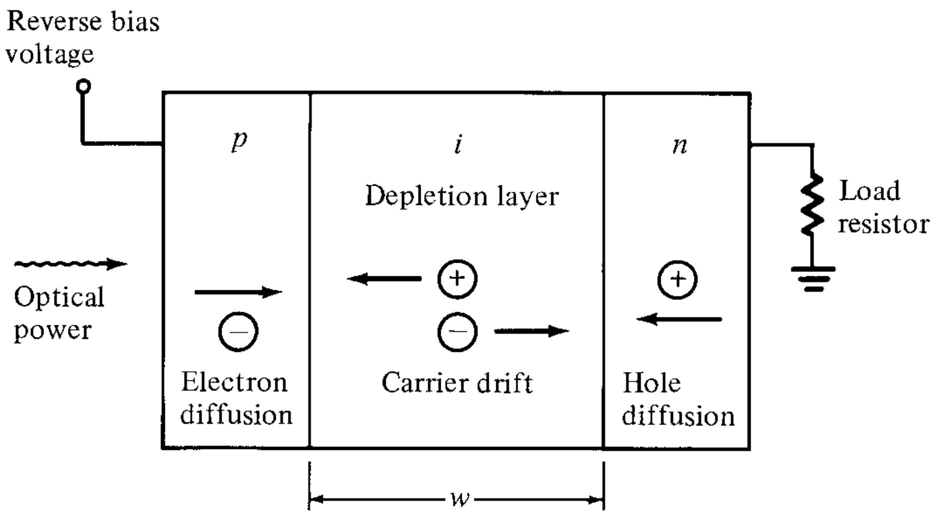
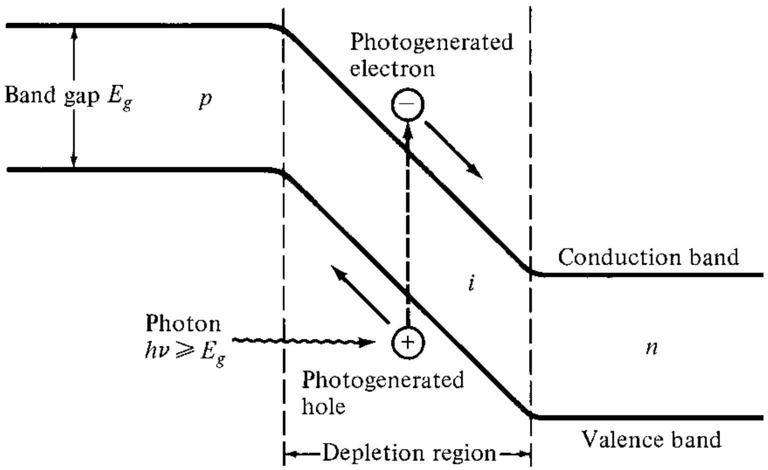
The *pin* Photodiode

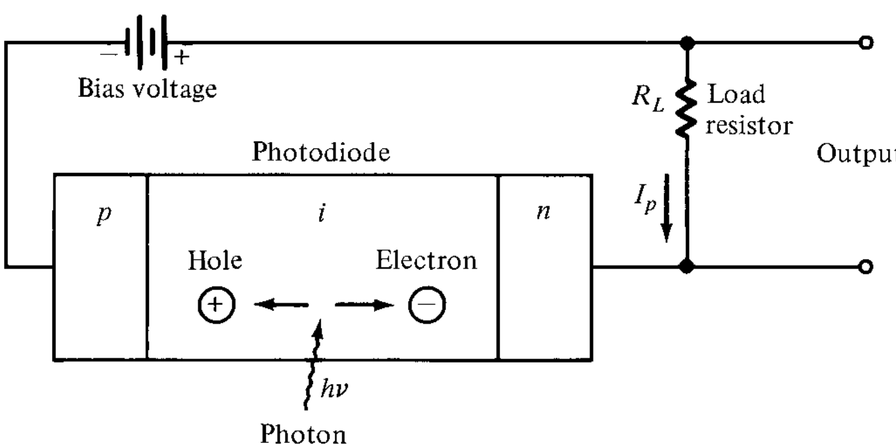
- Reverse-biased *p-i-n* photodiode



- *pin* energy-band diagram

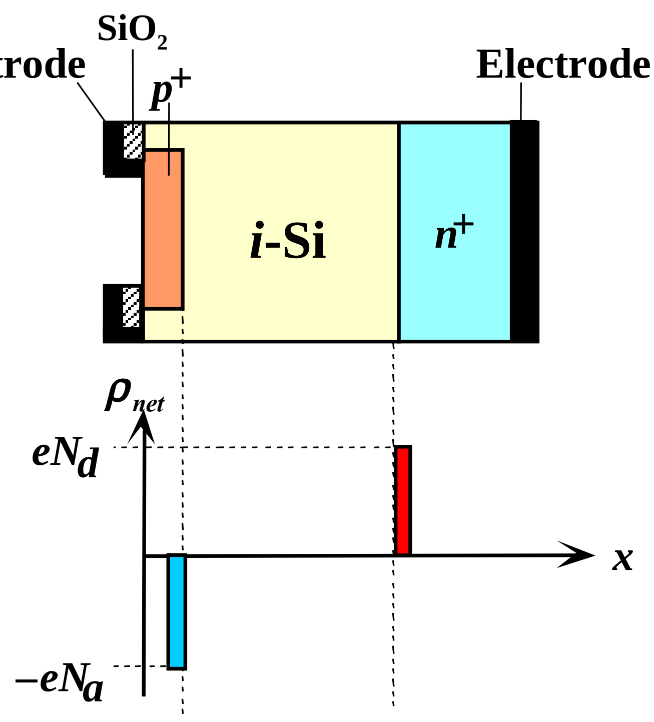


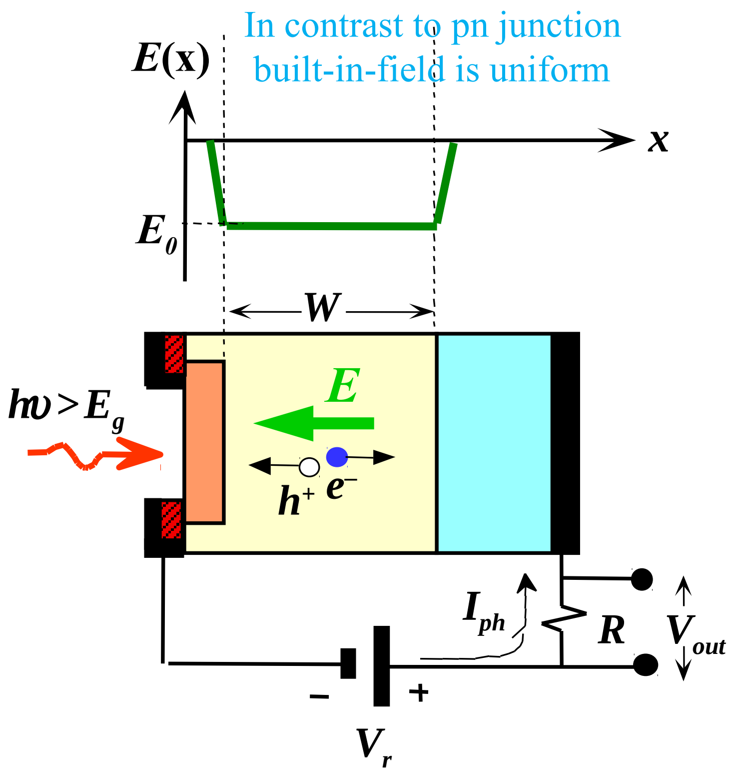
- *pin* photodiode circuit



The *pin* Photodiode

❑ Schematic diagram of *pin* photodiode





➢ <u>Small depletion layer capacitance</u> gives <u>high modulation frequencies</u>.

➢ <u>High Quantum efficiency</u>.

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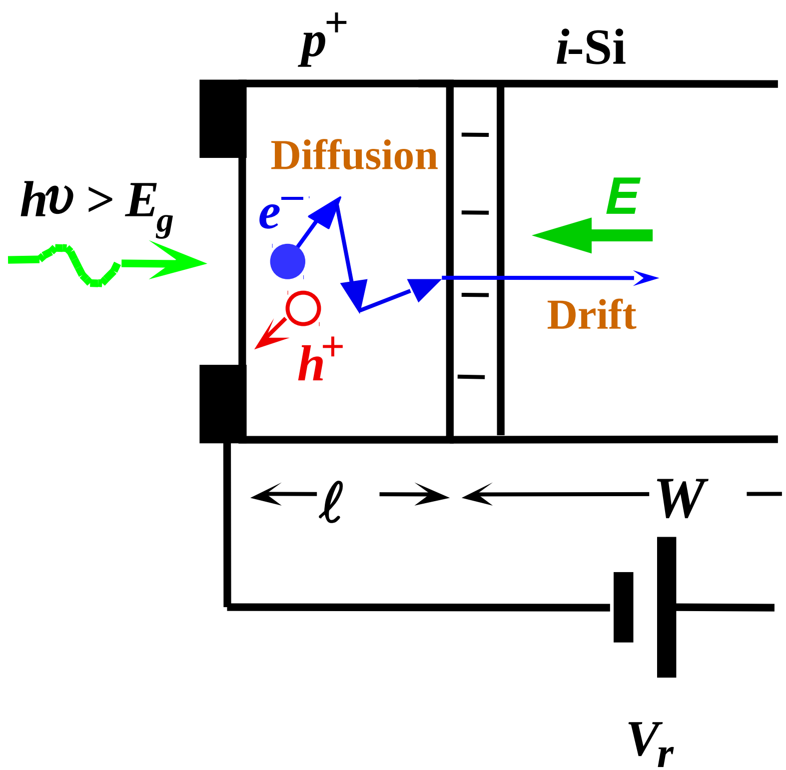
The *pin* Photodiode

- 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.



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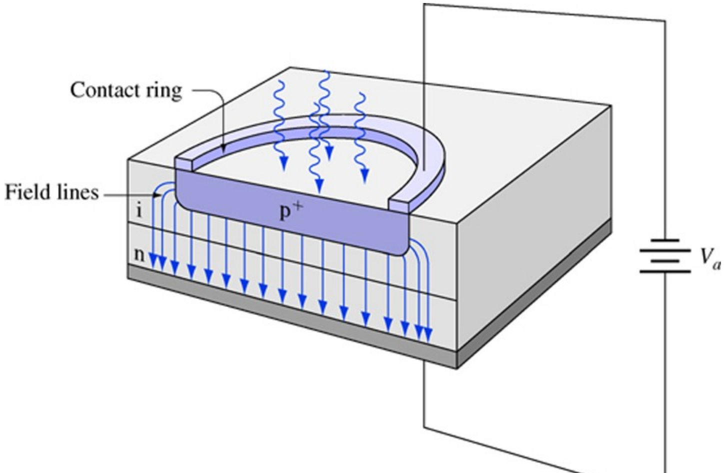
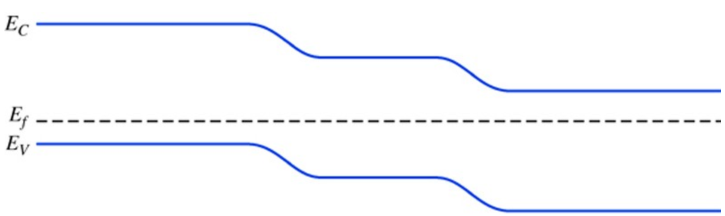
The *pin* Photodiode

***p-i-n* diode**



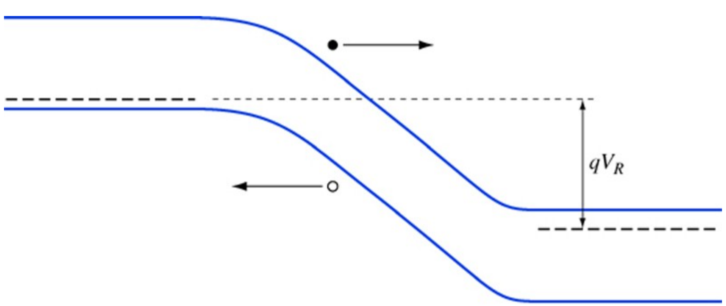
(a)

(a) The structure;



(b)

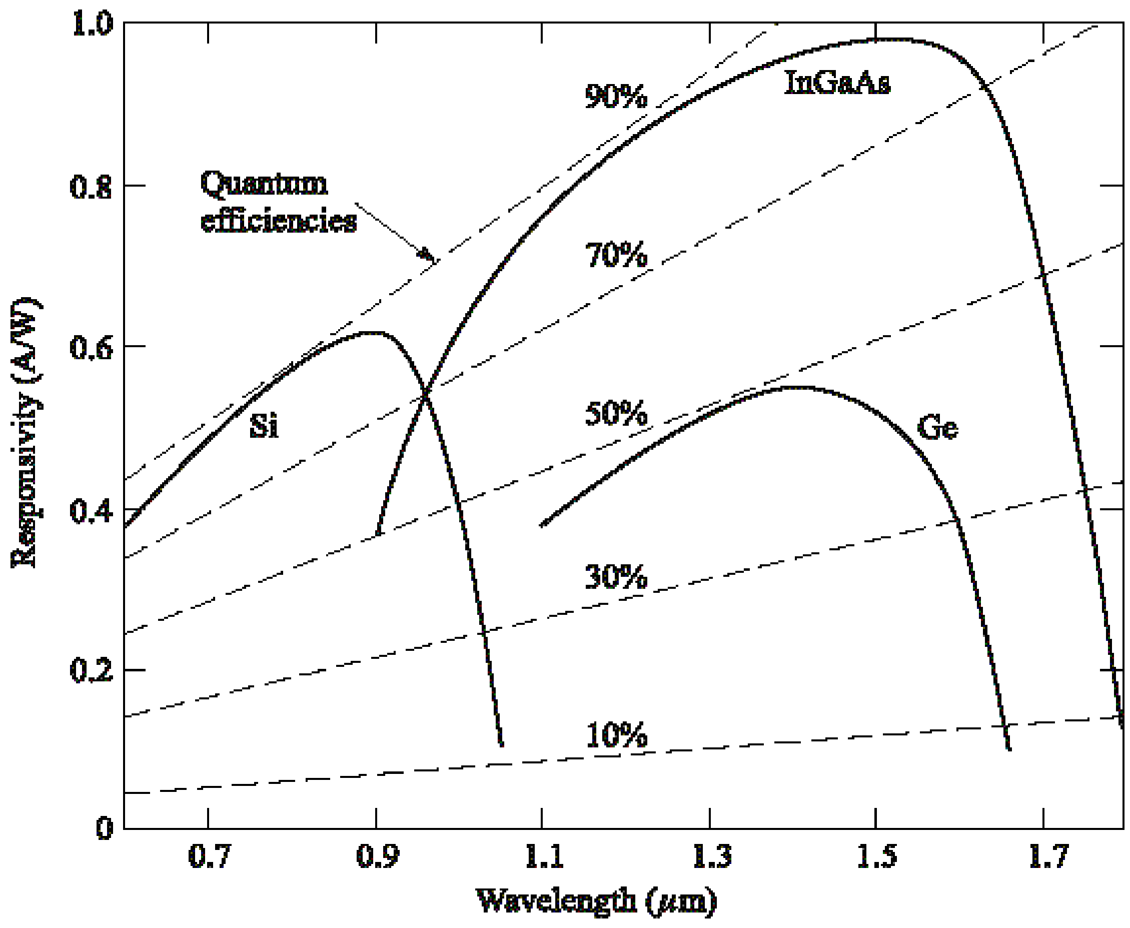
(b) equilibrium energy band diagram;



(c)

(c) energy band diagram under reverse bias.

- **The responsivity of *pin* photodiodes**



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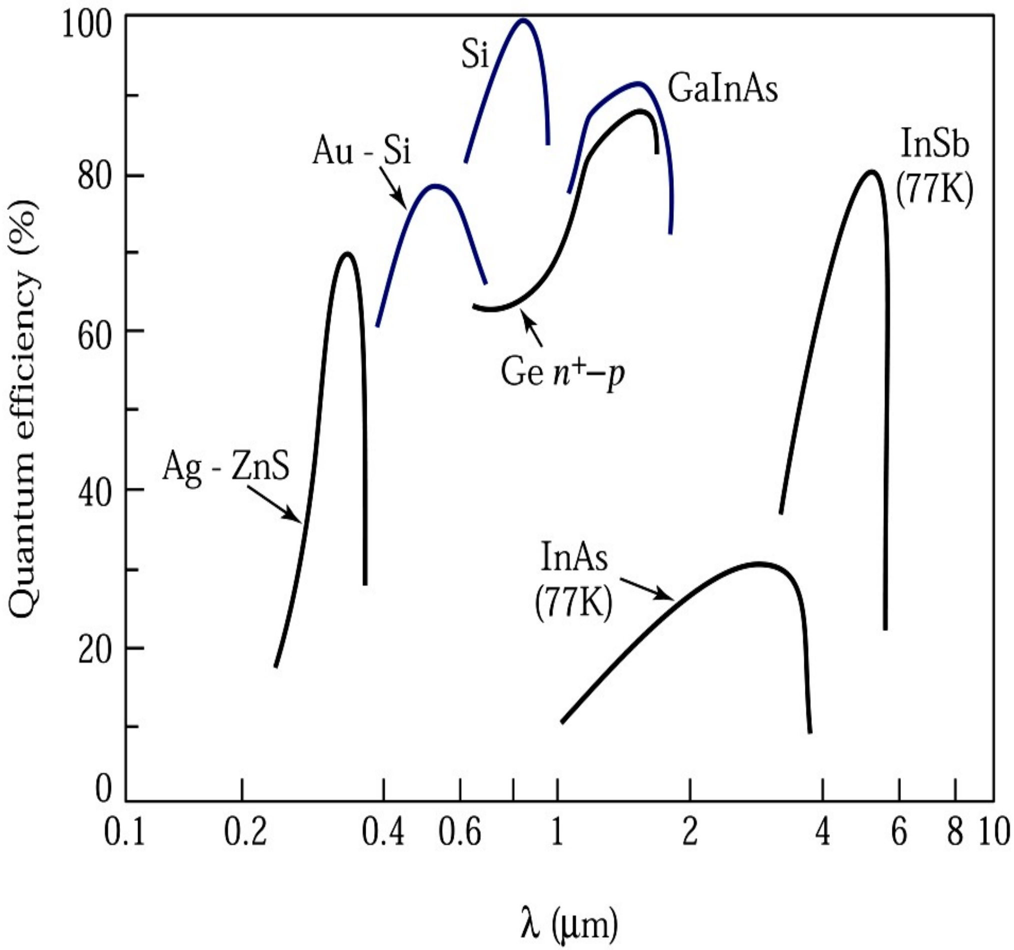
Photoconductive Detectors and Photoconductive gain

- **Quantum efficiency versus wavelength for various photodetectors.**



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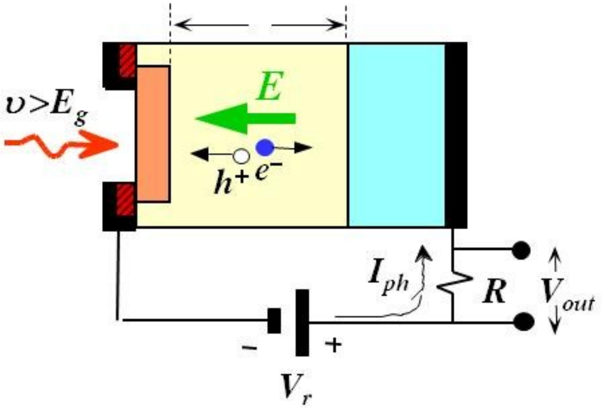
The *pin* Photodiode



- **Junction capacitance of *pin***

$$C_{dep} = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

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

- **Electric field of biased *pin***

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

- **Response time**

$$t_{drift} = \frac{W}{\mathrm{v}_d}$$

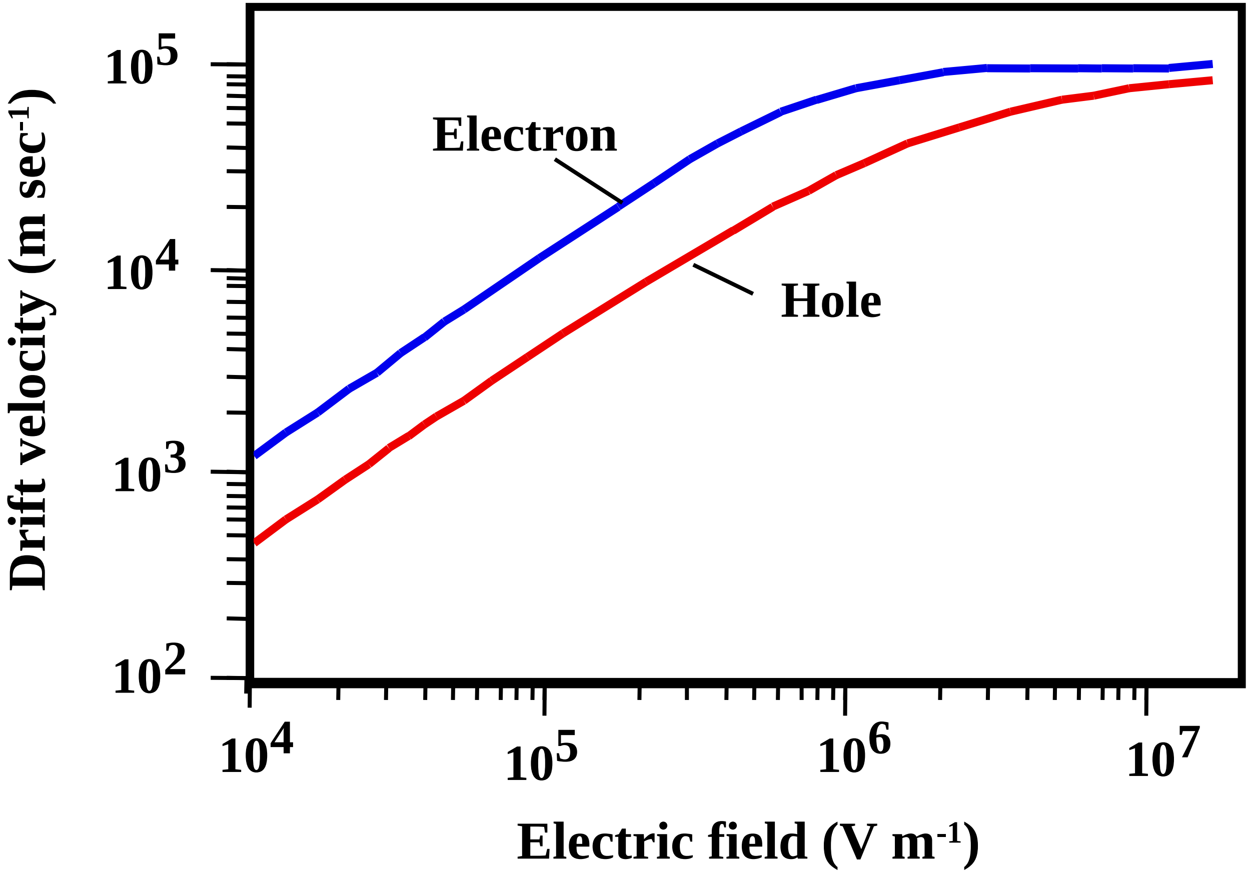
$$\mathrm{v}_d = \mu_d E$$

- 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 μm, the drift time is about is about 0.1 nsec.

Photodetectors

The *pin* Photodiode

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



A Si *pin* photodiode has an *i*-Si layer of width 20 μm. The p^+ layer on the illumination side is very thin (0.1 μm). 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 ~3×10^4 m^{-1} so that the absorption depth is ~33 μm 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 m s^{-1}, whereas the hole drift velocity v_h, is about 7×10^4 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 μm and the p^+ layer is 1 μm and the applied voltage is 120 V? The diffusion coefficient (D_e) of electrons in the heavily doped p^+ region is approximately 3×10^{-4} m^2 s^{-1}.

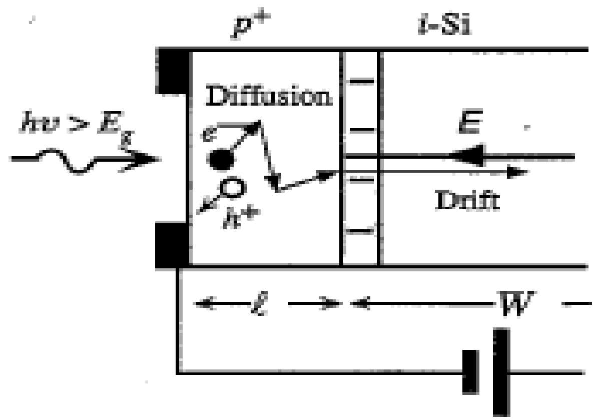


FIGURE 5.8 A reverse biased *pin* photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

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 ℓ given by[5]

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

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

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

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 m s^{-1}. The *drift time* across the *i*-Si layer is

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

Thus, the response time of the *pin* to a pulse of short wavelength radiation that is absorbed near the surface is about $t_{diff} + t_{drift}$ 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 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 $I = 0.1$ 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

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

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 5×10^{-2} cm^2 is irradiated with yellow light whose intensity is 20 mW cm^{-2}. Assuming that each photon generates one electron-hole pair, calculate the number of pairs generated per second.

Solution

(a) Given, λ = 600 nm, we need $E_{ph} = h\upsilon = E_g$ so that,

$E_g = hc/\lambda = (6.626\times10^{-34}\text{ J s})(3\times10^{8}\text{ m s}^{-1})/(600\times10^{-9}\text{ m}) = 2.07\text{ eV}$

(b) $Area = 5\times10^{-2}$ cm^2 and $I_{light} = 20\times10^{-3}$ W/cm^2.

The received power is

$P = Area \times I_{light} = (5\times10^{-2}\text{ cm}^2)(20\times10^{-3}\text{ W/cm}^2) = 10^{-3}\text{ W}$

N_{ph} = number of photons arriving per second $= P/E_{ph}$

$= (10^{-3}\text{ W})/(2.059\times1.60218\times10^{-19}\text{ J/eV})$

$= 2.9787\times10^{15}$ photons s^{-1} = 2.9787×10^{15} 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

$$\lambda = hc/E_g = (6.626\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})/(1.42\ \text{eV}\times1.6\times10^{-19}\ \text{J/eV})$$

$$= 873\ \text{nm (invisible IR)}$$

∴ 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,

$$\lambda_g = hc/E_g = (6.626\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})/(1.1\ \text{eV}\times1.6\times10^{-19}\ \text{J/eV})$$

$$= \mathbf{1120\ nm}$$

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_o is the intensity of the incoming radiation, the **number of photons absorbed** **per unit volume of sample is**

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

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 $In_{0.53}Ga_{0.47}As$ crystal layer that is needed for absorbing 90% of the incident radiation at 1.5 μm?

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

For $In_{0.53}Ga_{0.47}As$, $\alpha \approx 7.5 \times 10^5\ m^{-1}$ *at 1.5 μm* incident radiation.

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

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

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

For $In_{0.53}Ga_{0.47}As$, $\alpha \approx 7.5 \times 10^5\ m^{-1}$ *at 1.5 μm* incident radiation.

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

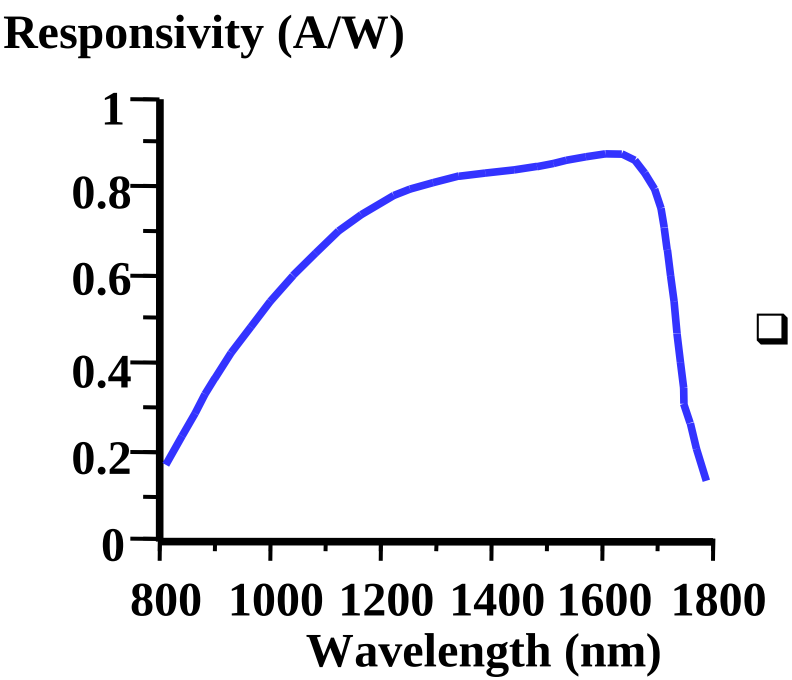
Example

InGaAs *pin* Photodiodes

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

(a) What optical power at a wavelength of 1.55 μm would give a photocurrent that is twice the dark current? What is the QE of the photodetector at 1.55 μm?

(b) What would be the photocurrent if the incident power in **a** was at 1.3 μm? What is the QE at 1.3 μm operation?



- **The responsivity of an InGaAs *pin* photodiode**

Solution

(a) At $\lambda = 1.55\times10^{-6}$ m, from the responsivity vs. wavelength curve we have $R \approx 0.87$ A/W. From the definition of responsivity,

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

we have

$$P_0 = \frac{I_{ph}}{R} = \frac{2I_{dark}}{R} = \frac{2\times5\times10^{-9}(A)}{0.87\ A/W)} = 11.5\ nW$$

From the definitions of quantum efficiency η and responsivity,

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

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62\times10^{-34}\,J\cdot\sec)(3\times10^{8}\,m/s)(0.87\,A/W)}{(1.6\times10^{-19}\,coul)(1.55\times10^{-6}\,m)} = 0.70\ (70\ \%)$$

Note the following dimensional identities: A = C s^{-1} and W = J s^{-1} so that A W^{-1} = 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 λ = 1.3×10^{-6} m, from the responsivity *vs*. wavelength curve, $\boldsymbol{R}$ = 0.82 A/W.

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

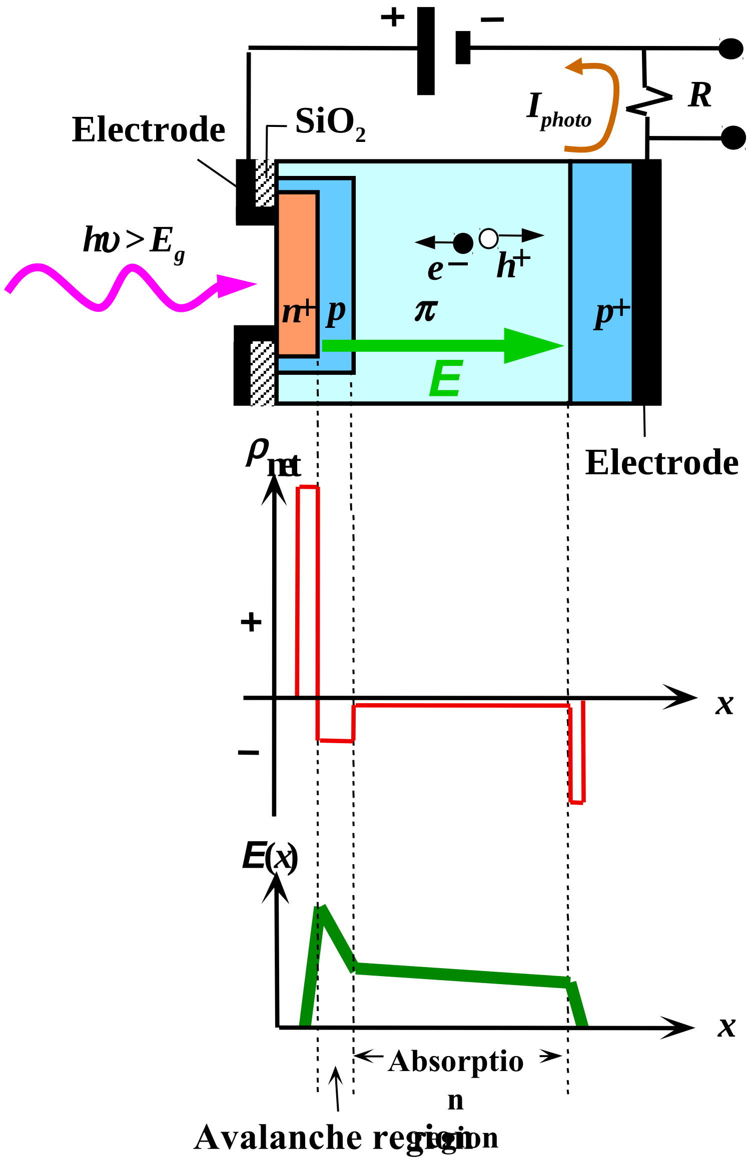
$$\boldsymbol{I_{ph} = R \cdot P_0 = (0.82\ A/W)(1.15\, nW) = 9.43\ nA}$$

The QE at λ = 1.3 μm is

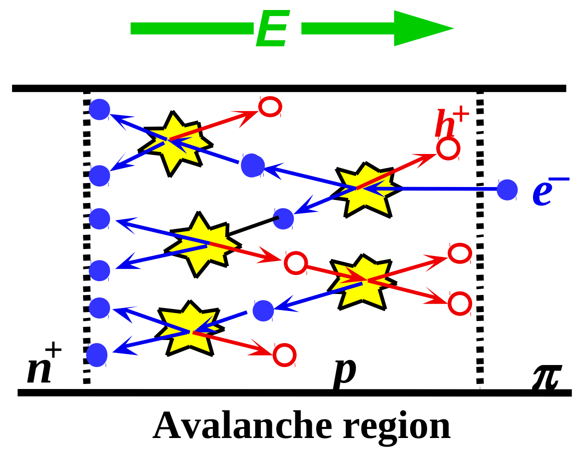
$$\boldsymbol{\eta = \frac{hcR}{e\lambda} = \frac{(6.62\times10^{-34}\, J \cdot \text{sec})(3\times10^{8}\, m/s)(0.82\, A/W)}{(1.6\times10^{-19}\, coul)(1.3\times10^{-6}\, m)} \approx 0.78\ (78\ \%)}$$

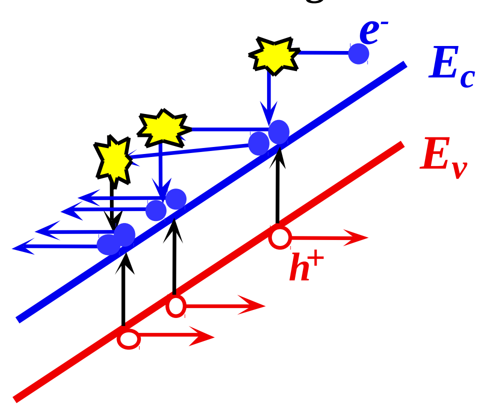
Photodetectors

Avalanche Photodiode (APD)



❑ **Impact ionization processes resulting avalanche multiplication**



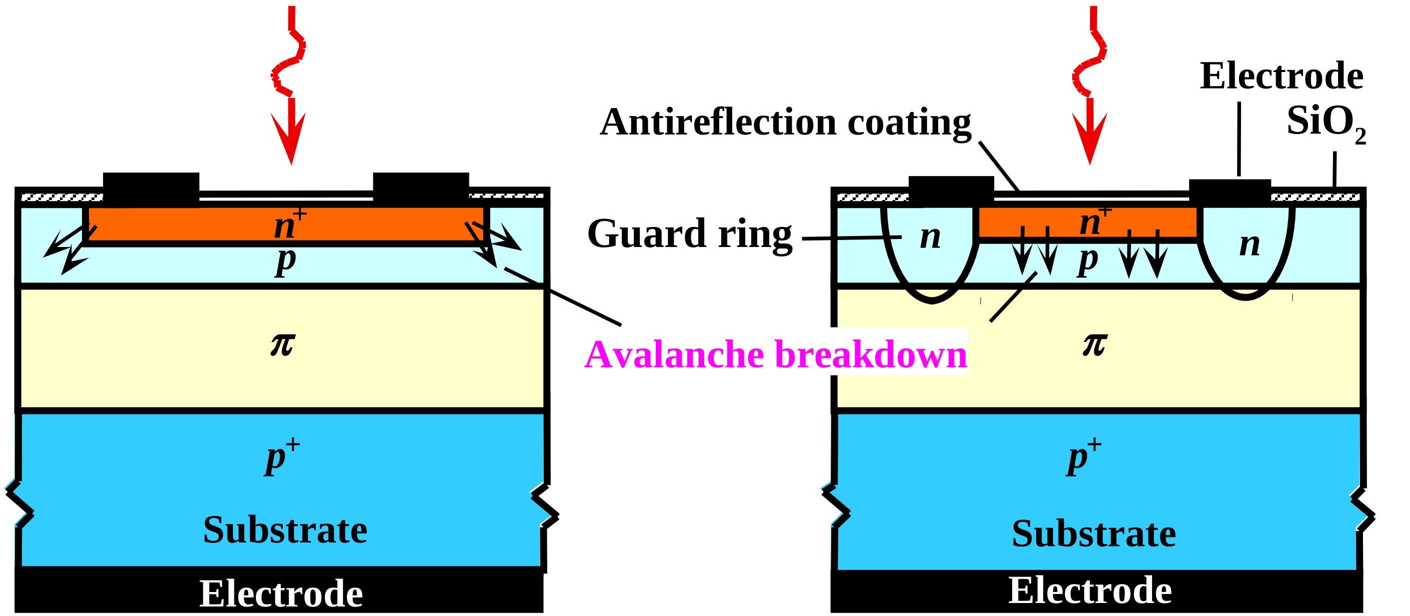


➢ **Impact of an energetic electron's kinetic energy excites VB electron to the CV.**

Photodetectors

Avalanche Photodiode (APD)

❑ **Schematic diagram of typical *Si* APD.**



Si APD structure without a guard ring

More practical *Si* APD

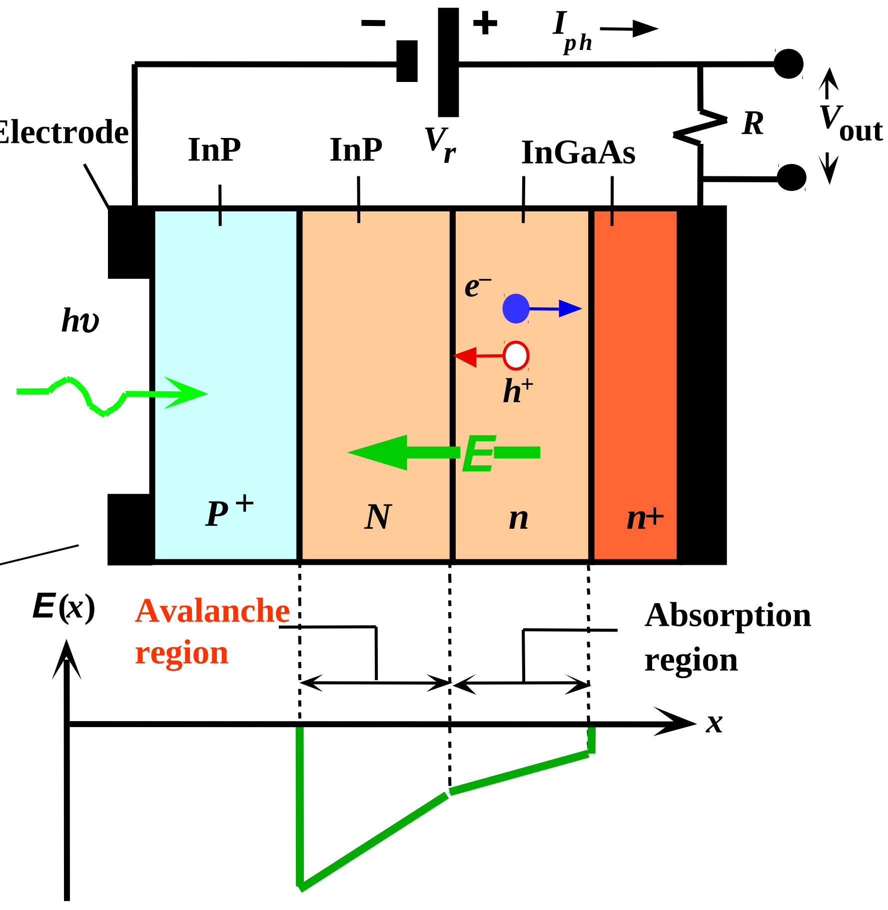
➢ **Breakdown voltage around periphery is higher and avalanche is confined more to illuminated region (n^+p junction).**

Photodetectors

Heterojunction Photodiode

Separate Absorption and Multiplication (SAM) APD

InGaAs-InP heterostructure Separate Absorption and Multiplication APD

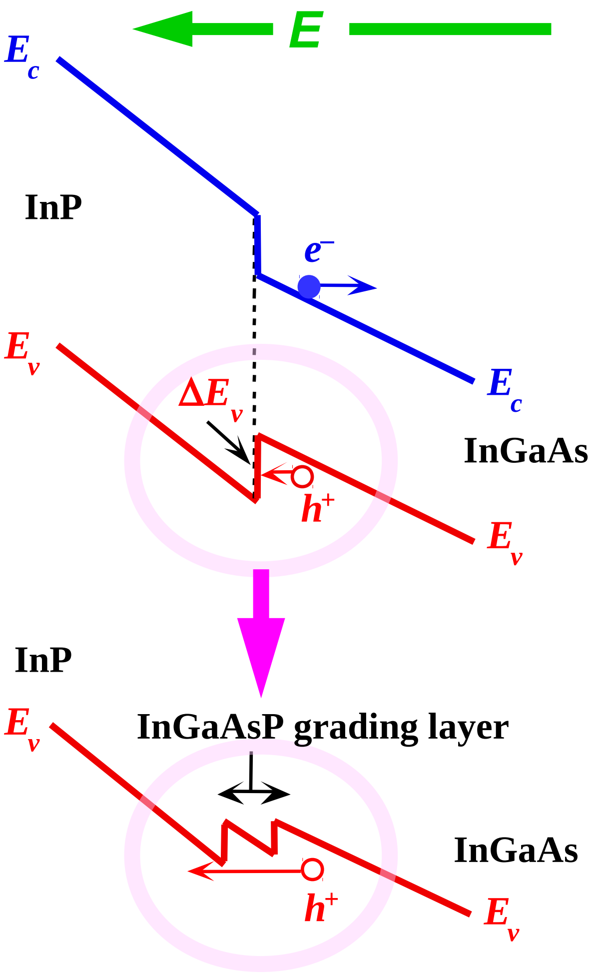


P and *N* refer to *p*- and *n*-type wider-bandgap semiconductor.

Photodetectors

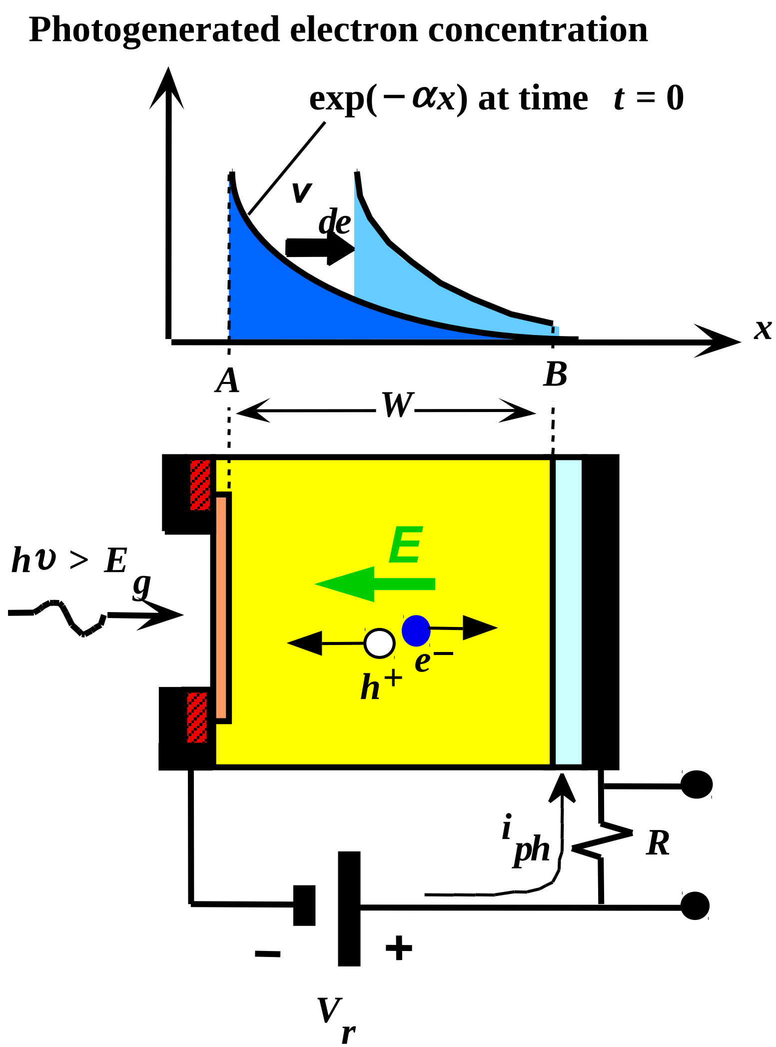
Heterojunction Photodiode

Separate Absorption and Multiplication (SAM) APD



(a) Energy band diagram for a **SAM heterojunction APD** where there is a <u>valence band step</u> ΔE_v from InGaAs to InP that slows hole entry into the InP layer.

(b) An interposing <u>grading layer</u> (InGaAsP) with an intermediate bandgap breaks ΔE_v and makes it easier for the hole to pass to the InP layer.



Photogenerated electron concentration
exp(−αx) at time t = 0
v
de
x
A
B
W
E
hυ > E
g
h+
e−
i
ph
R
−
+
V
r