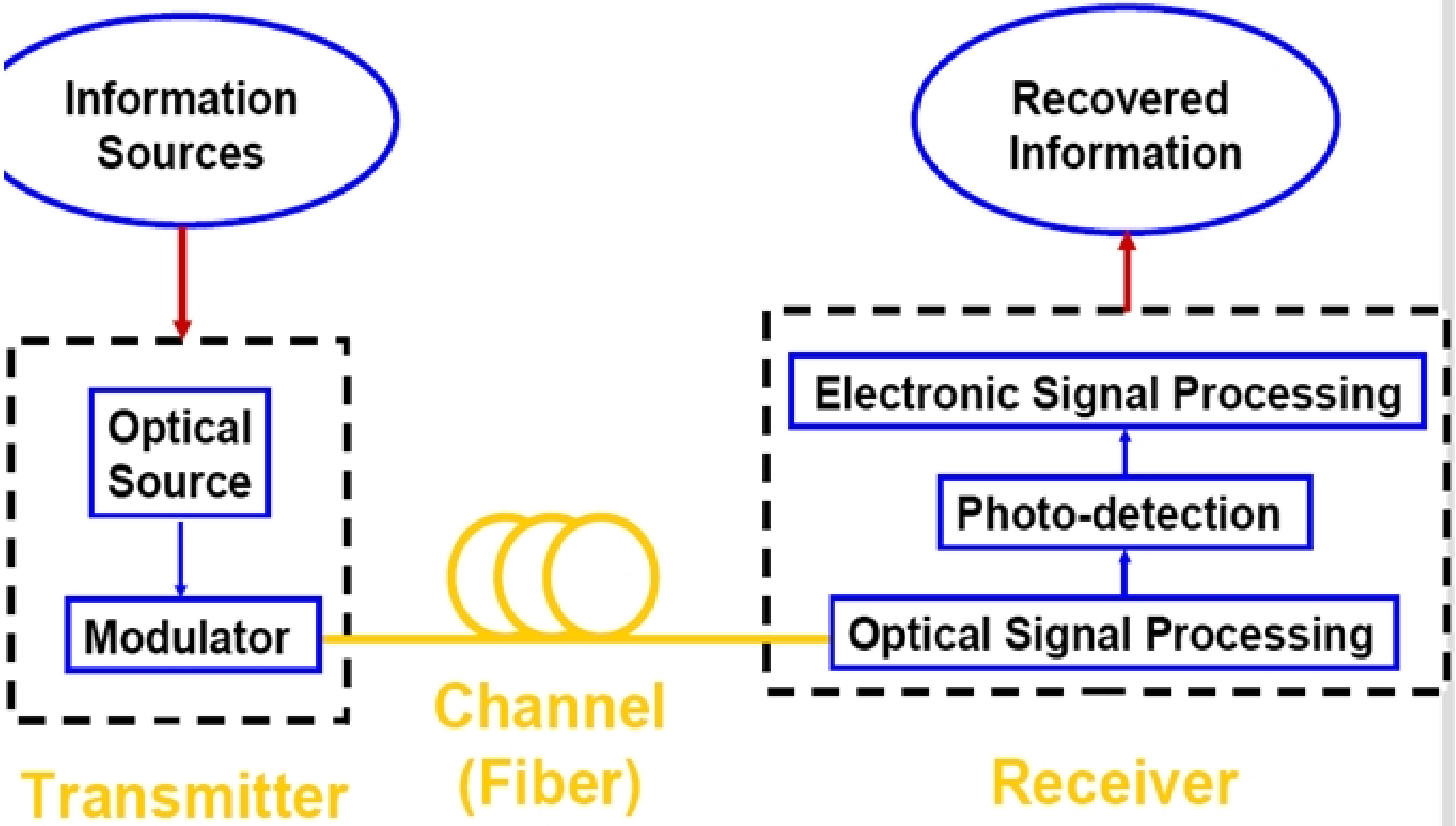
LECTURE 17

-Photodetectors

Topics to be covered

- Photodetectors
- PIN photodiode
- Avalanche Photodiode



Information Sources

Optical Source

Modulator

Transmitter

Channel (Fiber)

Recovered Information

Electronic Signal Processing

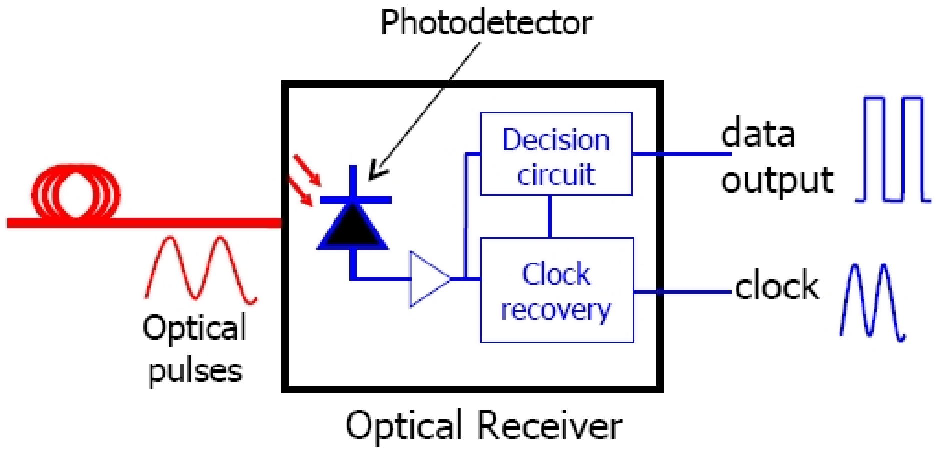
Photo-detection

Optical Signal Processing

Receiver

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

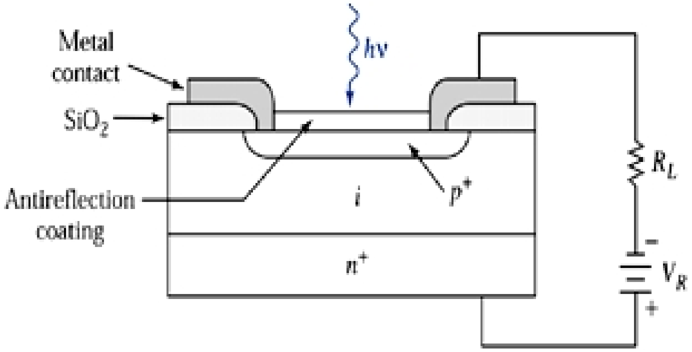
❑ Basic requirements of a photodetector

- 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

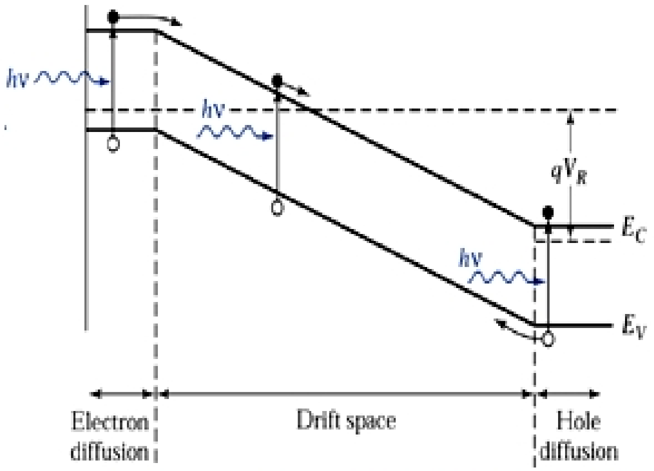
Photodetectors

Principle of the p-n junction Photodiode

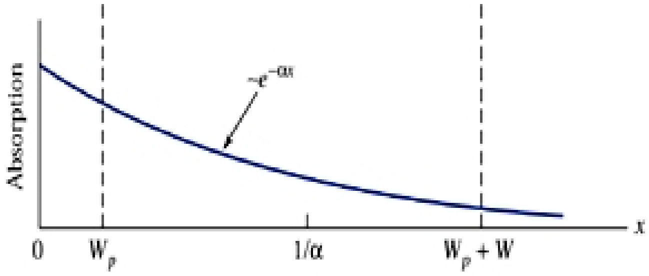
- Operation of a p-i-n photodiode.



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



(b) Energy band diagram under reverse bias.

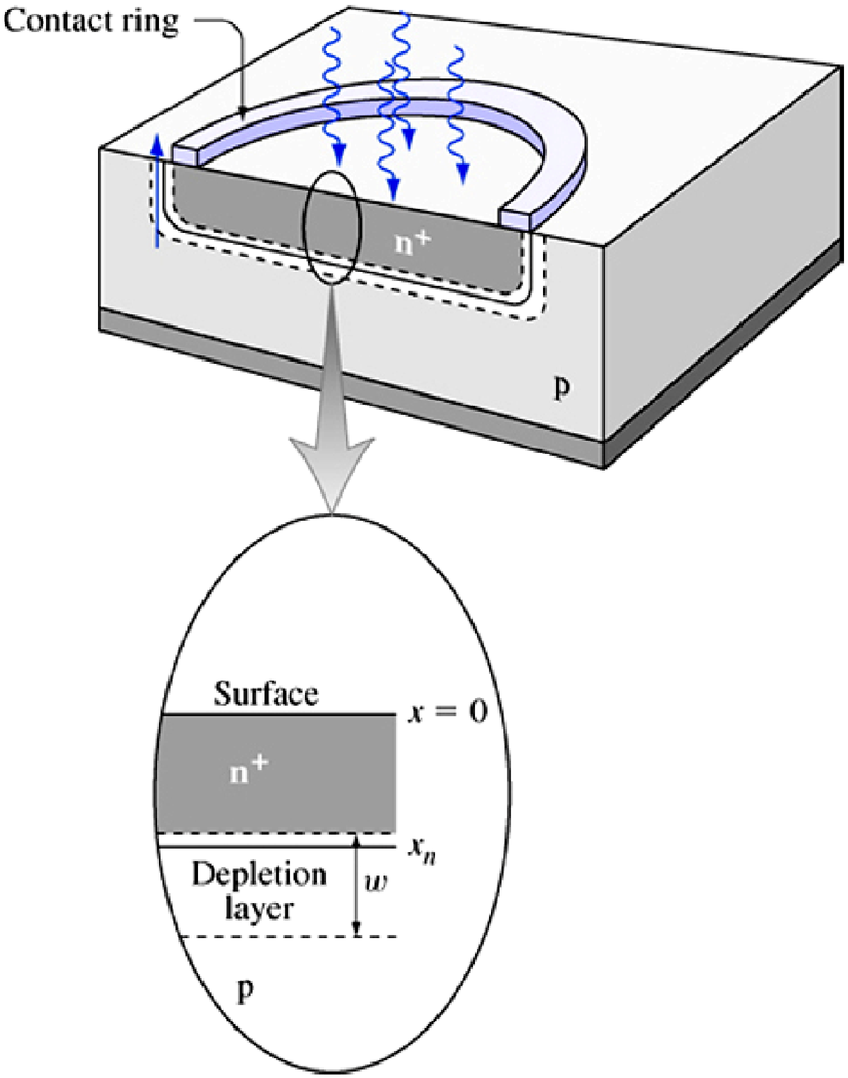


(c) Carrier absorption characteristics.

Photodetectors

Principle of the p-n junction Photodiode

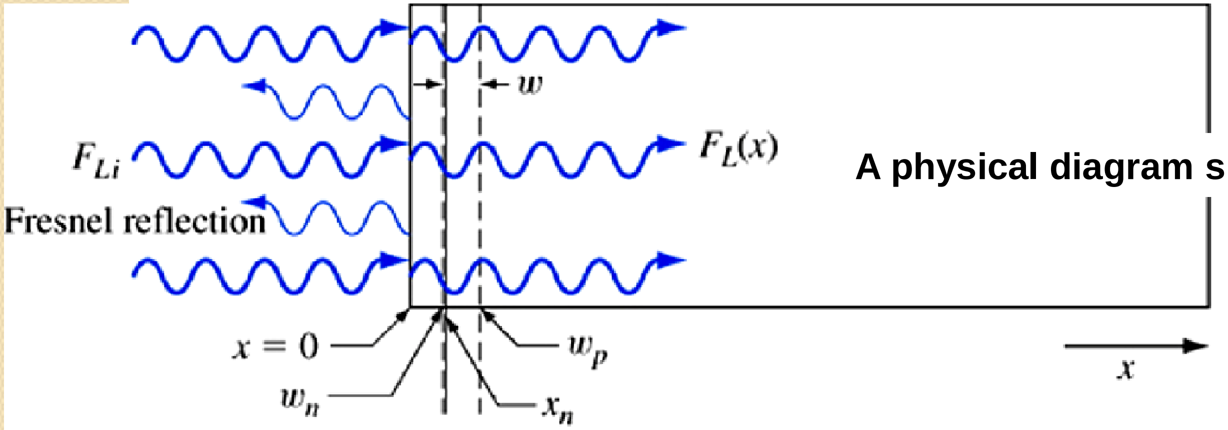
- ❑ A generic photodiode.



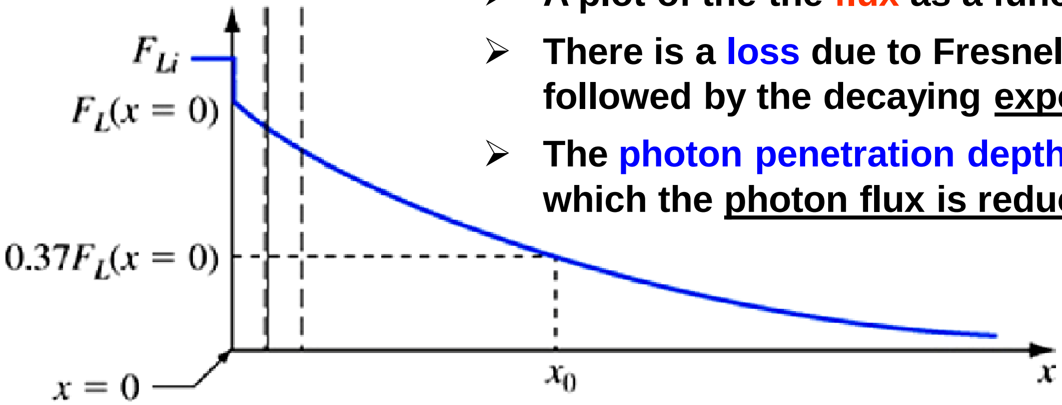
Photodetectors

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.

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

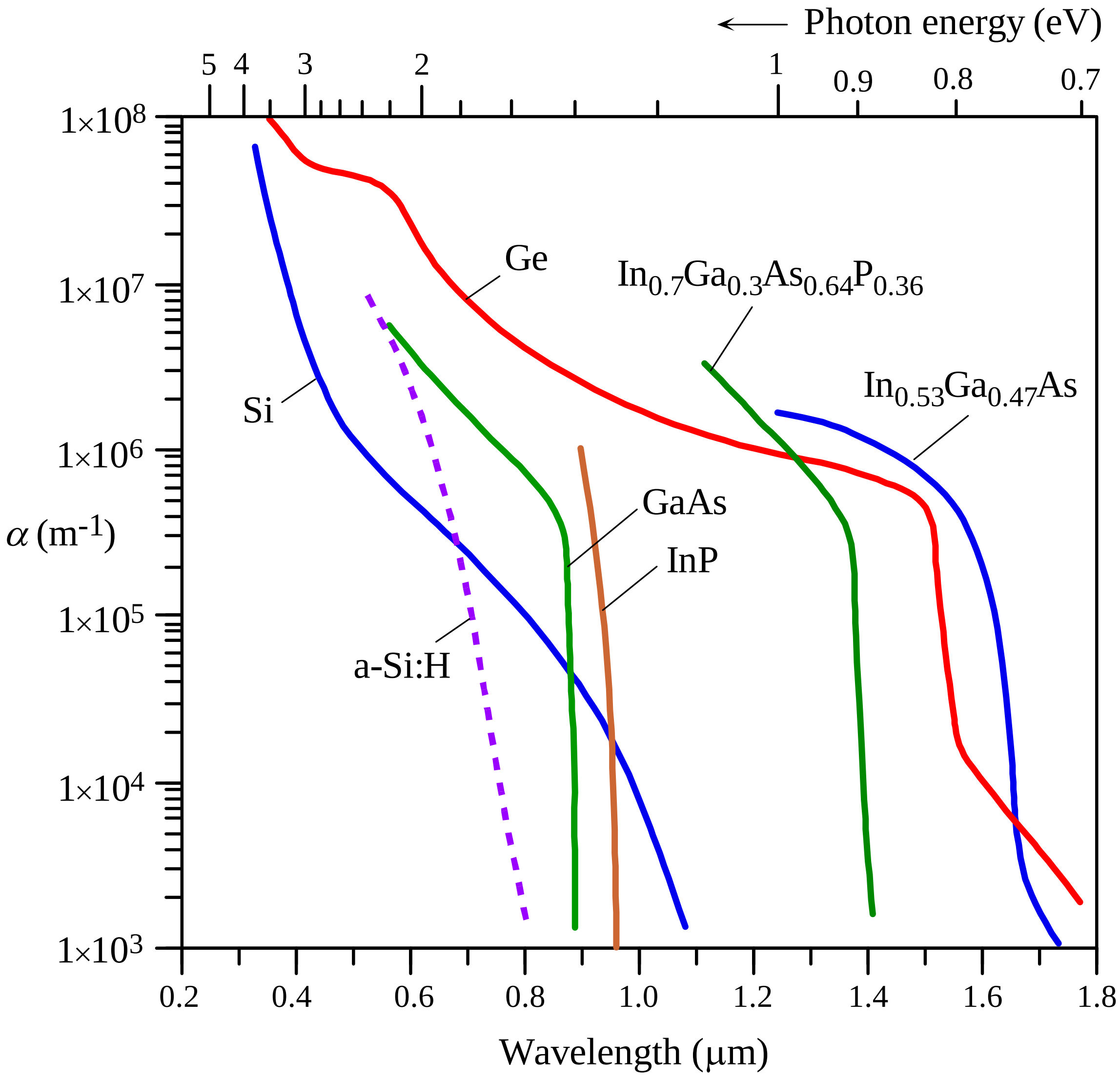
- Incident photons become absorbed as they travel in the semiconductor and <u>light intensity decays exponentially</u> with distance into the semiconductor.

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

Absorption coefficient

Absorption Coefficient

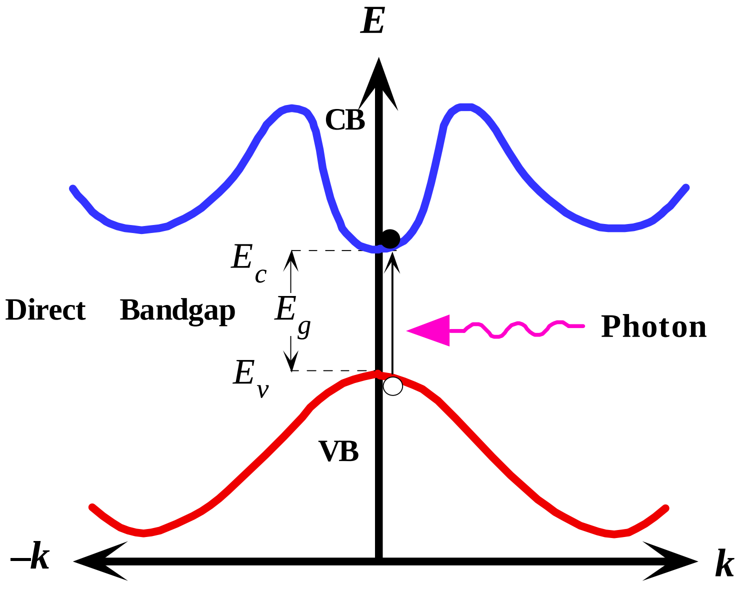
- Absorption coefficient α is a material property.
- Most of the photon absorption (63%) occurs over a distance 1/α (it is called **penetration depth** δ)



Absorption 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.

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

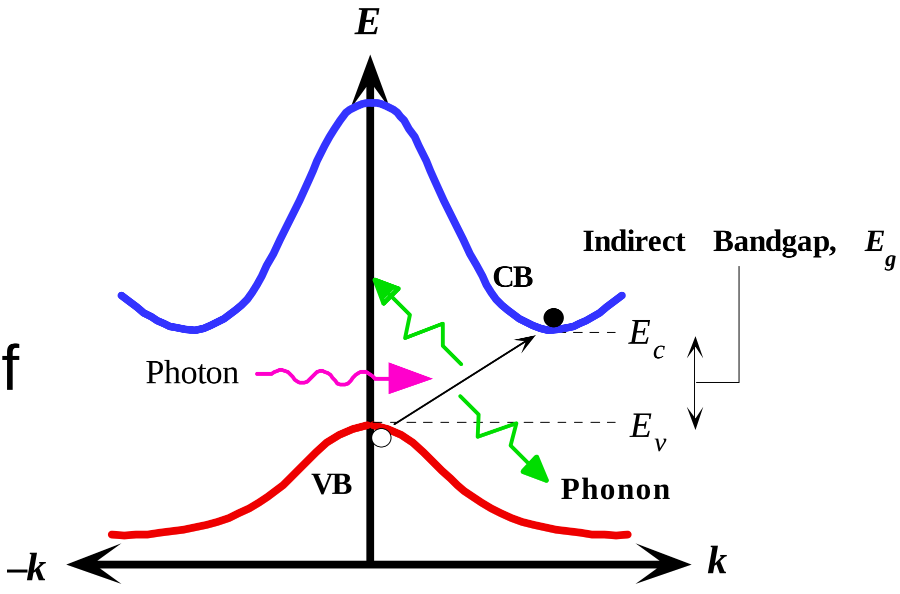


(a) GaAs (Direct bandgap)

- 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)

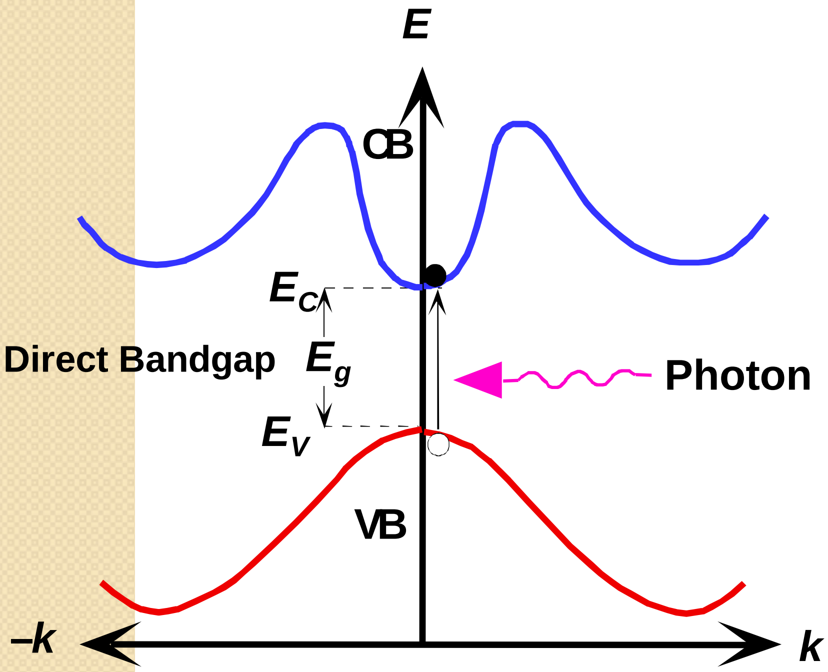
$$\hbar k_{\mathrm{CB}} - \hbar k_{\mathrm{VB}} = \text{phonon momentum} = \hbar K$$

- 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.

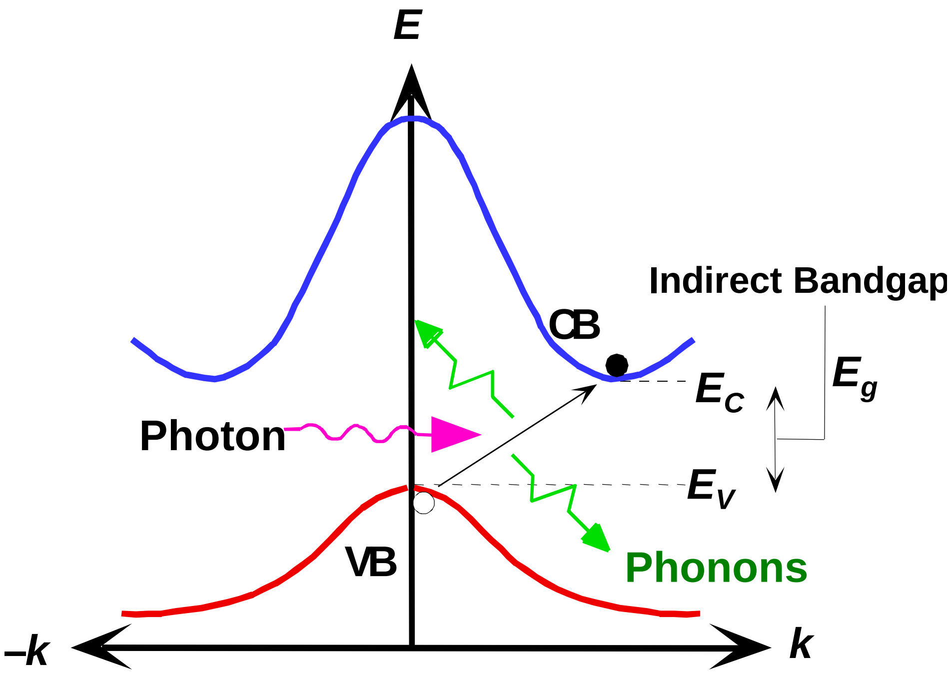
Photodetectors

Absorption Coefficient and Photodiode Materials

Photon absorption in a direct bandgap semiconductor.



Photon absorption in an indirect bandgap semiconductor



Photodetectors

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

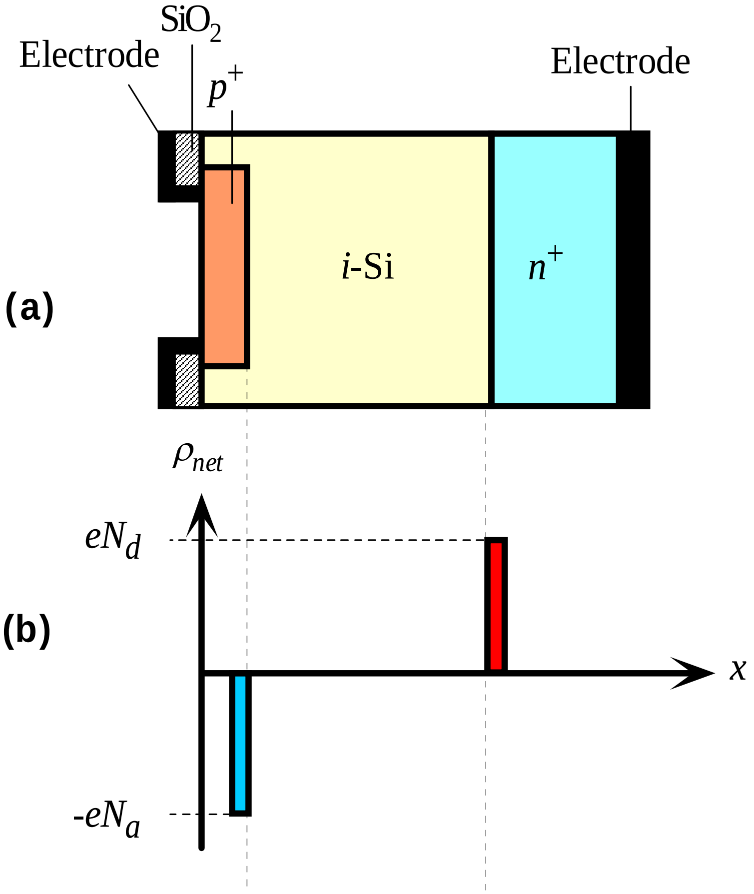
$$R = \frac{Photocurrent\ (A)}{Incident\ Optical\ \ Power\ (W)} = \frac{I_{ph}}{P_0}$$

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

Spectral Responsivity

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.

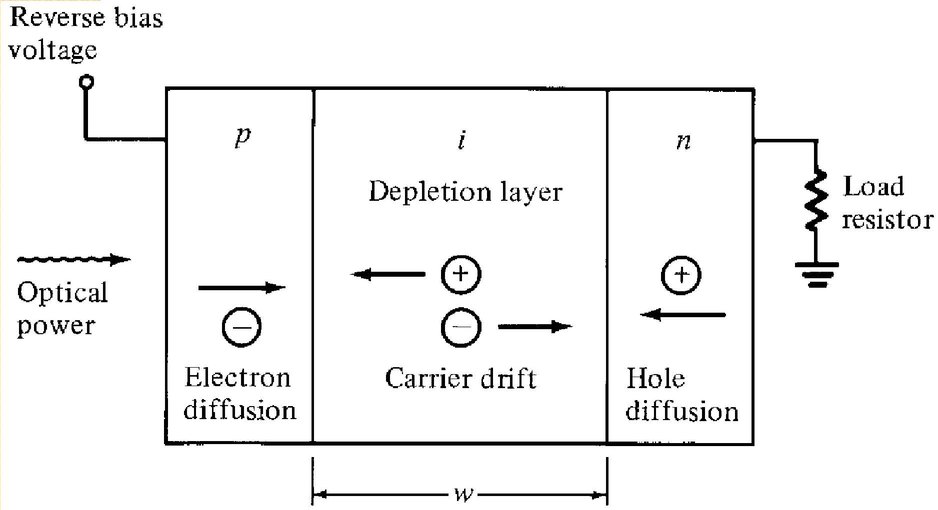


- Intrinsic layer has less doping and wider region (5 – 50 μm).

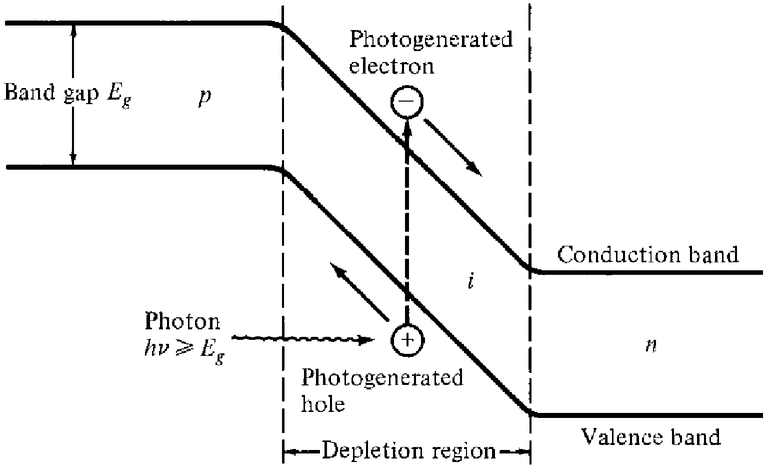
Photodetectors

The *pin* Photodiode

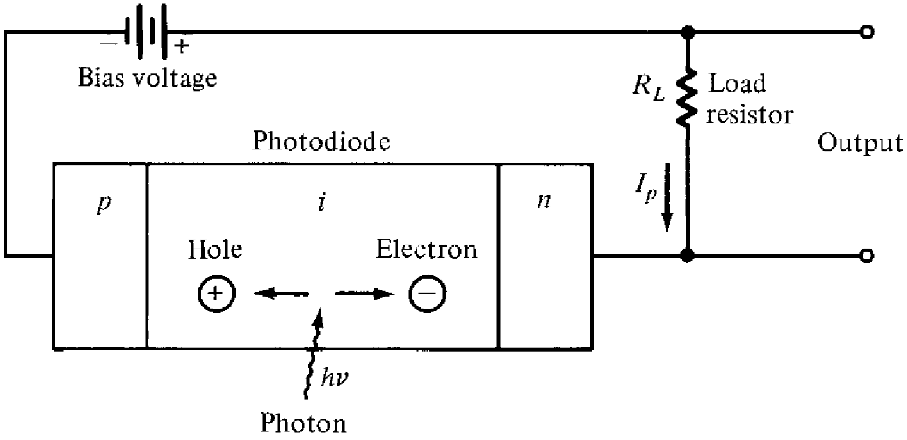
- ☐ **Reverse-biased *p-i-n* photodiode**



- ☐ ***pin* energy-band diagram**



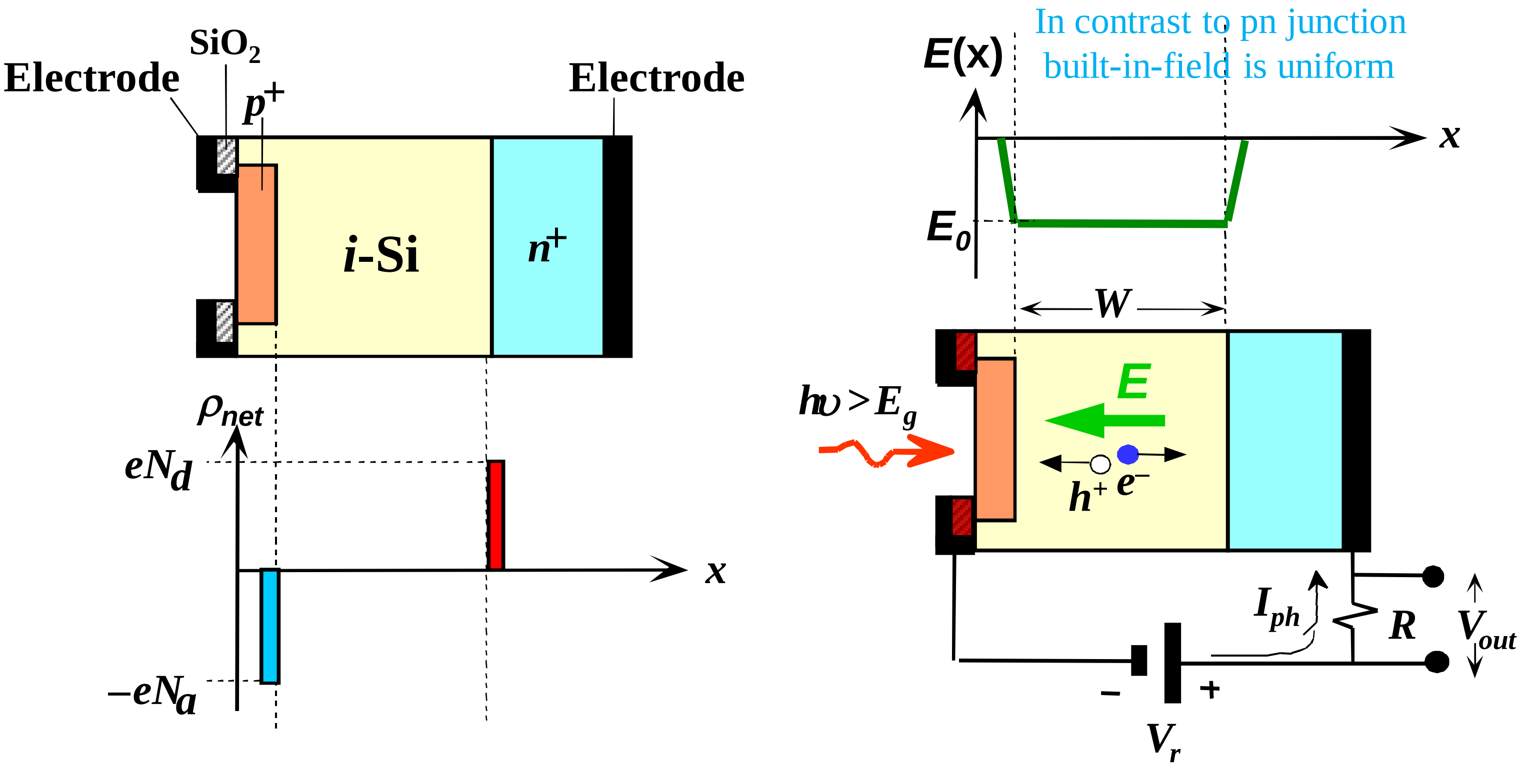
- ☐ ***pin* photodiode circuit**



Photodetectors

The *pin* Photodiode

- ❑ Schematic diagram of *pin* photodiode



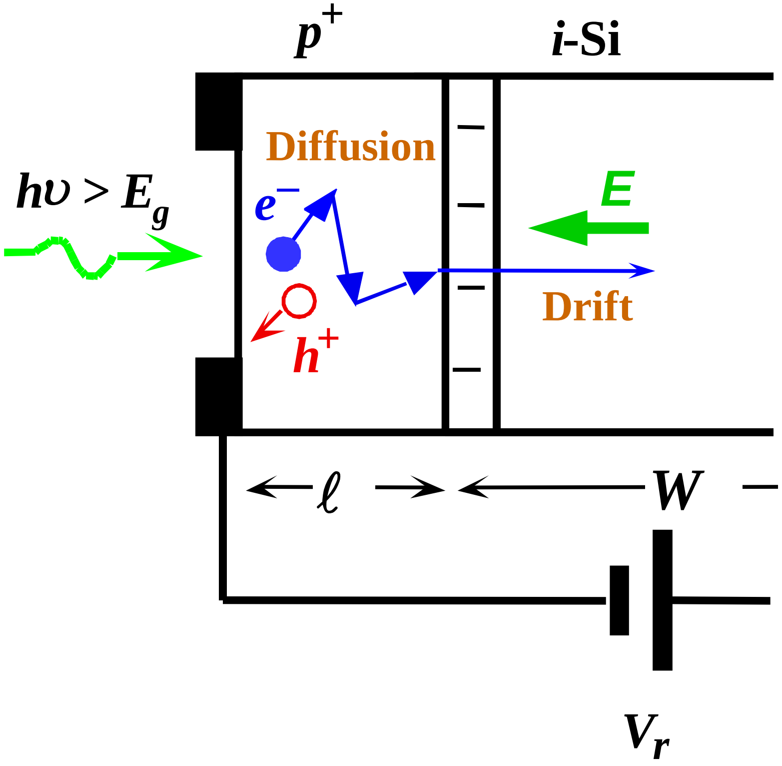
In contrast to pn junction built-in-field is uniform

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

Photodetectors

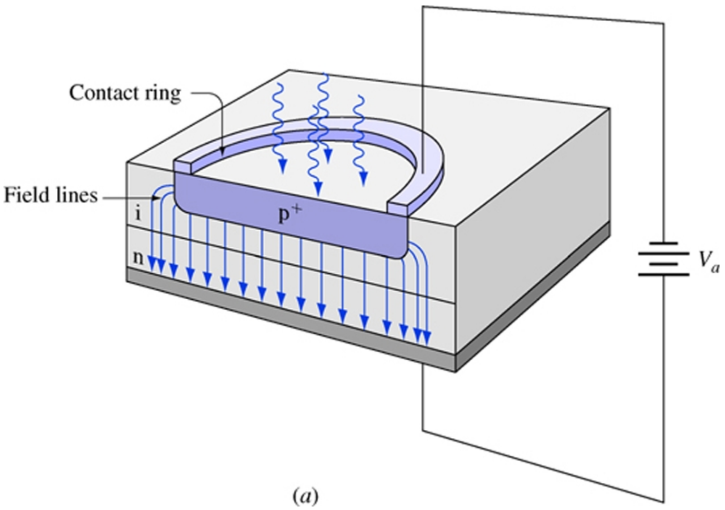
The *pin* Photodiode

- 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.

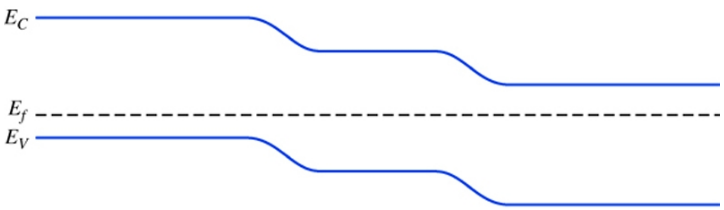


Photodetectors

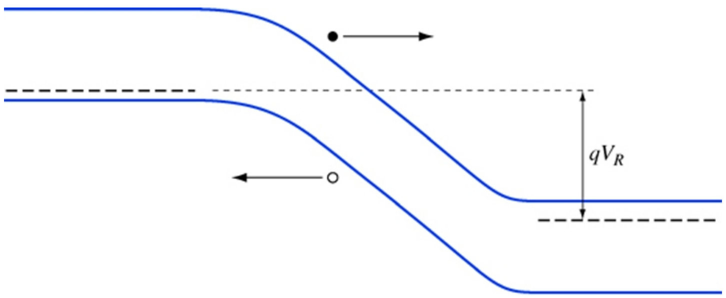
The *pin* Photodiode



(a)



(b)



(c)

p-i-n **diode**

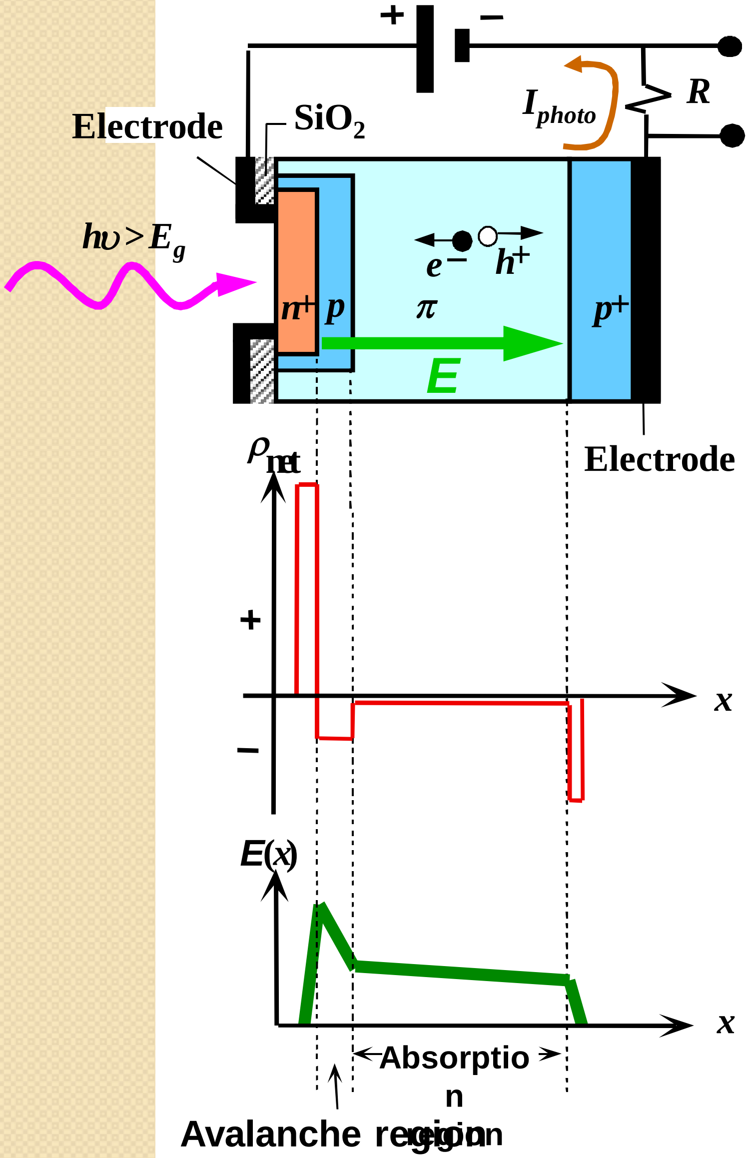
(a) The structure;

(b) equilibrium energy band diagram;

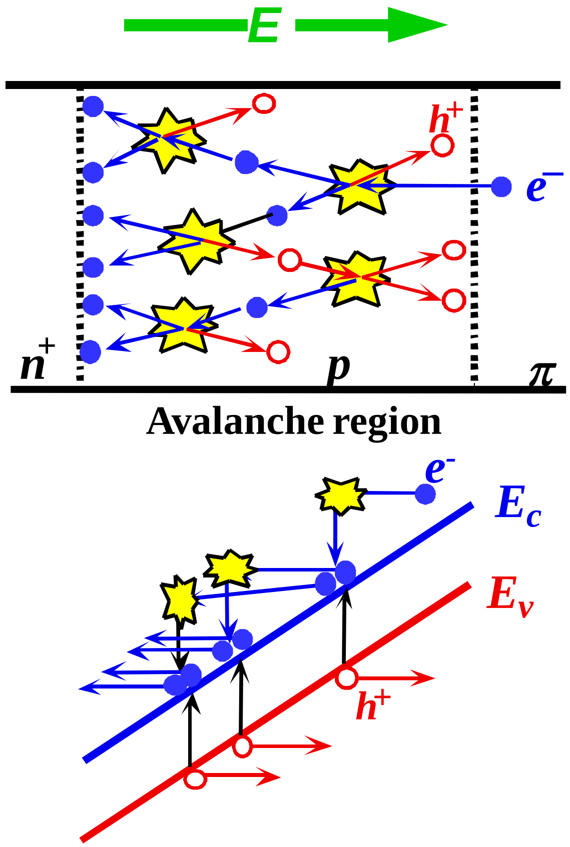
(c) energy band diagram under reverse bias.

Photodetectors

Avalanche Photodiode (APD)



❑ **Impact ionization processes resulting avalanche multiplication**

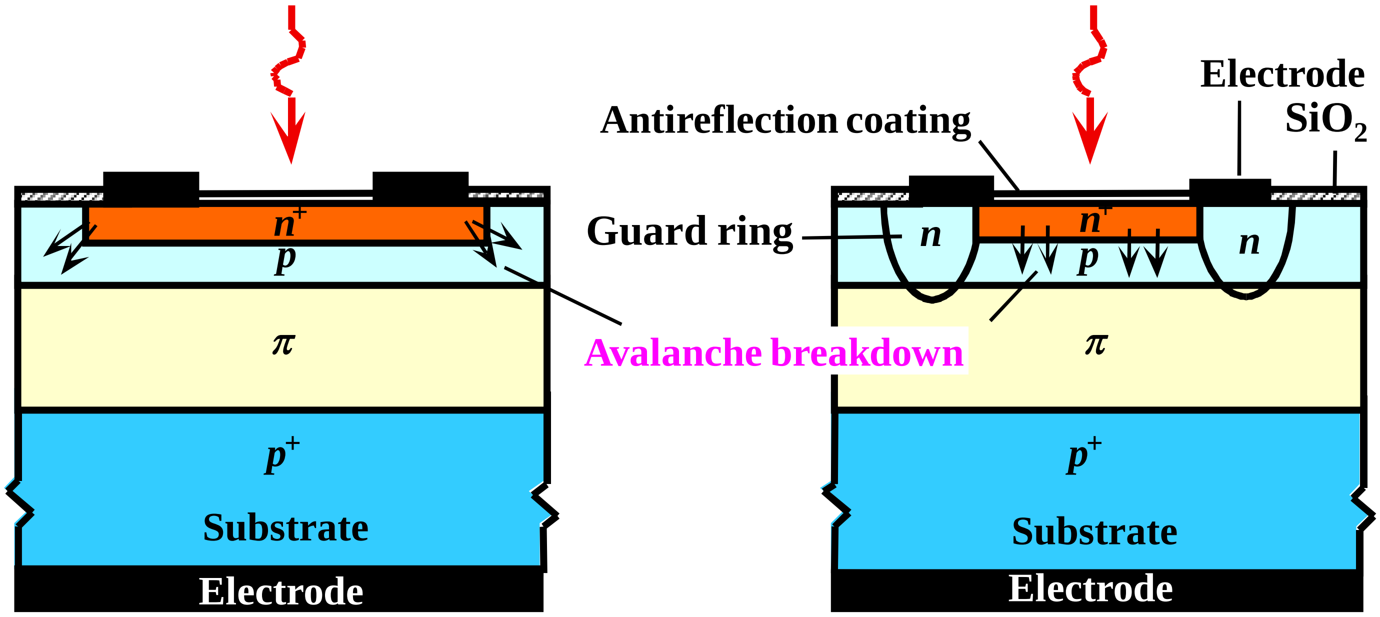


- ➢ **Impact of an energetic electron's kinetic energy excites VB electron to the CV.**

Photodetectors

Avalanche Photodiode (APD)

- Schematic diagram of typical *Si* APD.



Si APD structure without a guard ring

More practical *Si* APD

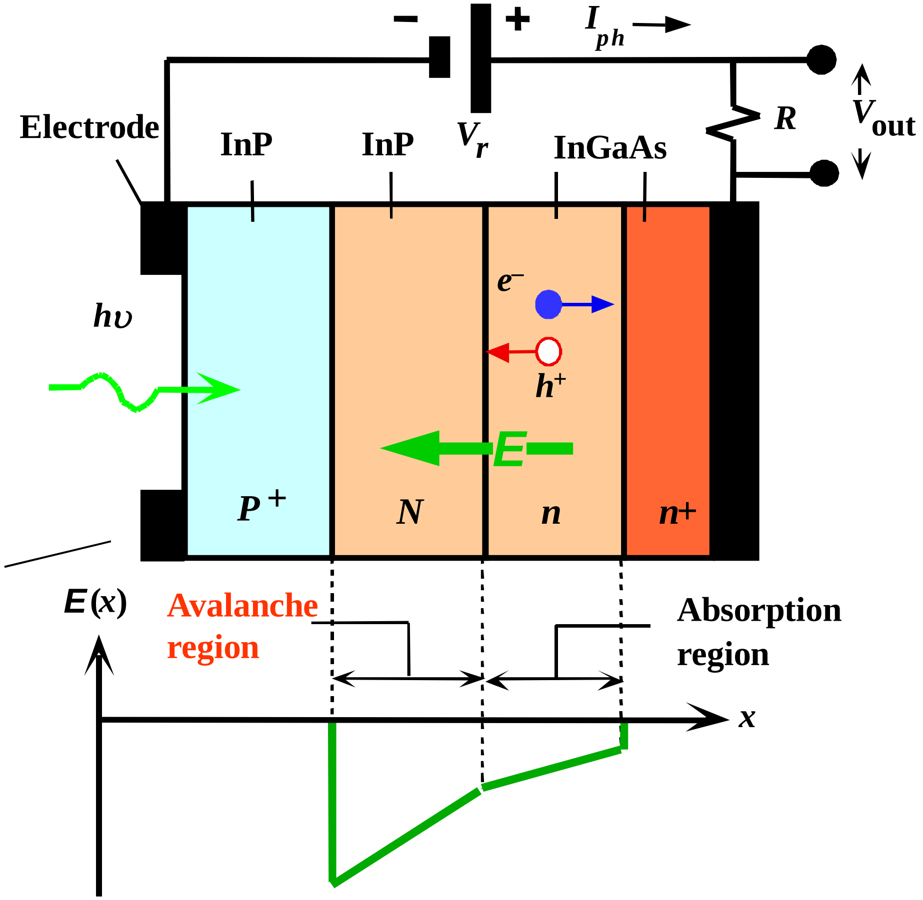
- Breakdown voltage around periphery is higher and avalanche is confined more to illuminated region (n^+p junction).

Photodetectors

Heterojunction Photodiode

Separate Absorption and Multiplication (SAM) APD

InGaAs-InP heterostructure Separate Absorption and Multiplication APD

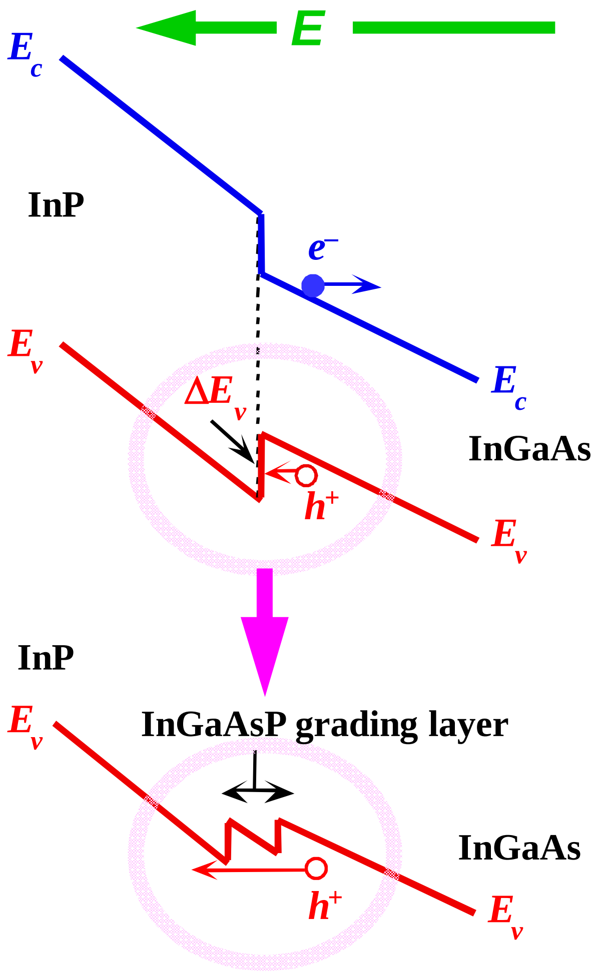


P and *N* refer to *p*- and *n*-type wider-bandgap semiconductor.

Photodetectors

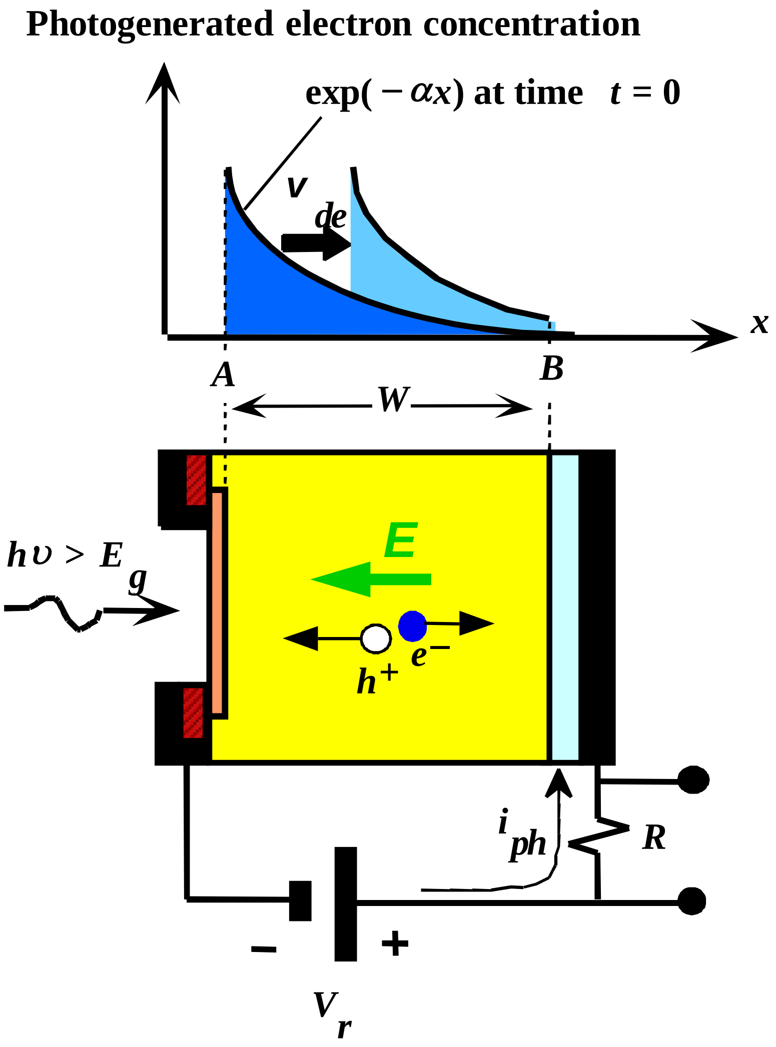
Heterojunction Photodiode

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
$h\upsilon > E_g$
E
h^+
e^-
i_{ph}
R
−
+
V_r