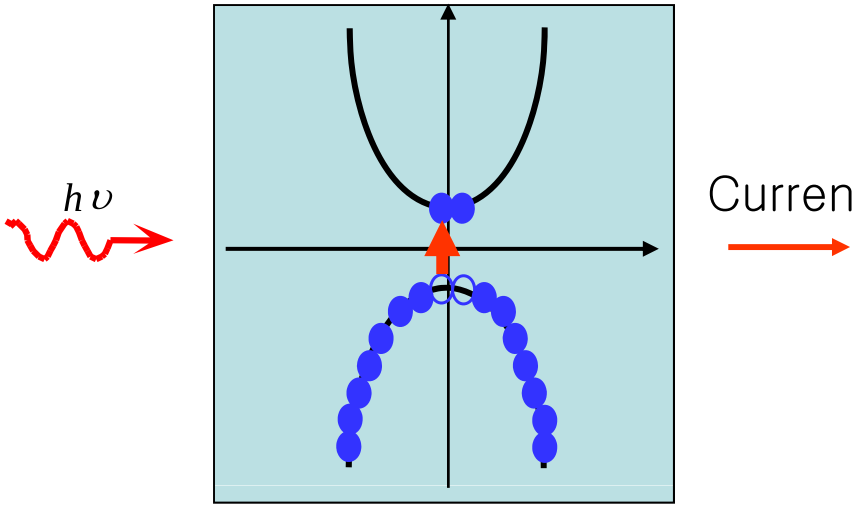
Photodetector Basics

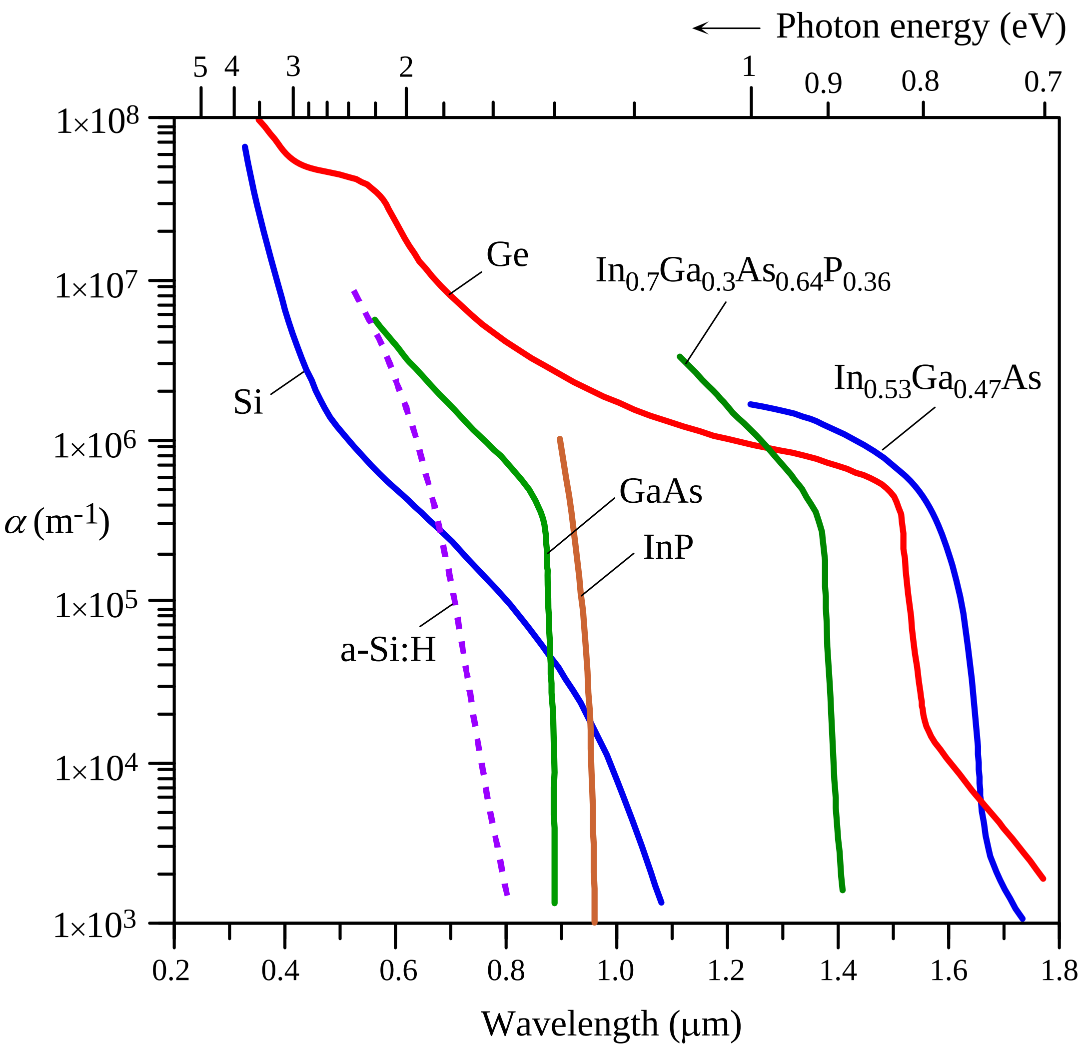
Photodetection: Absorption => Current Generation



Materials for photodetection: $E_g < h\nu$

Various methods for generating currents with photo-generated carriers: photoconductors, photodiodes, avalanche photodiodes

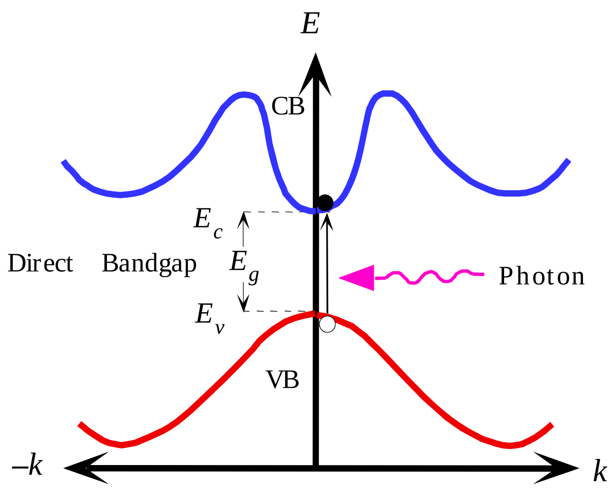
Photodetector Basics



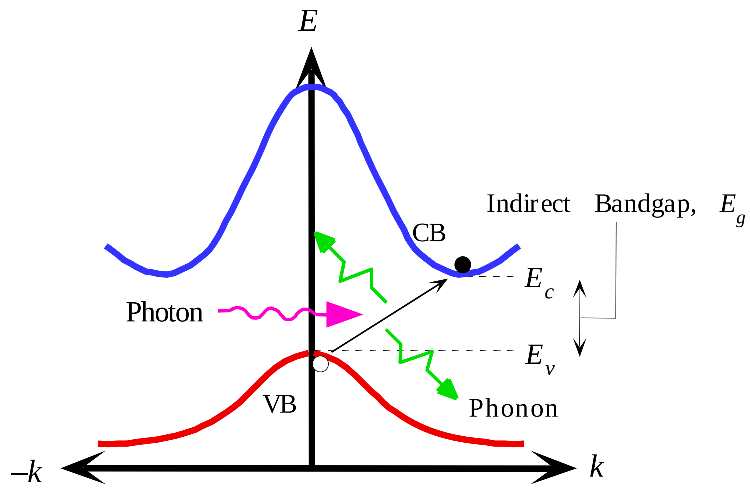
- Sharp decrease in α for $\lambda > E_g$
- Photodetection for indirect bandgap materials?

Photodetector Basics

- Photodetection for indirect bandgap materials?



(a) GaAs (Direct bandgap)



(b) Si (Indirect bandgap)

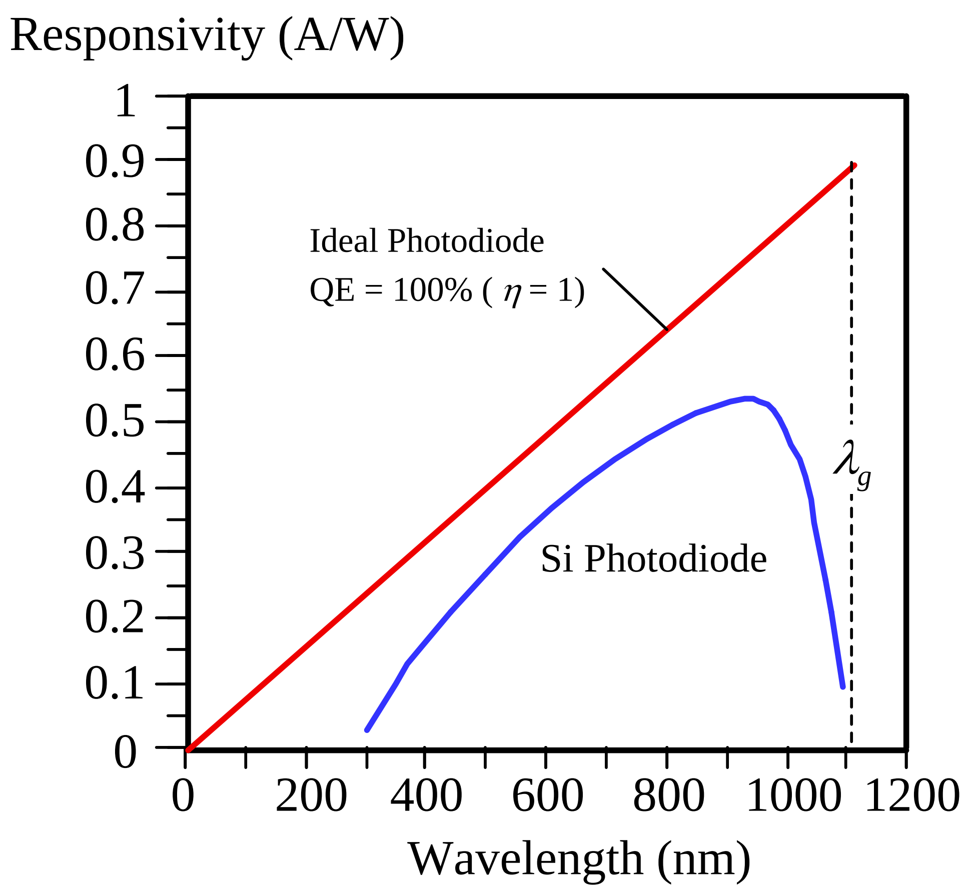
Photodetector Basics

Photodetection efficiency

$$R\text{ (Responsivity)} = \frac{I}{P}$$

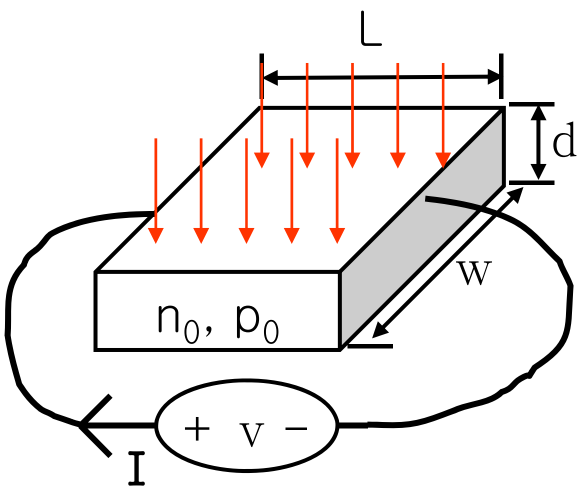
$$\eta\text{ (Quantum Efficiency)} = \frac{I/q}{P/h\nu}$$

$$R = \eta \cdot \frac{q}{h\nu} = \eta \cdot \frac{\lambda[\mu\text{m}]}{1.24}$$



Photodetector Basics

Photoconductor



Without light,

$$\text{Conductivity: } \sigma = q\mu_e n + q\mu_h p$$

$$(\mu_{e,h}: \text{electron, hole mobility})$$

$$J = \sigma E \text{ and } I = wd\sigma\frac{V}{L}$$

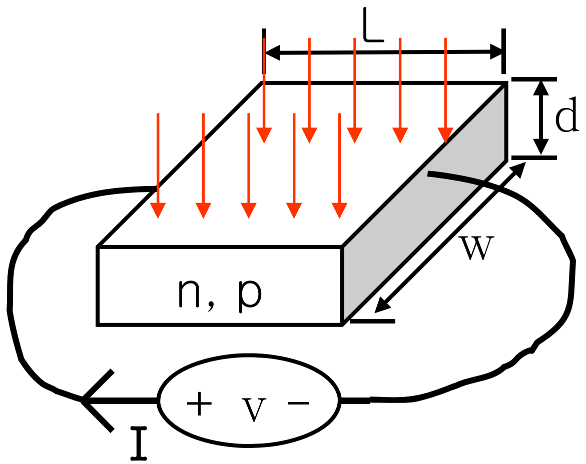
With light,

$$n = n_0 + \Delta n,\; p = p_0 + \Delta p$$

$$\sigma + \Delta\sigma = q\mu_e(n + \Delta n) + q\mu_h(p_0 + \Delta p)$$

$$\Delta I = wd \cdot \Delta\sigma \cdot \frac{V}{L} = wd \cdot (q\mu_e\Delta n + q\mu_h\Delta p) \cdot \frac{V}{L}$$

Photodetector Basics



With light,

$$\Delta I = wd\Delta\sigma\frac{V}{L} = wd\left(q\mu_e\Delta n + q\mu_h\Delta p\right)\frac{V}{L}$$

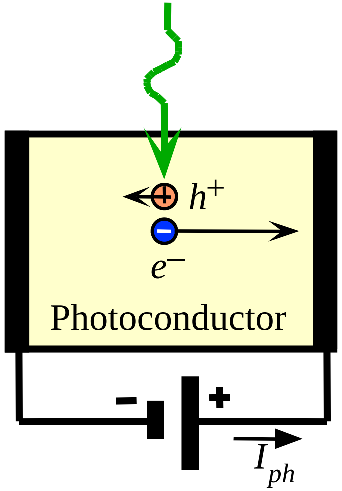
Since $\Delta n = \Delta p = \eta_{\text{int}}\cdot\frac{P}{h\nu}\cdot\frac{\tau}{wLd}$ and assuming $\Delta n, \Delta p$ are uniform,

$$\Delta I = wd\Delta\sigma\frac{V}{L} = wd\cdot q\left(\mu_e + \mu_h\right)\cdot\eta_{\text{int}}\frac{P}{h\nu}\frac{\tau}{wLd}\cdot\frac{V}{L} = q\left(\mu_e + \mu_h\right)\cdot\eta_{\text{int}}\cdot\frac{P}{h\nu}\cdot\frac{\tau}{L^2}\cdot V$$

$$\therefore R = \frac{\Delta I}{P}\text{(assuming dark current is small)} = \frac{q}{h\nu}\left(\mu_e + \mu_h\right)\cdot\eta_{\text{int}}\cdot\frac{\tau}{L^2}$$

$$\eta = \left(\mu_e + \mu_h\right)\cdot\eta_{\text{int}}\cdot\frac{\tau}{L^2} = G\cdot\eta_{\text{int}}$$

Photodetector Basics



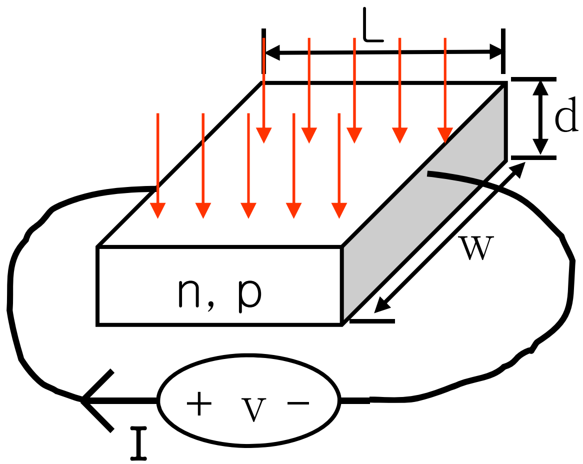
Gain: $G = (\mu_e + \mu_h) \cdot \frac{\tau}{L^2} \cdot V$

Assuming $\mu_e >> \mu_h$, $G = \mu_e \cdot \frac{\tau}{L^2} \cdot V = \frac{\tau}{L^2 / \mu_e \cdot V} = \frac{\tau}{\tau_e}$

$\tau_e = \frac{L}{\mu_e \cdot \frac{V}{L}} = \frac{L}{\mu_e \cdot E} = \frac{L}{v}$; time for travelling distance L

$\tau >> \tau_e$ ==> electrons circulate many time before recombination

Photodetector Basics



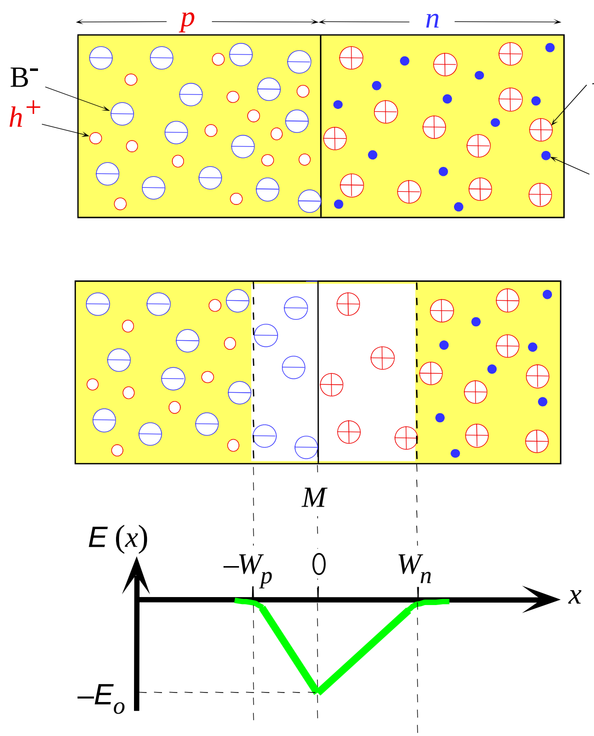
Photoconductors:

- Very easy to make
- Large gain
- But slow (speed limited by τ) and significant dark currents

Photodetector Basics

photodiode

Faster, dark-current-free photodetectors?



PN junction in reverse bias

- No significant current flow=> small dark currents

- Photo-generated carriers are removed
  by built-in field in depletion region
  (space charge region)

Photodetector Basics

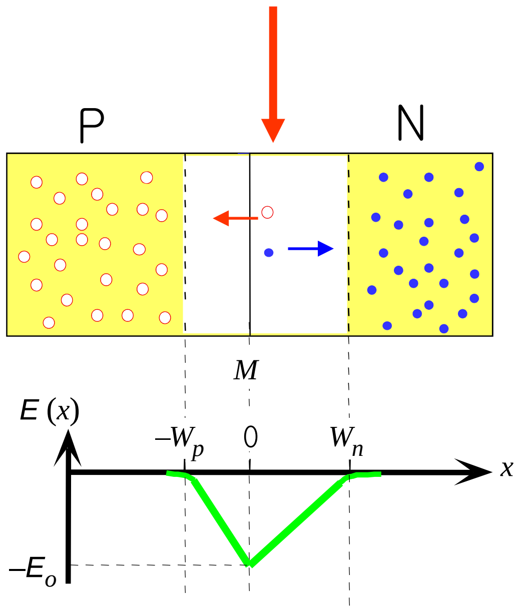


Photo-generated carriers drift into P (holes) and N (electrons) regions creating currents.

$$I = \eta_{\text{int}} \frac{P}{h\nu} q$$

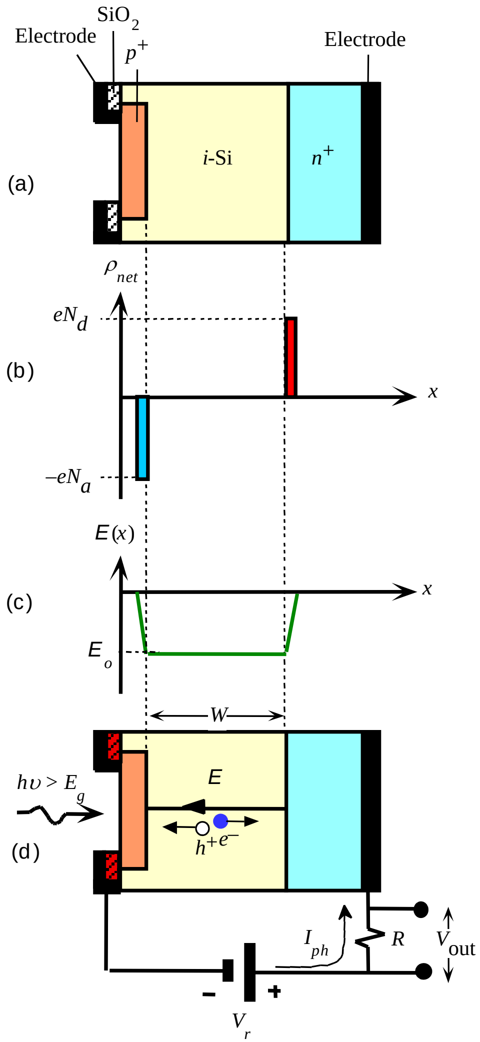
One photon creates electron and hole

Problem: depletion region is very thin (< 1 μm)

➔ η_{int} is very small.

=> Use PIN structure

Photodetector Basics

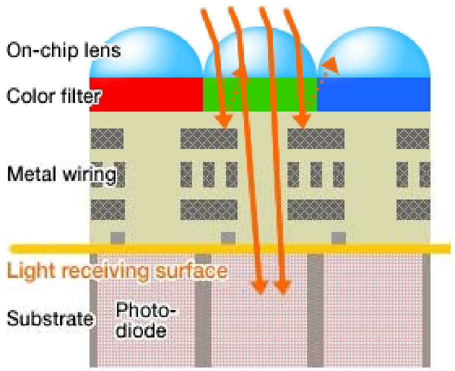


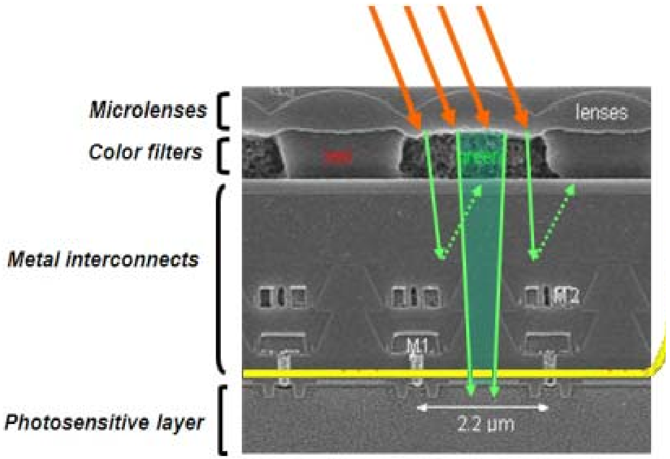
PIN Photodiode

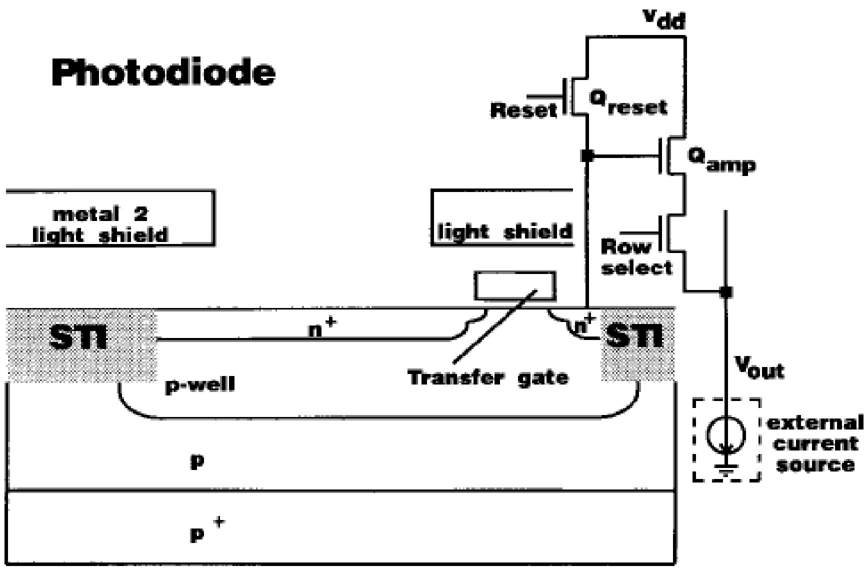
W.-Y. Choi

Photodetector Basics

CMOS Image Sensor

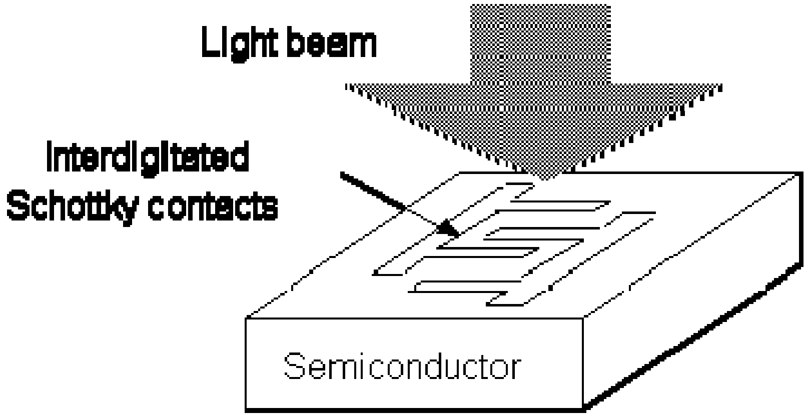






Photodetector Basics

MSM (Metal-Semiconductor Metal) PD



Carrier collection by lateral E-field provided by Schottky contacts

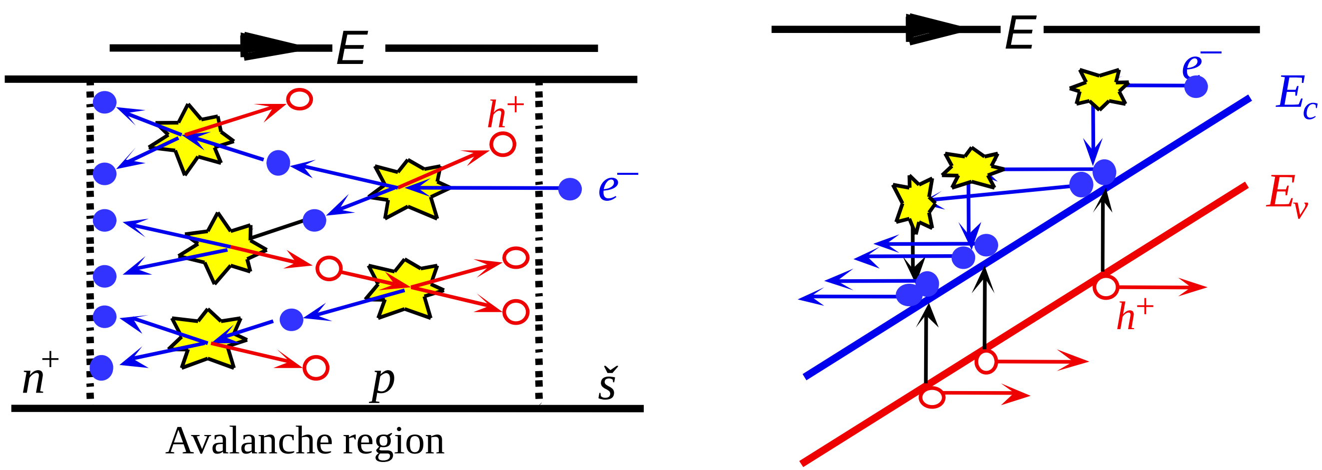
➔ Not very efficient but can be very fast

Photodetector Basics

Avalanche Photodiode (APD): PIN PD + Gain
(avalanche: a large mass of snow, ice, earth, rock, or other material in swift motion down a mountainside)

Achieve gain by multiplying electrons and/or holes.

Impact Ionization: Under high E-field, electrons and holes can have sufficiently high kinetic energies breaking bonds and creating new e-h pairs.



Photodetector Basics

In real APD, care is taken so that only one type of carrier (either electron or hole) causes impact ionization.

APD has limited application for optical communication since high-performance EDFA is easily available

➔ APD is very useful for optical interconnect applications.