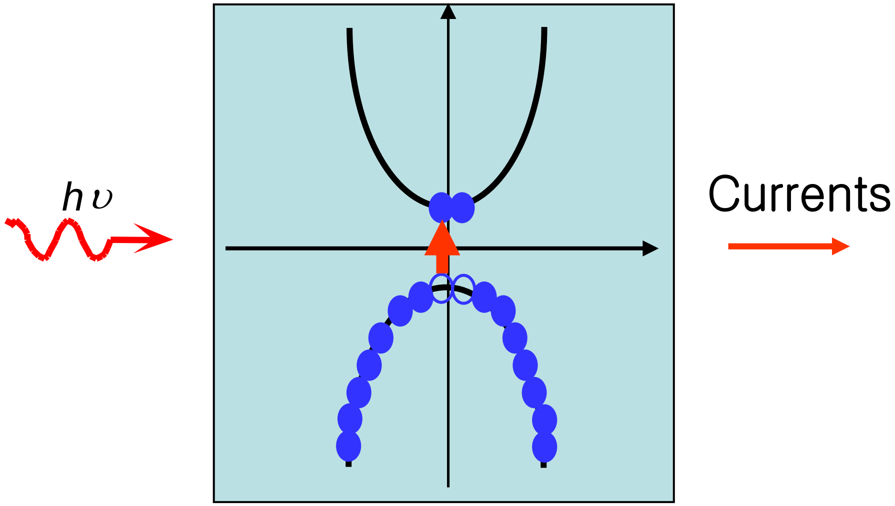
Lect. 22: Photodetectors

Photodetection: Absorption => Current Generation



Materials for photodetection: $E_g < h\nu$
Various methods for generating currents with photo-generated carriers:
photoconductors, photodiodes, avalanche photodiodes

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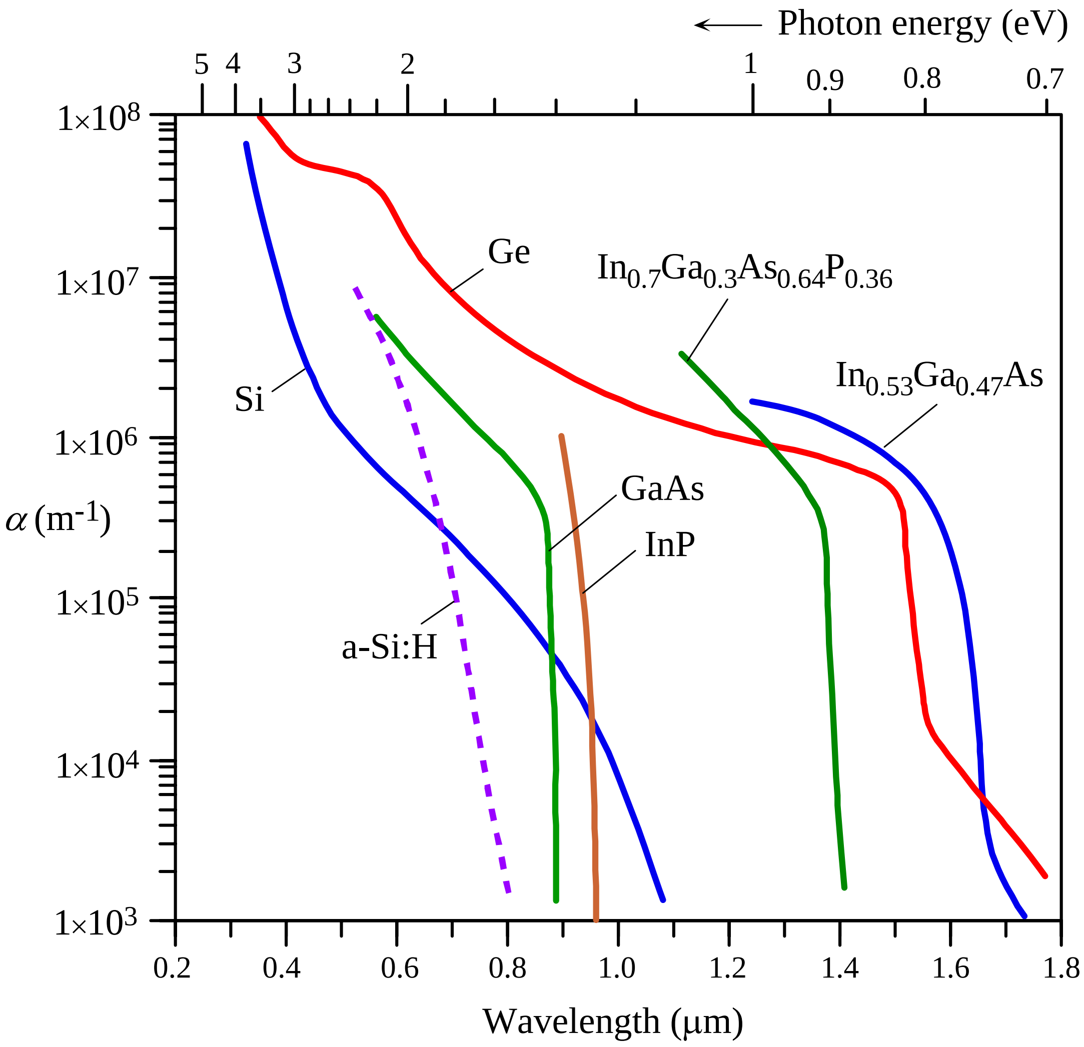

- Sharp decrease in α for $\lambda > E_g$
- Photodetection for indirect bandgap materials?

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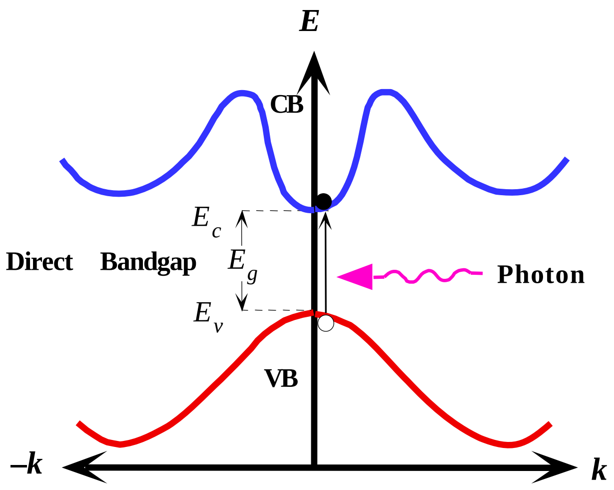
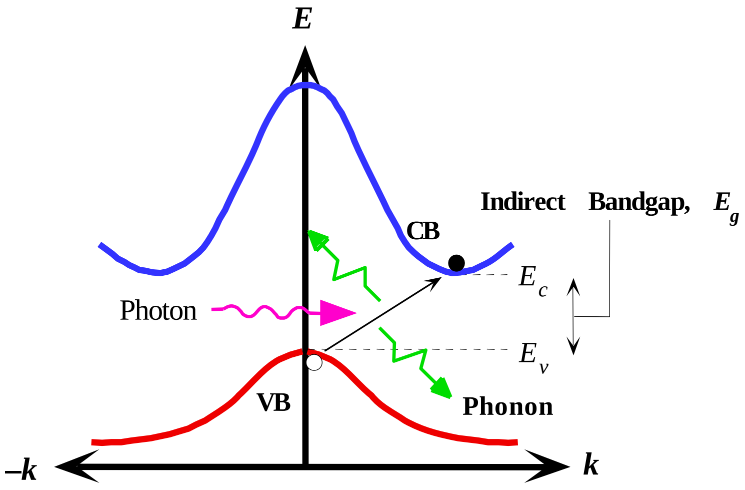
- Photodetection for indirect bandgap materials?



(a) GaAs (Direct bandgap)



(b) Si (Indirect bandgap)

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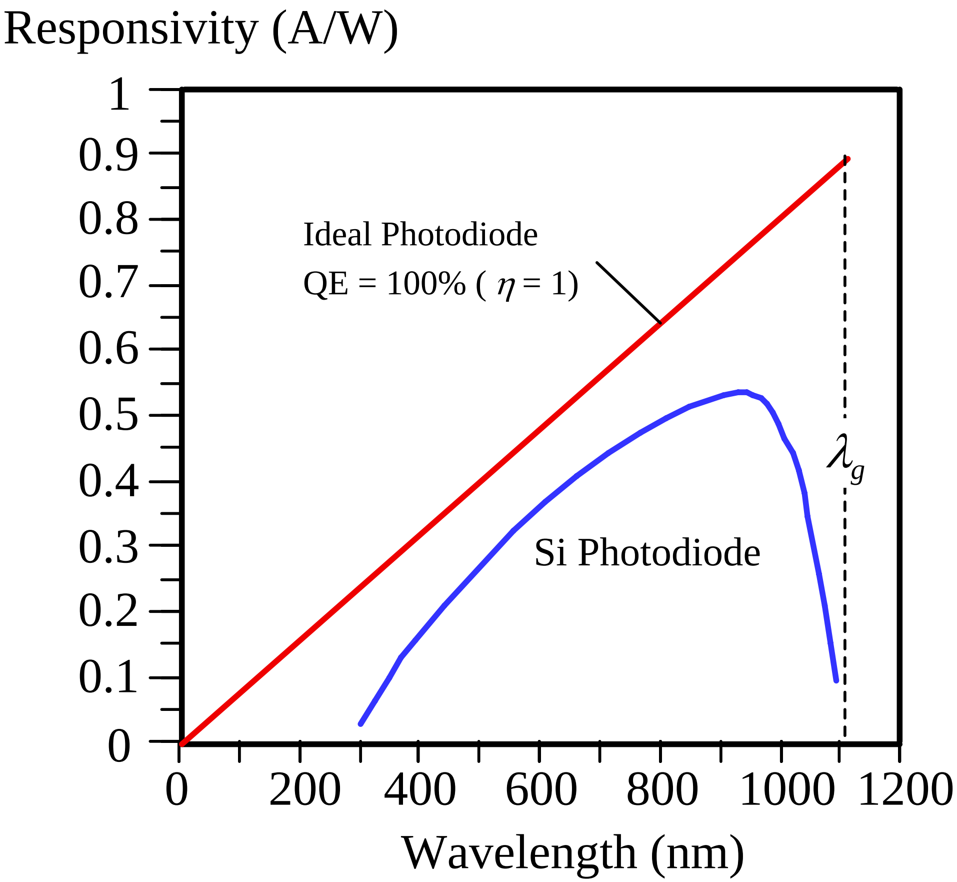
Photodetection efficiency

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

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

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



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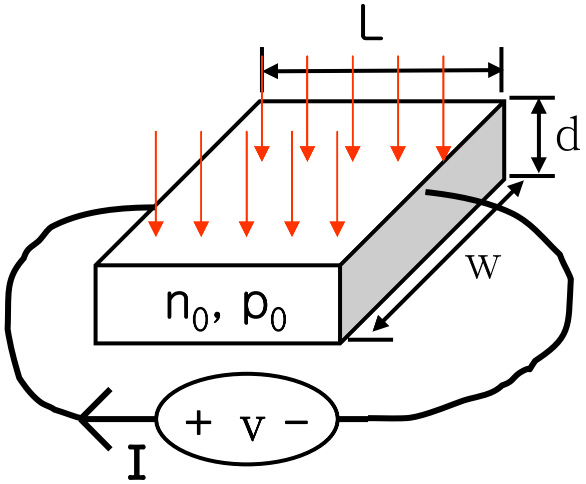
Photoconductor



Without light,

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

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

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

With light,

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

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

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

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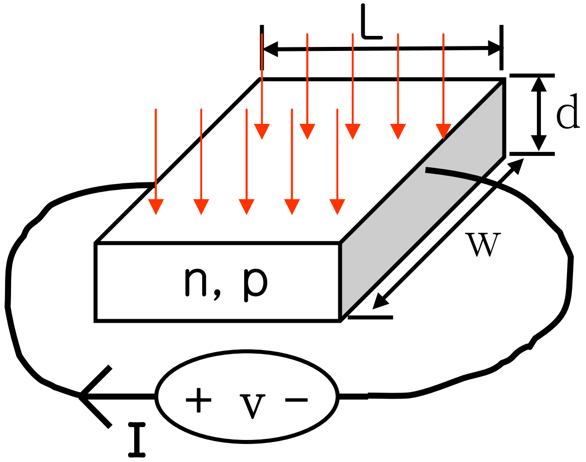

With light,

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

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

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

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,

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

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

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

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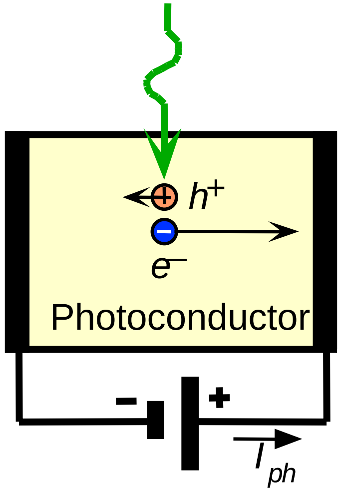

Gain: $G = (\mu_e + \mu_h)\cdot\frac{\tau}{L^2}\cdot V$

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

With μ_h

$$G = \frac{\tau}{L^2 / (\mu_e + \mu_h)\cdot V} = \frac{\tau}{\tau_{eh}}$$

$$\tau_{eh} = \frac{L}{(\mu_e+\mu_h)\cdot\frac{V}{L}} = \frac{L}{(\mu_e+\mu_h)\cdot E} = \frac{L}{v_e + v_h}$$

$$= \frac{1}{\frac{v_e+v_h}{L}} = \frac{1}{\frac{1}{\tau_e}+\frac{1}{\tau_h}} = \frac{\tau_e\cdot\tau_h}{(\tau_e+\tau_h)}$$

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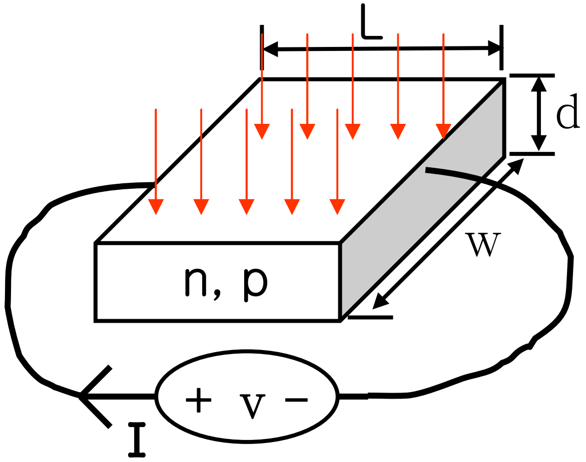

Photoconductors:

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

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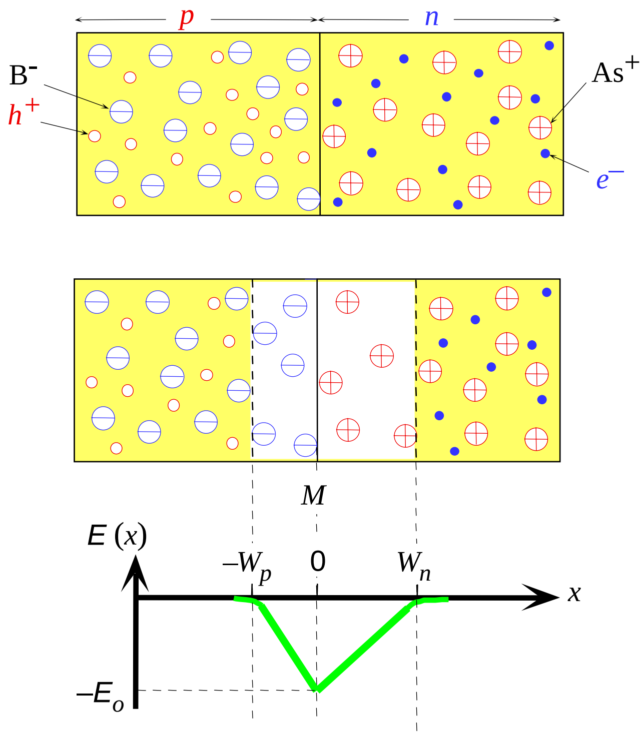
photodiode

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)

Lect. 22: Photodetectors

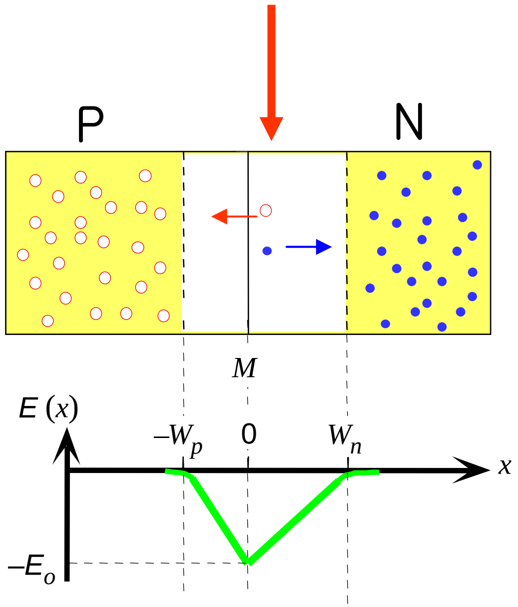


Photo-generated carriers drift into P (holes) and N (electrons) regions creating currents.

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

One photon creates electron and hole.
Why only one charge flowing?

Problem: depletion region is very thin (< 1 μm)
➔ η_{int} is very small.

=> Use PIN structure

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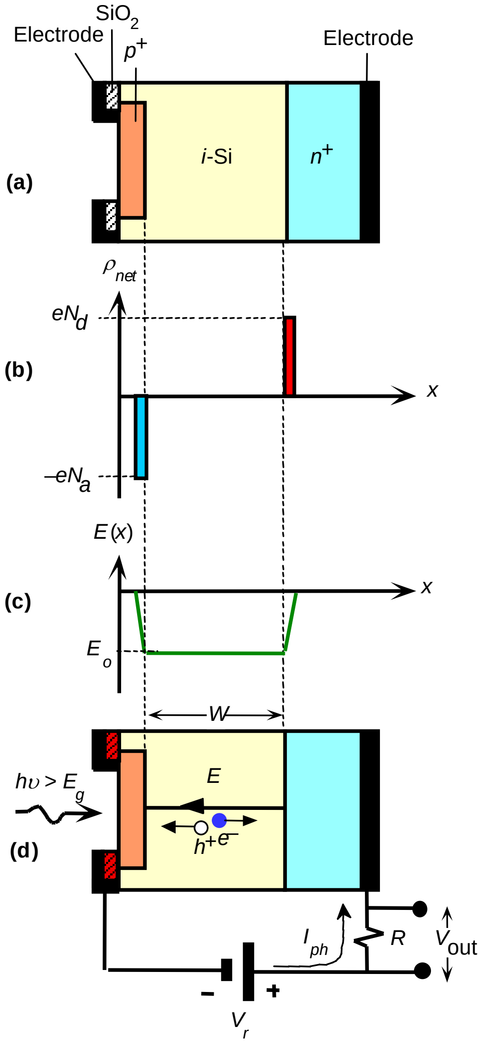

PIN Photodiode

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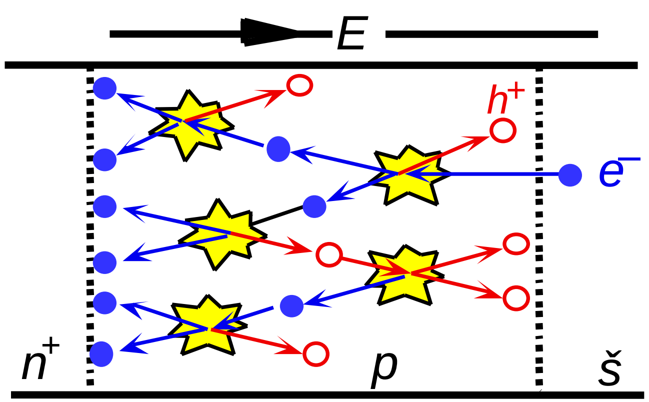
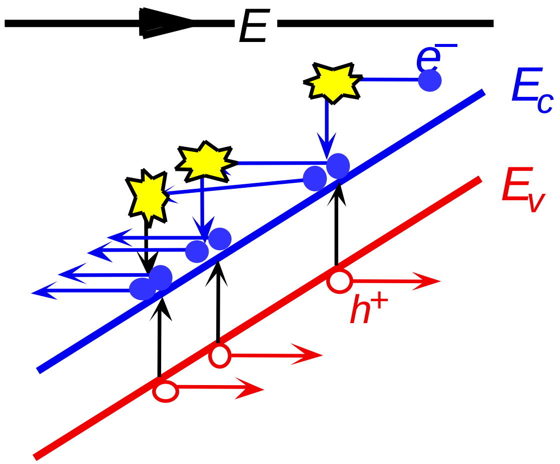
Avalanche Photodiode (APD): PIN PD + Gain
(avalanche: a large mass of snow, ice, earth, rock, or other material in swift motion down a mountainside)

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.



Avalanche region



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

APD has limited application since optical amplification (EDFA, for example) and electrical amplification (by IC) can be done easily.