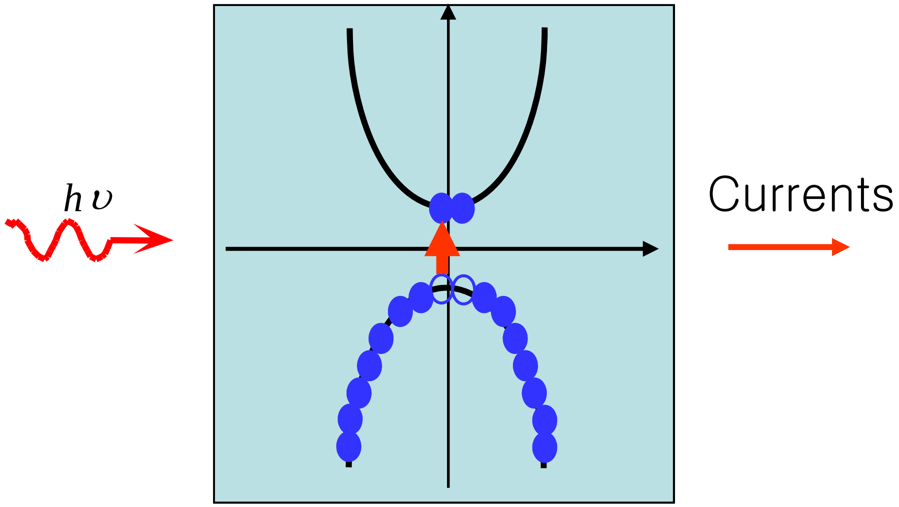
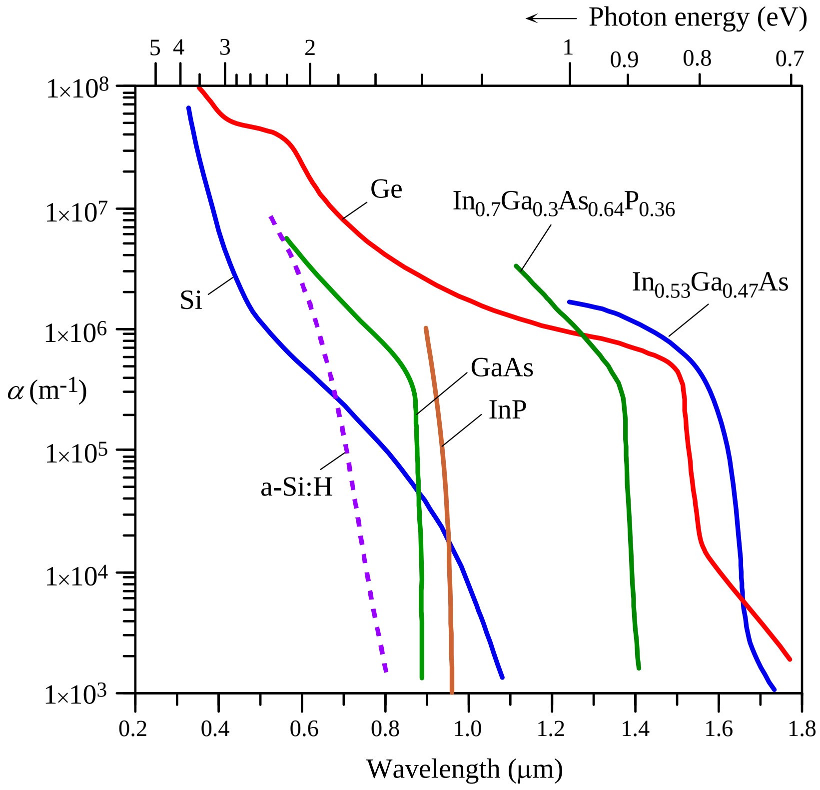
Lect. 24: Photodetectors

Photodetection: Absorption => Current Generation



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

Lect. 24: Photodetectors

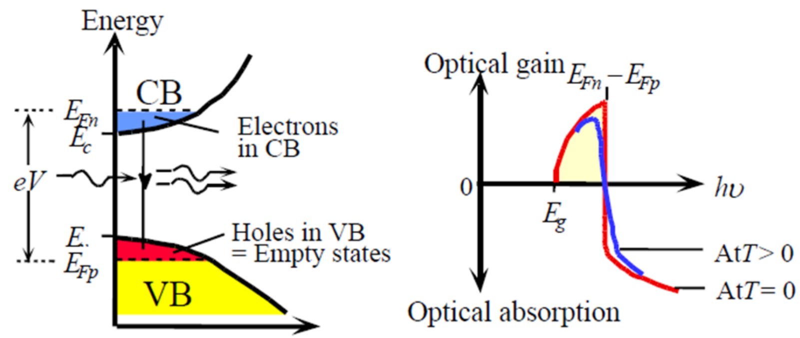


Sharp decrease in absorption for photon energy < E_g

$P_{out}/P_{in} = \exp(gL)$

$g < 0 \rightarrow \alpha = -g$

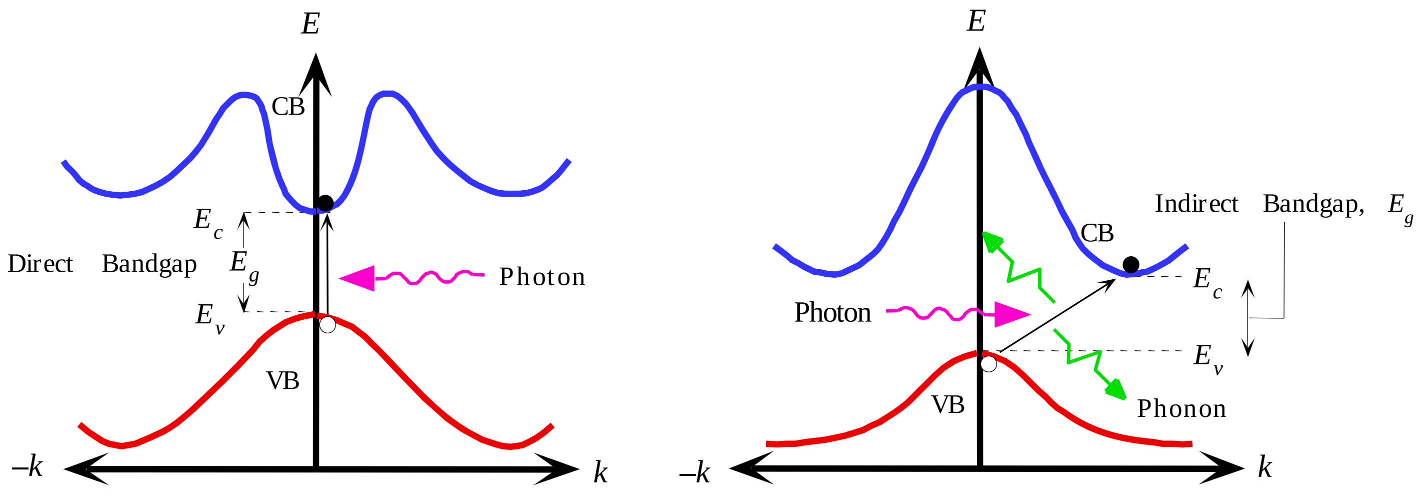
$$g(E_2 - E_1) \sim g_c(E_2) f_n(E_2) g_v(E_1)\left[1 - f_p(E_1)\right] - g_v(E_1) f_n(E_1) g_c(E_2)\left[1 - f_p(E_2)\right]$$



W.-Y. Choi

Lect. 24: Photodetectors

– Photodetection for indirect bandgap materials



(a) GaAs (Direct bandgap) (b) Si (Indirect bandgap)

Absorption in indirect bandgap semiconductor is possible

➔ Indirect semiconductors (Si) are used for solar cells and image censors

Lect. 24: Photodetectors

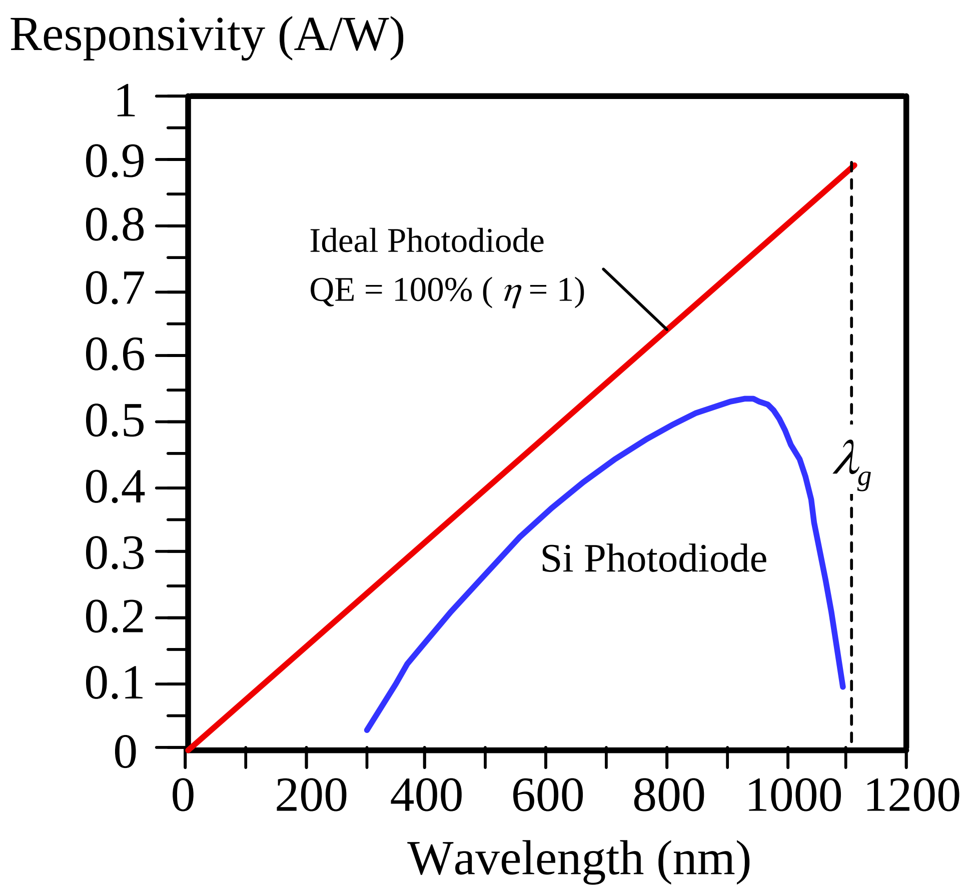
Photodetection efficiency

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

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

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

$$R = \eta \cdot q[C] \cdot \frac{\lambda}{1.24[eV]} = \eta \cdot \frac{\lambda}{1.24}[1/V]$$



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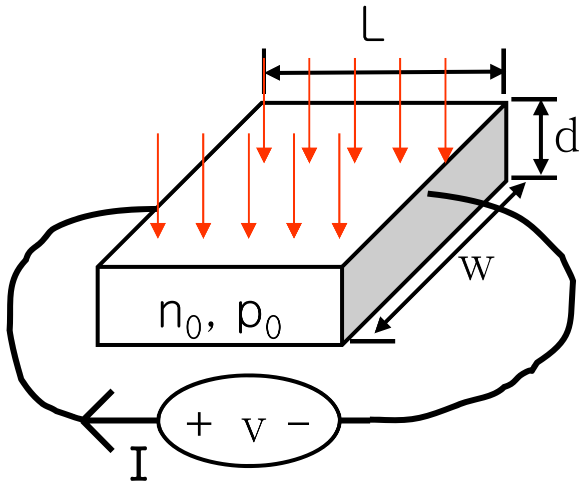
Photoconductor



$R = ?$

Without light,

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

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

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

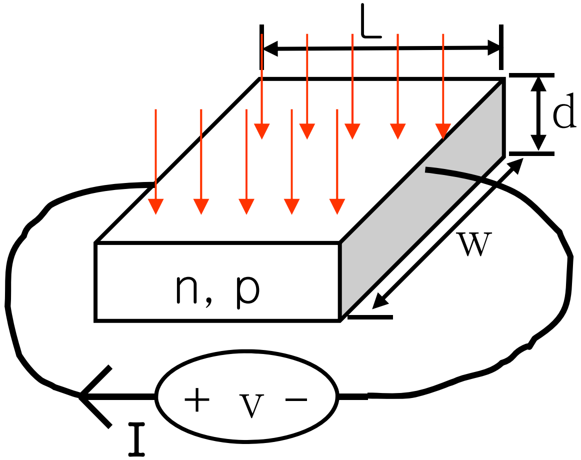
With light,

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

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

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

Lect. 24: Photodetectors



With light,

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

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

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

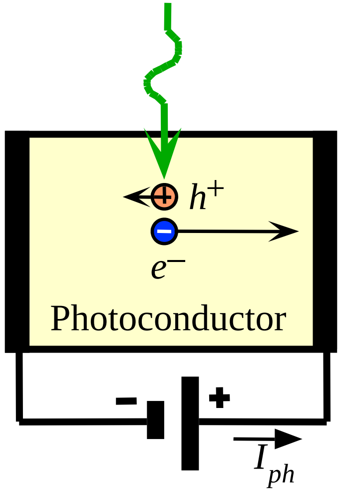
$$\Delta n = \Delta p = \eta_{\text{int}}\cdot\frac{P}{h\nu}\cdot\frac{\tau}{wLd}\ \text{(Assume } \Delta n, \Delta p \text{ are uniform)}$$

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

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

$$R = G\cdot\eta_{\text{int}}\frac{q}{h\nu} \quad \text{where } G = \left(\mu_e + \mu_h\right)\cdot\frac{\tau}{L^2}\cdot V$$

Lect. 24: Photodetectors



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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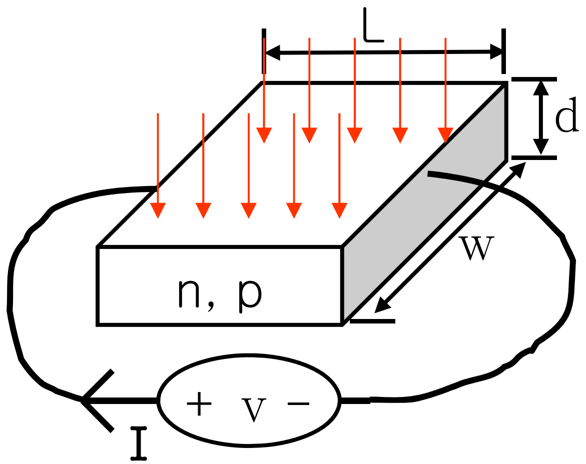
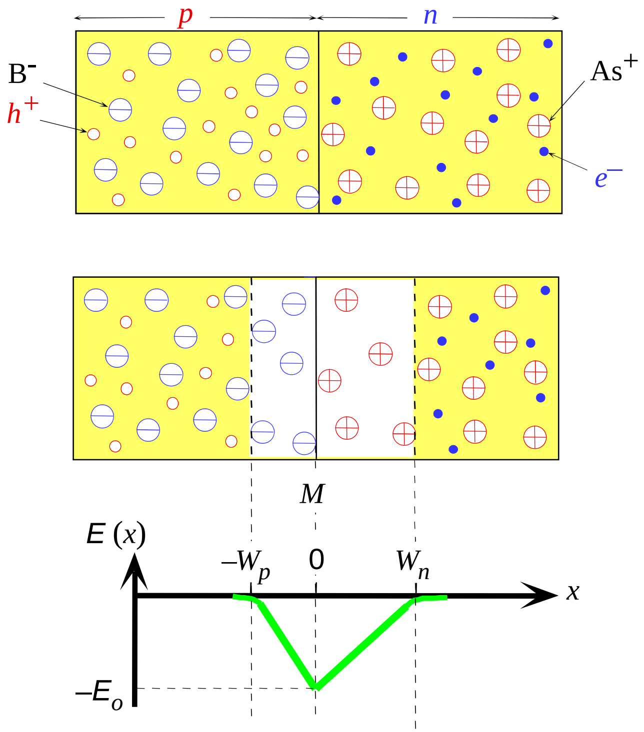


Photoconductors:

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

Lect. 24: Photodetectors

Faster, less dark-current photodetectors?   photodiode

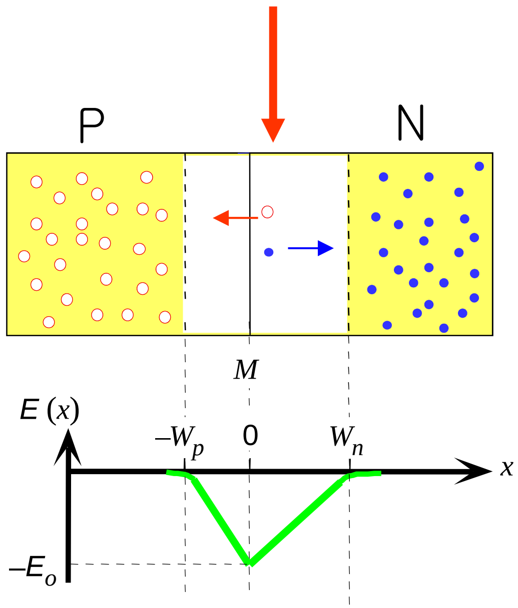


PN junction in reverse bias

- No significant current flow=> small dark currents

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

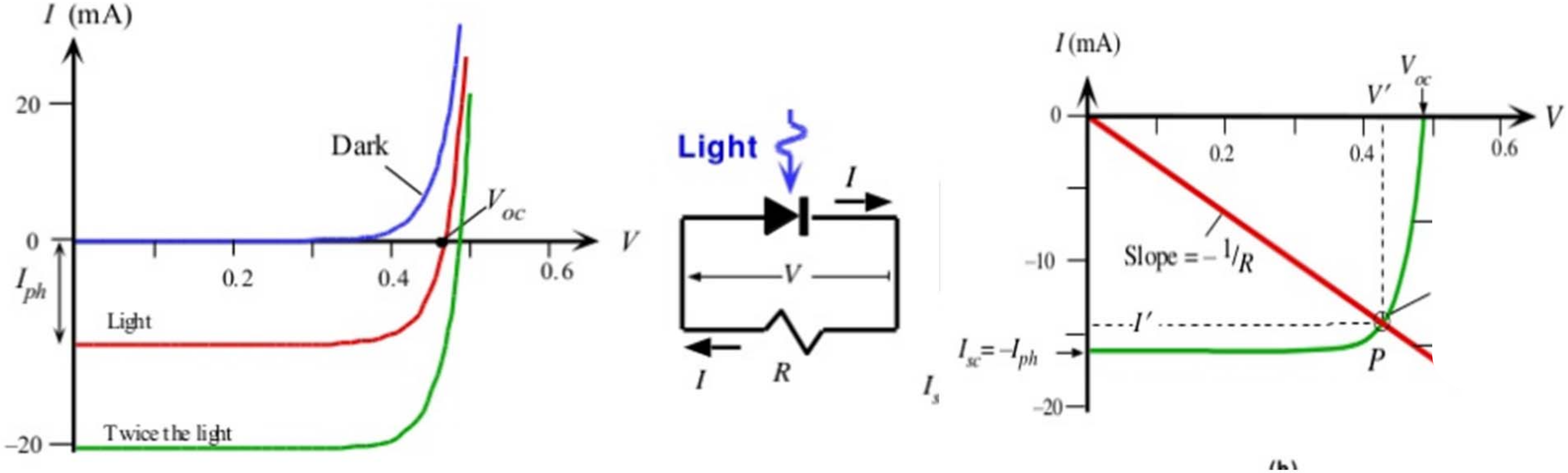
Lect. 24: Photodetectors



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

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

- One photon creates a pair of electron and hole



➔ Si Solar cell

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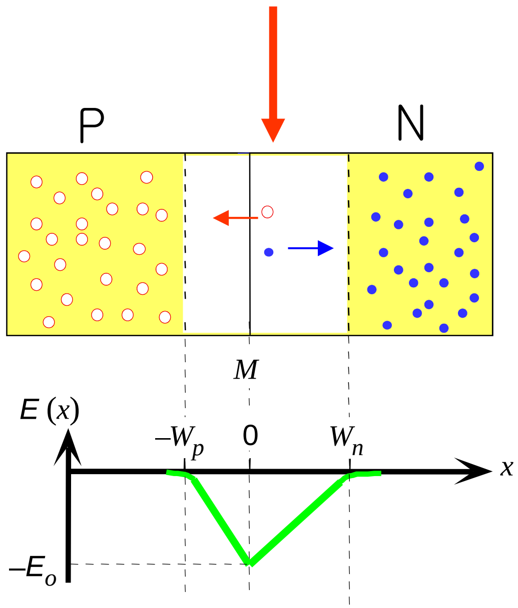

- Problem: depletion region is very thin (< 1 μm)
  ➔ η_{int} is very small

=> Use PIN structure

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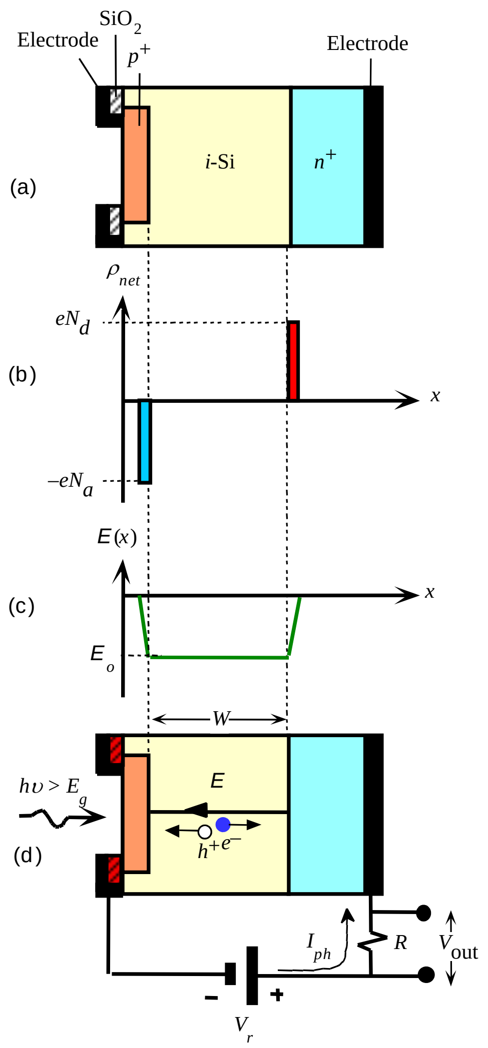


PIN Photodiode

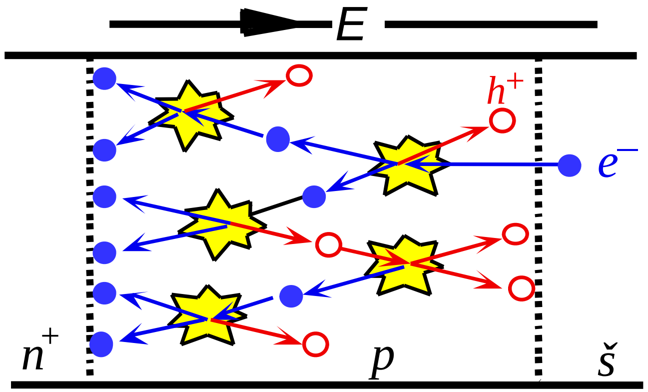
Lect. 24: Photodetectors

PD with gain?

Avalanche Photodiode (APD)
(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

It is preferred only one type of carrier (either electron or hole) causes impact Ionization

κ: ratio of ionization coefficients
(= hole/electron)