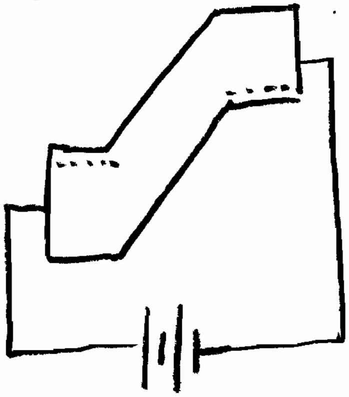
Photodetectors (Chuang Chap. 14)

Semiconductor absorbs photons
Photodetector separate and collect electrons
and holes generated by absorption.

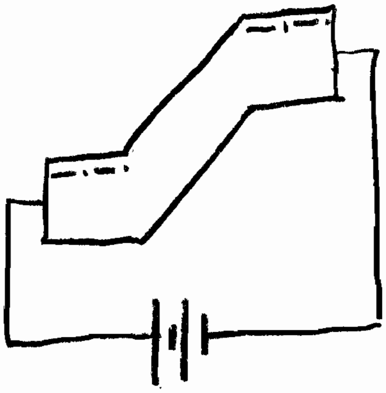
Key parameters

- Efficiency (%) or Responsivity (A/W)
- Bandwidth (f_{3dB})
- Gain
- Noise
  - Signal to noise ratio
  - Noise equivalent power (NEP)
- Spectral response
- Polarization dependence

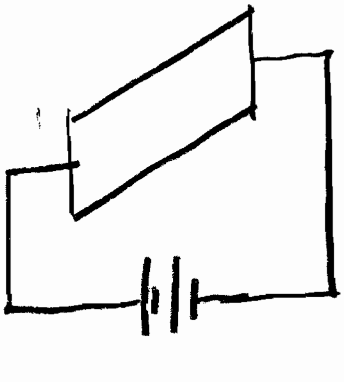
Major catagories of semiconductor photodetectors:



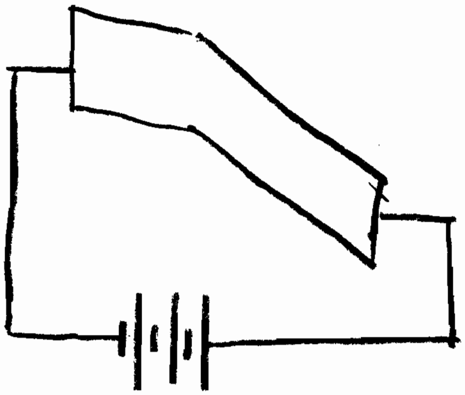
P-i-n



Photoconductor
(n-i-n)

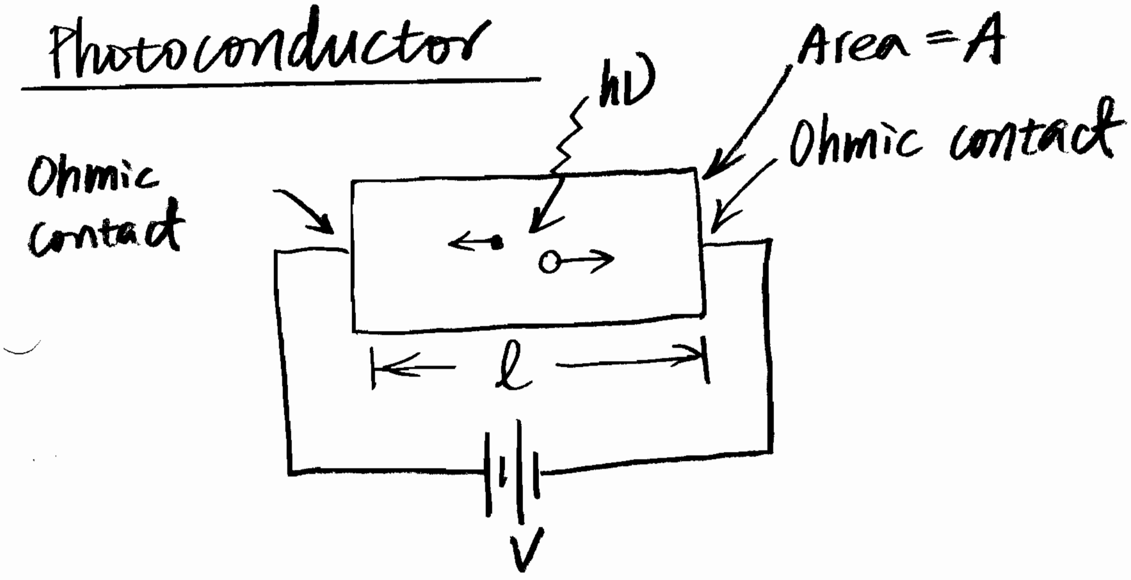


MSM
Metal-semiconductor
-metal



Avalanche Photodiode (APD)

Photoconductor



$J_0 = \sigma_0 E = (n_0 q \mu_n + p_0 q \mu_p) E$ (Dark current

With light illumination

$$\Delta I = A \Delta J = A \cdot \Delta\sigma \cdot E = \delta n \cdot q (\mu_n + \mu_p) \frac{A}{l} \cdot V$$

$$\delta n = G_0 \cdot \tau_n$$

← carrier recomb. lifetime.

↑ generation rate $\frac{1}{cm^3} \cdot \frac{1}{sec}$

(i) CW illumination

$$G_0 = \text{const} = \eta \frac{\left(\frac{P_{opt}}{\hbar\omega}\right)}{l \cdot w d}$$

$$\eta = \eta_i (1-R)(1-e^{-\alpha d})$$

d: dimension in light propagation direction

$$\Delta I = q(\mu_n + \mu_p) G_0 \tau_n \frac{A}{l} \cdot V$$

typically $\mu_n \gg \mu_p$

$$\Delta I \approx q \mu_n G_0 \tau_n \frac{A}{l} \cdot V$$

Transit time for electron

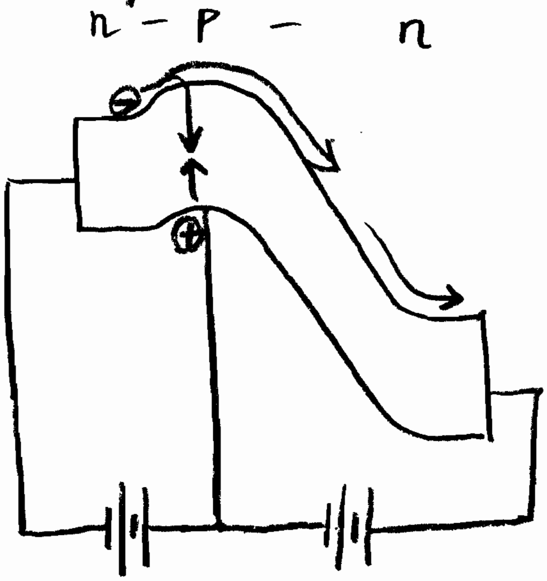
$$\tau_t = \frac{l}{v_n} = \frac{l}{\mu_n E} = \frac{l^2}{\mu_n V}$$

$$\Delta I = q \cdot (G_0 l A) \frac{\tau_n}{\tau_t}$$

$$G_0 l \cdot A = \eta \cdot \frac{1}{\hbar\omega} \cdot P_{opt}$$

$$\Delta I = \underbrace{\eta \cdot \underset{\substack{\downarrow \\ \frac{mA}{mW}}}{\left(\frac{q}{\hbar\omega}\right)} \cdot \underset{\substack{\downarrow \\ mW}}{P_{opt}}}_{\text{Photocurrent}} \cdot \underbrace{\left(\frac{\tau_n}{\tau_t}\right)}_{\text{Photoconductive } \underline{\text{GAIN}}}$$

Analogy to bipolar transistor



base recomb. time = τ_B

transit time = τ_t

current gain

$$= \frac{I_c}{I_B} = \frac{\tau_t}{\tau_B}$$

Bandwidth

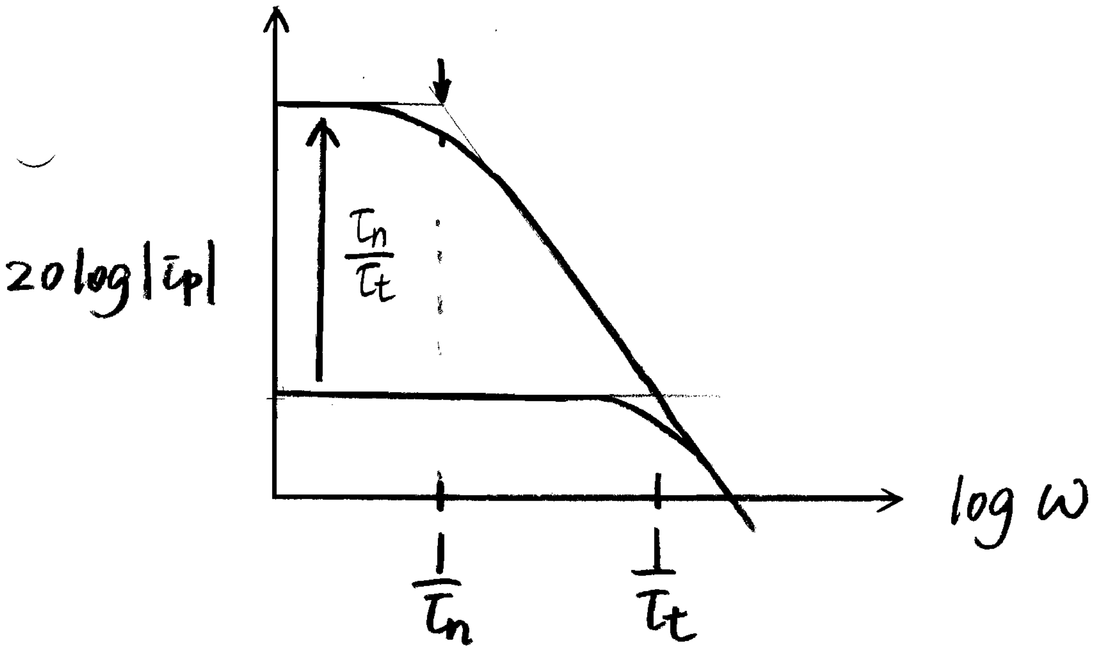
$$\frac{d\,\delta n}{dt} = G_0 - \frac{\delta n}{\tau_n} \quad ; \quad G_0 \sim e^{-i\omega t}$$

$$\delta n \sim e^{-i\omega t}$$

small-signal analysis

$$\delta n = \frac{G_0 \tau_n}{1 - i\omega\tau_n}$$

$$|i_p| = \eta \cdot \left(\frac{q}{\hbar\omega}\right) \cdot P_{opt,ac} \left(\frac{\tau_n}{\tau_t}\right) \frac{1}{\sqrt{1+\omega^2\tau_n^2}}$$



$$f_{3\text{-dB}} = \frac{1}{2\pi}\frac{1}{\tau_n}$$

Gain-bandwidth product

$$GB = \left(\frac{\tau_n}{\tau_t}\right)\frac{1}{2\pi}\cdot\frac{1}{\tau_n} = \frac{1}{2\pi}\frac{1}{\tau_t} = \text{const for a given device}$$

Gain is achieved at the expense of bandwidth.

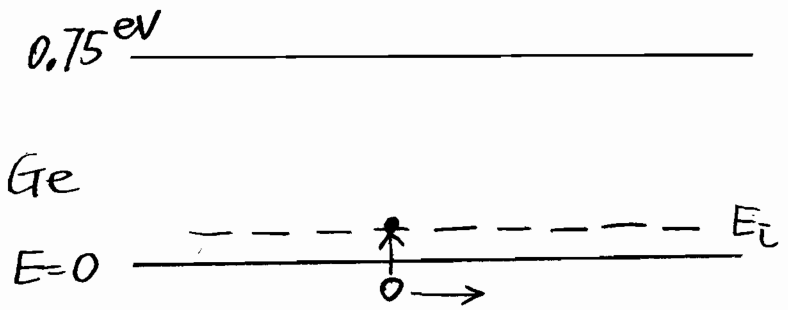
Note:

* G·B is a figure of merit for photoconductor
* $GB = \frac{1}{2\pi}\frac{1}{\tau_t}$

  τ_t is usually determined by other consideration (e.g. quantum efficiency or optical coupling) and cannot be made arbitrarily small.

Photoconductor can be used for very long wavelength photodetectors using bandage to impurity level transition

e.g.



Cu: $E_i = 0.04\ \text{eV} \Rightarrow \lambda = 32\ \mu m$

Hg: $E_i = 0.09\ \text{eV} \Rightarrow \lambda = 14\ \mu m$

Typical bias circuit