Photodetectors (Chuang Chap. 14)

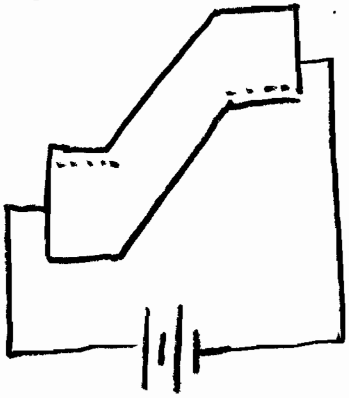
Semiconductor absorbs photons

Photodetector separate and collect electrons and holes generated by absorption.

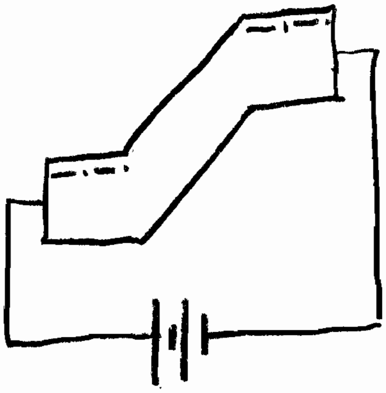
Key parameters

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

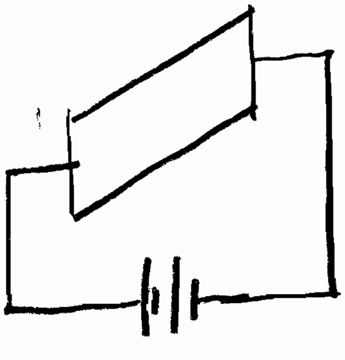
Major catagories of semiconductor photodetectors:



p-i-n

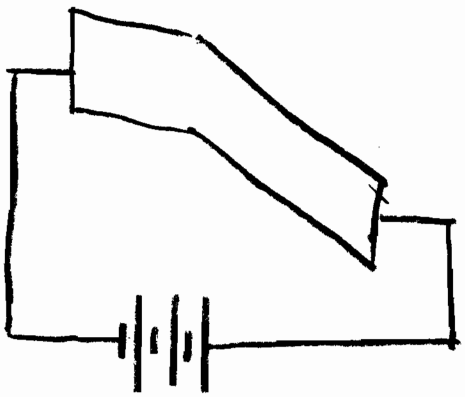


Photoconductor (n-i-n)



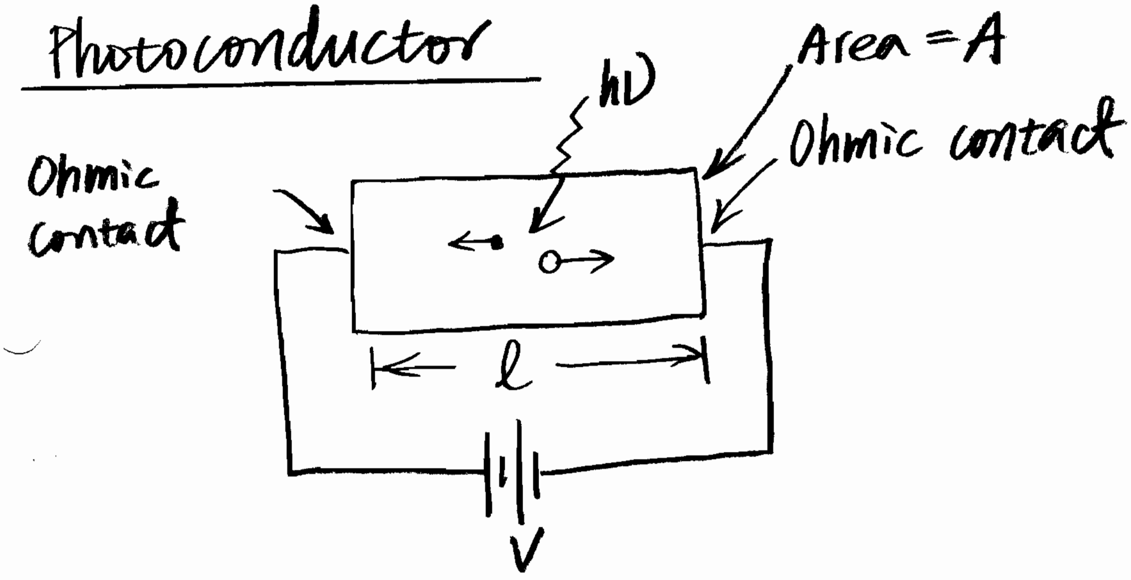
MSM

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

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

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

τ_n ← carrier recomb. lifetime.

G_0 ↑ 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

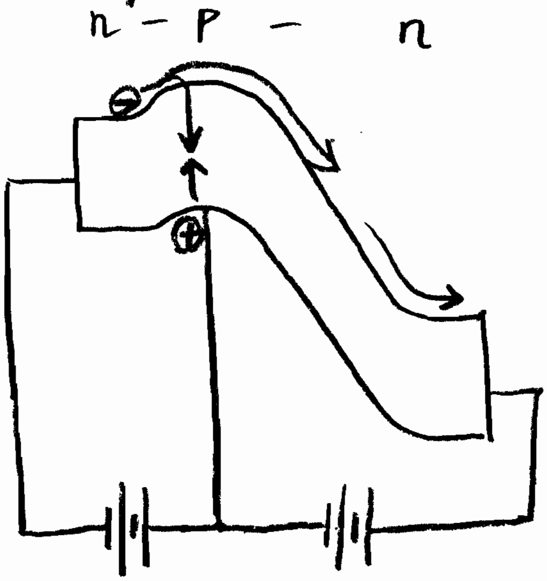
$$\tau_t = \frac{l}{v_n} = \frac{l}{\mu_n E} = \frac{l^2}{\mu_n V}$$

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

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

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

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

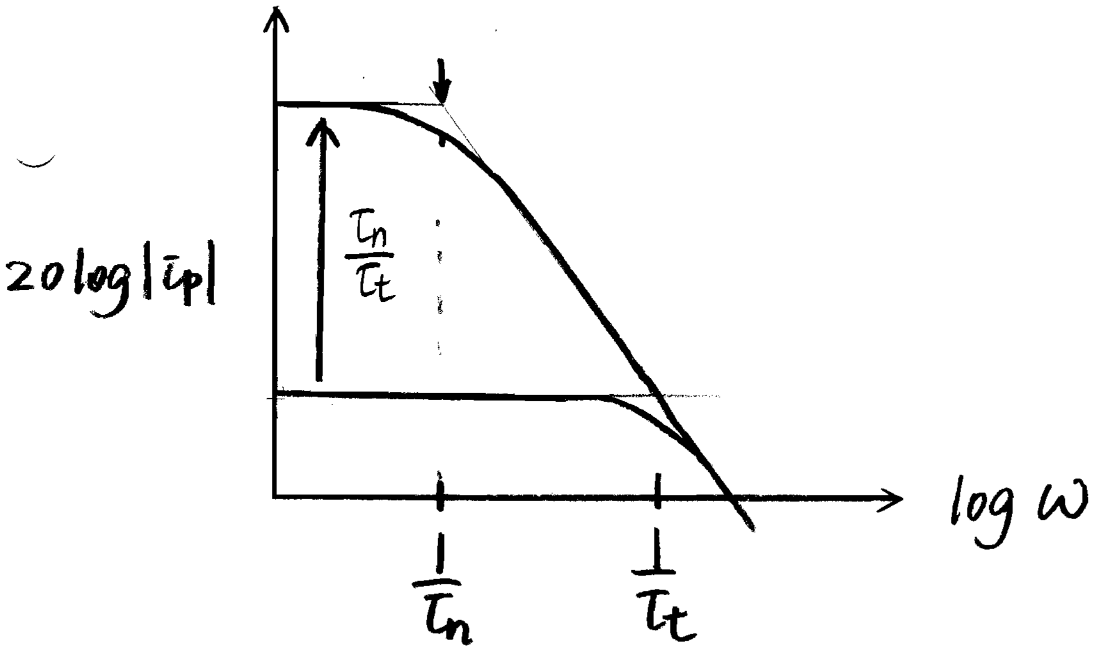
$$\frac{d\,\delta n}{dt} = G_0 - \frac{\delta n}{\tau_n} \quad ; \quad G_0 \sim e^{-i\omega t}$$

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

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

$$GB = \left(\frac{\tau_n}{\tau_t}\right)\frac{1}{2\pi}\cdot\frac{1}{\tau_n} = \frac{1}{2\pi}\frac{1}{\tau_t}$$ = 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.