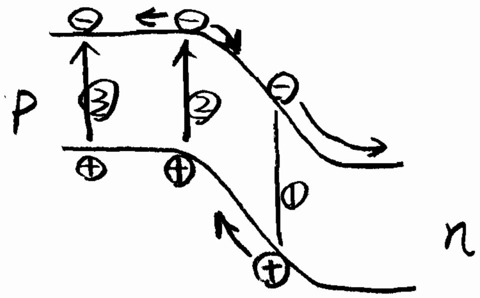
p-i-n Photodiode

Reverse-biased p-n junction.



Photon absorbed in

① depletion region. electrons and holes are separated and collected

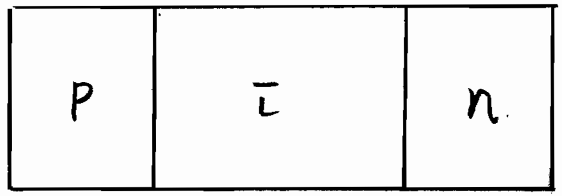
② depletion (e.g. on p-side): electron will diffuse to depletion region, and produce photocurrent

③ neutral region: recombine without generating i_{ph}

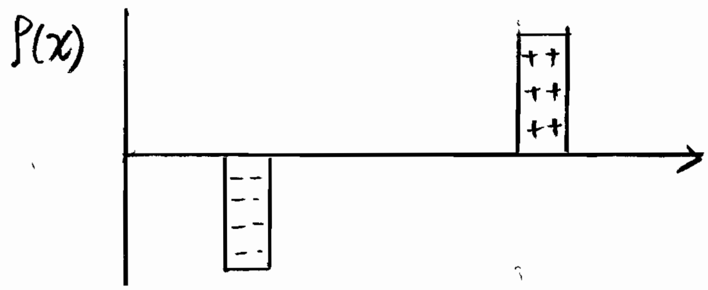
① most desirable

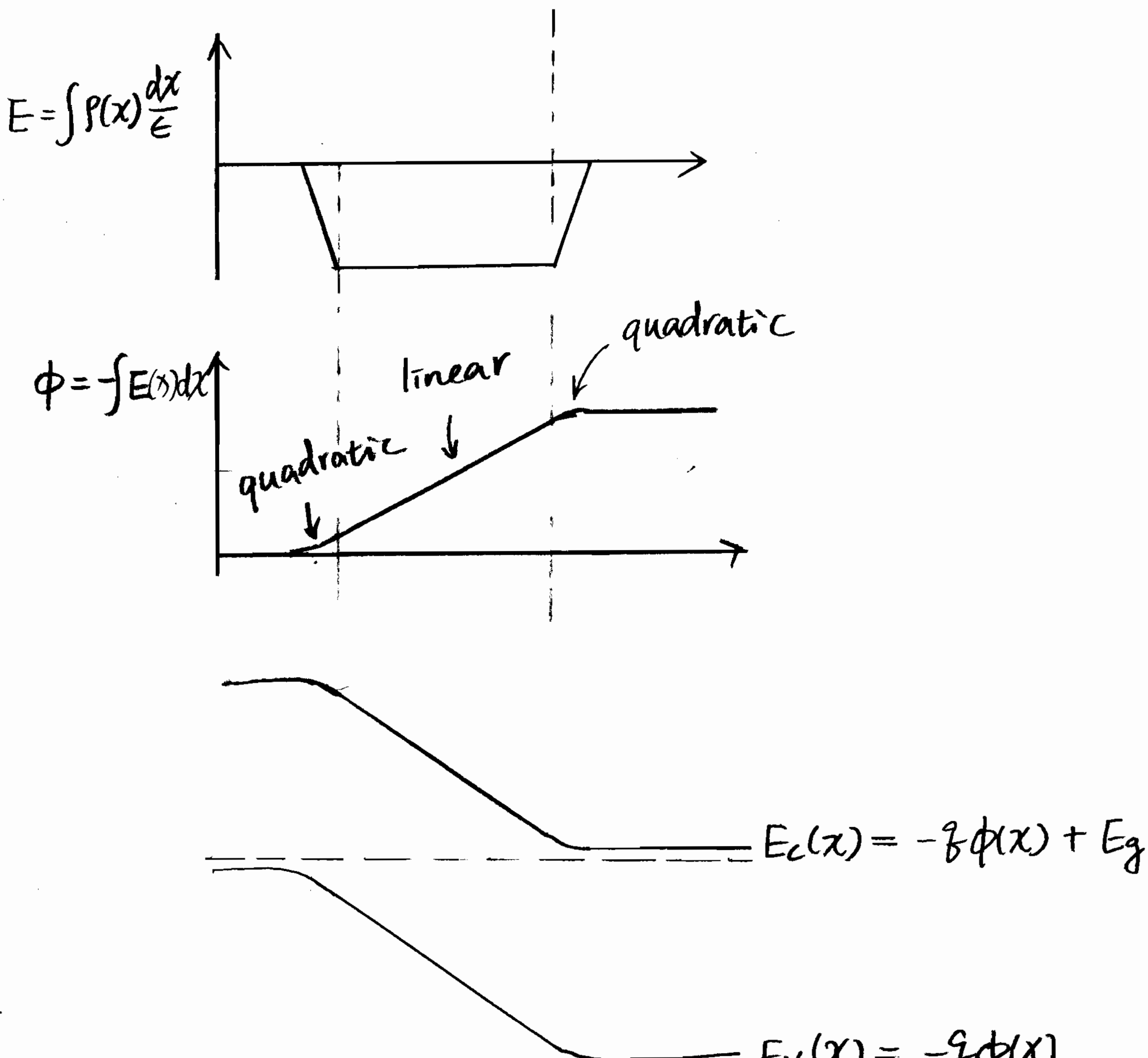
② may have long tail in temporal response (diffusion tail)

To widen depletion region. ⇒ p-i-n



P and n region can be large-E_g material to minimize absorption
$\Rightarrow$ P-i-N



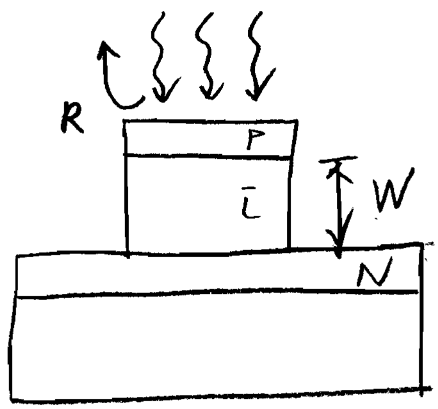


Additional benefits of P-I-N

- Smaller capacitance ⇒ smaller RC, higher speed
- Longer absorption ⇒ higher efficiency
- But longer transit time ⇒ lower speed.

Quantum Efficiency

① Surface-illuminated p-i-n



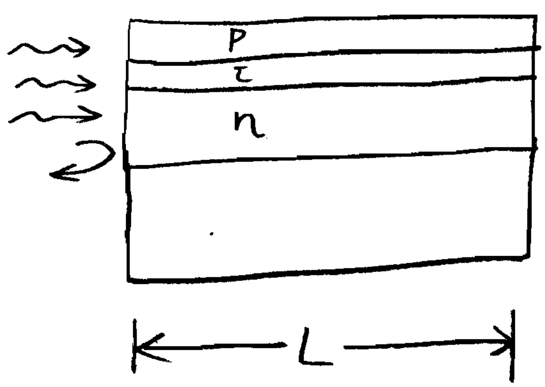
Neglect diffusion current

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

α = absorption coef

$\alpha \sim 10^4\ cm^{-1}$ for direct bandgap

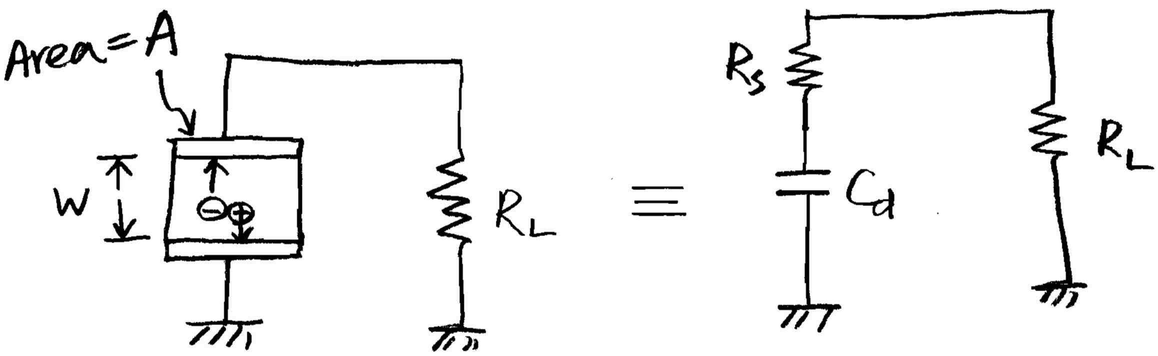
② Waveguide p-i-n



$$\eta = \eta_i (1-R)(1-e^{-\alpha \Gamma \cdot L})$$

Γ = confinement factor

Frequency Response



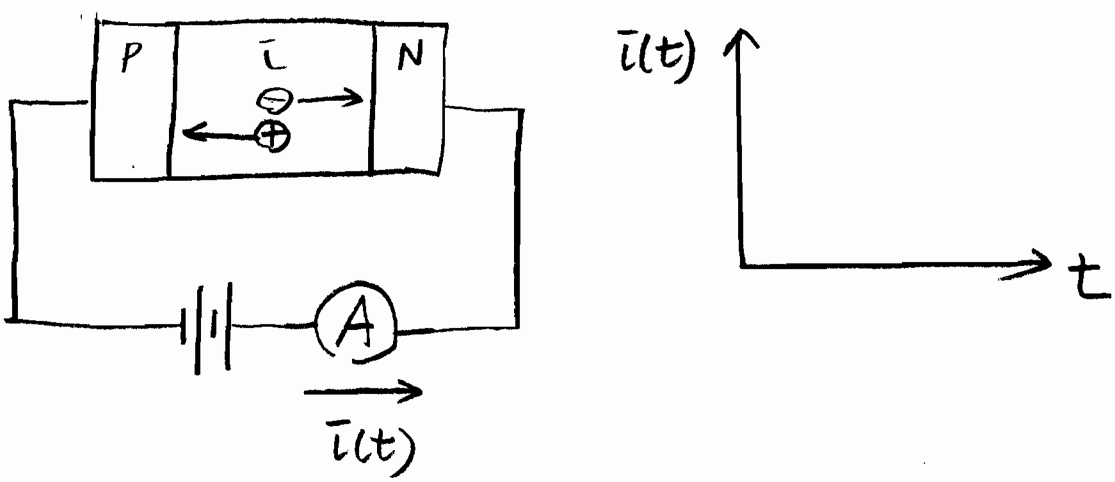
① RC charging
② Transit time

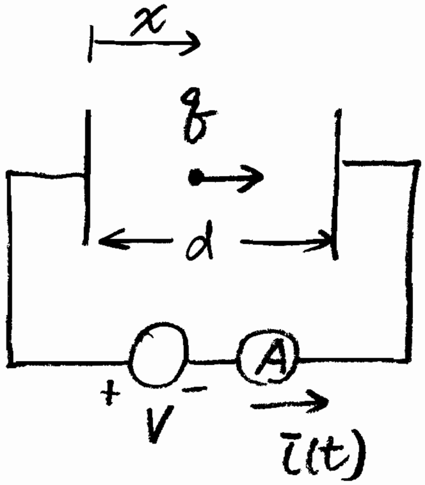
<u>RC</u>: $R = R_s + R_L$ ← input impedance of the following stage
↑ contact resistance + resistance of P and N region.

$$C_d = \frac{\epsilon A}{W}$$

$$\omega_{RC} = \frac{1}{R C_d}$$

<u>Transit time</u>:





Current caused in the external circuit by a moving charge q in a parallel plate capacitor with a separation of d and voltage bias of V:

$$i(t) = \frac{q\, v(t)}{d}$$

Proof: work done on the charge

$$W = \text{Force} \cdot \text{distance} = q E \cdot dx = q \frac{V}{d} \cdot dx$$

work provided by power supply

$$W = V \cdot i(t) \cdot dt$$

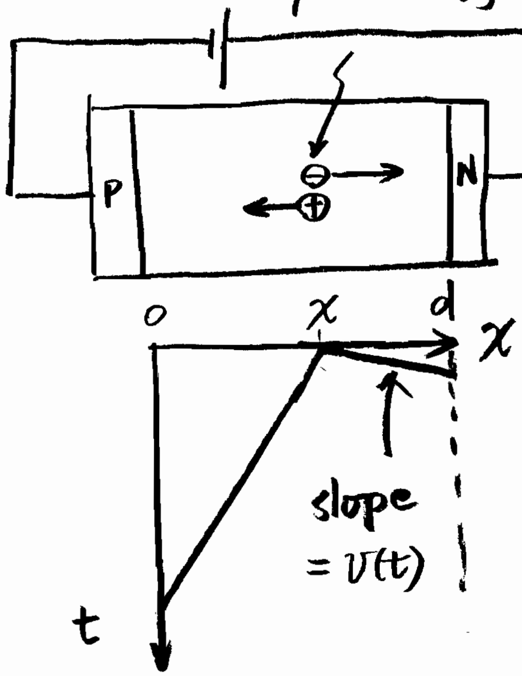
$$\Rightarrow V \cdot i(t)\, dt = V \cdot \frac{q}{d}\, dx$$

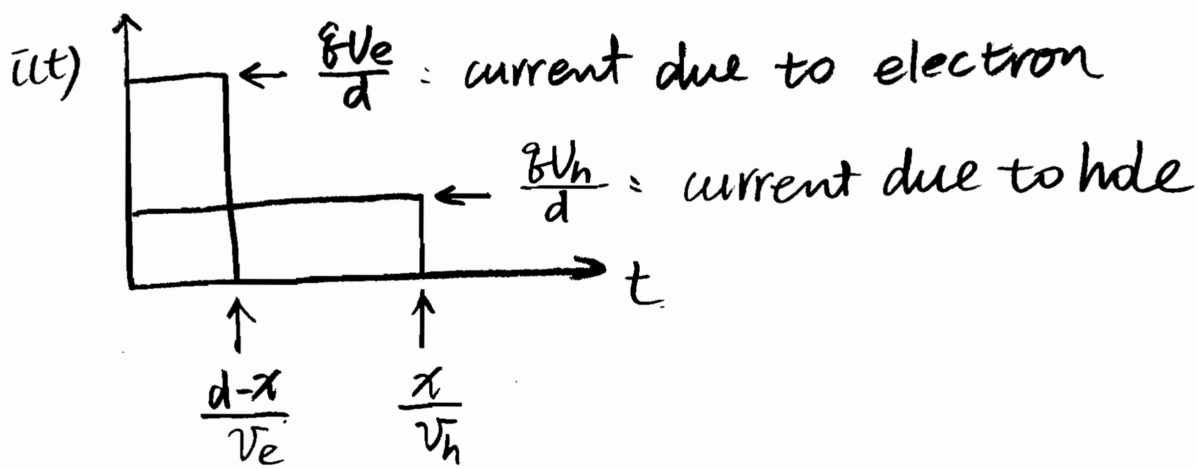
$$\Rightarrow i(t) = \frac{q}{d} \cdot \frac{dx}{dt} = \frac{q\, v(t)}{d}$$

#

Transit Time Concept

* Due to absorption of a single photon





Area = total charge induced in external circuit

$$\frac{qv_e}{d}\cdot\frac{d-x}{v_e} + \frac{qv_h}{d}\cdot\frac{x}{v_h} = q\left(\frac{d-x}{d} + \frac{x}{d}\right) = q$$

* Simple estimation of transit time

$\frac{d}{v_h}$ (hole is usually slower)

* Small-signal approach.

Incident optical field

$$e = E_s(1 + m\cdot\cos\omega_m t)\cdot\cos\omega t$$

modulating freq   optical freq.

$$= \mathrm{Re}[V(t)]$$

$$V(t) = E_s(1 + m\cos\omega_m t)\cdot e^{i\omega t}$$

Generation rate

$$G(t) = a\left\langle \tfrac{1}{2}V(t)\,V^*(t)\right\rangle$$

time average

$$= a\cdot E_s^2\left[1 + \frac{m^2}{2} + 2m\,e^{i\omega_m t}\right]$$

$$i(t) = \frac{e\bar{v}}{d} \qquad \tau_d = \frac{d}{\bar{v}} \text{ : transit time}$$

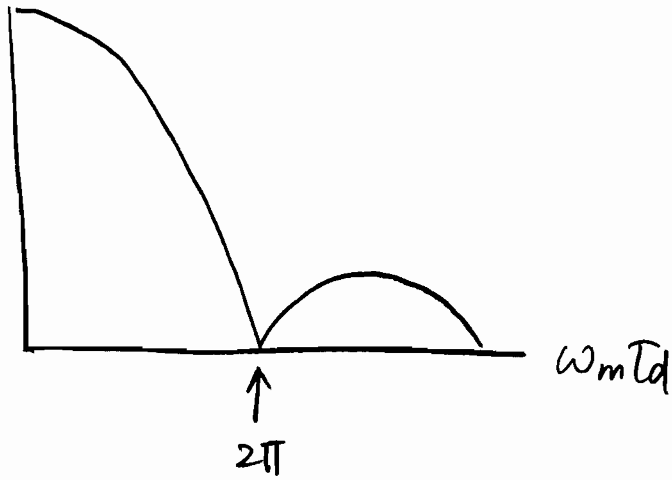
$$i(t) = \frac{e\bar{v}}{d}\cdot\int_{t-\tau_d}^{t} G(t')\,dt'$$

$$= \left(1 + \frac{m^2}{2}\right)e\cdot a\cdot E_s^2 + 2m\cdot e\cdot a\,E_s^2\cdot\left(\frac{1 - e^{-i\omega_m\tau_d}}{i\omega_m\tau_d}\right)\cdot e^{i\omega_m t}$$

Setting $m = 0$ $\quad I = \dfrac{Pe\eta}{\hbar\omega} = e\cdot a\cdot E_s^2$

$$i(t) = \frac{P\cdot e\cdot\eta}{\hbar\omega}\left[\left(1 + \frac{m^2}{2}\right) + 2m\cdot\left(\frac{1 - e^{-i\omega_m\tau_d}}{i\omega_m\tau_d}\right)e^{i\omega_m t}\right]$$

$$\left| i(t)_{ac} \right| \propto \left| \frac{1-e^{-i\omega_m \tau_d}}{i\omega_m \tau_d} \right| = \frac{\sin\left(\frac{\omega_m \tau_d}{2}\right)}{\left(\frac{\omega_m \tau_d}{2}\right)}$$



3-dB point ($\frac{1}{\sqrt{2}}$)

$$\frac{\omega_m \tau_d}{2} \approx 1.4$$

$$2\pi f_m \tau_d \approx 2.8$$

$$f_m = \frac{2.8}{2\pi} \cdot \frac{1}{\tau_d} \approx 0.44 \frac{1}{\tau_d}$$

1/e point

$$\frac{\omega_m \tau_d}{2} \approx 2.2$$

$$f_m \approx \frac{4.4}{2\pi} \frac{1}{\tau_d}$$

Total response time

$$\tau = \tau_{RC} + \tau_t = RC + \frac{1}{4.4}\tau_d$$

$$f = \frac{1}{2\pi}\frac{1}{\tau}$$

Example

p-i-n . $10\,\mu m \times 10\,\mu m$,

$R = 50\,\Omega$

$$RC = \frac{R\epsilon A}{d} = \frac{10^{-12}\cdot 10^{2}\times 10^{-8}}{d}\times 50$$

$$\tau_t = \frac{1}{4.4}\cdot\frac{d}{v_h}$$

$$RC + \tau_t \geq 2\sqrt{\frac{\epsilon A R}{d}\,\frac{d}{4.4 v_h}} = 2\sqrt{\frac{\epsilon A R}{4.4 v_h}}$$

Max freq achieved (min τ) when

$$RC = \tau_t$$

or $d = \sqrt{4.4\, v_h \cdot \epsilon A \cdot R}$ $\leftarrow 50\,\Omega$

10^{-12} F/cm $\quad 10^{-6}$ cm^2

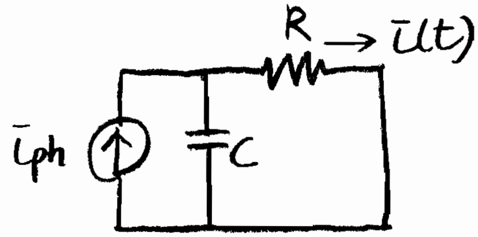
5×10^{6} cm/sec

$$d \approx 0.3\,\mu m$$

* More rigorous analysis

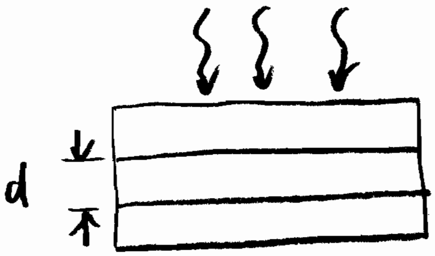
$$|i(t)| \propto \left|\frac{\frac{1}{i\omega C}}{R + \frac{1}{i\omega C}}\right| \cdot \operatorname{sinc}\left(\frac{\omega_m \tau_d}{2}\right)$$

$$= \left|\frac{1}{1 + i\omega RC}\right| \cdot \operatorname{sinc}\left(\frac{\omega_m \tau_d}{2}\right)$$



Equivalent circuit

Efficiency Consideration



Surface-illuminated p-i-n

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

There is a quantum efficiency — bandwidth trade-off

* High η → large d → long transit time
  → low bandwidth

* Simplified case, assume
  - Low efficiency $\eta(d) \approx \eta_i (1 - 1 + \alpha d) = \eta_i \alpha d$
  - Transit time limited BW

$$f_{3dB} \approx 0.44 \frac{v_h}{d}$$

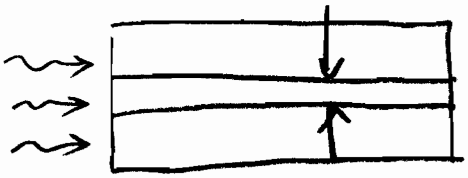
$$\eta \times f_{3dB} \approx \eta_i \alpha \cancel{d} \times 0.44 \frac{v_h}{\cancel{d}} \approx 0.44\, \eta_i\, \alpha \cdot v_h$$

$\alpha \sim 10^4\ cm^{-1}$

$v_h \sim 5 \times 10^6\ cm/sec$

$\eta_i \sim 100\%$

$$\eta \times f_{3dB} \approx 2.2 \times 10^{10}$$



Waveguide PD (edge-illuminated) does not have $\eta - f_{3dB}$ trade-off