# EE 232: Lightwave Devices
## Lecture #21 – Photodetectors

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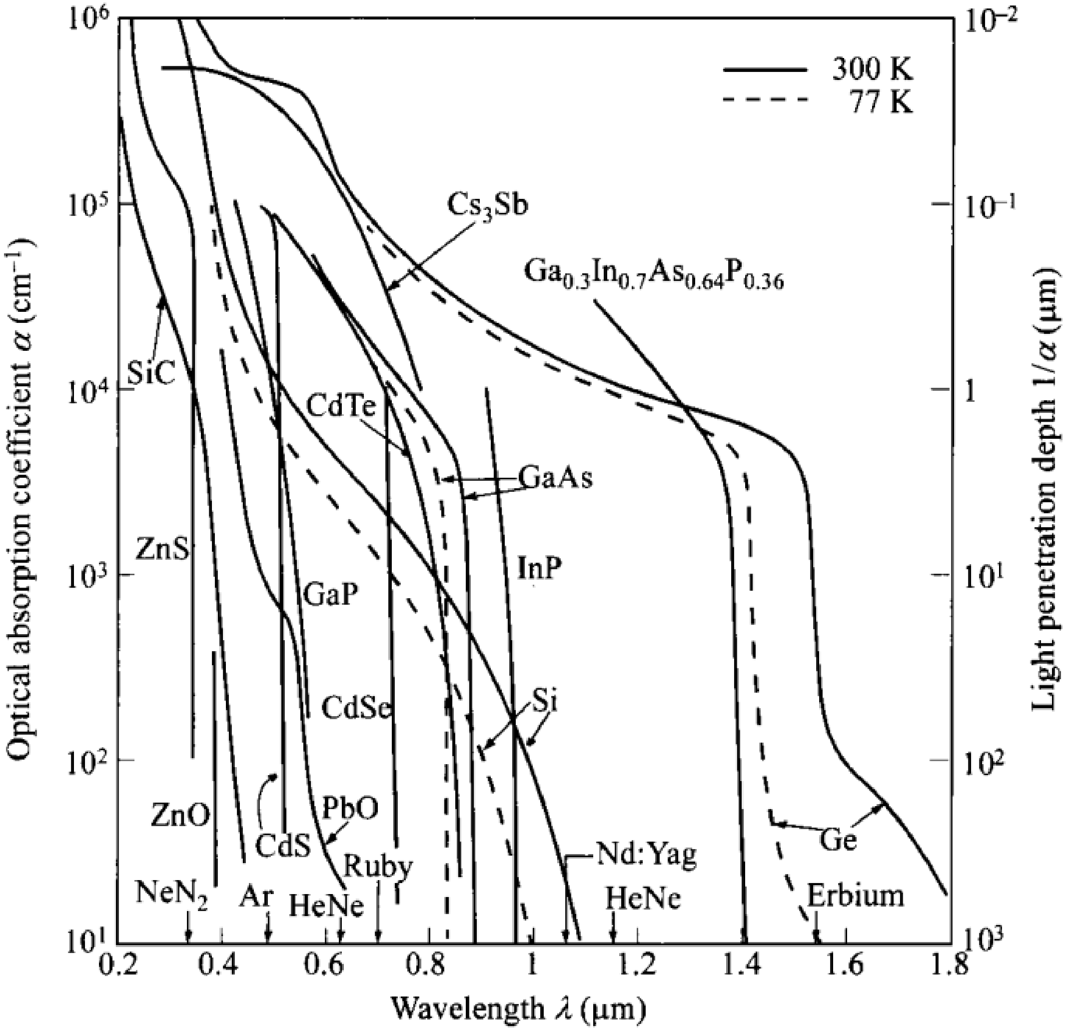
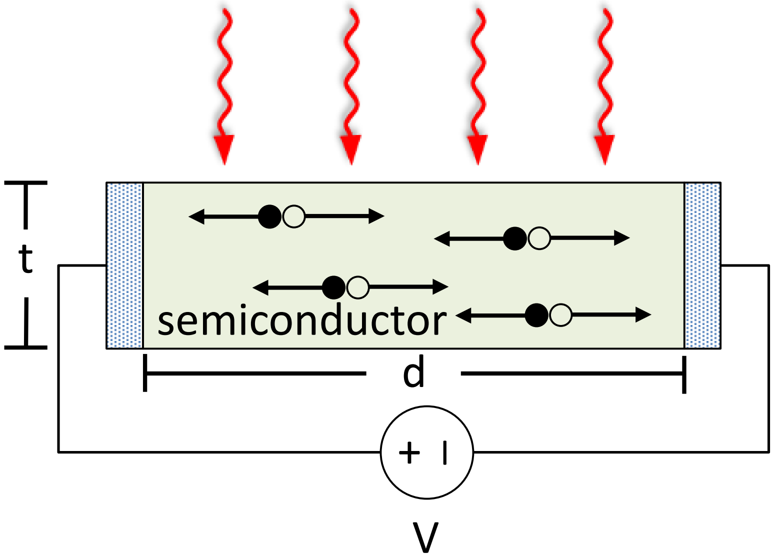
# Absorption coefficient



H. Melchior, “Laser Handbook”, Vol. 1 pp 725-835 (1972).

# Photoconductor



**Light off**

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

**Light on**

$$J \simeq J_0 + q(\mu_n \delta n + \mu_p p_0)E$$

(assuming p-type semiconductor and low-injection)

**Photocurrent**

$$I_{ph} = (J - J_0)A = q\mu_n \delta n E A$$

$$= q\mu_n A(\underbrace{G}_{\text{generation}}\underbrace{\tau_n}_{\text{electron lifetime}})\left(\frac{d}{\mu_n \underbrace{\tau_t}_{\text{transit time}}}\right)$$

$$G = \frac{\text{\# carriers injected}}{(\text{Volume})(\text{s})} = \eta \frac{P_{opt} / h\nu}{(A)(d)}$$

where $\eta = \eta_i \underbrace{(1 - R)}_{\text{surface reflectance}}\underbrace{(1 - e^{-\alpha t})}_{\text{absorption}}$

# Photoconductive gain

Putting it all together,

$$I_{ph} = \underbrace{\left( \eta q \frac{P_{opt}}{h\nu} \right)}_{\text{injected primary photocurrent}} \underbrace{\left( \frac{\tau_n}{\tau_t} \right)}_{\text{photoconductive gain}}$$

Responsivity is $R = \dfrac{\eta q}{h\nu}$

and has units of amps / watt

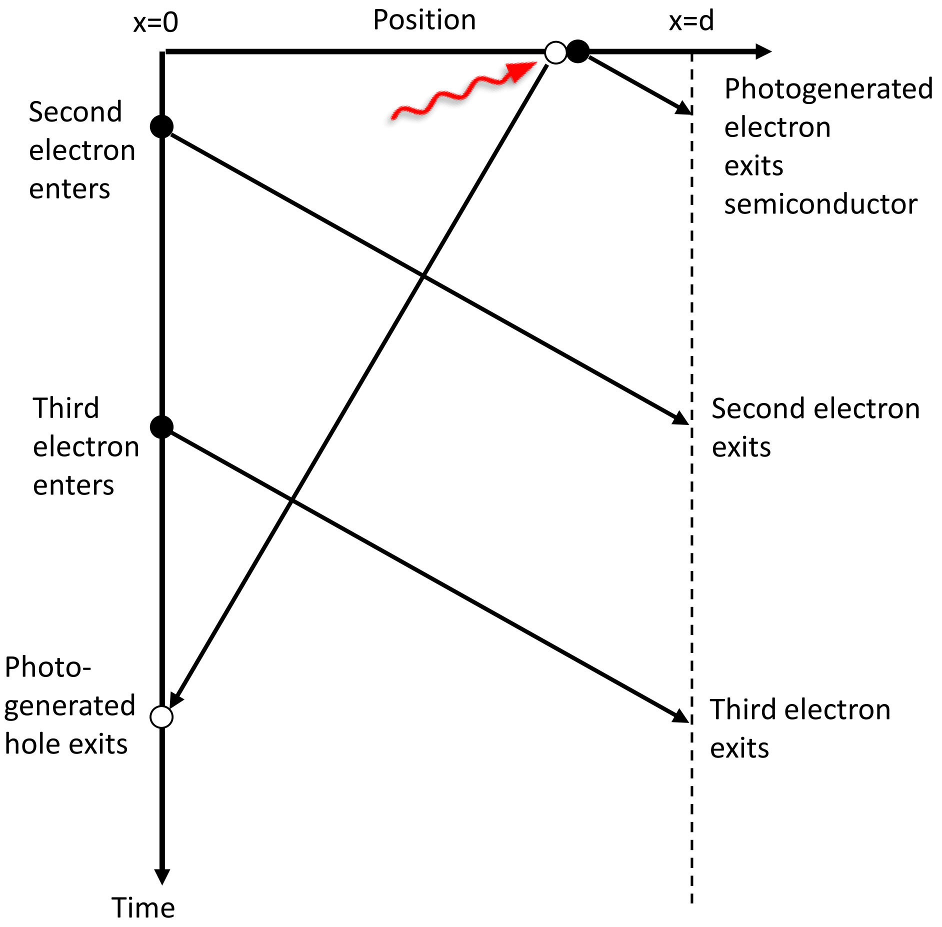


Illustration of photoconductive gain. An electron can contribute multiple times to photocurrent.

# Photoconductor high-frequency response

$$\frac{dn}{dt} = G(t) - \frac{n(t)}{\tau_n}$$

Let, $n(t) = n_0 + \mathrm{Re}[\Delta n(\omega)e^{-i\omega t}]$

$G(t) = G_0 + \mathrm{Re}[\Delta G(\omega)e^{-i\omega t}]$

etc…

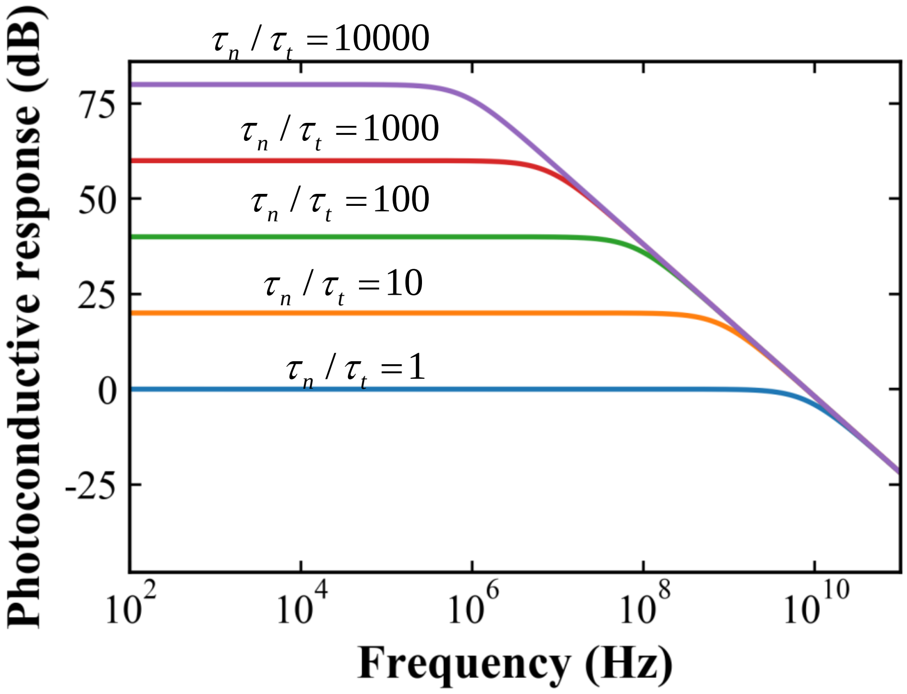
Then,

$$(-i\omega)\Delta n = \frac{\eta \Delta P_{opt} / h\nu}{(A)(d)} - \frac{\Delta n}{\tau_n}$$

$$\frac{\Delta n}{\Delta P_{opt}} = \frac{\eta \tau_n / h\nu}{(A)(d)} \left[ \frac{1}{1 - i\omega\tau_n} \right]$$

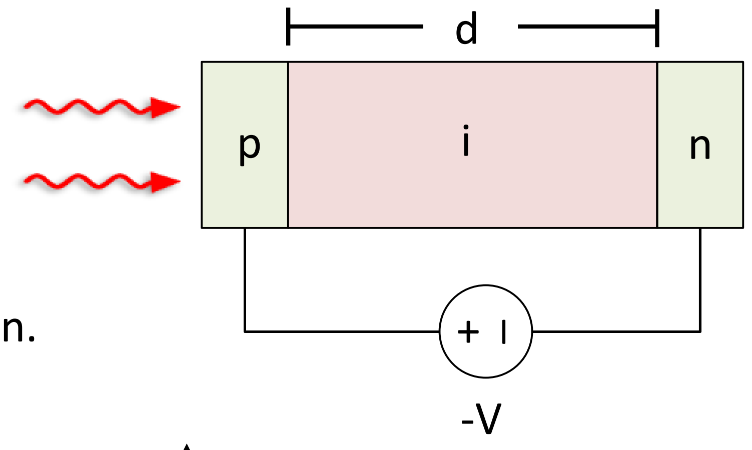
Note: $\Delta I_p = q v_n \Delta n A$

$$\boxed{\frac{\Delta I_p}{\Delta P_{opt}} = \frac{\eta q}{h\nu} \frac{\tau_n}{\tau_t} \left[ \frac{1}{1 - i\omega\tau_n} \right]}$$



# p-i-n photodiode

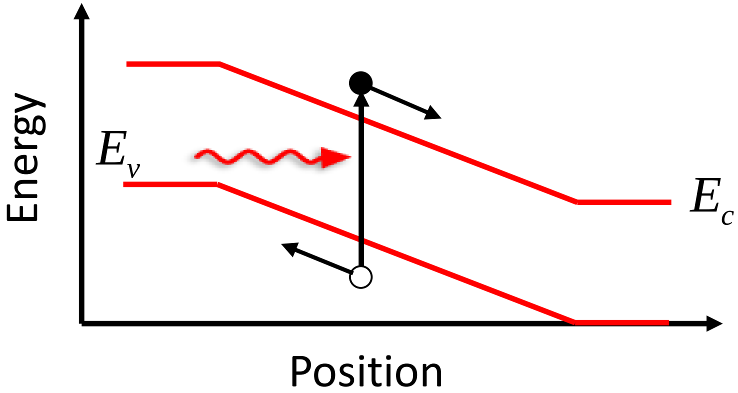
**p-i-n photodiode**: Undoped or lightly doped semiconductor inserted between p and n-type semiconductor. p and n-type regions may be higher bandgap than intrinsic region. Low noise and capable of high-speed.

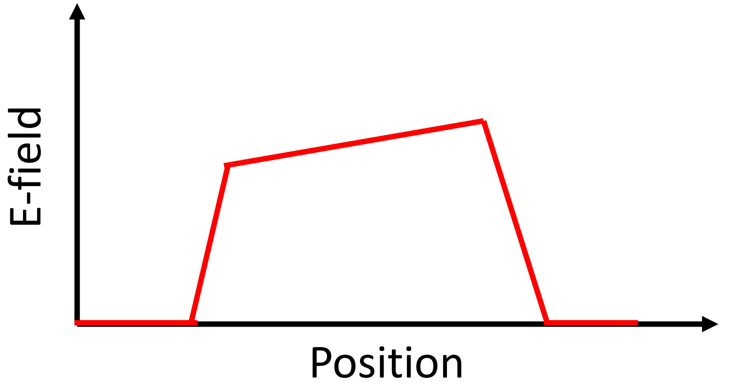


$$I = I_{dark} + I_{ph}$$

$$I_{dark} = I_0 \left( e^{\frac{qV}{kT}} - 1 \right)$$

$$\boxed{\begin{gathered} I_{ph} \simeq -\eta q \frac{P_{opt}}{h\nu} \\ \eta = \eta_i (1-R)(1-e^{-\alpha d}) \end{gathered}}$$





# p-i-n photodiode

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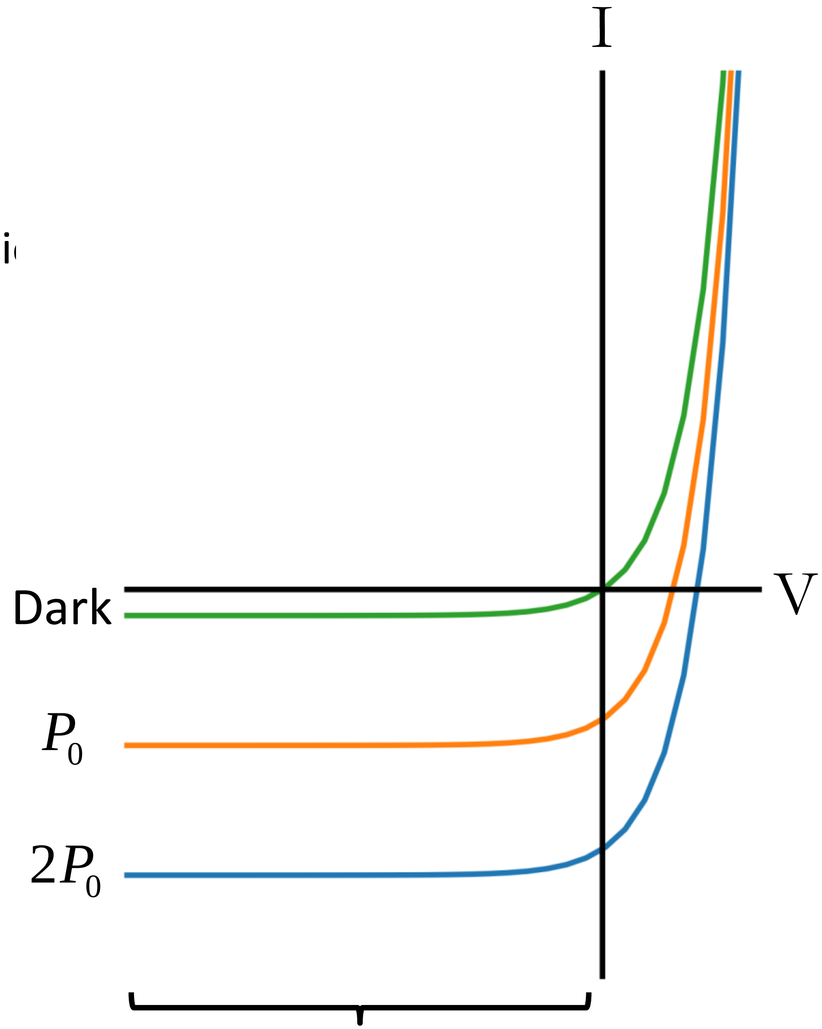
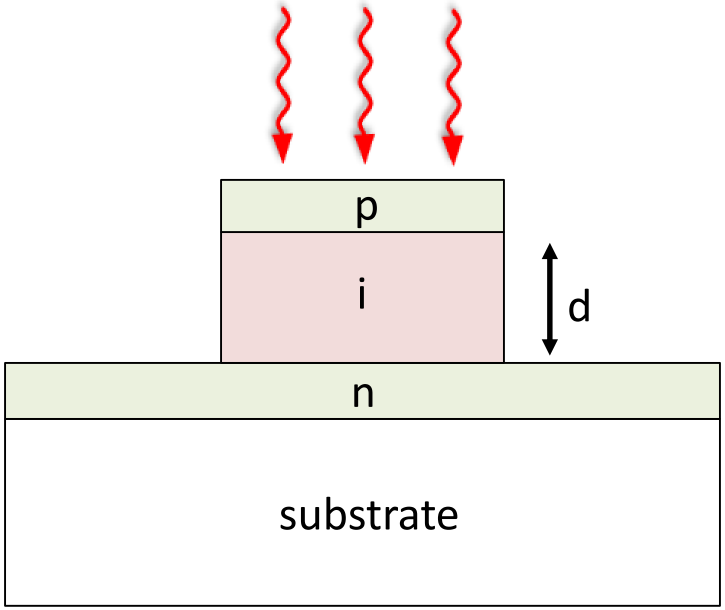


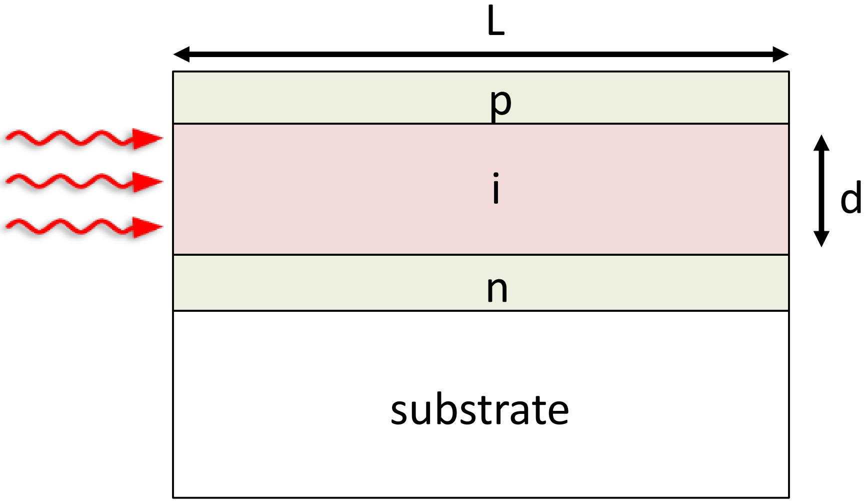
p-i-n diode is usually reverse biased

# Two types of p-i-n photodiodes



**Surface illuminated p-i-n**

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



**waveguide p-i-n**

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

confinement factor

# p-i-n high-frequency response

Time constant of hole transit across intrinsic region: $\tau_t = \frac{d}{v_h}$

RC time constant: $\tau_{RC} = R\frac{\epsilon A}{d}$

**Surface illuminated p-i-n**

Speed usually limited by hole transit time

$$\boxed{f_{3dB} \simeq \frac{1}{2\pi}\frac{v_h}{d}}$$

Efficiency-bandwidth product

$$f_{3dB} \times \eta = \eta_i (1-R)(1-e^{-\alpha d})\frac{1}{2\pi}\frac{v_h}{d}$$

$$\simeq \eta_i \alpha d \frac{1}{2\pi}\frac{v_h}{d}$$

$$\boxed{= \eta_i \alpha v_h / 2\pi}$$

**waveguide p-i-n**

Speed usually limited by RC time

$$\boxed{f_{3dB} \simeq \frac{1}{2\pi}\frac{d}{R\epsilon A}}$$

Efficiency-bandwidth product

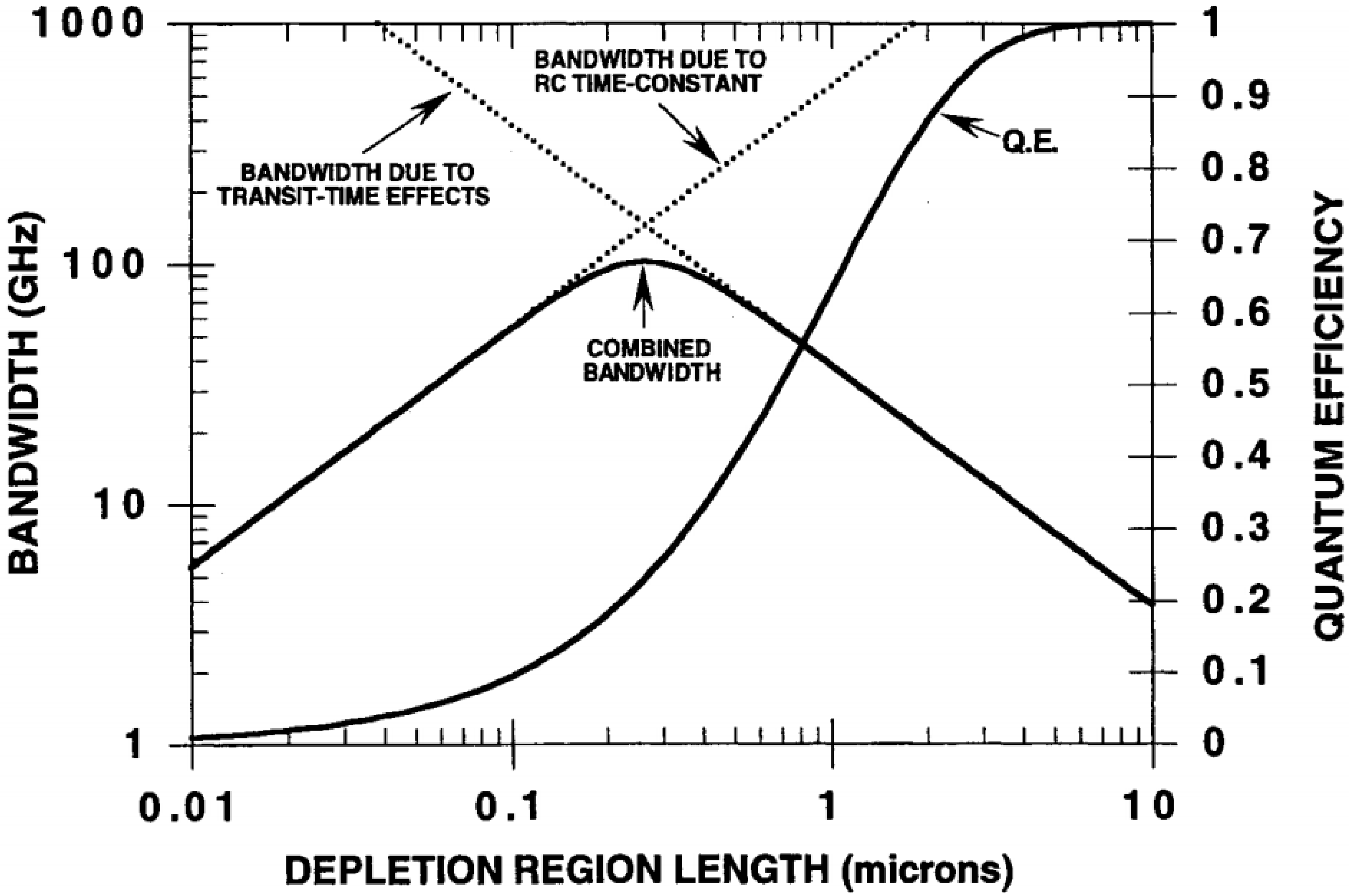
$$f_{3dB} \times \eta = \eta_i (1-R)(1-e^{-\Gamma \alpha L})\frac{1}{2\pi}\frac{d}{R\epsilon A}$$

$$\simeq \eta_i \Gamma \alpha L \frac{1}{2\pi}\frac{d}{R\epsilon A}$$

$$\boxed{= \frac{\eta_i \Gamma \alpha d}{2\pi R \epsilon w}}$$

w: waveguide width

# BW-efficiency product (surface illuminated p-i-n)



Stephen B. Alexander. Optical communication receiver design. 1997.

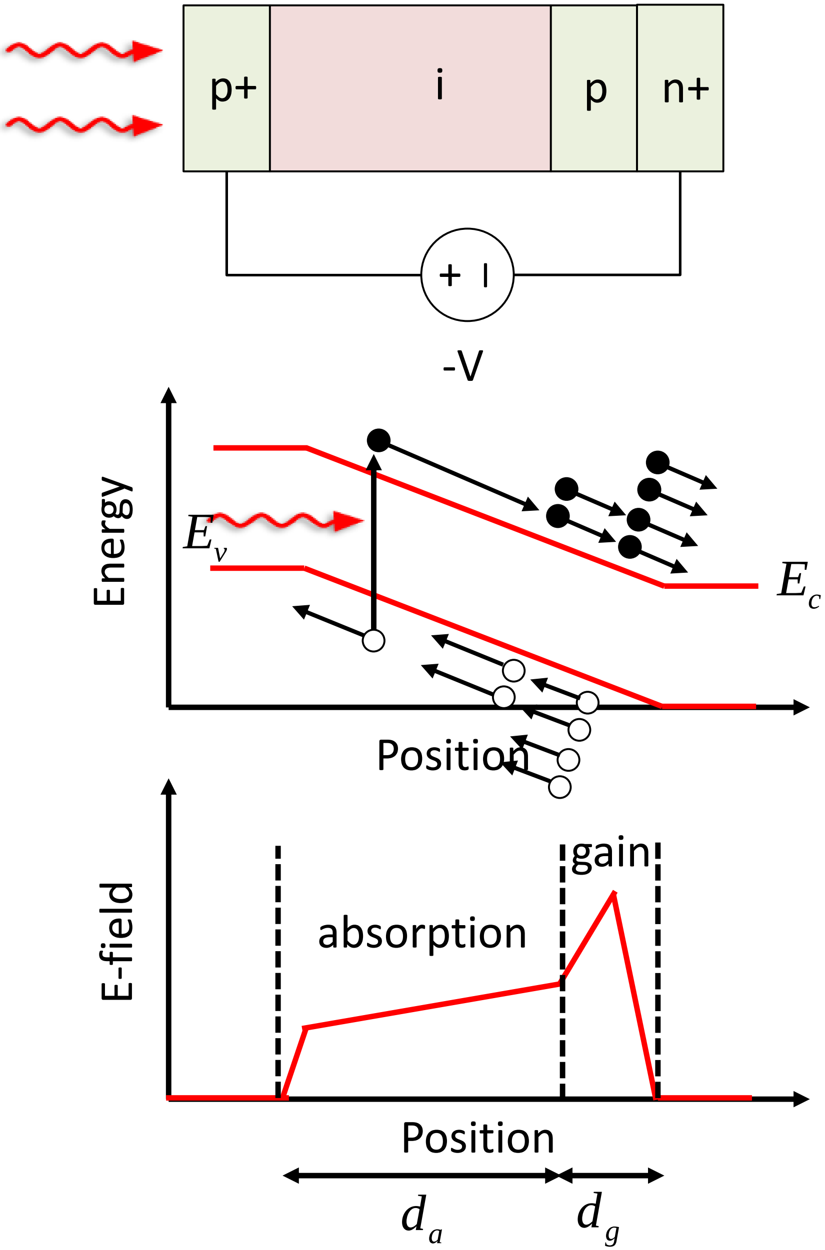
# Avalanche photodiode (APD)

**APD**: High-field region accelerates carriers resulting in impact ionization and creation of new carriers (avalanche breakdown). Unlike the p-i-n, the APD has gain. A single e-h pair can create a cascade of several others. Downside is additional noise.

$$\left| I_{ph} \right| = \eta q \frac{P_{opt}}{h\nu} M$$

multiplication factor

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



# Impact ionization and multiplication factor

$$\boxed{k = \frac{\beta_p}{\alpha_n}}$$

$\alpha_n$ : electron ionization coefficient

$\beta_p$ : hole ionization coefficient

$k$ : ionization ratio

| **Material** | **k-value** |
|---|---|
| Si | 0.02-0.05 |
| Ge | 0.7-1.0 |
| InGaAs | 0.5-0.7 |

Usually k << 1 is desirable for good noise properties (more on this later).
For example, silicon is an excellent material for APD.
When only electrons are injected into the gain region, it can be shown:

$$\boxed{M_n = \frac{1-k}{e^{-(1-k)\alpha_n d_g} - k}}$$

(electron multiplication factor)

# APD high-frequency response

High-frequency response limited by hole transit time and gain build-up time.

hole transit time $$\tau_h = \frac{d_a + d_g}{v_h} \simeq \frac{d_a}{v_h}$$

gain build-up time $$\tau_m = \frac{M_n k d_g}{v_n}$$

Usually, $$\tau_m > \tau_h \rightarrow \tau \simeq \frac{M_n k d_g}{v_n}$$ $$\boxed{f_{3dB} \simeq \frac{1}{2\pi} \frac{v_n}{M_n k d_g}}$$

**Gain-bandwidth product**

$$M \times f_{3dB} \simeq \frac{M_n}{2\pi} \frac{v_e}{M_n k d_g} = \boxed{\frac{v_e}{2\pi k d_g}}$$

Typical values are 100 to 200 GHz

# Summary

| **Photodetector** | $\left\| I_{ph} \right\|$ | **Pros** | **Cons** |
|---|---|---|---|
| Photoconductor | $\eta q \frac{P_{opt}}{h\nu} \frac{\tau_n}{\tau_t}$ | Simple device,<br>Gain,<br>Very fast | High noise |
| p-i-n | $\eta q \frac{P_{opt}}{h\nu}$ | Low noise,<br>Fast | No gain |
| APD | $\eta q \frac{P_{opt}}{h\nu} M$ | Gain,<br>Fast,<br>Increased sensitivity (sometimes) | Complicated,<br>Multiplication noise |

Recommended reading:
S.D. Personick, Optical Detectors and Receiver. J. Light. Technol. Vol. 26, No. 9, 2008.