Lecture 1:
Photoconductors and p-i-n Photodiodes

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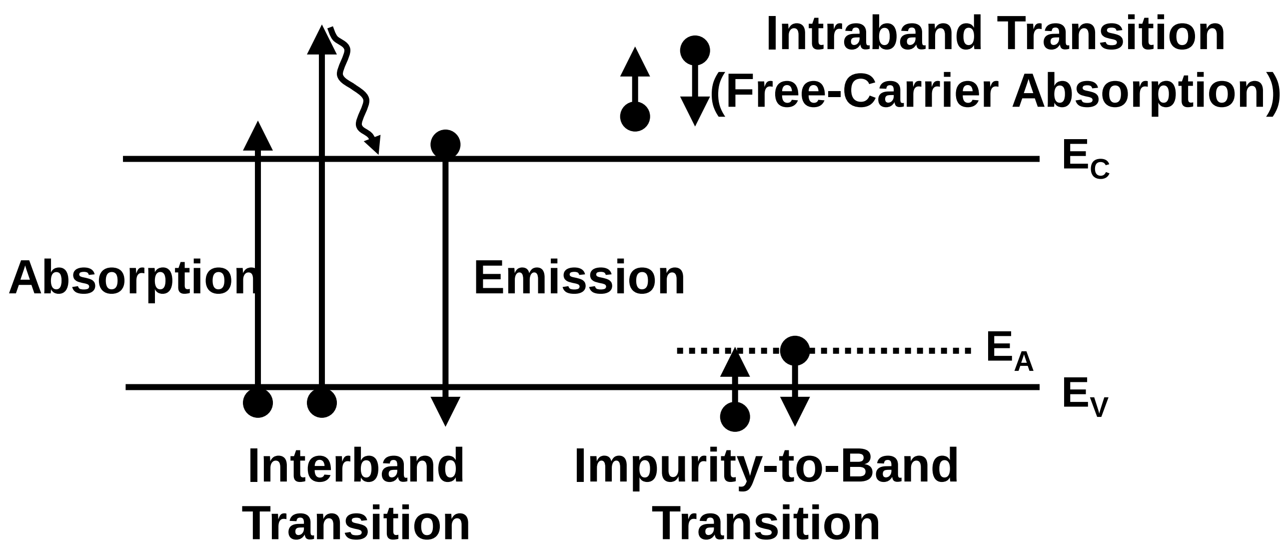
Photodetectors

- **Converts light to electric signals**
- **Main types of photodetectors**
  - **Photoconductors**
  - **P-i-n photodiodes**
  - **Metal-semiconductor-metal (MSM) photodetector**
  - **Avalanche photodetectors (APD)**
- **Key performance parameters**
  - **Responsivity [A/W]**
  - **Wavelength range**
  - **Modulation bandwidth**
  - **Noise characterisitics**

Optical Properties of Semiconductors



- **Optical transitions**
  - **Absorption: exciting an electron to a higher energy level by absorbing a photon**
  - **Emission: electron relaxing to a lower energy state by emitting a photon**

Band-to-Band Transition

- **Since most electrons and holes are near the band-edges, the photon energy of band-to-band (or interband) transition is approximately equal to the bandgap energy:**

$$h\nu = E_g$$

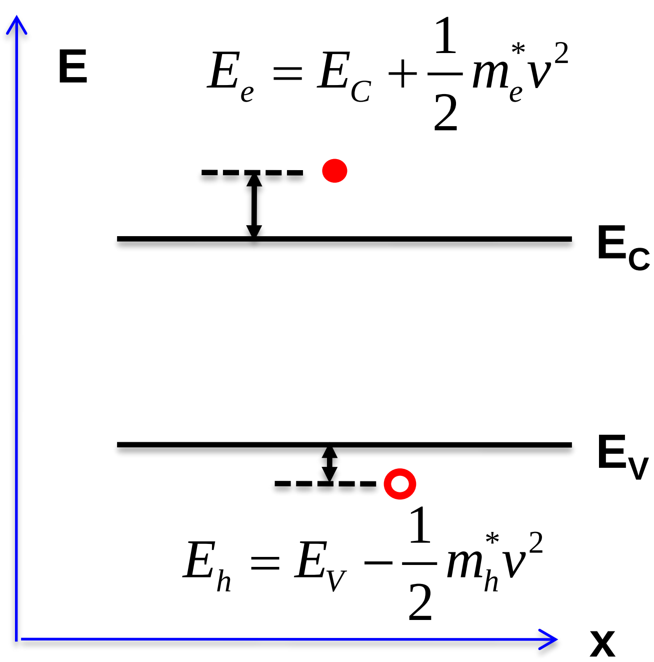
- **The optical wavelength of band-to-band transition can be approximated by**

$$\lambda \approx \frac{1.24}{E_g}$$

λ : wavelength in μm

E_g : energy bandgap in eV

Energy Band Diagram in Real Space and k-Space

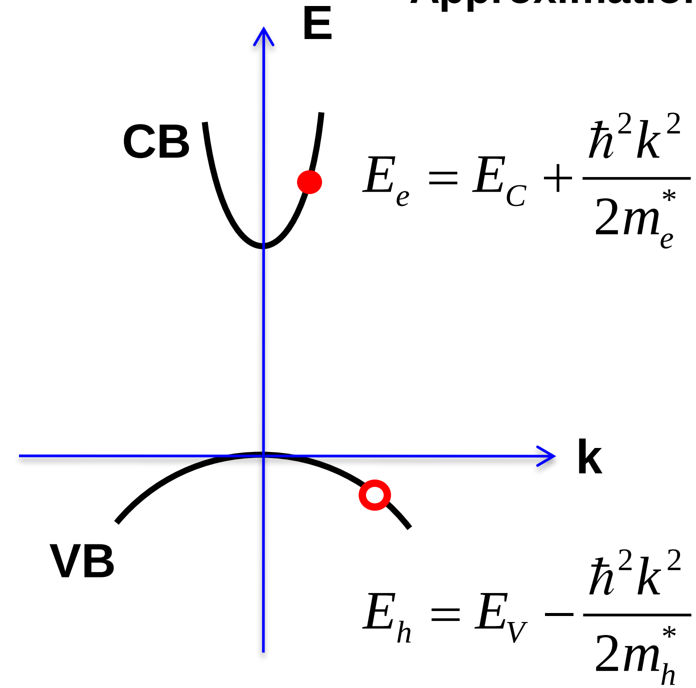


Real Space

Momentum:

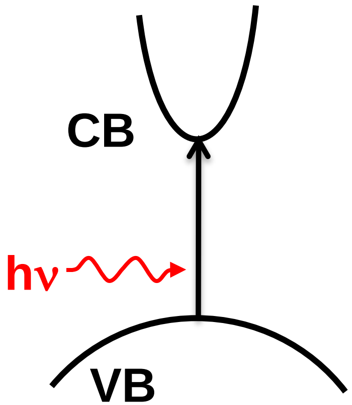
$$\hbar k = m_e^* v_e$$

Effective Mass Approximation



K-Space

Band-to-Band Transition



Absorption

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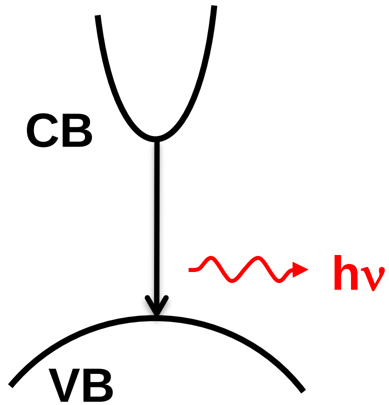
Photodetectors; Solar Cells



Spontaneous Emission

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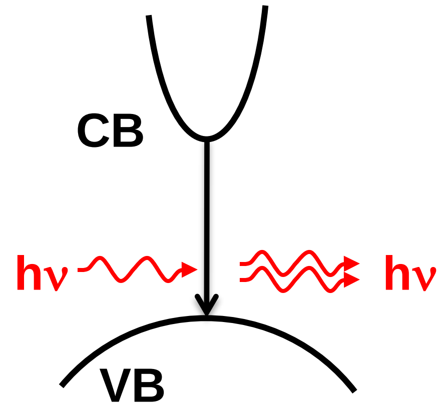
LED



Stimulated Emission

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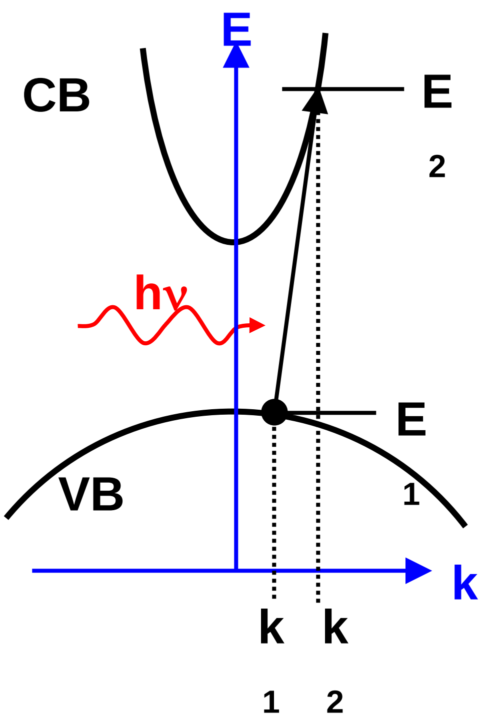
Optical Amplifiers; Semiconductor Lasers

Conservation of Energy and Momentum



Optical transitions are "vertical" lines

- **Conditions for optical absorption and emission:**
  - **Conservation of energy**

$$E_2 - E_1 = h\nu$$

  - **Conservation of momentum**

$$k_2 - k_1 = k_{h\nu}$$

$$k_2, k_1 \sim \frac{2\pi}{a}$$

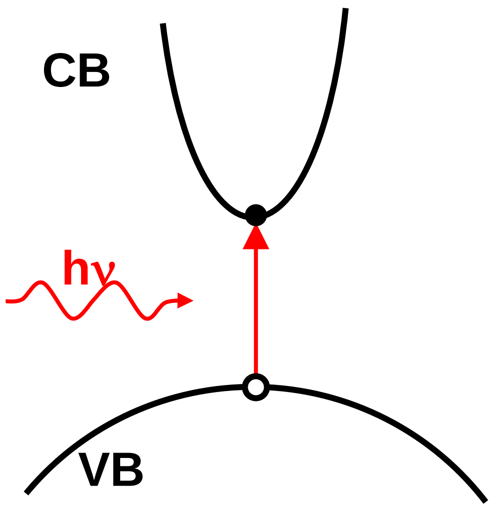
$$k_{h\nu} \sim \frac{2\pi}{\lambda}$$

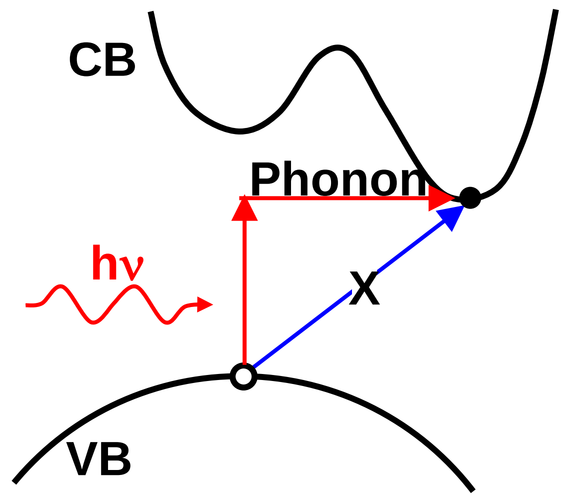
$$(a \sim 0.5nm) << (\lambda \sim 1\mu m)$$

Lattice Constant

$$\Rightarrow k_2 = k_1$$

Direct vs Indirect Bandgaps

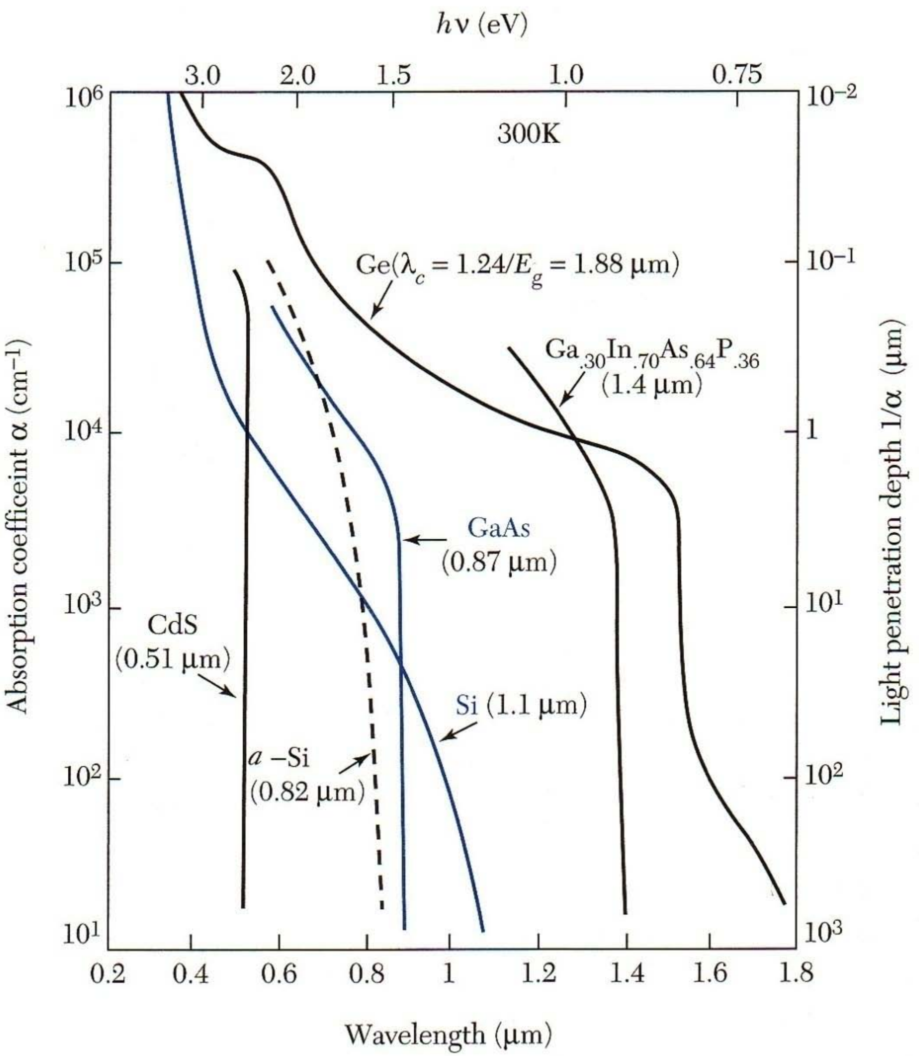




- Direct bandgap materials
  - CB minimum and VB maximum occur at the same k
  - Examples
    - GaAs, InP, InGaAsP
    - $(Al_xGa_{1-x})As$, $x < 0.45$

- Indirect bandgap materials
  - CB minimum and VB maximum occur at different k
  - Example
    - Si, Ge
    - $(Al_xGa_{1-x})As$, $x > 0.45$
  - Not “optically active”

Absorption Coefficient

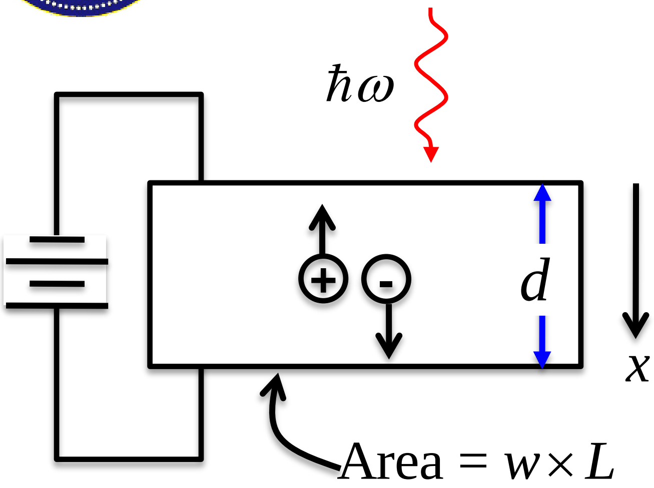


- Light intensity decays exponentially in semiconductor:

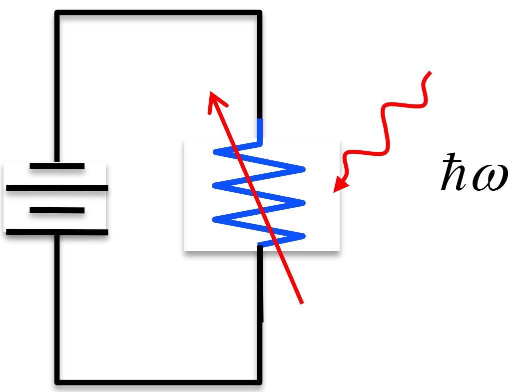
$$I(x) = I_0 e^{-\alpha x}$$

- Direct bandgap semiconductor has a sharp absorption edge
- Main photodetector materials
  - 1.3/1.55μm: InGaAs on InP
  - 850nm: GaAs or Si
- Si absorbs photons with hν > E_g = 1.1 eV, but the absorption coefficient is small due to indirect bandgap
  - Sufficient for CCD

Photoconductors



Equivalent Circuit



Dark current:

$$J_0 = \sigma_0 E = \left(n_0 q \mu_n + p_0 q \mu_p\right) E$$

Light illumination generate electron-hole pairs, increasing the conductivity:

$$\frac{d\delta n}{dt} = G_0 - \frac{\delta n}{\tau_n}$$

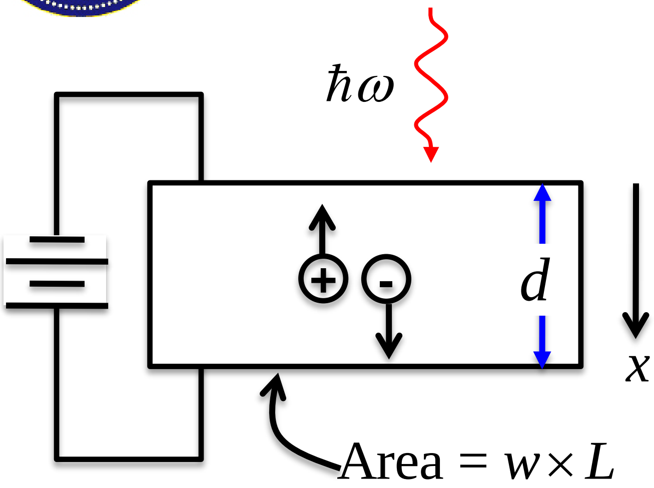
Steady state: d/dt --> 0

$$\delta n = G_0 \tau_n$$

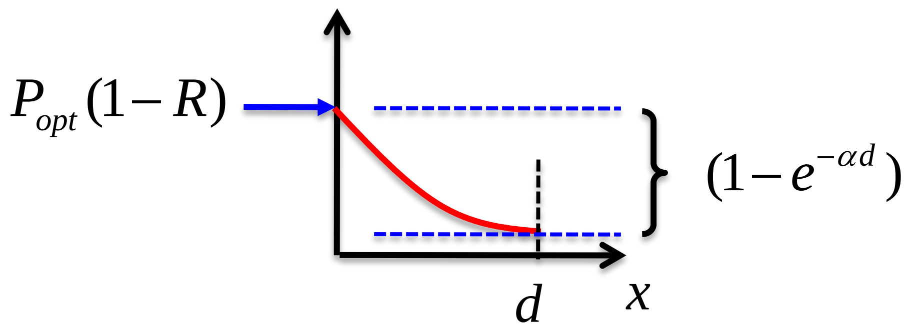
$$\Delta J = \delta n \cdot q\left(\mu_n + \mu_p\right) E$$

Photoconductor requires both contacts to be Ohmic

Photocarrier Generation Rate



Light Intensity $\propto e^{-\alpha x}$



$$G_0 = \eta \frac{P_{opt}}{\hbar\omega} \frac{1}{lwd}$$: photocarrier generation rate $[\frac{1}{cm^3 s}]$

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

R : reflectivity of photoconductor surface

α: absorption coefficient

d : absorption lenght

$e^{-\alpha d}$: fraction of light remains after absorption length d

Photoconductive Gain

$$\Delta I = lw\Delta J = lw\left(G_0 \tau_n q\right)\left(\mu_n + \mu_p\right)E$$

$$\Delta I = lw\left(\eta \frac{P_{opt}}{\hbar\omega}\frac{1}{lwd}\tau_n\right)q\left(\mu_n + \mu_p\right)E$$

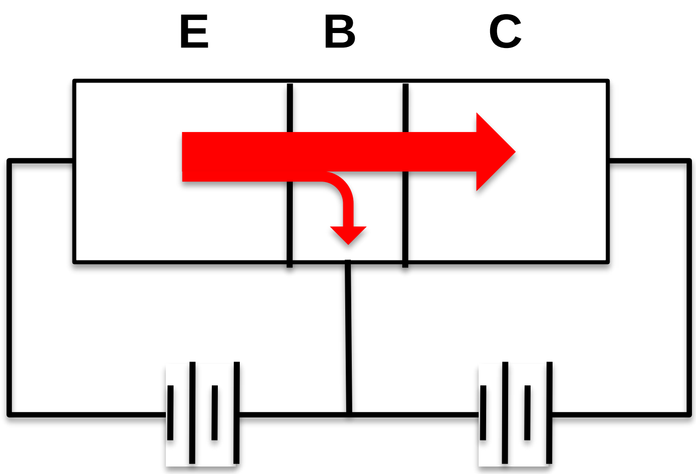
$$\Delta I \approx \eta \frac{P_{opt}}{\hbar\omega}\frac{1}{d}\tau_n q\left(\mu_n E\right) = \eta P_{opt}\frac{q}{\hbar\omega}\tau_n \frac{1}{d}v_n$$

$$\tau_t = \frac{d}{v_n} \text{ : transit time}$$

$$\boxed{\Delta I = \left(\eta P_{opt}\frac{q}{\hbar\omega}\right)\left(\frac{\tau_n}{\tau_t}\right)}$$

Photocurrent **Photoconductive Gain**

Analogy to Current Gain in Bipolar Transistor



Current gain in bipolar transistor:

$$\beta = \frac{I_C}{I_B}$$

The current gain can also be expressed as

$$\beta = \frac{\tau_{rb}}{\tau_t}$$

τ_t : transit time

τ_{rb} : carrier recombination lifetime in the base

Frequency of Photoconductors

$$\frac{dN}{dt} = \eta \frac{P_{opt}}{\hbar\omega} \frac{1}{lwd} - \frac{N}{\tau_n}$$

Small signal response:

$$N = N_0 + N_1 e^{j\omega t}$$

$$j\omega N_1 = \eta \frac{P_1}{\hbar\omega} \frac{1}{lwd} - \frac{N_1}{\tau_n}$$

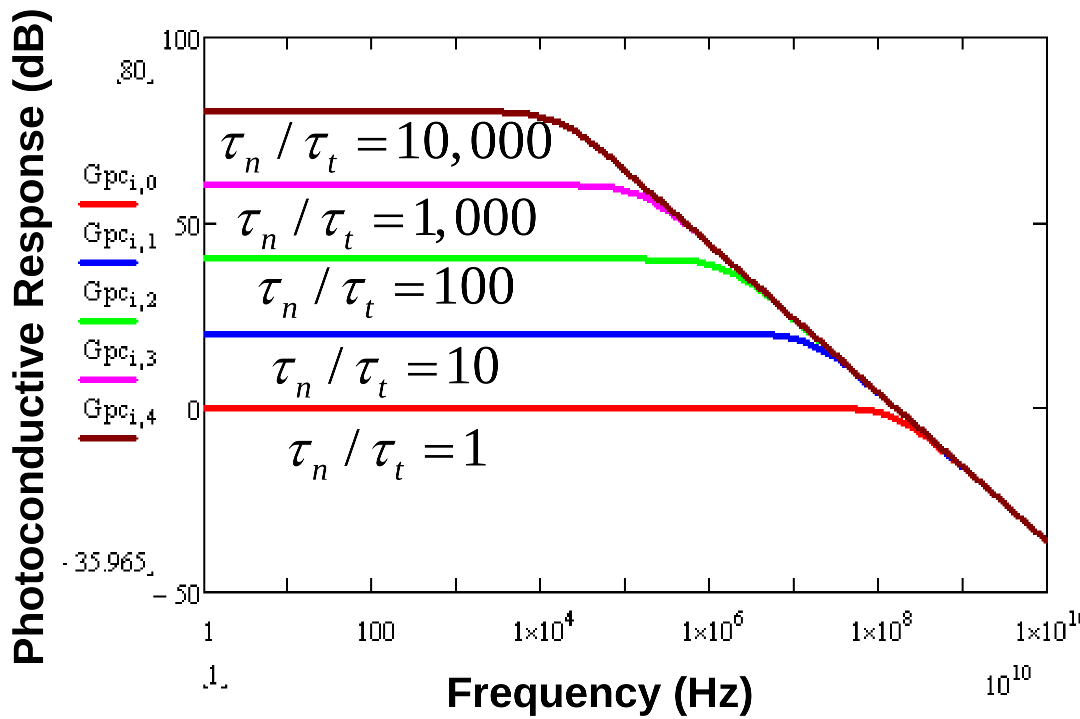
$$N_1 = \frac{\eta P_1}{\hbar\omega(lwd)} \frac{1}{j\omega + 1/\tau_n}$$

$$I_1 = J_1 lw = (N_1 q v_n) lw$$

$$\frac{I_1}{P_1} = \left(\frac{\eta q}{\hbar\omega}\right)\left(\frac{\tau_n}{\tau_t}\right)\frac{1}{j\omega\tau_n + 1}$$

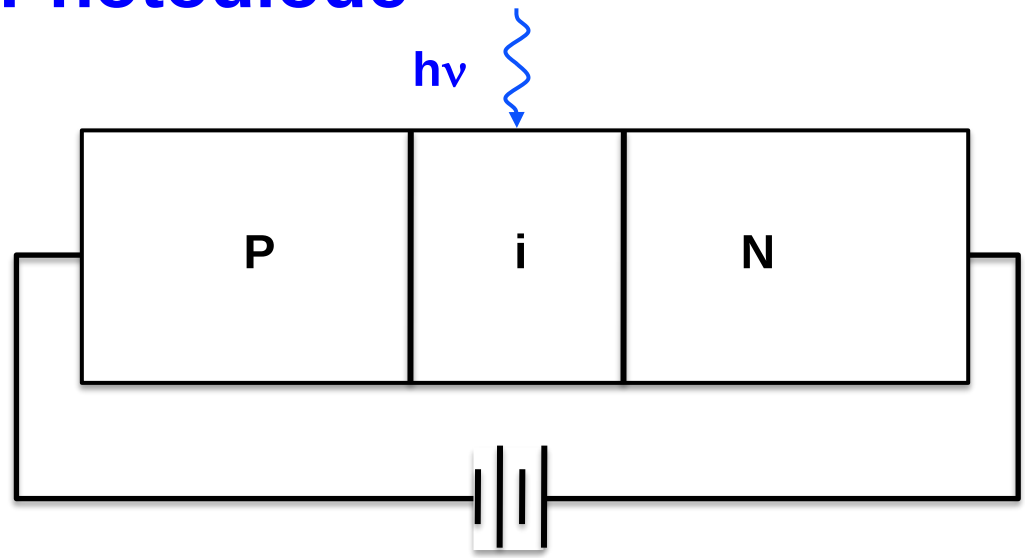
$$= (\text{DC Quantum Efficiency}) \times (\text{Photoconductive Gain}) \times$$

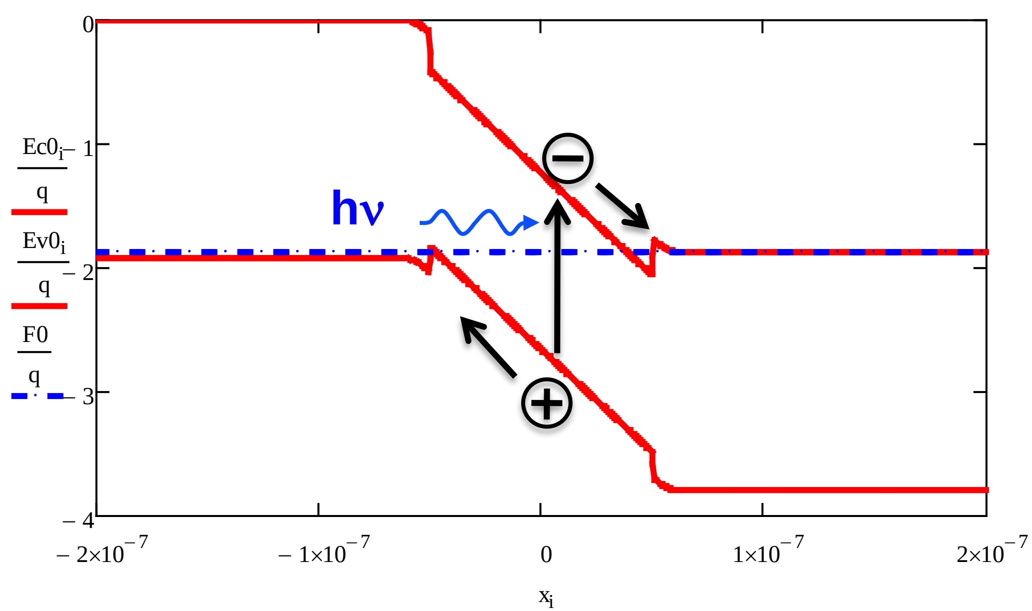
$$(\text{Normalized Frequency Response})$$



P-i-n Photodiode

- Reverse-biased p-i-n junction
- Most of the voltage drop across the i-region, the main absorption region
- High field separates photogenerated electron and hole
- Large bandgap materials are used for P and N if possible
- Fast response
- Low noise
- No gain (quantum efficiency < 100%)





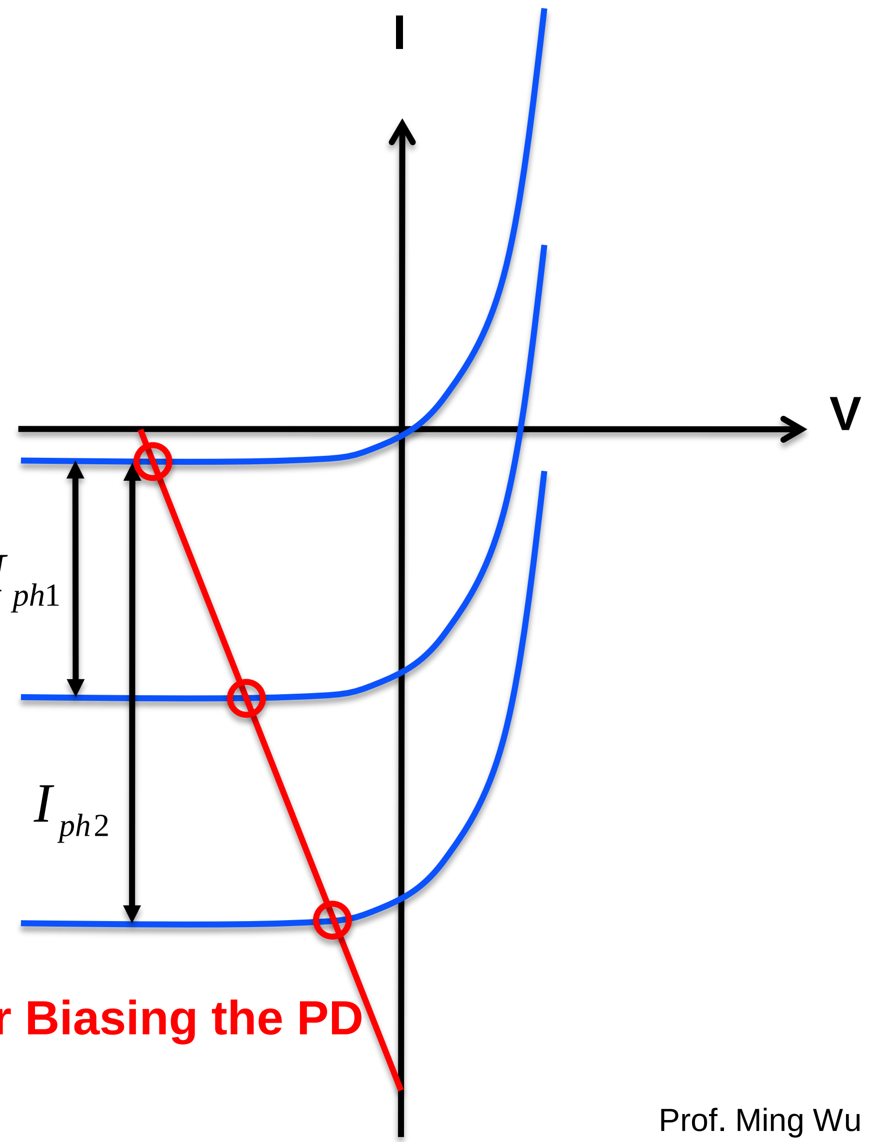
I-V Curve

Dark current: $I = I_0(e^{\frac{qV}{k_B T}} - 1)$

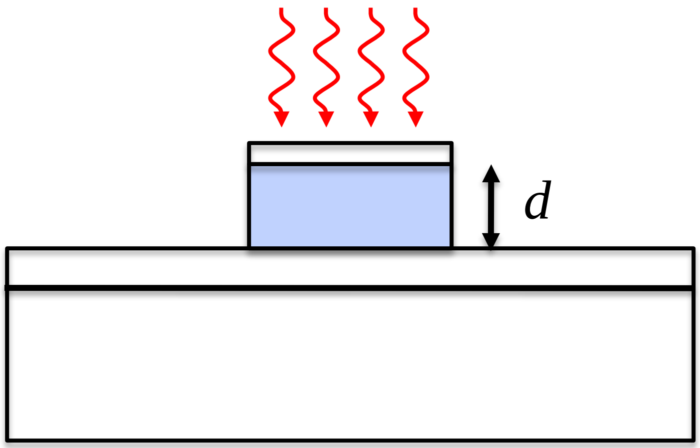
Photocurrent: $I_{ph} = \frac{\eta q}{\hbar\omega} P_{opt}$

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

Total current: $I = I_0(e^{\frac{qV}{k_B T}} - 1) + I_{ph}$



Two Types of p-i-n Photodiodes



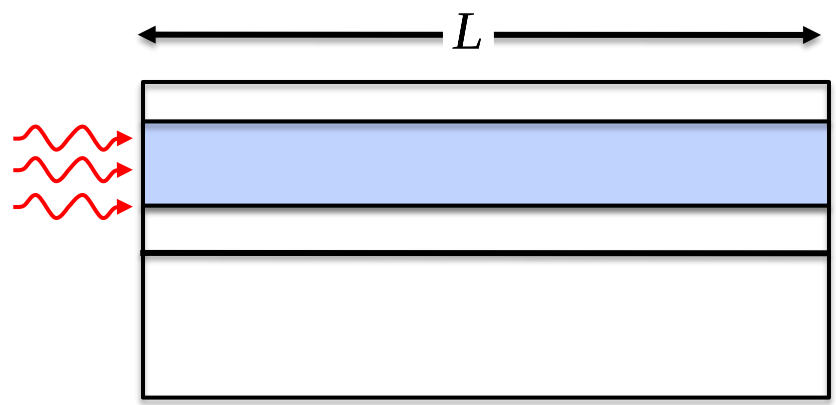
Surface-Illuminated p-i-n

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

η_i : internal quantum efficiency

R : reflectivity

d : absorption layer thickness



Waveguide p-i-n

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

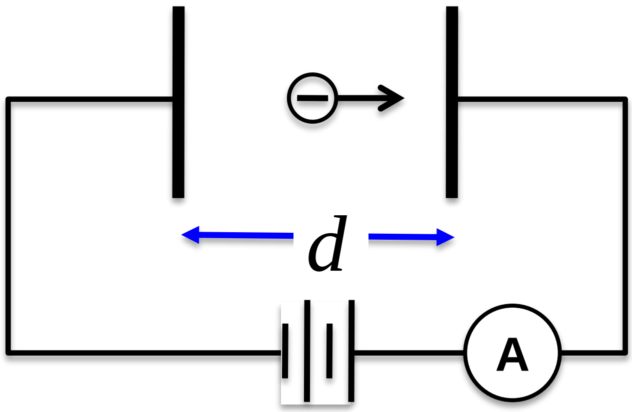
η_i : internal quantum efficiency

R : reflectivity

Γ : confinement factor

L : length of waveguide PD

Ramo's Theorem



The current caused in external circuit by a moving charge q moving at a volocity $v(t)$ in a parallel plate with a separation of d and a voltage bias of V is

$$i(t) = \frac{qv(t)}{d}$$

Proof:

Work done on the charge:

$$W = \text{Force} \times \text{Displacement}$$

$$= qEdx = q\frac{V}{d}dx$$

Work provided by power supply:

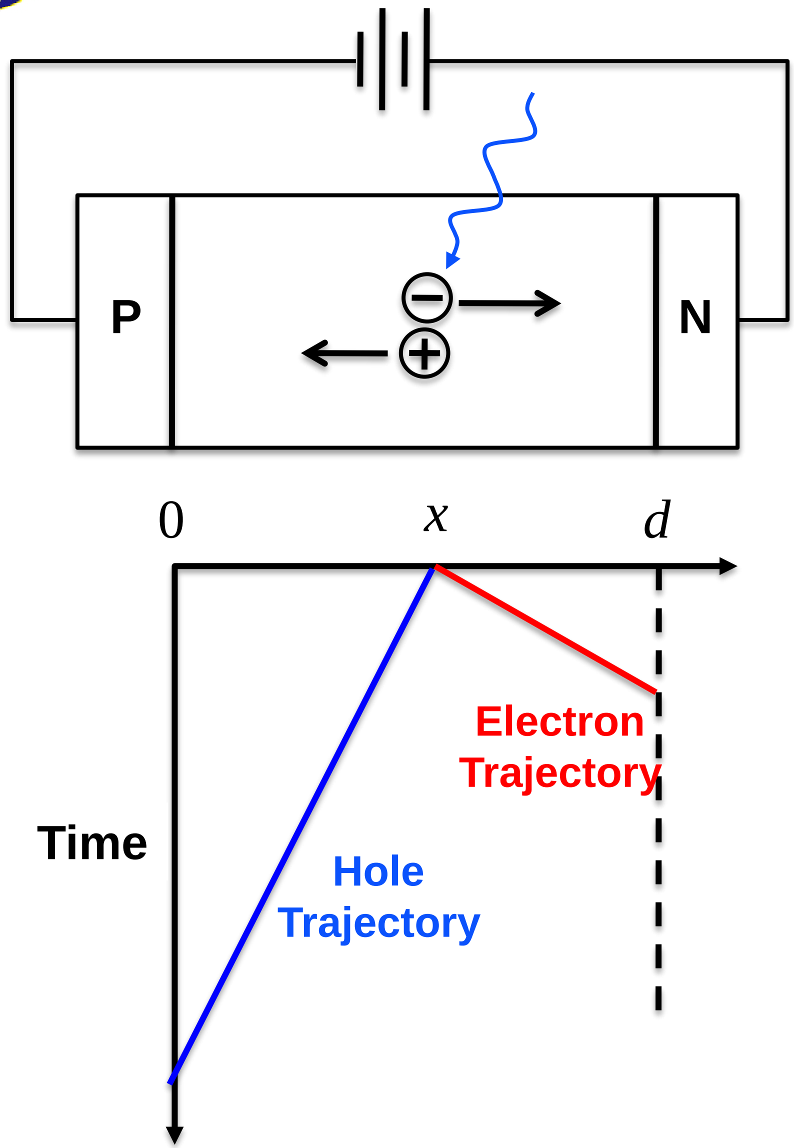
$$W = i(t)Vdt$$

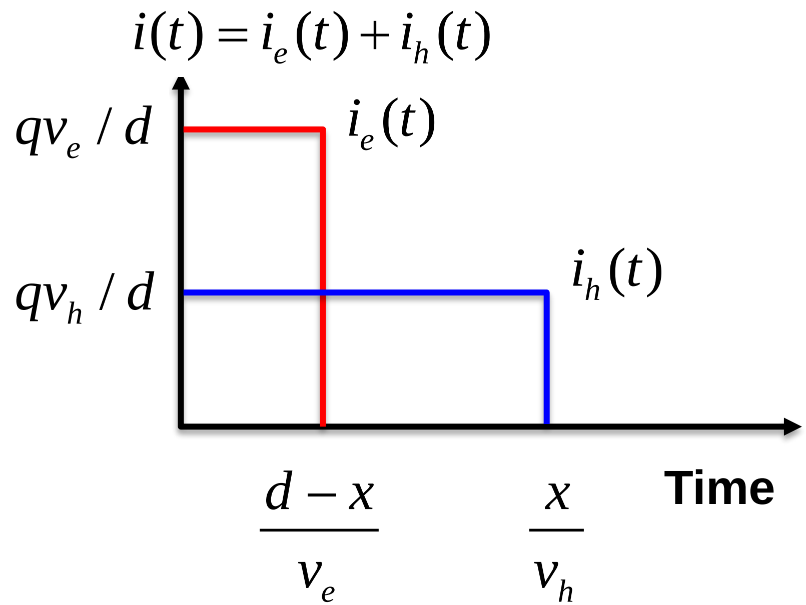
$$\Rightarrow$$

$$i(t)Vdt = q\frac{V}{d}dx$$

$$i(t) = \frac{q}{d}\frac{dx}{dt} = \frac{qv(t)}{d}$$

Response of One Photogenerated Electron-Hole Pair





Total charge generated:

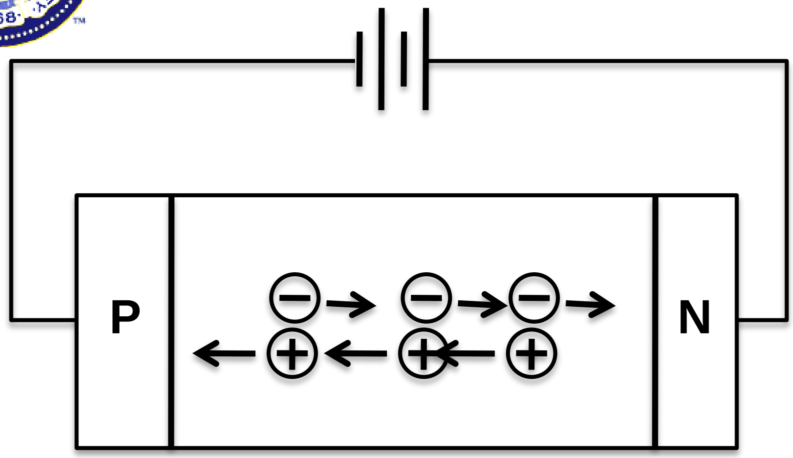
$$Q = \int_0^\infty i_e(t)dt + \int_0^\infty i_h(t)dt$$

$$= \frac{qv_e}{d}\frac{d-x}{v_e} + \frac{qv_h}{d}\frac{x}{v_h} = q$$

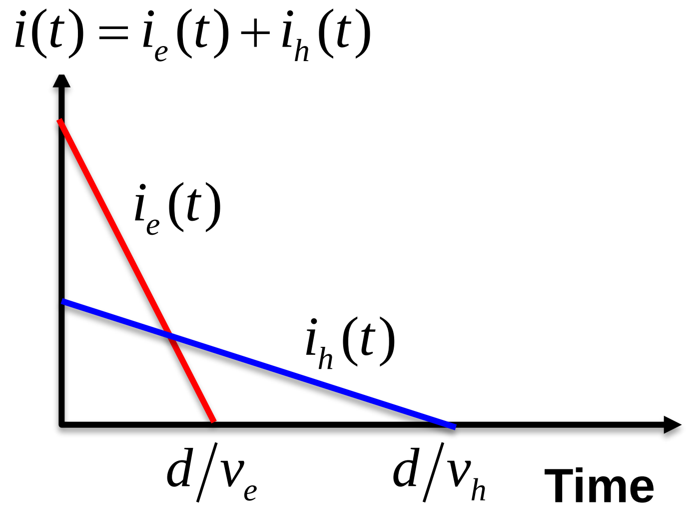
One absorbed photon $\rightarrow$

one charge detected

Transit Time



Many electron-hole pairs generated



Electron current ends when the last electron generated near P-side reaches N-electrode: $t = d/v_e$

Hole current ends when the last hole generated near N-side reaches P-electrode: $t = d/v_h$

Hole is usually slower $\rightarrow$ A conservative estimate of the transit time: $\boxed{\tau_t = \dfrac{d}{v_h}}$

Total Response Time of p-i-n

(1) RC time:

$$\tau_{RC} = RC = R\frac{\varepsilon A}{d} \qquad (A:\ \text{area of p-i-n})$$

(2) Transit time:

$$\tau_t = \frac{d}{v_h}$$

Total response time:

$$\tau = \tau_{RC} + \tau_t$$

$$f_{3dB} \approx \frac{1}{2\pi\tau}$$

Absorption layer thickness

for optimum frequency response:

$$\tau = \tau_{RC} + \tau_t = \frac{R\varepsilon A}{d} + \frac{d}{v_h}$$

$$\tau \geq 2\sqrt{\left(\frac{R\varepsilon A}{d}\right)\left(\frac{d}{v_h}\right)}$$

$$f_{3dB} \approx \frac{1}{2\pi\tau} \leq \frac{1}{4\pi}\sqrt{\frac{v_h}{R\varepsilon A}} = f_{3dB,\max}$$

Optimum bandwidth occurs when

$$\frac{R\varepsilon A}{d} = \frac{d}{v_h}$$

$$d_{optimum} = \sqrt{R\varepsilon A v_h}$$

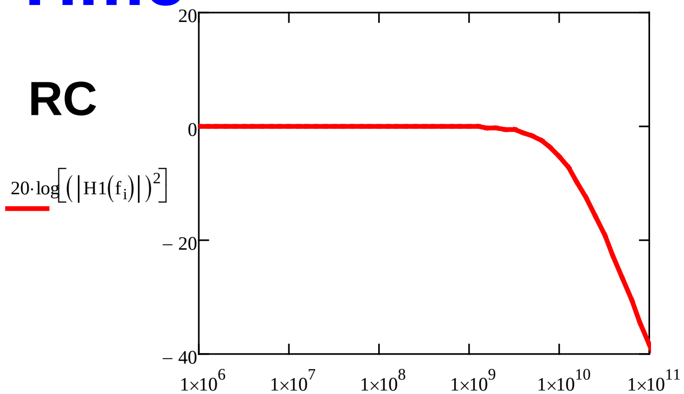
More Rigorous Analysis of p-i-n Response Time

Small-signal analysis: assume the input light is modulated at frequency ω, the photocurrent is proportional to

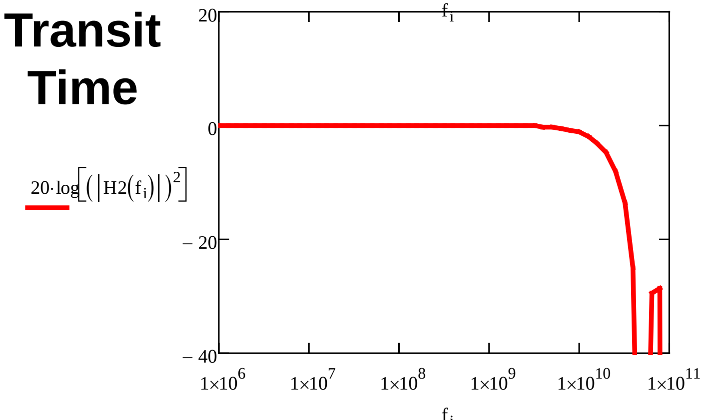
$$|i(t)| \propto \left|\frac{1}{1+j\omega RC}\right| \left|\frac{\sin^2\left(\frac{\omega\tau_t}{2}\right)}{\left(\frac{\omega\tau_t}{2}\right)^2}\right|$$

The first term is single-pole response from RC, while the second term is the phase delay due to transit time response.

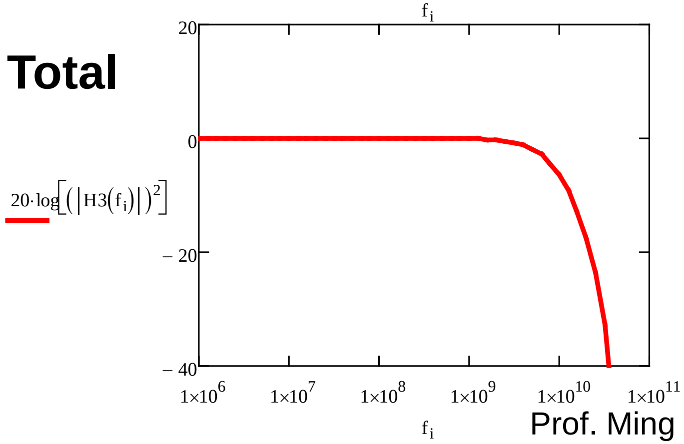
RC



Transit Time



Total



Comparison of Numeric Examples

Example:

$$\tau_{RC} = 14.4\,ps$$

$$\tau_t = 20\,ps$$

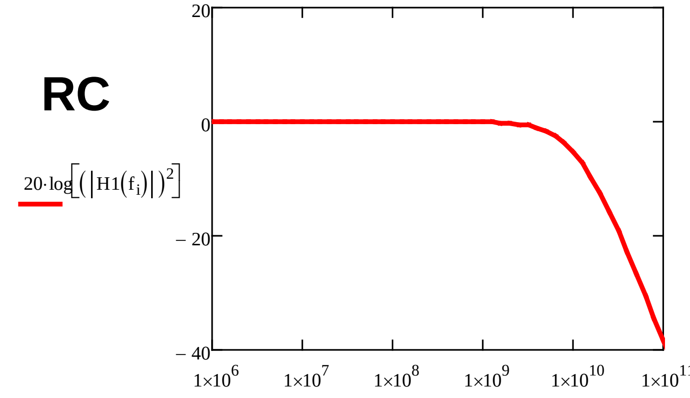
$$f_{3dB} = \frac{1}{2\pi}\frac{1}{\tau_{RC}+\tau_t} = 4.6\text{ GHz}$$

$$|i(t)| \propto \left|\frac{1}{1+j\omega RC}\right|\left|\frac{\sin^2\left(\frac{\omega\tau_t}{2}\right)}{\left(\frac{\omega\tau_t}{2}\right)^2}\right| = |H(\omega)|$$

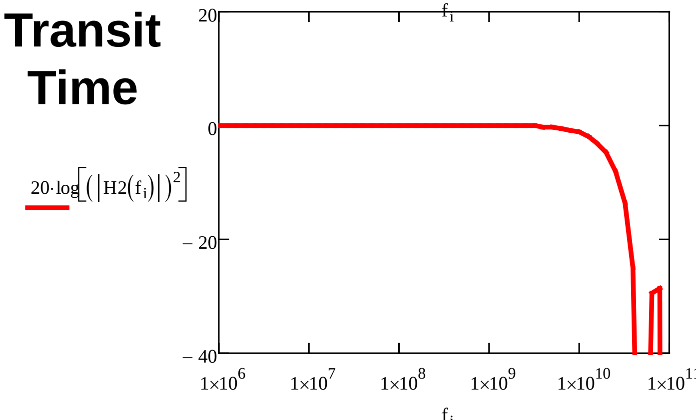
Solving $|H(\omega)| = \frac{1}{\sqrt{2}}$, $f_{3dB} = 9.7\text{ GHz}$

The discrepancy is smaller when RC dominates, and larger when transit time dominates. (Transit time response has a sharp drop-off).

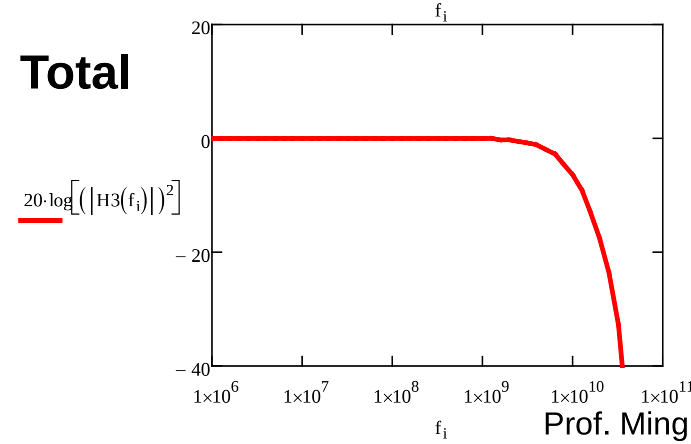
RC



Transit Time



Total



Bandwidth-Efficiency Product

(1) For surface-illuminated p-i-n (assume AR coating: R=0%), in the extreme of thin absorbing layer and transit-time-dominated response:

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

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

Bandwidth-efficiency product: $f_{3dB} \times \eta \approx \left(\frac{1}{2\pi} \frac{v_h}{d} \right) (\eta_i \alpha d) = \frac{\eta_i \alpha v_h}{2\pi}$

(2) On the other hand, the efficiency of waveguide p-i-n is

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

RC-limited bandwidth: $f_{3dB} \approx \frac{1}{2\pi} \frac{d}{R \varepsilon L w}$

Bandwidth-efficiency product: $f_{3dB} \times \eta \approx \left(\frac{1}{2\pi} \frac{d}{R \varepsilon L w} \right) (\eta_i \Gamma \alpha L) = \frac{\eta_i \Gamma \alpha d}{2\pi R \varepsilon w}$

$\Rightarrow$ In general, there is a bandwidth-efficiency trade-off