EE 232 Lightwave Devices
Lecture 21: Avalanche Photodiode (APD)

Reading: Chuang 15.4 (2nd Ed)

Instructor: Ming C. Wu

University of California, Berkeley
Electrical Engineering and Computer Sciences Dept.

Avalanche Photodiode (APD)

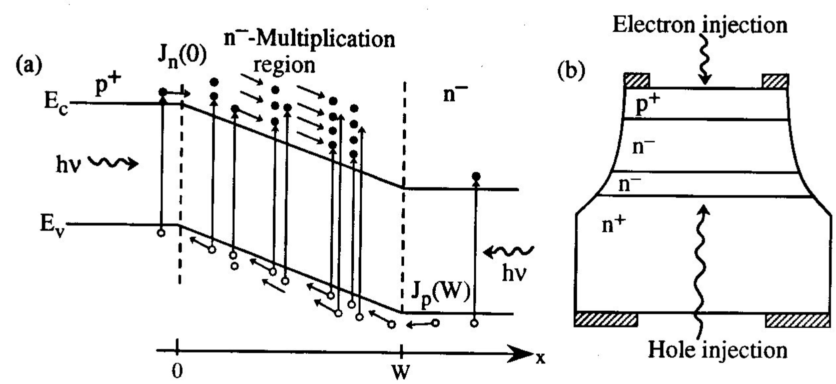


Figure 14.7. (a) The energy band diagram for an avalanche photodiode with the electron and hole ionization coefficients α_n and β_p. The electron and hole injections are given by $J_n(0)$ and $J_p(W)$. (b) A schematic diagram for an avalanche photodiode.

Typical APD Structure:
Separate Absorption and Multiplication (SAM) APD

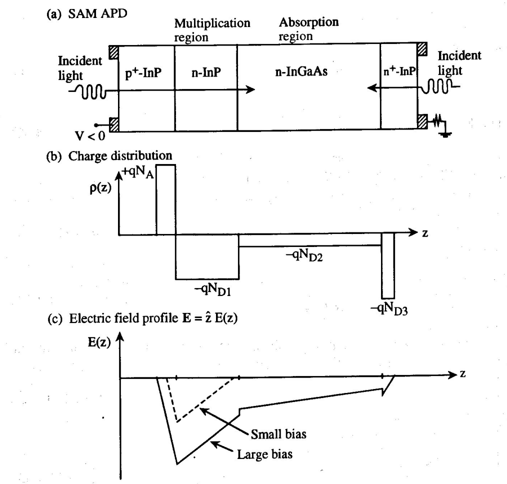


Figure 14.12. (a) A schematic diagram for a separate absorption and multiplication avalanche photodiode (SAM APD), where the absorption occurs at the narrow bandgap InGaAs region and the photogenerated carriers are swept into the InP multiplication region where the electric field is larger. (b) Charge density profile $\rho(z)$ under a large reverse bias. (c) The electric field profile (solid lines) under a large reverse bias. Dashed lines show the electric field profile for a small bias voltage.

Ideal APD:
Injection Impact Ionization Only

$$\frac{dJ_n(x)}{dx} = \alpha_n J_n(x)$$

α_n : electron ionization coefficient [cm^{-1}]

Electron current distribution along the field:

$$J_n(x) = J_n(0)e^{\alpha_n x}$$

Multiplication factor:

$$M_n = \frac{J_n(W)}{J_n(0)} = e^{\alpha_n W}$$

Practical APD:

Both Electron and Hole produce Impact Ionizations

$$\begin{cases} \dfrac{dJ_n(x)}{dx} = \alpha_n J_n(x) + \beta_p J_p(x) \\ -\dfrac{dJ_p(x)}{dx} = \alpha_n J_n(x) + \beta_p J_p(x) \end{cases}$$

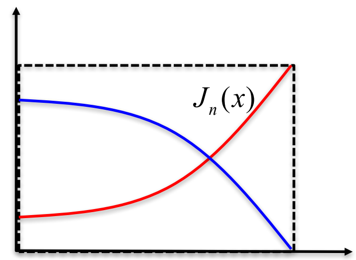
α_n : electron ionization coefficient [cm^{-1}]

β_p : hole ionization coefficient [cm^{-1}]

$$\frac{d}{dx}\left(J_n(x) + J_p(x)\right) = 0$$

$$J_n(x) + J_p(x) = J = \text{constant}$$

$$\frac{dJ_n(x)}{dx} - \left(\alpha_n - \beta_p\right) J_n(x) = \beta_p J$$



Multiplication Factor

Multiplication factor:

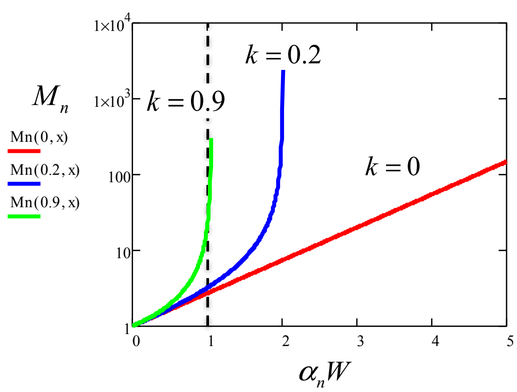
$$M_n = \frac{J}{J_n(0)} = \frac{1}{1 - \int_0^W dx' \alpha_n e^{-(\alpha_n - \beta_p)x'}}$$

$$M_n = \frac{1}{1 - \dfrac{\alpha_n}{\alpha_n - \beta_p}\left(1 - e^{-(\alpha_n - \beta_p)W}\right)}$$

$$= \frac{\alpha_n - \beta_p}{\alpha_n e^{-(\alpha_n - \beta_p)W} - \beta_p}$$

Define $k = \dfrac{\beta_p}{\alpha_n}$

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



Response Time

Response time =
transit time in absorption region
+ multiplication time

$\tau = \tau_t + \tau_m$

$$\begin{cases} \tau_m = \dfrac{M_n kW}{v_e} + \dfrac{W}{v_h} \approx \dfrac{M_n kW}{v_e} \\ \tau_t = \dfrac{W_{abs}}{v_h} \end{cases}$$

Usually τ_m ? τ_t $\rightarrow$ $\tau \approx \tau_m$

Gain-Bandwidth Product:

$$G \times BW = M_n \cdot \frac{1}{2\pi\tau_m} = M_n \cdot \frac{1}{2\pi} \frac{v_e}{M_n kW}$$

$$G \times BW = \frac{v_e}{2\pi kW} = \text{ constant}$$

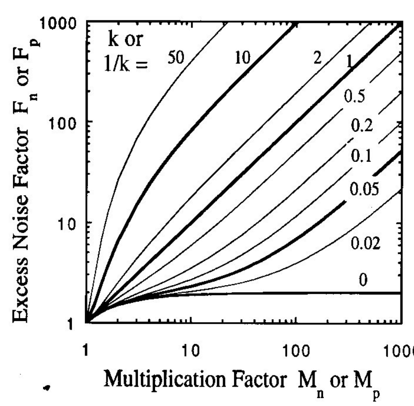
Noise Figure

Excess noise factor F
(due to fluctuation in gain):

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} = k\langle M_n \rangle + (1-k)\left(2 - \frac{1}{\langle M_n \rangle}\right)$$

Noise Figure:

$NF = 10 \log F$



Small k has small F under high gain $\langle M_n \rangle$

Minimum noise figure = 3 dB occurs when $k = 0$

APD Noises

Signal is amplified by the average gain $\langle M \rangle$:

$$i_p^2 = \frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2 \langle M \rangle^2$$

Shot noise is amplified by $\langle M^2 \rangle$:

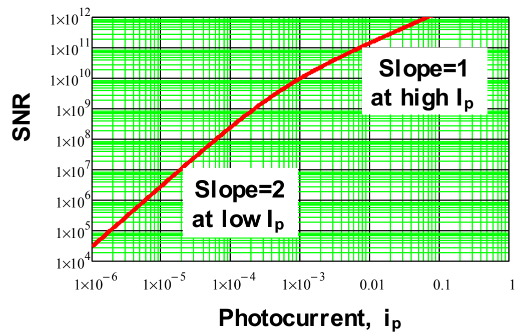
$$\langle i_S^2 \rangle = 2e(I_p + I_B + I_D)\langle M^2 \rangle dv$$
$$= 2e(I_p + I_B + I_D)F\langle M \rangle^2 dv$$

I_p : photocurrent;

I_B: background photocurrent

I_D: dark current

$$\langle i_T^2 \rangle = \frac{4k_B T\Delta v}{R}$$



$$SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2 \langle M \rangle^2}{2e(I_p + I_B + I_D)F\langle M \rangle^2 dv + \frac{4k_B T\Delta v}{R}}$$

SNR Comparison of p-i-n and APD

APD: $$SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2 \langle M \rangle^2}{2e(I_p + I_B + I_D)F\langle M \rangle^2 dv + \frac{4k_B T\Delta v}{R}}$$

p-i-n: set $\langle M \rangle = 1,\ F = 1$

$$SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2}{2e(I_p + I_B + I_D)dv + \frac{4k_B T\Delta v}{R}}$$