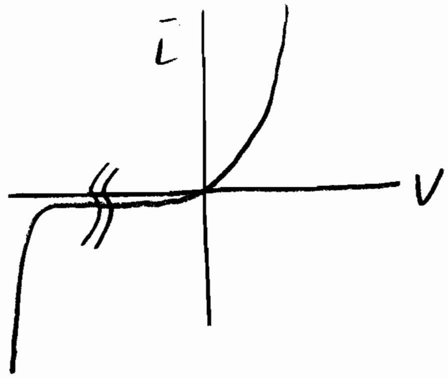
Avalanche Photodetector (APD)

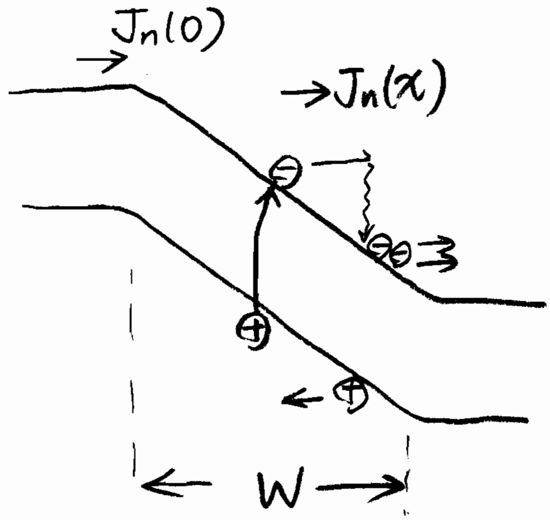
Biased near reverse breakdown



Avalanche:

Energetic electron (hole) release its kinetic energy by generating an additional electron-hole

⇒ impact ionization



Impact ionization coef

$\begin{cases} \text{for electron} : \alpha_n \ (cm^{-1}) \\ \text{for hole} : \beta_p \ (cm^{-1}) \end{cases}$

; # of e-h pair generated by one incident electron (hole)

Ideal case:

Electron impact ionization only

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

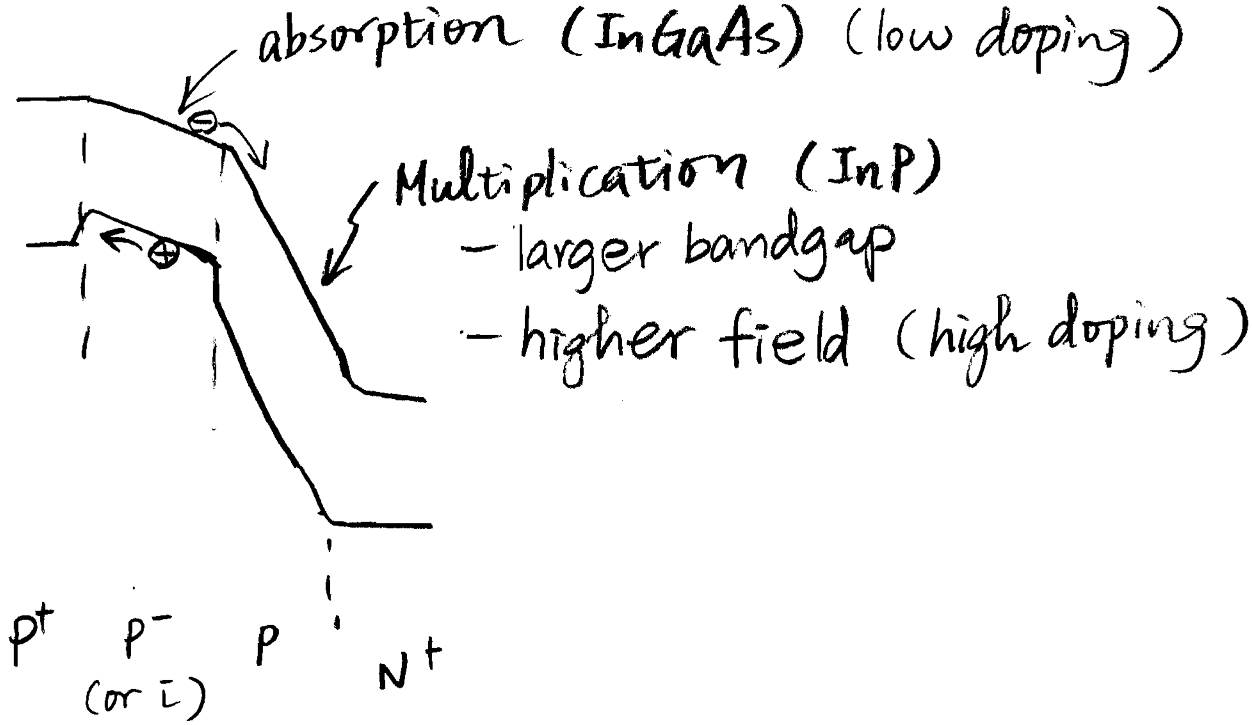
$$J_n(x) = J_n(0) \cdot e^{\alpha_n x}$$

At $x = W$, electron current only

$$J = J_n(x=W) = J_n(0)\, e^{\alpha_n W} = M_n \cdot J_n(0)$$

$M_n = e^{\alpha_n W}$: Multiplication factor

Usually separate absorption and multiplication (SAM) structure is used for APD



* Only electrons enters the multiplication region
* Photo-generated holes are collected directly.

* In the multiplication region, additional holes as well as electrons are generated
  - Holes could gain kinetic energy and cause impact ionization too

Aanalysis of multiplication region

$$\frac{d}{dx} J_n(x) = \alpha_n J_n(x) + \beta_p J_p(x) \quad \text{---①}$$

$\uparrow$ electron current $\uparrow$ electron impact ionization $\uparrow$ hole impact ionization

$$-\frac{d}{dx} J_p(x) = \alpha_n J_n(x) + \beta_p J_p(x) \quad \text{----②}$$

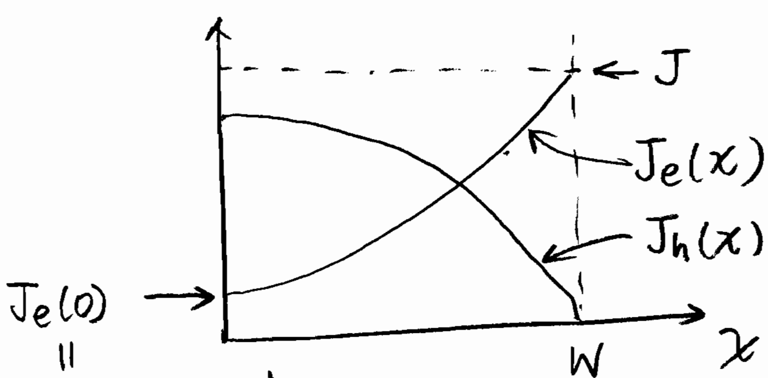
① - ② : $\frac{d}{dx}\left(J_n(x) + J_p(x) \right) = 0$

$$J_n(x) + J_p(x) = J = const \qquad (KCL)$$

$$J_p(x) = J - J_n(x)$$

$$\frac{d}{dx} J_n(x) - \alpha_n J_n(x) - \beta_p \left(J - J_n(x) \right) = 0$$

$$\frac{d}{dx} J_n(x) - [\alpha_n - \beta_p] J_n(x) = \beta_p J$$



$J_e(0)$ = photocurrent density from absorption region

Multiplication Factor (Eq. 14.4.27b in Chuang)

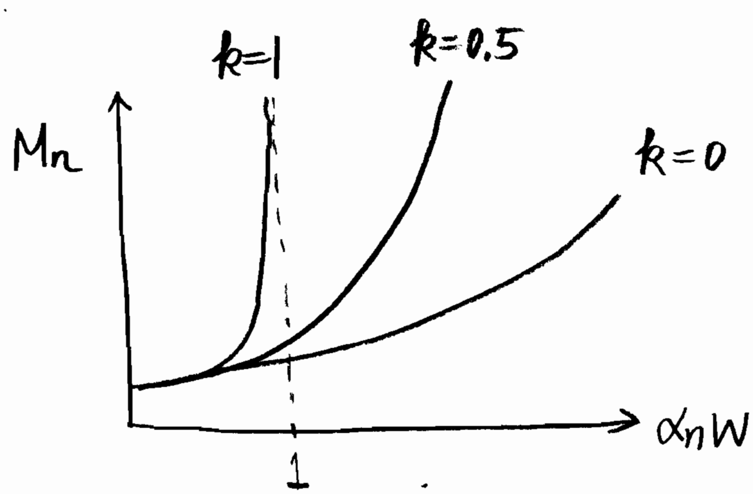
$$M_n = \frac{J}{J_n(0)} = \frac{1}{1 - \int_0^W dx' \cdot \alpha_n \cdot e^{-(\alpha_n - \beta_p)x'}}$$

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

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

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

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



$k=1$. $M_n \to \infty$ at $\alpha_n W = 1$ $\Rightarrow$ unstable

$k \ll 1$. Stable gain with lower noise

Response Time

$$\tau = \tau_t + \tau_m$$

transit time in absorption

multiplication time

$$\tau_m \approx \frac{M_n k W}{v_e} + \frac{W}{v_h} \approx \frac{M_n k W}{v_e} \qquad \text{when } M_n \gg 1$$

$$\tau \approx \tau_m$$

Gain-bandwidth product

$$G \times BW = M_n \cdot \left(\frac{1}{2\pi} \frac{1}{\tau_m} \right) = \cancel{M_n} \frac{1}{2\pi} \frac{v_e}{\cancel{M_n} k W} = \frac{1}{2\pi} \frac{v_e}{k W}$$

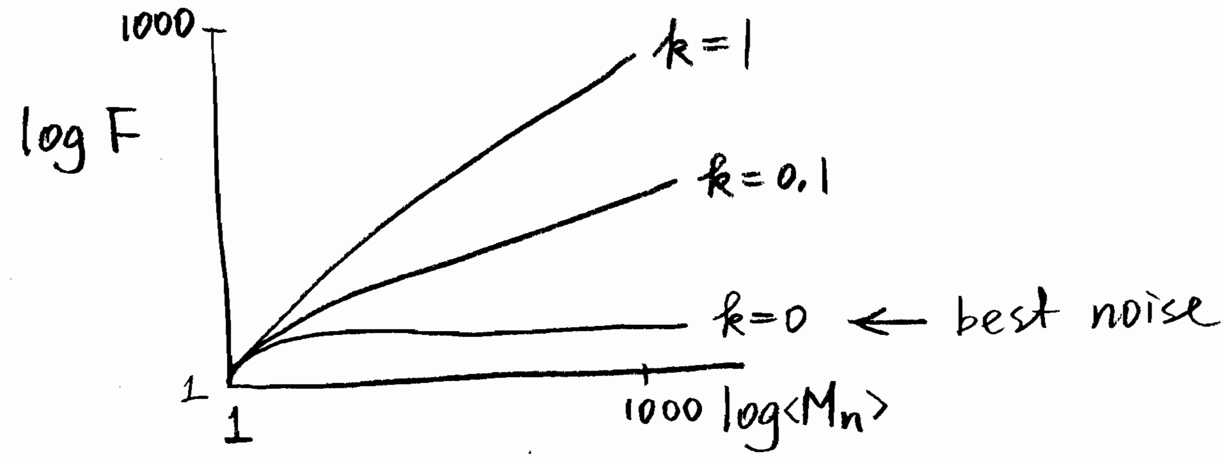
$$= \text{const}$$

APD Excess Noise

Fluctuation in gain M

Excess noise factor

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



small k → smaller F @ high gain

F_{min} at high gain $= 2$ when $k=0$

⇒ Minimum noise figure = 3 dB

APD signal $\quad \bar{i}_p = \eta \frac{q}{\hbar\omega} P\langle M\rangle = \bar{i}_{p0} \cdot \langle M\rangle$

average optical power

Shot noise

$$\langle i_s^2\rangle = 2q\,\bar{i}_{p0}\langle M^2\rangle \cdot \Delta f$$

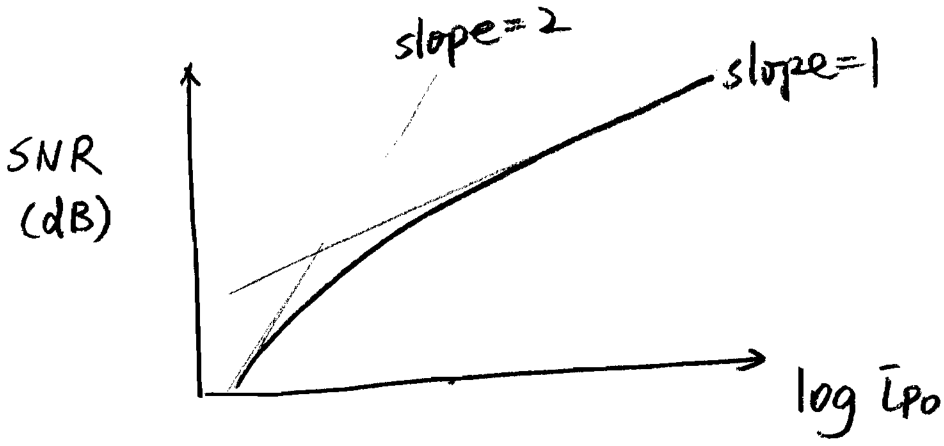
$$= 2q\,\bar{i}_{p0}\langle M\rangle^2 \cdot F \cdot \Delta f$$

shot noise is multiplied by gain $\langle M\rangle^2$
and further multiplied by excess noise factor

Thermal noise

$$\langle i_T^2\rangle = \frac{4k_T T}{R}\Delta f$$

$$SNR = \frac{\bar{i}_p^2}{\langle i_s^2\rangle + \langle \bar{i}_T^2\rangle} = \frac{\bar{i}_{p0}^2 \cdot \langle M\rangle^2}{2q\,\bar{i}_{p0}\langle M\rangle^2 \cdot F \cdot \Delta f + \frac{4k_T T}{R}\Delta f}$$



$$\bar{i}_{p0} = \eta \frac{q}{\hbar\omega} P_{avg}$$

For small $\bar{i}_{p0}$, $\quad SNR \to \frac{\bar{i}_{p0}^2 \langle M\rangle^2}{\left(\frac{4k_T T}{R}\right)\Delta f} \propto \bar{i}_{p0}^2$

large $\bar{i}_{p0}$ $\quad SNR \to \frac{\bar{i}_{p0}}{2q \cdot F\Delta f} \propto \bar{i}_{p0}$

SNR for p-i-n is the same expression with

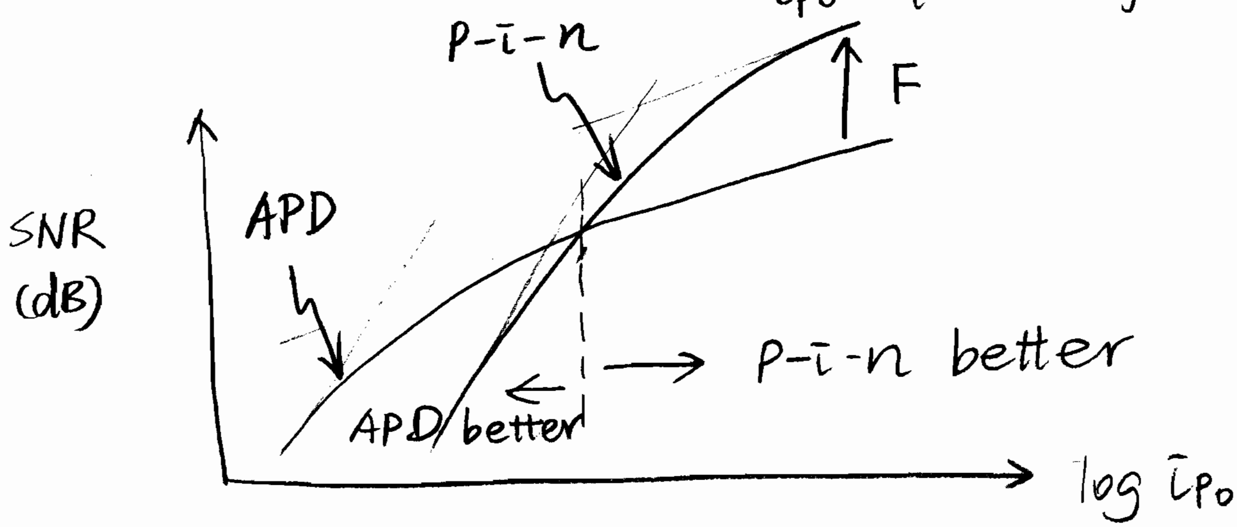
$\langle M \rangle = 1$

$F = 1$

$$SNR_{p\text{-}i\text{-}n} = \frac{\bar{i}_{po}^{2}}{2q\bar{i}_{po}\cdot\Delta f + \frac{4kT}{R}\Delta f}$$

Similarly. $SNR_{p\text{-}i\text{-}n} \propto \bar{i}_{po}^2$ for small $\bar{i}_{po}$

" $\propto \bar{i}_{po}$ for large $\bar{i}_{po}$



At high photocurrent ($\bar{i}_{po}$). $\dfrac{SNR_{p\text{-}i\text{-}n}}{SNR_{APD}} = F$

p-i-n better

At low photocurrent ($\bar{i}_{po}$), thermal noise dominant in p-i-n.

APD has higher SNR $\Rightarrow$ APD better

Cross Point

$$SNR_{APD} = SNR_{p\text{-}I\text{-}n}$$

$$\frac{\cancel{\bar{i}_{po}^{2}}\langle M\rangle^2}{\left(2q\bar{i}_{po}\langle M\rangle^2 F + \frac{4k_T T}{R}\right)\cancel{\Delta f}} = \frac{\cancel{\bar{i}_{po}^{2}}}{\left(2q\bar{i}_{po} + \frac{4k_T T}{R}\right)\cancel{\Delta f}}$$

$$\Rightarrow \quad 2q\bar{i}_{po}F + \frac{4k_T T}{R}\cdot\frac{1}{\langle M\rangle^2} = 2q\bar{i}_{po} + \frac{4k_T T}{R}$$

$$\Rightarrow \quad \bar{i}_{po} = \frac{\frac{4k_T T}{R}\left(1 - \frac{1}{\langle M\rangle^2}\right)}{2q(F-1)}$$

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Example

$k = 0.2$, $\alpha_n W = 1.9$

$$M = M_n = \frac{1-k}{e^{-(1-k)\alpha_n W} - k} = 42.8$$

$$F = k\cdot M + (1-k)\left(2 - \frac{1}{M}\right) = 10$$

$$\bar{i}_{po} = 2\cdot\underbrace{\frac{k_T T}{q}}_{0.026V}\cdot\underset{\uparrow\, 50\Omega}{\frac{1}{R}}\cdot\frac{1}{F-1} = 1.1\times10^{-4} \approx 110\,\mu A$$

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