3.46 PHOTONIC MATERIALS AND DEVICES

Lecture 17: Detectors—Part 2

Lecture	Notes

Detector Attributes

- efficiency
- noise
- speed
- linearity

"Digital" Sensitivity

1. Bit Error Rate
   - charge carriers are created by photons in a Poisson random process

a) probability that a pair is generated in time interval $dt = \rho(t)$

$$\rho(t)dt = \frac{RP(t)}{q}dt$$

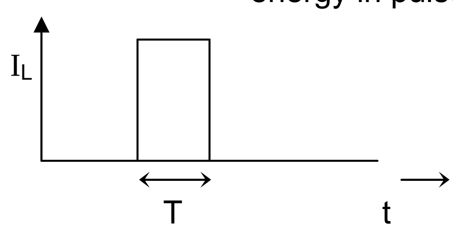
$$= \frac{\eta\lambda}{hc}P(t)dt$$

b) average # carriers generated

$$\bar{N} = \frac{\eta\lambda}{hc}\int_t^{t+T} P(t)dt$$

$$= \frac{\eta\lambda}{hc}E$$

energy in pulse of width T



c) probability the N = n charges in time interval T (average value of $N : \bar{N}$)

$$P(N = n) = \frac{\bar{N}^n e^{-\bar{N}}}{n!}$$

$$= \frac{\bar{N}^n \exp(-\eta\lambda E/hc)}{n!}$$

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Example

What is E required such that $P < 10^{-9}$ that a logical "0" will be detected when a logical "1" is transmitted?

- logical "0" $\equiv$ no e^- h^+ pairs
- $P(N=0) = \exp\left[-\frac{\eta\lambda E}{hc}\right] < 10^{-9}$

$$\Rightarrow E > 21\frac{h\nu}{\eta}$$

$$\Rightarrow \frac{21}{\eta}\text{photons required}$$

d) Each bit is T_B seconds long

$\Rightarrow$ required power at detector

$$P_{av} = \frac{21 \cdot h\nu/\eta}{2T_B}$$

- assumes only shot noise
- quantum limit of the detection process

$$\therefore \exp\left[-\frac{\eta E}{h\nu}\right] \leq \text{BER}$$

2. Noise

$$\frac{S}{N} = \frac{P_{signal}}{P_{noise}} = \frac{\langle i_S^2 \rangle}{\langle i_N^2 \rangle}$$

a) Shot Noise

- quantization of charge q
- quantization of light hν

$$\langle i_N^2 \rangle = 2qIB$$

I = average diode current

B = bandwidth of electronics

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- "white" noise
  - independent of center frequency
- AC noise dependent on DC value of output current

$$I = I_L + I_{background} + I_{dark}$$

- RMS noise current $\equiv \sqrt{\langle i_N^2 \rangle}$
- shot noise is multiplied by an APD

b) Thermal Noise
- attribute of any resistive load

$$\langle i_N^2 \rangle = \frac{4k_B TB}{R}$$

R = resistive load
T = noise temperature of device

- $\langle i_N^2 \rangle$ independent of signal

Example APD

M = 50
I_D = 10 nA
R_o = 0.6 A/W (unamplified)
R_L = 50 Ω
T = 300 K
B = 10 MHz
P_L = 5 nW

$$i_{S|M=1} = R_o P_i = 3 \text{ nA} = I_L$$

$$\frac{S}{N} = \frac{\langle i_S^2 \rangle M^2}{2q(I_L + I_D)M^2 B + \dfrac{4k_B TB}{R_L}}$$

$$\simeq 5.9$$

c) APD: shot noise dominates
PIN: thermal noise dominates

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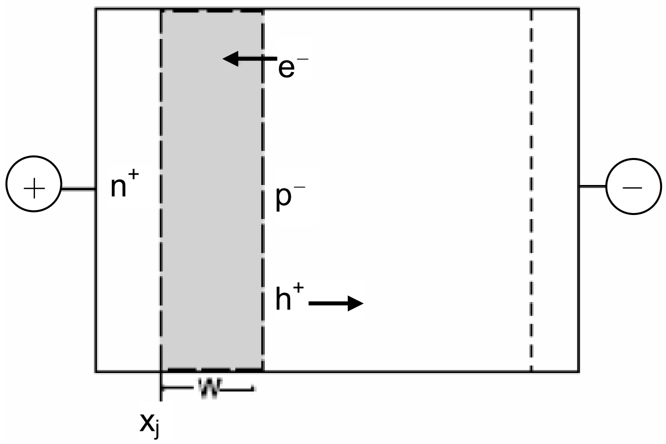
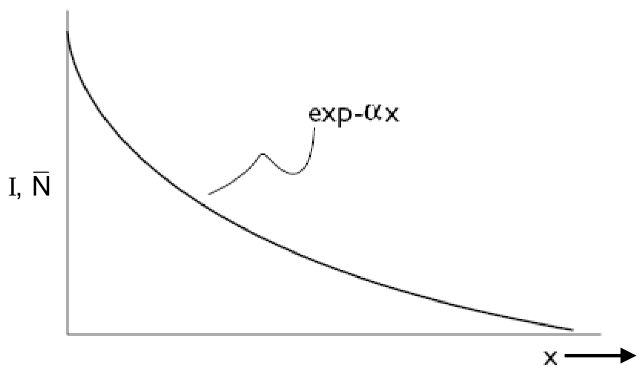
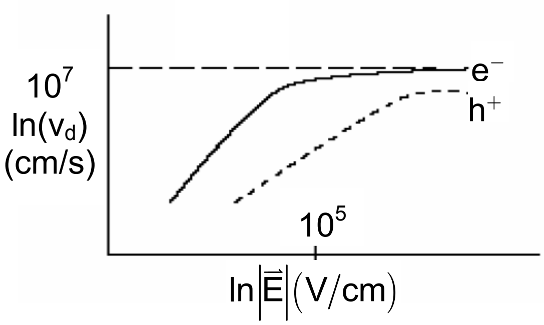
3. Speed





a) drift transit time (in depletion region)

Si:



$$\Delta t = \frac{w}{v_d} \approx 10^{-7}\,\frac{s}{cm} \times w$$
$$\Rightarrow 10\ \mu m = w,\ \Delta t = 10^{-10}\ s$$

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b) diffusion time (outside w)

$$\Delta t = \frac{x^2}{D_{n,p}}$$

$$D_{n,p} = \left(\frac{k_B T}{q}\right)\mu_{n,p}$$

$$D_n(\text{Si}) \simeq \frac{30\ \text{c}\ \ ^2}{\text{s}}$$

$$\Delta t(x = 10\ \mu\text{m}) = \frac{\left(10^{-3}\right)^2}{30} = 3\times10^{-8}\,\text{s}$$

- RC time constant

  $$C = \frac{\varepsilon A}{w} \le 1\,\text{pF}$$

Detector Design Rules

a) $\eta\uparrow$ as $w\uparrow$ as $C\downarrow$

b) $\tau_{tr}\uparrow$ as $w\uparrow$

c) design for $w \approx \dfrac{2}{\alpha}$

$$\tau_{tr} \approx RC$$

PIN limit $\equiv \tau_{tr}$

APD limit $\equiv$ carriers drift to avalanche region
+ drift of multiplied carriers out
+ avalanche time