

Photon Detection



The fundamental purpose of any photonic detector is to convert a photonic signal to an electrical signal.

The performance criteria vary significantly with their applications.

For example, a detector can be used for imaging.

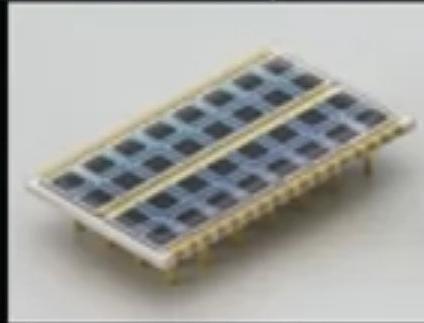
- Needs high spatial resolution and gray-scale resolution.
- It may have to operate on both high and low light levels.
- At low light levels, the detector may have to provide some gain.
- At high light level, it should not be prone to image smearing.

I'd like to tell you about photonic detection.



Detectors

Silicon avalanche photodiode



PIN photodiode



<http://www.hamamatsu.com/us/en/product/category/3100/4003/index.html>

Questions to answer

- How do different detectors work?
- What are pros/cons?
- State of the art?

including things like silicon avalanche photodiodes,

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- Imaging devices usually have to be two-dimensional, as well.

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Photon Detection



For optical communications, it should be designed to ensure signal recognition, avoid intersymbol interference, etc.

- The speed of detection, which is generally not important in imaging, becomes a crucial issue in this case.

In optical communications, the most important thing is to

Issue in Photodetection

Consider an electronic camera and estimate how many photons are captured and converted into electrons.

For simplicity, consider a monochromatic input light level of 200 lux, which corresponds to standard room lighting.

- $1 \text{ lux} = 1 \text{ lm/m}^2$
- At 555 nm, $1 \text{ W} = 680 \text{ lm}$.

$$200 \text{ lux} = 200 \left(\frac{\text{lm}}{\text{m}^2} \right) \left(\frac{1 \text{ W}}{680 \text{ lm}} \right) = 0.29 \text{ W/m}^2$$



Issue in Photodetection

So, 1 lux of monochromatic 555 nm light corresponds to

$$P_{opt} = 0.29 \text{ W/m}^{-2} \cdot A(\text{m}^2) \cdot \frac{\lambda}{hc} = \frac{\text{#of photons}}{\text{s}}$$



We can now find the photon flux,
Assuming an aperture radius of 0.5 cm, we
get

$$P_{opt} = \frac{0.29 \text{ W}}{\text{m}^2} \cdot 7.8 \times 10^{-5} (\text{m}^2) \cdot \frac{555 \times 10^{-9} (\text{m})}{1.99 \times 10^{-25} (\text{eV} \cdot \text{m})} = 6.31 \times 10^{13} (\text{s}^{-1})$$

Issues in Photodetection



Divide this quantity by the number of pixels, which we assume to be 2×10^6 , to obtain 3.16×10^7 photons/pixel/second.

Assume a quantum efficiency of 30%, the number of electrons generated by the input photons is 9.48×10^6 electrons/pixel/second.



Issues in Photodetection



With a shutter speed of 1/30 s, the total electrons generated by the input photons per pixel is 3.16×10^5 electrons/pixel.

If the input light level drops to ~ 1 lux (light level at night during a full moon), # of photogenerated electrons/pixel becomes ~ 1600 !

The detector should therefore be capable of counting very small number of electrons.

- For reliable detection, the noise level must be below the lowest possible signal level.



Noise

$$i = \frac{q_0 n}{T}$$

$$I = \langle i \rangle = \frac{q_0 \langle n \rangle}{T}$$

Mean = variance

$$\sigma^2 = \langle i_n^2 \rangle - \langle i \rangle^2$$
$$= \langle i^2 \rangle - \langle i \rangle^2$$

$$\begin{aligned}\langle i_n^2 \rangle &= \langle (i - \langle i \rangle)^2 \rangle \\ &= \left(\frac{q_0}{T}\right)^2 \underbrace{\langle (n - \langle n \rangle)^2 \rangle}_{\langle n \rangle}\end{aligned}$$

$$\langle i_n^2 \rangle = \frac{q_0^2 \langle n \rangle}{T^2} = \frac{q_0 I}{T}$$

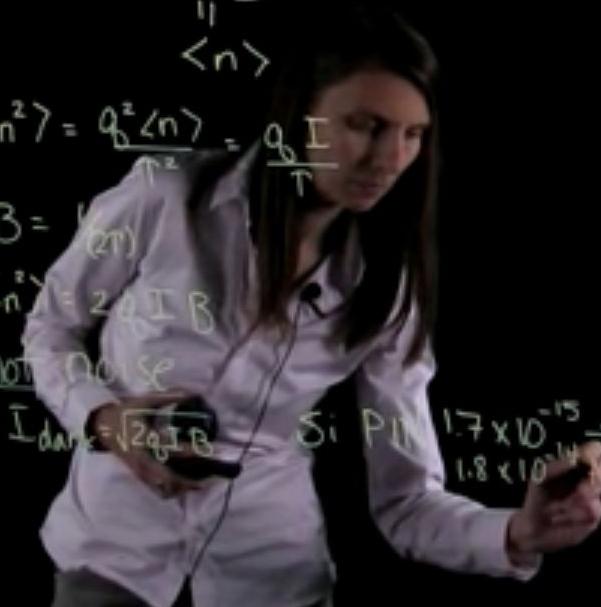
$$B = \frac{I}{(2T)}$$

$$\langle i_n^2 \rangle = 2q_0 I B$$

Shot noise

$$I_{dark} = \sqrt{2q_0 I B}$$

$$\text{Si PII } 1.7 \times 10^{-15} \rightarrow 1.8 \times 10^{-14}$$



Noise equivalent power

$$\text{signal/noise} = 1$$

$$SNR = \frac{signal}{noise}$$

$$(\text{signal} = \frac{qN P_s}{h\nu})$$

$$\langle i_n^z \rangle = 2q_i j_z B = \frac{2q^2 \pi P_s B}{\hbar v}$$

$$SNR = \frac{\langle signal^2 \rangle}{\langle i_n^2 \rangle} = \frac{N P_s}{2h\nu B} \quad \langle i_n^2 \rangle = 2q_b \langle i \rangle B \\ = \frac{2q_b^2 N (P_s + P_B) B}{h\nu}$$

$$SNR = 1 \rightarrow NEP = \frac{2hvB}{\eta}$$

$$B = \frac{1}{2T}$$

$$NEP = \frac{hv}{T} \Big|_{n=1}$$

$$\langle i_n^2 \rangle = 2q_b \langle i \rangle B$$

$$= \frac{2q_b^2 N(P_s + P_B)B}{1 - \gamma}$$

$$\frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = \frac{\eta P_s^2}{2\hbar\nu B(P_s + P_B)}$$

$$P_S \ll P_B$$

$$\sqrt{\frac{2mBP_B}{\eta}}$$



$$D = \frac{1}{NEP} \Big|_{BW=1\text{Hz}}$$

Ex PbSe

P_{min} to be 80dB
above noise floor

$$NEP = 1.5 \times 10^{-10} \frac{W}{\sqrt{\text{Hz}}}$$

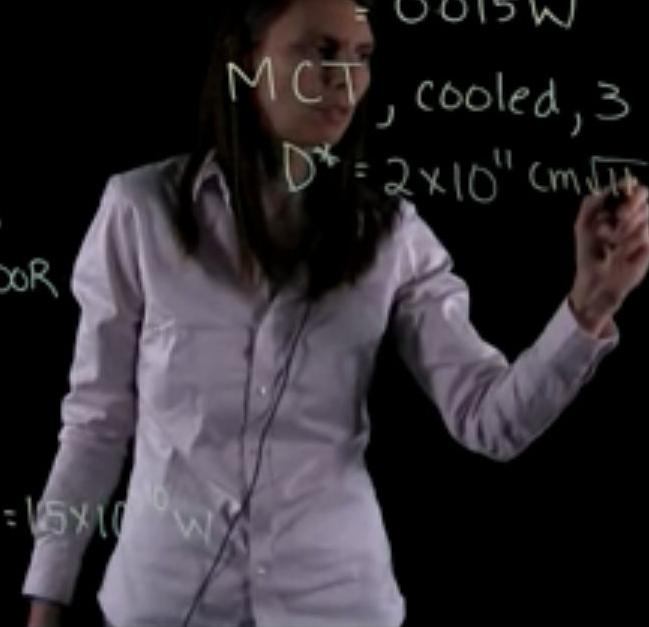
1Hz BW

$$\text{Noise floor} = \sqrt{B} NEP = 1.5 \times 10^{-10} W$$

$$P_{min} = (10^8)(1.5 \times 10^{-10} W)$$
$$= 0.015 W$$

MCT, cooled, 3 stages

$$D^* = 2 \times 10^{11} \text{ cm} \cdot \text{Hz}^{1/2}$$



References

The reference below is completely optional, but a great resource in understanding the subject.

K. F. Brennan, The Physics of Semiconductors, Cambridge, 1999.