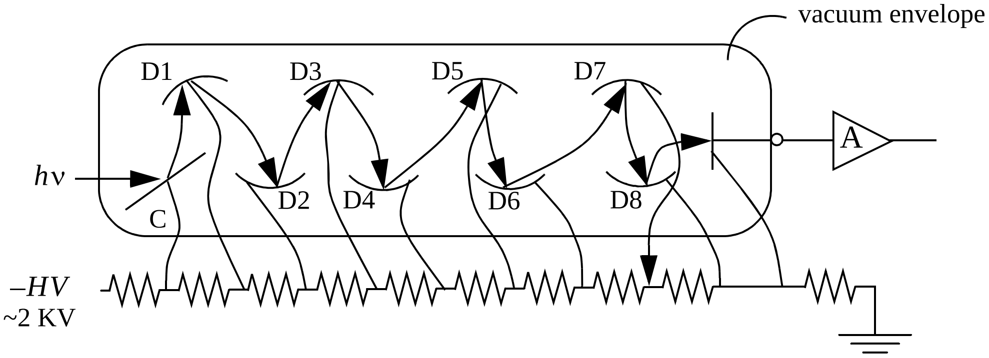
# Lecture 12
# OPTICAL DETECTORS

**(Reference: *Optical Electronics in Modern Communications*, A. Yariv, Oxford, 1977, Ch. 11.)**

### Photomultiplier Tube (PMT)

- Highly sensitive detector for light from near infrared → ultraviolet
- Can detect as little as $10^{-19}$ Watt!



Voltage divider chain to bias dynodes

R chosen to have ~100V drop per dynode

Photocathode C:– absorbs photon → ejects electron

– work function $\phi$ is the minimum energy needed to eject an electron

– the photon energy must exceed the work function $h\nu > \phi$ to get photoelectrons

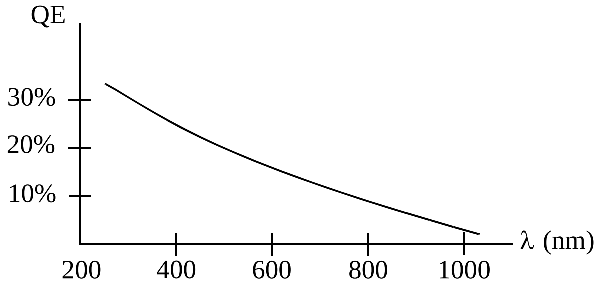
Dynodes D1-D8:Secondary electron emission. Electron from cathode accelerated by ~100 eV. Impact into dynode surface causes ejection of multiple electrons, $\delta \cong 5$.

For $N$ dynodes, the total gain is then $\delta^N$.

Photocathode quantum efficiency: $QE \equiv$ probability a photon will eject one electron

$0 \le QE \le 1$

Typical photocathode response



*Sensitivity*:

For 10 dynodes, $\delta = 5, G = 5^{10} \cong 10^7$.

Take 2eV photons (620 nm), 1 picoW = $10^{-12}$W = $10^{-12}$J/s

$$\boxed{1\text{ eV} = 1.6\times10^{-19}\text{J, so, } 10^{-12}\text{W} = 3\times10^6\text{ photons/s}}$$

With $QE = 30\%$, Anode current is

$$\boxed{(3\times10^6)(0.3)10^7 = 10^{13}\text{ electrons/s} = 1.6\times10^{-6}\text{ A}}$$

Phototube **dark current**:1) random thermal excitation of electrons from photocathode

2) cosmic rays, ambient radioactivity

- Thermal excitation rate is proportional to $\boxed{e^{-\Phi/kT}}$, where $\Phi$ represents the cathode work function

  so lower work function → IR sensitivity, **but** larger dark current

- For room temperature, typical cathode dark current, $I_{cd}$, is $\approx 10^4$ electrons/sec. Anode dark current is then $\boxed{I_{ad} = I_{cd}\cdot G}$

- Dark current sets a lower limit to phototube sensitivity to low light levels. To distinguish a light signal above the background dark current, the photoelectric cathode current must exceed the dark current. If $I_{cd}$ is $\approx 10^4\text{e/sec}$, then the sensitivity to light can be $\sim 3\times10^4$ photons/sec (assuming QE = 30%). $3\times10^4$ red photons/s $\cong$ **$10^{-14}$ W**!

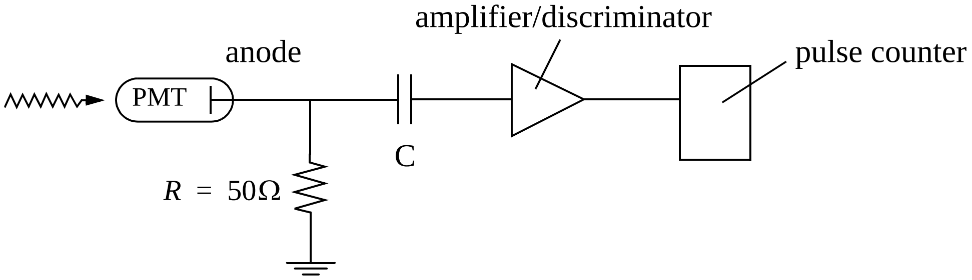
- Dark current can be reduced by *cooling*. Using thermoelectric cooling $T \equiv -40\text{C}$ is easily obtained. Assume a work function of $\Phi = 1.5$ eV

$$\frac{I_{cd}(260K)}{I_{cd}(300K)} = \frac{e^{-1.5/0.0225}}{e^{-1.5/0.026}} = e^{-1.5(44.4-38.5)} = e^{-8.8} \cong 1.4\times10^{-4}$$

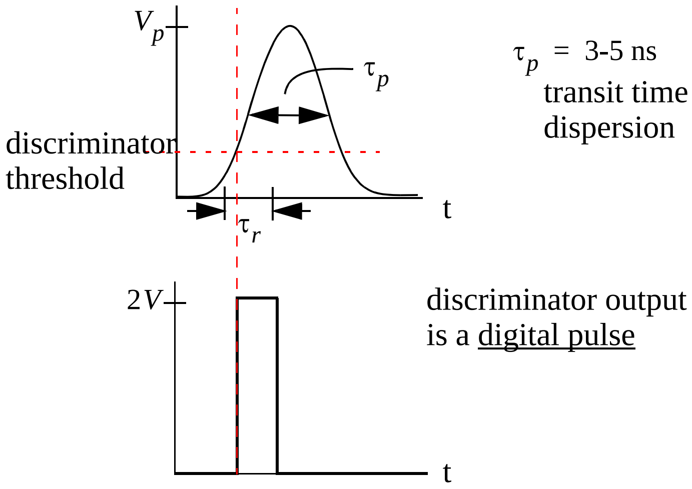
Dark current is reduced by this amount! → down to ~1 e/sec. Minimum detectable power become < $10^{-18}$ W!

Photon counting: PMT is so sensitive, we are really counting photons. Often, PMT circuits are specifically optimized to do this.

Photon counting system:

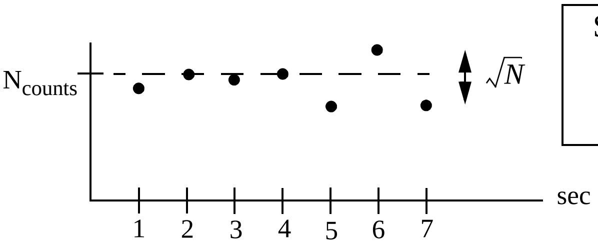


PMT output pulse



- How big is the PMT output pulse from one photon? For $G \sim 10^7$, we get $10^7$ electrons $\cong 10^{-12}$C. For $\tau_p = 10^{-8}$ sec, $I_{apk} \sim 10^{-4}$A. For $R = 50\Omega$, $V_p \sim 5$ mV.
- Discriminator eliminates electrical noise in < 1mV range. $V_p$ has a variation due to statistical nature of gain process. Discriminator also eliminates this.

*Shot noise*: Photon arrival is always statistical. Generally it follows Poisson statistics. Then if the photon arrival rate is $N$ ph/sec, and we count for 1 sec, we get $N$ on average. The standard deviation will be found to be $\sqrt{N}$. This means we have noise.



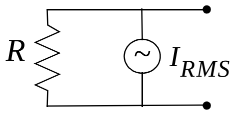
Signal/Noise ratio = $N/\sqrt{N} = \sqrt{N}$

clearly depends on counting time

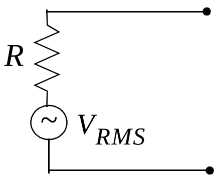
Shot noise is universal for light detection. Even if photons are not explicitly counted, the shot noise is a fundamental limit. It is most significant at low light levels, though, due to $\sqrt{N}$ dependence.

*Johnson noise:* Random thermal noise in any resistor, $R$

$$I_{RMS} = \sqrt{\frac{4kT}{R}B}$$



$$V_{RMS} = \sqrt{4kTRB}$$

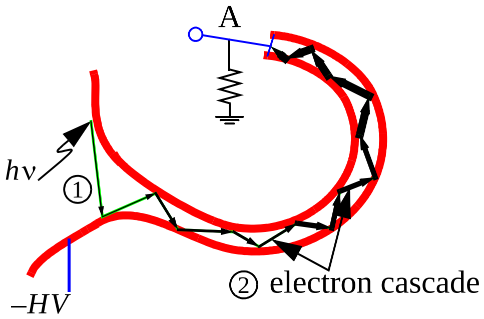


*B:* bandwidth (Hz)

Equivalent model of noise as either current or voltage source.

## Channel Electron Multiplier (Channeltron)

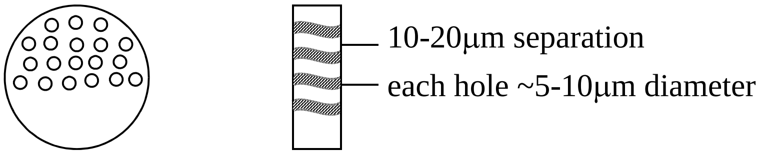
Single monolithic device functions as a PMT:



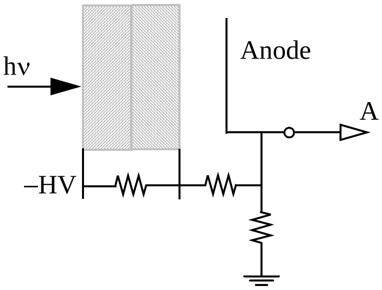
Glass tube bent around curve. One end open as a funnel shape. Coating acts as photocathode **and** secondary electron emitter. Also, coating has high, but not infinite electrical resistance.

**1.** Photon hits funnel portion
**2.** Electrons are accelerated into the bent tube by bias field
**3.** Secondary electron emission gives gain at each electron collision with wall
**4.** Must be operated in vacuum
**5.** Typical gain $\sim 10^4$
**6.** More compact and rugged than PMT

<u>Microchannel plate MCP</u> – array of *channeltrons*



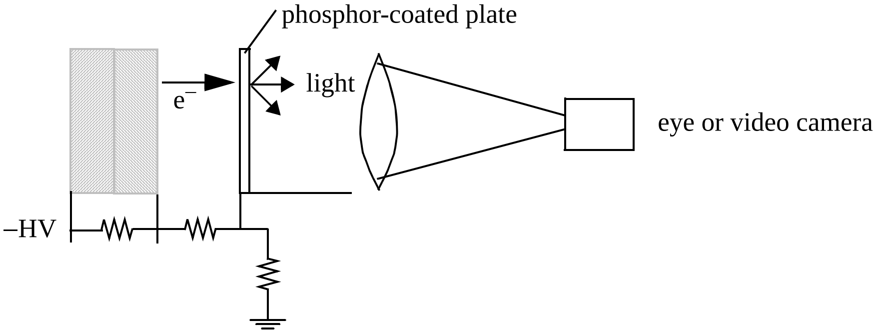
- each channel is a miniature channeltron
- gain $\sim 10^3$



gain $\sim 10^6$ HV ~1-2KV

Dual Plate MCP Detector

## MCP Image Intensifier



Single or Dual Plate MCP

- Electrons accelerated out of back of MCP into phosphor
- Phosphor QE ~50% photons/electrons

Image intensification $\boxed{QE_{\text{MCP}} \cdot G_{\text{MCP}} \cdot QE_{\text{phosphor}} \approx 10^5}$

→ Night vision goggles