Measurements Lab

Detectors

Photomultiplier tubes

Silicon photodiodes

Charge Coupled Device (CCD)

NC State University

Photomultiplier tubes

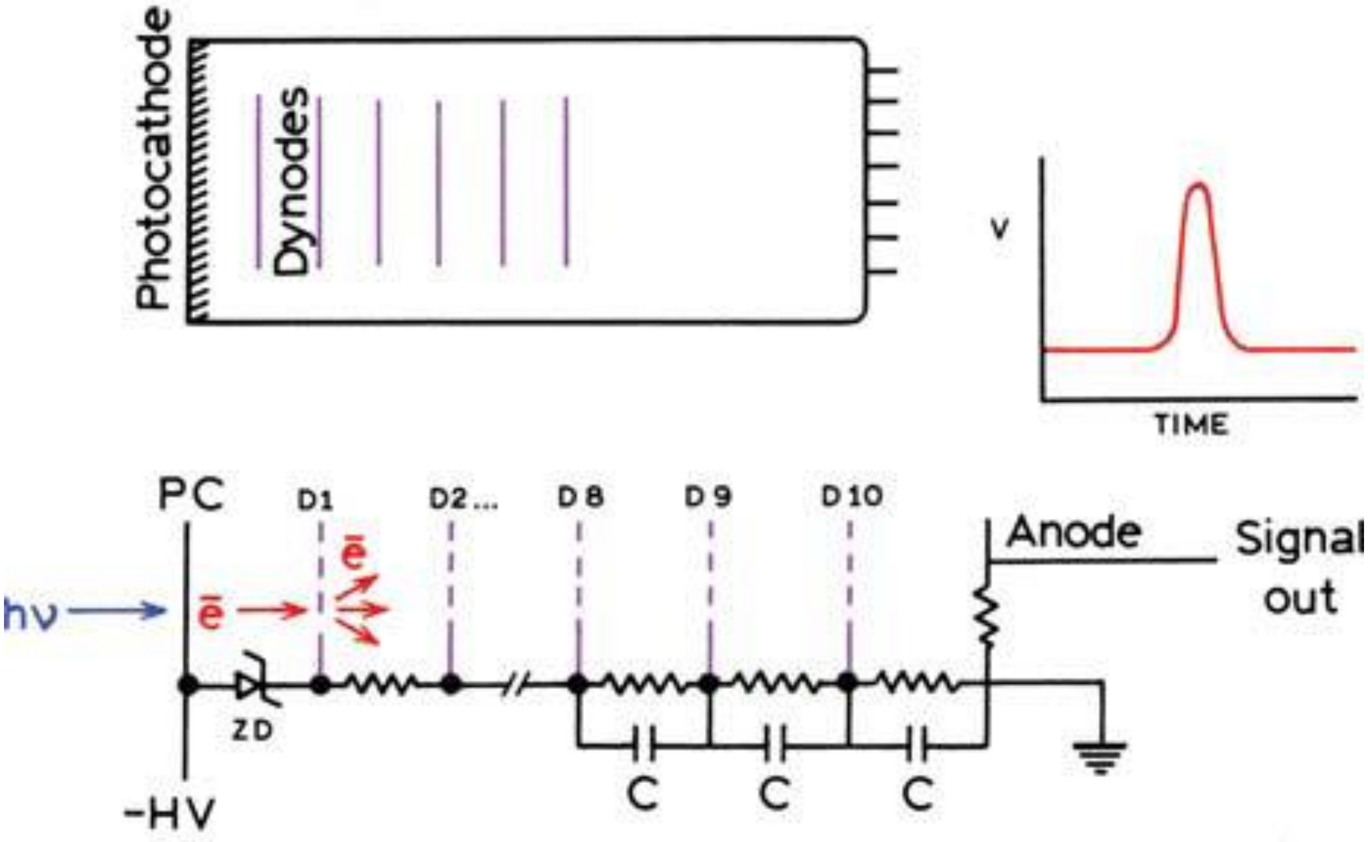
Current is proportional to light intensity.

Photon strikes the plate (photocathode) and causes an “electron cascade”, which is an amplification through a chain of dynodes.

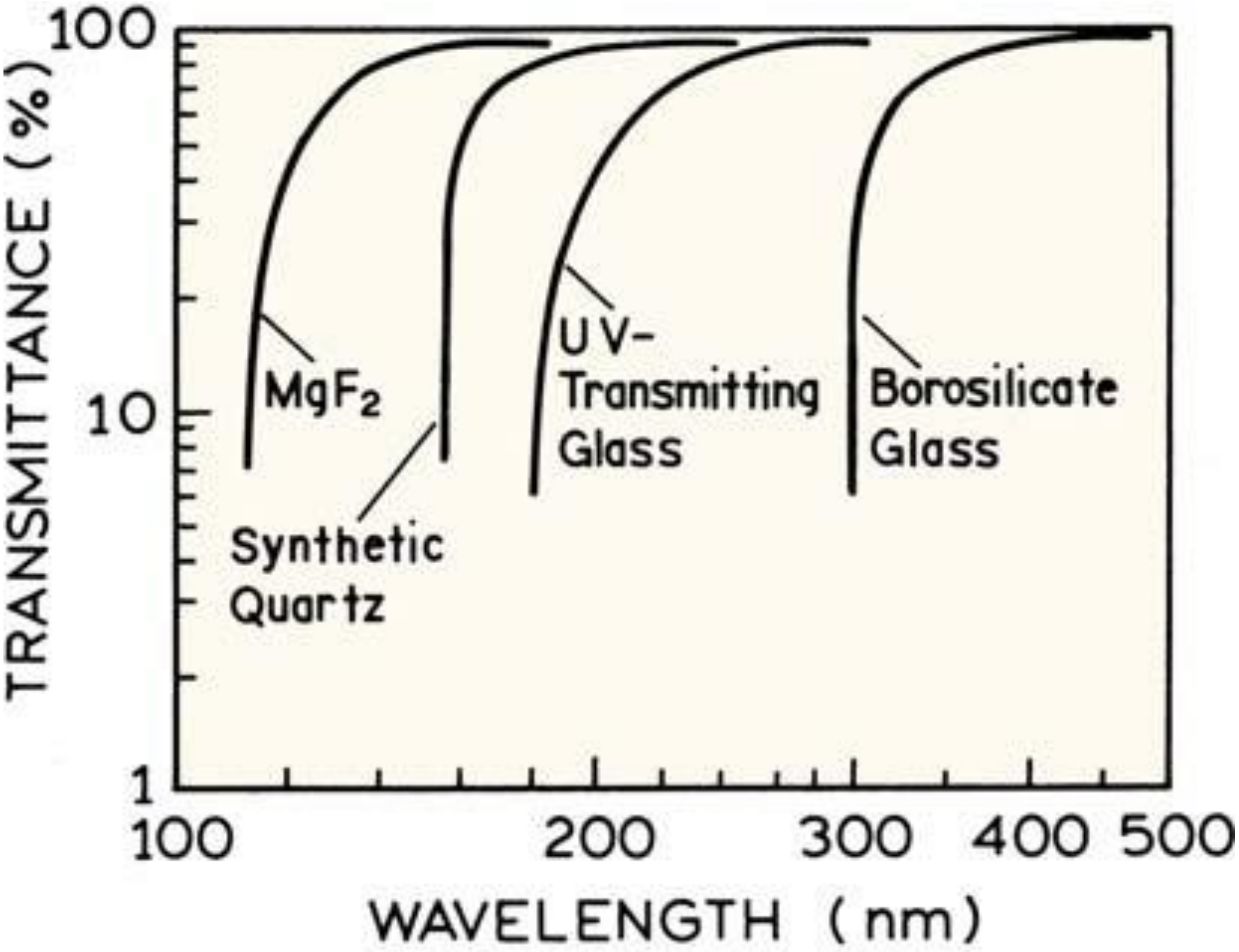
Photomultiplier tube plates are sensitive only over a narrow range of the spectrum. The next two slides show the combination of window coatings and photocathode materials that lead to specific spectral response.

The dynode chain

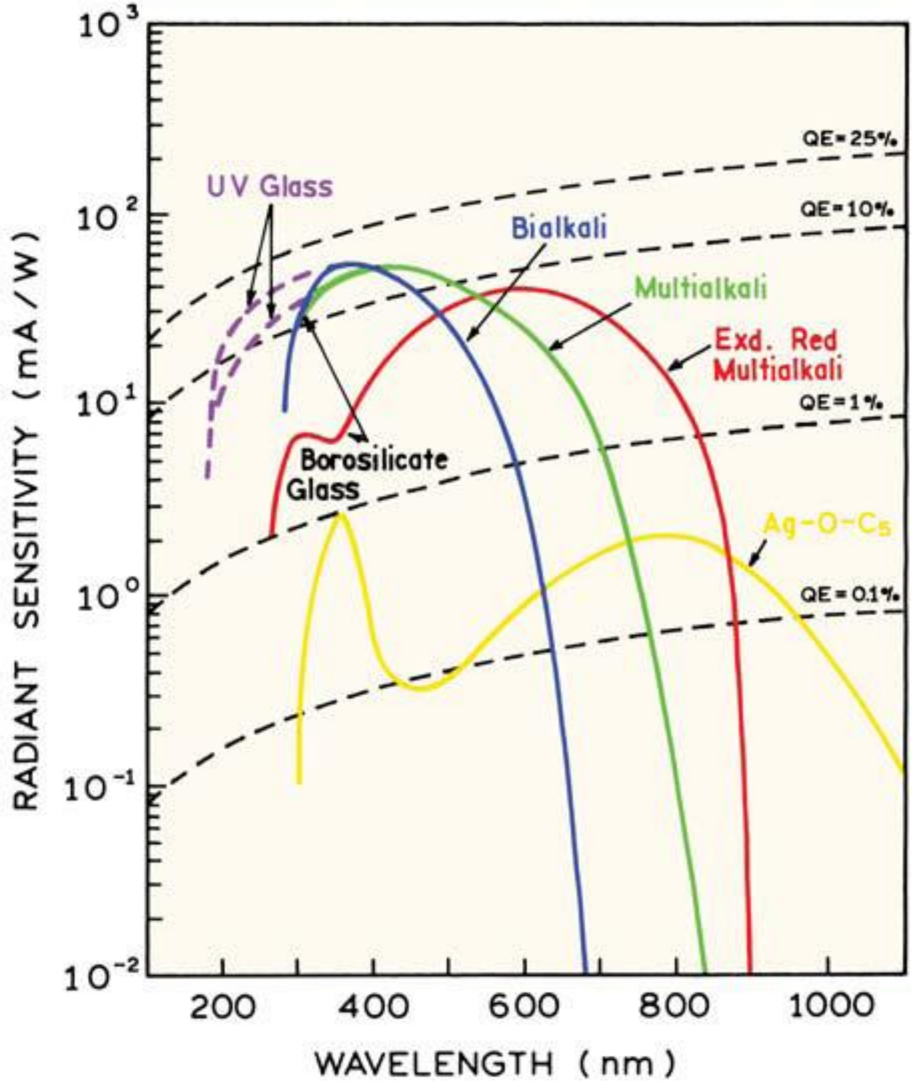
When an electron strikes the photocathode it initiates a cascade of electrons which in crease in number for each dynode. The amplification occurs in the dynode chain because a large bias voltage.



Photomultiplier tube windows



Photocathode spectral response



Linearity of detector response

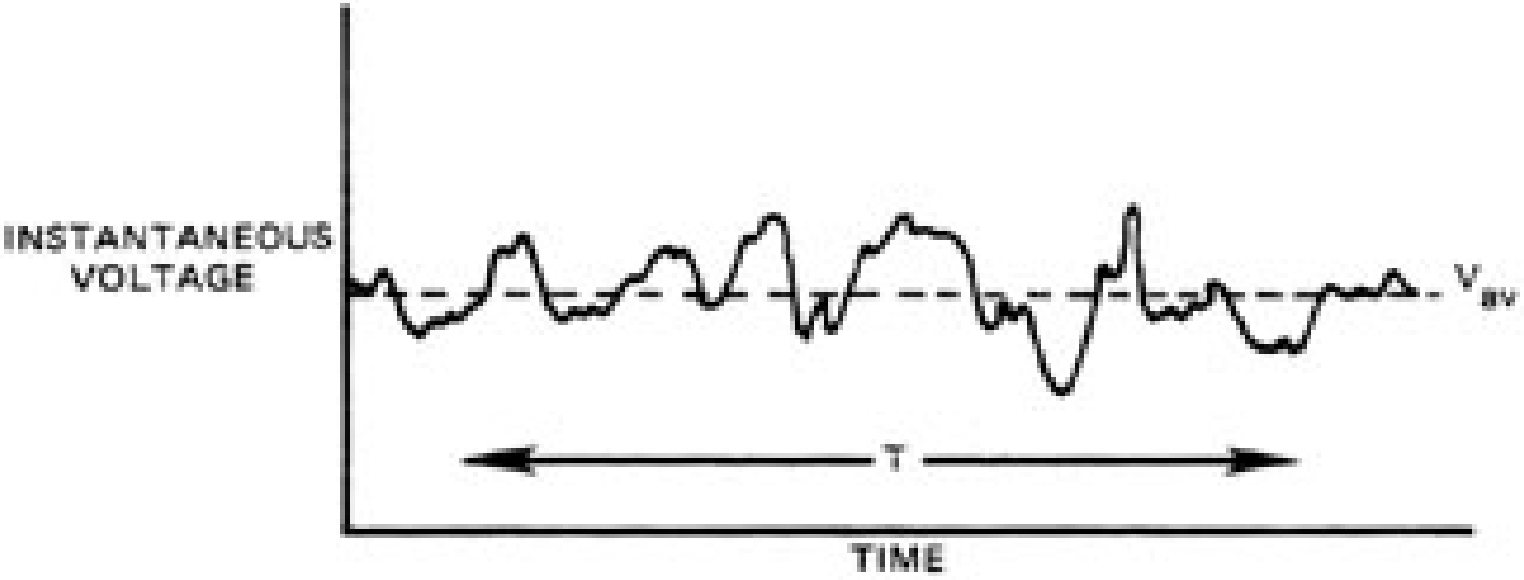
Photodetectors are characterized by a photocurrent response that's linear with incident radiation over a wide range. Any variation in responsivity with incident radiation represents a variation in the linearity of the detector. If we plot the output current of the detector versus the input radiation level, the slope of the line from the lowest level of radiation to the highest level of radiation should not change. Noise in the detector or system will determine the lowest level of incident radiation detectable. The upper limit of this input/output linearity characteristic is established by the maximum current capability that the detector can handle without becoming saturated (no change in output for a change in input).

Sources of noise in photodetectors

Noise can be divided into two categories: externally induced noise, and internally generated noise. External noise includes those disturbances that appear in the system as a result of an action outside the system. Two examples of external noise are hum picked up from 60-hertz power lines and static caused by electrical storms. Internal noise, on the other hand, includes all noise that's generated within the system itself. We now know that every resistor produces a discernible noise voltage and every electronic device (such as vacuum tubes and semiconductor elements) has internal sources of noise. You can think of internal noise as an ever-present limit to the smallest signal that the system can handle.

Voltage fluctuations as intrinsic noise

A record of the output from a random noise generator might look like that shown in the figure. Because of the random nature of the noise, the voltage fluctuates about an average value V_{av}. A simple average of these fluctuations is a meaningless description, since the average of the variations is zero. Rather, it's convenient to use the average of the squares of the deviations about V_{av}. The average is taken over a time interval T that's much longer than the period of the fluctuations in the voltage.



The root-mean-square voltage as a definition of noise

The mean square voltage is:

$$\langle V - V_{av} \rangle^2 = \frac{1}{T} \int_0^T (V - V_{av})\, dt$$

This is a convenient way of defining the fluctuation in a real System. The square root of this voltage is one measure of noise

$$V_{rms} = \sqrt{\langle V - V_{av} \rangle^2}$$

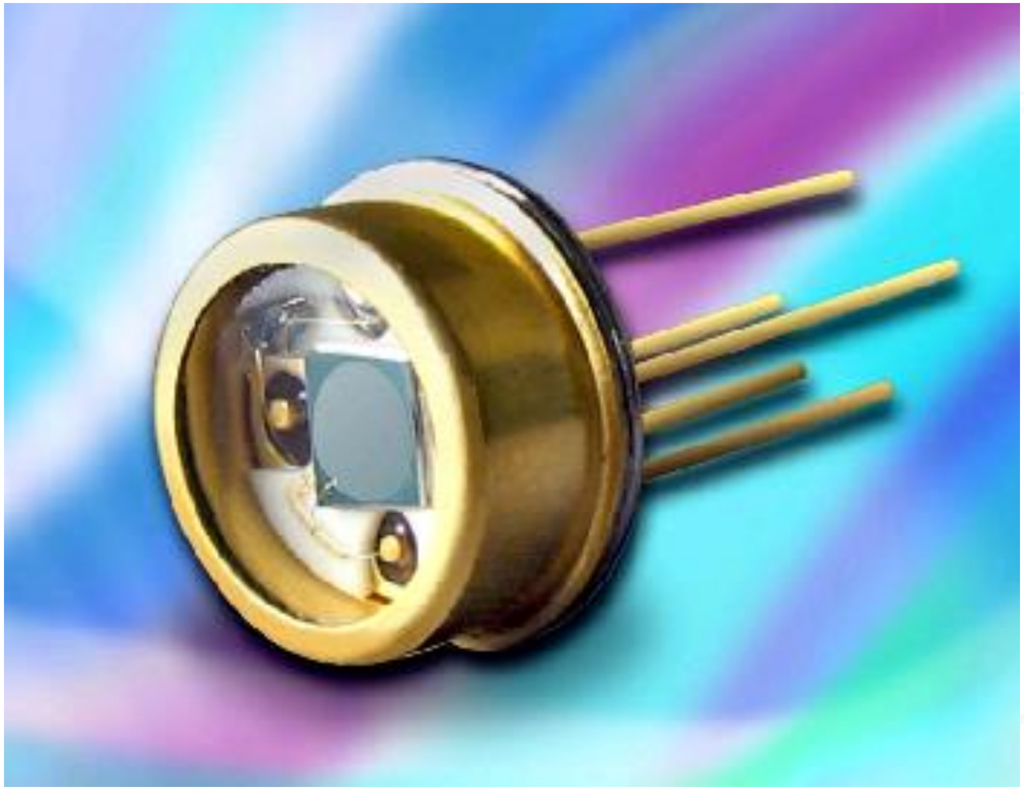
Shot noise

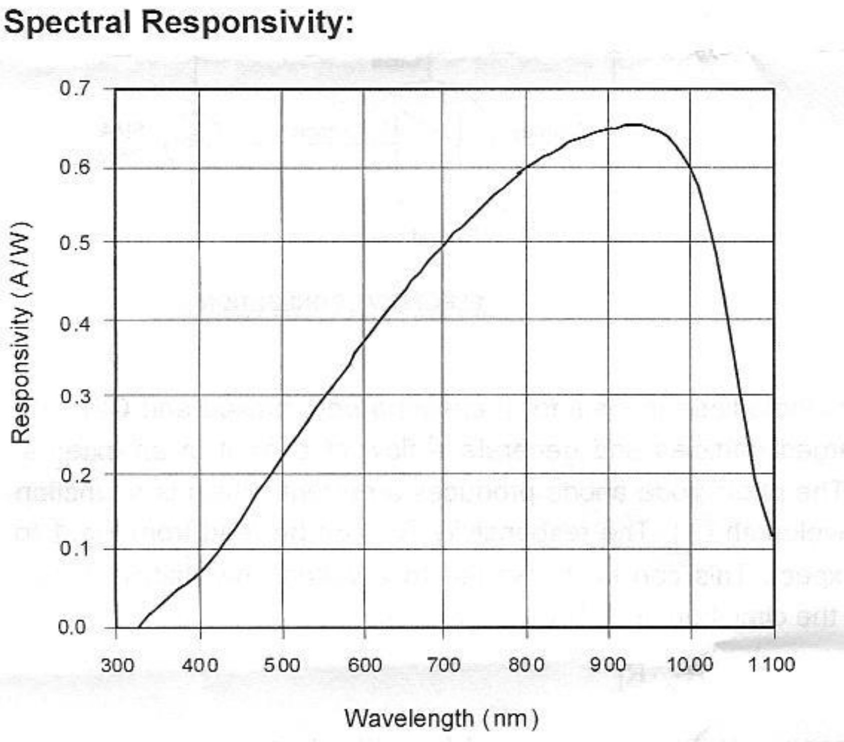
The term "shot noise" is normally associated with vacuum tubes in which the stream of electrons creates a noise due to the random fluctuations in the rate of arrival of electrons at the anode. This noise may be likened to the noise of a hail of shot striking a target. Hence the name shot noise. Shot noise is present in all photon detectors due to the random arrival rate of photons from the source of radiant energy under measurement and background radiation. This shot noise is often called "photon noise." Photon noise is the true ultimate limitation to detector performance. Even if all internal noise sources were eliminated, photon noise would set the ultimate limit for detector performance. Shot noise is proportional to the square root of the total number of counts on the detector. It is proportional to the square of the number of counts.

$$N_{shot} = \sqrt{N}$$

Silicon photodiode

Silicon photodiodes are not sufficiently sensitive to be used in most fluorescence applications where low light levels are common. However, the form the basis for technologies that are widely used such as Si avalanche photodiodes and CCDs.





Inverted operational amplifiers

Silicon photodiodes usually operate in a current mode. Light strikes the diode and generates a current. Gain can achieved using a operational amplifier (op-amp).

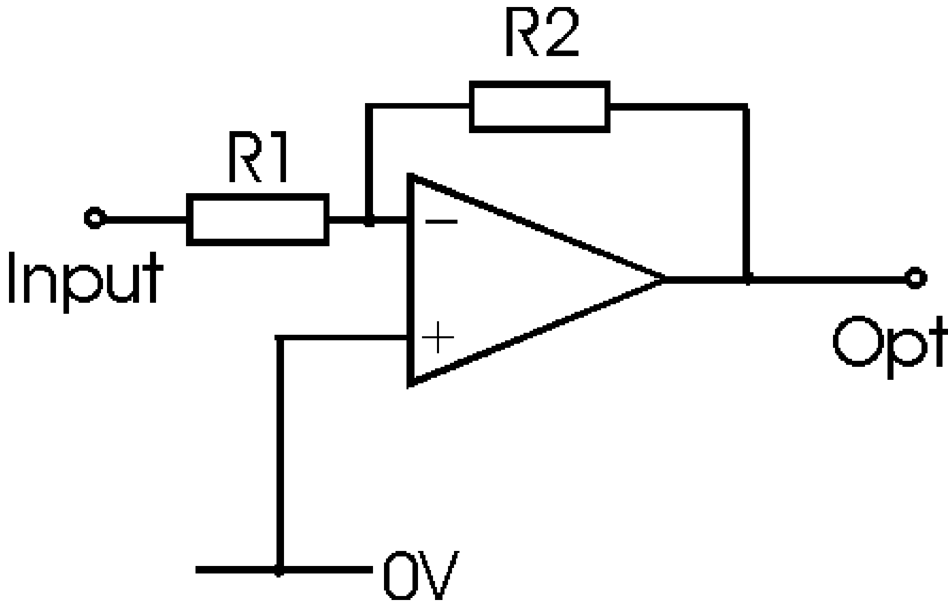
The circuit for the inverting op-amp configuration is shown. This circuit has the output 180 degrees out of phase with the input. The positive input is grounded.

The input to the op-amp itself ^{in}draws no current and this means that the current flowing in the resistors R1 and R2 is the same. Using ohms law

$$V_{out}/R2 = -V_{in}/R1.$$

Hence the voltage gain of the circuit is:

$$\text{Gain} = R2/R1$$



Current to voltage converter characteristic of op amps

Given the gain quation, you might think that it would be Possible to achieve a large gain by making the ratio of The two resistors R2/R1 very large. However, there are Intrinsic limitations. The resistor R1 determines the initial Voltage since V = I x R. The current flowing in from the Photodiode is usually quite smal and thus R1 must be large Enough to achieve an initial voltage in millivolt range at least. Secondly, the time response of the circuit is limited by the RC time constant. If the second resistor is very large then The circuit will be very slow to respond. This is a severe Limitation for time-resolved applications. Photodiodes op-amp Circuits can have time resolution of ca. 10 nanoseconds, but Seldom much better than that for common laboratory experiments.

RC time constant limits gain

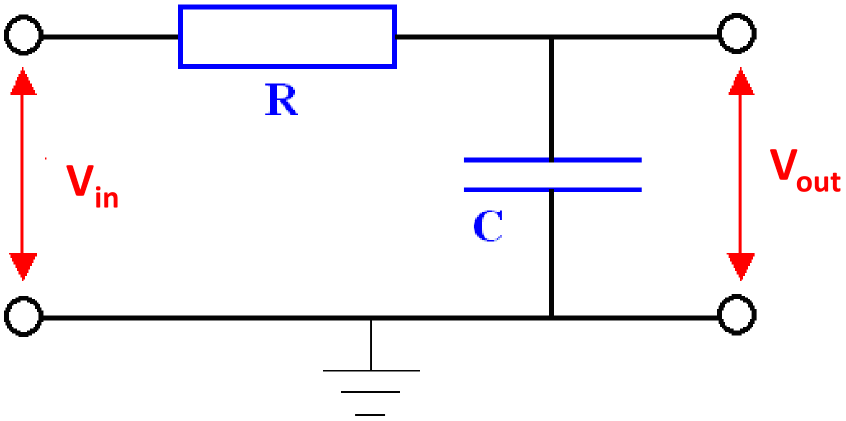
Even a bare wire has some resistance and some capacitance. In an op-amp circuit there is a significant resistance since this is the essence of gain. While the capacitance is kept to a minimum, it cannot be zero. So-called stray capacitance is at least a few picoFarads and that is enough to put severe limitations on the time response of an amplifier circuit.

RC time constant comes from the equation for charging of a capacitor.

$$I = C\frac{dV_{out}}{dt} = \frac{V_{in} - V_{out}}{R}$$

The solution has an exponential Form with a time constant of RC.

$$V_{out} = \Delta V\left(1 - e^{-t/RC}\right)$$



Silicon avalanche photodiode

An avalanche photodiode (APD) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity.

APDs are photodetectors that provide a built-in first stage of gain through avalanche multiplication. From a functional standpoint, they can be regarded as the semiconductor analog to photomultipliers. By applying a high reverse bias voltage (typically 100-200 V in silicon), APDs show an internal current gain effect (around 100) due to impact ionization (avalanche effect). However, some silicon APDs employ alternative doping and beveling techniques compared to traditional APDs that allow greater voltage to be applied (> 1500 V) before breakdown is reached and hence a greater operating gain (> 1000).

In general, the higher the reverse voltage the higher the gain.

An avalanche photodiode is a silicon-based semiconductor containing a **pn** junction consisting of a positively doped **p** region and a negatively doped **n** region sandwiching an area of neutral charge termed the **depletion region**. These diodes provide gain by the generation of electron-hole pairs from an energetic electron that creates an "avalanche" of electrons in the substrate. Incident photons pass through the **n** and **p** layers before entering the depletion region where they excite free electrons and holes, which then migrate to the cathode and anode, respectively. When a semiconductor diode has a reverse bias (voltage) applied and the crystal junction between the **p** and **n** layers is illuminated, then a current will flow in proportion to the number of photons

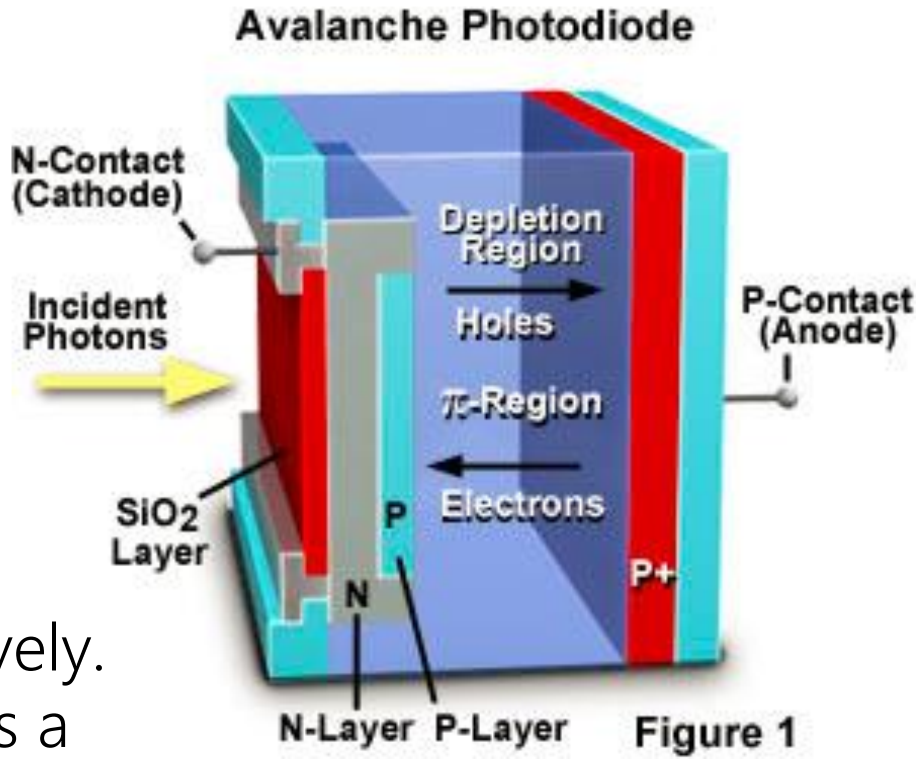
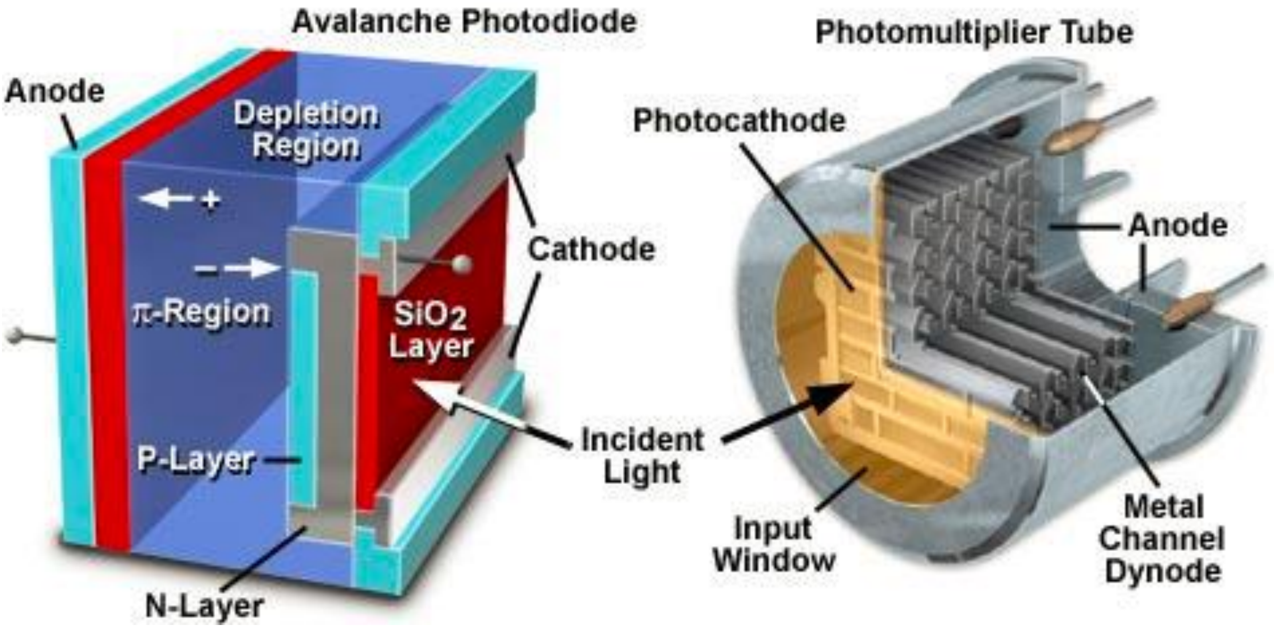


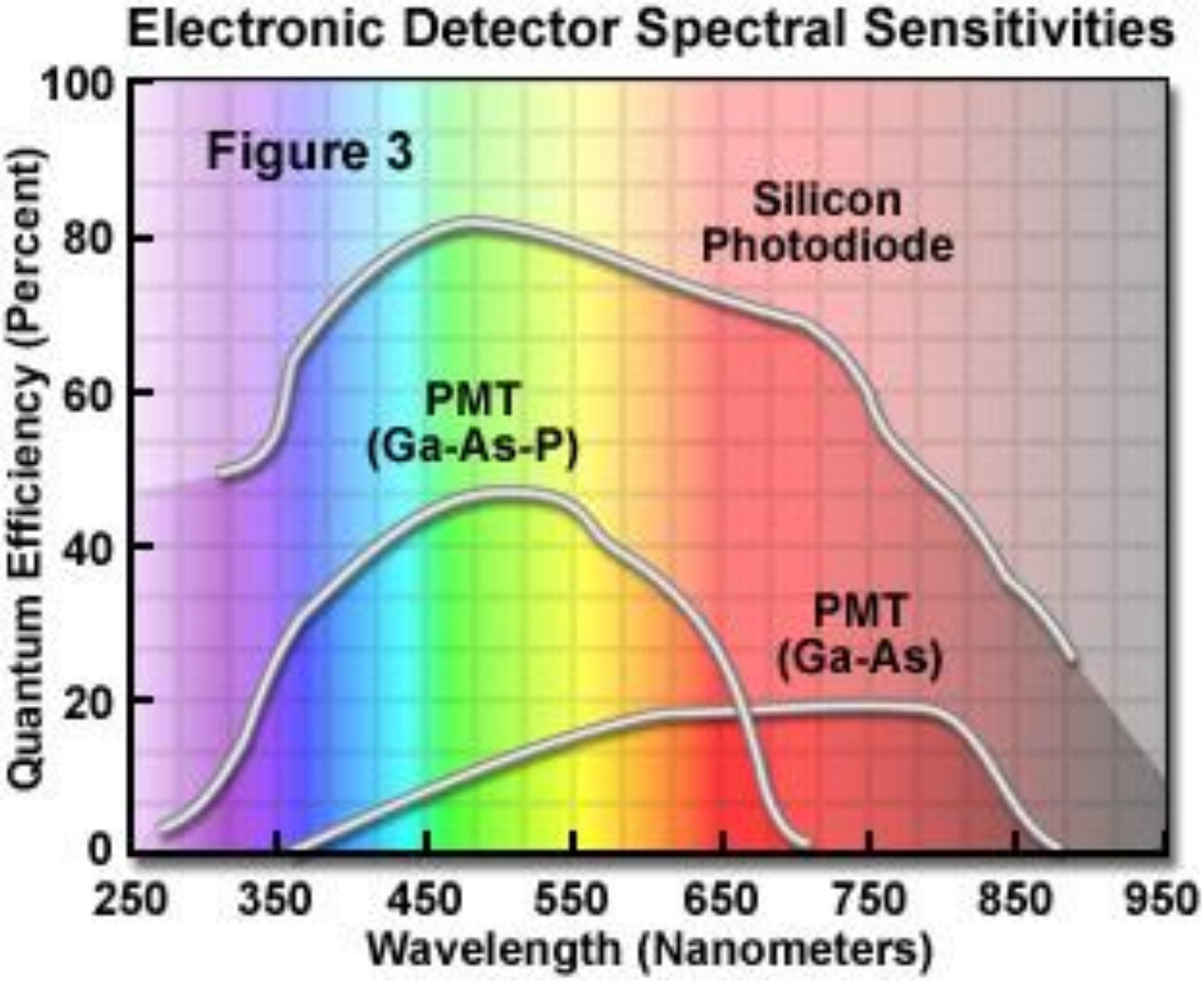
Figure 1

Si APD vs. PMT

The PMT and the Si APD photodiode both employ a photosensitive surface that captures incident photons and generates electronic charges that are sensed and amplified. PMTs respond when photons impinge on a photocathode and liberate electrons that are accelerated toward an electron multiplier composed of a series of curved plates, known as dynodes. The Si APD has similar concept of operation. Neither detector has spatial resolution.

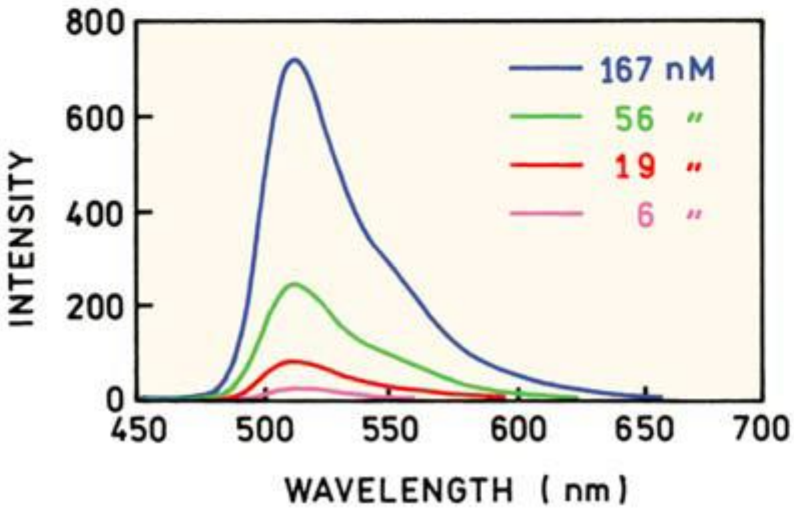


Quantum efficiencies of APDs and PMTs



CCD cameras

Modern CCD cameras are quite sensitive and can detect wavelengths over a range of the spectrum. Thus, one does not need to scan wavelength in order to obtain a fluorescence spectrum. The emitted light is dispersed across the CCD instead.



CCD principle of operation

In an imaging CCD for, there is a photoactive region (epitaxial Si), and a transmission region made out of a shift register shown in the Series of images on the right.
An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location.
Once the array has been exposed to the image, a control circuit causes each capacitor to shift the charge and finally to dump it to an amplifer, which converts it to a voltage for storage.