[3] Physics of Low Light Level Detectors

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The measurement of light by most detectors involves the conversion of light, or photons, into an electrical signal. Photons carry an increment of energy, E_{ph}, which depends inversely on the wavelength (λ) of the photon, $E_{ph} \alpha h/\lambda$ (h is Planck's constant = 6.63E-34 J-s). When a photon is absorbed by a material, the energy is used to excite the atoms or molecules in the material. If the photon carries energy greater than, or equal to, the "work function," E_w, of the molecule, an electron will be ejected. The energy above the work function ($E_{ph} - E_w$) is carried by the electron as kinetic energy. This process is called the photoelectric effect.[1]

Selection of a device to perform this conversion to an electrical signal depends on the type of measurement required. For low light level single point measurements the most commonly used device is the photomultiplier tube (PMT). This device has the advantage of being reasonably efficient, with high gain in a linear mode (on the order of 10^6) and a relatively low cost. A solid-state device, the avalanche photodiode (APD), has been introduced in many applications. The APD requires a lower supply voltage (100 V vs 500 V or greater) but has lower gain (approximately 100) when operating in a linear mode. When operating an APD in a nonlinear mode, gain can be increased greatly, thus the APD is more suited to counting single events (photon counting).

For two-dimensional (2D) measurements, array detectors are required. In this case, charge-coupled device (CCD) arrays dominate the market. Two methods exist for making a CCD into a low light detector. When longer integration times (0.1 sec to minutes) can be utilized, cooled CCD arrays allow the noise intrinsic to the device to be lowered, thus lower signals can be detected. This method of increasing the sensitivity of the CCD allows the device to maintain a large intrascene dynamic range (up to 16,000–60,000 to 1).

For some measurements, longer integration times are not appropriate, such as looking at the time development of a process. In this case, another device is added to the CCD array to preamplify the optical signal. This device is called an image intensifier and is much like adding a PMT for each point in the 2D CCD array. Image intensifiers increase the signal

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[1] A. Einstein, *in* "Great Experiments in Physics" (M. H. Shamosed, ed.), p. 232. Dover, New York, 1987.

obtained for each incident photon, but tend to reduce the dynamic range of the array by increasing the noise. The technology of these image intensifiers is developing rapidly and the costs are decreasing as they move into consumer markets (low light vision systems for sailors, etc.). The following discussion provides a simple description of how each type of detector works, but there are many similarities between the devices.

Photomultiplier Tubes

The oldest technique and most commonly commercially available low light level detector is the photomultiplier tube. Figure 1 shows a diagram of a side-illuminated PMT. The PMT consists of a photocathode, electron multiplier plates, and anode all contained in a vacuum tube. The photocathode is the site where the photoelectric effect takes place. Photoelectrons generated at the photocathode are accelerated in a large electric field, gaining energy, to an electron multiplier plate, or dynode. The collision of

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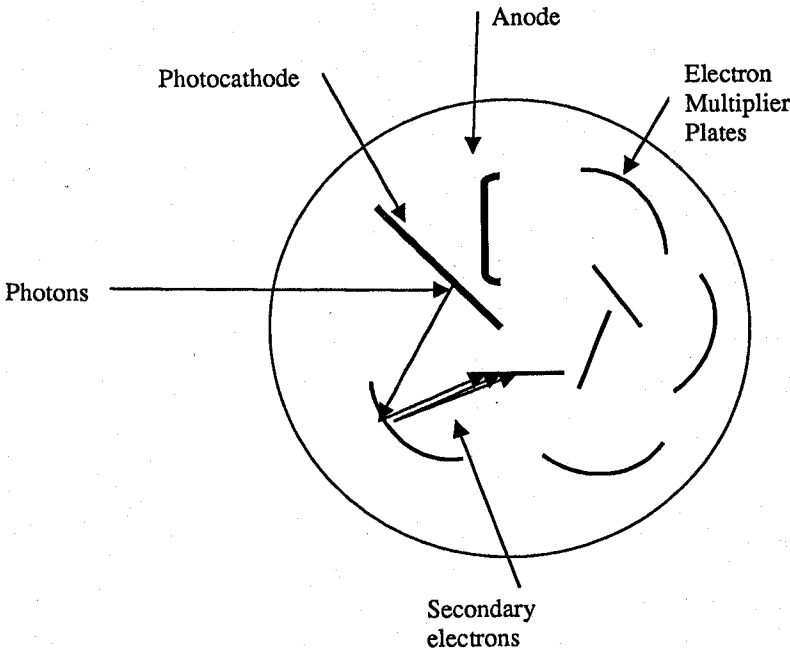The ph
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Fig. 1. Top view of a side-illuminated photomultiplier tube. Photons strike the photocathode, generating a photoelectron. These photoelectrons are accelerated into the electron multiplier plates, or dynodes, to produce multiple electrons ("secondary emission"), which are eventually collected by the anode.

these high-energy electrons with the plate causes the dynode to emit multiple electrons for each incident electron in a process called secondary emission. By having a series of dynodes, the initial photoelectron can be amplified greatly. At the end of a series of dynodes, the electrons are captured at the anode and are read as a current between the photocathode and the anode. The signal from the PMT depends on two factors: the quantum efficiency of the photocathode and the efficiency of the amplification process. Obviously the more efficient the photoelectric effect at the photocathode, the greater the output from the PMT. Similarly, the amplification efficiency of the PMT depends on the collection efficiency of the dynodes and the acceleration of the electrons between plates by the applied electric field. Selection of a specific PMT depends on the wavelength of the light to be measured, sensitivity required, and time response desired. These factors are used to select the photocathode material, window material, and tube design.

Photomultiplier Tube Design

Photomultiplier tubes come in two basic types: side illuminated and front end illuminated. The first commercially available PMT was a side-illuminated device, the 931 by RCA.[2] Side-illuminated PMTs are generally low priced and used in many commercial devices. In a side-illuminated PMT, the photocathode is opaque and electron multiplier plates are arranged in a circular cage structure, as shown in Fig. 1. These tubes have good sensitivity and amplification at relatively low supply voltage (typically ≤ 1000 V). Front end-illuminated PMTs use a semitransparent photocathode (diagram in Fig. 2). These PMTs typically have better spatial uniformity because the photoelectrons can be focused onto the electron multiplier plates more efficiently. The photocathode can have photosensitive areas ranging from tens of square millimeters to hundreds of square centimeters.[3] There are several designs for electron multiplier plate arrangements. Figure 2 shows a box and grid type of arrangement. Time response, spatial uniformity of the response, sensitivity to magnetic fields, and cost are all factors in choosing the design of electron multiplier plates. These factors tend to trade off so that selection is made on which factors are important for the particular application.

Photocathodes

The photocathode is the stage where the photoelectric process takes place. The conversion of photons to electrons is described by the quantum

[2] R. W. Engstrom, "Photomultiplier Handbook." RCA Solid State Division, Lancaster, 1980.
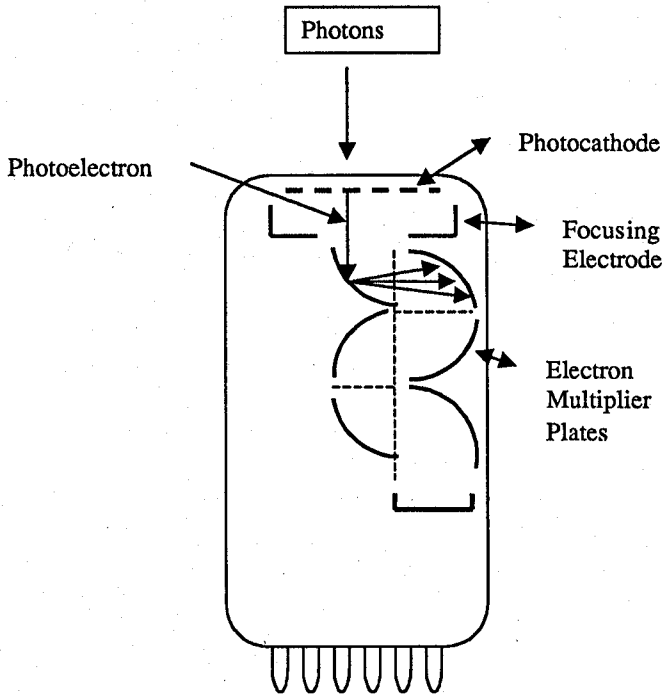[3] "Photomultiplier Tubes." Hamamatsu, Shimokanzo, Japan, 1990.

FIG. 2. Side view of an end-on illuminated photomultiplier tube. The operating structure is similar to the side-illuminated PMT shown in Fig. 1.

efficiency (ratio of electrons generated per incident photon) of the photocathode. The quantum efficiency varies with wavelength of the incident photon as it depends on the incident photon having enough energy to ionize the photocathode and cause the ejection of the electron. Because the energy of the photon varies inversely with wavelength, photocathodes for red to infrared radiation must have lower work functions then those used for violet or ultraviolet radiation. With the lower work functions, intrinsic thermal noise can eject electrons easier. Thus red sensitive photocathodes tend to have higher noise. The dark signal is exponentially proportional to temperature. Thus by cooling these PMTs, the thermal noise can be reduced. Cooling is generally required for infrared detectors.

The photocathode material used depends on the application and the desired wavelength sensitivity required. Typically the spectral limit imposed by the photocathode occurs on the red end of the spectrum, as the photons on the blue end increase in energy. The blue end cutoff of a PMT is typically due to the window material used for the PMT envelope. Optical glasses start
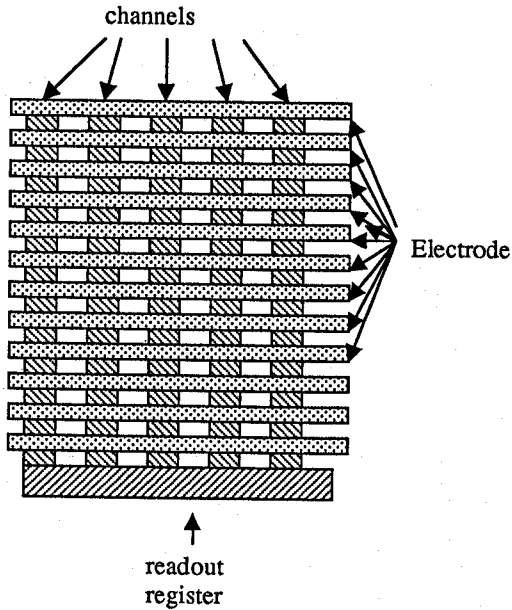
channels

Electrode

readout
register

FIG. 3. Top view of a simplified structure for CCD array. Conduction channels are separated by insulating barriers. Electrodes are used to control charge location along the conduction channels. Photoelectrons are transported along the conduction channels to the readout register, where they are moved off of the side of the array to be read electronically.

to absorb light at around 350–400 nm. For ultraviolet light measurement, materials such as quartz must be used for the optical window.

Charge-Coupled Device Arrays

Charge-coupled device arrays are one- to two-dimensional arrays of "potential wells," pixels, which hold the electrons generated by the photoelectric process.[4] Figures 3 and 4 illustrate the top and side view of a simplified structure, whereas Fig. 5 shows the CCD operation. In the CCD array structure, channels of p-type silicon are separated by insulating strips. The whole structure is overlaid with an insulating layer of SiO_2, onto which transparent conducting electrodes are deposited. In a structure such as this, three electrodes and a conducting channel define a single pixel. For example, Fig. 3 would illustrate a five column by four row imager, thus 20 pixels. Looking along one of the columns, Fig. 4 shows a side view of the device.

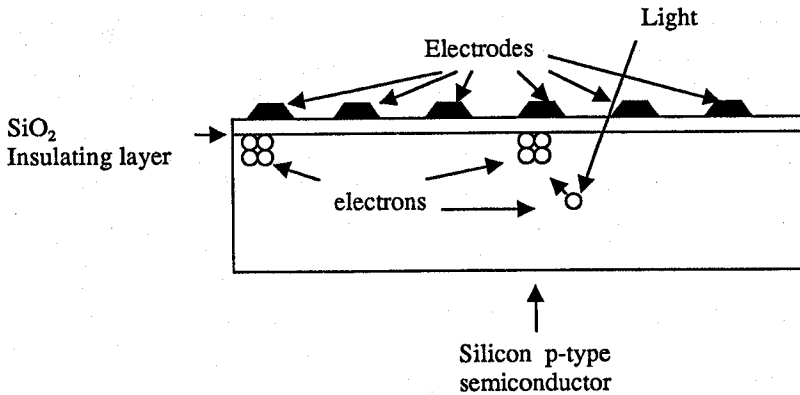[4] G. F. Amelio, *Sci. Am.* **230**, 23 (1974).

FIG. 4. Side view, along a conduction channel, of a CCD array. Each pixel is defined in this structure by the conduction channel and three electrodes. Photoelectrons are captured by setting one electrode in each pixel to a positive voltage when compared to the other two electrodes. This creates a potential well, which holds the photoelectrons in place. An insulating layer exists between the electrodes and the bulk semiconductor.
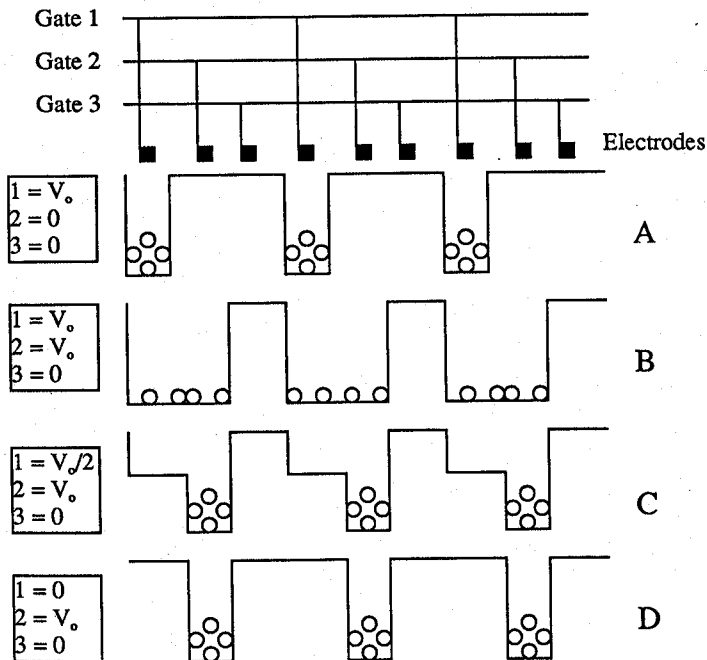

FIG. 5. Schematic of the three-phase system to transport photoelectrons along the conduction channels in the array. By varying the voltage to the three electrodes in each pixel, the photoelectrons can be transported to the readout register and then off of the array.

Light incident on the array generates a photoelectron in the bulk material and in each pixel one electrode is charged to a positive voltage attracting the photoelectron. To measure the amount of charge (electrons) in each pixel, the pixels are shifted down along the conduction column to the readout register. The readout register is then shifted to the left or right sequentially by the same process and the charge in each pixel is measured.

Figure 5 illustrates how the electrons contained in one pixel can be shifted into a neighboring pixel in a three-step process. This design is referred to as a three-phase system because there are three electrodes per pixel. While the array is being exposed to light, a positive voltage is applied to gate 1. This captures the electrons as shown in diagram A. After the light is blocked, gate 2 is brought to voltage V_o, allowing the electrons to spread into the area under this electrode. Gate 1 is then brought to $V_o/2$, which pushes the electrons into the area under gate 2. When the electrons are all under gate 2, gate 1 is brought to 0 V, which results in all the electrons being confined under gate 2. Electrons can be moved sequentially in this manner from the array onto the readout register, and then off the array to be counted. The total charge measured for each pixel is proportional to the incident flux, thus giving a measure of the incident light. This process must be very efficient at transporting all the photoelectrons for the array to work. Transfer efficiencies limit the speed an array may be emptied (read out) and the size of an array. These transfer efficiencies are greater than 0.9999/transfer for modern arrays.[4]

The process just described is for a three-phase transfer in a surface channel device (photoelectrons carried near the insulator–silicon interface). Other designs exist for the transferring mechanism, such as two-phase systems, which reduce the number of conduction gates required. Buried channel devices use ion implantation to keep the potential wells from being near the surface. These are more complicated to build, but have lower noise and better transfer efficiencies.[5] The light incident on the array must go through the electrodes and insulating layer before interacting with the doped silicon to produce photoelectrons. Because these electrodes are only semitransparent, there are losses associated with this. For low light applications, backside-illuminated CCDs can be used to avoid this problem. Photoelectrons can also recombine with the silicon substrate on the way to the pixel potential well. "Thinned" arrays can be used to reduce this effect by reducing the pathlength the photoelectron must travel in the material.

Variables for CCDs include quantum efficiency, dark noise, electronic noise (from amplification and reading out of the array), and array size and

[5] A. F. Milton, *in* "Topics in Applied Physics: Optical and Infrared Detectors" (R. J. Keyes, ed.), p. 197. Springer-Verlag, Berlin New York, 1977.

pixel dimensions. One important variable for a CCD array is the pixel well capacity. In other words, how many electrons can be contained within a pixel before overflowing the potential well into neighboring pixels. This process is called "blooming" and can be recognized by bright pixels extending along columns in the array or image. The electron capacity of each well is dependent on the size of the pixel and the design of the potential well, but in general the more pixels (higher resolution) in the array the lower the electron capacity.

Low light levels can be investigated with CCD arrays in two ways. By cooling the array first, thermally generated dark noise can be reduced significantly. This allows the light falling on the array to be integrated for longer times, thus increasing the signal-to-noise ratio (more photoelectrons than noise electrons from dark noise and fixed readout and electronic noise). Cooled arrays are commonly used where large dynamic range and spectral range are required and the integration times can be extended.
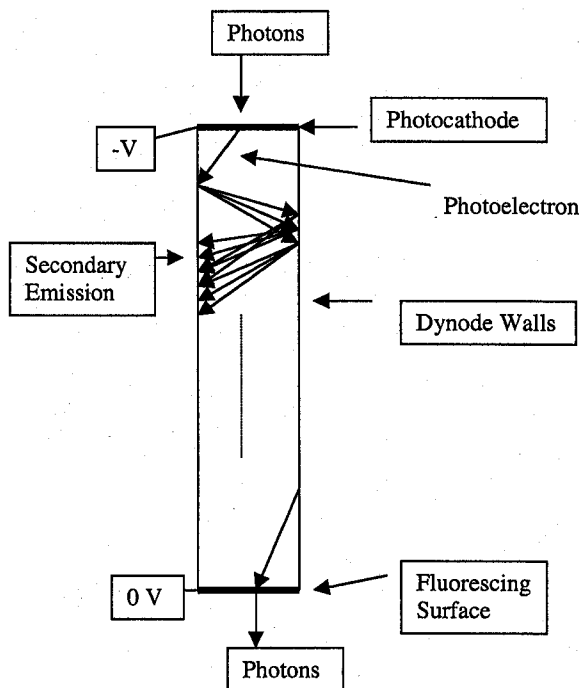

FIG. 6. Schematic of a single image intensifier tube. Operation is much like a PMT tube, but in the end the electrons are turned into photons again by the fluorescing surface. These amplified photons are collected by the CCD array. An image intensifier will typically have 1.5 million of these tubes for the array.

The other method of increasing the signal from a CCD array is by adding an intensifier stage to the device. This is somewhat like adding a photomultiplier tube to each pixel in an array. A diagram of a single intensifier tube is shown in Fig. 6. An intensifier stage would typically contain an array of 1.5 million of these tubes. Here a photocathode converts the incident photon into an electron. The electron is accelerated down a dynode "tube" interacting with the walls of the tube and causing secondary emission from the walls. At the end of the tube the electrons hit a fluorescing surface that converts these electrons into photons, which are then incident on the CCD. Thus one incident photon can be amplified into many photons by the intensifier and collected on the CCD. An important issue is, as with a PMT, determining the proper photocathode for the intensifier. Intensifiers tend to reduce dynamic range and increase noise, as opposed to cooled CCDs. However, they can help when gain is required, a large dynamic range is not necessary, and long integration times are not available.

Avalanche Photodiodes

Avalanche photodiodes are modern solid-state devices that convert a detected photon into a large number of electrons. They operate much like a PMT, except the electrons are transported in a doped silicon medium rather than a vacuum. The basic device contains two regions, an absorption region and a gain region. The absorption region is a relatively thick region where the photons are converted to photoelectrons. A small electric field is applied in this region to sweep the photoelectrons to the gain region. In the gain region a large electric field is applied. This causes the photoelectrons to accelerate inside the material and gain energy. The high energy electrons interact with the substrate and, through the process of impact ionization, cause additional free electrons. As these electrons increase in energy they can cause additional electrons to be created and a cascade of electrons is formed from the single initial photoelectron. When operated in a linear mode, APDs can have gains of 100 or more with applied voltages of 100 V. For more gain the APD can be operated in "Geiger"mode.[6] In this mode a voltage greater than the breakdown voltage is applied to the APD (approximately 400 V or more). When either a photoelectron or an electron generated by noise (typically thermal) is produced, large gains can occur $(10^4–10^8)$. Low noise APDs can be selected and the devices can be cooled to reduce the number of thermally generated electrons. In the Geiger mode, single photon detection efficiencies of close to 70% can be achieved.

[6] H. Dautet, P. Deschamps, B. Dion, A. D. MacGregor, Darleene MacSween, Robert J. McIntyre, Claude Trottier, and P. P. Webb, *Appl. Opt.* **32,** 3894 (1993).