PHOTOMULTIPLIERS

Photomultiplier tubes are vacuum tubes that detect light energy in the ultraviolet (UV), visible, and near-infrared regions of the electromagnetic spectrum. The detected light energy is converted into electrical current, which is internally amplified to a measurable level. Output signal current is ideally proportional to input illumination. Photomultiplier tubes are extremely sensitive, and some types are capable of detecting and counting single photons. Photomultiplier tubes are widely used in medical, scientific, and industrial applications for the detection and measurement of low-intensity light. Some examples are cancer detection, exhaust emission monitoring, high-energy physics research, baggage inspection, and oil exploration. The light being detected can be of a variety of types including incandescent, fluorescent, Laser, and Cerenkov radiation. Nuclear radiation can also be detected by using a photomultiplier tube to detect light flashes in an optically coupled scintillating material. Material defects or optical density variations can be measured by passing a semitransparent test material in the path between the light (or radiation) source and photomultiplier tube. Photomultiplier tubes give excellent performance in many radiation detection applications by providing relatively noise free gain and wide bandwidth amplification.

Optimum performance in each application is achieved through knowledge of tube design and tube operating characteristics. Information is the key to selecting the correct tube for the application. Photomultiplier tube manufacturers are the primary sources of such information. Manufacturers provide catalogues and technical handbooks with detailed information on physical and chemical principles, tube construction, tube operation, performance characteristics, and test methods. Textbooks, patents, and journal articles are also excellent sources of detailed information. Application requirements dictate choices in tube characteristics; size, spectral range, sensitivity, dark current, noise, gain, speed, linearity, and cost are the primary factors.

FUNCTIONS

The overall function of a photomultiplier tube is to detect light and generate an electrical signal. The process is best understood by analyzing the individual functions occurring within the tube. The first function is detection. Light is detected by the photocathode, which is formed within the vacuum environment. A window provides access for external light to reach the photocathode. Window materials are designed to be highly transparent in the wavelength region of interest. When incident light energy in or near the visible region is absorbed by the photocathode, photoelectrons are emitted into the vacuum space adjacent to the photocathode surface. The photocathode sensitivity range and the light transmission cutoff characteristics of the window material limit the useful range of tube sensitivity. The photocathode is typically the limiting factor at the red end of the spectrum; the window material, typically glass, tends to be highly absorbing in the blue end of the spectrum.

Emitted photoelectrons are directed and focused toward the multiplier section by the focus element, which is positioned above the first dynode. A voltage difference generated between the photocathode and the focus element creates an electrostatic field, which draws the electrons toward the first dynode in the multiplier section.

The multiplier section amplifies the signal by increasing the number of electrons as the electrons traverse the section. The multiplier section is composed of a series of plates, or dynodes, having successively higher applied positive voltage. These plates are made with secondary emitting surfaces and are arranged such that electrons emitted from one are attracted to the next. Primary electrons striking each dynode give rise to an increased number of secondary electrons, which are in turn attracted to the next dynode. The number of electrons grows geometrically as the charge pulse moves through the multiplier section. Multiplier-section gain can range from about 1000 up to 100 million.

The anode is the last element in the photomultiplier tube and has the most positive applied voltage. The anode is typically positioned between the last two dynodes, so as to function as both accelerating grid and collector of electrons. The electron charge collected by the anode is conducted to external circuitry, which is used to further amplify or process the output signal. The photocathode, focus element, dynodes, and anode are electrically connected to external leads by vacuum feed-through wires.

TUBE OPERATION

Photomultiplier tubes are manufactured in a clean environment using metal, ceramic, and glass parts. The focus element, multiplier section, and anode are sealed inside an envelope (usually glass), leaving only a small vacuum port. Air is evacuated through the vacuum port. While under vacuum, the photocathode and secondary emitting surfaces are formed by vapor deposition of alkali metals. When the vapor deposition processing is completed, the vacuum port is sealed and tubes are given additional stabilization processing through application of voltage, light, and heat.

Photomultiplier tubes are operated by applying a direct-current (dc) voltage to each of the tube elements and dynodes. One high-voltage dc source is normally used to power a photomultiplier tube. A resistor string voltage divider distributes voltage among the tube elements. External circuitry is connected to the anode to detect tube output signal. Extraneous light and other disruptive inputs are excluded before applying voltage. Measurements are made by exposing the tube's photocathode to the light source of interest.

Photomultiplier tubes are easily damaged by improper use. For example, exposure to helium is to be avoided as helium readily diffuses through certain types of glasses, raising the internal gas pressure. Damage also may result if photomultiplier tubes are operated outside the manufacturer's maximum rating for applied voltage, current, temperature, or other environmental conditions. Exposure to ambient lighting while the tube is under voltage also may damage the photocathode and dynodes. Personal precautions are recommended when working with high voltage. Eye and face protection is recommended when handling large tubes where danger of implosion is present.

TUBE STRUCTURE

Functional Parts

The photomultiplier tube is composed of five basic functional parts: (1) window, (2) photocathode, (3) focus element, (4) multiplier section, and (5) anode. The window allows light to reach the photocathode. The photocathode converts light energy into free electrons. The focus element directs the photoelectrons into the multiplier section. The multiplier section amplifies the photoelectrons, and the anode outputs the resulting amplified signal. Figure 1 shows a typical end-window photomultiplier tube and the location of functional parts. Tubes are evacuated to provide the proper environment for the formation and survival of the photocathode and secondary emitting surfaces. Internal vacuum in the range 10^{-8} torr is needed for photomultiplier tube operation. Good vacuum is

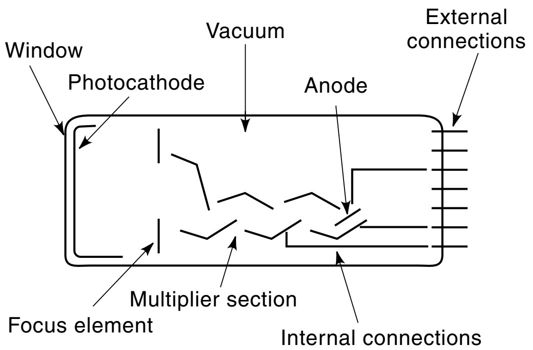

Figure 1. Photomultiplier-tube cross section showing basic structure and location of functional parts.

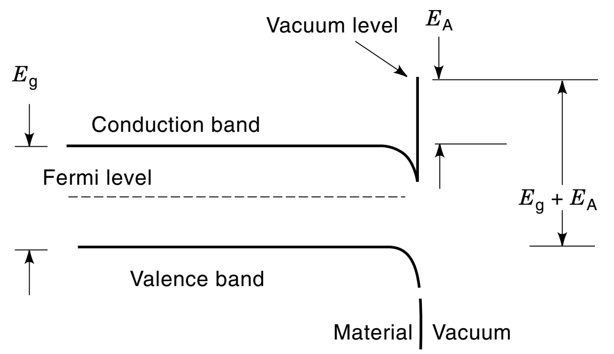

Figure 3. Band-gap model showing the minimum photon energy ($E_G + E_A$) required to achieve emission of a photoelectron.

also necessary to minimize the presence of gas molecules and to ensure that the mean free paths of the electrons far exceed the distance between dynodes. Electrons which strike gas molecules generate ions that disrupt tube function and damage the photocathode.

The most common window materials for photomultiplier tubes are borosilicate (hard) glass and lime (soft) glass. Window materials are chosen so as not to restrict photocathode sensitivity in the region of interest. The type of window material is important when working in or near the ultraviolet part of the spectrum because the transmission of most window materials cut off at short wavelengths. Quartz and special ultraviolet transmitting glasses are normally used in these applications. Magnesium fluoride and sapphire extend the range further into the ultraviolet region. Figure 2 shows the transmission characteristics of common window materials. The 10% cutoff points for these materials are 115 nm for MgF_2, 140 nm for sapphire, 160 nm for quartz, 190 nm for UV glass, 270 nm for borosilicate glass, and 300 nm for lime glass. Optical losses may occur due to index of refraction mismatches between the tube window and the surrounding environment. Most of the common window materials have an index of refraction of about 1.5.

Photocathode material may be deposited directly on the inside surface of the window, inside the tube but opposite to the window, or on an internal structure. Photocathodes of the first variety are called transmission mode photocathodes, and the light energy incident on one side produces photoelectrons on the opposite side. Light passing through the window may be absorbed or reflected by the photocathode, or it may pass on through the photocathode without generating photoelectrons. The other types of photocathodes are called reflective mode photocathodes and emit photoelectrons on the same side as the incident light energy. A reflective mode photocathode is deposited on a reflective nonwindow surface within the tube. Light striking the photocathode has two chances to be absorbed: first on the initial pass and again on the reflected pass if not absorbed on the first.

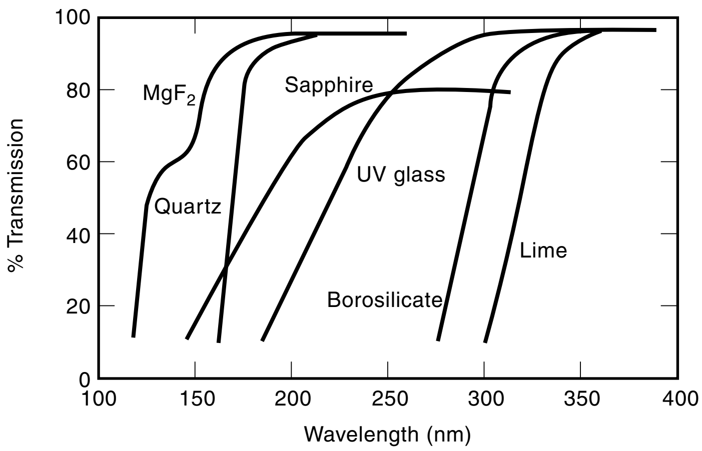

Figure 2. Window material cutoff characteristics may limit tube sensitivity at short wavelengths, even though photocathode sensitivity extends beyond the cutoff point.

Photoemission is the end product of a three-step process: (1) absorption of a photon which transfers energy to an electron, (2) movement of the electron having increased energy toward the surface of the photocathode, and (3) escape of energized electron from the photocathode surface into the vacuum. Photoelectrons generated deep inside the photocathode tend not to be emitted as they lose energy through lattice collisions and collisions with other electrons before reaching the surface. The ideal photocathode would produce one photoelectron for each incident photon. Typical photocathodes produce about one photoelectron for every three or four incident photons. High photocathode sensitivity, or quantum efficiency, is important in determining tube performance.

Photoemission occurs when an excited electron has sufficient energy to escape from the surface of the photocathode. To generate a free electron, a photon striking the photocathode must have energy $h\nu$ sufficient to raise a valence-band electron to the vacuum level. In the band-gap model shown in Fig. 3, this minimum required energy is the sum of band-gap energy (E_G) and electron affinity (E_A). Band-gap energy is the energy required to raise an electron from the valence band to the conduction band. Electron affinity is the energy required for an electron in the conduction band to escape into vacuum. Values for (E_G) and (E_A) are dependent on the photocathode type and composition.

Light in the visual region has energy in the range of 1.6 to 3 eV. To be sensitive in the visual region, a photocathode material must be able to produce photoelectrons with input photons having energies of 3 eV or less. The relationship between energy and wavelength is

$$E = \frac{hc}{\lambda}, \qquad \text{using}\, \lambda = \frac{c}{\nu}$$

where E is energy, h is Planck's constant, c is the speed of light in a vacuum, λ is wavelength of light, and ν is frequency.

Electron affinity can be reduced by lowering the surface work function. With sufficient downward band bending at the surface, the vacuum level becomes lower than the bottom of the conduction band and electron affinity becomes negative. This class of photocathodes is called negative electron affinity (NEA). For NEA photocathodes, lower-energy (longer-wavelength) photons are able to produce photoelectrons, thus extending sensitivity out into the near-infrared region. The two commonly used solid-state NEA photocathodes are GaAs(Cs) and InGaAs(Cs).

The most common photocathodes are made from the alkali metals: lithium, sodium, potassium, rubidium, and cesium. Alkali metals are chosen for having low electron affinity. The photocathodes are composed of thin layers of alkali metal grown by vapor deposition on surface materials such as antimony or magnesium oxide. The pure alkali materials for the photocathode are produced by thermal reduction of alkali metal salts. Vacuum must be maintained during and after photocathode formation as the evaporated alkali metals quickly react with air, oxygen, or water vapor.

Alkali metal combinations are used to create unique characteristics. Photocathodes composed of two mixed alkali metals are called bialkali cathodes. Mixture combinations of more than two alkali metals, called multialkali, are used to create photocathodes with wider band sensitivity extending further toward the red. Photocathodes are tailored for special applications such as matching sensitivity with a scintillating source or having low dark current at elevated temperatures for oil-well logging. Common bialkali cathodes are KCsSb or RbCsSb. NaKSb is used for high-temperature bialkali cathodes. Multialkali or extended red multialkali (ERMA) cathodes are made of NaKCsSb.

Photocathode radiant sensitivity is measured in terms of radiant flux, with units being amperes per watt. Figure 4 shows the photocathode radiant sensitivity and range of sensitivity for several common photocathodes, as a function of wavelength.

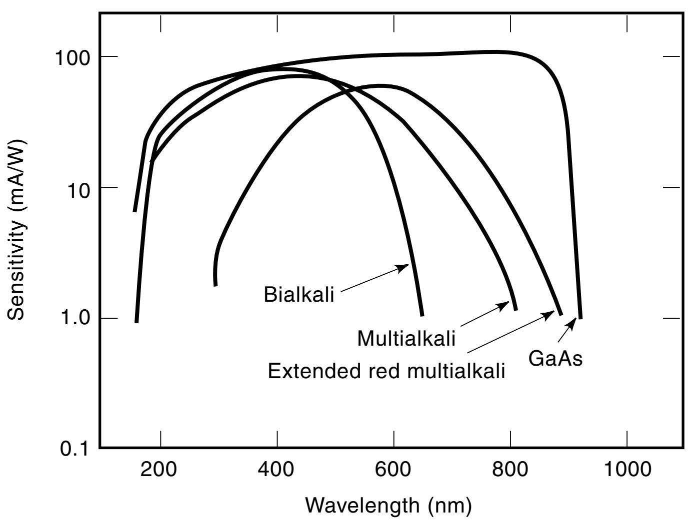

Figure 4. Sensitivity ranges of common photocathodes falling in the UV, visual, and near-infrared region.

Quantum efficiency (QE) is the ratio of the number of emitted photoelectrons to the number of incident photons at a given wavelength, expressed in percent.

$$\mathrm{QE}(\lambda) = \frac{n_\mathrm{k}}{n_\mathrm{p}} = \frac{Sh\nu}{e} = \frac{Shc}{\lambda e}$$

where n_k is number of photoelectrons emitted, n_p is number of incident photons, S is cathode radiant sensitivity at the given wavelength, h is Planck's constant, ν is frequency, e is electron charge, c is speed of light in a vacuum, and λ is the wavelength of light. The peak quantum efficiency reaches about 25% to 30% for most photocathodes at the wavelength of maximum emission. The photocathode surface may be flat, or curved to equalize electron path lengths to dynode 1. The concave inner window surface shortens the electron path lengths at the edges of the photocathode and improves timing uniformity across the photocathode. The electron optics design of the photocathode, focus element, and first dynode is critical in determining collection efficiency and timing characteristics.

The focus element is designed to attract and focus all possible photoelectrons to the prime area of the first dynode in the multiplier section. The focus element is physically positioned between the photocathode and dynode 1. Mechanical shape, distance from photocathode, and applied voltage are adjusted to optimize the electron optics. The focus element is sometimes given a voltage intermediate to the photocathode and dynode 1 voltages. Unipotential lenses are also commonly used, with the focus element voltage equal to first dynode voltage.

The multiplier section is composed of a series of secondary electron emitting plates called dynodes. The physical processes of secondary emission are similar to those of photoemission except that electron bombardment causes electron emission. Incident electrons interact with, and transfer energy to, one or more electrons in the secondary emitting material. Some of the energized electrons move toward the material surface, and those reaching the solid–vacuum surface with sufficient remaining energy to escape are emitted into the vacuum. The average number of secondary electrons emitted per primary striking electron is called the secondary emission ratio.

The common dynode substrate materials are beryllium copper, nickel, and stainless steel. Nickel and stainless steel dynodes are typically coated with antimony, and the secondary emitting surface is alkali antimonide formed by the reaction between the surface antimony and the alkali metals present in the tube during the photocathode building process. Beryllium copper is treated to produce a uniform surface layer of beryllium oxide. Alkali metals are deposited to increase secondary emission properties by lowering the surface work function. The principles of negative electron affinity can also be applied to secondary emitting materials. Gallium phosphide treated with cesium, or cesium plus oxygen, makes an NEA material with useful photomultiplier tube properties. GaP is typically used as a first dynode to provide a high secondary emission ratio and improve energy resolution.

Current amplification, or gain, is achieved through a cascade process as electrons move from dynode to dynode. The number of electrons is increased at each stage by the secondary emission ratio of the dynode at that stage. For dynode 1, we have

$$\delta_1 = a\left(\frac{I_1}{I_k}\right)$$

where δ_1 is the secondary emission ratio of dynode 1, a is the collection efficiency, I_1 is current leaving dynode 1, and I_k is current leaving the cathode. For each successive dynode where unity collection efficiency is assumed, we have

$$\delta_m = \frac{I_m}{I_{m-1}}$$

where m represents dynode position number. Total current amplification (gain) for the multiplier section is the product of the individual dynode gains, or anode current divided by photocathode current:

$$\text{Gain} = \delta_1\delta_2, \ldots, \delta_m = \frac{I_p}{I_k}$$

where I_p is anode current. For equal secondary emission ratios at each dynode, we have

$$\text{Gain} = \delta^n$$

where n is the number of dynodes.

Multiplier sections, also called cages, are constructed in several forms, with each having an advantage for certain characteristics. The basic multiplier section classifications are circular, box and grid, venetian blind, linear focused, and mesh. The circular cage takes little space and has fast time response. The larger dynode box and grid-type cage has good collection efficiency and energy resolution. The venetian blind type is simple in design and has good collection efficiency. The linear focused type has fast time response and good pulse linearity. The mesh type is short in length and is much less affected by magnetic fields.

Voltage Divider

Photomultiplier tubes require external electrical circuits to operate which are called voltage dividers (also referred to as resistor networks or bleeder strings). The voltage divider is usually a string of resistors that provide successively increasing voltage potentials from the photocathode, through the dynode elements, and to the anode. Typical examples of voltage divider circuits are shown in Fig. 5. The application of the photomultiplier tube determines what the voltage distribution should be among the photocathode, dynodes, and anode. In many applications the resistors can be of equal value. The voltage difference between each stage is

$$V(m) = \frac{V(T)R(m)}{R(T)}$$

where $V(m)$ is the voltage difference between stages separated by resistor $R(m)$, $V(T)$ is the photocathode to anode voltage, and $R(T)$ is the total resistance between the photocathode and anode.

For timing applications the voltage difference between the photocathode and the first dynode may be increased with respect to the voltage differences between the other elements to decrease the time of arrival of photoelectrons collected at the first dynode.

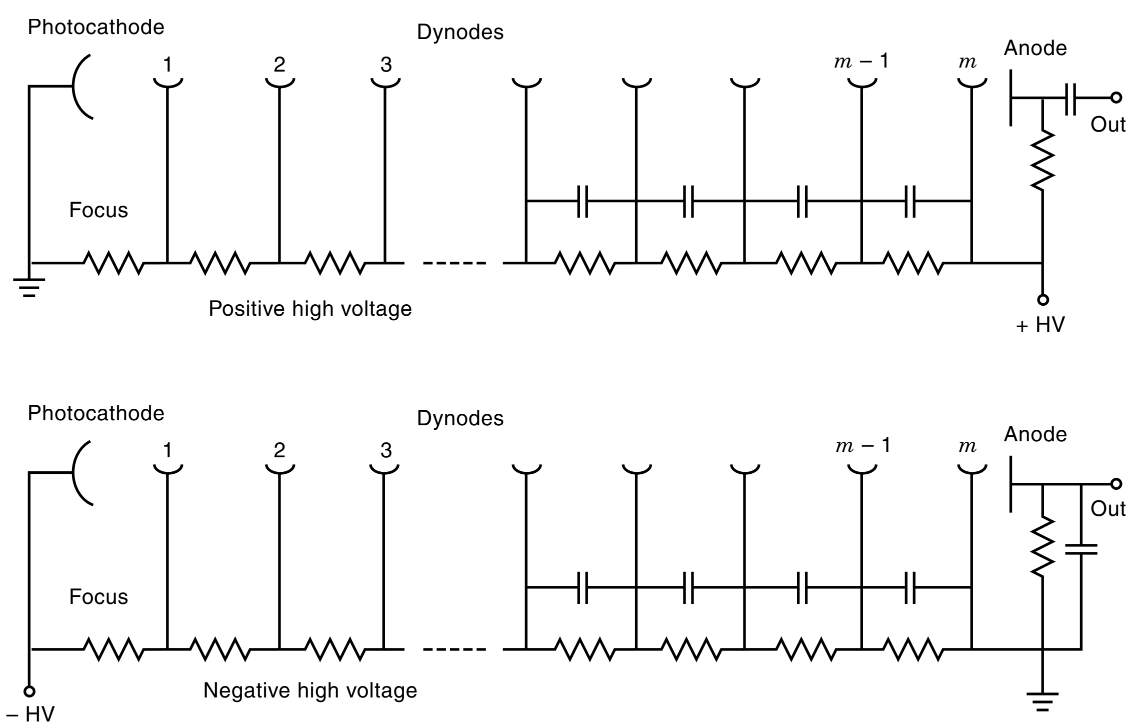

Figure 5. Examples of voltage divider circuits for positive and negative high voltage, showing how applied high voltage across the divider distributes voltage to each tube element.

$V(T)$ and $R(T)$ determine the total current, I, passing through the divider network. The value of $R(m)$ represents a compromise between high and low divider chain current applications, but typically ranges between 50 kΩ and 5000 kΩ. Care should be exercised to choose the power rating of the resistors to ensure adequate heat dissipation.

A voltage divider powers the photomultiplier tube using positive or negative high voltage. For positive high-voltage operation the photocathode is at ground potential, and the dynodes and anode are at positive voltage. In this mode of operation (also called the pulse mode), an anode capacitor blocks dc current and dc high voltage from the external electronics and allows the passage of only a charge pulse. The combination of the load resistor and anode capacitor creates a time constant that affects the shape of the output pulse.

For negative high-voltage operation (also called the dc mode, or current mode) the photocathode is operated at negative voltage, the dynodes are at successively increasing voltage, and the anode is at ground potential. A load resistor may be placed between the anode and ground, and a capacitor between the anode and external electronics is not needed. External electronics can therefore measure dc current and charge pulses directly from the anode. The outside surface of the photomultiplier tube glass envelope should be at the same voltage as the photocathode. Negative high-voltage operation usually requires a conductive coating over the glass envelope which is connected at the photocathode voltage. This prevents ions from migrating through the glass envelope that can result in loss of photomultiplier tube sensitivity. An insulator to protect the user from electrical shock is placed over the conductive covering. The conductive coating also serves as an electrostatic shield which reduces noise.

Stray capacitance and inductance should be minimized in the divider chain since these distort pulse shape. Coaxial cable is used to connect the anode signal lead to the processing electronics for high-frequency and pulsed signals.

TUBE CHARACTERISTICS

Sensitivity

Luminous sensitivity is a term given to describe photomultiplier tube output per unit luminance input. Luminous sensitivity is measured using a light source of suitable broadband spectral emission characteristics over a range of wavelengths where photomultiplier tubes are operated. A common practice is to specify the photomultiplier tube sensitivity using a tungsten lamp with a lime glass window operated at a color temperature of 2856 K as a light source. Sensitivity is also measured using the same light source with a blue band-pass filter to simulate the expected response within the emission spectrum range of a thallium-doped sodium iodide scintillator. Known constant values of luminous flux at the photocathode faceplate are used to determine luminous sensitivity.

Sensitivity is reported in three ways by photomultiplier tube manufacturers. Photocathode sensitivity is a measure of the integral quantum efficiency of the photocathode. It is normally determined by measuring the current flowing between the negatively biased photocathode and remaining elements inside the photomultiplier tube at ground potential. The gain of the photomultiplier tube is not taken into account for this measurement. Anode sensitivity is a measure of integral quantum efficiency of the photocathode, the collection efficiencies and gains of the dynodes, and collection efficiency of the anode measured at the anode output. It is frequently used to determine the expected output of the photomultiplier tube when the user knows the input luminous flux. Both photocathode and anode sensitivity are expressed in units of amperes per lumen. Photocathode radiant sensitivity is the photocathode output current divided by unit radiant flux input for a given wavelength or range of wavelengths. Photocathode radiant sensitivity indicates the spectral sensitivity of the photomultiplier tube. It is typically expressed in units of amperes per incident watt.

Dark Current and Noise

Dark current is a term that refers to the anode current present when the photomultiplier tube is kept completely in the dark while under bias. It is typically measured at a given high voltage and temperature. There are many contributions to the noise of a photomultiplier tube. Thermionic noise is a result of thermionic emission of single electrons from the photocathode. These single electrons are then multiplied in the dynode chain and collected by the anode. This noise component is temperature-dependent, and reducing the temperature at which the photomultiplier tube is operated can minimize the thermionic emission rate. The relationship between this noise component and temperature can be generalized by (1)

$$J = \text{constant}\, T^2 e^{(-W/kT)}$$

where J is the thermionic current density, T is temperature in degrees kelvin, W is the thermionic work function, and k is the Boltzmann constant.

Ohmic noise is caused by leakage current across various insulators used in the construction of the photomultiplier tube. It can be distinguished from other noise sources in that it generally has a linear relationship with applied high voltage. This may be caused by simple resistances such as contaminants on the inside or outside surface of the photomultiplier tube envelope.

The presence of very long-lived radioactive impurities within the photomultiplier tube envelope contributes to the overall noise. Natural potassium contains 0.0118% of potassium-40, which has a half-life of 1.3×10^9 years. It is present in many bialkali and multialkali photocathode materials and in the glass used in making photomultiplier tube envelopes. The decay scheme of potassium-40 is such that beta particles and gamma rays can be emitted during the decay process. Glass used in manufacturing modern photomultiplier tubes is usually selected to have a low potassium content.

Afterpulses and light emission are regenerative sources of noise and are kept to very low levels in modern photomultiplier tubes. Afterpulses are caused by the feedback of positive ions to parts of the dynode elements and the photocathode, and occur at a time after the signal pulse. Afterpulses are caused by the presence of residual gasses inside the photomultiplier tube envelope. Different residual gases give rise to afterpulses of different delay times. For example, impurity gases of Xe^+, Ar^+, N_2^+, and H_2^+ have afterpulses of characteristic delays of 2.5, 1.34, 1.17, and 0.32 μs, respectively (2).

Electron bombardment and subsequent luminescence of construction materials and impurities on the internal parts of the photomultiplier tube can cause light emission. Emitted photons may be detected by photosensitive elements inside the photomultiplier tube giving rise to a nonsignal increase of photomultiplier tube current. Light emission and feedback in linearly focused photomultiplier tubes can be a source of noise when the photomultiplier tube is operated at very high gains (3).

Field emission is the emission of electrons from the internal elements of the photomultiplier tube when localized electric fields become very high due to sharp edges or surface roughness. Good manufacturing and design practices reduce points of intense localized electric fields and control field emission.

Exposure of the photomultiplier tube to light may result in phosphorescence from its components. This phosphorescence has been attributed primarily to metastable excitation mechanisms primarily from the glass faceplate (3). It is a temporary source of noise that typically decays away in time periods from minutes to hours and is particularly troublesome in low light level applications such as single-photon counting. Keeping the photomultiplier tube in the dark immediately before use may minimize this source of noise.

Three different figures of merit are used to characterize dark current noise using generalized methods rather than simply stating the dark current in amperes at a given high voltage. Equivalent anode dark current input (EADCI) characterizes the dark current for different values of anode sensitivity. EADCI is the value of the luminous flux incident on the photocathode required to produce an anode current equal to the observed dark current. It is the ratio of the dark current divided by the anode luminous sensitivity at a given high voltage. Units reported for EADCI are either in lumens, watts at the wavelength of maximum cathode responsivity, or watts at a specified wavelength. Equivalent noise input (ENI) may be a useful means to characterize noise if the light source is modulating and its bandwidth is known. ENI is the value of luminous flux which, when modulated in a known manner, produces an rms output current equal to the rms noise current within the specified bandwidth. Noise equivalent power (NEP) is very close to being the same as ENI, except units of power (watts) are used instead of luminous flux (lumens) to characterize the light incident on the photocathode.

Linearity

Linearity refers to the linear curve obtained when the logarithm of the anode output current is plotted against the logarithm of the incident luminous flux. This curve maintains a linear nature over several orders for magnitude of incident luminous flux. Saturation of the anode output occurs at very high levels of incident flux. This is generally caused by a space-charge limiting effect between the last two dynode stages between which the anode is situated and may be dependent on the design of the photomultiplier tube. Linearity may be extended by increasing the voltage difference between the last few dynodes compared to the voltage differences between the other dynodes.

Another cause for deviation from linearity is the use of an improper divider chain. Nonlinearity can result when the anode current is of the same order of magnitude as the divider chain current. The voltage divider should be designed for at least 10 times the current of the anticipated anode output to prevent this type of nonlinearity.

STABILITY

Magnetics

The gain stability of a photomultiplier tube is sensitive to changes in surrounding magnetic fields, including the earth's magnetic field. Magnetic fields can deflect the path of electrons moving inside the photomultiplier tube. The degree of sensitivity is dependent upon the design of the photomultiplier tube and its orientation in the magnetic field. Magnetic sensitivity is usually high for photomultiplier tubes used for scintillation counting because of long distances between the photocathode and first dynode. Stability is improved by enclosing the photomultiplier in high magnetic permeability metals called mu-metal shields for all types of photomultiplier tubes. These shields can be cylinders of foils or solid metal. Optimum stability is obtained when magnetic shields are at the same potential as the photocathode. Magnetic shields must be isolated electrically to prevent electrical shock hazard when the photomultiplier tube is operated with its photocathode at negative potential.

Fatigue and Drift

Photomultiplier tubes that operate under conditions of excessively high anode currents for long periods of time may exhibit an abnormal decrease in their anode sensitivity. This anode sensitivity decrease is referred to as fatigue (4). Fatigue of a photomultiplier tube is thought to be due to a degradation of the secondary electron emission process occurring on the dynode surfaces because of intense electron bombardment and surface dynode polarization (5,6). Electron bombardment may result in cesium migration from the surface of the dynode that causes a decrease in secondary electron emission. Some photomultiplier tubes undergo less fatigue than others because of design or materials used in construction.

Drift is a change in anode output under normal conditions of constant photocathode illumination. Individual photomultiplier tubes may increase or decrease in gain during the drift measurement time period (7). Charging of the insulator elements internal to the photomultiplier tube after the light source is activated may cause short-term drift.

There is a generalized method developed to measure drift. This generalized method employs a light source providing a constant signal input to the photomultiplier tube. Drift is then quantified according to the relation (8)

$$\text{Drift} = \left(\sum_{l=1}^{n} |p - p(l)|/n \right) (100/p)$$

where p is the mean pulse height averaged over n readings, p is the pulse height at the lth reading, and n is the total number of readings. Characterization of drift using this expression usually commences after an initial stabilization time period of the photomultiplier tube. Readings are then taken at regular intervals thereafter.

Changes in the input signal count rate can produce shifts in the amount of charge per pulse at the anode output. This is particularly true in the case of scintillation counting. Count rate shifts may be due to the design of the voltage divider and the photomultiplier tube. The voltage between dynodes may vary with count rate if the voltage divider has too low a current that results in changing gain. Photomultiplier tubes employing different dynode materials and structures may have different count rate shift properties.

External gain correction circuitry may be required in photomultiplier tube applications which require a high degree of stability for long periods of time. This is especially the case when external environmental conditions such as ambient temperature are known to vary.

ADVANCED SECTION

Output Characteristics

The intensity and shape of the output pulse is dependent on the intensity and shape of the input pulse, internal photomultiplier tube resistance and capacitance, and total resistance and capacitance in the anode circuit when noise can be neglected. In general, the shape of the pulse viewed at the anode will take the form (9,10):

$$V(t) = (\alpha Q/C)(1/[\alpha - \tau])(e^{-\tau t} - e^{-\alpha t})$$

where $\tau = 1/RC$, R is the total anode output resistance, C is the total anode output capacitance, Q is the charge per pulse collected at the anode, α is the decay constant with units of inverse time for the input signal, and t is time. It is assumed that the input signal has an exponential decay of the form $e^{-\alpha t}$, the rise time is negligible with respect to the decay time, and the input pulse shape is not disturbed by the photomultiplier tube.

From this equation certain useful approximations can be deduced. The first is when $\tau \gg \alpha$. For this case the shape of the output pulse may be approximated by

$$V(\mathrm{t}) \sim (Q/C)(\alpha/\tau)(1 - e^{-\tau t})$$

for short time periods t, and by

$$V(t) \sim (Q/C)(\alpha/\tau)e^{-\alpha t}$$

for long time periods t.

In these situations the anode pulse has an amplitude proportional to Q, the rise time of the anode pulse has a shape dominated by τ, and the decay time of the anode pulse approximates the decay constant of the signal pulse for longer time periods t. The intensity of the anode output pulse is usually small.

The second useful approximation occurs when $\tau \ll \alpha$. For this case the shape of the output pulse may be approximated by

$$V(t) \sim (Q/C)(1 - e^{-\alpha t})$$

for short time periods t, and by

$$V(t) \sim (Q/C)e^{-\tau t}$$

for long time periods t.

In these situations the anode pulse has an amplitude proportional to Q, the rise time of the anode pulse is dominated by the decay constant of the signal pulse, and the decay time of the anode pulse is dominated by τ. The intensity of the anode output pulse is usually large.

The application of the pulse counting system may determine which of the two above approximations should be employed. The anode output pulse is proportional to Q in both of the above approximations. Circuits designed with $\tau \gg \alpha$ may be considered when it is necessary to learn the decay characteristics of the input signal by simply viewing the decay of the anode output pulse, and also in timing applications. However, the anode signal level is usually small, and the noise contribution of the measurement system should be kept at a minimum to keep the signal-to-noise ratio high. Circuits designed with $\tau \ll \alpha$ may be considered when high anode outputs are needed for signal processing and gain is at a premium. However, the pulse rate capabilities for these circuits may be limited since the decay time of the anode pulse may be longer than the decay time of the input signal.

Temporal Characteristics

Photomultiplier tubes are sometimes required to produce output pulses of specific temporal characteristics for applications requiring coincident and anti-coincident circuits. This is especially true in applications involving positron emission tomography (PET) and time of flight (TOF). Useful properties that describe temporal characteristics are rise time, fall time, transit time, and transit time spread. These properties are usually measured using a light pulse having the approximate shape of a delta function. Practical light sources producing light pulses approximately the shape of a delta function include light emitting diodes, mode-locked Lasers, and spark sources.

Rise time is the time required by the leading edge of the pulse to increase in magnitude from 10% to 90% of the maximum amplitude of the pulse as shown in Fig. 6. Fall time is the time required by the trailing edge of the pulse to decrease in magnitude from 90% to 10% of the maximum amplitude of the pulse.

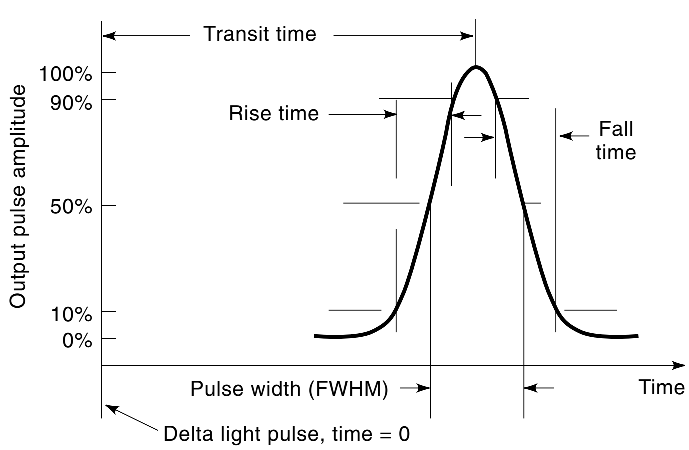

Figure 6. Timing definitions for the photomultiplier tube output pulse, referenced from the time that light arrives at the photocathode.

Transit time is the time interval between the arrival of the delta function light pulse at the photomultiplier tube entrance window and the time at which the output pulse at the anode reaches peak amplitude. Transit time varies considerably for spot source illumination across the face of the photocathode when the area of the spot source is much less than the active area of the photocathode. This is because the distance between different points on the photocathode and the first dynode varies, and the electric field intensity across the photocathode is not completely uniform, which results in different electron velocities. Transit-time difference is the time maximum difference between peak current outputs of different regions of the photocathode for simultaneous small spot illumination.

Transit time spread is the full-width half-maximum of the time distribution of a set of pulses, each of which corresponds to the photomultiplier tube transit time for that individual event. It is a measure of the distribution in time for a charge pulse when collected at the anode. Transit time spread is influenced by the same factors that cause differences in the transit time for spot illumination and by the number of photoelectrons. A photomultiplier tube with poor transit time spread characteristics may yield inferior time information since the pulse has been broadened in time.

Rise time, fall time, transit time, and transit time spread may be evaluated using a 50 Ω load at the anode output. With a 50 Ω load the output of the photomultiplier tube approximates a current pulse, which tends to preserve time information and helps to minimize electrical pulse reflections in the associated measuring electronics.

Scintillation Counting

One of the more important uses of photomultiplier tubes is their application in scintillation detectors for the measurement of ionizing radiation. A scintillation detector is a scintillator optically coupled to a photodetector, such as a photomultiplier tube or photodiode. A scintillator is a material that emits a light pulse when it absorbs ionizing radiation. The intensity and shape of the light pulse contains information on the ionizing radiation being absorbed in the scintillation material. Two of the more important solid scintillation materials presently used in fields of nuclear medical imaging are crystals of thallium-doped sodium iodide (NaI(Tl)) and bismuth germanium oxide ($Bi_4Ge_3O_{12}$). Presently, tens to hundreds of thousands of photomultiplier tubes are consumed for these commercial and academic purposes each year.

The scintillation detector produces a charge pulse output whose intensity is proportional to the energy of a totally absorbed gamma ray. This charge pulse is then processed, and information is extracted from the absorbed gamma ray, such as energy. The variance in the charge collected for successive pulses from the scintillation detector is an extremely important parameter to minimize since it affects the ability to resolve the energy of the gamma ray. Statistically, the variance in the charge per pulse output of the scintillation detector can be separated into components arising from the photomultiplier tube and scintillator and represented by the relationship (11):

$$\sigma^2(\mathrm{D}) = \sigma^2(\mathrm{S}) + \sigma^2(\mathrm{P})$$

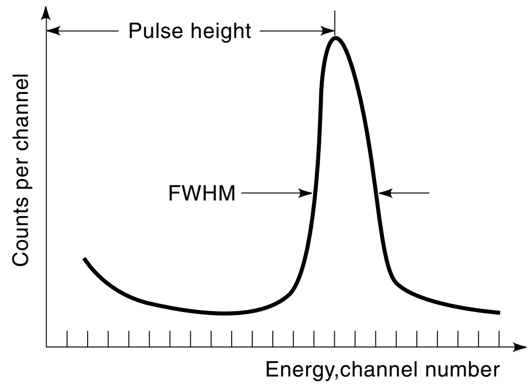

Figure 7. Energy distribution of photomultiplier output pulses as collected and displayed using a multichannel analyzer. Percent pulse height resolution (PHR) is a figure of merit calculated as 100 times the full-width half-maximum in channels divided by the pulse height in channels.

where σ(D) is the variance of the charge per pulse output of the detector, σ(S) represents the variance in the number of photons impinging on the photocathode from the scintillator, and σ(P) represents the variance on the number of electrons per charge pulse due to photomultiplier tube alone. Statistically, high photocathode quantum efficiency, good first dynode collection efficiency, and high first dynode gain are essential in reducing the variance on the charge per pulse collected at the anode (12).

Frequently the charge output of the scintillation detector is converted into a voltage pulse for processing. Variances in the charge per pulse then cause fluctuations in the magnitude of the resulting voltage pulses. Pulse height resolution (PHR) is a number used in nuclear spectroscopy to quantify these voltage fluctuations and is normally measured using a multichannel analyzer. The multichannel analyzer displays the accumulation of voltage pulses in the form of a photopeak. A photopeak is a histogram where the x axis represents voltage (proportional to gamma ray energy). The y axis of the histogram represents frequency of occurrence (number of counts per counting time interval per voltage increment). The position along the x axis for the centroid of the histogram usually represents the pulse height (mean value of voltage for a Gaussian shaped distribution corresponding to the energy of the gamma ray being measured). Referring to Fig. 7, PHR is calculated according to

$$\mathrm{PHR}(\%) = (\mathrm{FWHM}/\mathrm{PH}) \times 100$$

where FWHM is the full-width half-maximum of the histogram and PH is the position of the centroid. Mathematically, σ(D) and FHWM are directly proportional if sources of noise other than the detector can be neglected (10). Low PHR values are essential for the separation of photopeaks when gamma rays of many different energies are simultaneously present and to discriminate against lower-energy scattered gamma rays. This implies an advantage for low values of σ(P). Photomultiplier tube manufacturers will typically publish PHR numbers along with the conditions for which PHR is determined as a figure of merit for σ(P) to aid in the selection of photomultiplier tubes.

Future Developments

Future trends in photomultiplier tube applications involve the development of compact designs, position-sensitive photomultiplier tubes for nuclear medical imaging, microchannel plates, and hybrid photomultiplier tubes. Compact designs typically result in photomultiplier tubes whose overall length is shorter and weigh less than what is presently available (13). Position-sensitive photomultiplier tubes offer the prospect of providing discreet positional readout (14,15). Microchannel plates offer fast time response and insensitivity to magnetic fields (12). Hybrid photomultiplier tubes are compact devices consisting of an evacuated housing containing a window and photocathode where the photoelectrons are accelerated and impinge on a silicon target to create a charge output with gain (16).

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