I. INTRODUCTION

The widespread use of scintillation counting in radiation detection and spectroscopy would be impossible without the availability of devices to convert the extremely weak light output of a scintillation pulse into a corresponding electrical signal. The photomultiplier (PM) tube accomplishes this task remarkably well, converting light signals that typically consist of no more than a few hundred photons into a usable current pulse without adding a large amount of random noise to the signal. Although some applications of light-sensitive semiconductor diodes in scintillation counting have been reported\(^1,2\), the photomultiplier tube is almost universally used for this purpose. A great variety of commercially available PM tubes are sensitive to radiant energy in the ultraviolet, visible, and near infrared regions of the electromagnetic spectrum. They find many applications in optical spectroscopy, laser measurements, and astronomy. A useful review of PM tube properties and design characteristics can be found in Ref. 3. In this chapter the discussion is limited to those designs of primary interest for scintillation counting. Morton has recently published\(^4\) a very readable historical account of the development of tubes for this purpose. Useful guides and standards for the testing of PM tubes for scintillation counting have been developed as part of a series of such standards published\(^5\) by the IEEE.

The simplified structure of a typical photomultiplier tube is illustrated in Fig. 9-1. The two major elements consist of a photosensitive layer called the photocathode, coupled to an electron multiplier structure. The photocathode serves to convert as many of the incident light photons as possible into low-energy electrons. If the light consists of a pulse from a scintillation crystal, the photoelectrons produced will also be a pulse of similar time duration. Because only a few hundred photoelectrons may be involved in a typical pulse,
their charge is too small at this point to serve as a detectable electrical signal. The electron multiplier section in a PM tube provides an efficient collection geometry for the photoelectrons as well as serving as a near-ideal amplifier to greatly increase their number. After amplification through the multiplier structure, a typical scintillation pulse will give rise to $10^7$–$10^{10}$ electrons, sufficient to easily serve as the charge signal for the original scintillation event. This charge is conventionally collected at the anode or output stage of the multiplier structure.

Most photomultipliers perform this charge amplification in a very linear manner, producing an output pulse that remains proportional to the number of
original photoelectrons over a wide range of amplitude. Much of the timing information of the original light pulse is also retained. Typical tubes, when illuminated by a very short duration light pulse, will produce an electron pulse with a time width of a few nanoseconds after a delay time of 20-50 ns.

PM tubes are commercially available in a wide variety of sizes and properties. We begin our discussion with the important elements of PM tube design and their influence on overall performance.

II. THE PHOTOCATHODE

A. The Photoemission Process

The first step to be performed by the PM tube is the conversion of incident light photons into electrons. This process of photoemission can be thought of as occurring in three sequential stages: (1) the absorption of the incident photon and transfer of energy to an electron within the photoemissive material, (2) the migration of that electron to the surface, and (3) the escape of the electron from the surface of the photocathode.

The energy that can be transferred from the photon to an electron in the first step is given by the quantum energy of the photon \( \hbar \nu \). For blue light typical of that emitted by many scintillators, the quantum energy is about 3 eV. In step 2, some of that energy will be lost through electron-electron collisions in the migration process. Finally, in step 3, there must be sufficient energy left for the electron to overcome the inherent potential barrier which always exists at any interface between material and vacuum. This potential barrier (often called the “work function”) is normally greater than 3 or 4 eV for most metals, but can be as low as 1.5-2 eV for suitably prepared semiconductors.

From these energy considerations, some general comments can be made regarding photocathodes. First, the finite potential barrier in step 3 imposes a minimum energy on the incoming light photon even if all other energy losses are zero. All photocathodes will therefore have a long wavelength (small \( \nu \)) cutoff which will usually be in the red or near infrared portion of the spectrum. Even for higher energy light photons, the surface barrier should be as low as possible to maximize the number of escaping electrons. The rate of energy loss as the electron migrates to the surface should be kept small in order to maximize the depth in the material at which electrons may originate and still reach the surface with sufficient energy to overcome the potential barrier (called the “escape depth”). The rate of energy loss in metals is relatively high, and an electron can travel no more than a few nanometers before its energy drops below the potential barrier. Therefore, only the very thin layer of material lying within a few nanometers of the surface will contribute any photoelectrons from common metals. In semiconductors, the rate of energy loss is much lower and the escape depth can extend to about 25 nm. This, however, is still a very small thickness even with respect to stopping visible light. Photocathodes of this thickness are
semitransparent and will cause less than half the visible light to interact within the photosensitive layer. Therefore, such photocathodes cannot come close to converting all the visible light photons into electrons, no matter how low the potential barrier may be.

In order for an incident light photon to be absorbed in a semiconductor, its energy must exceed the bandgap energy \( E_g \). (For a discussion of the band structure in semiconductors, see Chapter 11.) The absorption process consists simply of elevating an electron from the normally populated valence band to the conduction band. Within about a picosecond, these electrons rapidly lose energy through phonon interactions with the crystal until their energy is at the bottom of the conduction band. In normal semiconductors, the electron potential outside the surface is higher than the bottom of the conduction band by an amount called the “electron affinity.” If an electron is to escape, it must reach the surface in the short time before phonon interactions have reduced its energy to the bottom of the conduction band. The electron, however, will remain at the bottom of the conduction band for perhaps another 100 ps before recombining with a hole and dropping to the valence band. The use of negative electron affinity materials, discussed more fully later in this chapter, leads to a much greater escape depth by allowing electrons that have dropped to the bottom of the conduction band to also escape if they reach the surface (see Fig. 9-4).

B. Thermionic Electron Emission

The surface potential barrier influences another important property of photocathodes: thermionic noise. Normal conduction electrons within the photocathode material will always have some thermal kinetic energy which, at room temperature, will average about 0.025 eV. There is a spread in this distribution, however, and those electrons at the extreme upper end of the distribution can occasionally have an energy that exceeds the potential barrier. If that electron is close enough to the surface, it may escape and give rise to a spontaneous thermally induced signal. In metals, the thermal emission rate is low (~100/m^2-s) because of the relatively high potential barrier. In semiconductors, the lower potential barrier leads to thermal emission rates as high as 10^6–10^8/m^2-s. Their superior photosensitivity is therefore achieved only at the price of a higher noise rate from thermally stimulated electron emission.

C. Fabrication of Photocathodes

Photocathodes can be constructed as either opaque or semitransparent layers. Each type is utilized in a somewhat different geometric arrangement. An opaque photocathode is normally fabricated with a thickness somewhat greater than the maximum escape depth, and is supported by a thick backing material. Photoelectrons are collected from the same surface on which the light is incident. Semitransparent photocathodes generally are no thicker than the escape depth and are deposited on a transparent backing (often the glass end window of the
PM tube). Light first passes through the transparent backing and subsequently into the photocathode layer, and photoelectrons are collected from the opposite surface. Because they are more readily adaptable to tube designs that use a flat end window, semitransparent photocathodes are more common in PM tubes designed for scintillation counters.

An important practical property of photocathodes is the uniformity to which their thickness can be held over the entire area of the photocathode. Variations in thickness give rise to corresponding changes in the sensitivity of the photocathode and can be one source of resolution loss in scintillation counters. This problem is especially serious for large-diameter photomultiplier tubes.

D. Quantum Efficiency and Spectral Response

The sensitivity of photocathodes can be quoted in several ways. When applied to dc light measurements, it is traditional to quote an overall photocathode efficiency in terms of current produced per unit light flux on its surface (amperes per lumen). A unit of greater significance in scintillation counting is the quantum efficiency (QE) of the photocathode. The quantum efficiency is simple defined as

\[
QE = \frac{\text{no. of photoelectrons emitted}}{\text{no. of incident photons}}
\]

The quantum efficiency would be 100 percent for an ideal photocathode. Because of the limitations mentioned earlier, practical photocathodes show maximum quantum efficiencies of 20-30 percent.

The quantum efficiency of any photocathode will be a strong function of wavelength or quantum energy of the incident light, as shown in Fig. 9-2. In order to estimate the effective quantum efficiency when used with a particular scintillator, these curves must be averaged over the emission spectrum of the scintillator. One consideration in selecting a photocathode is to match the spectral response curve as closely as possible to that of the emission spectrum of the scintillator being used.

The sensitivity at the long wavelength or low photon energy end of the scale is largely limited by the reduced absorption of light in the photocathode and the low energy imparted to the photoelectron. At a sufficiently high \( A \) this electron no longer has sufficient energy to escape the surface of the photocathode and the response drops to zero. The response at the opposite end of the scale is normally not a function of the photocathode itself but rather of the window through which the light must enter to reach the photoemissive layer. For normal glass, the cutoff will be at a wavelength in the region of 350 nm, which is usually adequate for most scintillation materials. For some scintillators (e.g., noble gases), however, a significant part of the emission spectrum can be in the ultraviolet region with shorter wavelength. For such applications, special photo-
multiplier tubes with entrance windows made from fused silica or quartz can be used to extend the sensitivity to wavelengths as short as about 160 nm.

Presently available materials for photocathodes include a “multi-alkali” material based on the compound Na₂K₃Sb. Prepared by activation with a small amount of cesium, this material was the first to show a relatively high quantum efficiency of up to 30 percent in the blue region of the spectrum. A later formulation based on K₂CsSb activated with oxygen and cesium is given the name “bi-alkali” and can show an even higher efficiency in the blue. Furthermore, thermonic emission from bi-alkali photocathodes tends to be significantly lower than that from the multi-alkali materials, leading to lower spontaneous noise rates from tubes with this photocathode. Negative electron affinity materia-
als are under active development as photocathodes and hold promise, for high quantum efficiency over a wide spectral range. Results reported on one of these materials, GaAs, show excellent efficiency well into the infrared region.

III. ELECTRON MULTIPLICATION

A. Secondary Electron Emission
The multiplier portion of a PM tube is based on the phenomenon of secondary electron emission. Electrons from the photocathode are accelerated and caused to strike the surface of an electrode, called a dynode. If the dynode material is properly chosen, the energy deposited by the incident electron can result in the re-emission of more than one electron from the same surface. The process of secondary electron emission is similar to that of photoemission discussed in the previous section. In this case, however, electrons within the dynode material are excited by the passage of the energetic electron originally incident on the surface rather than by an optical photon.

Electrons leaving the photocathode have a kinetic energy on the order of 1 eV or less. Therefore, if the first dynode is held at a positive potential of several hundred volts, the kinetic energy of electrons upon arrival at the dynode is determined almost entirely by the magnitude of the accelerating voltage. The creation of an excited electron within the dynode material requires an energy at least equal to the bandgap, which typically may be of the order of 2-3 eV. Therefore, it is theoretically possible for one incident electron to create on the order of 30 excited electrons per 100 volts of accelerating voltage. Because the direction of motion of these electrons is essentially random, many will not reach the surface before their de-excitation. Others that do arrive at the surface will have lost sufficient energy so that they cannot overcome the potential barrier at the surface, and are therefore incapable of escaping. Therefore, only a small fraction of the excited electrons ultimately contribute to the secondary electron yield from the dynode surface.

The secondary electron yield is a sensitive function of incident electron energy. If a relatively low-energy electron strikes the dynode surface, little energy is available for transfer to electrons in the dynode material, and relatively few electrons will be excited across the gap between the valence and conduction bands. At the same time, because the distance of penetration is not large, most of these excited electrons will be formed near the surface. For incident electrons of higher energy, more excited electrons will be created near the surface. For incident electrons of higher energy, more excited electrons will be created within the dynode but at a greater average depth. Because the probability of escape will diminish with increasing depth, the observed electron yield will be maximized at an optimum incident electron energy.

The overall multiplication factor for a single dynode is given by

$$\delta = \frac{\text{number of secondary electrons emitted}}{\text{primary incident electron}}$$

(9-2)
and should be as large as possible for maximum amplification per stage in the photomultiplier tube. A plot of $\delta$ versus incident electron energy is given in Fig. 9-3 for several dynode materials. For the conventional dynode materials of BeO, MgO, and CsSb, the maximum multiplication factor reaches about 10 for an optimum incident energy near 1 keV, although values of 4 to 6 are more typical at conventional interdynode voltages of a few hundred volts.

**B. Negative Electron Affinity Materials**

The introduction of negative electron affinity (NEA) dynode materials\(^7,8\) is a very significant recent development. The most successful of these materials has been gallium phosphide (GaP), heavily doped to a concentration of about $10^{19}$ atoms/cm\(^3\) with a p-type material such as zinc. The zinc creates acceptor sites within the bulk of the gallium phosphide. A thin, nearly monatomic layer of an electropositive material such as cesium is then applied to one surface. The acceptors at the surface attract an electron from the electropositive cesium, and each cesium atom becomes ionized and is held to the surface by electrostatic forces.

The effect of this surface treatment can best be illustrated through the band structure diagram shown in Fig. 9-4. At the left is shown a conventional band diagram for undoped gallium phosphide, which is also representative of conventional dynode materials. The series of arrows on the left shows a typical history of an electron that does not escape. The original excitation causes a number of electrons to be elevated from the valence band to some point well up into the conduction band. As these electrons diffuse, they lose energy primarily through phonon interactions, such that within about a picosecond, these “hot” electrons have come into thermal equilibrium with their local environment and their energy has relaxed to near the bottom of the conduction band. If this electron is to escape, it must reach the surface with an energy greater than the potential that exists on the vacuum side of the surface. Once the electron drops to the bottom of the conduction band, its energy is normally below the vacuum potential and is too low to permit escape. In this case only a short time is available for the electron to escape and it cannot travel large distances from its
point of origin. Therefore, relatively small escape depths of only a few nanometers are possible. However, the electron will tend to diffuse for a substantially longer time (typically 100 ps) before dropping across the gap to rejoin the valence band.

On the right is shown the band bending created by the filling of acceptor sites at the surface by the thin cesium layer. The effect of the bending is to bring the vacuum potential below that of the bottom of the conduction band in the interior of the material. Therefore, electrons that have already dropped to the bottom of the conduction band still have sufficient energy to escape if they happen to diffuse to the surface. Because the thickness of the bent-band region is very small, it can be less than a mean free path and the electron may escape without further energy loss in the surface region. The net effect is that the electrons that have already reached the bottom of the conduction band are still candidates for escape and remain so for a period of time which is about 100 times greater than in the previous case. The average escape depth will therefore tend to be much greater and can reach tens or hundreds of nanometers.

The effect of this change on the secondary electron yield is profound. The increased time over which electrons may escape enhances the escape probability for any typical electron. Furthermore, excited electrons created deep within the dynode material remain candidates for escape. Therefore, the secondary electron yield will continue to increase with increasing primary electron energy until the distance of penetration of the primary is very large. These effects are reflected in the yield curve for a GaP (Cs) dynode shown in Fig. 9-3. Secondary electron yields of 50 or 60 are readily achieved with an interstage voltage of 1000 volts, and much higher values are possible in principle if even larger voltages are permitted by the PM tube design.

A secondary advantage of NEA materials is evident in PM tubes used for ultrafast timing applications. Because almost all escaping electrons have previously dropped to the bottom of the conduction band, their average energy is lower and much more uniform than secondary electron energies from conventional materials. Because variations in initial energy contribute to the time spread in the multiplier section; a narrower distribution leads to lower time
broadening. Furthermore, the higher gain per stage permits a reduction in the number of stages required for a given total gain, also reducing the overall time spread.

The principles behind NEA materials are stressed here simply because their much improved properties have had a revolutionary influence on PM tube performance\textsuperscript{6–11} and are likely to have a major effect on future development. Because the performance of the first dynode is most important from a statistical point of view, early commercial emphasis has been on providing tubes with only the first dynode made from NEA material and the remainder of the dynodes from more conventional materials. Tubes with entire dynode structures of NEA materials are now available which can provide unique timing and statistical performance for demanding applications.

C. Multiple Stage Multiplication

In order to achieve electron gains on the order of $10^6$, all PM tubes employ multiple stages. Electrons leaving the photocathode are attracted to the first dynode and produce $\delta$ electrons for each incident photoelectron. The secondaries that are produced at the surface of the first dynode again have very low energies, typically a few eV. Thus they are quite easily guided by another electrostatic field established between the first dynode and a second similar dynode. This process can be repeated many times, with low-energy secondary electrons from each dynode accelerated toward the following dynode. If $N$ stages are provided in the multiplier section, the overall gain for the PM tube should be given simply by

$$\text{Overall gain} = \alpha \delta^N$$  \hspace{1cm} (9-3)

where $\alpha$ is the fraction of all photoelectrons collected by the multiplier structure. Conventional dynode materials are characterized by a typical value of $\delta = 5$, and $\alpha$ is near unity for well-designed tubes. Ten stages will therefore result in an overall tube gain of $5^{10}$, or about $10^7$. If high-yield NEA dynodes are used with $\delta = 55$, the same gain can be achieved with only four stages.

The overall gain of a PM tube is a sensitive function of applied voltage $V$. If $\delta$ were a linear function of interdynode voltage, then the overall gain of a 10-stage tube would vary as $V^{10}$. As shown in Fig. 9-3, however, $\delta$ for conventional dynodes varies as some fractional power of interdynode voltage so that the overall gain is more typically proportional to $V^6$ to $V^9$.

D. Statistics of Electron Multiplication

If $\delta$ were strictly a constant, each photoelectron would be subject to exactly the same multiplication factor. Under fixed operating conditions, all output pulses that originate from a single photoelectron would then have the same amplitude. In actuality, the emission of secondary electrons is a statistical process, and therefore the specific value of $\delta$ at a given dynode will fluctuate from event to
event about its mean value. The shape of the single photoelectron pulse-height spectrum observed from a real PM tube is an indirect measure of the degree of fluctuation in $\delta$, and has thus been the subject of extensive investigation.

In the most simple model, the production of secondary electrons at a dynode can be assumed to follow a Poisson distribution about the average yield. For a single photoelectron incident on the first dynode, the number of secondaries produced has a mean value of $\delta$ and standard deviation $\sigma$ of $\sqrt{\delta}$ (see Chapter

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**FIGURE 9-5.** Statistical broadening of the secondary electron yield from the first dynode of a PM tube. Numbers identify the number of incident photoelectrons. Two cases are shown representing conventional dynodes ($\delta = 5$) and NEA materials ($\delta = 26$).
4). The relative variance, defined as \((\sigma/\delta)^2\), is thus equal to \(1/\delta\). When this process is now compounded over \(N\) identical stages of the PM tube, the mean number of electrons collected at the anode (and hence the pulse amplitude) is given by \(\delta^N\). It can be demonstrated from the properties of Poisson statistics that the relative variance in this number is now

\[
\frac{1}{\delta} + \frac{1}{\delta^2} + \frac{1}{\delta^3} + \cdots + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1}
\]  

(9-4)

Thus, if \(\delta \gg 1\), the relative variance or spread in the output pulse amplitude is dominated by fluctuations in the yield from the first dynode where the absolute number of electrons is smallest.

In many applications of scintillators, hundreds or thousands of photoelectrons contribute to each pulse, and they are therefore much larger than single photoelectron pulses. When poor light collection or low energy radiations are involved, however, signal pulses corresponding to only a few photoelectrons may be involved. Then the fluctuations in electron multiplication may interfere with

FIGURE 9-6. The measured pulse height spectrum for weak scintillation events obtained from a RCA 8850 photomultiplier tube. The high-gain first dynode results in distinguishable peaks in the spectrum corresponding to one, two, and three photoelectrons per pulse. (From Houtermans\textsuperscript{12}.)

the ability to discriminate against noise events, many of which correspond to single photoelectrons. Figure 9-5 shows the expected distribution in the number of secondaries produced by the first dynode when struck by different numbers of photoelectrons. If the value of $\delta$ is small, it is impossible to cleanly separate the events caused by one photoelectron from those in which more photoelectrons are involved. If the dynodes are characterized by a larger value of $\delta$, however, the separation is much more distinct and it is possible to distinguish peaks in the distribution corresponding to discrete numbers of photoelectrons up to about 4 or 5. This behavior is demonstrated in Fig. 9-6 in the pulse height spectrum observed from a PM tube with a high-$\delta$ first dynode made from a NEA material.

Experimental measurements of the single photoelectron pulse-height spectra from PM tubes generally show a peaked distribution\textsuperscript{13,14}, but with a larger relative variance than that predicted by the Poisson model. In fact, observations made under some conditions show no peak at all, but rather an exponential-like distribution\textsuperscript{15}. These discrepancies have led to alternate models of the multiplication statistics in which a Polya distribution\textsuperscript{16} or compound Poisson\textsuperscript{17,18} is substituted for the simple Poisson description of electron multiplication. No universal descriptions have as yet emerged which can accommodate all experimental measurements, and it is possible that differences in specific electron trajectories and dynode properties may preclude a general model applicable to all PM tubes.

IV. PHOTOMULTIPLIER TUBE CHARACTERISTICS

A. Structural Differences

Figure 9-7 shows some representative construction details of photomultiplier tubes of various designs. All consist of a semitransparent photocathode, a photoelectron collection region between the photocathode and the first dynode, a multistage electron multiplier section, and an anode for collection of the amplified charge. These structures are enclosed in a glass vacuum envelope, through which electrical leads are conducted at the base. Tubes with flat end plate windows are the only types now in general use for scintillation counting, so cylindrical scintillation crystals can be easily mounted directly on the end window adjacent to the photocathode.

The “Venetian blind” type of construction is one of the oldest used for photomultiplier tubes. It is readily adaptable to tubes of varying numbers of stages, but suffers from a relatively slow response time due to low electric fields at the surface of the dynodes. The “box and grid” structure is also fairly old and slow. The circular grid and linear multiplier structures were introduced to speed up the electron transit time through the multiplier structure and are used in those PM tubes with the fastest response time.