CHAPTER 2
BASIC PRINCIPLES OF PHOTOMULTIPLIER TUBES [1)-5)]

A photomultiplier tube is a vacuum tube consisting of an input window, a photocathode, focusing electrodes, an electron multiplier and an anode usually sealed into an evacuated glass tube. Figure 2-1 shows the schematic construction of a photomultiplier tube.

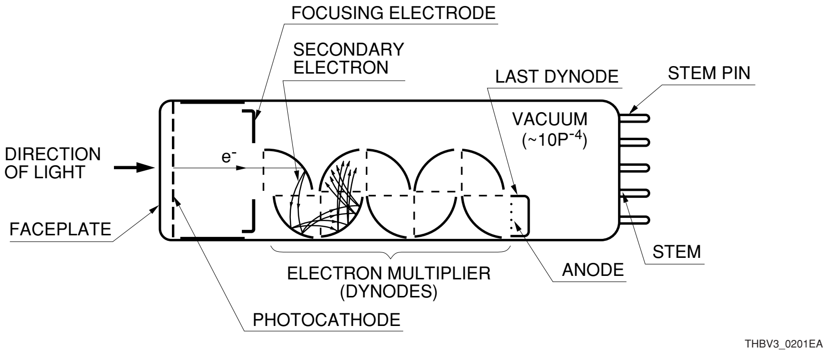

Figure 2-1: Construction of a photomultiplier tube

Light which enters a photomultiplier tube is detected and produces an output signal through the following processes.

(1) Light passes through the input window.

(2) Light excites the electrons in the photocathode so that photoelectrons are emitted into the vacuum (external photoelectric effect).

(3) Photoelectrons are accelerated and focused by the focusing electrode onto the first dynode where they are multiplied by means of secondary electron emission. This secondary emission is repeated at each of the successive dynodes.

(4) The multiplied secondary electrons emitted from the last dynode are finally collected by the anode.

This chapter describes the principles of photoelectron emission, electron trajectory, and the design and function of electron multipliers. The electron multipliers used for photomultiplier tubes are classified into two types: normal discrete dynodes consisting of multiple stages and continuous dynodes such as microchannel plates. Since both types of dynodes differ considerably in operating principle, photomultiplier tubes using microchannel plates (MCP-PMTs) are separately described in Chapter 10. Furthermore, electron multipliers for various particle beams and ion detectors are discussed in Chapter 12.

2.1 Photoelectron Emission[6) 7)]

Photoelectric conversion is broadly classified into external photoelectric effects by which photoelectrons are emitted into the vacuum from a material and internal photoelectric effects by which photoelectrons are excited into the conduction band of a material. The photocathode has the former effect and the latter are represented by the photoconductive or photovoltaic effect.

Since a photocathode is a semiconductor, it can be described using band models as shown in Figure 2-2: (1) alkali photocathode and (2) III-V compound semiconductor photocathode.

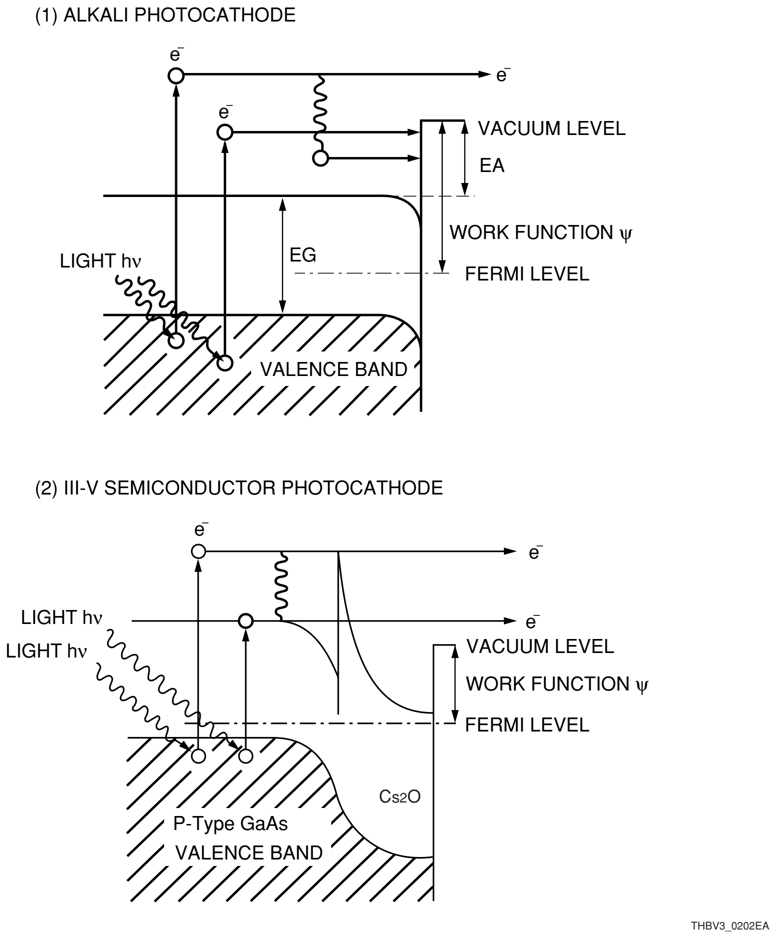

Figure 2-2: Photocathode band models

In a semiconductor band model, there exist a forbidden-band gap or energy gap (EG) that cannot be occupied by electrons, electron affinity (EA) which is an interval between the conduction band and the vacuum level barrier (vacuum level), and work function (ψ) which is an energy difference between the Fermi level and the vacuum level. When photons strike a photocathode, electrons in the valence band absorb photon energy ($h\nu$) and become excited, diffusing toward the photocathode surface. If the diffused electrons have enough energy to overcome the vacuum level barrier, they are emitted into the vacuum as photoelectrons. This can be expressed in a probability process, and the quantum efficiency $\eta(\nu)$, i.e., the ratio of output electrons to incident photons is given by

$$\eta(\nu) = (1-R)\, \frac{P\nu}{k} \cdot \left(\frac{1}{1+1/kL}\right) \cdot Ps$$

where

R : reflection coefficient
k : full absorption coefficient of photons
Pν : probability that light absorption may excite electrons to a level greater than the vacuum level
L : mean escape length of excited electrons
Ps : probability that electrons reaching the photocathode surface may be released into the vacuum
ν : frequency of light

In the above equation, if we have chosen an appropriate material which determines parameters R, k and Pν, the factors that dominate the quantum efficiency will be L (mean escape length of excited electrons) and Ps (probability that electrons may be emitted into the vacuum). L becomes longer by use of a better crystal and Ps greatly depends on electron affinity (EA).

Figure 2-2 (2) shows the band model of a photocathode using III-V compound semiconductors.[8)-10)] If a surface layer of electropositive material such as Cs_2O is applied to this photocathode, a depletion layer is formed, causing the band structure to be bent downward. This bending can make the electron affinity negative. This state is called NEA (negative electron affinity). The NEA effect increases the probability (Ps) that the electrons reaching the photocathode surface may be emitted into the vacuum. In particular, it enhances the quantum efficiency at long wavelengths with lower excitation energy. In addition, it lengthens the mean escape distance (L) of excited electrons due to the depletion layer.

Photocathodes can be classified by photoelectron emission process into a reflection mode and a transmission mode. The reflection mode photocathode is usually formed on a metal plate, and photoelectrons are emitted in the opposite direction of the incident light. The transmission mode photocathode is usually deposited as a thin film on a glass plate which is optically transparent. Photoelectrons are emitted in the same direction as that of the incident light. (Refer to Figures 2-3, 2-4 and 2-5.) The reflection mode photocathode is mainly used for the side-on photomultiplier tubes which receive light through the side of the glass bulb, while the transmission mode photocathode is used for the head-on photomultiplier tubes which detect the input light through the end of a cylindrical bulb.

The wavelength of maximum response and long-wavelength cutoff are determined by the combination of alkali metals used for the photocathode and its fabrication process. As an international designation, photocathode sensitivity[11)] as a function of wavelength is registered as an "S" number by the JEDEC (Joint Electron Devices Engineering Council). This "S" number indicates the combination of a photocathode and window material and at present, numbers from S-1 through S-25 have been registered. However, other than S-1, S-11, S-20 and S-25 these numbers are scarcely used. Refer to Chapter 4 for the spectral response characteristics of various photocathodes and window materials.

2.2 Electron Trajectory

In order to collect photoelectrons and secondary electrons efficiently on a dynode and also to minimize the electron transit time spread, electrode design must be optimized through an analysis of the electron trajectory.[12)-16)]

Electron movement in a photomultiplier tube is influenced by the electric field which is dominated by the electrode configuration, arrangement, and also the voltage applied to the electrode. Numerical analysis of the electron trajectory using high-speed, large-capacity computers have come into use. This method divides the area to be analyzed into a grid-like pattern to give boundary conditions, and obtains an approximation by repeating computations until the error converges to a certain level. By solving the equation for motion based on the potential distribution obtained using this method, the electron trajectory can be predicted.

When designing a photomultiplier tube, the electron trajectory from the photocathode to the first dynode must be carefully designed in consideration of the photocathode shape (planar or spherical window), the shape and arrangement of the focusing electrode and the supply voltage, so that the photoelectrons emitted from the photocathode are efficiently focused onto the first dynode. The collection efficiency of the first dynode is the ratio of the number of electrons landing on the effective area of the first dynode to the number of emitted photoelectrons. This is usually better than 60 to 90 percent. In some applications where the electron transit time needs to be minimized, the electrode should be designed not only for optimum configuration but also for higher electric fields than usual.

The dynode section is usually constructed from several to more than ten stages of secondary-emissive electrodes (dynodes) having a curved surface. To enhance the collection efficiency of each dynode and minimize the electron transit time spread, the optimum configuration and arrangement should be determined from an analysis of the electron trajectory. The arrangement of the dynodes must be designed in order to prevent ion or light feedback from the latter stages.

In addition, various characteristics of a photomultiplier tube can also be calculated by computer simulation. For example, the collection efficiency, uniformity, and electron transit time can be calculated using a Monte Carlo simulation by setting the initial conditions of photoelectrons and secondary electrons. This allows collective evaluation of photomultiplier tubes. Figures 2-3, 2-4 and 2-5 are cross sections of photomultiplier tubes having a circular-cage, box-and-grid, and linear-focused dynode structures, respectively, showing their typical electron trajectories.

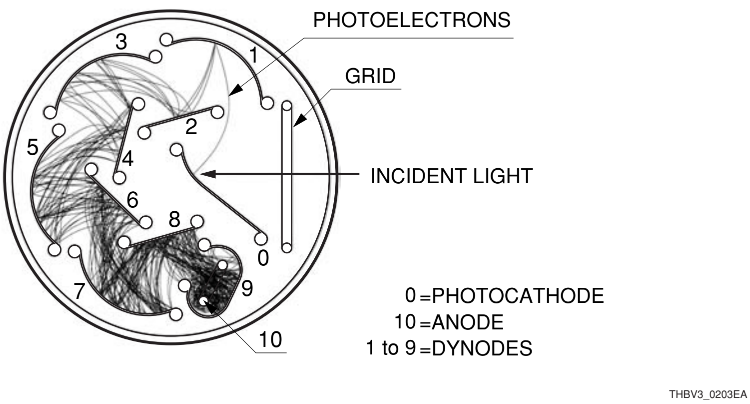

Figure 2-3: Circular-cage type

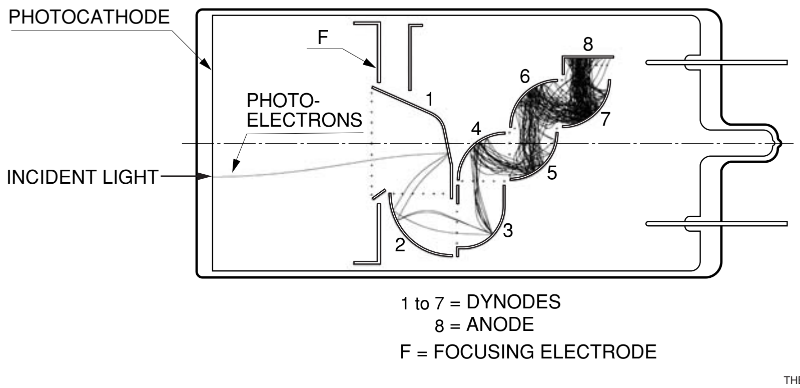

Figure 2-4: Box-and-grid type

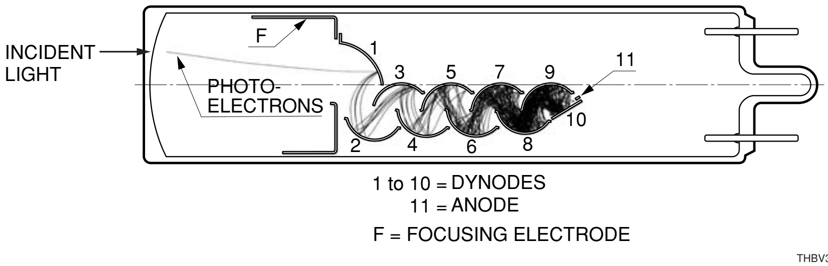

Figure 2-5: Linear-focused type

2.3 Electron Multiplier (Dynode Section)

As stated above, the potential distribution and electrode structure of a photomultiplier tube is designed to provide optimum performance. Photoelectrons emitted from the photocathode are multiplied by the first dynode through the last dynode (up to 19 dynodes), with current amplification ranging from 10 to as much as 108 times, and are finally sent to the anode.

Major secondary emissive materials[17)-21)] used for dynodes are alkali antimonide, beryllium oxide (BeO), magnesium oxide (MgO), gallium phosphide (GaP) and gallium phosphide (GaAsP). These materials are coated onto a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. Figure 2-6 shows a model of the secondary emission multiplication of a dynode.

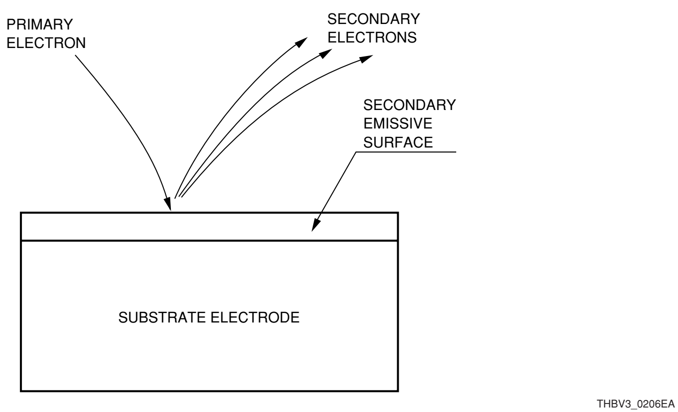

Figure 2-6: Secondary emission of dynode

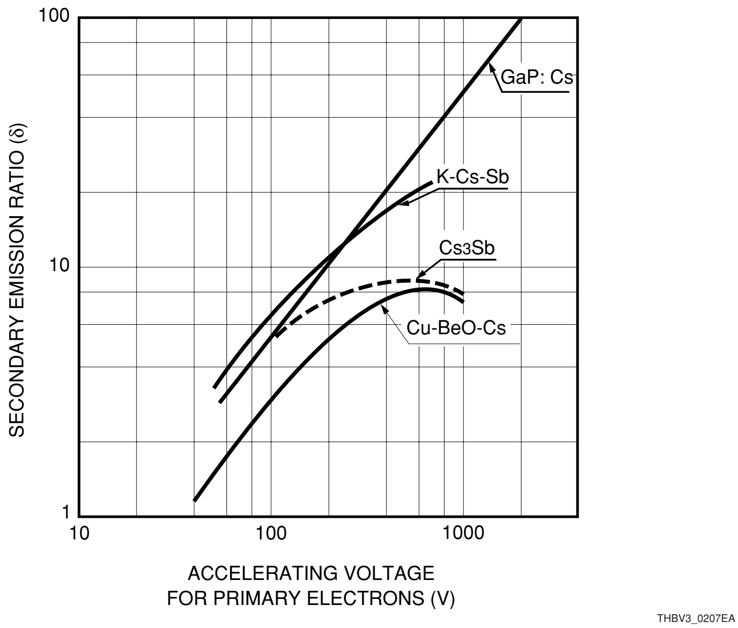

Figure 2-7: Secondary emission ratio

When a primary electron with initial energy Ep strikes the surface of a dynode, δ secondary electrons are emitted. This δ, the number of secondary electrons per primary electron, is called the secondary emission ratio. Figure 2-7 shows the secondary emission ratio δ for various dynode materials as a function of the accelerating voltage for the primary electrons.

Ideally, the current amplification or gain of a photomultiplier tube having the number of dynode stages n and the average secondary emission ratio δ per stage will be δ^n. Refer to section 4.2.2 in Chapter 4 for more details on the gain.

Because a variety of dynode structures are available and their gain, time response and linearity differ depending on the number of dynode stages and other factors, the optimum dynode type must be selected according to your application. These characteristics are described in Chapter 4, section 4.2.1.

2.4 Anode

The anode of a photomultiplier tube is an electrode that collects secondary electrons multiplied in the cascade process through multi-stage dynodes and outputs the electron current to an external circuit.

Anodes are carefully designed to have a structure optimized for the electron trajectories discussed previously. Generally, an anode is fabricated in the form of a rod, plate or mesh electrode. One of the most important factors in designing an anode is that an adequate potential difference can be established between the last dynode and the anode in order to prevent space charge effects and obtain a large output current.

References in Chapter 2

1) Hamamatsu Photonics: "Photomultiplier Tubes and Related Products" (revised Feb. 2006)
2) Hamamatsu Photonics: "Characteristics and Uses of Photomultiplier Tubes" No.79-57-03 (1982).
3) S.K. Poultney: Advances in Electronics and Electron Physics 31, 39 (1972).
4) D.H. Seib and L.W. Ankerman: Advances in Electronics and Electron Physics, 34, 95 (1973).
5) J.P. Boutot, et al.: Advances in Electronics and Electron Physics 60, 223 (1983).
6) T. Hiruma: SAMPE Journal, 24, 6, 35-40 (1988).
7) T. Hayashi: Bunkou Kenkyuu, 22, 233 (1973).
8) H. Sonnenberg: Appl. Phys. Lett., 16, 245 (1970).
9) W.E. Spicer, et al.: Pub. Astrom. Soc. Pacific, 84, 110 (1972).
10) M. Hagino, et al.: Television Journal, 32, 670 (1978).
11) A. Honma: Bunseki, 1, 52 (1982).
12) K.J. Van Oostrum: Philips Technical Review, 42, 3 (1985).
13) K. Oba and Ito: Advances in Electronics and Electron Physics, 64B, 343.
14) A.M. Yakobson: Radiotekh & Electron, 11, 1813 (1966).
15) H. Bruining: Physics and Applications of Secondary Electron Emission, (1954).
16) J. Rodney and M. Vaughan: IEEE Transaction on Electron Devices, 36, 9 (1989).
17) B. Gross and R. Hessel: IEEE Transaction on Electrical Insulation, 26, 1 (1991).
18) H.R. Krall, et al.: IEEE Trans. Nucl. Sci. NS-17, 71 (1970).
19) J.S. Allen: Rev. Sci. Instr., 18 (1947).
20) A.M. Tyutikov: Radio Engineering And Electronic Physics, 84, 725 (1963).
21) A.H. Sommer: J. Appl. Phys., 29, 598 (1958).

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