7 Photomultiplier tubes

Photomultiplier tubes (PMTs) are extremely sensitive detectors of light in the ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum. These detectors multiply the current produced by incident light by as much as 100 million times, in multiple dynode stages, enabling individual photons to be detected when the incident amount of light is low. Fig. 7.1 shows a schematic diagram of a PMT.

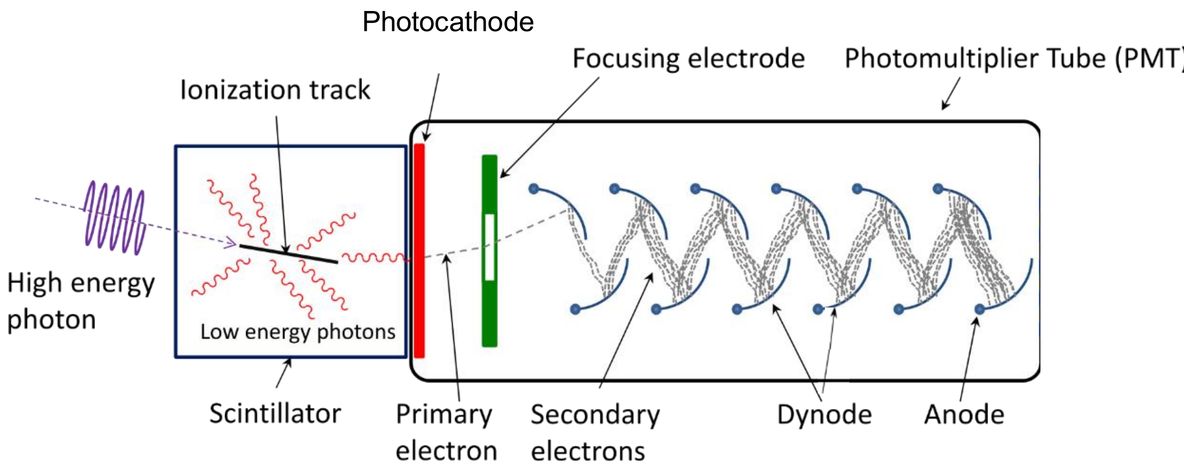

Fig. 7.1

<u>Principle of operation of a PMT</u>

Photomultipliers are typically constructed with an evacuated glass housing (using an extremely tight and durable glass-to-metal seal like other vacuum tubes), containing a photocathode, several dynodes, and an anode.

Incident photons strike the photocathode material, which is usually a thin vapour–deposited conducting layer on the inside of the entry window of the device. Electrons are ejected from the surface as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission.

The PMT consists of a number of electrodes called *dynodes*. Each dynode is held at a more positive potential, by approximately 100 volt, than the preceding one.

A primary electron leaves the photocathode with the energy of the incoming photon, of about 3 eV for "blue" photons, minus the work function of the photocathode. A small group of primary electrons is created by the arrival of a group of initial photons. The primary electrons move toward the first dynode because they are accelerated by the electric field.

They each arrive with approximately 100 eV kinetic energy imparted by the potential difference. Upon striking the first dynode, more low energy electrons are emitted, and these electrons are in turn accelerated toward the second dynode.

The geometry of the dynode chain is such that a cascade occurs with an exponentially-increasing number of electrons being produced at each stage. This last stage is called the anode. This large number of electrons reaching the anode results in a sharp current pulse that is easily detectable, signaling the arrival of the photon(s) at the photocathode approximately 50 nanoseconds earlier.

The detected current depends on two factors: the number of electrons ejected from the photocathode (which in turn depends on the number of incoming photons and on their energy), and the Quantum Efficiency η of the photomultiplier. The Quantum Efficiency is defined as the number of electrons collected at the anode per unit time relative to the number of incident photons per unit time on the photocathode expressed as a percentage.

Fig. 7.2 shows the graph of photocathode responsivity R versus wavelength of incident light λ and some of Quantum Efficiency (QE) lines of a metal used as photocathode in the PMT. The intersections of the graph and the QE lines show the Quantum Efficiencies at various wavelengths.

For example, when the graph and the QE lines intersect at M as shown in Fig. 7.2, it means that the number of electrons collected at the anode per unit time is 10% of the total number of incident photons per unit time when a light of 510 nm is incident on the photocathode.

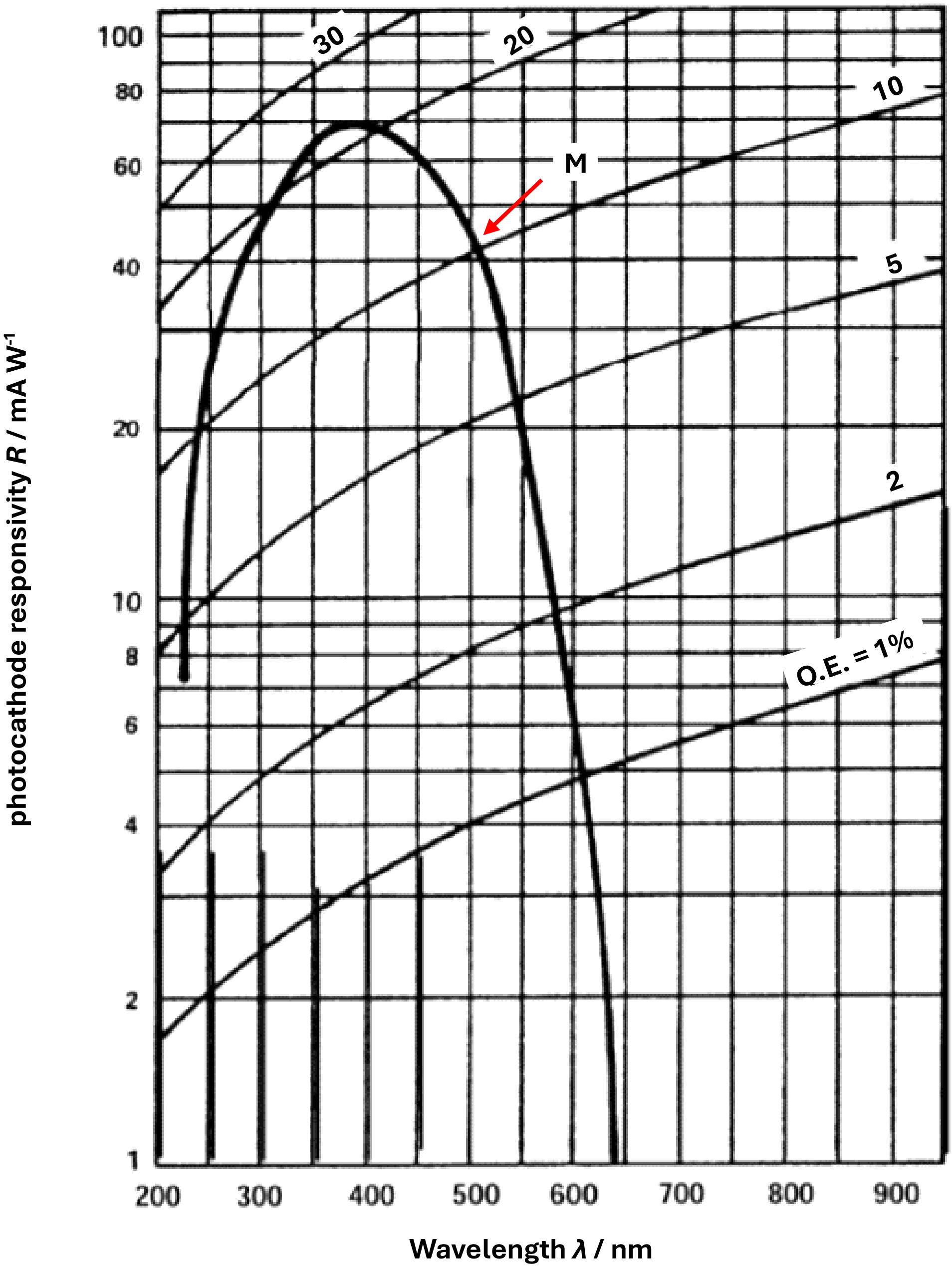
30
20
10
M
5
2
O.E. = 1%
100
80
60
40
20
10
8
6
4
2
1
200
300
400
500
600
700
800
900
photocathode responsivity R / mA W-1
Wavelength λ / nm

Fig 7.2

(a) **(i)** Explain what is meant by the term photoelectric effect.

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....[1]

(ii) State the wavelength that allows the photocathode to achieve its optimum responsivity.

wavelength = ... nm [1]

(iii) With reference to Fig. 7.2, state the threshold wavelength and explain how it was determined.

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....[2]

(iv) The photocathode has a threshold frequency of 4.76×10^{14} Hz.

If a photomultiplier detects radiation of 450 nm, calculate the maximum speed of the photoelectron emitted from the photocathode.

maximum speed = ……………………… m s^{-1} [3]

(v) Explain clearly why the photocathode used in a photomultiplier should preferably be one with a low work function.

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(b) Light of wavelength 610 nm is now incident on the PMT.

(i) Given that the detected current from the PMT is 7.8×10^{-4} A, calculate the number of electrons per unit time reaching the anode.

number of electrons per unit time = ... s^{-1} [2]

(ii) Hence, using Fig. 7.2, calculate the number of incident photons per unit time on the photocathode.

number of incident photons per unit time = ... s^{-1} [1]

(iii) From Fig. 7.2, the photocathode responsivity of the PMT can be estimated to be 4.8 mA W^{-1}. Use your understanding of current and power, suggest the meaning of 4.8 mA W^{-1}

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....[1]

(c) **(i)** The relationship between Responsivity R and Quantum Efficiency η is stated as

$$\eta = \frac{Rhc}{e\lambda}$$

where λ is the wavelength of the incident light, h is the Planck constant and e is the elementary charge.

Using Fig. 7.2, show that for the photocathode used in the PMT, this relationship is true when η is 5 %.

[2]

(ii) Using the equation given in **(c)(i)**, complete Fig. 7.3.

η / %	λ / nm	R / mA W^{-1}
3	300	7.2
3	400	

3	500	12
3	600	
3	700	17

Fig. 7.3

[2]

(iii) Hence, plot the line η = 3 % on Fig. 7.2. [2]

(d) **(i)** Photomultipliers are usually shielded by a layer of soft iron at cathode potential. The external shield must also be electrically insulated.

Suggest why photomultipliers are electrically insulated.

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....[1]

(ii) Suggest a possible application of photomultiplier that can be used in the industry.

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....[1]

[Total: 20]

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