

CHAPTER II

PHOTO-CELLS FOR THE VISIBLE AND ULTRA-VIOLET

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1. INTRODUCTION

PHOTO-ELECTRIC cells are devices in which the absorption of electromagnetic radiation in the visible, infra-red or ultra-violet range of the spectrum causes electrons to be liberated from a surface or causes either a change in the electrical conductivity of a material or an electro-motive force to be set up. The first-mentioned effect is called the photo-emissive or external photo effect, the second one the photo-conductive or internal photo effect, and the third one the photo-voltaic effect.

In this chapter we shall confine ourselves to the discussion of photo-cells which are sensitive mainly to the visible and ultra-violet part of the spectrum.

2. PHOTO-EMISSIVE CELLS

(a) HISTORY

The photo-emissive effect is observed on the surface of metals or metal compounds. It was discovered by Hertz¹ in the course of experiments on electrical resonance of tuned spark gaps. Soon afterwards, Hallwachs² discovered that ultra-violet illumination of a freshly scraped zinc or aluminium plate caused the liberation of negative charges from it. Stoletov³ observed that a battery could maintain a continuous current between two such electrodes, when the negative electrode was illuminated with the ultra-violet light. Elster and Geitel⁴ made cells with amalgams of sodium and potassium. They also arranged their electrodes in evacuated glass bulbs and can thus be called the first producers of modern photo-cells.

(b) THEORY OF PHOTO-EMISSION

Fig. 31 shows a diagram of the basic design and circuit of a photo-emissive cell. A bulb 1 contains two electrodes; the cathode 2, and the anode or collector 3. The cathode is connected to the negative terminal of a battery 4, the anode to the positive terminal through a galvanometer 5. As soon as light falls on the photo-sensitive surface, electrons are liberated from it. Thus, electrons are accelerated towards the anode by the electrostatic field and a current begins to flow in the circuit. When the current

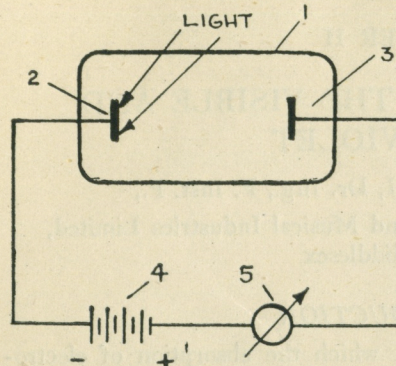


Fig. 31. Photo-cell and circuit. 1 glass envelope; 2 cathode; 3 anode; 4 battery; 5 galvanometer.

is measured and plotted as a function of the potential difference between cathode and anode, while the cathode is illuminated with monochromatic light, the curves shown in Fig. 32 are obtained. The potential of the anode with respect to that of the cathode is plotted as abscissa, and the photo-current as ordinate. The parameter is the light flux intercepted by the photo-cathode. The solid line curves are obtained for illumination with red light, the broken lines for green light and the dotted lines for blue light. The curves show that for a sufficiently positive potential

on the anode the electron current reaches saturation for a given light flux. This saturation value is strictly proportional to the light flux. A decreasing number of electrons continues to reach the collector, even when it is made increasingly negative with respect to the cathode, until beyond a

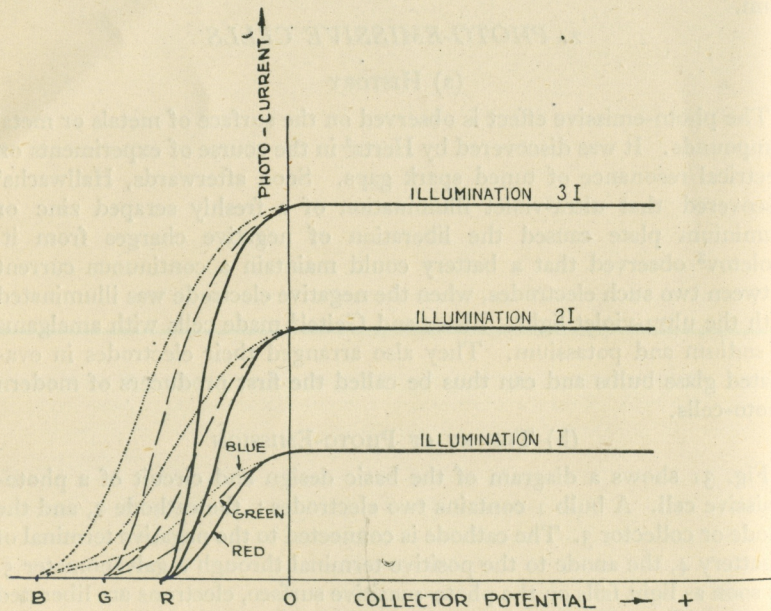


Fig. 32. Current-voltage characteristics of photo-emissive cell for three colours of monochromatic light and three different illuminations.

certain negative potential no electrons are collected at all. The value of this critical potential was found to depend on the colour of the light, but not on its intensity.⁵ The higher the frequency of the light, the more negative is the critical potential as shown by the broken and dotted lines in Fig. 32, where R, G, and B are the threshold values for red, green and blue light respectively. This behaviour indicates that the photo-electrons are emitted with varying kinetic energies which enable them to reach the collector electrode against a retarding electrostatic field.

The photo-emissive effect is practically instantaneous. The time interval between the absorption of the light and the emission of a photo-electron is, according to measurements⁶, certainly less than 3×10^{-9} sec.

Within wide limits, the emission is independent of the temperature. None of these experimentally determined facts is reconcilable with classical physics, according to which, for instance, the emission energy of the photo-electrons and not their number should be a function of the light intensity. Moreover, calculations based on a uniform absorption of radiant energy continuously distributed over the wave front would postulate an enormous lag between the time of light absorption and the time of the emission of the photo-electron at low light intensities.⁷ In 1905, Einstein⁸ took the momentous step of applying the quantum theory to the photo-electric effect in order to overcome the difficulties experienced by classical physics. According to the quantum theory, light consists of discrete quanta or photons. The energy of a photon is :

$$E_{ph} = h\nu$$

where $h = 6.624 \times 10^{-27}$ erg. sec. is Planck's constant and ν is the frequency of light in c.p.s.

Einstein postulated that light energy is absorbed in a quantised manner, the energy of each photon being completely transformed into kinetic energy of an electron inside the metal. The electron, by absorbing the energy from the photon, acquires sufficient energy to overcome the potential barrier at the surface of the metal and escape. Einstein formulated this conception in his photo-electric equation ;

$$E_{el} \leq h\nu - e\phi \dots\dots\dots(1)$$

where E_{el} is the emission energy of the photo-electron ; $e = 1.60 \times 10^{-20}$ e.m.u. is the charge of the electron ; ϕ is a measure of the energy required to overcome the potential barrier at the metal surface (generally called the work function of the material). According to this equation, the energy of the photo-electron after leaving the cathode is equal to the difference between the energy of the photon and the energy expended in surmounting the potential barrier at the surface. The

inequality sign takes into account the possibility that the electron may not travel in a direction normal to the metal surface. If equation (1) were strictly true, no electrons should have kinetic energies greater than $h\nu - e\phi$. However, according to theoretical considerations⁹ of the energy distribution of the electrons inside the metal at room temperature, some electrons are able to leave the cathode with higher energies, but this is a second order effect and we shall not deal with it in more detail. Substituting numerical values for h and e and substituting $\frac{c}{\lambda} = \nu$ where $c = 3 \times 10^{10}$ cm. sec.⁻¹ is the velocity of light, we can write equation (1) as follows :

$$E = \frac{12.3 \times 10^3}{\lambda} - \phi \dots\dots\dots(2)$$

where E is now the voltage to which the emission energy of the photo-electrons corresponds ; λ the wavelength of the light in \AA ; ϕ the work function of the cathode material in volts.

Furthermore, it follows from Einstein's equation that for each type of photo-cathode there exists a long-wave "threshold" wavelength of the exciting light beyond which electrons do not acquire enough energy to leave the cathode surface. We can calculate this threshold wavelength by putting $E = 0$ in equation (2) and obtain :

$$\lambda_t = \frac{12.3 \times 10^3}{\phi} \text{ \AA} \dots\dots\dots(3)$$

The lower the work function ϕ , the further the threshold is shifted towards longer wavelengths. This fact has important applications to photo-cells sensitive to infra-red radiation which are treated in Chapter 3. From equation (3) it also follows that photo-surfaces which are to respond to long-wave radiation at the red end of the spectrum (for example, $\lambda > 7,000 \text{ \AA}$), must have a work function :

$$\phi < \frac{12.3 \times 10^3}{7,000} = 1.75 \text{ v}$$

We see that one of the conditions for photo-emission in the visible spectrum is comparatively low work function. Moreover, the material constituting the photo-cathode should be able to absorb as much light as possible to transform it into kinetic energy of the electrons. Therefore, an efficient photo-emissive layer will be neither highly reflective nor highly transparent. Another condition for efficient photo-emission

is, of course, that the atoms of the cathode material part with electrons easily. This is the case for elements in the first column of the periodic system which have only one electron in their outer shells. Of these, again, the electrons in the outer shells of the heavier atoms will be removed more easily than those of the lighter atoms with fewer completed shells, because of the screening effect of the electrons in the inner shells on the electric field of the nucleus and because of the greater distances. Thus, the photo-electric effect was observed to occur most strongly with cathodes made of alkali-metals which are in the first column of the periodic system. Moreover, it was observed that both efficiency and long-wave threshold (being an indication of low work function) are improved within the column from the lighter to the heavier elements. The work function of a surface having a monatomic layer of one of these electro-positive materials adsorbed on a base metal is particularly low and, in fact, the silver-oxygen-caesium photo-cathode which is one of the most important types of photo-cathode, probably possesses such a layer.

(c) COLOUR RESPONSE AND EFFICIENCY

An important characteristic of photo-cells is their colour response. Photo-cells do not usually exhibit a uniform sensitivity over the whole spectrum but their response varies considerably with the wavelength of the light. In Fig. 33, spectral response curves for equal energy spectrum are

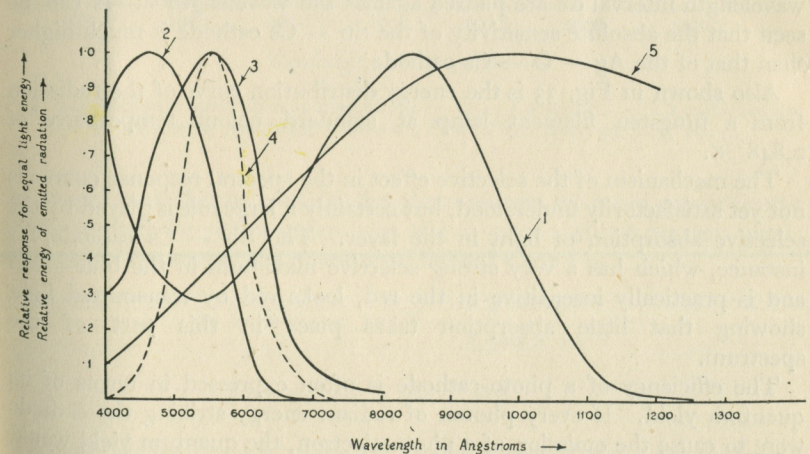


Fig. 33. Relative spectral response of various photocells for equal energy spectrum, and spectral emission of tungsten filament source. Peaks adjusted to unity. 1 Ag - O - Cs cell ; 2 Sb - Cs cell ; 3 EEL photovoltaic cell (courtesy of Evans Electro Selenium Ltd.) ; 4 response of human eye ; 5 spectral distribution of emission from tungsten filament at standard colour temperature of 2,848°K.

shown* for some representative types of photo-cells, both photo-emissive and photo-voltaic, in comparison with the spectral response curve of the human eye at high illumination, the so-called photopic luminosity curve. In this figure it is intended to show the relative distribution of the sensitivity of the various devices throughout the spectrum. Therefore, the maxima of their response curves have been made equal to unity. From Fig. 33 it can be seen that the response curves usually exhibit one or more selective maxima. The position and height of these maxima vary with the type of surface. Thus, the silver-oxygen-caesium cathode (hereafter called Ag — O — Cs cathode), has a long-wave maximum in the near infra-red round about 8,000 Å and a second one in the ultra-violet at about 3,500 Å, whereas the antimony-caesium cathode (Sb — Cs cathode) has its maximum sensitivity at about 4,600 Å, i.e., in the blue. The shape of the spectral response curve is important from the point of view of the use of the cells. Where measurements are to be made in the red and infra-red range of the spectrum or where the maximum radiation of the source is predominantly in that region, the Ag — O — Cs photo-cell is the most suitable photo-emissive cell,† whereas for most of the visible spectrum, i.e., for wavelengths below 6,500 Å and in the ultra-violet the Sb — Cs cathode is far superior. This can be seen from Fig. 34, where the absolute sensitivities of Ag — O — Cs and Sb — Cs photo-cathodes are plotted for "equal energy spectrum."²⁰ For this purpose, the photo-currents released per watt of incident radiant energy contained in a given small wavelength interval $d\lambda$ are plotted against the wavelength λ . It can be seen that the absolute sensitivity of the Sb — Cs cathode is much higher than that of the Ag — O — Cs cathode.

Also shown in Fig. 33 is the energy distribution curve of the radiation from a tungsten filament lamp at standard colour temperature of 2,848° K.

The mechanism of the selective effect in the spectral response curves is not yet satisfactorily understood, but certainly a large role is played by the selective absorption of light in the layer. The Sb — Cs cathode, for instance, which has a very strong selective maximum in the blue-green and is practically insensitive in the red, looks red by transmitted light showing that little absorption takes place in this part of the spectrum.

The efficiency of a photo-cathode is often expressed in terms of its quantum yield. If every photon of radiant energy striking the cathode were to cause the emission of a photo-electron, the quantum yield would

* The curves for the photovoltaic cell are by courtesy of Evans ElectroSelenium Ltd.

† For more detailed information on photo-conductive cells for the infra-red see Chapter 3.

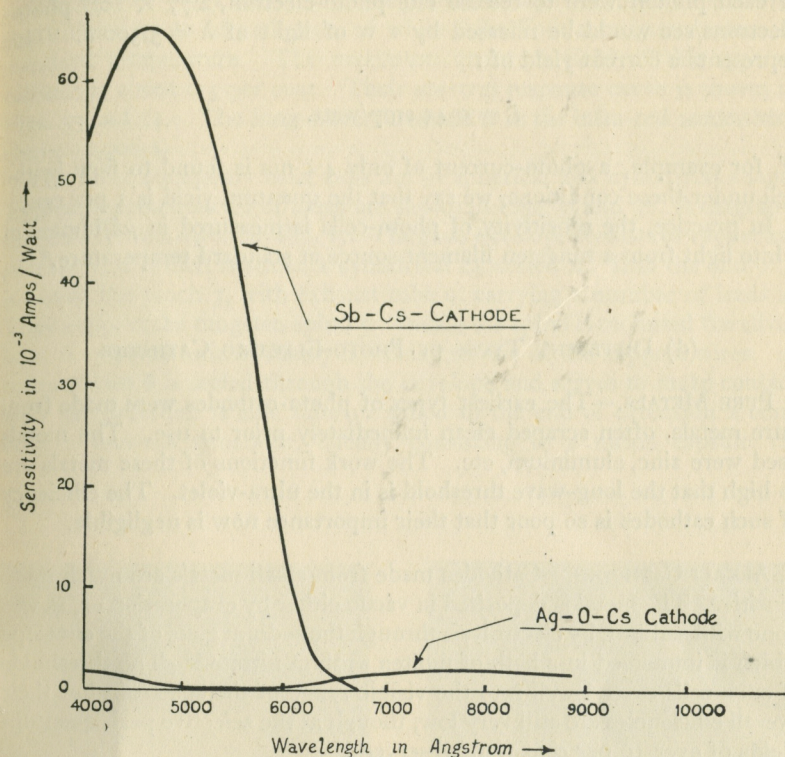


Fig. 34. Absolute spectral response of Ag — O — Cs and Sb — Cs cathodes for equal energy spectrum (*Sommer., Proc. Phys. Soc., 55, 145, 1943*).

be 100 per cent. Let us consider the photo-current we could expect from a photo-cathode for yellow-green light of $\lambda = 5,500$ Å at 100 per cent quantum yield. The energy of a quantum of light of 5,500 Å is

$$h\nu = 6.624 \times 10^{-27} \times \frac{3 \times 10^{10}}{5,500 \times 10^{-8}}$$

$$h\nu = 3.61 \times 10^{-12} \text{ erg.}$$

and therefore with 1 joule = 10^7 erg., 1 W of green light of 5,500 Å carries:

$$\frac{10^7}{3.61 \times 10^{-12}} = 2.77 \times 10^{18} \text{ photons/sec.}$$

If each photon were to release one photo-electron, 2.77×10^{18} photo-electrons/sec would be released by 1 w of light of $\lambda = 5,500 \text{ \AA}$. This represents a current yield of:

$$i = 0.44 \text{ amp/watt.}$$

If, for example, a photo-current of only 4.4 ma is found to flow in the cell under these conditions, we say that the quantum yield is 1 per cent.

In practice, the sensitivity of photo-cells is measured in $\mu\text{a/lumen}$ of white light from a tungsten filament source at standard temperature.*

(d) DIFFERENT TYPES OF PHOTO-ELECTRIC CATHODES

i. PURE METALS.—The earliest types of photo-cathodes were made from pure metals, often scraped clean immediately prior to use. The metals used were zinc, aluminium, etc. The work functions of these metals are so high that the long-wave threshold is in the ultra-violet. The efficiency of such cathodes is so poor that their importance now is negligible.

ii. ALKALI CATHODES.—Cathodes made from alkali metals are much more sensitive. The metal is deposited in vacuo either by evaporation or, as was done with sodium, by electrolysis through the sodium glass of the envelope which is immersed in a bath of molten sodium nitrate.¹⁰ The thresholds of such cells extend well into the visible range of the spectrum but their overall efficiencies are still very low, though at the selective peak quantum yields of over 10 per cent were observed.¹¹

iii. ALKALI-HYDRIDE CATHODES.—Certain alkali metal surfaces can be "sensitised" by forming hydrides in a hydrogen glow discharge.¹² Increases in sensitivity of the order of 40:1 have been achieved in this way. These surfaces usually show strong selective maxima. Their maximum response is in the blue and ultra-violet part of the spectrum. Due to their high work function, the dark currents from such surfaces are very low.† They are still used for measurements in the ultra-violet.

iv. COMPOSITE CATHODES.—The composite cathodes of the type where an alkali metal is deposited on a specially treated base layer of another metal can be considered the first of the modern photo-cells.^{13,14} Of these, the most generally used at present is the Ag — O — Cs cathode. Because of its great importance, its manufacture and properties will be described in more detail.

* See p. 58.

† See paragraph on dark currents, p. 74.

The Ag — O — Cs Cathode.—These photo-surfaces can now be made with sensitivities up to $60 \mu\text{a/lumen}$ of white light from a tungsten source at standard temperature. The maximum quantum yield of this type of cathode is about 0.3 per cent. Their spectral response curve is shown in Figs. 33 and 34. The long-wave threshold is in the infra-red somewhere above 12,000 \AA .

The most commonly used cells are of spherical and cylindrical shape. Typical representatives of these are shown in Figs. 35 and 36. A diagrammatical sketch is shown in Fig. 37. The glass envelope consists of a spherical portion 1, to which is sealed a cylindrical extension 2. Into the end of 2 is sealed the pinch 3, with exhaust tube 9, carrying a number of leads 4. They support the tungsten spiral 5. Inside the spiral is mounted the silver bead 6. A small nickel disc 7 is welded to one of the support wires. A contact wire 8 is sealed through the envelope and serves to make contact with the cathode. A side tube 10 sealed to the end of extension 2 contains a caesium generator, usually consisting of a nickel capsule 11,

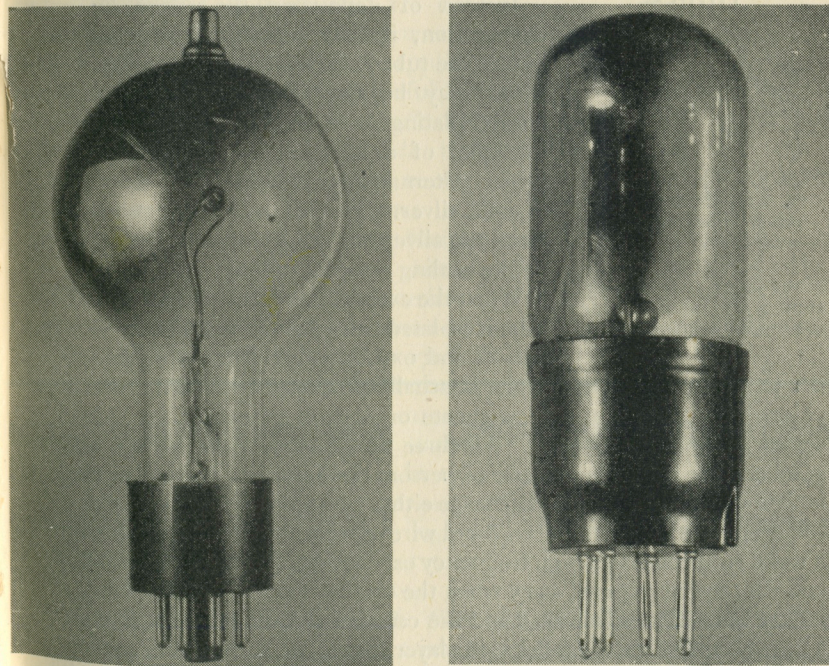


Fig. 35 and Fig. 36. Examples of commercial photo-emissive cells.

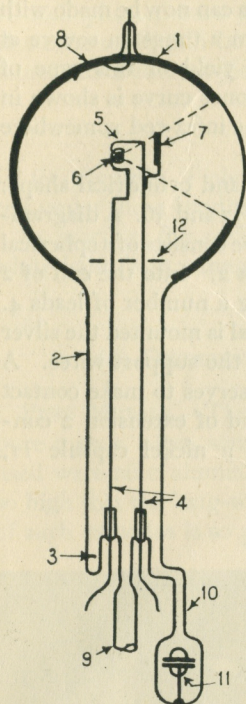


Fig. 37. Photo-emissive cell. 1 envelope; 2 neck; 3 pinch; 4 support wires; 5 evaporator spiral; 6 silver bead; 7 shield; 8 silver layer; 9 exhaust stem; 10 caesium side tube; 11 caesium pellet.

0.1 to 1 mm. Hg. The oxygen is usually produced by heating potassium chlorate or potassium permanganate or barium peroxide in a side tube sealed to the pump system. All three methods are more or less equally good and the choice is a matter of personal preference. The silver surface is then oxidised by a glow discharge either by applying a voltage of several hundred volts between contact 8 and wires 4 or by approaching the bulb with a wand connected to a high frequency oscillator. The oxidation is stopped and the oxygen pumped away when the colour of the silver has changed to a deep blue. The silver bead and the caesium capsule are then flashed for a few seconds to drive off the oxide layer formed on them and constrictions on exhaust and caesium tubes heated to softening point for outgassing. The cell is then baked for approximately 10 minutes to a temperature of 160° -

containing a pellet from which caesium can be liberated by heating. This may be done by passing a current through the capsule or by eddy-currents generated by a high frequency generator.

The tube is sealed to the pump, exhausted and baked at 350° - 500° C. according to the glass used for the envelope. This bake is for the purpose of removing films of gas and water adsorbed on the walls. The cell is then allowed to cool and the caesium capsule degassed by heating to a dull red heat for a few minutes. The silver bead is heated by passing a current through the tungsten spiral until an opaque layer of evaporated silver is formed on the glass wall. The small disc 7 casts a shadow as indicated by the dotted lines, thus leaving a clear window for the light to enter. A disc 12 protects the pinch from the silver beam so as to prevent electrical leaks.

Instead of depositing the silver layer by evaporation, it may be deposited chemically before the tube is sealed on to the pump or the silver may be deposited by evaporation or electro-plating on a metal base consisting, for example, of a nickel sheet supported in the tube. Alternatively, the base plate may consist of solid silver. In that case it is necessary to clean the silver surface by etching or deplating before sealing into the tube.

When the evaporation has been completed, the tube is isolated from the pump by a tap or other cut-off and oxygen is admitted to a pressure of

170° C., to drive off oxygen adsorbed on the walls. Then the caesium capsule is heated until caesium is liberated from the pellet; the caesium is driven into the tube with a flame, while the tube is still hot.

A caesium pellet usually consists of a mixture of caesium chromate and silicon or aluminium powder with an addition of tungsten or tantalum powder, all intimately mixed and pressed into pellet form in a die under high pressure. When such pellets are heated, an exothermic reaction is started, aluminium oxide is formed and the caesium is set free. The tungsten or tantalum are added to act as a retarding agent and to getter any gas liberated during the reaction. Alternatively, the caesium may be developed by heating caesium bromide in the presence of calcium.

The amount of caesium required depends on the size of photo-cathode, cell envelope and the presence and surface area of materials in the tube which are capable of absorbing caesium. Once defined, this amount remains fairly constant for a given type of tube and in large-scale production weighed caesium pellets are often used, from which a definite quantity of caesium can be obtained.

The activation process is observed by connecting the cell to an activation unit shown diagrammatically in Fig. 38. A battery 1 is connected to the cell 3 through a galvanometer 2. The silver evaporator acts as collector anode. The switch 4 allows the voltage applied to the cell to be varied. This is useful for reasons given below. The photo-cell can be illuminated by a lamp inside the baking oven or from an external source through a suitably arranged window.

Within a short time after introducing the caesium into the hot tube, a colour change takes place on the cathode surface. The colour may vary from pale green to purple. The cell is then baked to 170° C. When the dose of caesium has been sufficient, usually a large leak current appears which may be of the order of hundreds of micro-amperes. As the cell warms up this leak current disappears rapidly and photo-sensitivity begins to appear. The discrimination between dark- and photo-current is done by switching the light source on and off. When the dose of caesium was sufficient, the photo-sensitivity rises to a maximum during the bake and then stays constant for a time. Superimposed upon the photo-current will be another current which does not change with illumination. This is due

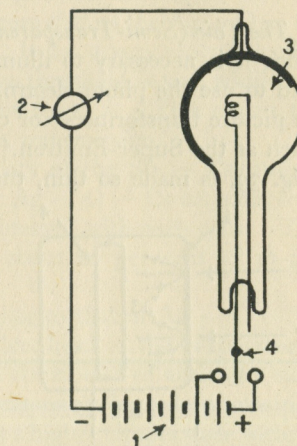


Fig. 38. Activating circuit. 1 battery; 2 galvanometer; 3 photocell; 4 switch.

to thermionic emission from the cathode. We can discriminate between thermionic and leak-current by means of switch 4, Fig. 38. The leak-current is found to be proportional to the applied voltage, whereas the thermionic current exhibits saturation with voltage. When the sensitivity shows no further increase, the bake is stopped and the sensitivity observed during the cooling of the cell. If it goes up, the amount of caesium introduced has been sufficient.

The sensitivity can now be substantially increased by a process first described by Asao and Suzuki.¹⁵ It consists of the evaporation of an additional layer of silver on top of the photo-surface. The sensitivity is found to increase during the evaporation, sometimes by a factor of 4-5 times, reach a maximum and fall again. The evaporation is continued until the sensitivity has passed the maximum. The spectral response curve of the tube will have changed during the deposition, the threshold shifting to shorter wavelengths, and the sensitivity to infra-red light having decreased. The thermionic emission also decreases.

The tube is then baked again to 170°C. until the sensitivity rises to a new maximum which is usually higher than the previous maximum. During this bake the previous spectral response is found to be restored. The cell is then cooled and sealed off.

The Thin (Semi-Transparent) Ag - O - Cs Cathode.—In some applications it is necessary to illuminate the back of the photo-sensitive layer and to use the photo-electrons liberated from the front as, for example, in picture transformers* or certain types of television transmitting tubes such as the Super-Emitron.†¹⁶ In this case the photo-sensitive layer 1, Fig. 39, is made so thin, that the light 2 can penetrate through it and release photo-electrons 3 from the opposite side which are collected by the anode 4.

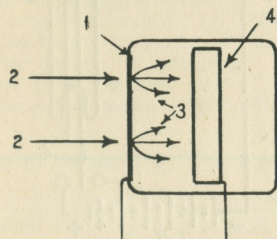


Fig. 39. Semi-transparent photo-emissive cell. 1 cathode; 2 light; 3 photo-electrons; 4 anode.

The colour response is similar to that of thick layer cells. Sensitivities for standard tungsten source of light are of the order of 20-40 $\mu\text{a/lumen}$.

The preparation of the cathode is very similar to that of the opaque Ag - O - Cs cathode, the main difference being the thickness of the original silver base layer. Silver is evaporated on to a transparent base such as glass or mica until the layer has an absorption for visible light of about

50 per cent. During this process the colour of the layer changes from yellow through mauve to blue. The layer is then completely oxidised

* See the corresponding paragraph below p. 93.

† See Chapter 4.

by a glow discharge until it becomes invisible. From then onwards, the process is the same as for opaque cells, except that the colour change on introduction of the caesium is less spectacular, the colour being a greyish blue or mauve.

Very Thin Layers.—The colour response of this type of cell can be altered considerably by making the layer so thin that it is no longer a conductor. The maximum of the response curve for such surfaces is shifted towards the green and the whole response curve approaches much more closely that of the human eye.*

v. ALLOY CATHODES.—There is another, more recent, type of photo-sensitive surface which has gained an importance equal to that of the Ag - O - Cs cathode, partly because of its desirable colour response and greater efficiency, partly because of the ease of its manufacture. It is the alloy cathode. It was discovered^{17,18} that antimony when exposed to caesium vapour forms an alloy with the caesium which is highly photo-sensitive. The same effect was also observed^{17,18} with bismuth, arsenic, lead and gold.⁵⁰

The Antimony-Caesium Cathode.—The most important of the alloy cathodes is the antimony-caesium cathode (Sb - Cs cathode).

The colour response is entirely different from that of the Ag - O - Cs cathode and is shown in the Figs. 33 and 34. It has a very sharp selective maximum in the blue-green. The long-wave threshold is well within the visible part of the spectrum, being at about 6,500 Å. This makes the Sb - Cs cathode very suitable for television transmission.

As is seen in Fig. 34, the overall sensitivity of the Sb - Cs cathode shows a great improvement over that of the Ag - O - Cs cathode, sensitivities up to 120 $\mu\text{a/lumen}$ having been obtained with such cells. The maximum quantum yield (in the blue) is about 20 per cent to 30 per cent.^{19,20}

The design of Sb - Cs cells is very similar to that of Ag - O - Cs cells as shown in Fig. 37, except that the silver bead in the evaporator is replaced by a bead of pure antimony or of a compound of antimony such as Pd Sb₂ or Pt Sb₂.²¹ The latter have a reasonably high decomposition temperature and allow the tube to be baked at a higher temperature without undue evaporation of the antimony.

The tube is sealed to the pump, exhausted and baked. When a pure antimony bead is used, the baking temperature has to be kept below 350°C., whereas a compound bead stands up to 450°-500°C.

After the baking process the bead is heated and an antimony layer formed by evaporation. The tube is then heated to 170°C and caesium introduced

* This type of surface was developed by the late Dr. L. Klatzow of Electric and Musical Industries Ltd., Hayes, and is described in Chapter 4. It is used in the Emitron tube for television transmission.

by any of the methods described in connection with the Ag — O — Cs cathode.*

The colour of the layer thereupon changes from neutral grey to a bright orange red in transmitted light. The bake is continued at 170°C. until the photo-sensitivity has reached a maximum. Thermionic emission is practically absent. The bake is then interrupted. If the sensitivity goes up on cooling, this is again an indication that the amount of caesium has been sufficient. If it goes down, a further dose of caesium is required and the bake is repeated. After the final bake, the sensitivity is still further increased by exposing the alloy layer to oxygen.

This oxidation process is very critical, and the oxygen must therefore be pumped away immediately the sensitivity reaches a maximum. The cell is then sealed off the pump without further bake. During the oxidation the sensitivity of the cell usually increases 2 to 10 times, though very much greater factors have sometimes been observed.

The Semi-transparent Sb — Cs Cathode.—These cathodes can also be made as semi-transparent layers. The only difference consists in the fact that instead of an opaque layer, a layer of only about 50 per cent absorption for visible light is evaporated.

The activation process is identical with that for thick layers. Sensitivities of up to 60 $\mu\text{A}/\text{lumen}$ from a standard tungsten source have been obtained for illumination from the back, the average being 30–50 $\mu\text{A}/\text{lumen}$.

The resistivity of the antimony-caesium alloy is very high, being of the order of 1.6 $\Omega\text{ cm.}^{20}$ for layers of average thickness. This often causes an apparent lack of saturation and non-linearity at high illuminations because a considerable potential drop is set up along the layer by large photo-currents. This may cause some of the photo-electrons released at the end of the cathode near the contact to re-strike the cathode and instead of going to the anode to release secondary electrons¹⁸ thus amplifying the original photo-current. Where high precision of linearity is required it is therefore advisable in the case of opaque cathodes to deposit the antimony layer on a base layer of silver²² or some other metal. In the case of semi-transparent cathodes, a grille of fine conducting metal lines may be sintered into the glass base prior to the deposition of the antimony layer. This does not cause a great loss of light and keeps the potential uniform across the surface.

The colour response is substantially the same as that of an opaque Sb — Cs cathode, the peak of the curve being shifted to 5,000 Å for illumination from the back (probably due to absorption of blue light in passing through the thin layer).

This type of cathode may be used in certain types of television transmission tubes.

* See p. 63.

Other Alloy Cathodes.—Cathodes with Bi — Cs and As — Cs alloys have also been made^{17,23} but are, so far, of less importance because their yield is lower than that of the Sb — Cs cathodes.

There is, however, one type of cathode, the bismuth-silver oxide-caesium cathode which shows promise. Its colour response resembles that of the human eye still more closely than that of the Sb — Cs cathode and its sensitivity lies between those of the Sb — Cs and the Ag — O — Cs cathodes.⁷⁹

(e) GAS-FILLED CELLS

The sensitivity of photo-electric cells can be greatly increased by introducing a small amount of inert gas into the bulb before sealing it off the pump.¹³ If the pressure is such that the mean free path of the photo-electrons is smaller than the distance between the electrodes and if the potential across the cell is sufficiently high, the photo-electrons will be able to ionise the gas molecules. Over a certain range of pressures, the number of ionising collisions increases with the pressure of the gas because of the reduction of the mean free path. Beyond this range, the mean free paths become so short that the electrons gain insufficient energy from the electric field between collisions. The latter become elastic and ionisation is reduced. From the foregoing it is obvious that the optimum gas pressure also depends on the geometrical dimensions of the bulb. If the potential difference across the cell is smaller than the ionisation potential of the gas, the collisions are elastic and no ionisation takes place. In each ionising collision a pair of charged particles is generated, the positive ion moving towards the cathode and the electron moving towards the anode. Thus an amplification of the original photo-current is effected. The gas filling consists normally of an inert gas, usually argon, because of its low ionising potential and because its atoms have little tendency to form metastable states which have a detrimental effect on the frequency response. If the potential across the cell is increased still further, the electrons gather sufficient energy from the electrostatic field after the first collision to produce one or more further ionisations on their way from cathode to anode. The amplification can thus reach values as high as 100 times. Because of the increase in the number of ionising collisions with the voltage across the cell, we cannot expect a gas-filled cell to have a saturated voltage-current characteristic such as exhibited by a vacuum photo-cell. Fig. 40 shows a typical family of amplification *vs.* voltage characteristics for a gas-filled cell at constant illumination and different gas pressures.²⁴ A limit to the useful amplification is set by the fact that at higher voltages the positive ions can gather sufficient energy from the electrostatic field to produce substantial ionisation themselves and to release a considerable number of secondary electrons from the photo-cathode. Then the dis-

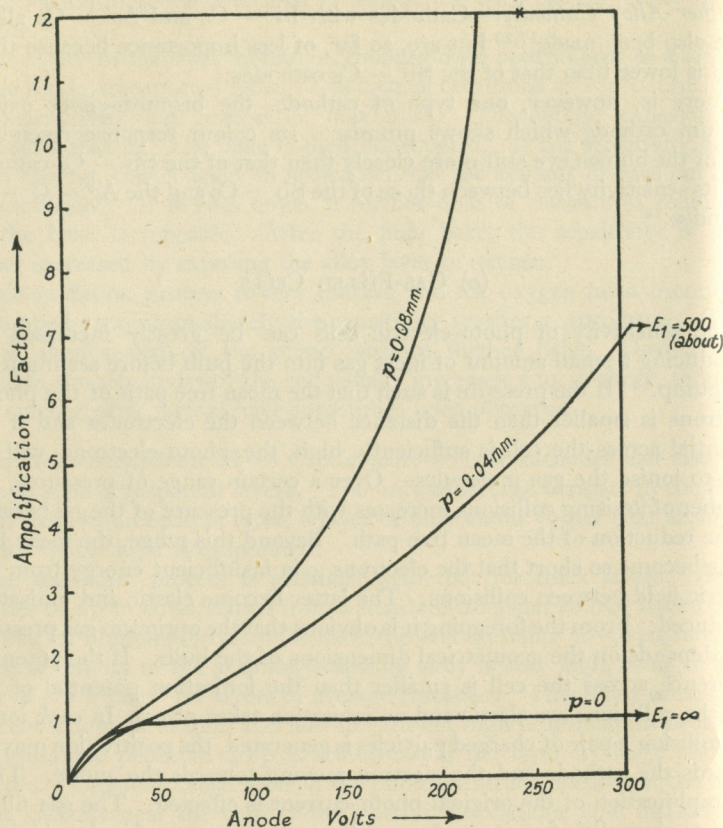


Fig. 40. Gas-amplification of gas-filled photo-cell for various gas pressures (Campbell and Ritchie, *Photoelectric Cells*, Pitman, 1929.)

charge becomes independent of the light. Moreover, for large voltages the ions strike the cathode with considerable energy and are able gradually to destroy the photo-active centres.¹³ Therefore in practice voltages between 90–200 v. are generally used in gas-filled cells.

At strong illumination the photo-currents in gas-filled cells deviate from proportionality with the illumination²⁴, the rise in current being more than proportional to the light.

(f) ELECTRON MULTIPLIER PHOTO-CELLS

A method of amplifying the original photo-current other than by gas filling consists in using the phenomenon of secondary emission.

i. SECONDARY EMISSION.—When primary electrons are made to strike a target they may liberate secondary electrons from it. The yield of secondary electrons, i.e. the average number of secondary electrons released by each primary electron, is called the secondary emission coefficient. This coefficient depends on the energy of the primary electrons, the surface structure and the work function of the target material and the angle of incidence of the primary electrons. Fig. 41 shows a typical curve of the secondary emission

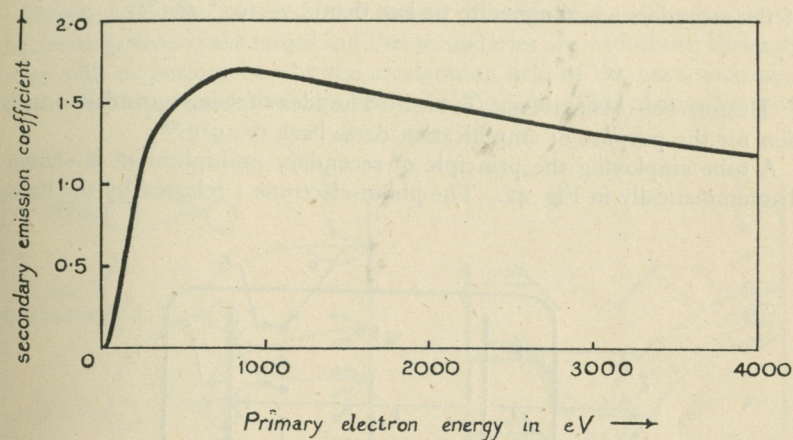


Fig. 41. Secondary emission characteristic.

coefficient plotted as a function of the energy of the primary electrons. At very low primary energies practically no secondaries are released. The higher the energy of the primaries, the further they penetrate into the target material after entering the target. They transmit along their path to an increasing number of electrons sufficient energy to escape, and thus secondary emission yield increases. The effective cross-section of an atom is reduced for primaries of very high energy, and the latter only begin to release secondaries efficiently well below the surface. Most of the secondaries are therefore released at greater depths and some will be unable to leave the target because they lose too much energy by collisions inside it and cannot overcome the potential barrier at the surface. Therefore, after reaching a maximum, the curve falls again. The position of the maximum varies between 450 and 1,000 eV primary energy.

The secondary emission yield increases with increasing angle of incidence. This can be understood on the basis of the above mechanism. When the primary beam strikes the target at a glancing angle, the secondary electrons are released at a smaller depth and stand a better chance of escaping than is the case for normal incidence.

In general, it can be said that the secondary emission yield of a material is high when its work function is low. While the maximum yield of pure metals is generally low, being of the order of 2, yields of 5-20 have been obtained from specially prepared surfaces such as Ag - O - Cs, Sb - Cs and from oxidised alloy surfaces, such as, for example, 95-98 per cent silver and 5-2 per cent magnesium or copper and beryllium.²⁵

The process of secondary emission has practically no time lag. The time interval between the arrival of the primary electrons and the emission of the secondaries is assumed to be less than 2×10^{-9} sec.²⁷

ii. DESIGN FOR MULTIPLIER TUBES.—The idea of using secondary emission for the purpose of amplification dates back to 1919.²⁶

A tube employing the principle of secondary multiplication is shown diagrammatically in Fig. 42. The photo-electrons 1 released by the light

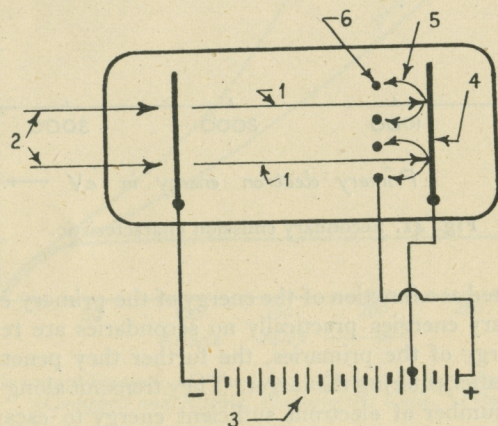


Fig. 42. Photo-multiplier with solid target. 1 photo-electrons; 2 light; 3 battery; 4 secondary emitting target; 5 secondary electrons; 6 collector grid.

are accelerated by the electric field produced by battery 3 so as to strike target 4 where they liberate secondary electrons 5 which are collected by the collector 6. This collector may have the form of a grid. Instead of collecting the secondaries on the grid, they may be accelerated and made to strike another target where they release tertiary electrons. The process can be repeated still further in the tube, the final amplified current being collected on the last electrode. If the secondary emission factor of the target is K , the current amplification in each stage is K and the total

amplification in n stages K^n . Extremely high multiplication factors can thus be achieved in multistage tubes which are now available commercially, such as, for example, the R.C.A. 931 tube which has an amplification factor of more than 10^5 . Such tubes are becoming of ever increasing importance because of their great operating sensitivities. There are a great number of publications and patents concerned with the structure and design of multipliers which it is impossible to quote within the scope of this chapter.

In general, the targets in such tubes can be divided into two groups:

Targets which are pervious to electrons: The primary electrons strike the front surface of the target and the secondaries are withdrawn through holes, slits or perforations by the accelerating field of the next electrode. Two typical representatives are shown in Fig. 43. The photo-electrons

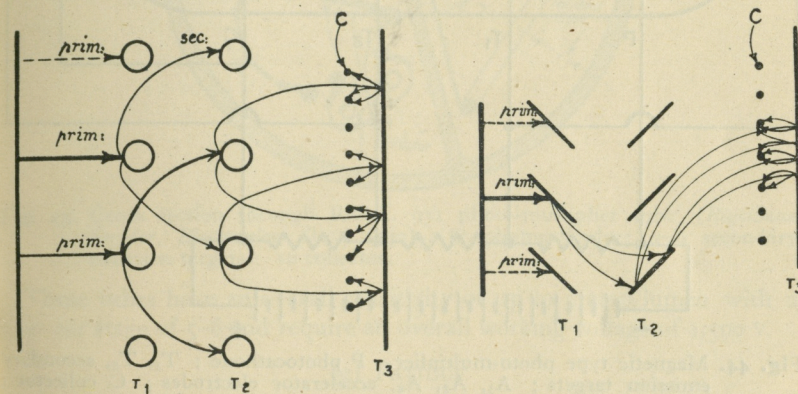


Fig. 43. Photo-multipliers with pervious targets. (a) grid-type targets; (b) louvre-type targets; T_1 , T_2 , T_3 , secondary emission targets; C collector.

are drawn to a series of mesh grids or louvres T_1 , T_2 , kept at increasingly positive potentials. The last target T_3 is usually made solid for better efficiency and the amplified current is finally collected on a wide mesh grid C having a low shadow ratio. Targets of the mesh type are, generally, of low efficiency because only a fraction of the electrons are intercepted by the mesh, the rest flying through the apertures without contributing to the multiplication. If the shadow ratio of the mesh is increased, more electrons are intercepted but simultaneously the withdrawal of the secondaries is less efficient. Thus gains of not more than 2.5 per stage at potential differences of 100 v/stage have been achieved with meshes. For targets of the louvre type, where most of the electrons are intercepted in each stage, much improved efficiencies are obtainable.

Solid targets: The liberated secondaries are accelerated away from the

target surface and directed on to the next one. This can be achieved by a target arrangement as shown in Fig. 44 where a magnetic field H is applied²⁸

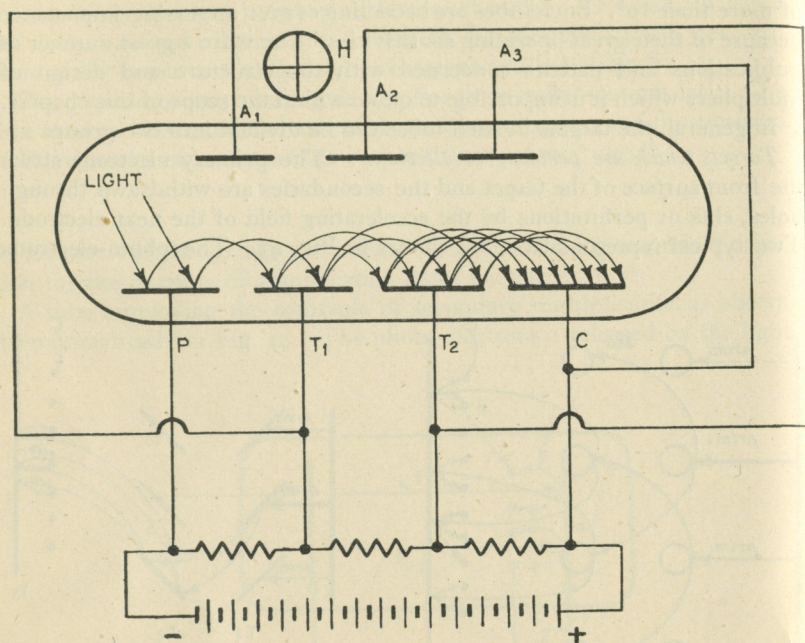


Fig. 44. Magnetic type photo-multiplier. P photocathode ; T_1 , T_2 , secondary emission targets ; A_1 , A_2 , A_3 , accelerator electrodes ; C collector ; H direction of magnetic field (normal to plane of paper).

so as to deflect the secondaries in a direction opposite to that of the primaries. Photo-electrons liberated at P by the light are accelerated by electrode A_1 , kept at a positive potential with respect to the cathode. The magnetic field H having a direction normal to the plane of the paper bends their paths and makes them strike target T_1 . The liberated secondaries are accelerated by electrode A_2 and the magnetic field deflects them on to the target T_2 , etc., until the amplified stream of electrons finally reaches the collector C.

The amplification of such tubes was found to depend rather critically on the correct adjustment of voltages and magnetic fields and they have been largely superseded by an electrode design in which the same effect is achieved by purely electrostatic means. This type of multiplier is known as the zig-zag type and Fig. 45 shows a cross-section through the electrode system of the R.C.A. 931 multiplier photo-tube^{29,30} where an ingenious shape of electrode ensures that the secondaries released at any target are

all withdrawn from it and intercepted by the next target. The shape of the electrodes was arrived at as the result of tracing the paths of the electrons with a rubber membrane model.³¹

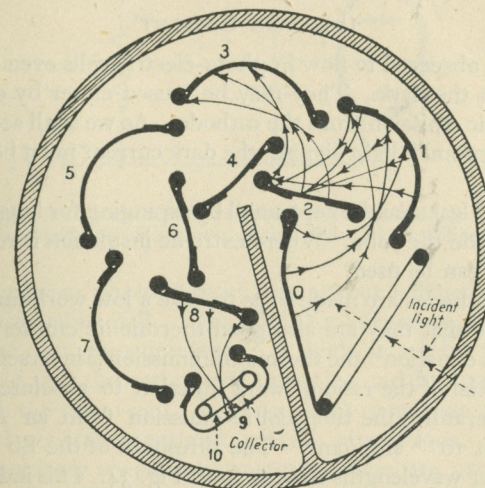


Fig. 45. Cross section through R.C.A. 931 photo-multiplier tube (Rajchman Snyder, *Electronics*, Dec., 1940). O photocathode ; 1-9 secondary emission targets ; 10 collector.

These tubes have an overall sensitivity of up to 5 amp/lumen with a gain per stage of 5-6 and require an overall working voltage of 1,500 v.

(g) FATIGUE

All photo-cells show fatigue under certain conditions. It is not yet clear what changes actually take place in the photo-cathode to produce this fatigue. De Boer³² assumes that in the Ag — O — Cs cathode the supply of electrons to the sensitive layer is insufficient and experiments on cooling the cathode to low temperatures seem to indicate such an effect. Conversely, short heating to 200°C. or irradiation with infra-red light quickly restores the sensitivity. He also found that no noticeable fatigue is produced when the exciting light is in the red or infra-red range of the spectrum.³³

There is, however, a more serious, irreversible fatigue effect. When a cell is greatly overloaded with light while connected to a circuit so that it will deliver current, the sensitivity drops rapidly without ever recovering. Sb — Cs cells, for example, when exposed to illuminations of 1,000-ft. candles on the cathode rapidly lost 50 per cent of their sensitivity and did not recover.³⁴ On the other hand, strong illumination on a photo-cathode when in open circuit does not appear to have a bad effect unless the illumination is so strong that the surface is heated appreciably.

Approximate figures for the safe loading under working conditions are : $0.5 \mu\text{a}/\text{cm}^2$ for Ag — O — Cs cells and $0.1 \mu\text{a}/\text{cm}^2$ for Sb — Cs cells.³⁵ Fatigue is very pronounced in gas-filled cells.

(h) DARK CURRENT

Currents are observed to flow in photo-electric cells even when they are kept entirely in the dark. They may be caused either by electrical leaks or by thermionic emission from the cathode. As we shall see later, for the detection of very small light signals, the dark current must be kept as small as possible.

The electrical leaks can be kept small by arranging for long leakage paths inside and outside the tube. Where extreme insulation is required, guard ring electrodes can be used.

The photo-cathodes are made so as to have a low work function. This, however, means that they are also good thermionic emitters. According to Richardson's equation³⁶ the thermionic emission is inversely proportional to the exponential of the ratio of work function to absolute temperature. At room temperature, the thermionic emission from an Ag — O — Cs cathode is about 10^{-9} amp/cm². The threshold of the Sb — Cs cathode occurs at shorter wavelengths as seen from Fig. 34. This indicates that the work function is higher and indeed, it is, found that the thermionic emission at room temperature from such a cathode is only 10^{-13} amp/cm². The thermionic emission of an Ag — O — Cs cathode can be reduced by an order of magnitude by evaporating a thin layer of silver on top of the cathode and omitting the bake which usually follows this operation.* This effect is however not permanent.

The thermionic emission can, of course, be enormously reduced by cooling the cell with CO₂ snow or liquid air, but this involves a number of complications which make the application difficult. In multiplier photo-cells it was found advantageous to abandon Ag — O — Cs as a secondary emitter and concentrate on the development of Sb — Cs and the new Ag — Mg alloys, which require no caesium at all.²⁵ As the thermionic current is proportional to the cathode area, the latter should be kept as small as the use of the cell will permit.

(j) ASSOCIATED CIRCUITS AND FREQUENCY RESPONSE

i. CIRCUITS.—The basic circuit for the use of photo-emissive cells is shown in Fig. 31. Obviously, this circuit is suitable only where very slow variations of the illumination are to be measured. Also, the use of sensitive galvanometers is often cumbersome.

D.C. measurements.—The galvanometer can be replaced by a load resistance R as shown in Fig. 46. The voltage drop generated across R by the photo-electric current is made to control the grid of the amplifier

* See p. 64.

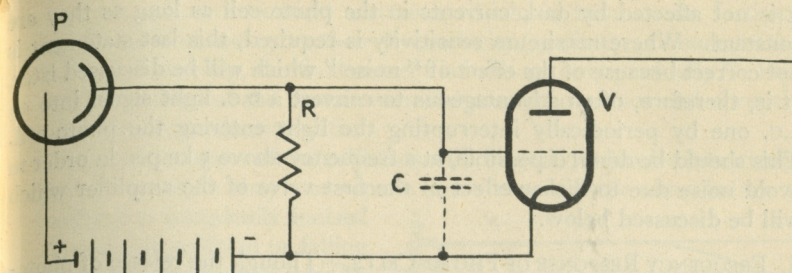


Fig. 46. Basic photo-cell and amplifier circuit. P photo-cell; R signal resistance; C stray capacitance of circuit; V first valve of amplifier.

valve V. For a given photo-current, the output voltage drop across R increases with the value of R. This holds for very slow variations of the light flux or for D.C. measurements. A limit is set by the insulation between the grid and the cathode of the valve and by the dark current flowing through the photo-cell. In general not more than 20 MΩ can be used as a load resistance without special precautions. When great sensitivity is required, special electrometer valves are used in the first stage of the amplifier. These are designed to have very high insulation between grid and cathode and make possible the use of an output resistance of the order of 10^{12} Ω. Thus currents of 10^{-16} amp. can be detected, corresponding to 10^{-12} lumen for a photo-cell of 100 $\mu\text{a}/\text{lumen}$ sensitivity.

A.C. measurements.—If the frequency of the light variations becomes large enough, the capacitance of the grid circuit of the valve can no longer be neglected. This capacitance C acts as a shunt to the load resistance R and is indicated by the dotted lines in Fig. 46. The resultant impedance of the grid circuit is :

$$Z = \frac{R}{\sqrt{1 + \omega^2 C^2 R^2}} \dots\dots\dots(4)$$

where $\omega = 2\pi f$ and f is the frequency of the signal.

The impedance and, with it, the signal decreases with increasing frequency. The capacitance of the grid circuit of a valve comprising the inter-electrode capacitance of valve and photo-cell can easily be of the order of 30×10^{-12} F. To give an example, at a frequency of $f = 50$ c.p.s., with $R = 1$ MΩ, the impedance is still $Z_{50} = 1$ MΩ, whereas at $f = 1$ Mc.p.s. the impedance is only $Z_1 = 5300$ Ω and the signal output would be correspondingly reduced by a factor of about 200 : 1. Therefore, either a correction for the frequency response must be made in the circuits of the amplifier or a suitable small value of R must be chosen.

In general, an A.C. amplifier is more convenient to use than a D.C. amplifier because of its greater stability and freedom from drift. Moreover,

it is not affected by dark currents in the photo-cell as long as they are constant. Where maximum sensitivity is required, this last statement is not correct because of the effect of "noise" which will be discussed later. It is, therefore, often advantageous to convert a D.C. light signal into an A.C. one by periodically interrupting the light entering the photo-cell. This should be done, if possible, at a frequency above 5 kc.p.s. in order to avoid noise due to flicker effect in the first valve of the amplifier which will be discussed below.

ii. FREQUENCY RESPONSE OF PHOTO-CELLS.—Though the release of photo-electrons by the light is practically instantaneous, there are some factors which limit the response of a photo-cell at high frequencies.

Vacuum Photo-Cell.—The only limit to the frequency response is the transit time of the electrons from cathode to anode. Taking as an example a photo-cell with parallel plane electrodes at a distance of $s = 2$ cm., and a voltage across the cell of $V = 200$ v, the transit time of an electron will be :

$$t = \frac{2s}{v} \dots\dots\dots(5)$$

where $v = 6 \times 10^7 \sqrt{V}$ cm/sec. is the velocity of a photo-electron upon arrival at the anode. Using the above numerical values, the transit time is

$$t = \frac{2 \times 2}{6 \times 10^7 \sqrt{200}} = 5 \times 10^{-9} \text{ sec.}$$

Vacuum Multiplier Photo-Cell.—Here, again, transit time of the electrons is the only limiting factor.

In the multiplier of the grid type, where an appreciable number of electrons can pass through a number of stages without being intercepted, the maximum transit time may be as high as corresponds to the total distance between photo-cathode and collector. If this distance is $s = 10$ cm., and the total voltage $V = 1,500$ v, the transit time is of the order of 10^{-8} sec.

In the solid target multiplier, where all electrons leaving a target are intercepted by the next one, only the transit time of the electrons from the last target to the collector matters.

Gas-Filled Photo-Cells.—The frequency response of gas-filled photo-cells is very much inferior to that of vacuum photo-cells. The ions produced by the electrons have very much smaller mobilities. In the case of argon, for instance, the ion mobility is approximately 300 times smaller than the mobility of the electrons. These ions can be removed from the discharge path either by collection on the cathode or by recombination with electrons. The ions formed further away from the cathode may, therefore, have to travel the entire distance between the electrodes before they are eliminated. Moreover, the positive ions upon striking the

cathode release secondary electrons which, in turn, create further ions. As these ions, owing to their low velocity, reach the cathode with considerable time lag, the final current is built up only gradually.³⁷ Equally, after cessation of the illumination the current does not end abruptly but shows a decay characteristic.

Moreover, some of the collisions will raise the molecules into metastable states in which they can remain for a considerable time before either becoming completely ionised by another collision or falling back into the neutral state.³⁸

On account of these factors, the response of gas-filled cells, as shown in Fig. 47, falls off at frequencies above 1,000 c.p.s. and is down to about 70 per cent at 10 kc.p.s. as compared with the response at low frequencies.

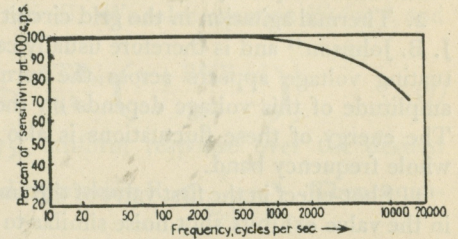


Fig. 47. Frequency response of gas-filled photo-cell. (Millman and Seely, *Electronics*, Fig. 10-15. McGraw Hill.)

(k) NOISE AND SENSITIVITY*

With the requirements regarding sensitivity being pushed ever more to the ultimate limits, the problem of noise becomes increasingly more important. The following considerations will make it possible to calculate the accuracy of measurement obtainable under given conditions or, vice versa, the required illumination or photo-electric sensitivity for a desired operating accuracy.

When only very low light intensities are available the phenomenon of random fluctuations or so-called noise becomes important. These fluctuations are superimposed upon the signal and may be so large that the latter will become unintelligible. Therefore, the ratio of signal/noise must be made as high as possible. The requirements depend on the desired accuracy and on the type of measurement. Where, for example, only the detection of the presence or absence of a light signal is required, a signal/noise ratio of 2-3 may suffice. If, however, the amplitude of the signal is to be measured, very much higher signal/noise ratios are necessary.

In calculations of noise, it is customary to work with noise energies rather than noise voltages because this allows simple addition of noise from different sources.

(i) SOURCES OF NOISE.—The total noise energy at the grid of the first valve of the amplifier shown in Fig. 46 arises from different sources :

* For detailed treatment of noise, see E. B. Moullin, *Spontaneous Fluctuations of Voltage*, Oxford University Press, 1938.

1. Shot-effect in the photo-current: the photo-current is composed of electrons liberated at random from the photo-cathode. This manifests itself in fluctuations of the current about a mean value and is known as the shot-effect.^{39,40} The current fluctuations due to the shot-effect cause voltage fluctuations across the impedance of the grid circuit. The fluctuation energies of shot noise are uniformly distributed over the whole transmitted frequency band.

2. Thermal agitation in the grid circuit: This effect was discovered by J. B. Johnson⁴¹ and is therefore usually called "Johnson" noise. A fluctuating voltage appears across the terminals of any resistance. The amplitude of this voltage depends on the temperature of the resistance. The energy of these fluctuations is also uniformly distributed over the whole frequency band.

3. Shot-effect in the first valve of the amplifier: The thermionic current in the valve exhibits shot noise similar to that of the photo-current. The noise energy which appears at the grid of the valve depends on the design of the valve, its slope, etc. It is customary in noise calculations to use a hypothetical equivalent resistance R_N which, when substituted for the valve, will produce a thermal agitation of an energy equal to that of the shot-noise of the valve. The value of R_N for the best commercially available triode valves is about $R_N = 500 \Omega$. Multi-grid valves are worse for reasons which are outside the scope of this chapter.

4. Flicker-effect in the first valve of the amplifier: This is a fluctuation of the valve current which is probably due to irregularities in the emission from the valve cathode.^{42,43} The fluctuations occur at a low frequency lying in the band between 0 and 5 kc.p.s. By limiting the response of the amplifier (where possible) to frequencies above 5 kc.p.s., this source of noise can be eliminated and will not be considered below.

(ii) CALCULATION OF NOISE.—Taking into account the sources of noise 1-3, and the impedance Z of the grid circuit according to equation (4), the ratio of:

$$\frac{\text{mean square noise voltage}}{\text{mean square signal voltage}} = \frac{1}{S^2} = \frac{f_0}{i_s^2} \left\{ 2e\bar{i} + \frac{4kT}{R} + \frac{4kTR_N}{R^2} \left(1 + \frac{1}{3} R^2 C^2 \omega_0^2 \right) \right\} \dots\dots\dots(6)^{44}$$

where S = signal/noise ratio; e the charge of an electron; \bar{i} = mean photo-current in amps*; i_s = the r.m.s. signal current from the photo-cell in amp.; f_0 = maximum frequency to be transmitted in c.p.s.; k = Boltzmann's constant; T = ambient temperature in °K, usually taken

* Due to dark current, standing light, etc.

as room temperature of $T = 300^\circ\text{K}$; R = output resistance in Ω and C = lumped capacity of the grid circuit in farad; $\omega_0 = 2\pi f_0$.

The first term is the shot-noise contributed by the photo-cell, the second term is the thermal agitation noise contributed by the output resistance and the third term is the noise contributed by the shot-effect in the valve. We are often interested in the question of how much light must fall on a photo-cell of given sensitivity in order to make measurements with a desired signal/noise ratio S . We solve equation (6) for i_s and write:

$$i_s^2 = S^2 f_0 \left\{ 2e\bar{i} + \frac{4kT}{R} + \frac{4kTR_N}{R^2} \left(\frac{3 + R^2 C^2 \omega_0^2}{3} \right) \right\} \dots\dots\dots(7)$$

As already mentioned on p. 75., uniform response over the desired frequency band can be achieved by making $R \ll \frac{1}{\omega_0 C}$. * Then equation (7) is simplified to:

$$i_s^2 = S^2 f_0 \left\{ 2e\bar{i} + 4kT \left(\frac{1}{R} + \frac{R_N}{R^2} \right) \right\} \dots\dots\dots(8)$$

putting in the numerical values and assuming $R_N = 500 \Omega$ (see page 78) we get: (using $e = 1.60 \times 10^{-19}$ coulomb and $k = 1.38 \times 10^{-23}$ joule/deg.)

$$i_s^2 = S^2 f_0 \left\{ 2 \times 1.60 \times 10^{-19} \times \bar{i} + 4 \times 1.38 \times 10^{-23} \times 300 \left(\frac{1}{R} + \frac{500}{R^2} \right) \right\}$$

$$i_s^2 = S^2 f_0 \left\{ 3.20 \times 10^{-9} \times \bar{i} + 1.65 \times 10^{-20} \left(\frac{1}{R} + \frac{500}{R^2} \right) \right\} \dots\dots\dots(8a)$$

Uniform response can, however, also be achieved by making $R \gg \frac{1}{\omega_0 C}$ and compensating for the loss in high frequency response by correction in the later stages of the amplifier.^{45,44} In this case, if $R \gg R_N$, equation (7) becomes:

$$i_s^2 = S^2 f_0 \left\{ 2e\bar{i} + 4kT \left(\frac{1}{R} + \frac{R_N C^2 \omega_0^2}{3} \right) \right\} \dots\dots\dots(9)$$

Using again the above numerical values:

$$i_s^2 = S^2 f_0 \left\{ 3.20 \times 10^{-9} \times \bar{i} + 1.65 \times 10^{-20} \left(\frac{1}{R} + 167 C^2 \omega_0^2 \right) \right\} \dots\dots\dots(9a)$$

By increasing R still further, the second term can be made negligibly small compared with the third term and R disappears from the equation. This means that the noise contributed by the output resistance R is eliminated. Moreover, the signal amplitude at low frequencies is increased so much that the flicker-effect, which is a low frequency noise, is also eliminated. Further increase of the value of R beyond this value is of no use.

* For a more detailed treatment see Moullin, loc. cit. p. 205.

We now return to the example given on p. 75 and calculate the signal-current i_s required to give a signal/noise ratio $S = 10$ in both cases :

1) $R \ll \frac{1}{\omega_0 C}$:

$$f_0 = 10^6 \text{ c.p.s.}; \omega_0 = 2\pi f_0; S = 10; C = 3 \times 10^{-11} \text{ F};$$

then $\frac{1}{\omega_0 C} = 5,300 \Omega$. To obtain uniform response without correction we

choose $R = 2,000 \Omega$. Assuming $\bar{i} = 10^{-7}$ amp and substituting these values into equation (8a), we find that $i_s = 3 \times 10^{-8}$ amp is required. Hence with a photo-cell of $50 \mu\text{a/lumen}$ sensitivity, we require a light flux of :

$$L = \frac{3 \times 10^{-8}}{50 \times 10^{-6}} = 6 \times 10^{-4} \text{ lumen RMS};$$

2) $R \gg \frac{1}{\omega_0 C}$ and correction for frequency response :

using the same numerical values and substituting them into equation (9a),

we find that for $R = 10^6 \Omega$ the term $\frac{1}{R}$ becomes negligible compared with $167 C^2 \omega_0^2$. Using this value for R in equation (9a), we find :

$$i_s = 4 \times 10^{-9} \text{ amp.}$$

and using the same photo-cell, the required light flux is reduced to :

$$L = 8 \times 10^{-5} \text{ lumen RMS};$$

thus an improvement of nearly 8 : 1 in sensitivity is achieved for the same signal/noise ratio.

(iii) USE OF MULTIPLIER PHOTO-CELL.—We shall now consider the use of secondary electron multiplication. Let the original photo-current be amplified n times by secondary electron multiplication in a multiplier photo-cell before being fed into an amplifier. A characteristic feature of secondary electron multiplication is that the additional noise introduced by the multiplication process is negligible. In other words, the signal/noise ratio in the multiplied photo-current is the same as in the original photo-current. Thus, the mean square signal current delivered by the multiplier will now be $I_s^2 = n^2 i_s^2$ carrying a mean square fluctuation current of $n^2 \times 2e\bar{i}f_0$. Substituting these values into equation (9) and dividing by n^2 we get :

$$i_s^2 = S^2 f_0 \left\{ 2e\bar{i} + \frac{4kT}{n^2} \left(\frac{1}{R} + \frac{R_N C^2 \omega_0^2}{3} \right) \right\} \dots\dots\dots (10)$$

From this equation it can be seen that a still further reduction of the noise can be achieved by making the multiplication n so great that the second and third terms in the bracket become negligibly small compared with the first one. Physically, this means that the original signal and the original noise are multiplied without the addition of further noise to a level where the shot noise carried by the signal is large compared with both thermal agitation of the grid circuit and shot noise in the first valve.

Using again the numerical values of the example above, with $R = 10^6 \Omega$; it can be seen from equation (10) that for $n \geq 6$ the values of the second and third terms amount to only 10 per cent of the value of the first term. The second and third terms can therefore be neglected. In other words, by using a multiplier cell with a multiplication factor of 6 which can be achieved by using 1 or 2 multiplying stages, the signal current required for the same signal/noise ratio is reduced to :

$$i_s = S \sqrt{2e\bar{i}f_0}$$

$$i_s = 1.8 \times 10^{-9} \text{ amp.}$$

Hence, for the same photo-cathode sensitivity of $50 \mu\text{a/lumen}$ the required light flux is only :

$$L = 3.6 \times 10^{-5} \text{ lumen RMS.}$$

giving a further improvement of 2 : 1 over the second case above. If the average current \bar{i} is reduced still further by reducing the dark current, the sensitivity can be further increased by using higher multiplication factors. This shows that the elimination of dark current becomes very important in cases where maximum sensitivity is required.

In practice, it is often advantageous to use multiplication factors considerably greater than those required by considerations of signal/noise ratio alone, because of the ease of amplification as compared with a multi-stage valve amplifier, especially where wide frequency bands are concerned.

3. PHOTO-CONDUCTIVE CELLS

In 1873 Smith and May discovered the photo-conductive effect in selenium. They observed a reversible change in the electrical resistance of selenium on exposure to light. Since that time this effect has been the subject of intensive investigation, and many semi-conducting crystals have been found to exhibit the same effect.

A photo-conductive cell is shown diagrammatically in Fig. 48. Two electrodes 1 and 2 make contact with the sensitive material 3. They are connected to a battery 4. When light falls on the material, a current begins to flow which is measured by the galvanometer 5.

Under the influence of light, electrons are liberated inside the crystal.

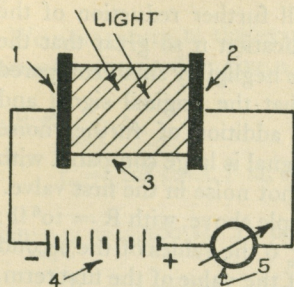


Fig. 48. Photo-conductive cell. 1, 2 electrodes; 3 crystal; 4 battery; 5 galvanometer.

consists of two components, a very weak primary effect which is proportional to the light intensity and shows no time lag and a secondary effect caused by the former which is much stronger and exhibits considerable time lag. In most photo-electric crystals the secondary current is so large that it completely masks the primary current.

The most efficient photo-conductive materials known at present are pure selenium and the sulphides, selenides and tellurides of a number of elements such as zinc, thallium and lead.

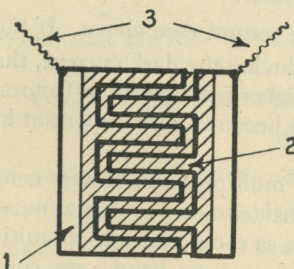


Fig. 49. Electrode arrangement of photo-conductive cell. 1 electrodes of interlocking comb pattern; 2 photo-conductive layer (hatched area); 3 leads.

The electric field causes the liberated electrons to move through the crystal lattice towards the anode. The mobility of the electrons is increased if the lattice is distorted or made non-uniform due to the presence of defects such as foreign atoms interspersed in the lattice. The electrons move from one defect to the next and are able to travel over distances of several millimetres in the crystal. It has been established, mainly by investigations of Gudden and Pohl⁴⁶, that the photo-electric effect in crystals consists of two components, a very weak primary effect which is proportional to the light intensity and shows no time lag and a secondary effect caused by the former which is much stronger and exhibits considerable time lag. In most photo-electric crystals the secondary current is so large that it completely masks the primary current.

The sensitive layer 2 is usually deposited on an interlocking comb-pattern of metallic electrodes 1 with leads 3 (Fig. 49) which serves the purpose of reducing the impedance of the cells.

The spectral response of photo-conductive cells is mainly in the red and infra-red range of the spectrum. They are treated more fully in Chapter 3. For a detailed survey see also F. E. Nix.⁴⁷

4. PHOTO-VOLTAIC CELLS

The photo-voltaic cells are of greater importance in the visible range of the spectrum than the photo-conductive cells. In the photo-voltaic effect radiation incident on the cell causes an electro-motive force to be set up at the terminals of the cell which in turn causes a current to flow in an external circuit.

(a) HISTORY

The effect was discovered by Becquerel⁴⁸ in electrolytic cells. An e.m.f. was observed to appear between two silver electrodes, coated with

a silver halide and immersed in an electrolyte of dilute sulphuric acid, when one of them was exposed to light. Until recently, such cells could not be made very sensitive and have not gained much importance. Recently, however, a very sensitive cell of this type has been described.⁸⁰

The development of the modern photo-voltaic cells began with Grondahl's⁴⁹ discovery of a photo-voltaic effect between copper and copper oxide.

(b) MECHANISM AND CHARACTERISTICS OF VARIOUS TYPES OF CELL

The photo-voltaic effect occurs under certain conditions at the boundary between a metal and a semi-conductor. The phenomena are very involved and not yet entirely explained. Essential for the occurrence of the effect is the existence of a barrier layer of high resistance between the two materials. Such barrier layers have the property of permitting an easy flow of electrons from the metal into the semi-conductor, but not vice versa. Such layers had been used in copper-copper oxide rectifiers for a number of years, and it was in rectifier cells of this type that the photo-voltaic effect was discovered. In this early type of cell the light had to penetrate through the copper oxide to the barrier layer between the oxide and the copper base, and the cell was therefore called "back-wall" cell.

In modern cells the barrier layer is produced between the front surface and a semi-transparent metal layer deposited on the semi-conductor. These cells are called "front-wall" cells. They are much more sensitive than "back-wall" cells. Fig. 50 is a diagrammatical sketch of such a cell.

A selenium layer 2 is applied to an iron base 1. The barrier layer 4 is produced by sputtering a semi-transparent metal layer 3 on the semi-conductor 2. The former is provided with a thicker metal ring 5 for making contact. It is remarkable

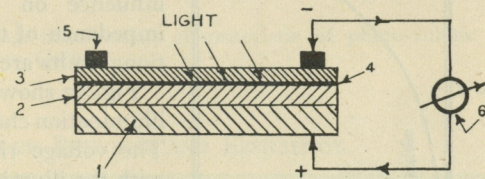


Fig. 50. Photo-voltaic cell. 1 iron base; 2 selenium layer; 3 semi-transparent metal layer; 4 barrier layer; 5 contact ring; 6 galvanometer.

that the photo-voltaic effect and the rectifier effect occur only when the semi-transparent metal layer is produced by cathode sputtering but not if it is produced by evaporation. It appears that the photons absorbed in the cell Fig. 50, eject electrons from the semi-conductor 2 across the barrier layer into the metal 3 (i.e., in the "blocking direction") whence they return to the semi-conductor partly in the easy-flow direction through the barrier layer and partly through the external circuit (galvanometer 6). The higher the resistance of the barrier layer, the greater is the proportion

of electrons flowing back through the external circuit and, therefore, the greater the efficiency of the cell

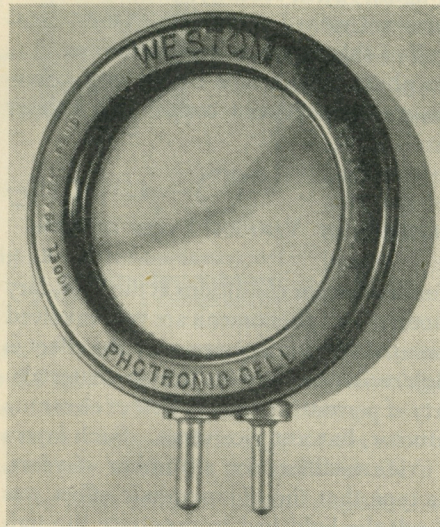


Fig. 51. Commercial photo-voltaic cell. (Weston Electr. Instr. Corp.)

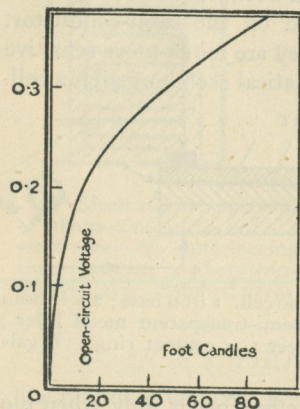


Fig. 52. Current - illumination characteristic of photo-voltaic cell for various external load resistances. (Evans Electro-Selenium, Ltd.)

* Courtesy of Weston Electrical Instrument Corporation.
† Courtesy of Evans Electro-Selenium, Ltd.

Cells with artificial barrier layers consisting of MgO , CaF_2 or rosin have also been produced⁵¹ but never gained much importance.

Practically the only type of photo-voltaic cell commercially available is the selenium cell because of its great sensitivity. Fig. 51 shows a typical photo-voltaic cell.*

The resistance of the barrier layer and consequently the efficiency of the cell decrease rapidly with increasing illumination. This makes it difficult to match the cell to an amplifier circuit, in applications where great variations in illumination occur. Moreover, if part of the cell surface remains non-

illuminated it acts as a shunt for the illuminated part and thus reduces the efficiency of the cell. The size of the cell also has an influence on the efficiency because the impedance of the cell is inversely proportional to its area.

Fig. 52 shows the open circuit voltage vs. illumination characteristic of an EEL—cell.† The voltage rises, at first nearly linearly, with the illumination on the cell.

Fig. 53 shows a family of curves showing the photo-current as a function of the illumination for a Weston Photronic cell for various external resistances.* The smaller the external resistance, the larger the useful photo-current but the smaller the power output. For large external resistances, the characteristic deviates considerably from linearity.

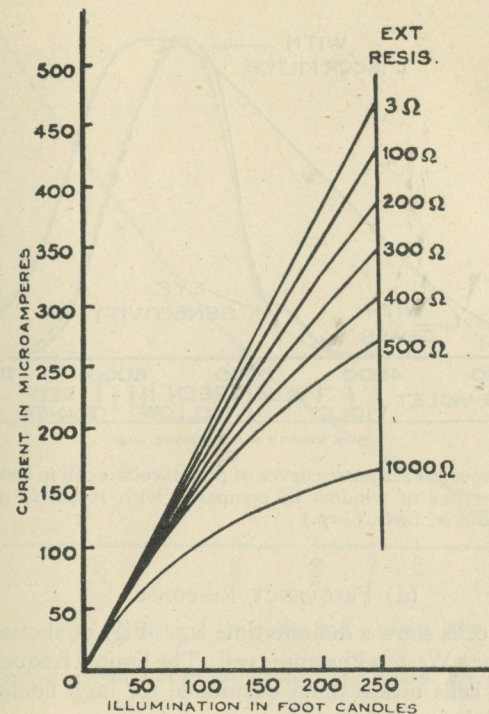


Fig. 53. Open circuit voltage-illumination characteristic of photo-voltaic cell. (Weston Electr. Instr. Corp.)

(c) COLOUR RESPONSE AND EFFICIENCY

The colour response of selenium photo-voltaic cells has a peak at about 5,700 Å. The long-wave threshold is beyond 7,500 Å, while the sensitivity in the short wavelength range of the spectrum extends to below 3,000 Å as is shown in Fig. 54.* By using a suitable filter the colour response can be made very similar to that of the human eye. For comparison, the response curve of the eye is also shown in Fig. 54. The peaks of the curves have been adjusted to unity.

The quantum efficiency of photo-voltaic cells is high, reaching 30 per cent in the peak of the response curve. The sensitivity is of the order of 500 μa /lumen.

* Courtesy of Weston Electrical Instrument Corporation.

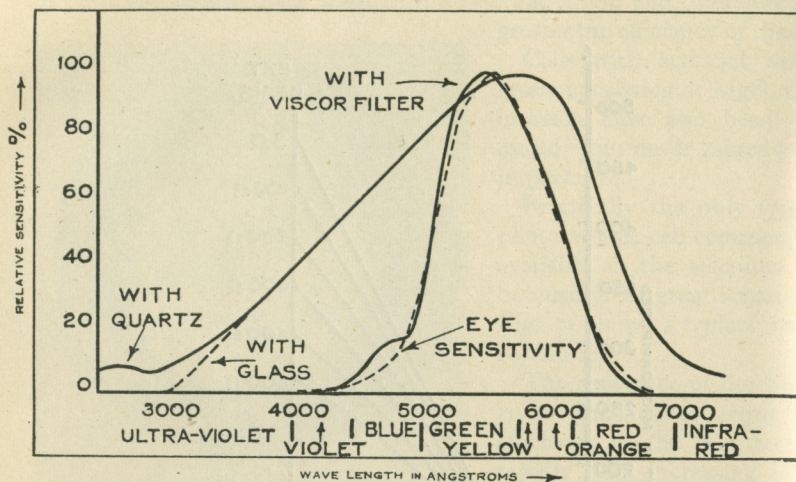


Fig. 54. Relative spectral response curves of photo-voltaic cell in combination with different types of window as compared with response of human eye. (Weston Electr. Instr. Corp.)

(d) FREQUENCY RESPONSE

Photo-voltaic cells show a definite time lag. Fig. 55 shows a frequency response curve for a Weston Photronic cell. The limited frequency response of photo-voltaic cells makes them unsuitable for high fidelity sound reproduction or high frequency work.

(e) FATIGUE

Photo-voltaic cells show a strong reversible fatigue effect. Measurements on selenium cells⁵² showed that their sensitivity drops rapidly to about 75 per cent of its initial value upon illumination with light of a wavelength longer than 6,400 Å. The cells recover quickly in the dark. Light of a wavelength shorter than 6,400 Å was found to cause practically no fatigue.

(f) MANUFACTURE

The details of manufacturing processes of photo-voltaic cells are kept more or less secret by the manufacturers. In general, the production of selenium cells is as follows :

Nickel plated iron discs are covered with selenium powder. The discs are then heated, often under pressure, until the selenium is melted into a uniform film of 0.05–0.1 mm. thickness. The discs are then cooled and a semi-transparent layer consisting of a metal such as cadmium or platinum or a mixture of several metals is deposited by cathode sputtering. Usually

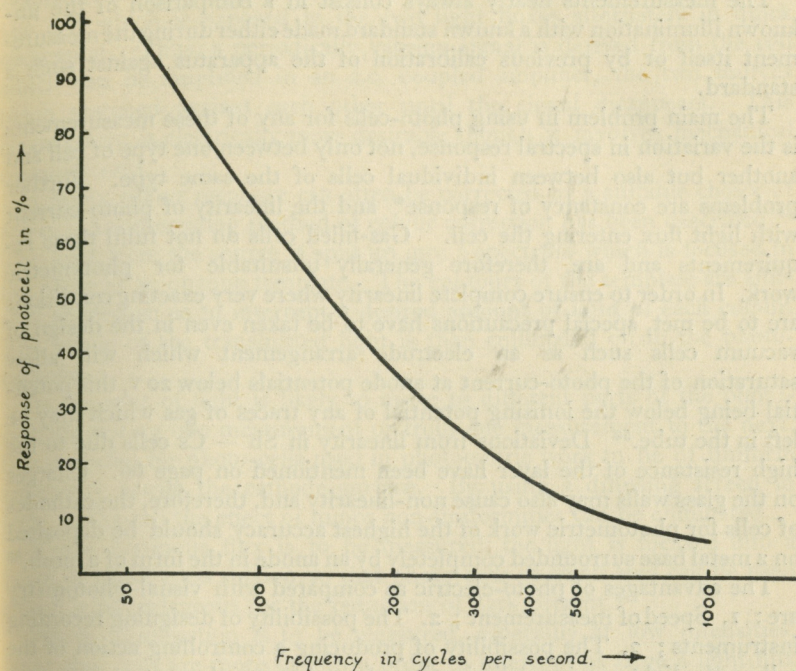


Fig. 55. Frequency response of photo-voltaic cell. (Weston Electr. Instr. Corp.)

a thick metal rim is evaporated on top of the thin layer for making contact and a protective coat of transparent varnish painted over the whole cell.

5. APPLICATIONS

The choice of the type of photo-cell for a particular application depends on a number of factors. Chief among these are : 1. The sensitivity required and the amount of light available ; 2. The matching of the spectral response of the cell to the spectral emission of the source and the spectral range of the measurements ; 3. The technical requirements such as simplicity of apparatus, accuracy of measurement, necessity to work over extended periods without attention, life of the cell, etc.

(a) PHOTOMETRY

This subject can be divided into two groups which are, however, inter-related. They are on the one hand the measurement of luminous intensity, luminous flux, brightness and illumination, and on the other hand the measurement of colour.

The measurements nearly always consist in a comparison of the unknown illumination with a known standard made either during the measurement itself or by previous calibration of the apparatus against such a standard.

The main problem in using photo-cells for any of these measurements is the variation in spectral response, not only between one type of cell and another but also between individual cells of the same type. Further problems are constancy of response* and the linearity of photo-current with light flux entering the cell. Gas-filled cells do not fulfil these requirements and are, therefore generally unsuitable for photometric work. In order to ensure complete linearity where very exacting conditions are to be met, special precautions have to be taken even in the design of vacuum cells such as an electrode arrangement which will allow saturation of the photo-current at anode potentials below 20 v, this potential being below the ionising potential of any traces of gas which may be left in the tube.⁵³ Deviations from linearity in Sb — Cs cells due to the high resistance of the layer have been mentioned on page 66. Charges on the glass walls may also cause non-linearity and, therefore, the cathodes of cells for photometric work of the highest accuracy should be deposited on a metal base surrounded completely by an anode in the form of a mesh.⁵³

The advantages of photo-electric as compared with visual photometry are: 1. Speed of measurement; 2. The possibility of designing recording instruments; 3. The possibility of producing a controlling action of the cell on the light source; elimination of the human element.

i. GENERAL PHOTOMETRY.—If the spectral emission of the unknown source differs from that of the standard source, exact measurements are impossible unless the spectral emission characteristics of the two sources and the colour response of the individual photo-cell used in the measurement are known. Fortunately, for a large number of applications such as the testing and calibration of lamps of equal filament rating the variations in colour are so small that the errors are negligible.

The simplest method of measuring luminous flux, brightness or illumination is to use a calibrated photo-cell and galvanometer. Where photo-currents of the order of $1 \mu\text{a}$ are obtainable and an accuracy of not more than 5 per cent is required most photo-cells, both photo-emissive and photo-voltaic, are satisfactory. Thus, photo-voltaic cells are widely used in photographic exposure meters and other light meters where size and portability are of importance.

The more accurate photometers are, however, nearly all based on a null-method whereby the standard light source is balanced against the unknown source. This can be done by throwing the standard and the unknown flux on to two different cells, the output of which is then balanced

* See the paragraphs on fatigue, p. 73 and 86.

against each other. Another and more common method is the use of only one cell which is exposed to the two light fluxes alternately in quick succession. Thus, a periodically varying signal is derived from the cell which can be amplified in an a.c. coupled amplifier, the two sources being matched against each other until the signal disappears. This arrangement is electrically more desirable though it involves mechanical complications.

A faulty colour response can often be corrected by a suitable choice of filters. An interesting method of colour correction has been described.⁵⁴ The light from the source is split up into a spectrum which is focused in the plane of an opaque template. The contours of the template are suitably shaped so as to intercept a desired amount of light of each colour. The whole of the transmitted light is then collimated on to the photo-cathode.

As the spot of light is likely to move to different parts of the photo-cathode during one measurement or from one measurement to the next, it is essential for photo-cells used in photometric work to be of uniform sensitivity across the cathode surface. By using a diffusing screen in front of the cell the effect of minor non-uniformities can be eliminated.

Where luminous flux is to be measured, the light is focused into a beam of small cross section, so that photo-cells of small area can be used which is advantageous for the reduction of dark current.*

Where illumination is to be measured, especially at low intensities, large area cells are more useful in order to intercept as large a light flux as possible, but at the same time the requirements for uniform sensitivity across the cathode surface become more stringent.

ii. SPECTROPHOTOMETRY.—The application of photo-electric cells to spectrophotometry is usually governed by much more exacting conditions than general black-white photometry, because only the energy contained in a narrow band of the total spectral emission of the source is available for the measurement. We have to deal, therefore, with very small photo-currents which may be as low as 10^{-15} amp. Here, the multiplier cell proves to be very useful.

There are two main types of physical spectrophotometers. In the first type, the eye is replaced by a photo-cell with calibrated spectral response.⁵⁵ The other type is a recording instrument which automatically plots the spectral transmission or reflection of a specimen throughout the whole spectral range, such as, for example, the Hardy spectrophotometer^{56,57} which is designed to measure photo-currents of the order of 10^{-12} amp. with an accuracy of 0.1 per cent.

In astronomic photometry and spectrophotometry very small light energies only are available and photo-emissive cells in connection with

* See p. 74.

electrometer valves are mostly used at present.⁵⁸ The Sb - Cs surface with its peak response in the blue part of the spectrum is very efficient for this work, especially in multiplier photo-cells.⁵⁹ Colours of stars of magnitude 7.5 have thus been measured in combination with colour filters. Here also, multiplier cells designed to have especially low dark currents will be of great advantage.

Due to its practically instantaneous response, the photo-electric spectrophotometer makes it possible to investigate processes which were previously rather inaccessible to measurement, such as the spectral distribution of the light emitted during the decay time of phosphors or the lines emitted by a gas at different phases of an arc discharge. Recently, such an apparatus was described⁶⁰, making use of a multiplier photo-cell in combination with a cathode-ray oscillograph.

Photo-electric photometers incorporating cells sensitive to ultra-violet light are widely used in physiological work. An example is the determination of the vitamin A content of solutions. This determination is carried out by measuring the absorption of the solution for radiation of wavelength 3,300 Å, the absorption being an indication of the vitamin A content.⁶¹

Photo-cells in combination with colour filters⁶³ or in the arrangement described on page 89⁵⁴ are also used for physical colorimetry. They are used, for example, in physiological work for the determination of haemoglobin⁶⁴ and chlorophyll⁶⁵ contents of solutions.

Recently, a direct-reading colour-densitometer has been described⁶⁶ using a multiplier photo-cell. For a detailed account of photo-electric photometry see J. S. Preston.⁶²

(b) CHECKING, CONTROL AND COUNTING OPERATIONS

Simple photo-electric colorimeters and nephelometers are widely used in continuous automatic supervision of chemical and industrial processes in industry. Examples are the measurement of smoke density in flue-gases⁶⁷ and the measurement of colour and gloss of fibres and materials in the textile industry.⁶⁸ Photo-voltaic cells are used in a glossmeter for the inspection of the quality of machined surfaces.⁶⁹

Photo-voltaic cells operating straight into a micro-relay are widely used for checking the uniformity of products in mass production and for sorting operations, thus speeding up production processes. One of the best known examples is the supervision of automatic packing in the cigarette industry. The cigarettes pass under a photo-cell on the conveyer belt. If a cigarette is in the wrong position in the box, it is detected by the photo-cell and automatically packed correctly. For the supervision of packing processes, special black and white or coloured patterns are often incorporated in the printed design on the packages to assist the photo-cells in their job.

Other uses of photo-cells are the automatic opening of doors in restaurants, garages etc., the counting of passing trains or vehicles, operation of burglar alarms, etc.⁷⁰

Where the control operations require larger power outputs, especially at high speeds, photo-emissive cells are used to control the current of thermionic relays, such as thyatron tubes. The basic design of such control circuits is shown in Fig. 56, where the potential drop across the

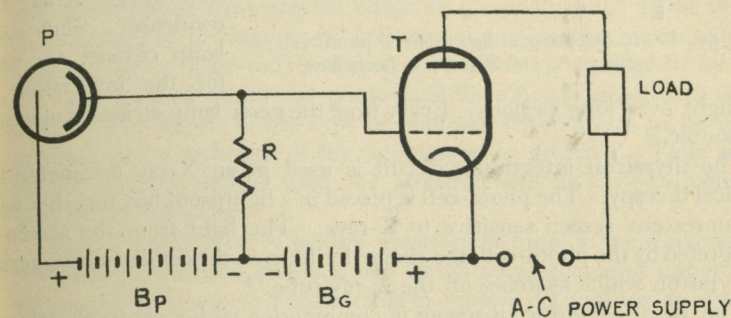


Fig. 56. Photo-cell thyatron control circuit. P photo-cell; R signal resistance; B_p photo-cell battery; B_G grid bias battery of thyatron; T thyatron tube.

output resistance R of the photo-cell P is used to fire the thyatron T. The battery B_p supplies the photo-cell, the battery B_G provides the grid bias for the thyatron.

Photo-cells are also used for regulation and control of variable quantities. An example is the voltage control of an H.T. unit. A light beam is reflected by a mirror attached to a voltmeter so as to illuminate one or the other of two photo-cells which in turn control the output of the voltage supply unit.⁷¹

An interesting application is the suspension of the rotor of an ultra-centrifuge.⁷² In order to avoid friction, the rotor is suspended in free space by magnetic attraction from an electro-magnet arranged above the rotor. The magnet is energised by short pulses at constant frequency. The amplitude or duration of the pulses is controlled by a photo-cell, the illumination of which is made to depend on the height of the rotor which intercepts a light beam directed on to the photo-cell. Thus the rotor is restored to a predetermined height within very fine limits.

Mention should also be made of the use of photo-cells for integrating purposes. The basic integrating circuit for photo-cells is shown in Fig. 57. The photo-current charges a condenser C, the voltage across its terminals being measured either by impressing it on the grid of a valve or, as shown in the figure, by connecting a neon lamp L across the condenser. As soon as the striking voltage of the lamp is reached, the

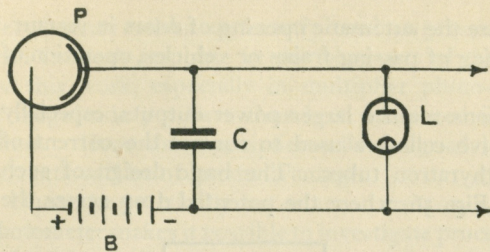


Fig. 57. Photo-cell integrating circuit. P photo-cell; B battery; C condenser; L neon lamp.

daylight over long periods. Every time the neon lamp strikes it operates a counter.⁷³

The thyatron integrating circuit is used in an X-ray dosimeter for clinical therapy. The photo-cell is placed in a lightproof box together with a fluorescent screen sensitive to X-rays. The light from the screen is integrated by the photo-cell, the charge built up on the condenser triggering a thyatron which switches off the X-ray tube.⁷⁴

The use of a fluorescent screen in combination with a photo-electric cell has also been described in an apparatus for the detection or measurement of radioactive sources.⁷⁵

(c) ACOUSTICS

Photo-electric cells are widely used in sound reproduction. The sound is recorded on film or paper in the form of a black and white pattern of variable width or transparency.⁷⁶ For reproduction, this pattern is made to modulate the intensity of a fine pencil of light illuminating a photo-cell, the output current of which is then amplified. Lately, multiple photo-cells have been used for this purpose because of their superior power output. Photo-voltaic cells are unsuitable for high fidelity sound reproduction because of their bad frequency characteristic.

Photo-cells are also used in combination with modulated light sources for light telephony and light telegraphy.

An interesting application is the light siren.³⁸ A sound generator of continuously varying frequency is made by spinning a disc, having a number of holes along its circumference, at varying speed so as to interrupt a light beam falling on a photo-cell the output of which is then amplified.

(d) PICTURE TELEGRAPHY AND TELEVISION

For these applications see Chapter 4.

(e) PICTURE FORMING DEVICES

Apart from the simple photo-cell used for measuring the amount of light or its variations with time, a new type of photo-cell has gained

importance during the last few years. This is the picture transformer, a device in which the picture of an object is focused on to the cathode of a photo-emissive cell. The intensity of the beam of photo-electrons leaving an elemental area of the cathode surface depends upon the intensity of illumination on that elemental area. This electron beam of varying intensity is accelerated and focused on to a fluorescent screen by suitable electro-static or electro-magnetic lenses and produces a light image which is a replica of the original image on the photo-cell. These tubes can thus be used to produce a visible image of an object by means of invisible (ultra-violet or infra-red) radiation emitted from or reflected by the object and focused on to the photo-cathode which is sensitive to this radiation. The choice of the type of photosensitive surface to be used depends on the wavelength of the radiation to be detected. Thus an Ag—O—Cs cathode will be used for infra-red and an Sb—Cs cathode for ultra-violet radiation.

Another application of picture transformer tubes is the conversion of a coloured picture into monochrome which may become of importance in the film industry where it is desirable to observe the appearance of a natural scene in black and white before actually taking a film.

A further development of the picture transformer is the picture multiplier, where the electron beam is focused on to one or more successive secondary emitting targets before finally being focused on the fluorescent screen.^{77,78} Such tubes have been operated experimentally¹⁶ but with more than one stage of multiplication, resolution and contrast deteriorate rapidly.

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