CHAPTER VII

PHOTOCELLS WITH GAS AMPLIFICATION

VII-a **Introduction**

Means exist for transforming nearly all forms of energy into electricity. For example, a dynamo or a piezo-electric crystal may serve for the transformation of mechanical energy; a thermocouple changes heat into electricity, and various types of microphones can be used to produce electricity from sound energy. Light is transformed into electricity by the photosensitive layer of a photocell, which emits electrons when it is illuminated; under the influence of an electric field, these electrons give rise to the photoelectric current.

Many investigations in the field of photoelectricity were made by men like W. Smith, W. G. Adams and A.E. Day around 1875. The sensitivity of the semiconductor selenium to light was noticed and studied. It was found possible to transform light variations into variations in the current flowing through a circuit incorporating a selenium cell, since the resistance of this photocell depended on the amount of light falling on it. This phenomenon is called an *internal photoelectric effect,* since the changes take place inside the substance which is illuminated.

The *external photoelectric effect,* i.e. the emission of electrons by certain substances when they are illuminated, which was discovered in 1887 by H. Hertz and W. Hallwachs, has however proved to be of much more importance. For the sake of completeness we will briefly mention here a third type of photocell, the photovoltaic cell, which produces a slight e.m.f. when illuminated.

The number of photons available to stimulate the emission of electrons in the external photoelectric effect is usually relatively small; and as we will see later, even if there were much more light, the current would be limited by the size and emissive power of the photosensitive layer. The emission current produced is thus very small, of the order of a few microamperes. It has however proved possible to use this photoelectric current for various applications, by amplifying it in one way or another.

PHOTOEMISSION

Einstein's law has already been given in Chapter I: a photosensitive substance can only absorb radiation (light) in quanta; the absorption of these

current cannot increase any more. This region is represented by the horizontal portion of the I_a/V_a characteristic shown in Fig. 196. In this region, the cell current is not sensitive to fluctuations in the anode voltage.

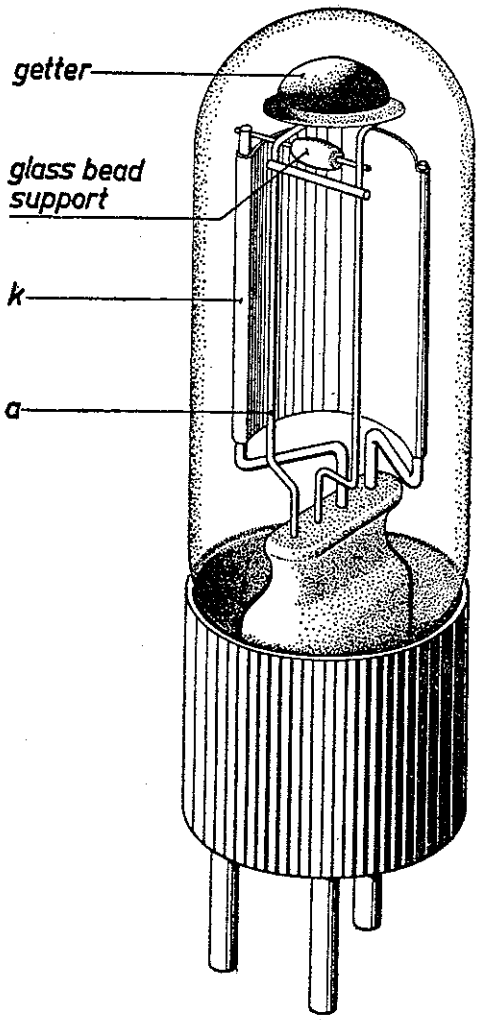


Fig. 193
Photoelectric cell having a semicylindrical metal cathode support and a frame-shaped anode.

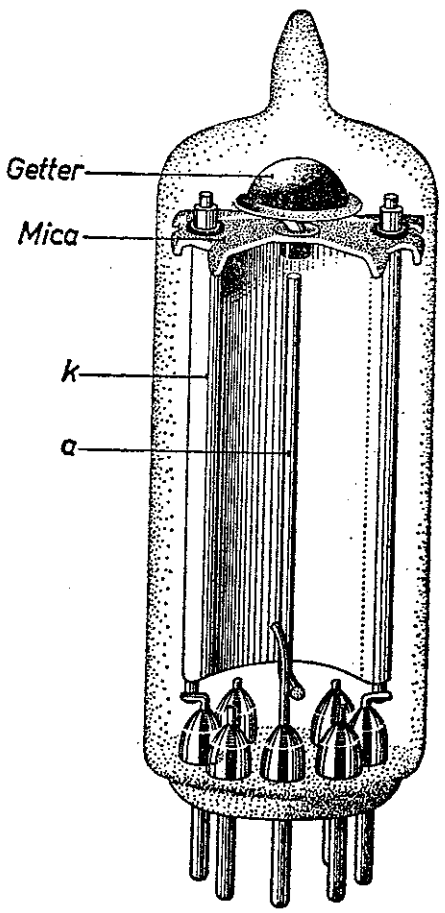
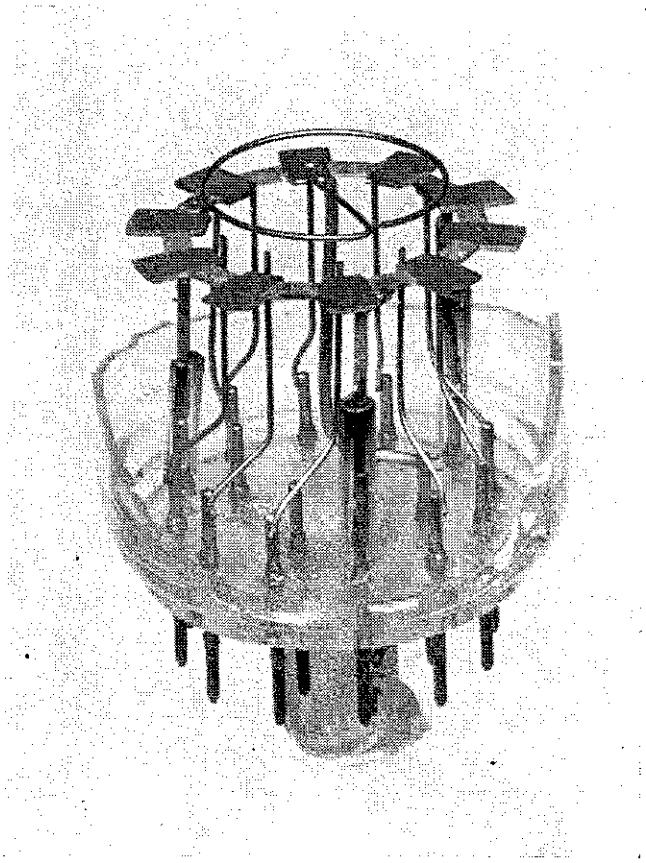


Fig. 194
Photoelectric cell; the cathode k is prepared on a metal plate. The anode a has the shape of a rod. A getter is evaporated on the top of the tube; it is screened from the cathode by a mica disc.

Photo 12

Assembled electrode system of an indicator tube for a decimal counting circuit using transistors [58].



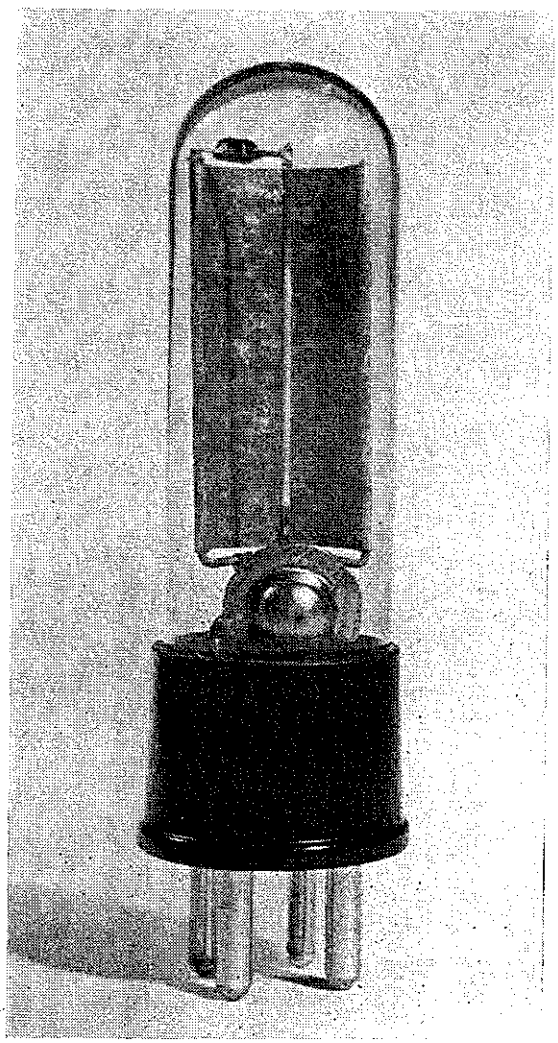


Photo 13

Philips gas-filled photocell 3554.

quanta gives rise to the emission of electrons. For each such substance there exists a minimum value of the frequency of the light, ν_0 below which electron emission is no longer possible; this is known as the red frequency limit [48]. The minimum energy which an electron must possess in order to be able to escape from the solid phase is known as the work function $e\varphi$; it follows that

$$h\nu_0 = e\varphi \tag{1}$$

In other words, it is not the *intensity* of the light but its *frequency* which determines whether electron emission will occur; but the value of the emission current is proportional to the luminous flux. The sensitivity of the cell is expressed in amperes per lumen (see Types of Photocathodes, page 260).

APPLICATIONS

The amplified signal obtained from the photocell can be used to activate a relay, or for sound transmission. The most usual applications are in talking films, brightness control of lights and the automation of all sorts of industrial processes.

THE CONSTRUCTION OF THE PHOTOCELL

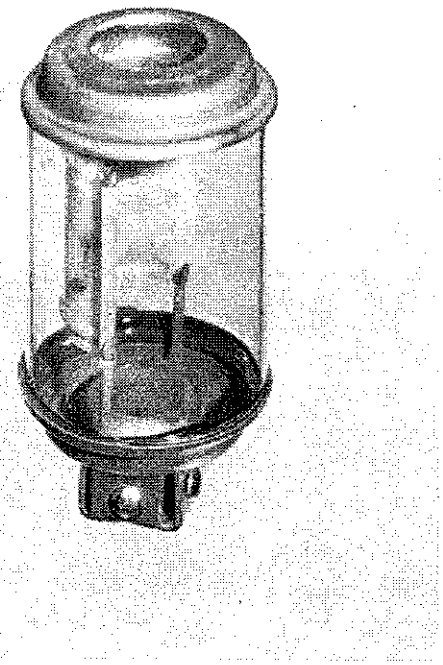
The photocathode has already been described in II-c-4. The construction of the gas-filled photocell does not differ from that of the vacuum photocell. We will now give a few examples of the types of constructions used.

The outside of a photocell is not very impressive: there are a number of styles, which are used for all the models. (Fig. 193, 194, 195). A photocell. We will now give a few examples of the types of constructions used. one end to support the electrodes. An insulating cap with lead pins can then be cemented on to the edge of the seal; or the base can be made of sintered glass (see II-f-2) with the leads melted into it. The photocathode is sometimes deposited on the inside of the glass envelope. In one much used style, the cathode has the form of half a cylindrical plate, with the anode in the form of a rod near the axis of the cylinder. The anode is also sometimes a wire frame; it is usually designed so as to interrupt the incident light as little as possible. In the types shown in Fig. 193 and 194, the light enters from the side; Fig. 195 shows a type in which the light enters from above.

SATURATION OF THE VACUUM PHOTOCELL

If the voltage across a vacuum photocell is increased at a constant luminous intensity, the emission current increases rapidly at first, but then more and more slowly until after a certain value of the voltage the *saturation* region is reached: all the electrons emitted by the cathode reach the anode, so the

Photo 14
RCA gas-filled photocell 921.



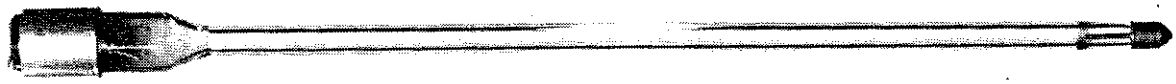


Photo 15
Philips neon-filled noise diode K 50 A.

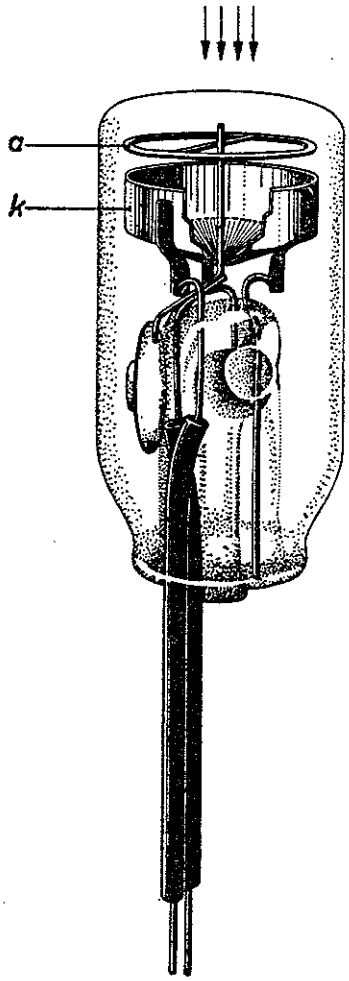


Fig. 195

Philips photoelectric cell 58 CG having a cup-shaped metal cathode-support *k* and an anular anode *a*. The light enters from above.

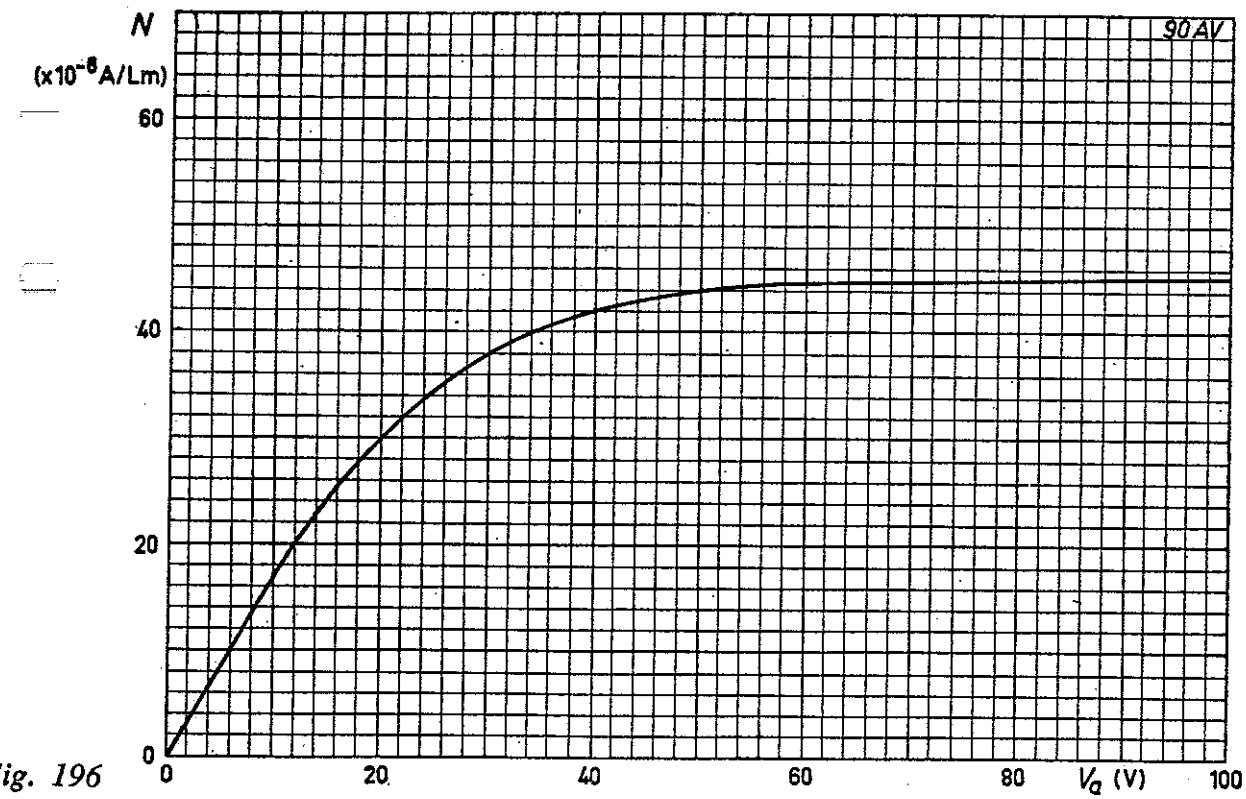


Fig. 196

Current-voltage characteristic for a vacuum photoelectric cell measured at constant illumination.

TYPES OF PHOTOCATHODES

We will only consider here the two most important types of photocathodes: the caesium-caesium oxide type and the caesium-antimony type. From now on, we will call the caesium-caesium oxide type simply the "*C*" type; this is prepared by depositing a layer of caesium on a layer of silver oxide. The silver oxide converts part of the caesium to caesium oxide, and remains behind as silver particles finely dispersed among the caesium oxide, thus increasing the conductivity of the oxide. A minute layer of pure caesium remains on the surface.

We will call the caesium-antimony photocathode the "*A*" cathode from now on: this is made by depositing caesium on a thin layer of antimony.

These two types differ mainly in the way their sensitivity varies with the wavelength of the incident light. Fig. 197 shwos the spectral sensitivity curves of both types. Curve I, for the *C*-cathode, has a maximum in the region of red to infrared; while curve II, for the *A*-cathode, has its maximum in the ultraviolet to violet.

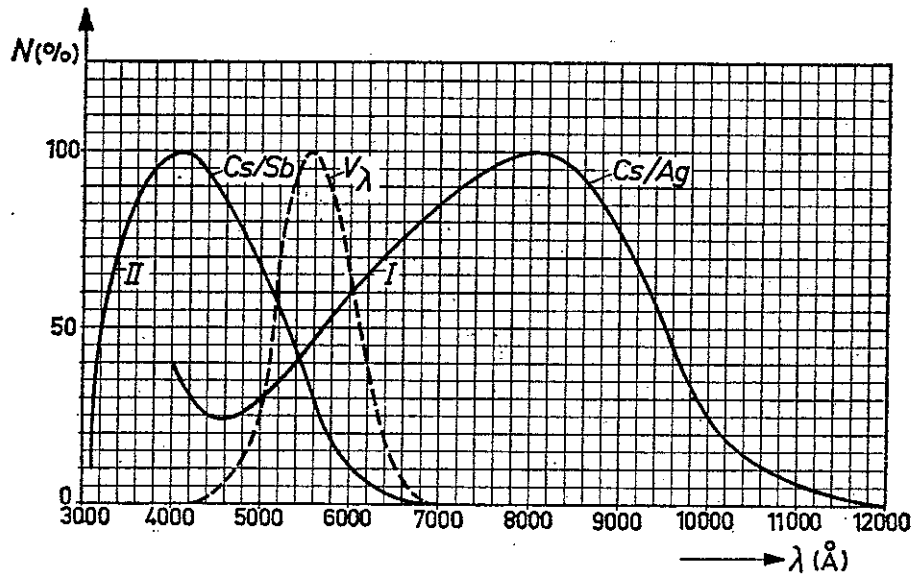


Fig. 197

Spectral sensitivity curves.
I. for *C*-cathode consisting of caesium on silver oxide,
II. for *A*-cathode consisting of caesium on antimony,
V_λ for the human eye.

Since the luminous flux of the light falling on the cell is determined with the aid of V_λ*), the photocell with a *C*-cathode will give a relatively large current with a light source such as an incandescent lamp which emits a large amount of red and infrared and a relatively small current with daylight which contains only a small amount of red. The reverse is true with a cell having an *A*-cathode.

*) The spectral sensitivity curve V_λ for the human eye lies between curves I and II.

If the temperature of the filament of the electric lamp is increased, the relative amount of blue and violet light it emits is increased: published data on the sensitivity of the photocell therefore always include the filament temperature of the lamp used for the measurements.

Thus, the sensitivity of a given *C*-cathode in a vacuum photocell for an electric lamp with a filament temperature of 2700 °K was 20×10^{-6} A/Lm, but only 4×10^{-6} A/Lm for daylight; while the sensitivity of an A-cathode for daylight is about 80×10^{-6} A/Lm, and for an electric lamp with a filament temperature of 2700 °K only 45×10^{-6} A/Lm.

THE ENVELOPE

The envelope of a photocell is practically always made of glass. This transmits visible light and other radiation with wavelengths of above 3500 Å satisfactorily; if radiation with smaller wavelengths has to reach the cathode, the envelope must be made of glass which is transparant to UV, or of quartz glass.

It is sometimes desired to measure radiation with wavelengths lying in a narrow range. A light filter in the form of e.g. a piece of glass of suitable composition is then placed between the light source and the photocell.

DARK CURRENT AND LIMITING TEMPERATURE

A photocathode still emits a small number of electrons even if it is not illuminated. This is attributed to the low value of the work function of the cathode, so that thermal emission is possible even at room temperature. The photocell current due to this effect is known as the *dark current*; it is however very small (of the order of magnitude of 0.01 μA in vacuum cells). It increases rapidly with an increase in the temperature. The maximum permissible ambient temperature is therefore usually 75 °C, or at most 100 °C. Another reason for limiting the temperature is to prevent deterioration of the sensitivity as a result of changes in the cathode surface.

VII-b **The photocell with gas amplification**

It often happens that the electron current excited by the light in a vacuum photocell is so small that it must be amplified considerably. Now the noise present in any circuit as a result of such things as the thermal motion of the electrons in the resistors, etc., is also amplified along with the useful signal, and it may even happen that the useful signal is completely masked in the noise so that there is no point in using the photocell.

If we could amplify the signal inside the cell, we could obtain a better signal-to-noise ratio. In other words, the output signal of the photocell would then be made big enough not to be masked by the noise. This can be done in one of two ways:

a. by use of an electron multiplier;
b. by filling the photocell with gas.

In method a., the photo-current impinges on a series of electrodes which have a high secondary-emission factor, so that the anode current is much greater than the current from the cathode. The amplification obtained in this way can be 10^6 or more, but the construction of the tube is very complicated. Such a photocell is called a photo-multiplier, a detailed description of this falls outside the scope of this book. The interested reader is referred to references [48] and [49].

GAS AMPLIFICATION

In simple cases, where the amplification need not be very great, a gas filling may be used. The tube is then of simple construction, like the vacuum cell. This second method is based on an increase in the electron production as a result of ionization of the inert gas in the cell. An inert gas filling is used because it does not react with the photosensitive layer. In practice, argon is generally used because it has a low ionization potential compared to other inert gases, and not too high an atomic weight. The amplification thus obtained depends on:

1. the number of electrons n produced in each avalanche by one primary electron (the α effect);
2. the number of secondary electrons γ $(n-1)$ emitted by the cathode owing to bombardment by the $(n-1)$ ions produced by one primary electron (the γ effect).

The effectiveness of the α effect depends on the mean free path of the electrons in the gas i.e. on the density of the gas, the size of the molecules and the anode voltage. At low pressures there are not many collisions, and at high pressures the electrons lose too much energy by

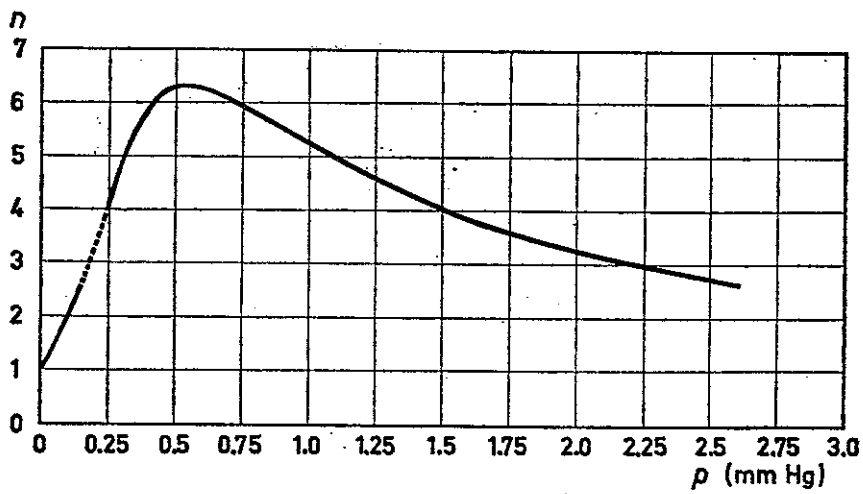


Fig. 198

Number of electrons n formed in each avalanche in an argon-filled cell as a function of pressure p at a constant anode voltage [51].

elastic collisions so that they cannot gain the velocity which they need in order to cause ionization. Fig. 198 shows the number of electrons formed in each avalanche as a function of the pressure at a constant anode voltage. According to this figure, the optimum pressure is about 0.55 mm Hg; but in fact low pressures (about 0.1 mm Hg) are used to keep the inertia of the cell low (cf. VII-d).

Calculation shows (see I-g-1 and ref. [48], page 125) that as long as breakdown does not occur the total number N of electrons formed by one photoelectron is

$$N = \frac{n}{1-\gamma\,(n-1)} \tag{2}$$

This number is called the gas amplification.
The value of γ is about 1/3.

The above-mentioned phenomena can be traced in the current-voltage characteristic of the photocell at constant illumination of the photocathode (fig. 199): as long as the voltage V_a is less than the ionization potential of argon (15.7 V), the curve is more or less the same as that for a vacuum photocell (concave to the horizontal axis). The saturation region is reached at about 15 V. If V_a is made more than the ionization potential, new electrons and ions are formed in the gas, and the value of N becomes greater than 1. The curve thus becomes convex to the horizontal axis. The value of N at a given value of V_a can be determined from Fig. 199: it is simply

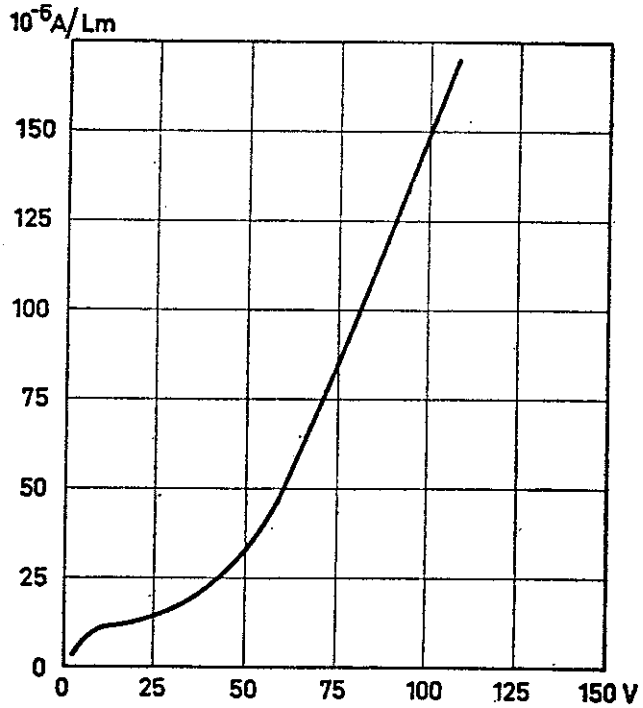


Fig. 199
Current-voltage characteristic of a gas-filled photoelectric cell at constant illumination.

equal to the ratio of the current at V_a to that at $V_a = 15$ V. Since the current through the gas cell varies so strongly with the anode voltage, it is necessary to keep the latter very nearly constant if the cell is to be used for measurements.

A vacuum cell illuminated by daylight (cf. page 259) may have a sensitivity of 80×10^{-6} A/Lm, while a gas cell can give a sensitivity of about 600×10^{-6} A/Lm under favourable circumstances.

BREAKDOWN

For values of V_a under about 100 V, the discharge produced in the gas-filled photocell is not self-sustaining; the current depends on the illumination, and becomes zero if there is no illumination. If however the voltage is increased much above 100 V, we get breakdown and the discharge changes to a self-sustaining glow discharge. The voltage at which this occurs depends on the nature of the gas, the density of the gas, the geometry of the tube and to a certain extent on the intensity of illumination. A breakdown voltage of about 150 V has been measured for several types of photocell in the dark.

A self-sustaining glow discharge arises when the value of n becomes so large that the value of $\gamma(n-1)$ becomes equal to 1 (see I-g-1). Under these conditions the current is independent of the illumination and is only limited by the resistance in series with the cell. The cell thus no longer reacts to the light falling on it.

The photocathode is damaged by the glow discharge, which must therefore be avoided.

THE VALUE OF N

N will of course be increased if the anode voltage is raised but care must be taken not to approach too close to the breakdown voltage. For example at $V_a = 120$ V, N is found to be 7.5 in Fig. 199 and it may assumed that N will always lie between 5 and 10 in practice. But the higher the value of N, the greater the "random" variation in the current at constant illumination. This superimposes an extra amount of noise on the signal; this effect is discussed further in VII-e.

If moreover the light is modulated, the amplification will be found to decrease as the modulation frequency increases. This effect is discussed in VII-d.

VII-c **Permissible cathode load**

The permissible current density from the photocathode of a gas-filled cell is the same as for a vacuum cell, varying from 1 to 5×10^{-2} A/m^2 according to circumstances. If this value is exceeded, the sensitivity of the

of the photo-electric current produced by a light signal with a constant depth of modulation decreases as the modulation frequency increases. In other words, the optimum pressure (0.55 mm Hg) gives a large amplification but a quick drop in the frequency characteristic of the cell; while a lower pressure gives a lower value of N but a more nearly level characteristic.

Calculations [51] show that the number of ion transit times which must elapse for the photoelectric current to fall off to a negligible amount is a function of γ $(n-1)$ (see VII-b). Taking reasonable values for the variables involved, it can be shown that the inertia of the cell will cause an appreciable distortion of the output signal at modulation frequencies above 15 kc/s. The results of measurements made in this connection are shown in Fig. 200. This figure shows the value of the amplification,

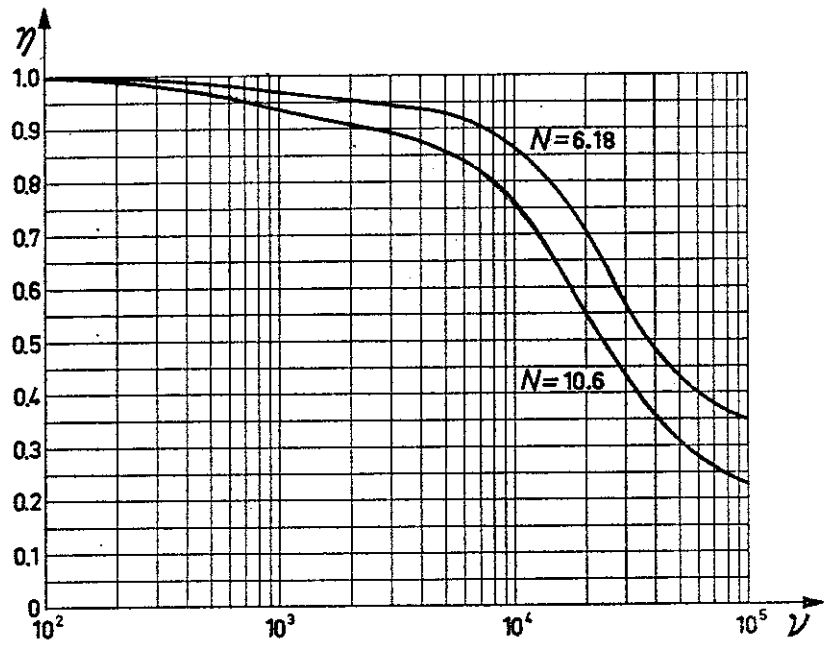


Fig. 200

Fraction η of the amplification N for low frequencies that is obtained for higher frequencies ν. Measured curves for the values $N = 6.18$ and $N = 10.6$ [51].

expressed as a fraction η of its value at low frequencies, as a function of the frequency for two different values of N. At very high frequencies the value of η for $N = 6.18$ approches 0.35, i.e. the fraction of the amplification due to the inertialess electrons without the intervention of the γ effect is 0.35 of the total amplification at low frequencies. In other words, the cell current at very high frequencies tends to n times the direct photocurrent, where $n = 0.35 \times 6.18 = 2.2$.

The η–ν characteristic of a photocell as measured deviates to a certain extent from that calculated on the above-mentioned considerations, espe-

cially in the frequency range from 1 to 5 kc/s. This has been explained as being due to the presence of particles which are even slower than ions, i.e. metastable atoms (see Campbell [53]. These excited atoms, having no charge, move quite independently of the field. Some of these will diffuse towards the cathode, following the "drunk man's walk" typical of thermal motion, and thus taking considerably longer than the ions to get there. On colliding with the cathode, they will free electrons from its surface which will also contribute to the photoelectric current, but with an appreciable delay. This explanation has been verified [54].

THE MODULATION-FREQUENCY CHARACTERISTICS IN PRACTICE

We must now enquire how important this attenuation of the high frequencies is in practice. One important application of photocells is the sound pick-up in talking films, where modulation frequencies of up to about 10 kc/s must be dealth with. In order that all frequencies below this value should be adequately reproduced, the characteristic must not fall by more than 2 dB in this range, i.e. the value of η at 10 kc/s must be at least 0.75.

It will be seen from Fig. 200 that this condition is just satisfied with the maximum attainable gas amplification $N = 10$. If necessary, this decrease of 25 % in η can be compensated by a suitable choice of the frequency characteristic of the amplifier.

In the field of television, however, the frequencies to be dealt with extend right up to several Mc/s: a gasfilled photocell for television purposes has therefore nothing but disadvantages compared to a vacuum photocell or a photomultiplier.

VII-e **Noise in gas amplification**

We will consider only one application of gas-filled photocells in this section: the reproduction of sound for talking films. If the reproduction is to be good, the background noise accompanying the recording must be kept as low as possible. In other words, the signal/noise ratio must be kept high. Both the signal and the noise voltage are taken from the resistance R in series with the photecell. Apart from the noise produced in R itself by thermal motions which we have already discussed, there is also the noise produced in the photocell (see ref. [49], pages 431—432).

The noise from the cell appears to depend mainly on two things:

1. the shot effect at the cathode;
2. the magnitude of the gas amplification factor N.

The shot effect depends on the fact that the primary electrons do not leave the cathode in a constant stream, even if the illumination is constant, but

randomly. This effect is however slight at normal luminous intensities. The mean square of the current fluctuation $\bar{I}$ is proportional to the band width $\Delta\nu$ considered and to the mean photoelectric current $\bar{I}_f$:

$$\bar{I}^2 = F^2 \cdot 2e\,\bar{I}_f\,\Delta\,\nu. \qquad (3)$$

where e is the charge of the electron and F the noise factor, which expresses the fact that the shot effect is partly annulled by the space charge.

In a gas-filled cell the primary photocurrent through the cell is amplified by the factor N; as we have seen, this means that the noise energy due to the shot effect is approximately proportional to N^2, since by the amplification in the gas both $\bar{I}_f$ and e in quation (3) are multiplied by N. But the signal energy also increases as N^2, so the ratio

$$\frac{\textit{thermal noise energy in the load resistance} + \textit{shot-effect energy}}{\textit{signal energy}}$$

will decrease approximately as $1/N^2$, provided that the first term in the numerator is large compared to the second one, which is usually the case.

INFLUENCE OF THE VOLTAGE

The factor F^2 in equation (3) depends on the anode voltage. The value of F^2 is less than 1 in a vacuum cell at low anode voltages, and increases to 1 as the voltage is increased to the point where the current becomes saturating. The shot-effect energy due to the primary electrons is here proportional to the primary photoelectric current $\bar{I}_f$.

In a gas-filled cell the number of electrons is increased and the current amounts to $N\,\bar{I}_f$, however, the proportionality factor for the shot-effect energy is increased by a factor $N^2\,(1 + Q^2)$, where Q is an extra scatter factor caused by the spread of the individual values of N, which is negligible for $N = 5$ to 6 or less, but which must be taken into account for $N = 10$, i.e. at high anode voltages. It is therefore advisable to keep V_a as low as possible not only to prevent breakdown but also to keep the noise level low.

VII-f **Some examples**

Photocells were originally fairly big things. This does not matter much for many industrial applications, but as the sound reproduction methods in talking films developed the demand for small photocells became steadily greater. A small photocell can be placed in the sound head together with the first amplifier tube, which is advantageous for several reasons.

Photo 13 shows a Philips photocell 3554, specially suitable for industrial uses because of the relatively large cathode area. Table XX includes the

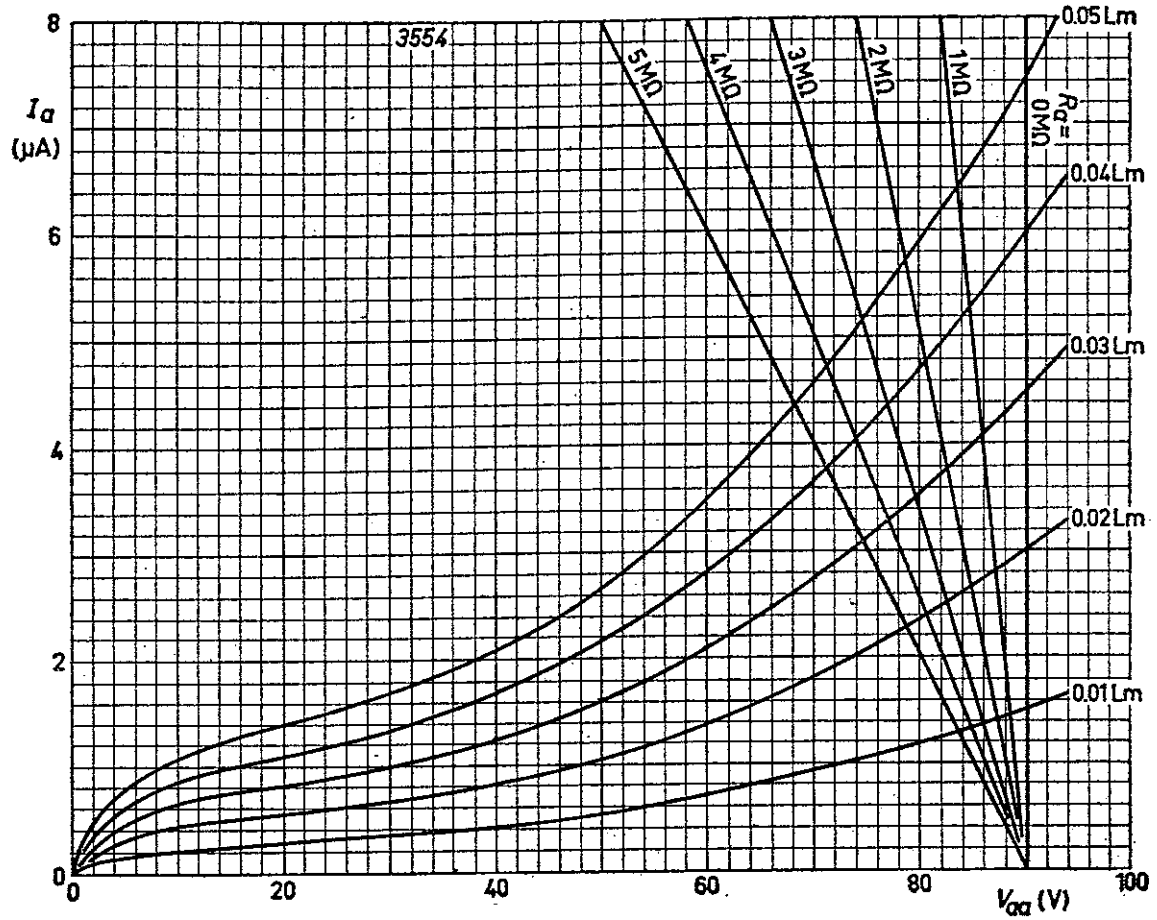


Fig. 201

Current-voltage characteristics for Philips photocell 3554.
Illumination varied in steps:
0.01 Lm; 0.02 Lm; 0.03 Lm; 0.04 Lm and 0.05 Lm.
Resistance lines $V_a = V_{aa} - I_a R$ shown for $R = 1 \text{ - - - } 5$ M Ω and $V_{aa} = 90$ V.

operating data of this photocell. The photo-sensitive layer is deposited on a semi-cylindrical metal cathode, and the rod which forms the anode is placed at the axis of the cathode cylinder. Some I_a/V_a characteristics of this cell are shown in Fig. 201.

The recent model of the RCA type 921 (see Photo 14) is smaller than the above-mentioned photocell. Two metal end plates are sealed on to the cylindrical glass envelope. One of these bears a small plate which serves as the anode and does not obstruct any of the incoming light. The semi-cylindrical cathode is fastened to the other end plate. The sealed-off end of the glass tube which was sealed on to this plate and through which the cell was evacuated, is protected against damage by a metal cap. This cap and a cavity in the anode cover serve as the terminals.

The smallest photocell sold at present is the Philips 58 CG (Fig. 195). The annular anode is mounted above the cup-shaped cathode. The simplest model of this photocell has two lead wires coming out of the glass envelope, by means of which the cell can be soldered directly into the amplifier.

The amount of light falling on to the cell through the slit in the film is usually so small that there is no danger that the sensitivity will be prematurely reduced, as long as the operating instructions are complied with; but the light source should be switched off as soon as the film is removed.

The usual circuit is shown in Fig. 202. The resistor R_1 shown in this figure serves at the same time to limit the anode current and to couple the circuit with the next amplifier stage.

This resistance determines the magnitude of the output signal, and also

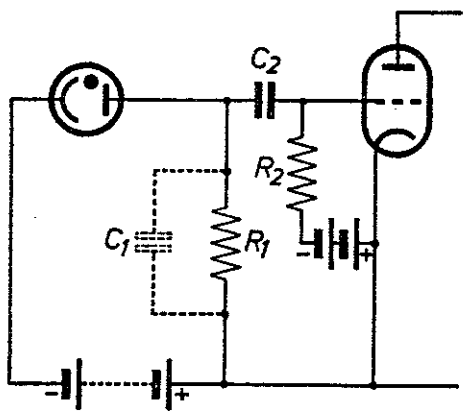


Fig. 202
Usual photocell circuit
R_1 = load resistance
C_1 = parasitic anode capacitance
R_2 = grid resistance
C_2 = coupling capacity

its quality in connection with the interelectrode capacitance of the cell and the unavoidable parasitic shunt capacitance due to the leads of the following amplifier tube. A photocell with a low interelectrode capacitance is therefore to be recommended, but above all the leads to the first amplifier tube should have a low capacitance. This is one of the reasons why the photocell is almost always built into the sound head together with this tube.

TABLE XX

DATA OF SOME GAS-FILLED PHOTOCELLS

	PHILIPS type 3554	R.C.A. type 921	PHILIPS type 58 CG
photosensitive layer	caesium on oxidized silver	caesium on oxidized silver	caesium on oxidized silver
region of maximum sensitivity	red and infrared	red and infrared	red and infrared
projected cathode surface	5.2 cm^2	2.8 cm^2	1.1 cm^2
sensitivity at V_a = ...V	150×10^{-6}A/Lm *) 90 V	at 0 c/s 135×10^{-6}A/Lm at 5000 c/s 119×10^{-6}A/Lm at 10000 c/s 108×10^{-6}A/Lm **) 90 V	108×10^{-6}A/Lm *) 85 V
dark current at V_a = ...V	90 V a) <0.1 μA ($t_{amb}=50°$ C) b) <2.5 μA ($t_{amb}=100°$ C)	— 0.01 μA (25° C)	85 V a) <0.1 μA ($t_{amb}=50°$ C) b) <2.5 μA ($t_{amb}=100°$ C)
series resistance	1 M Ω	2.5 M Ω (I>2 μA) 0.1 M Ω (I<2 μA)	1 M Ω
gas amplification factor	≤ 7	10	≤ 7
C_{ak}	3.4 pF	1 pF	3.0 pF
max cell voltage	90 V	90 V	90 V
max cathode current density	20×10^{-3}A/m²	45×10^{-3}A/m²	15×10^{-3}A/m²
max ambient temp.	100° C	100° C	100° C
total length excluding pins	max. 88 mm	max. 44 mm	max. 33 mm
max diameter	30 mm	22.5 mm	16 mm

*) Measured with an incandescent lamp of colour temperature 2700 °K.
**) Measured with an incandescent lamp of colour temperature 2870 °K.