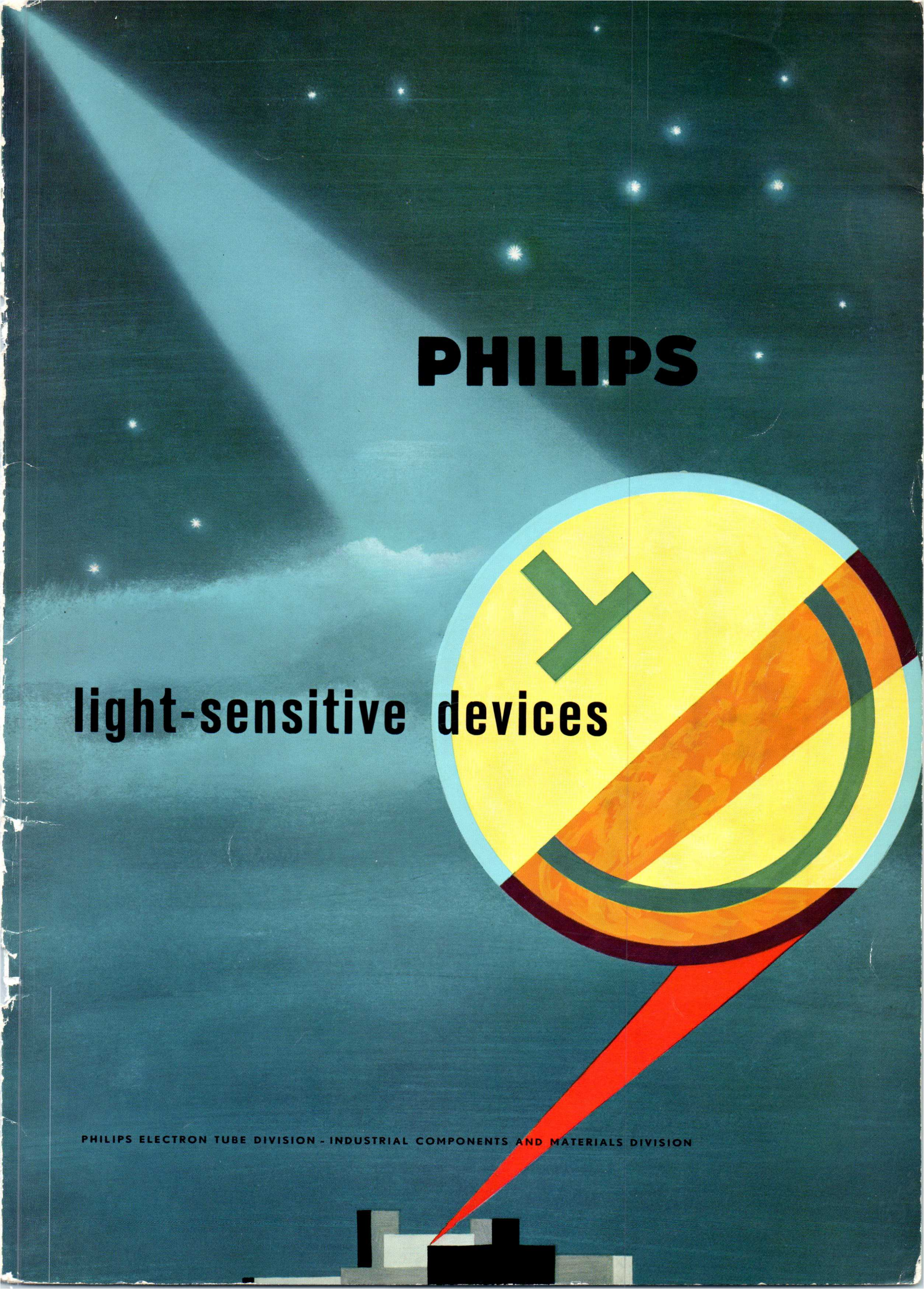

PHILIPS

light-sensitive devices

PHILIPS ELECTRON TUBE DIVISION - INDUSTRIAL COMPONENTS AND MATERIALS DIVISION

Preface

Since the introduction of electronic equipment its development has proceeded rapidly to meet the ever-increasing demands for high reliability, speed and power of the apparatus which are used in the many fields of modern life where electronics are applied. At present, the picture presented by research, industry and business is determined to a large extent by the application of accurate and rapid methods of measurement, regulation and control, which are realised with the aid of a large variety of electronic devices.

The light-sensitive devices display a similar development. In addition to the familiar high-vacuum and gas-filled phototubes, a complete new range of solid-state types has become available. The favourable properties of the latter, such as high sensitivity, inherent sturdiness, compactness and large power-handling capacity, render them an important acquisition to the arsenal of electronic expedients.

The applications of the light-sensitive device are manifold - especially in the domain of automation and mechanisation. In industry it supervises and controls all kinds of processes, such as counting, filling, positioning, safeguarding and warning. It has thus proved its usefulness in numerous cases where it can perform the task of the human eye. As a matter of fact it is in many respects even superior to the eye, as it is indefatigable, more reliable, and sensitive also to invisible light.

New construction techniques have enabled our research and development engineers to make devices which can cope with powers even exceeding 1 watt. These types open the very attractive possibility of directly operating a relay at the appearance or interruption of a beam of light. The amplifier, which is always necessary when conventional phototubes are used, can now be dispensed with, thereby simplifying circuit lay-out and decreasing the cost. In addition a substantial gain in reliability is obtained.

The small dimensions of several newly developed types enable them to be incorporated in miniaturised apparatus, where a large number of them have to be mounted in a small space, e.g. in punched-tape reading equipment. A transistor amplifier circuit equipped with these miniature devices thus constitutes a small,but powerful switching unit.

This publication gives a survey of the current types of photosensitive devices, subdivided into high-vacuum and gas-filled phototubes, photoresistors, photodiodes and phototransitors.

First the physical principles underlying the photo-electric effect are discussed, starting from the modern insights in the structure of solid materials. Further the principles and definitions of photometry are described briefly, followed by a detailed examination of the properties of the light-sensitive devices with a view to their suitability for certain applications. In a separate section several methods of illuminating the photosensitive surface are discussed extensively.

The field of application is subdivided into three groups. The first group comprises on-off applications, where the light-sensitive device ensures a reaction when a light beam either strikes the sensitive surface, or when it is interrupted. In this way a relay can be energised, thus performing counting and switching operations, actuating alarms, etc. The second group of application is the action on fluctuating illumination, where the optical signal is converted into a likewise fluctuating electric one. Examples are the scanning of sound tracks of films, the control of brightness and contrast in television receivers, stabilisation of the illumination level in show windows, etc. Thirdly the photosensitive devices can be used for the detection and, if required, the measurement of weak optical signals.

In Part 2 of this publication a number of elaborate circuits are described. Finally, Part 3 gives a survey of the data and characteristics of the current types of photosensitive devices.

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GENERAL PRINCIPLES

PART 2

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PART 1

General Principles

For a thorough understanding of the properties of photosensitive devices and the way in which several influences can affect their performance, some knowledge of the basic physical principles involved is necessary. The first chapter of this publication is therefore devoted to certain aspects of modern concepts of the structure of solid materials. This will provide an acceptable explanation of various electric properties of solids, particularly of why some materials are conductors, others insulators and yet others are classed as semi-conductors. As will be seen, the last group is of special importance for the most recently developed photosensitive devices.

After a short survey of photometry, its concepts and definitions, in this part the properties of the photosensitive devices are further gone into, and the field of their application is surveyed. Finally, the illumination of the photosensitive surface is discussed, resulting in some suggestions for possible systems of illumination.

1

The structure and electrical properties of solids

1.1. STRUCTURE

In solids, the atoms of which the material consists are arranged in an orderly pattern at definite distances from each other, thus forming a regular three-dimensional lattice. If this lattice occupies a considerable volume of space the block of material is termed a single crystal. The electrical properties of crystals appear to be mainly determined by the behaviour of the electrons moving in the outer orbits of the atom.

It is well-known that the orbital electrons possess definite and different amounts of energy. These quantities of energy do not cover a continuous range, but occupy a series of discrete levels, each level corresponding to a particular orbit. Fig.1 shows this diagrammatically for the case of a single atom. The possible amounts of energy which individual electrons may possess can be calculated by applying the principles of quantum mechanics.

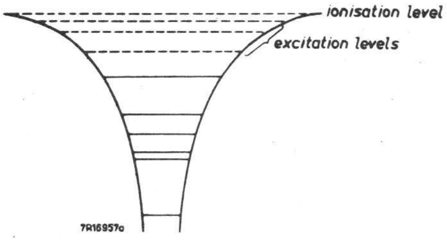


Fig. 1. Energy-level diagram of an atom (not to scale). The distances between the horizontal lines indicate the energy levels, and the lengths of these lines indicate the diameters of the electron orbits.

The nearer an electron is to the nucleus, the smaller is its energy. Now it is one of the laws of Nature that a system always tends to attain a state of equilibrium at which the amount of energy is at a minimum. It might be expected that all the electrons would occupy the lowest level. According to a further physical principle, however, only a certain number of electrons in one atom can exist at any particular energy level. The available levels will therefore be filled up in succession from the lowest upwards until all the available electrons have been placed.

The higher energy levels at which the electrons are permitted to exist are normally empty. They can become occupied, however, if a specific amount of additional energy is imparted to an electron, which causes it to jump to one of the free levels. The electron is then said to be excited, and the free levels are called excitation levels.

If sufficient additional energy is imparted to it, an electron may reach the highest level and pass beyond the influence of the nucleus. This process is termed ionisation and when an electron leaves the atom in this way the atom is said to be ionised. The energy level at which ionisation occurs is called the ionisation level. Usually it is electrons from the highest normally occupied level (outer orbits) which take part in ionisation. These electrons are called the valence electrons.

Fig.2 is a similar diagram to Fig.1, but for two atoms in close proximity. Each original level of the individual atoms now becomes a double one, as the result of a coupling process between the electrons.

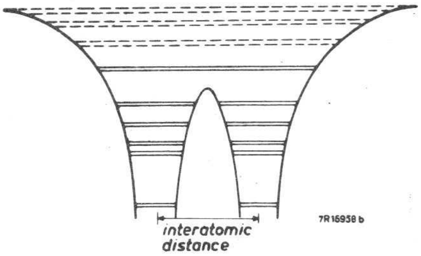


Fig.2. Energy-level diagram of a di-atomic molecule.

The higher energy levels are seen to be shared by both atoms. This means that each of the valence electrons no longer belongs to only one of the atoms, but its orbit is such that the electron revolves around both nuclei, thus binding the atoms together.

The nature of this bond depends on the number of valence electrons in the individual atoms. In this connection it must be accepted that a total of eight electrons forms a very stable combination. For example, the atom of germanium, which has four valence electrons, constitutes its bond by sharing its valence electrons with its neighbouring atoms, so that each atom now has the effective possession of eight valence electrons, as indicated in Fig.3.

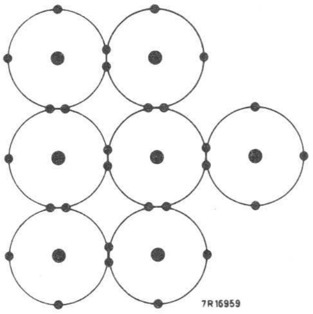


Fig.3. Schematic drawing of germanium atoms, showing the coupling of the valence electrons.

The energy diagram of a crystal is illustrated in Fig.4. It is seen to consist of a series of bands, each containing a large number of levels. These semi-continuous bands are separated from each other by an energy gap, or "forbidden band" of substantial width. Electrons cannot assume energies within this range of values. This is analogous to the discrete energies which the electrons in a single atom can attain, as determined by applying the principles of quantum mechanics to the movement of electrons around the nucleus.

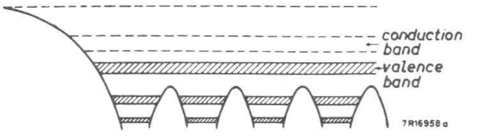


Fig.4. Energy-level diagram of a crystal.

The existence of forbidden bands in a crystal is analogous to the diffraction of X-rays by a crystal, illustrated in Fig.5. Dependent on the angle of incidence of the rays and the distance between the atoms, certain wavelengths are reflected, namely those for which the difference of path length for two adjacent waves is an integral multiple of that wavelength. It can thus be said that those wavelengths are not "allowed" or are forbidden in the crystal.

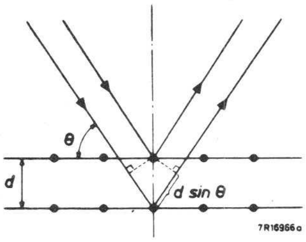


Fig.5. Reflection of an X-ray beam in a crystal. $2d \sin\theta = n\lambda$; $n = 1, 2, 3$.

Now the movement of electrons in a crystal is equivalent to vibration in a number of modes, with definite wavelengths, each wavelength corresponding to a certain energy. Here again certain wavelengths cannot occur in the crystal, hence the existence of the forbidden bands.

The highest permissible energy band which electrons normally occupy in a given crystal is called the valence band. Electrons in the valence band can be brought to a higher energy state by excitation, thus passing into one of the excitation bands. It is usual to call the lowest of the excitation bands the conduction band, since it is the electrons which have entered this band which, under the influence of an electric field, constitute the flow of electrons, familiarly known as an electric current.

When an electron is removed from the atom, it passes through the ionisation level. The difference of energy between the highest occupied level in the valence band and the ionisation level is called the work function of the material.

1.2. CONDUCTORS, INSULATORS AND SEMI-CONDUCTORS

On the basis of the concept of energy bands in a crystal, the fundamental difference between conductors and non-conductors can be explained.

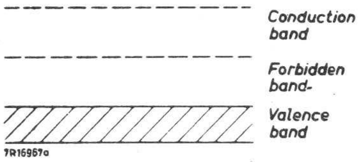


Fig.6. Electron distribution in the energy bands of an insulator.

Consider first a material in which, at the absolute zero of temperature, a number of bands is completely filled, and the higher permissible bands are entirely empty. This condition is illustrated in Fig.6. In such a material, due to the existence of the forbidden bands, it will be impossible to accelerate the electrons by the application of an electric field. In order to do so it would be necessary to supply *instantaneously* an amount of energy equal to the difference of energy between the top of the valence band and the bottom of the conduction band. This is clearly an impossibility since acceleration is a process involving a time dimension. Consequently a material in which this distribution of energy occurs must be classed as an insulator or non-conductor.

In a material the valence band of which is only partly filled, however, the electrons can be accelerated gradually by an applied electric field and can achieve higher levels in the valence band, as indicated in Fig.7. An electric current can now be established - the material is a conductor. This condition may be described as the existence of a "free gas" of electrons.

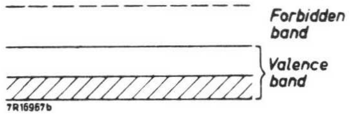


Fig.7. Electron distribution in the energy bands of a conductor.

At temperatures above the absolute zero, for example at room temperature, a small proportion of the electrons tend to achieve higher energies as the result of thermal agitation. In insulators, this tendency is opposed by the width of the forbidden band. Only in those materials in which this energy gap is small can some electrons pass from the valence band into the conduction band and, on the application of an electric field, contribute to an electric current.

Those insulators which have such a narrow forbidden band that at room temperature they have lost their insulating properties, are called semi-conductors. The typical characteristic of these materials is that their conductivity increases with increasing temperatures, since the number of free electrons increases with temperature, whereas in the case of conductors the conductivity decreases with rising temperature as the current flow is impaired by thermal motion of the atoms.

Increase of temperature is not the only cause of excitation. Electrons can also be excited by irradiation with electromagnetic radiation of wavelengths in the infrared region (heat radiation of wavelengths greater than 800 mμ); in the visible region (light waves of wavelengths between 400 and 800 mμ approx.); and in the ultra-violet region (wavelengths less than 400 mμ). This radiation is emitted in discrete energy "packets", termed quanta. In the case of the wavelengths mentioned above the quanta are called photons. A photon has an energy $E = h\nu$ in which h is Planck's constant and $\nu = c/\lambda$ is the frequency of the radiation of wavelength λ, c being the velocity of electromagnetic waves (i.e. the velocity of light). By absorbing a photon, an electron can jump into a higher level of energy.

When a detectable electric effect appears in a circuit, due to the excitation of electrons resulting from irradiation of some element in the circuit, this effect is called a photo-electric effect. The photo-electric effects dealt with in this publication include photo-emission, photoconductivity and the photovoltaic effect.

1.3. PHOTO-ELECTRIC EFFECTS

1.3.1. PHOTO-EMISSION

Photo-emission occurs with materials the work function of which is so low that the energy $h\nu$ of the incident photons is sufficient to ionise the atoms. The electrons released from a thin surface layer of the material are able to leave the photosensitive body with a kinetic energy the maximum value of which is $h\nu - w$, where w is the work function of the material. The photo-emissive effect has a threshold at the long-wave end of the spectrum, i.e. in the region of small quanta $h\nu$, since the energy of the incident radiation must at least be equal to the work function.

Most electrons liberated at greater depths below the surface of the material are recaptured by the ions that are created in the surface layer.

If an electric field is applied between a cathode of photosensitive material and a suitable anode, the photo-electrons emitted from the cathode will be accelerated towards the anode. A current, termed the photocurrent, will therefore flow in the external anode circuit as shown in Fig.8. In other words, the external anode circuit receives electrons from the anode and delivers electrons to the cathode to replace those lost by photo-emission. Devices, which operate on this principle, include high-vacuum and gas-filled phototubes and photomultipliers.

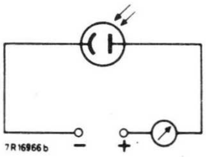


Fig.8. Schematic drawing of a phototube in an electric circuit.

So long as the voltage applied between anode and cathode is small, a negative space charge will exist in the region of the cathode, and, by opposing the field due to the anode potential, will cause emitted electrons to return to the cathode. However, if the anode voltage exceeds a certain critical value, all the emitted electrons will be collected by the anode.

In the case of high-vacuum photocells this condition is termed saturation, and the corresponding value of the anode current is termed the saturation current, the value of which is proportional to the incident lightflux, i.e. to the number of photons with a certain energy which reach the photocathode in unit time. The voltage at which saturation commences is called the saturation voltage V_s (Fig.9).

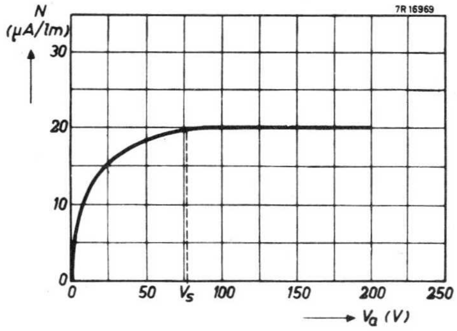


Fig.9. Sensitivity of a high-vacuum phototube as a function of the applied voltage.

Saturation does not occur with gas-filled phototubes, in which the bulb contains a small quantity of inert gas. In this case the photocurrent is amplified due to ionisation of the gas filling resulting from collisions between the photo-electrons emitted from the cathode and the gas atoms. The positive ions thus produced will flow towards the cathode, while the secondary electrons, together with the original photoelectrons, are accelerated towards the anode. On their way these electrons can ionise still other gas atoms, so that for each electron that is liberated by light from the cathode, several electrons reach the anode.

The positive ions reaching the cathode will strike it with sufficient energy to eject more electrons, thus further increasing the current. Typical I-V characteristics of a gas-filled phototube are shown in Fig.10.

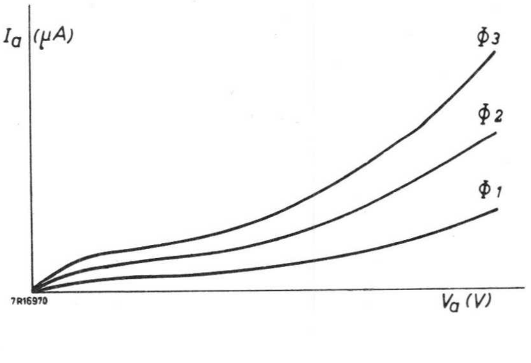


Fig.10. The photocurrent plotted against the applied voltage in a gas-filled phototube, at various values of the incident flux.

The gas amplification increases with the applied voltage, since the velocity of the electrons is proportional to the voltage traversed, so that at high applied voltages ionisation occurs more frequently.

In the third type of photo-emissive tube, namely the photomultiplier, the photocurrent is amplified considerably by secondary emission from a number of auxiliary electrodes (dynodes) situated between the cathode and the anode. For each electron that strikes a dynode, several electrons are liberated and are accelerated towards the next dynode from which still more electrons are ejected, thus further amplifying the current.

In a photomultiplier with ten dynode stages the total current gain is in the order of 10^6 to 10^7. This form of amplification is more advantageous for some applications than the use of a thermionic amplifier. However, since the photomultiplier needs an applied voltage of 1000 to 2000 V, it is not often used for light measurement. For this reason the photomultiplier is not described in any greater detail in this publication. Interested readers are invited to ask for a copy of the publication entitled "Photomultipliers", in which the use of these devices for radiation detection is described.

1.3.2. PHOTOCONDUCTIVITY

Another important photo-electric effect is photoconductivity, that is to say the considerable increase in the conductivity of certain crystals when exposed to an incident light flux. All materials which show photoconductivity are semiconductors, and those most generally employed in photosensitive devices include germanium, silicon, cadmium sulphide and lead sulphide. In these devices electrodes of a suitable material are fitted to the crystal, so that when connected to an electric supply source electrons may enter at the cathode (negative electrode) and leave the crystal at the anode (positive electrode).

As explained previously, in semiconductors the valence band is completely filled with electrons, and between this band and the conduction band there is a narrow energy gap or forbidden band. A very stable bond is constituted, since the electrons are coupled in pairs.

Due to thermal agitation there are always a few electrons in the conduction band at room temperature, so that the material has a certain low conductivity even in the absence of incident light. This corresponds to a "dark resistance" which is finite but of high value.

When light falls upon the material, so-called hole-electron pairs are produced, i.e. electrons are removed from the valence band to the conduction band, each departing electron leaving an empty level or "hole" in the atomic bond.

Since the conductivity is determined by the number of electrons that can be accellerated by an applied voltage, it is increased both by the introduction of electrons in the conduction band and by the formation of holes in the valence band. A hole in the valence band can be filled by an electron from a neighbouring atom, this electron moving from its original energy level into the vacant level of the valence band. Each electron so transferred leaves a hole behind, so that there is, in effect, a current of holes moving in a direction opposite to the drift of the electrons. It will be understood that a hole thus has a positive charge, which is equal to the absolute value of the negative charge of an electron.

It is thus usual to describe the photoelectric current as a current of free electrons moving towards the positive electrode, and a current of free holes moving towards the negative electrode.

However, after some time an electron from the conduction band and a hole from the valence band will recombine, thus neutralising each other. At any given temperature of the crystal there is a state of equilibrium between the production of hole-electron pairs and the recombination. Both processes are influenced by irregularities in the crystal lattice and by the presence of impurities etc.

The average life-time of the hole-electron pairs determines the concentration of the charge carriers, and consequently the conductivity of the material. It is possible to increase the life-time by introducing very small numbers of atoms of suitable impurities into the crystal lattice.

1.3.2.1. Cadmium-sulphide and lead-sulphide cells

In this way various photoconductive cells or light-dependent resistors (LDR) have been developed. Two types of these devices are described below, namely those in which the photosensitive material is cadmium sulphide (CdS), and those employing lead sulphide (PbS).

The dark resistance of both types is very high, namely 10^6 to 10^8 Ω, dependent on the type of cell, while when illuminated the resistance falls rapidly to values in the order of 1 kΩ.

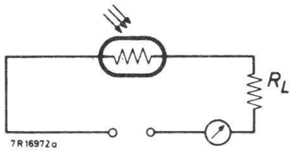


Fig.11. Schematic drawing of a photoconductive cell in an electric circuit.

Fig.11 represents schematically a photoconductive cell in an electric circuit. The photocurrent, as might be expected, is independent of the polarity of the applied voltage.

The impurities which improve the conductivity as indicated above, operate as "cavities", that is to say each impurity atom captures an electron or a hole and retains it for a short time interval, thus prolonging its life-time. This action differs from that of the impurities employed in the crystal junction types of photosensitive semiconductive devices described in the next two sections.

1.3.2.2. The p-n Junction Photodiode

As explained previously, the germanium atom has four valence electrons that are shared with four neighbouring atoms, so that each germanium atom has the stable electron configuration of a filled valence shell.

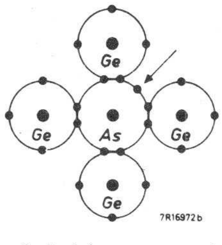


Fig. 12. Arsenic atom included in a germanium crystal. The surplus electron is indicated by an arrow. Only the outer orbits are shown.

If a germanium atom is replaced in the crystal lattice by an atom of a pentavalent element, for example arsenic, one of its five valence electrons cannot partake in the stable bond and will easily be removed from its atom (Fig. 12). Germanium which is activated with pentavalent atoms in a small concentration (1 in 10^7) is called n-germanium. The *n* stands for negative and the pentavalent atoms are called donors since they contribute free electrons.

It is thus seen that at room temperature the n-germanium possesses hole-electron pairs due to the thermal agitation, and an excess of free electrons originating with the donor atoms. These atoms, having lost an electron, are positively charged, but the crystal as a whole is electrically neutral since these positive charges are neutralised by the free electrons.

Similarly a germanium crystal can be activated with trivalent atoms, such as indium. In this case there will be an excess of free holes, since each trivalent atom introduces a deficiency of one electron in the stable bond of eight electrons. This deficiency can be filled by an electron from another atom. This type of germanium is called the p-type; (*p* standing for positive), and the trivalent atoms are called acceptors since each accepts one electron to complete the crystal bond.

A crystal produced in such a way that one part of it is of the n-type and the other part of the p-type, is said to possess a p-n junction. The distribution of free charge carriers in such a crystal is indicated in Fig.13. The electrons that are present in excess in the n-type will tend to diffuse through the junction and recombine with the excess holes in the p-type. Likewise the holes of the p-type will tend to diffuse to the n-type and recombine with the excess electrons.

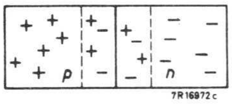


Fig.13. p-n junction in a crystal ; + free holes; - free electrons.

Originally both parts of the crystal were electrically neutral, since the charges of the donor or acceptor ions was neutralised by the free charge carriers, electrons or holes, moving at random through the crystal. But due to the diffusion of the carriers, a boundary layer or zone, exhibiting a space charge and of substantial width, is produced on each side of the junction. The space charge on the p-germanium side of the junction is negative, and on the n-type side of the junction positive (see Fig.14). Across the junction, therefore, a difference of potential is built up, which prevents further diffusion of the carriers across the junction.

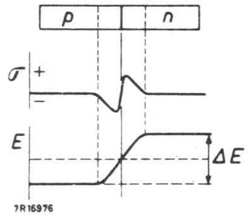


Fig.14. Space charge and corresponding potential difference at a p-n junction.

It is convenient to consider this situation as arising from four currents: two equal currents of electrons flowing respectively from n to p, and from p to n, thus cancelling each other, and two equal currents of holes which also neutralise each other. The currents of minority carriers (i.e. holes in the n-type or electrons in the p-type), arise from the hole-electron pairs which are produced by thermal agitation and move through the crystal. When a minority carrier reaches the junction it is drawn across the junction by the electric field into the region of opposite type germanium, where it ranks as a majority. All minority carriers that reach the junction will pass through it. Consequently, the currents they represent are saturation currents, independent of the height of the potential barrier.

In equilibrium, the effect of these currents is neutralised by currents of majority carriers (i.e. electrons in the n-type and holes in the p-type material). According to Boltzmann, the distribution of energy of the majority carriers is such that the probability of a majority carrier having an energy between E and $E + \mathrm{d}E$ is

$$P(E) = \text{const. } \exp(-E/kT)\,\mathrm{d}E,$$

in which k is Boltzmann's constant and T the absolute temperature. This means that a certain number of the majority carriers will have energies exceeding the potential barrier and will pass through the junction.

When electrodes are attached to the crystal and a voltage is applied, the state of equilibrium is upset. If the polarity of the voltage is such that the p-type zone of the crystal is connected to the positive terminal, the potential barrier is lowered (Fig.15). The majority currents rise exponentially with the applied voltage whereas the minority currents remain constant. Under these circumstances a current in the circuit flows in the crystal from p to n (forward direction), since electrons leave or enter the crystal via the electrodes in order to neutralise the charge that the crystal now has obtained.

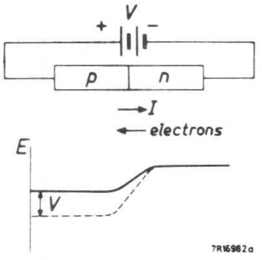


Fig.15. Junction diode biased in the forward direction.

If the positive pole of the supply source is connected to the n-type material, the current of majority carriers decreases exponentially with the voltage, since the potential barrier is increased. The junction is then said to be biased in the reverse direction, and the minority carriers now determine the current through the crystal. This current is a saturation current, independent of the applied voltage. It is proportional to the product of the minority concentrations in the p-type and in the n-type material.

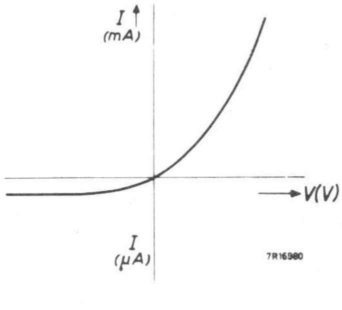


Fig.16. Current versus voltage characteristic of a crystal diode.

The current-voltage characteristic of a junction diode is thus similar to that of a high-vacuum diode, the typical form being shown in Fig.16.

If light falls on the semiconductor, hole-electron pairs are produced, in addition to those due to thermal agitation. Whereas the concentration of the majority carriers is practically constant, the minority concentrations are modified considerably by the incident light, with the result that the reverse current is increased. This phenomenon is exploited in the germanium photodiode. The voltage being applied in the reverse direction, the photocurrent is proportional to the incident light flux and independent of the voltage, as is indicated in the typical characteristics reproduced in Fig.17.

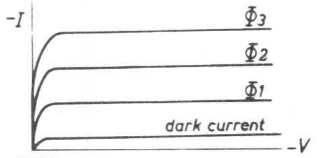


Fig.17. Current versus voltage (in reversed direction) characteristic of a photodiode, at various values of the light flux.

1.3.2.3. The Transistor

In the preceding section the properties of a germanium crystal with one p-n junction were described, and particularly its rectifying action and its behaviour under incident light - properties which have permitted the development of the photodiode. Another form of crystal device is that comprising three zones, separated by two junctions. The transistor consists essentially of such a three-zone crystal (in which the central zone is very thin), with an electrode connected to each zone. The three zones are called the emitter, the base and the collector respectively, the central zone being the base. Two types of transistor are possible: the p-n-p type in which the base is of n-type material, the emitter and collector being of p-type germanium, and the n-p-n type in which the base is of p-type and the emitter and collector of n-type germanium. Only the p-n-p type transistor is described in detail below.

For effective transistor action it is necessary that the base is a thin region of the n-type (in a p-n-p transistor), lying between the two zones of p-type germanium. In operation, a small bias voltage in the forward direction (from *p* to *n*) is applied to the emitter circuit, while the collector circuit receives a greater bias in reverse direction, as indicated in Fig.18.

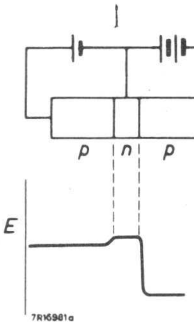


Fig.18. Bias voltages of a p-n-p junction transistor.

A current of holes (majority carriers) will flow from the emitter into the base by diffusion. Since the base is very thin, the greater proportion of the holes will traverse the base, only a very small number recombining with electrons which are in excess in the n-type base material. Those electrons in the base which do recombine are replaced from the base-emitter battery via the base connection, so that a base current flows in the external circuit.

The collector current thus approximately equals the emitter current and represents, in effect, the flow of holes emanating from the emitter and reaching the collector junction. Since, in normal operation, the input impedance of the transistor is low with the emitter circuit biased in the forward direction, and the output impedance is high with the collector circuit biased in the reverse direction, the transistor action is amplification of power.

If the emitter voltage or the base current are varied, corresponding variations will occur in the collector current. The collector/emitter current amplification factor is defined as the ratio of the alternating component of the collector current to the alternating component of the emitter current: $\alpha = i_c/i_e$. It is clear that this factor is less than unity (in practice 0.95 - 0.98).

The current amplification factor between collector and base, α', is equal to i_c/i_b, and is clearly much greater than unity.

The material germanium is sensitive to light. In normal transistors, therefore, the glass envelope is rendered opaque by a coating of varnish, so that the collector current is controlled only by varying the base current or emitter voltage. In the phototransistor, on the other hand, light is used to control the collector current, and for this purpose the envelope is left unscreened. Phototransistors are usually operated with the base contact open-circuited, the positive terminal of the bias supply being connected to the emitter and the negative terminal to the collector contact.

The light falling on the base material produces hole-electron pairs. The holes are attracted into the collector by the negative potential so that the base becomes negatively charged, as a result of which holes are drawn from the emitter. For each hole that is produced in the base by the action of light, $\alpha' + 1$ holes will leave the emitter, thus amplifying the original photocurrent.

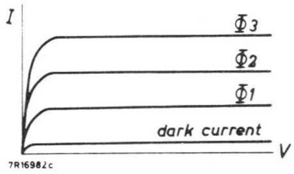


Fig. 19. Collector current versus voltage characteristics of a phototransistor, at various values of the light flux.

The collector circuit thus behaves as a junction diode and the emitter circuit as an amplifier. The phototransistor is about α' times as sensitive as the photodiode, Its current vs. voltage characteristics are analogous to those of the diode, as indicated in Fig.19.

1.3.3. PHOTOVOLTAIC EFFECT

In the preceding sections two forms of photoelectric effects were dealt with, namely photoemission and photoconductivity. A third effect, very similar to the latter, is the photovoltaic effect.

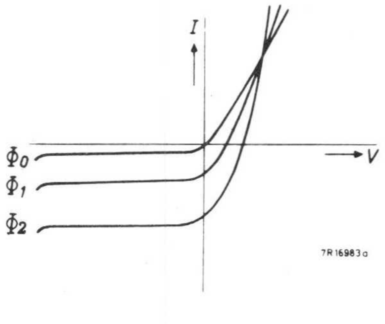


Fig. 20. Current versus-voltage characteristics of a p-n junction.

As can be seen from the characteristics of a p-n junction (Fig.20), a current will flow with the device short-circuited, i.e. at $V = 0$, when it is exposed to light. This is a current in the reverse direction, and consists of minority carriers produced under the influence of the incident light.

Conversely, when light falls on an open-circuited photodiode, a voltage will appear across the device. This is called the photo e.m.f.

The phenomenon is exploited in the solar cells which are used for the conversion of solar energy into electric energy. The efficiency attainable is low, and depends on the properties of the semiconductor, such as its energy gap, and the donor and acceptor concentrations in the n-type and the p-type zones respectively. Furthermore, the conversion efficiency is affected by the spectral distribution of the incident light.

In the earliest form of photopile employing selenium, the effeciency was at the most 1%, but modern silicon photodevices have operating efficiencies of about 10 %. There is a promising future for these elements for low-power applications.

2

Photometric concepts, definitions and units

Before the different types of photosensitive devices are further discussed, thus enabling the user to choose the most suitable type for a particular application, some basic quantitative photometric concepts must be considered.

A light source emits radiation of many different wavelengths and in all directions into space. The spectral distribution of the emitted radiation, i.e. the distribution of energy at different wavelengths, is determined by the properties of the source. Thus, practically all the light emitted by a sodium lamp is of one characteristic wavelength (589 mμ). This is called monochromatic light. Other sources, such as fluorescent lamps, emit light of a number of discrete wavelengths, together with a continuous spectrum, so that the spectral distribution approximates to that of daylight. On the other hand, an incandescent light source, such as a tungsten lamp, emits radiation over a continuous range of wavelengths only. The intensity of the flux depends on the material of the filament and its temperature.

As the radiation of a black body (full radiator) can be expressed by an exact formula, so that for a given temperature the spectral distribution of energy is fixed (Fig.21), the flux of an incandescent lamp is referred to the black-body radiation.

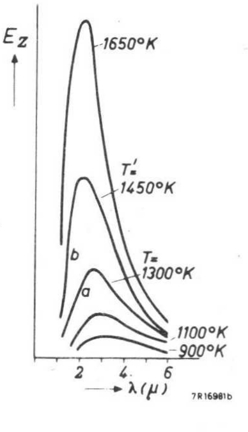


Fig.21. Black-body radiation as a function of the wavelength.

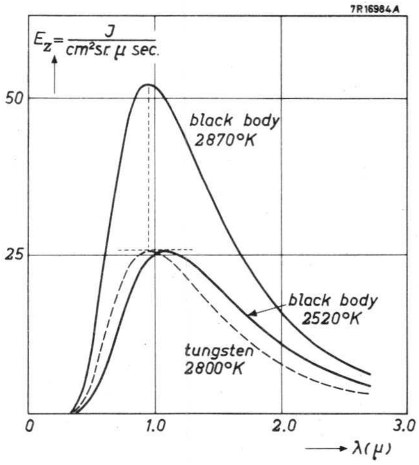
Wien has shown that curve *a* of Fig.21 can be transposed into curve *b* by multiplying the wavelengths by T/T', and the ordinates by $(T'/T)^5$. The curves therefore have a uniform shape.

Now the spectral distribution of the radiation emitted by an incandescent lamp is approximately the same as that of a black-body radiator; but its intensity is less by a factor less than unity. By definition, this factor, which is called the emission factor, is equal to unity only for a black body. For tungsten the emission factor is about 0.5, slightly increasing from longer to shorter wavelengths, so that the maximum of radiation is shifted slightly to the left compared with a black body. The intensity of the radiation of a tungsten lamp can be expressed as the "luminance temperature", i.e. the absolute temperature a black body should have in order to emit radiation of the same intensity as the tungsten lamp. This luminance temperature of tungsten is obviously some hundreds of degrees below the true temperature of the filament.

The spectral distribution of the radiation from an incandescent lamp is expressed by the colour temperature, i.e. the absolute temperature of a black body when its maximum of radiation is of the same wavelength as that of the tungsten radiation. As the emission factor of tungsten is almost constant, the colour temperature is practically equal to the true temperature (Fig.22).

Fig. 22. Curves relating the radiation of a tungsten filament with black-body radiation.

true temperature	2800 °K
luminance temperature	2520 °K
colour temperature	2870 °K



In general, the flux of energy emitted is expressed in watts. In photometry, however, it is usual to express the light flux, that is to say the total amount of visible radiation emitted or received by a given surface, in lumens. This quantity, denoted by Φ, is given by the expression

$$\Phi = 680 \int_{380}^{760} v_\lambda E_\lambda d\lambda \text{ lumen}$$

where E_λ is the flux in watts between λ and $\lambda + d\lambda$, and v_λ the "international luminosity factor", representing the sensitivity of the average human eye as a function of the wavelength (Fig.23). The constant 680 has the dimension of lumens per watt. It can thus be seen that at the maximum sensitivity of the eye (550 mμ) 1 watt corresponds to 680 lumen (since then $v_\lambda = 1$).

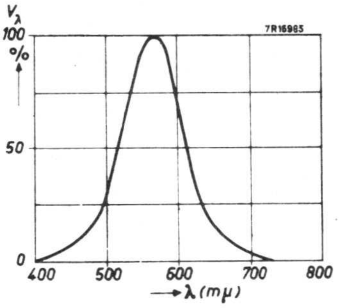


Fig. 23. Sensitivity of the human eye as a function of the wavelength.

In the case of an incandescent lamp the flux is completely described by its colour temperature and the number of lumens which it emits.

The illumination E of an area A is defined as the incident light flux per square metre, i.e. $E = d\Phi/dA$. The unit of illumination is the lux, one lux corresponding to one lumen per square metre.

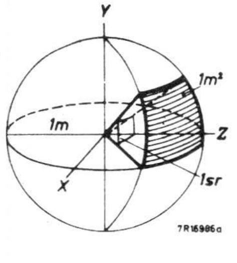


Fig.24. Diagram illustrating the definition of the solid angle.

The portion of a spherical space occupied by a given beam of light emitted from a light source (point source) situated at the centre of the sphere is called the solid angle of the beam, and is expressed in steradians (sr). The steradian is defined as follows: Imagine a point source located at the centre of a sphere of 1 metre radius (Fig.24). A beam impinging upon one square metre of the surface of the sphere is said to have a solid angle of one steradian.

If the radius of the sphere is increased to R m, this beam of 1 sr will irradiate a surface of $R^2 \mathrm{m}^2$. Consequently, a spherical surface S at a distance R from the source receives radiation over a solid angle $\omega = S/R^2$ sr. A sphere contains a total of 4π sr.

The light flux in lumens emitted in a given direction per unit of solid angle is called the intensity of the source. The intensity $I = \mathrm{d}\Phi/\mathrm{d}\omega$ and is expressed in candela (cd) or lumens per steradian.

Finally the luminance is defined as the flux in lumens radiated into a steradian of solid angle per unit of projected area as seen in the considered direction. In other words, the luminance is the intensity per projected unit area of radiating surface (in cm^2) in a given direction. Thus $B = \mathrm{d}I/\mathrm{d}A\cos\varphi$; it is expressed in candela per square centimetre ($\mathrm{cd/cm}^2$) i.e. lumens per square centimetre per steradian.

The relationships between the above-mentioned units are indicated in a simple manner in Fig.25:

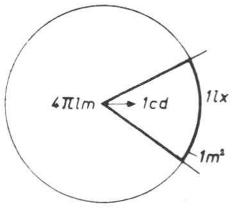


Fig.25. Relation between various photometric units.

If a light source which radiates with a uniform intensity of 1 cd in all directions is located at the centre of a sphere of radius 1 m, it emits a light flux of 1 lumen into each steradian of solid angle. The total emission of this light source is 4π lm. The illumination of the surface of the sphere is 1 lx. If this light source has a radiating surface of 1 cm^2 perpendicular to the considered direction, its luminance is 1 $\mathrm{cd/cm}^2$.

Consider now a surface S located at a distance R from a light source of intensity I (cd) in the direction of the line joining the source and the surface S. This surface receives a flux of IS/R^2 lumens, provided the direction of the beam is normal to the surface, and no optical system is inserted between the lamp and the surface (Fig.26). The normal incandescent lamps (General Lighting Service) are manufactured for a colour temperature of 2700 - 2900 $^{\circ}$K. Their emission, in lumens/watt, is therefore approximately constant. A value of 13 lm/W can be taken for design calculations. If the lamps emitted equally in all directions, the intensity would be $1/4\pi$ times the flux. For practical purposes, the intensity in candela in the forward direction is equal to the number of lumens divided by 10.

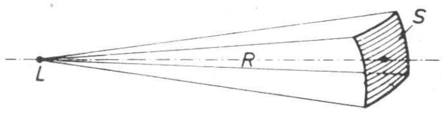


Fig.26. Point source L illuminating area S.

The photometric units described above are those employed in modern practice. However, a number of older, obsolete units are still met with occasionally. The relation between the old and the new units is given below:

$$\text{Illumination } E = \frac{\text{light flux}}{\text{surface}};$$

$$\text{unit: lux} \quad (\text{lx}) = \frac{\text{lumen}}{\text{metre}^2}.$$

$$\text{foot-candle } (\text{fc}) = \frac{\text{lumen}}{\text{foot}^2}.$$

$$\text{phot} \quad (\text{ph}) = \frac{\text{lumen}}{\text{cm}^2}$$

$$1 \text{ lux} = 1/10.764 \text{ foot-candle}$$
$$= 10^{-4} \text{ phot.}$$

$$\text{Luminance } B = \frac{\text{light flux}}{\text{surface area x solid angle}};$$

$$\text{nit} = \frac{\text{candela}}{\text{metre}^2} = \frac{\text{lumen}}{\text{m}^2 \text{ steradian}}$$

$$\text{stilb} = \frac{\text{cd}}{\text{cm}^2}$$

$$\text{apostilb} = \frac{\text{lux}}{\pi \text{ steradian}}$$

$$\text{foot-lambert} = \frac{\text{foot-candle}}{\pi \text{ steradian}}$$

$$\text{lambert} = \frac{\text{phot}}{\pi \text{ steradian}}$$

$$1 \text{ cd/cm}^2 = 1 \text{ stilb}$$
$$= 10^4 \text{ nit}$$
$$= \pi \cdot 10^4 \text{ apostilb}$$
$$= \frac{1}{3.426} \cdot 10^4 \text{ foot-lambert}$$
$$= \pi \text{ lambert}$$

3

The properties of photosensitive devices

In Chapter 1 a number of photosensitive devices have been mentioned. Two main groups can be distinguished:

A. Photoemissive types
(1) high-vacuum phototubes;
(2) gas-filled phototubes.

Instead of the familiar thermionic emission, electrons leave the cathode by the agency of incident light. In the gas-filled phototubes gas amplification of the photocurrent occurs.

B. Photoconductive types
(3) photoconductive cells or light-dependent resistors (LDR);
(4) photodiodes;
(5) phototransistors.

The incident light produces hole-electron pairs which improve the conductivity of the sensitive material (decrease its resistance). In the photodiode a p-n junction is introduced thus giving the device rectifying properties. The phototransistor can be considered as a photodiode in which the current is amplified by the emitter circuit.

In this chapter these devices will be compared in respect of their more important properties.

3.1. SPECTRAL RESPONSE

Photosensitive devices produce an electric effect only with incident radiation of a limited range of wavelengths. At the red end of the spectrum there is a threshold wavelength above which no photoelectric effect can occur. The photons ($h\nu$) of that radiation carry insufficient energy to ionise the atoms to permit photoemission, or, in the case of photoconductivity, to excite the electrons to cross the energy gap between the valence band and the conduction band.

At wavelengths lower than the treshold value the response increases at first, because as the energy of the photons increases, more electrons are excited. There is, however, a critical wavelength below which the absorption of the glass envelope of the device has a perceptible effect and the response decreases.

The spectral response curve is the curve which shows the relationship between the electric signal and the wavelength of the incident flux of constant value (in watts), the ordinates indicating the ratio of the signal at a given wavelength to the signal at the wavelength where the signal is a maximum. The spectral sensitivity is determined by the properties of the photosensitive material.

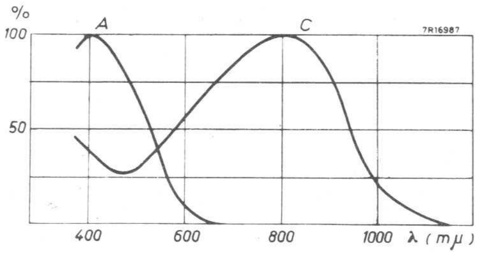


Fig.27. Relative spectral response of phototubes with *A*-type and *C*-type cathodes.

Photo-emissive cells are produced in two types by using different cathode materials, one red-sensitive and the other blue-sensitive. It has been found that caesium-on-oxidised silver is a very good red-sensitive cathode. It is known as the C-type of cathode. A phototube with maximum response in blue has a cathode of caesium-on-antimony, termed the A-type cathode. The spectral responses of the two types are shown in Fig.27. Both curves are cut off at approximately 385 mμ, since radiation of lower wavelengths is absorbed by the glass. If a tube is required for operation with ultraviolet radiation, the bulb must be provided with a quartz window which transmits these wavelengths.

Photosensitive devices of the cadmium-sulphide type have their maximum response at about 700 mμ in the red region, whereas the lead-sulphide cells are particularly sensitive to heat radiation, i.e. infra-red, with a maximum at 2.5 μ, as indicated in Fig.28.

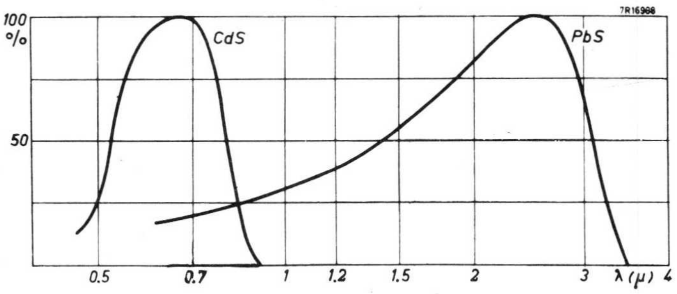


Fig.28. Spectral response curves of the cadmium-sulphide and lead-sulphide photo devices.

Germanium photodiodes and phototransistors are most suitable for use in the infra-red region, their response being maximal at 1.55 μ, but still have a considerable sensitivity to visible radiation, as can be seen from Fig.29.

The photoelectric signal is, of course, the result of the summation of the response for each wavelength to the incident flux for that particular wavelength.

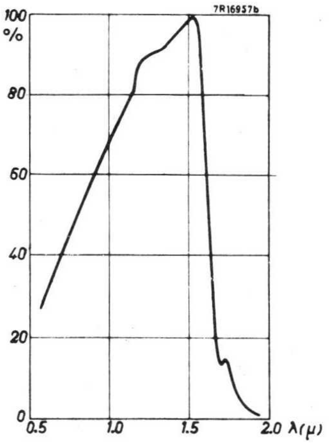


Fig.29. Spectral response curve of the germanium photodiode and phototransistor.

Thus

$$I_p = C \int g_\lambda E_\lambda d\lambda,$$

the integral being taken over the range of wavelengths where g_λ and E_λ differ from zero.

g_λ is the relative spectral response,
E_λ is the spectral emission of the light source in watt/mμ,
C is a constant having the dimension mA/W.

3.2. SENSITIVITY

The relative spectral response is measured at an incident flux of 1 W on the sensitive surface. The sensitivity is a measure of the total response at a given illumination, expressed either as the photoelectric current in mA per lumen of incident light flux, or that photocurrent at a certain illumination in lux. In the first case it is referred to as the lumen-sensitivity, and in the latter case as the lux-sensitivity. The lux-sensitivity can be calculated from the lumen-sensitivity by multiplying the lumen sensitivity by the sensitive area: lux-sensitivity = lumen-sensitivity x sensitive area.

The sensitivity is quoted for a specified colour temperature of the light source, since, as can be seen from the spectral response curve, the devices are also sensitive to radiation outside the visible range. The colour temperature fixes the distribution of energy of the incident radiation on the wavelengths, and consequently the amount of flux in the infra-red region that contributes to the photoelectric signal. This infra-red radiation is not included in the number of lumens. It may thus happen that two different amounts of radiated energy indicate equal amounts of light flux but produce different photocurrents, due to the fact that they contain different infra-red components.

For tungsten incandescent light sources this is of little importance, since all these lamps have approximately the same colour temperature. The photocurrent then can be determined by calculating the flux falling on the projected sensitive area S of the device and multiplying this by the lumen-sensitivity. As explained earlier, this flux is IS/R^2, I being the intensity of the lamp and R the distance between the lamp and the photosensitive device.

The photocurrent is also equal to the lux-sensitivity multiplied by the illumination E, ($E = I/R^2$). This illumination can be measured directly with a lux meter on the plane of the sensitive surface.

As the devices have a somewhat large spread of sensitivity, this method is sufficiently accurate to give an approximate determination of the photocurrent to be expected. For exact measurements with the aid of photosensitive devices the light source and the devices must be calibrated. This the manufacturer will do on request.

If it is desired to calculate the signal caused by coloured light or infra-red radiation, such as are met with in applications in colorimetry, alarms etc., a more complex method must be used.

For this purpose the radiation in a comparatively narrow band of wavelengths is used. This can be obtained by means of a filter which transmits only the desired narrow range of wavelengths, the others being attenuated or suppressed. The emission for a given wavelength λ is then $t_\lambda E_\lambda$, t_λ being the relative spectral transmission of the filter, and E_λ the spectral emission of the applied light source, which may also be a monochromatic light source.

The values of E_λ are given in tables. Those for tungsten lamps will be found in "The Emissivity of Tungsten Ribbon", by J.C. de Vos (Thesis V.U. 1953).

In general, when the distribution of energy falling on the sensitive surface is E_λ, the photocurrent is

$$I_p = C \int g_\lambda E_\lambda d\lambda,$$

where g_λ is the relative spectral response of the device.

The sensitivity s, measured with an incandescent lamp of colour temperature T, is expressed in milliamperes per lumen. The number of lumens this lamp emits is

$680 \int v_\lambda E_{T\lambda} d\lambda$, where v_λ is the international luminosity factor. The photocurrent is therefore:

$$I_p = 680\, s \int v_\lambda E_{T\lambda} d\lambda = C \int g_\lambda E_{T\lambda} d\lambda,$$

so that with an arbitrary light source:

$$I_p = s \frac{680 \int v_\lambda E_{T\lambda} d\lambda}{\int g_\lambda E_{T\lambda} d\lambda} \int g_\lambda E_\lambda d\lambda,$$

the integrals being taken from zero to infinity, or, what amounts to the same thing, for the range of wavelengths over which v_λ and g_λ have values different from zero.

It can be proved, that for all photosensitive devices

$$I_p = K e \Phi \frac{\tau}{\theta},$$

in which

Φ is the number of photons that liberate an electron,

K is the quantum efficiency, i.e. the fraction of Φ that causes a photoelectric effect,

e is the charge of the electron,

τ is the life time of the photoelectrons and θ their transit time, i.e. the time which they take in moving from one electrode to the other.

In photo-emissive cells the quantum efficiency is very much less than unity, since the electrons liberated at some distance below the surface are recaptured and their energy is converted into heat. The dimensionless factor τ/θ equals unity for high-vacuum cells, but for gas-filled cells it represents the gas amplification factor. Gas-filled cells are thus about 5 to 10 times as sensitive as vacuum cells.

In semiconductive elements the quantum efficiency closely approximates to its maximum value, i.e. unity. Carriers, moving in an electric field of field strength E cover in a time θ a distance d, according to the expression $d = \mu E \theta$, where μ is defined as the mobility of the carriers. Thus if a voltage V is applied at a CdS device, the transit time of the electrons between electrodes spaced at a distance d apart is $\theta = d^2/\mu \mathrm{V}$.

Substituting this in the general formula $I = K e \Phi \tau/\theta$, it can be shown that

$$I = \frac{e \Phi \tau \mu}{d^2} \mathrm{V},$$

or

$$R = \frac{V}{I} = d^2/e \Phi \tau \mu,$$

i.e. the resistance of the device decreases in proportion to the increase of the incident light flux.

The factor τ/θ now is again an amplification factor which in this case has values in the order of 10^3. This can be explained by the fact that, when the device is illuminated, the photoelectrons circulate many times through the external circuits before being recaptured. Thus the sensitivity of these devices is much higher than that of photoemissive cells.

The sensitivity of the photodiode can be studied by reference to the photodiode OAP 12, which has a surface junction perpendicular to the incident light, as illustrated in Fig.30. The photons pass through a thin layer of n-type germanium, in which they produce hole-electron pairs. The photo-electric effect becomes manifest

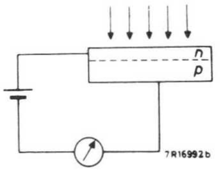


Fig.30. Photodiode with surface junction in an electric circuit.

as an increase in the hole current across the junction. Since this is a saturation current, the sensitivity of the device is independent of the applied voltage. The quantum efficiency is in this case the probability that a hole reaches the junction. This probability and the transit time both depend on the distance the injected holes have to travel, so that, in the photodiode, and equally in the phototransistor, the current is dependent on the direction of the incident light. The preferred direction is indicated in the published data on the devices.

A summary of the lumen- and lux-sensitivity of various types is given in the table below.

type	sensitivity (mA/lm)	sensitive surface (m^2)	sensitivity ($\mu A/lx$)
high-vacuum cell 92 AV	$45 \cdot 10^{-3}$	$2.1 \cdot 10^{-4}$	$10 \cdot 10^{-3}$
gas-filled cell 92 AG	$130 \cdot 10^{-3}$	$2.1 \cdot 10^{-4}$	$27 \cdot 10^{-3}$
photomultiplier 50 AVP	$5 \cdot 10^{5}$	$8 \cdot 10^{-4}$	$4 \cdot 10^{5}$
photoconductive cell ORP 90 (at 10 V)	10^3	$1.8 \cdot 10^{-4}$	180
photodiode OAP 12	50	$1 \cdot 10^{-6}$	$50 \cdot 10^{-3}$
phototransistor OCP 70	130	$7 \cdot 10^{-6}$	$920 \cdot 10^{-3}$

The CdS light-dependent resistor (LDR) is commonly rated in terms of the light value of its resistance at a certain illumination, and its dark value, measured in total darkness. In Fig.31 the variation of the resistance with change of illumination is shown for a typical sample.

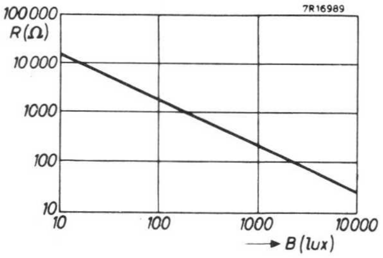


Fig. 31. Resistance of a light-dependent resistor (LDR) as a function of the illumination.

As the PbS photoconductive cells are particularly sensitive to radiation in the infra-red region, their performance is usually expressed in volts across the cell load per watt of total radiation of source energy at some specified temperature (black-body radiator). The sensitivity increases rapidly with the temperature of the source, for example by a factor of about 100 when the temperature is increased from 200 °C to 500 °C.

3.3. FREQUENCY RESPONSE

When intermittent light falls on a photosensitive device the photocurrent is also intermittent and can be considered as a direct current, corresponding to the mean value of the light flux, on which is superimposed an alternating current corresponding to the variations of light flux above and below the mean value. When the light is first switched on the electrical signal tends to rise towards its final value, its rate of increase being represented by the factor $(1 - e^{-t/\tau})$. The signal decreases according to the same factor when the light is switched off.

The time constant τ is determined by parasitic capacitances and the transit time of the carriers. At higher modulation frequencies of the incident light the sensitivity will drop, according to the expression

$$\frac{s(f)}{s(0)} = \frac{1}{\sqrt{1 + (2\pi f\tau)^2}}.$$

The cut-off frequency is defined as the frequency at which the sensitivity has dropped to $1/\sqrt{2}$ of its original value, i.e. at a frequency $f = 1/2\pi\tau$. This frequency is dependent on the external load and on the shape of the curve which relates light intensity and time, that is to say the waveform of the modulating light signal.

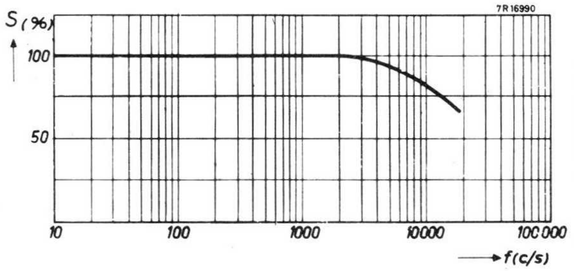


Fig.32. Frequency response of a gas-filled phototube.

The cut-off frequency of high-vacuum phototubes is very high, about 100 Mc/s. The behaviour of gas-filled tubes at the higher modulation frequencies is determined by the transit time of the positive ions. These ions are more massive and consequently attain lower velocities than the electrons. When the light is switched off, therefore, the ions still move towards the cathode, where they release electrons by collision. These electrons are accelerated towards the anode and will ionise a few gas atoms, so that there is a tendency to maintain the current. The number of newly produced ions and electrons is, however, too small to keep the anode current flowing, so that after a short time the tube extinguishes. With a light modulation frequency of 1 kc/s the sensitivity begins to drop, but, as shown in Fig.32, this decrease is negligible for practical applications at modulation frequencies up to 10 kc/s.

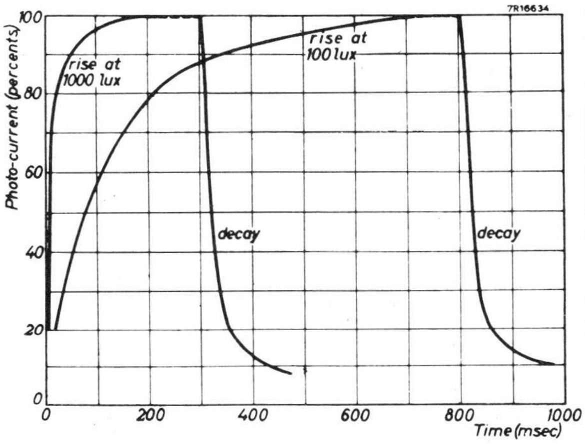


Fig.33. Response time of CdS photoconductive cells, at various values of the illumination.

Photoconductive cells have a large time constant, so that, at modulation frequencies of a few cycles per second, the signal decreases already. This is due to the long life time of the carriers. The higher the level of illumination, the smaller the response time, as the cell resistance and consequently the time constant is smaller (see Fig.33).

Junction devices have a self-capacitance resulting from the space charge that exists at the junction. The cut-off frequency of the photodiodes is about 40 kc/s. For the phototransistor, however, it is only about 3 kc/s. This is much lower than with a comparable normal transistor, because the hole-electron pairs are introduced in the base at different distances from the collector junction. Individual carriers thus have different transit times and this is detrimental to good frequency response.

Photosensitive devices are always used in connection with some other electronic device such as an amplifier, measuring equipment, relay etc. The cells must therefore be considered as a part of the circuit to which they deliver a certain amount of power.

The active part of the equivalent circuit of a photosensitive cell can be represented by a voltage or current generator, the properties of which depend on the frequency and the time constant. With a pure sinusoidal signal, the ratio of the amplitude at modulation frequency f to that with unmodulated light is:

$$\frac{a(f)}{a(0)} = \frac{1}{\sqrt{1 + (2\pi f\tau)^2}},$$

and the phase lag amounts to

$$\varphi = \arctan 2\pi f\tau,$$

assuming, of course, that the associated circuit does not limit the frequency.

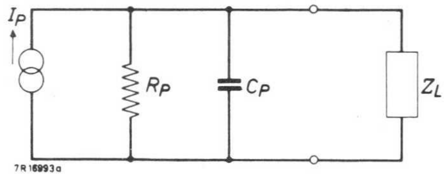


Fig.34. Equivalent circuit of a photosensitive device in an electric circuit.

In the equivalent circuit represented in Fig.34, the internal resistance and the capacitance are shown as a parallel resistor and capacitor, and the load as an impedance. It will be clear, therefore, that the frequency behaviour is determined not only by the properties of the photoelectric material but also by those of the following circuit.

3.4. TEMPERATURE DEPENDENCE

The range of applications of photosensitive devices is somewhat restricted because their performance is affected by heat agitation and ambient radiation.

If a voltage is applied to one of these devices a current will flow even if the device is not illuminated. This is called the dark current. Like the photocurrent, the dark current consists either of electrons released from the cathode of a photoemissive cell, or, in the case of semiconductor devices, of electrons excited from the valence band into the conduction band. As was seen earlier, this effect is the result of thermal agitation, since at temperatures above zero electrons attain higher energies. The dark current therefore increases with the ambient temperature and can be deminished by cooling the device.

In addition, ambient radiation - both heat and light - from stray sources produces dark current. This radiation will be in a continuous spectrum of wavelengths and those stray photons having energies above the threshold value will excite electrons.

This treshold is fixed by the work function in the case of photoemissive material, and by the energy gap of photosensitive semiconductors, so that the greater the threshold wavelength, the easier it is for the electrons to be excited, and the more sensitive the devices will be to variations of the ambient temperature. Thus the energy gap and the dark current are closely related.

Moreover, the intensity of the ambient radiation is usually greater in the infra-red region than in the visible region, so that the dark current of devices the spectral response of which is in the infra-red (small ΔE) is greater than of those having maximum spectral response in the visible region.

When the sensitive surface is illuminated, a small fraction of the total photocurrent represents the dark current. Any fluctuation of the dark current is perceptible as noise in the photoelectric signal.

Theoretical considerations show that the shot noise of a primary current, i.e. a current that is not amplified, is proportional to the current and to the modulation bandwidth: $i^2 = 2eI\delta f$. With semiconductive devices, the noise power at low frequencies is inversely proportional to the frequency. At high frequencies, however, the amplitude of the fluctuations is independent of the frequency, over a certain bandwidth.

Like the dark current, the noise is affected by the ambient temperature and the spectrum of ambient radiation, since it depends on the energy gap of the photosensitive material. Thus the dark current is a measure for the noise of the devices.

In order to define the noise, a figure called the equivalent noise power is quoted by the manufacturer. This is the energy (in watts) which would produce an electric signal, the effective value of which is equal to that of the noise. Consequently, the equivalent noise power determines the threshold of sensitivity, i.e. the smallest signal that can be detected by the device. The equivalent noise power is, of course, quoted for specified conditions as to bandwidth, frequency, incident radiation and temperature.

To avoid damage to photosensitive devices, limitations are imposed upon the permissible ambient temperature, during use and in storage. This means that the permissible dissipation of the devices for a given ambient temperature is also limited, since flow of current through the device increases its temperature. In the case of the phototransistor, for example, the temperature rise above the ambient is about 0.4 $^{\circ}$C per mW dissipation.

Again, with the photodiode and the phototransistor the reverse current increases considerably if the applied voltage in the reverse direction is higher than a critical value, the avalanche or Zener voltage. The electrons then pass in a large number through the junction by shock ionisation or tunnel effect respectively. The voltage must therefore not be allowed to exceed this critical value, which is in the region of 50 V.

In gas-filled phototubes a glow discharge may occur and damage the cell, if the applied voltage is too high. To prevent accidental overrunning a load resistor of at least 0.1 MΩ should be inserted in the external circuit.

The sensitivity of photoconductive cells decreases with increase of ambient temperature. With the CdS cell this decrease is only 0.4 % per $^{\circ}$C, i.e. the cell has about the same temperature coefficient as copper wire. The sensitivity of PbS cells decreases by about 2 % per $^{\circ}$C.

In the following table the values of the photo-electric threshold are given for several types of photosensitive devices, together with their permissible dissipation or maximum current and their dark current.

type	threshold		maximum dissipation (current)	T_{amb}	dark current (room temp.)
	$\lambda(\mu)$	E(eV)			
vacuum tube 92 AV	0.56	2.2	2.6 μA	70 °C	0.05 μA (85 V)
vacuum tube 90 CV	1.0	1.24	7.2 μA	100 °C	0.05 μA (50 V)
gas-filled tube 92 AG	0.56	2.2	5.2 μA	70 °C	0.1 μA (85 V)
gas-filled tube 90 CG	1.0	1.24	1.7 μA	100 °C	0.1 μA (85 V)
CdS-device:					
ORP 90	0.9	1.4	1 W (25 °C)	-40 °C to + 70 °C	2.5 μA (300 V)
LDR (B8 731 03)	0.9	1.4	0.2 W (40 °C)	- 20 °C to + 60 °C	max. 10 μA (100 V)
PbS cell 61 SV	2.8	0.44	0.3 mA	60 °C	~100 μA (200 V)
Ge diode OAP 12	1.8	0.69	30 mW	75 °C*	15 μA (-10 V)
Ge transistor OCP 70	1.8	0.69	25 mW	75 °C*	325 μA (-4.5 V)

*) junction temperature.

4

Construction of photosensitive devices

The various forms of photosensitive devices differ greatly in their appearance and structure. In the present Chapter brief descriptions are given of their general construction.

4.1. PHOTO-EMISSIVE CELLS (phototubes)

These devices consist of a cathode and an anode, enclosed in a glass bulb. The photosensitive cathode has a large surface, in order that it may receive a large amount of light flux and thus produce a correspondingly large photoelectric effect. The cathode material may be precipitated either on a silver plate or on the glass wall of the envelope. In the blue-sensitive (*A*-type) cathode, the photosensitive material is caesium-on-antimony; the red-sensitive (*C*-type) cathode employs caesium on oxidised silver.

The anode is placed in front of the sensitive surface of the cathode, and parallel to it, so that it is situated between the light source and the cathode. In order to intercept as little light as possible, the anode is made in the form of a thin rod or bent wire. There is no need to provide a large anode surface for cooling, the photocurrent being only very small - less than 10 μA.

The currently preferred types of high-vacuum phototubes are:

90 CV (red sensitive),
3545 (red sensitive),
92 AV (blue sensitive).

In the gas-filled tubes a small quantity of inert gas is admitted into the envelope, thus making possible gas amplification of the photocurrent. The preferred types are:

90 CG (red sensitive),
3546 (red sensitive),
3554 (red sensitive),
92 AG (blue sensitive).

If the tubes are used only intermittently, their properties remain almost constant during life, the decline of sensitivity being restored during the inoperative periods. Under continuous service, however, the sensitivity may drop after 500 hours to about half of its initial value.

4.2. CADMIUM SULPHIDE CELLS

CdS devices consist of plates of pressed and sintered cadmium sulphide powder. The material is highly purified in order to remove deleterious components, after which suitable additives are introduced in order to improve the photo-electric properties.

It has been shown that the photocurrent in the devices is:

$$I_p = \frac{\mu \tau e \Phi}{d^2} V,$$

where Φ is the incident flux (i.e. the number of photons which produce the photoelectric effect), and d is the distance between the electrodes.

In order to obtain a large signal, therefore, it is desirable to combine a large sensitive area with close electrode spacing. This requirement has led to the use of inter-leaving comb-like electrodes, as illustrated in Fig.35. They are formed by precipitating a suitable material on the surface of the CdS plate. Two forms of cadmium sulphide cells are available, namely side-sensitive and top-sensitive cells. Types ORP 90 and ORP 61 are side-sensitive cells, and types ORP 30, ORP 60 and ORP 11 are top-sensitive cells. A sturdy construction is achieved by mounting the plate on two support rods, the whole being enclosed in an evacuated glass envelope for protection against mechanical damage and moisture. Types ORP 60 and ORP 61 are miniature devices, particularly suitable for use in small spaces.

Fig.35. Electrode configuration of the CdS devices.

In practice, the photocurrent is proportional to $\Phi^{\alpha}V^{\beta}$, in which α is approx. 0.85 and $\beta \approx 1.27$. These values vary slightly for different devices.

In addition, the top-sensitive light-dependent resistor LDR-03, type B3 731 03, has been developed. This also is a subminiature CdS device; this time encapsulated in glass and a special impermeable synthetic resin.

4.3. LEAD SULPHIDE CELLS

The lead sulphide cell type 61 SV consists of a layer of PbS, precipitated on a glass plate and provided with electrodes. It is sealed into an evacuated glass envelope which in turn is enclosed in a cylindrical metal cover. It is thus screened from ambient heat radiation, to which the cell is extremely sensitive.

4.4. PHOTODIODES AND PHOTOTRANSISTORS

These devices are made from small slices of n-type germanium cut from a highly purified rod. The n-type germanium is obtained by melting the rod and adding to the melt a small, controlled proportion of arsenic.

To produce a photodiode (for example OAP 12), which has a p-n junction, a droplet of indium is deposited on the n-type plate. At a high temperature atoms of indium diffuse into the germanium, thus forming a thin layer of p-type material, the junction being parallel to the plate surface. The diode is mounted in such a way that the incident light falls perpendicularly on this surface. The sensitive area of the diode is approximately the same size as the indium droplet, i.e. 1 square millimetre and is of circular shape.

The element is enclosed in a metallic cylinder filled with silicon grease to provide protection. At one end a glass lens is fitted and so adjusted that the incident light is directed as a convergent beam on the sensitive area. The metal screen is hermetically sealed by means of a glass-metal seal, so that the cell is perfectly moisture-proof, thus ensuring stable characteristics.

An electrode is attached to the indium droplet and another to the n-type germanium plate. The former, i.e. the p-type electrode, is identified by a green spot and must be connected to the negative terminal of the battery or other bias source.

A special feature of this type of cell is its very compact size, the length being about 8 mm, and the diameter approximately 3 mm.

The phototransistor type OCP 70 has similar dimensions. The base in this device consists of a thin plate of n-type germanium; the p-type collector and emitter are both formed by diffusion of indium droplets, so that the transistor is of the p-n-p alloy type.

The emitter droplet is made smaller than the collector. The light that is to fall on the base is directed from the emitter side of the transistor by preference, in order to minimise the amount of light intercepted by the p-type zone.

The transistor is mounted in a glass envelope filled with silicon grease, thus ensuring mechanical protection and rigid construction. The collector electrode is indicated by a red dot.

5

Applications of photosensitive devices

The uses of photosensitive devices as detectors of optical signals can be classified in three main groups:

1. On-off applications in which the device is used to detect the presence or absence of radiation.
2. Action on fluctuating illumination. In these applications the detector is required to translate accurately a varying optical signal into a correspondingly varying electric signal.
3. Detection of weak signals.

There is no clear-cut separation between these groups, some applications partaking of the nature of two or even all three. On the basis of this main classification, however, it is possible to indicate which of the available devices might be preferable for a given application.

5.1. ON-OFF APPLICATIONS

Examples of this group are control equipment, e.g. flame control, edge-position control etc.; alarm and safety devices; automatic control and many others. All these applications have in common that action is taken when light is interrupted.

For example, in flame control a photosensitive device watches the flame in a furnace. When the flame extinguishes the device gives a signal, which reacts to cut off the fuel supply.

In edge-position control, sheets of paper, cloth, metal, plastics etc. can be guided on their way through the factory. Two photo devices are so located that the edge of the sheet passes between them. When conditions are normal, one device is always illuminated and the other is always screened. If the sheet is displaced sideways, action is taken in order to restore the right position.

In alarm and safety devices a certain zone or location is traversed by beams of light, directed on a photosensitive device. This zone may be a corridor, door, etc. or it may be a plane in front of heavy machinery presses, punches or drills for example, that are fed with material by hand. When the light beam is interrupted, an alarm signal can be given, or the machine may be stopped to prevent injury to the operator.

The general principles of automatic counting, filling, level control etc. are obvious and need no further explanation. Many other examples could be mentioned.

The requirements for devices for use in this type of application are good sensitivity, reliability and simplicity of operation. Moreover, in certain cases compact dimensions may be of great advantage. Cadmium-sulphide cells are usually the best choice. Not only do these devices best satisfy the above-mentioned conditions, but because of their great sensitivity and large dissipation they can be used for the direct control of thyratrons, transistor circuits and even relays.

Photodiodes can be employed in these applications, in combination with a cold-cathode tube or a transistor circuit for amplification. Photoemissive tubes are also suitable, but must always be followed by an amplifier.

The photodiode is not suitable for flame control, as its spectral response reaches far in the infra-red, so that it also reacts on heat radiation, whereas the CdS cell has maximum response to light. Sometimes it is advisible to use these cells in combination with a near-infra-red filter, such as, for example, the Schott BG 19.

On account of its small dimensions the photodiode is especially suitable for applications where a large number of elements has to be placed in a small space. A typical example is in statistical machines such as those for the reading of punched cards. Its good response to high frequencies also renders this device very suitable for these applications.

5.2. ACTION ON FLUCTUATING ILLUMINATION

For slowly fluctuating signals the somewhat sluggish CdS devices can be used satisfactorily. A notable application in this field is the automatic control of contrast and brightness in TV receivers, where the intensity of the picture beam is varied in accordance with the ambient illumination. Another example is automatic light control systems intended to maintain a reasonably constant level of illumination, for example by switching on and off the street lighting when the daylight falls below or rises above a certain level. In another type of application a CdS device can be applied as a noisefree potentiometer, possibly with remote control, the circuit resistance being adjusted by means of an incandescent lamp, the luminance of which is controlled by a normal potentiometer.

In most cases, however, applications involve fluctuating signals of rather high frequencies, such as sound scanning in the reproduction of films. For this application gas-filled phototubes are widely used, in conjunction with an amplifying circuit. They are more sensitive than the high-vacuum tubes, but their I_a - V_a characteristics are slightly curved, so that the voltage across the load resistor will not be exactly proportional to the light flux falling on the cathode. This has negligible effect with the normal values of load resistor employed in sound film apparatus. For high-fidelity reproduction, however, high-vacuum tubes will be used, as in other high-frequency applications.

Photodiodes are suitable for the reproduction of signals up to high frequencies and, since they can deliver much larger photo-currents than photoemissive tubes, at least one stage of amplification may be saved. The dark current increases exponentially with temperature, so that the "light" current is increased by a like amount. The photocurrent however, (i.e. "light" current minus the dark current) is proportional to the illumination (at low levels of illumination) and is independent of temperature. When the d.c. component is eliminated, the variations of the electric signal are proportional to the variation of the light signal.

5.3. DETECTION OF WEAK SIGNALS

The detection of weak signals, and possibly the measurement of their amplitude, is not often required in industry. The applications in this group are mainly in the field of optical observation and measurement, for example in photometry, spectrophotometry, observation of weak or remote sources, etc.

When selecting a suitable photosensitive unit, the spectral distribution of the flux to be detected must first be considered. For radiation in the near-infra-red region (wavelengths between 0.8 and 1.6 μ) the germanium devices can be used, as they have their maximum of sensitivity in this region.

A red-sensitive phototube detects radiation of wavelengths between approximately 500 and 1000 mμ. The red-sensitive photomultiplier is even more satisfactory as it introduces less noise than the combination of a high-vacuum phototube with a thermionic amplifier.

Radiation of wavelengths between 300 and 600 mμ are detected by means of a blue-sensitive photomultiplier or high-vacuum phototube having a quartz window in order to avoid the absorption of the wavelengths below about 385 mμ by the glass envelope.

The lead sulphide photoconductive cell is very sensitive to radiation above 1.6 μ.

For the detection of weak signals the noise in the detector and appertaining circuit must be as small as possible. Ambient radiation from stray sources must therefore be excluded by efficient screening. It is advisable in addition to apply artificial cooling of the photosensitive unit in order to reduce the thermal noise.

If the radiation to be detected is interrupted by a chopper the photocurrent will be an alternating current having a frequency equal to the interruption frequency. This signal can then be amplified by means of a selective linear amplifier, whereby the noise frequencies outside the frequency range of the amplifier are blocked, and the signal-to-noise ratio greatly increases.

Finally the detection of weak signals is facilitated if the flux to be detected is directed in the sensitive area as a convergent beam by means of an optical system. This aspect is dealt with in greater detail in the next chapter.

6

Illumination of photosensitive devices

When the type of device for a certain application in view has been chosen, the illumination of the photosensitive surface must be considered.

The flux Φ in lumens (or the illumination E in lux) needed to produce the desired photoelectric signal can be calculated from the quantitative design of the circuit. Dependent on the type of device, this will be in the order of some hundredths to some tenths of a lumen (up to 1000 lx). The determination need not be exact, as the production spread in the devices is rather large. Constructors should be conservative in the circuit calculations, particularly as regards to the limiting values, and must include a variable resistor for regulating the photocurrent.

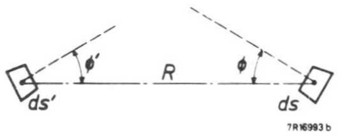


Fig.36. Diagram illustrating the photometric law: $\Phi = BdS'\cos\Phi'\cdot dS\cos\Phi/R^2$.

The general expression for the flux of light, emanating from a radiating surface dS' with luminance B, and falling on a surface dS at a distance R (see Fig.36) is:

$$\Phi = B\frac{dS'\cos\varphi' dS\ \cos\varphi}{R^2}.$$

The normals to the surfaces make angles of φ' and φ respectively with the line joining the centres of the surfaces. The intensity I of the light source in the direction of the surface dS is BdS'cos φ', while dS cos φ/R^2 represents the solid angle by which the receiving surface is "seen" by the centre of the emitting surface. The flux on the projected sensitive area of the photodevice is $\Phi = IS/R^2$ and the illumination of a plane on a distance R of the lamp is equal to $E = I/R^2$.

As was seen in Chapter 2, the incandescent lamps have an intensity of approximately 1.3 cd/W in the forward direction. Thus a 6 V - 15 W lamp has an intensity of 20 cd, and a 40 W incandescent lamp about 50 cd.

If a 20 cd lamp is placed at a distance of 50 cm facing a device with a projected sensitive area of 2 cm^2, the flux on that area is $\Phi = 20 \times 2/50^2 = 0.016$ lm. By selecting suitable values for the lamp intensity and the distance between the lamp and the photo-sensitive device, the flux can be adjusted to the desired value. With cells of large surface area, this arrangement, (i.e. with the lamp directly in front of the cell) will be possible for distances up to some tens of centimetres.

If the amount of incident light should be too small, for instance when it is desired to place the lamp at a greater distance, or when using a device having a small sensitive area, or when the light is filtered or is passed through a diaphragm as in sound scanning, a lens should be inserted between the light source and the photosensitive unit. This increases the solid angle of the beam that provides the illumination, thus increasing the amount of light received. The number of lumens received is then proportional to the intensity I of the source and to the area A of the lens and inversely proportional to the square of the distance s from lamp to lens (Fig.37). As the light is partly reflected at the surfaces of the lens a transmission factor of 0.9 should be included, so that $\Phi = 0.9\, IA/s^2$.

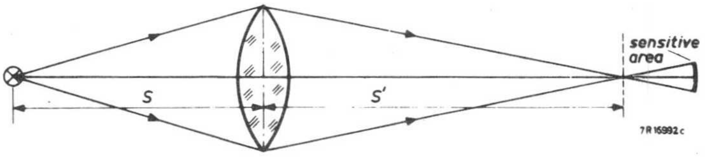


Fig.37. Focusing effect of a convex lens.

As a practical example, with a lens diameter of 5 cm (area of 20 cm^2) and $s = 12$ cm, the flux is $\phi = 0.9 \times 20 \times 20/12^2 = 2.5$ lm. If the focal length f of the lens is 10 cm, the beam comes to a focus at a point $s' = 60$ cm from the lens, according to the well-known optical formula $1/s + 1/s' = 1/f$.

Without a lens the amount of light falling on a sensitive area of 2 cm^2 at a distance of 72 cm from the source would have been $\phi = 20 \times 2/72^2 = 0.01$ lm approximately. It is seen, therefore, that the insertion of a lens increases the flux considerably. Even when the amount of light is reduced by a film or filter, or only part of it is transmitted via a slit, a large flux will still reach the sensitive device.

With feeble light sources the relative aperture D/f of the lens should be large, so that a lens should be chosen having a large diameter D and/or small focal length f. The light source then can be placed at a short distance from such a lens, so that the transmitted flux is large. For normal applications a simple lens may be used, as large-diameter, short-focus lenses are rather expensive.

Care must be taken that the photo-sensitive device is not placed exactly at the focus of the beam, as the sensitive area would then be damaged by heat.

With applications where it is necessary to mount the lamp at a considerable distance from the cell, such as in some alarm installations and in counting devices, a succession of lenses will be used.

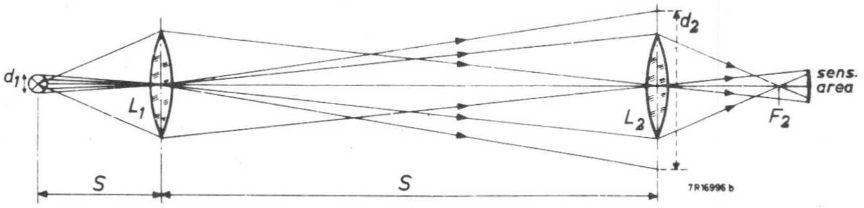


Fig.38. Optical system for uniform illumination suggested by Köhler.

Uniform illumination of the cell can be ensured by employing the optical system suggested by Köhler and illustrated in Fig.38. The lamp is so positioned that it is slightly out of focus with respect to lens L_1, which therefore produces an enlarged image of the filament. This image is projected on to the second lens L_2. This lens depicts the uniformly illuminated lens L_1 in F_2. The photosensitive device is placed at a sufficient distance from F_2 to ensure that the sensitive area is just filled.

If, for example, the distance between the lenses is 5 metres, the diameter of each lens is 10 cm (area 78 cm^2) and the focal length of the first lens is 20 cm, the amount of light reaching the first lens from a 50 cd incandescent lamp will be $\phi = 0.9 \times 50 \times 78/20^2 = 8.7$ lm. The ratio of the diameters of the filament and its image equals the ratio of their distances from the first lens, i.e. $d_1/d_2 = s/s'$. The lamp should be placed near the focal point of the lens, so that $s \approx f = 20$ cm, $s' = 500$ cm. If d_1 is 2 cm, the diameter of the filament image will be 50 cm, which is much greater than that of the second lens. Thus only fraction of the flux will be transmitted, in proportion to the ratio of area of the lens to the cross-sectional area of the beam. In this case this ratio is 78/1962. The amount of light falling on the photosensitive area will then be $\Phi = 0.9 \times 8.7 \times 78/1962 = 0.3$ lm. In practice, the amount of light will be smaller than the calculated value as the beam is scattered by dust particles.

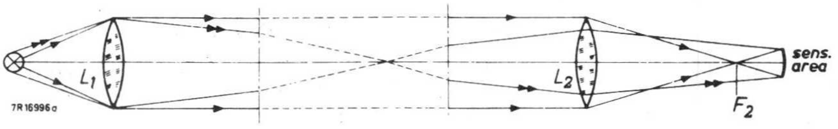


Fig.39. System for illuminating a photo-electric cell by a distant source of light.

Another system of illumination, which may be used if the lamp has to be located at a considerable distance from the photosensitive device, is that in which the lamp is placed exactly at the focal point of the lens L_1, so that a parallel beam results, as indicated in Fig.39. By means of a second lens this beam is brought to a focus at F_2. This system is a development from the Köhler system in which the light source is placed near but not actually at the focal point of L_1.

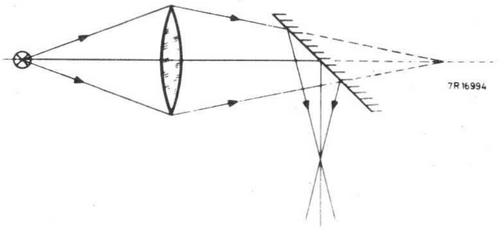


Fig.40. Deflection of the path of light by means of a plane mirror.

The path of the beam can be bent by inserting one or more plane mirrors between the lenses, as shown in Fig.40. By suitably placing a number of mirrors the beam can be reflected backwards and forwards across a space, and also around corners. This arrangement is particularly useful in burglar alarm systems, since it permits a large area to be protected using only one light source and one photocell. As the reflection coefficient of each mirror is approximately 0.96 a considerable loss of flux occurs after the beam has been reflected a number of times. Care must be taken that the mirrors do not limit the cross-section of the beam, since this would introduce further loss of light.

In measurement, counting and similar applications employing reflection of the beam, the light from the lamp is projected on the reflecting surface by one lens and the reflected light is concentrated on the photosensitive device by means of a second lens as shown in Fig.41. If, for example, L_1 has a diameter of 5 cm (area of 20 cm^2) and a focal length of 8 cm, it can be calculated from the formula $1/s + 1/s' = 1/f$ that for $s = 12$ cm, s' will be 24 cm. The flux transmitted by lens L_1 when using a 20 cd lamp is $\Phi = 0.9 \times 20 \times 20/12^2 = 2.5$ lm. Assuming that the reflecting surface has a reflection coefficient of 0.7 and that it is diffuse, i.e. the light is reflected uniformly in all directions, (B = constant), the intensity in a direction making an angle φ with the normal to the surface will be $I_1 = I_o \cos\varphi$, where I_o is $0.7\ \Phi/\pi$. Thus the intensity of the beam directed on the second lens is $I_1 = 0.7\ \Phi\cos 45^\circ/\pi$, when φ is taken to be 45°. If this lens also has a diameter of 5 cm and is placed at a distance of 12 cm, the flux falling on the sensitive area of the device is

$$\Phi' = 0.7 \times 0.9 \frac{2.5 \times \frac{1}{2}\sqrt{2} \times 20}{12^2\pi} = 0.05 \text{ lm.}$$

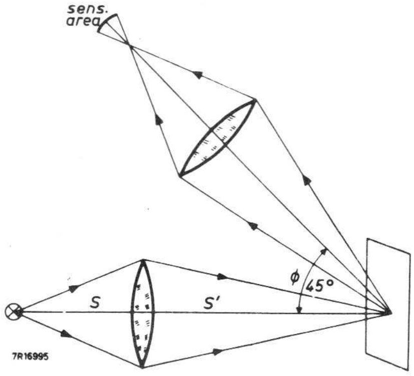


Fig.41. Illumination of the photosensitive area with reflected light.

For comparative measurements the light beam may be divided into two by means of a semi-transparent mirror, or by a dividing prism. The apparatus must be calibrated in order to ascertain the ratio of the two fluxes, and for precision work the reflection and transmission coefficients of the applied mirrors and lenses should also be taken into account.

It is thus seen that a number of systems of illumination are available, enabling a suitable arrangement to be selected for each individual application. The lenses need not be corrected, but for precision measurements the optical system should be adjusted sufficiently accurately to ensure that the whole beam falls on the sensitive area.

PART 2

Practical Circuits

In on-off applications the photosensitive device is used to ensure that action is taken either on the appearance or on the disappearance of light. Thus a relay can be energised, either directly or via a thyratron, a trigger tube or a transistor amplifier circuit, for switching operations or for actuating alarms, etc. When operating on fluctuating light signals the photosensitive device translates the optical signal into an electric one of the same shape, that, if necessary, is further amplified and applied to the stage to be controlled.

On the following pages descriptions are given of a number of practical circuits for typical applications of both kinds.

1

Control of brightness and contrast in television receivers

One very important application of operation on fluctuating illumination is the automatic control of contrast and brightness in TV receivers. When the ambient illumination of the TV screen changes, the amplitude of the picture signal (contrast) and its black level (brightness) should change accordingly, so as to give the viewer constant picture quality. Adjustment by hand when the illumination changes at frequent intervals is troublesome; moreover it is difficult to obtain optimum adjustment as the picture content is always changing. Automatic control can be achieved by means of a cadmium-sulphide cell which, when exposed to the ambient light, converts the changes of the illumination into changes of the electric circuit parameters, as the result of which the picture is modified in the desired way.

Several circuits are possible. For example, by using a type ORP 90 cell the screen-grid voltage changes of the video output tube can be modified in accordance with the ambient light, so that contrast and brightness are kept correctly related as well as matched to the ambient illumination.

If the photoconductive cell is connected in the screen-grid circuit however, it is rather heavily loaded (0.5 W), because a voltage divider with a rather heavy bleeder current is required in order to keep the screen-grid voltage independent of the picture content and the modulation depth.

This difficulty can be avoided if the video signal is modified by means of a light-sensitive element in the control-grid circuit of the video output tube. Since the control grid needs but little driving power, it is possible to use the miniature photoconductive cells types ORP 60 or ORP 61. The maximum permissible dissipation of these cells is 70 mW at 25 °C (20 mW at 70 °C); the latter value is not exceeded in the circuit illustrated in Fig.42.

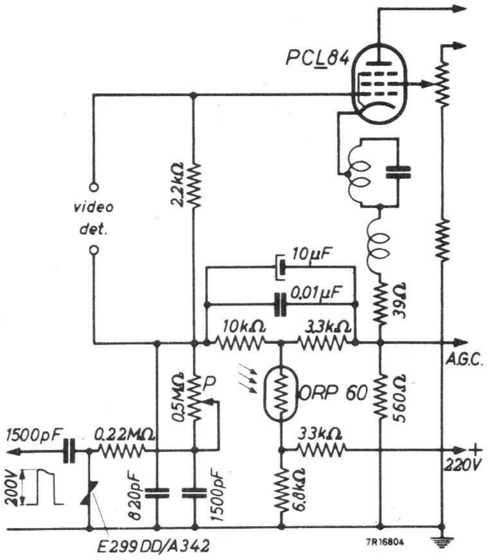


Fig.42. Automatic contrast control in TV receivers by means of an ORP 60 in the control-grid circuit of the video output tube.

The photoconductive cell ORP 60 together with a relatively low ohmic resistor (shunted by a capacitor), is connected in series with the detector circuit. The current in this resistor is thus controlled by the ambient light, so that the control grid is biased in accordance with the illumination of the photoconductive cell.

With this arrangement only slight negative d.c. feedback occurs. Heavy feedback would lead to deterioration of the picture as it counteracts background shift. With varying picture background the variations of the mean cathode voltage are present at the lower end of the detection circuit.

When the photoconductive cell is in darkness, its resistance is very high, so that there is no control voltage across the 3.3 kΩ resistor. With increasing illumination of the cell its resistance decreases, as a result of which the control-grid voltage of the video tube is shifted in a positive direction. The anode peak current now rises, so that the contrast is increased. Since the peaks of the synchronising pulses are held constant by the A.G.C., the brightness also increases, the black level shifting automatically with increasing contrast.

The contrast can be adjusted with the ORP 60 in darkness, by applying a negative voltage to the control grid via potentiometer *P*. This voltage is derived from a line flyback pulse which is rectified by a VDR, giving about -30 V. Other sources may be used instead, for example the line output stage; when this stage is stabilised, however, the use of its negative voltage is not recommended, as the stabilisation circuit may be upset by the extra load.

In any case it is necessary to provide the usual manual controls for contrast and brightness, because the modulation factor of various transmitters may differ. These controls can take the form of a variable resistor in the screen-grid circuit or the control-grid circuit.

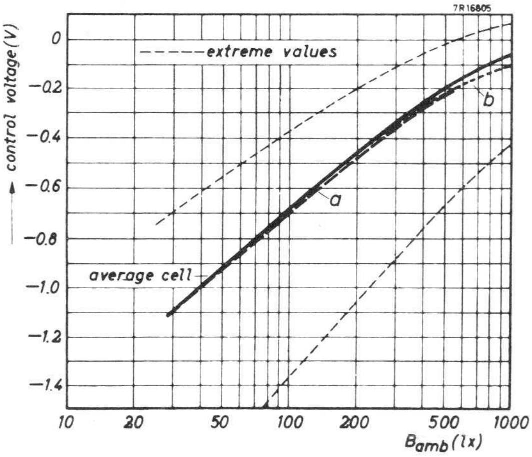


Fig.43. Control voltage as a function of ambient light.

The curves given in Fig.43 show the control voltage as a function of the ambient light, both for an average cell and for the extreme samples out of a batch of 18 cells tested. When, with these extreme cells, the control voltage was adjusted by *P* to $V_c = -1.1$ V at $B_{amb} = 30$ lux (at a definite value of the screen-grid voltage) the curves *a* and *b* were obtained, from which it is seen that at this adjustment the influence of the spread of the cells can be almost entirely eliminated. The graphs further show that when *P* is adjusted for correct contrast at a low value of ambient light, the control grid of the video tube does not become positive, so that no grid current will flow.

Another system for automatic control of contrast and brightness is with the photosensitive device connected between the anode of the video output tube and the cathode of the picture tube. A suitable circuit is shown in Fig.44, in which the photosensitive device is the LDR-03 (type B8 731 03).

The anode of the video tube PCL 84 is connected to the supply voltage via the resistors R_1 - R_2. A voltage divider is connected across R_1, the potential at the tapping point being varied in accordance with the ambient light by means of the LDR in the circuit. From the tapping point of the divider the video signal is applied to the cathode of the picture tube.

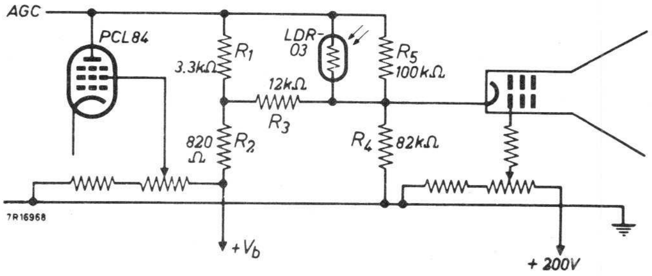


Fig.44. Automatic contrast and brightness control by means of an LDR-03 in the anode circuit of the video output tube.

With the LDR in darkness, its resistance is several megohms, so that the video amplitude (contrast) is determined by the ratio R_1/R_2. When the LDR is illuminated (and its resistance becomes smaller) almost the full amplitude of the video signal is applied to the picture tube via the LDR, so that the picture contrast increases.

In this arrangement the LDR influences the video amplitude directly, as distinct from adjustment of the operating point of the video tube by means of a varying direct voltage on a grid of the tube. Thus a constant video signal appears at the anode of the PCL 84, from which the signal for the AGC is taken.

With the control in the anode circuit of the video tube, however, fluctuations of the ambient illumination, such as at 50 c/s, resulting in a fluctuating resistance of the LDR will disturb the video signal. Therefore a cell having a slow response must be used.

With increasing ambient light the brightness must be increased as well as the contrast, as otherwise part of the gradation of the picture would be lost. The brightness is determined by the black level of the video signal. The resistors R_3 - R_4 constitute a voltage divider so proportioned that, with the LDR in darkness, the black level is lower than when the LDR is illuminated. One LDR thus controls the contrast in combination with R_3, and the brightness in conjunction with R_4.

To decrease the influence of the LDR the resistor R_5 is inserted in parallel. The capacitance of the LDR compensates for the loss of the higher frequencies in the video signal due to the series resistor R_3 and to the parasitic capacitances of the circuit.

Manual controls, both for contrast and brightness must still be provided, and are indicated by the potentiometer arrangement in Fig.44.

In order to prevent undue radiation, the connecting leads to the LDR should be as short as possible. As a rule, little trouble will be met with if the total length of the leads does not exceed 40 cm.

2

Flame failure device

The cadmium sulphide cell is widely used in flame control apparatus, as a light-sensitive device that "watches" the flame in a furnace. When the flame extinguishes the fuel supply is stopped and an alarm is given. A simple circuit for this application, employing the photoconductive cell ORP 61 and the trigger tube Z 805 U, is shown in Fig.45.

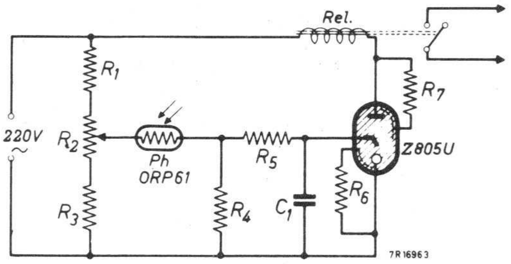


Fig.45. A simple set-up for a flame-control apparatus, equipped with the ORP 61.

R_1 ≐ 15 kΩ, 2 W
R_2 = 100 kΩ, ¼ W
R_3 = 100 kΩ, ½ W
R_4 = 1 MΩ, ½ W

R_5 = 1 MΩ, ½ W
R_6,R_7 = 10 MΩ, ½ W
C_1 = 100 pF, 500 V
Rel = 1500 Ω

The trigger voltage is taken from the voltage divider R_1 - R_2 - R_3, via the photoconductive cell ORP 61. The resistance of this cell decreases when illuminated, so that the voltage at the junction point of *Ph* and R_4 then rises. At a certain level of illumination the voltage on the trigger rises above the ignition voltage, and tube Z 805 U is triggered, energising the a.c. relay.

The illumination level at which the tube ignites can be adjusted by means of the potentiometer R_2.

The trigger current is limited by the resistor R_5.

3

A light-sensitive relay operated by a cadmium-sulphide cell

Owing to their high sensitivity and permissible dissipation, cadmium-sulphide cells permit the operation of relays directly. An elaborate circuit, in which the on and off positions of the relay depend on the magnitude of the illumination of the cell, as in twillight switching, flame control etc., is given in Fig.46.

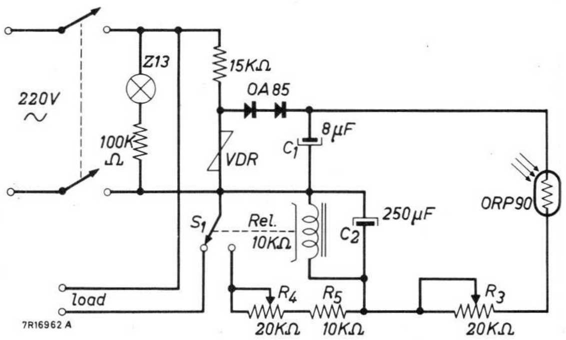


Fig.46. Elaborate circuit for a photoelectric switch equipped with the ORP 90.
VDR E 299 AH/P236

When the CdS cell ORP 90 is in darkness, its resistance is high, so that the current flow through the relay coil is small. The left-hand contact of the relay is closed, so that the lamps, connected to the "load" terminals are alight. When the daylight on the CdS cell reaches a certain level the current through the relay coil increases and the relay operates to switch off the lamps.

This circuit includes several important features:

(a) *Compensation for mains-voltage fluctuations*
Compensation to an appreciable extent for mains voltage fluctuations is effected by a VDR in series with the resistor of 15 kΩ. By this means 10 % mains fluctuations are reduced to about 5 %. Moreover, the d.c. supply voltage for the ORP 90 is reduced to a suitably low value, thus preventing the cell from being overloaded. A further advantage of using a low voltage for the cell is that for equal variations of illumination, the absolute changes in internal resistance of the photoconductive cell are larger compared with those obtained with a higher voltage. The maximum direct voltage on the ORP 90 will be about 70 V.

(b) *Control of illumination level*
The level of daylight at which the relay closes can be adjusted by means of the variable resistor R_3.

(c) *Production spread*
Resistor R_3 also permits differences of cell sensitivity to be compensated.

(d) *Relay on-off conditions*
The current required to actuate a d.c. relay is, in general, about twice as large as that at which it will fall off. This ratio may be too large in certain cases where the level of illumination decreases. Therefore a special arrangement has

been incorporated to decrease the current through the relay coil as soon as the relay has been closed. To this end the armature, which is mechanically coupled to the microswitch S_1, shunts the resistors R_4 and R_5 across the relay coil when the relay is energised, so that the coil current then is reduced. In this way the illumination level at which the relay falls off becomes closer to that at which the relay closes. The on-off relation can be controlled by varying R_4.

(e) *Time delay for switching*

In practice it is desirable to prevent immediate switching if, for any reason, the illumination varies for a short interval only. The large capacitor C_2 in parallel with the relay provides a suitable time delay.

(f) *Mounting of the photosensitive device*

The sensitivity of the ORP 90 is so high that a small amount of light is sufficient to produce the necessary energising current. It is therefore necessary to limit the amount of daylight falling on the cell, and this can be achieved by placing an aperture or a filter in front of the cell. The mutual positions of the cell and the aperture must be adjusted correctly in order to prevent illumination of only a small part of the sensitive layer, which would damage the cell.

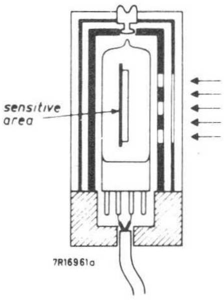


Fig.47. Assembly for protecting the photo device against excessive illumination.

The assembly shown in Fig.47 can be used. In an aluminium cylinder surrounding the cell several small holes are drilled. Daylight passes through the holes and is reflected and diffused by the inner wall of the cylinder. The sensitive surface of the cell faces away from the holes. This combination is built in a "Perspex" holder, the inner walls of which are blackened except for a small part, serving as a window. The aluminium cylinder is provided with four rows of holes of different sizes, spaced 90° apart. This arrangement provides a rough adjustment of the light by choosing a suitable aperture, which can be accomplished by turning the cylinder by means of a screwdriver from the outside.

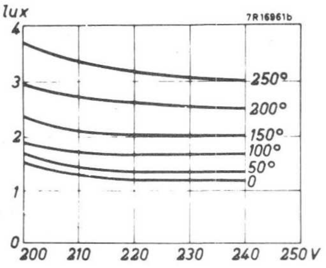


Fig. 48. Required illumination versus mains voltage, with various positions of R_3 as parameter.

Fig.48 gives an approximate idea of the illumination required for energising the relay at different mains voltages and with the position of R_3 as a parameter. It can be seen that the influence of mains-voltage fluctuations is strongly reduced.

4

Illumination stabiliser

Stabilisation of illumination or of illumination contrast can be performed by an ORP 90 CdS-cell controlling two power thyratrons connected in anti-parallel and without an amplifier. The method is suitable for the control of a load that may consist of incandescent as well as of fluorescent lamps. By making a small alteration, the same circuit can be used to maintain constant contrast between two illumination levels, for instance between daylight and artificial light in, for example, show-windows.

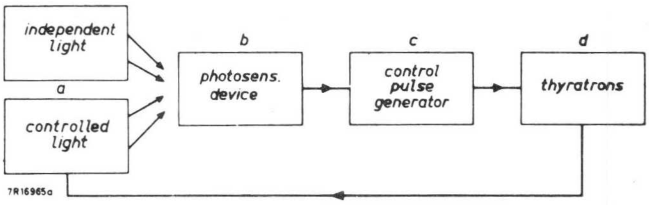
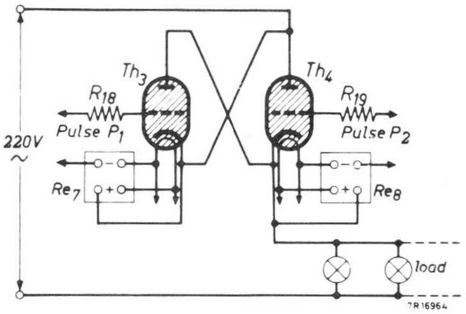


Fig.49. Block diagram showing the operating principle of the illumination stabiliser.

The principle of control is shown in the block diagram of Fig.49. The two thyratrons of unit *d* serve as an electronic switch. The periodic ignition point of the alternating anode voltage (mains) can be shifted by means of the phase of the control voltage on the grids. Thus the current through the lamp load, connected in series with the thyratrons, is controlled. If the load consists of incandescent lamps the r.m.s.-value of the sine voltage part will be a measure for the illumination. If fluorescent gas-filled lamps are used, the discharge will be periodically ignited until the ignition angle has reached a value at which the instantaneous voltage has become too low.



Th_3, Th_4 = PL 5559

R_{18}, R_{19} = 10 kΩ, 1 W

Fig. 50. Control of the load current by means of two power thyratrons in anti-parallel connection (part *d* of Fig.49).

In Fig.50 the grid voltage arrangement for the two thyratrons is given (unit *d* of Fig.49).

Each control grid is at a fixed negative voltage of about 50 V, delivered by a Type 1289 rectifier, on which the positive pulses, generated in unit c, are superimposed. Dependent on the phase situation, each thyratron will ignite at an earlier or later instant during the cycle of the anode voltage sinewave.

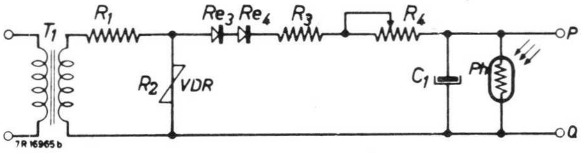


Fig.51. Light-sensitive part of the illumination stabilised circuit (part *b* of Fig.49).

Unit *b* of Fig.49 is shown in Fig.51.

Part of the voltage of a 1:1 insulating transformer T_1 is stabilised by means of the VDR R_2. After rectification it is smoothed and the direct voltage on C_1 finally depends on the instantaneous value of the resistance of the photocell Ph, i.e. on its illumination. The upper limit of the voltage can be fixed by choosing a suitable value for R_1; the lower limit initially depends on the maximum available illumination of the photocell. With the values given in the parts list the voltage between *P* and *Q* varies between 30 and 60 V, the lower value of which can be adjusted by means of R_4.

The control pulse generator may consist of two symmetrical control circuits to deliver the necessary pulses for the grids of the power thyratrons in unit *d*. It is obvious that these thyratrons must be symmetrically controlled. If one of them conducts during a longer interval of the half cycle involved than the other, certain components in the power circuit will be loaded with a d.c.-component. The core of a transformer (if used) will become pre-magnetised and, in the event of the control device being loaded with fluorescent lamps, the impedance of the series-choke will decrease for the same reason. In order to avoid this, the circuit of Fig.52 has been developed, in which only one control thyratron is used. With this circuit under all circumstances of phase shift two control pulses will be generated with a mutual electrical phase difference of 180°.

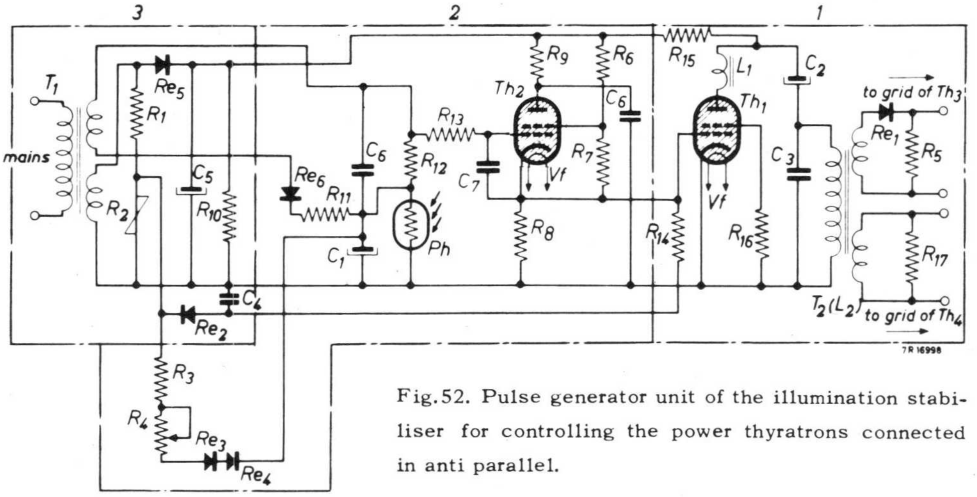


Fig.52. Pulse generator unit of the illumination stabiliser for controlling the power thyratrons connected in anti parallel.

Th_1, Th_2 = PL 5727
Ph = ORP 90
T_1 = 1N 348 70
$T_2(L_2)$ = 84590
R_1 = 15 kΩ, 1 W
R_2 = VD150B/112VP
R_3 = 50 kΩ, 3 W
R_4, R_7 = 10 kΩ, 1 W
R_5 = 22 kΩ, 1 W
R_6 = 100 kΩ, 1 W
R_8 = 1 kΩ, 1 W

R_9 = 470 kΩ, 1 W
R_{10} = 220 kΩ, 1 W
R_{11} = 22 kΩ, 1 W
R_{12}, R_{14} = 100 kΩ, 1 W
R_{13} = 330 kΩ, 1 W
R_{15} = 10 kΩ, 2 W
R_{16} = 10 kΩ, 1 W
R_{17} = 470 kΩ, 1 W
C_1 = 8 μF, 350 V
C_2, C_5 = 25 μF, 350 V
C_3 = 1 μF, 500 V

C_4 = 150 kpF, 350 V
C_6 = 3.3 kpF, 500 V
C_7 = 1 kpF, 500 V
Re_1 = OA 85
Re_2 = OA 85
(2x in series)
Re_3, Re_4 = OA 85
Re_5 = Sel. rect.
Re_6 = Sel. rect.
L_1 = Choke coil

The pulse-pair generator itself is given in section 1 of Fig.52, where the thyratron Th_1 serves as a rapid switch. Each time Th_1 opens, C_2 partly discharges into C_3 in series with choke L_1 (C_2 being very much greater than C_3). The relatively small capacitor of the oscillatory circuit L_2 - C_3 is rapidly charged, and Th_1 quenches again. The value of C_3 is so chosen that L_2 - C_3 oscillates at the applied (mains) frequency ($f = 50$). Now L_2 is the resulting inductance measured at the primary side of a conventional peaking transformer T_2. Voltage peaks can be taken from the two separate secondary coils of T_2. Every ignition of Th_1 thus results in two peaks of about 100 V, and of opposite polarity for each coil. Each voltage peak controls one of the power thyratrons.

The inevitable small difference in the peaks are corrected by means of the damping resistor R_5 in series with the rectifier Re_1.

Th_1 must be ignited periodically by means of a sharp control pulse. Normally it is cut off by a negative bias voltage, taken from C_4 in section 3 of Fig.52.

The control pulses for thyratron Th_1 in section 1 are generated in section 2 of Fig.52. The grid of Th_2 is controlled by a sawtooth-voltage, generated at C_6 in series with R_{11} and Re_6. The necessary d.c. component is taken from the photocell Ph in the circuit of Fig.51. The instant of ignition of Th_2 can be varied over an interval of more than 180°, dependent on the illumination level of Ph.

The screen grid of Th_2 is positively biased, the bias voltage being taken from the voltage divider R_6 - R_7 - R_8, in order to prevent Th_2 from giving spurious voltage peaks on R_8 during the interval during which the sawtooth voltage keeps the control grid of Th_2 positive after ignition.

Section 3 of the current provides three supply voltages. From capacitor C_5 an anode supply voltage of 300 V can be taken. The a.c. voltage on the VDR R_2 is more or less stabilised, and is converted to a negative bias for Th_1 by rectifier Re_2. A third direct voltage is obtained from Re_3, Re_4 giving the supply for the photodevice *Ph*.

5

Electronic relay operated by radiant heat

There are numerous cases in industrial manufacturing processes, where an electronic relay is required to respond to infra-red radiation (heat), for instance in controlling heating processes, the movement of heated workpieces, the temperature of furnaces, etc. Such a relay may also be used as a burglar alarm or for traffic control and in other applications where control by visible light is not convenient.

With this application, use can be made of the 61 SV lead-sulphide photoconductive cell, the maximum sensitivity of which occurs at 2.5 μ.

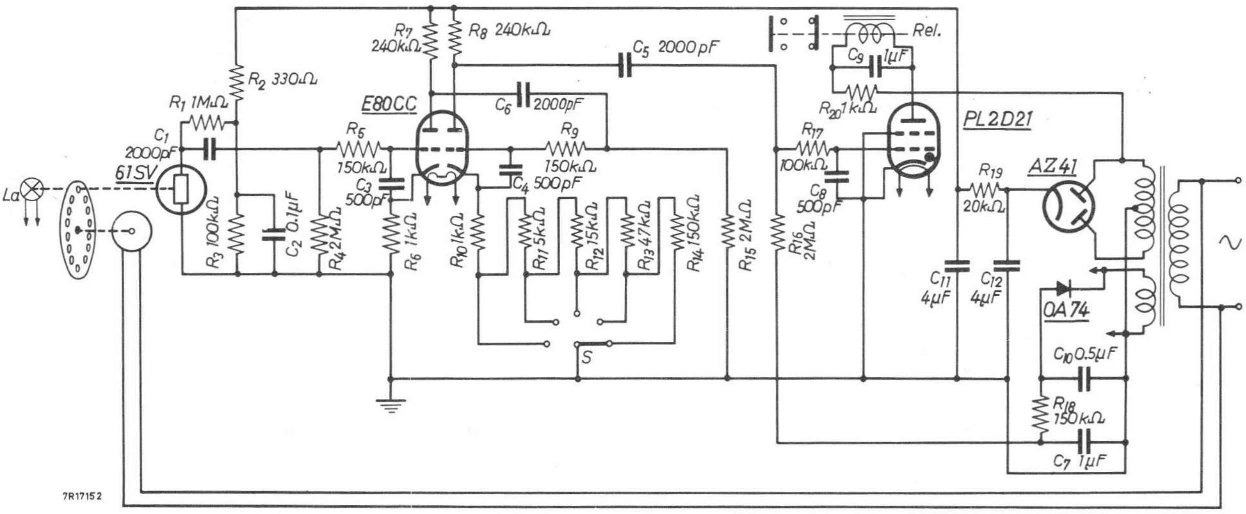


Fig.53. Circuit of an electronic relay operated by radiant heat, equipped with the 61 SV.

The circuit of the electronic relay is given in Fig.53. With the gain of the E 80CC amplifier adjusted to the maximum by the step switch S, the relay operates at temperatures of about 390 °C at an emitting surface of 25 mm diameter at a distance of about 0.3 m. At an emitter temperature of approximately 675 °C, this distance may even be 3.5 m. The reaction time is less than 0.1 second.

The circuit functions in the following way:

The beam from the radiant source *La* is chopped by the motor-driven perforated disc at a frequency of 281 c/s before it reaches the 61 SV cell. The voltage pulses produced are passed via C_1 to the grid of the left-hand system of the double triode E 80 CC. The two triodes of this tube are connected in cascade, together giving a gain adjustable between 16 and 330, dependent on the setting of switch S, which varies the value of the cathode resistor in the right-hand system. The amplified voltage pulses are applied to the first grid of the PL2D21, which is negatively biased by rectification of the heater voltage with a crystal diode. At a certain level of radiation, the pulses are of sufficient amplitude to cause the thyratron to strike in each positive half cycle of the anode voltage. The relay is thus energised.

The use of a lead-sulphide cell makes the apparatus practically insensitive to the influence of daylight. Since the sensitivity decreases with increasing ambient temperature, the incorporation of a water cooling pipe in the measuring head is recommended if the apparatus is to be used near objects which radiate heat.

6

Colour density and brightness control

Although several other types of photosensitive devices may be used for switching applications, where stability and constancy are required the high-vacuum phototube are preferable. An example of the use of this type of tube is the colour density and brightness control described below.

When in the printing, textile or chemical industries colouring-matter or dyes are produced or used, it is as a rule necessary to ensure that the density and brightness of the colours are not subject to any noticeable variations. Even when the processes are supervised by an expert, such variations may pass undetected, due to fatigue of the eyes. However, an electronic control device has been developed by means of which the density and brightness of the colour are continuously compared with a reference sample. By using a bridge circuit, supply voltage fluctuations and variations of the light source which is used introduce no errors whatsoever. The device has a very high sensitivity, and will detect minor differences between the reference sample and the sample to be tested.

CIRCUIT DESCRIPTION

Fig.54 is the circuit diagram of the control device. Two identical phototubes, P_1 and P_2, are used, the reflected light from the reference sample impinging on the cathode of one phototube, whilst the reflected light from the sample under test is directed on the cathode of the other phototube. Either blue-sensitive phototubes type 92 AV or red-sensitive phototubes type 90 CV should be employed, according to the colours involved. The anodes of the phototubes are connected to the control grids of two special-quality pentodes E 80 F. The cathodes of the phototubes are fed with a direct voltage of -85 V which is stabilised by means of a voltage reference tube 85 A 2. The load resistances are formed by the grid leak resistors of the two pentodes. These tubes are balanced by means of a 10 kΩ potentiometer which is connected between their anode load resistors. The screen grids of the pentodes are fed from a potential divider, but their anodes are connected to the 300 V supply voltage via 0.1 MΩ resistors and the balancing potentiometer.

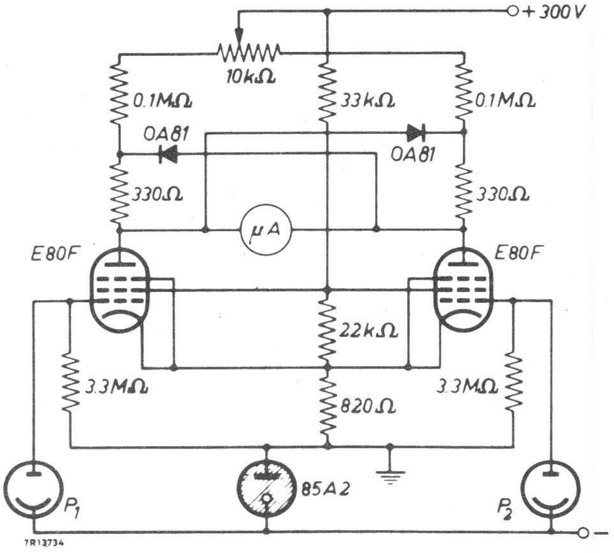


Fig.54. Circuit diagram of the colour-density and brightness-control device.

A centre zero microammeter with a range of 50-0-50 μA is connected between the two anodes. This instrument is safeguarded against overloading by connecting biased germanium diodes OA 81 in both directions across its terminals. The bias voltages for these diodes are produced across 330 Ω resistors included in the anode circuits of the pentodes.

The direct supply voltage can be obtained by means of a selenium rectifier type SR 250 B 100 and a smoothing filter.

OPERATION

The control device is first balanced by illuminating a sample with diffuse light, so that the quantities of reflected light impinging of the phototubes are equal. The same voltage drop will thus be produced across the grid leak resistors of the pentodes. Small differences between the phototubes and the pentodes can be compensated by means of the potentiometer. When the bridge is exactly balanced the currents flowing through the pentodes will be equal and the same voltages will be produced across their anode load resistors, so that the centre zero instrument will be in its neutral position. If the control device is completely unbalanced there is no risk of the instrument being overloaded; for in that case the bias of one of the germanium diodes will be exceeded, as a result of which it becomes conducting, limiting the current which flows through the instrument to a safe value.

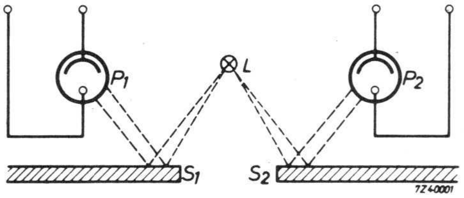


Fig.55. Set-up of the measuring device.

S_1: reference sample, S_2: sample under test, L: light source.

After the control device has been balanced, the reference sample remains opposite one phototube, while the sample under test is placed opposite the other phototube, both samples being illuminated by the same light source (see Fig.55).

SENSITIVITY

Due to the use of a bridge circuit, mains-voltage fluctuations of ±10 % have no influence and variations of the light source will not affect the measuring results either, since it illuminates both samples simultaneously. It is convenient to provide the scale of the instrument with reference marks which correspond to the permissible deviations of the samples under test.

A deflection of 50 μA will be obtained at a grid bias of 60 mV. Since the grid leak has a value of 3.3 MΩ, this corresponds to a variation of the photoelectric current of 1.8×10^{-8} A, i.e. in the case of the phototube 90 CV, a variation of the luminous flux as small as about 1.8×10^{-5} lumen will give a clear reading.

7

Relay circuits employing photodiodes and phototransistors

The germanium devices, i.e. the photodiode and the phototransistor, also can be used in on-off applications, such as edge control, safety and alarm installations, automation etc. Incorporated in a transistor circuit, the supply voltage can be derived from batteries, and, owing to their small dimensions, the elements can be built in miniature units.

As they have high sensitivity to near infra-red radiation, it is possible to use an under-run exciter lamp, thus greatly increasing lamp life.

7.1. RELAY EMPLOYING A PHOTODIODE

An example of a relay circuit, equipped with the OAP 12 photodiode, is given in Fig.56. The photoelectric signal is amplified by the transistor OC 71, so that a comparatively inexpensive relay can be used, and more dependable operation is ensured.

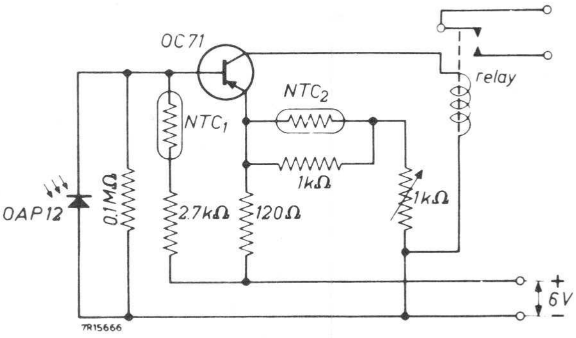


Fig. 56. Photoelectric relay circuit with thermal stabilisation, equipped with the OAP 12.

NTC_1: type number 83922

NTC_2: type number B8 32001P/500E

Relay: 2400 Ω

The variations of the base current of the OC 71 are amplified, the relay forming the collector load. At a certain value of collector current, corresponding to a certain level of illumination, the relay closes; below a certain limit of I_C the relay is open. The circuit includes stabilising elements to ensure completely reliable operation of the relay at temperatures between 0 °C and 50 °C.

Temperature stabilisation is partly achieved by connecting the negative temperature coefficient resistor NTC_1 between the base and earth in the amplifier circuit. Since the resistance decreases with increasing temperature the collector current is reduced, thus tending to counteract the increase of this current at the higher temperature. For further correction a second NTC is placed in series with the variable resistor in the emitter circuit. As a result, the current through the resistors increases with the temperature, so that the emitter voltage decreases and with it the collector current.

Fig.57 indicates:

(1) the variations of the collector current as a function of the temperature,

(2) the limit below which the relay ceases to close,

(3) the limit above which the relay fails to open.

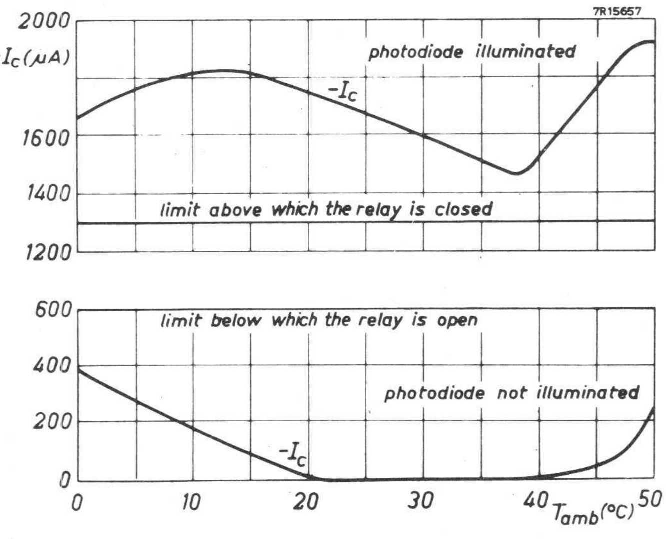


Fig.57. Variation of the collector current as a function of the ambient temperature.

A small safety margin has been left at both ends of the temperature range. The shapes of the curves show nevertheless that it is wise not to depart greatly from the limits fixed. It is possible to adopt correcting elements operating on the same principle in other classes of amplifiers, but it may then be necessary to choose different values for the NTC and the fixed resistors.

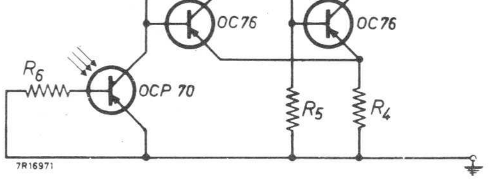
The collector current is initially set to zero at an average temperature and with the photodiode not illuminated. According to the type of photodiode and transistor employed, it may be necessary to reduce the collector current still further at the appropriate mean temperature, but a check must be made to ensure that the amount of current required for closing the relay is still attainable. It is suggested that this test be carried out in a temperature-controlled space, or at the spot where the relay circuit is to be used.

A lamp of the type employed for illuminating the dial of a radio receiver (6.3 V, 0.3 A) constitutes the light source and is located 5 cm from the photodiode.

7.2. RELAY EMPLOYING A PHOTOTRANSISTOR

A relay circuit, equipped with the phototransistor OCP 70 in combination with a Schmitt trigger, is shown in Fig.58. The relay is energised at the appearance of light.

The values of R_2, R_3 and R_5 are so chosen that with the cell unilluminated and with a certain value of the voltage across the OCP 70, and a corresponding current flow in Tr_1, the base of Tr_2 is biased positively with respect to the common emitter. Thus Tr_2 is blocked, i.e. the relay is open.



R_1 = 22 kΩ, ¼ W
R_2 = 1.2 kΩ, 1 W
R_3 = 2.7 kΩ, ¼ W
R_4 = 22 Ω, ¼ W
R_5 = 470 Ω, ¼ W
R_6 = 100 kΩ, ¼ W

Fig.58. Photoelectric relay energised at the appearance of light on the ORP 70 photo transistor.

When, due to illumination of the phototransistor, the voltage on the OCP 70 is reduced, the current through Tr_1 decreases. As a result, the voltage drop across R_2 and R_4 decreases accordingly, and at a certain level of illumination Tr_2 starts to conduct. Due to the current flow through Tr_2 the voltage on R_4 rises, by which the current through Tr_1 is further reduced rapidly and the transistor ultimately ceases to conduct. The relay is now energised. With increasing voltage on the OCP 70, i.e. decreasing illumination, the current again switches to Tr_1 and the relay opens.

With a supply voltage of 24 V, a relay of 600 Ω is energised with a current of 34 mA. The component values are so chosen that at an ambient temperature of 25 °C the relay is energised when the resistance of the OCP 70 is 600 Ω, and opens when this resistance rises to 1200 Ω. At higher temperatures (40 - 50 °C) the base resistance of the phototransistor should be reduced to 30 kΩ. To compensate for the decrease of sensitivity the intensity of the light source should then be increased.

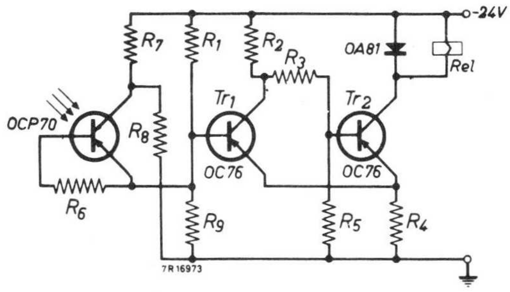


Fig.59. Photoelectric relay, similar to that of Fig.58, but operating at the disappearance of light.

R_1 = 22 kΩ
R_2 = 1.2 kΩ
R_3 = 2.7 kΩ
R_4 = 22 Ω
R_5 = 470 Ω
R_6 = 100 kΩ
R_7 = 4.7 kΩ
R_8 = 2.2 kΩ
R_9 = 1 kΩ

By a slight modification of the circuit, the photoelectric relay is caused to close on the disappearance of light (see Fig.59). Here the phototransistor is applied in conjunction with the voltage divider R_7, R_8. With the OCP 70 illuminated, the current flows through Tr_1, and Tr_2 is blocked. On the disappearance of the light the voltage on the base of Tr_1 rises, so that the current switches to Tr_2 and the relay is energised.

8

Light-operated flip-flop with cold-cathode trigger tubes

In addition to operation in conjunction with a transistor circuit, photosensitive devices can be used with a cold-cathode tube. For example, a flip-flop circuit can be constructed with two trigger tubes, controlled by a photodiode. Triggering is quite sharp, as the tubes have two clearly defined stable states. However, ionisation phenomena introduce a time element which limits the speed of response when the circuits are operated at industrial frequencies.

In Fig.60 a circuit is shown incorporating two Z 70 U trigger tubes and the OAP 12 photodiode.

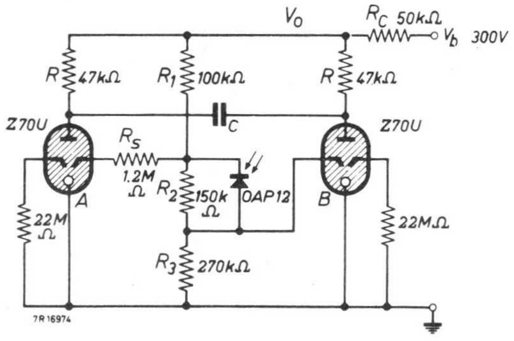


Fig.60. Photodiode OAP 12 controlling a flip-flop circuit with two Z70U trigger tubes.

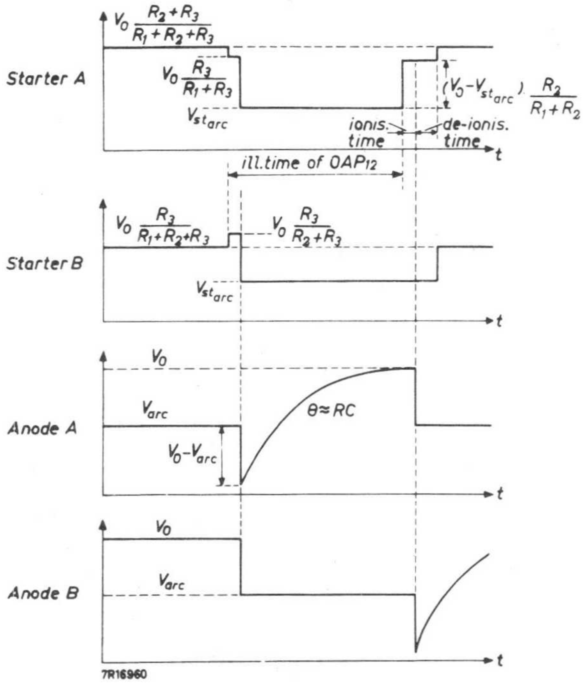


Fig.61. Shapes of the voltages at the anodes and starters of the trigger tubes when the photodiode is illuminated.

The voltage on the photodiode must be lower than the Zener voltage to prevent break-down of the device. The OAP 12 photodiode is therefore shunted by the resistance R_2 in order to limit the current, and thus to prevent the maximum permissible dissipation being exceeded.

The voltage divider R_1 - R_2 - R_3 is so calculated that with the photodiode in darkness tube A is ignited and tube B extinguished. The resistor R_s is inserted to prevent the ignition of A affecting the partition of the voltages in the divider.

When the photodiode is illuminated with a sufficient flux, the voltage on the trigger of B rises above the ignition voltage, so that B ignites. Its anode voltage now drops to V_{arc}. This voltage drop is transmitted via the commutating capacitor C to the anode of tube A, which is thereupon extinguished. The capacitor now recharges with reverse polarity, with time constant RC. Tube A remains extinguished as long as the OAP 12 is illuminated, as its trigger voltage is below the ignition value.

The shape of the various voltages is shown in Fig.61.

The operation of the flip-flop is improved by the inclusion of the common resistor R_c, since it gives another mutual coupling between the trigger electrodes. At each ignition (either of A or of B) a sudden voltage drop occurs across R_c and appears at the trigger electrodes so that the extinction of the tube is made still more certain. Furthermore, R_c reduces the influence of supply voltage fluctuations, as the current through this resistor, and thus the voltage drop, increases with increasing supply voltage.

9

Relay employing a phototube and a thyratron

When phototubes are used in the on-off applications, the photoelectric signal is too small to operate even the most sensitive relay, so that some form of amplifier is always necessary. If the exciter lamp, the amplifier and the phototube can be fed directly from the a.c. mains (and especially when phenomena of a slow character are to be registered or controlled), the circuit can still be comparatively simple, as is seen in Fig.62, which gives the lay-out of a simple a.c.-fed photoelectric relay.

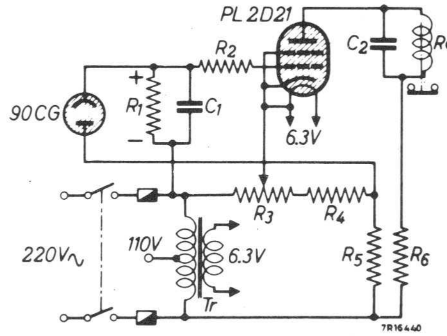


Fig.62. Photoelectric relay circuit with the 90CG gas-filled phototube, operated from 220 V mains.

R_1 = 1 MΩ R_4 = 20 kΩ C_1 = 0.01 μF
R_2 = 0.1 MΩ R_5 = 60 kΩ C_2 = 2 μF
R_3 = 5 kΩ R_6 = 1 kΩ Rel = relay 15 kΩ

The operation of the circuit can be explained as follows. Assume that the photoelectric tube is not exposed to light, so that no current flows through resistor R_1. The control-grid voltage of the PL2D21 thyratron is now determined solely by the voltage derived from the potentiometer R_3. This voltage is in anti-phase with the anode voltage. R_3 is so adjusted that the tube does not ignite.

When the phototube is exposed to light a voltage drop with the polarity indicated will be produced across R_1. The control-grid of the PL2D21 will consequently become more positive, the tube will ignite, and relay *Rel* will be energised. Relay *Rel* is shunted by capacitor C_2, whilst a current-limiting series resistor R_6 is also included.

10

General-purpose electronic switch for industrial applications

In Fig.63 is shown the circuit of a very elaborate device for photoelectric counting and control. The functions of the several components are as follows:

(*a*) The double-pole switch S_1 permits the change-over from a "light" circuit (in which case the relay is operated by light impinging on the photocathode) to a "dark" circuit (in which case the relay is operated by darkness).

(*b*) By incorporating the capacitor C_3 a certain leading phase shift (α in Fig.64) is introduced between the trigger voltage and the anode voltage of the trigger tube, thus ensuring that the duration of the current pulse flowing through the relay (β in Fig.64) is a maximum.

(c) A more reliable action is obtained by using a 15 000 Ω relay instead of the normal 2000 Ω relay, especially in respect of fluttering when operated on light signals of low intensity.

(*d*) The resistor R_7 of 1 kΩ has been incorporated in the cathode circuit of the trigger tube to limit the peak starter current and to provide the required voltage difference between the voltage for switching-on and the voltage at which the relay switches off.

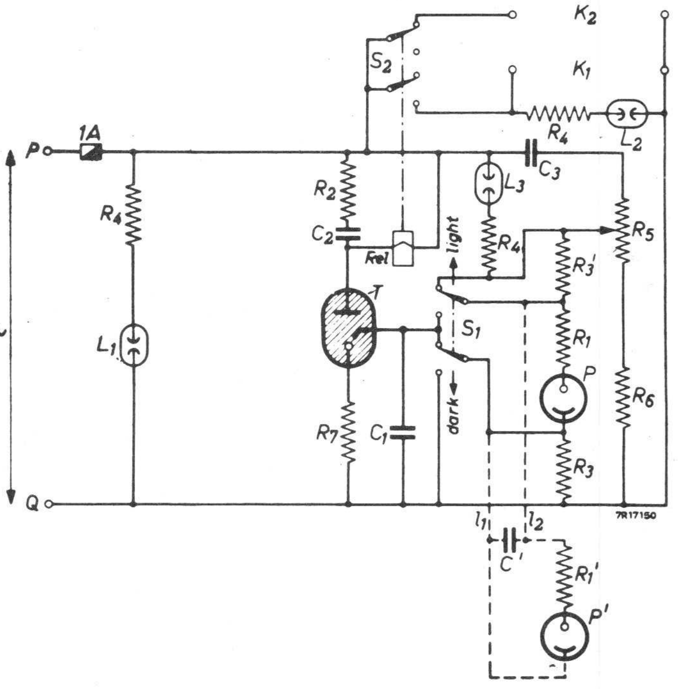


Fig.63. Elaborate circuit of an electronic switch equipped with a 90CV phototube.

R_1 = 1 MΩ, ½ W
R_1' = 1 MΩ, ½ W
R_2 = 1 kΩ, ½ W
R_3 = 10 MΩ, ½ W

R_3' = 10 MΩ, ½ W
R_4 = 200 kΩ, ½ W
R_5 = 500 kΩ, ½ W
R_6 = 1 MΩ, ½ W

R_7 = 1 kΩ, ½ W
C_1 = 120 pF
C_2 = 5 μF
C_3 = 0.022 μF

T = Z900T/5823
P=P' = 90CV
L_1-L_3 = Z8

(*e*) The sensitivity of the apparatus is adjustable by varying the phototube voltage by means of the potentiometer R_5.

(*f*) The resistor R_3 of 10 MΩ constitutes a voltage divider with the phototube *P* (and its protecting resistor R_1) in the "light" circuit; resistor R_3' has the same function in the "dark" circuit.

When in the "light" circuit, i.e. when the switch S_1 occupies the position indicated in Fig.63, the phototube is in darkness, the trigger voltage is too low to trigger the tube, so that the relay is open. With increasing illumination on the 90 CV the voltage at the connection of R_3 and *P* rises, trigger tube *T* is triggered and relay *Rel* is energised. The loaded capacitor C_1 then discharges across the trigger circuit.

In the "dark" circuit the elements in the voltage divider are interchanged, so that the relay is energised when the illumination level drops below a certain value.

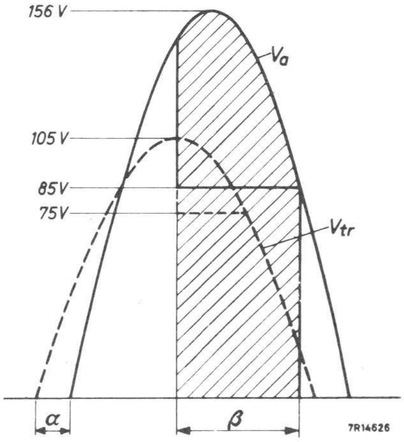


Fig.64. Anode and starter voltages of the trigger tube.
X-leading phase angle. β = anode-current angle.

The neon pilot lamps L_1 and L_2 have the following functions. The lamp L_1 indicates whether the mains voltage is switched on, while L_2 shows whether the relay is energised. In the latter case the mains voltage appears at the plug sockets K_1, and in the non-energised condition the mains voltage appears at the sockets K_2.

The circuit drawn in broken lines provides for the case where the phototube is mounted at some distance from the electronic switch, as, for example, when the apparatus is used as a flame control. In this case provision must be made for a warning to be given if a short-circuit occurs in the long phototube leads. For the "light" circuit this is achieved by means of neon pilot lamp L_3. It should be borne in mind that the cable introduces a parasitic capacitance *C'* across the phototube which reduces its sensitivity, and, when of high value, causes a short circuit. In the "dark" circuit this effect can be weakened by reducing C_1 accordingly.

11

Perforated-tape reader using photodiodes type OAP 12

Owing to its small dimensions the photodiode OAP 12 is very well suited for applications, in which quite a number of elements have to be accommodated in a small space. A typical example is in equipment for reading punched tape, a transistorised system for which is described in principle below.

In the punched tape system, information is transmitted by groups of perforations, each group being arranged transversely across the tape. According to the code employed, groups may have a maximum of 5, 6, 7 or 8 perforations. In addition, a continuous longitudinal line of perforations of smaller diameter (feed holes) is used to produce a photoelectric signal for controlling the running of the driving motor.

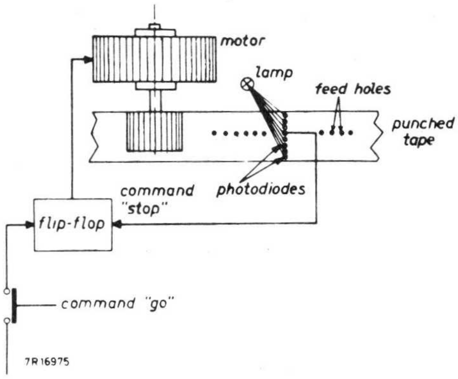


Fig.65. Principle of the feed control of the punched tape.

Fig.65 shows the basic principle of the system. The punched tape moves between a lamp and a series of photodiodes which are mounted in such a way that each cell is illuminated only through the perforations in a particular longitudinal channel.

The movement of the tape is often obtained by the friction of a rotating wheel, driven by the motor. A reading speed of 50 characters per second can easily be achieved by existing equipment, and speeds of a hundred characters per second are not unattainable.

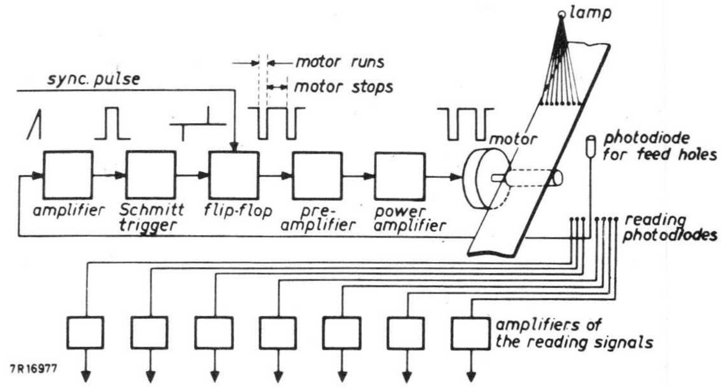


Fig.66. Block-diagram of the punched-tape reader.

The motor is started up by an external signal. For the reading action the tape must be stopped momentarily when each transverse row of perforations comes opposite to the row of photodiodes. The block diagram in Fig.66 shows the various parts of the apparatus, with the shape of the signals at the input of each stage, while in Fig.67 the electronic circuit of the motor control is given.

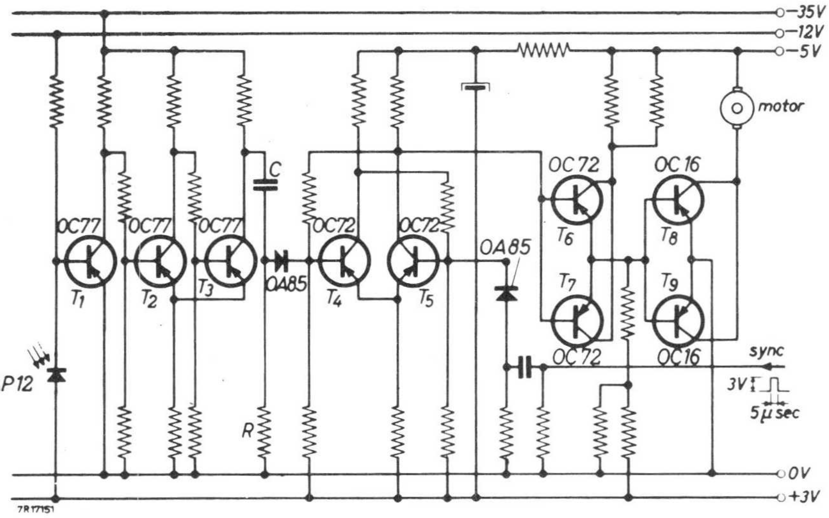


Fig.67. Electronic circuit for controlling the motor.

The flip-flop T_4 - T_5 receives on the one hand the sync-pulse to start the motor and on the other hand a signal to stop the motor momentarily for the reading. The latter signal is received from the Schmitt-trigger T_2 - T_3 which is controlled by the photodiode OAP 12 reading the central line of perforation.

The external sync-pulse causes the transistor T_5 to be cut off, and T_4 conducts, so that a negative pulse appears on the bases of T_6 - T_7. These two transistors now become conducting; the signal is amplified and the motor is energised.

The next feed hole passes a light pulse on to the OAP 12. The Schmitt-trigger thereupon switches from T_3 to T_2 and back again, so that a negative pulse appears at C. This pulse is differentiated by C - R, a positive voltage jump being transmitted through the diode OA 85, causing the flip-flop to reverse, and the motor stops. The photodiodes can now read the perforations. The next sync-pulse again starts the motor.

The shape of the pulses delivered by the photodiodes which read the perforations is similar to that shown in Fig.66. Usually a clear-cut signal with steep edges is required. This can be achieved by amplifying the signal of the photodiode as indicated in Fig.68. The circuit is so adjusted that with the photodiode illuminated the base of the transistor receives a positive voltage, so that the transistor is blocked. With the photodiode in darkness the base voltage falls to a negative value and a collector current flows, the circuit thus delivering quasi-rectangular signals.

The motor must be so constructed that the rotor has a small inertia, enabling high speeds of reading to be obtained.

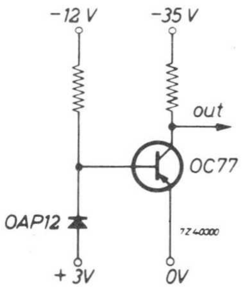


Fig.68. A first amplifier stage for the reading photodiodes.

12

A pyrometer employing a phototransistor

With the aid of a phototransistor a pyrometer can be constructed for measuring the temperatures of objects such as electrodes of electron tubes that cannot be brought in contact with a conventional thermometer. As the germanium is sensitive to wavelengths up to 2 μ, it is very suitable for detecting the radiation from objects at temperatures of some hundreds of degrees Centigrade, i.e. in the infra-red region.

A full-size image of the object is projected on a diaphragm *D* by the lens *L* (Fig. 69). The diaphragm has a small opening, behind which is placed the phototransistor, which thus receives radiation from only a small part of the object. By moving the object it can be examined point by point.

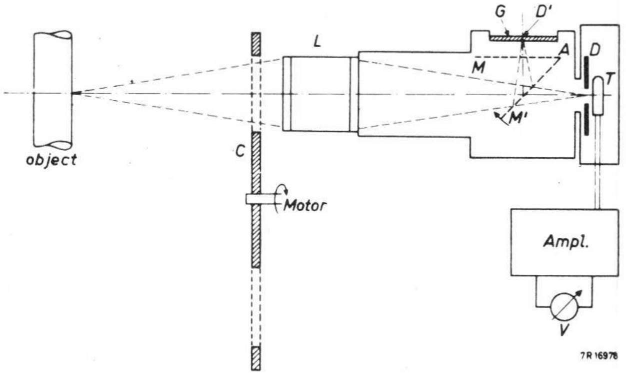


Fig. 69. Set up of an experimental pyrometer, employing the phototransistor OCP 70.

Mirror AM, in the position AM', shows which point of the object is being examined, as this part is depicted at D', on the translucent glass screen G.

The radiation from the object is chopped by a rotating perforated disc C, for example 175 times per second, so that the photoelectric signal has a ripple of 175 c/s. Its amplitude is a measure of the intensity of the incident radiation, and thus of the temperature of the radiator.

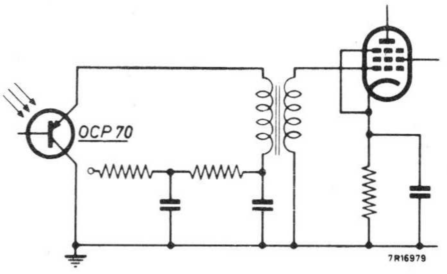


Fig. 70. First stage of the selective amplifier for the output signal supplied by the OCP 70.

The signal is amplified by a selective amplifier (Fig.70). The noise frequencies other than near 175 c/s, are thus filtered out, thereby increasing the signal-to-noise ratio. This ratio determines the lower limit of the radiation that can be detected.

The noise can be further reduced by placing the phototransistor in a block of aluminium, through which cooling water circulates. The temperature is thus reduced and stabilised at about 16 °C.

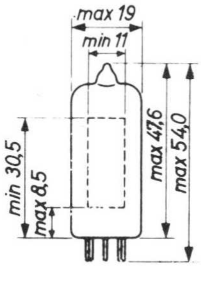
By calibrating the pyrometer with a black-body radiator the apparent temperature of the object can be determined, i.e. the temperature that gives the same meter reading as the black body. If necessary, the true temperature can be calculated therefrom, or determined by further calibrations.

In an experimental equipment, temperatures could be determined with a lower limit of 200 °C (black body), and a standard deviation of 1 °C.

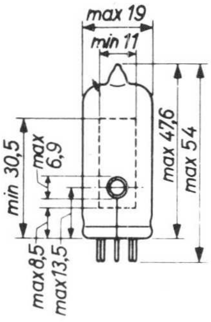
PART 3

Data on Current Types of Photosensitive Devices

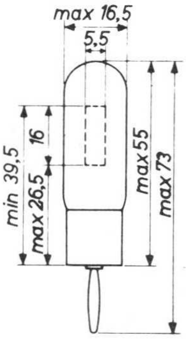
	90 CV	3545 PW 3545	92 AV	90 CG	3546 PW 3546	3554	92 AG
spectral response	red	red	blue	red	red	red	blue
cathode surface	Cs-Ag_2O	Cs-Ag_2O	Cs-Sb	Cs-Ag_2O	Cs-Ag_2O	Cs-Ag_2O	Cs-Sb
proj. sens. area (cm^2)	2.4	0.9	2.1	2.4	0.9	5.2	2.1
mounting position	any	any	any	any	any	any	any
capacitance C_{ak} (pF)	0.6	2	0.9	0.6	2	3.4	0.9
OPERATING CHARACTERISTICS							
anode supply voltage (V)	50	90	85	85	90	90	85
corresponding dark current at room temp. (μA)	<0.05	<0.05	<0.05	<0.1	<0.1	<0.1	<0.1
corresp. sensitivity (μA/lm) (colour temp. 2700 °K)	20	25	45	125	150	150	130
anode resistor (MΩ)	1	1	1	1	1	1	1
LIMITING VALUES							
$V_{b\max}$ (V)	250	250	100	90	90	90	90
$I_{k\max}$ per mm^2 (μA)	0.03	0.05	0.025	0.007	0.02	0.02	0.0125
$T_{amb\max}$ (°C)	100	100	70	100	100	100	70



90 CV/90 CG



92 AV/92 AG



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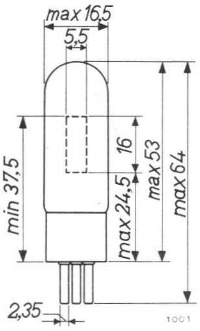
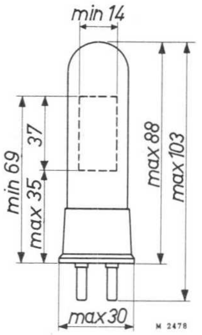


3546 PW



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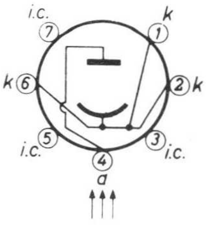
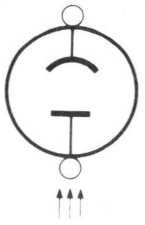
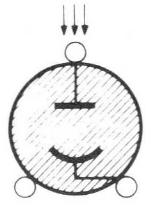
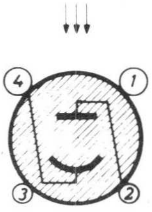
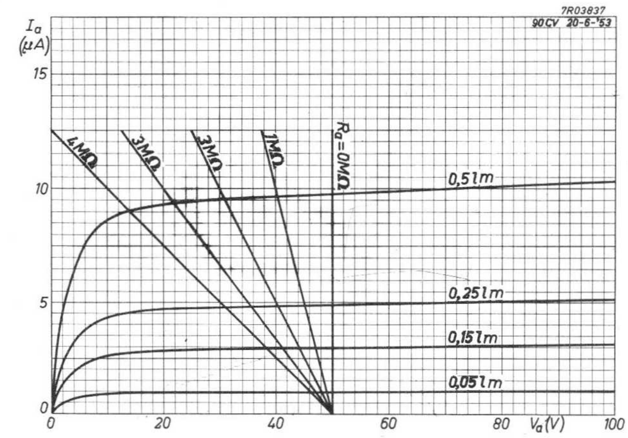


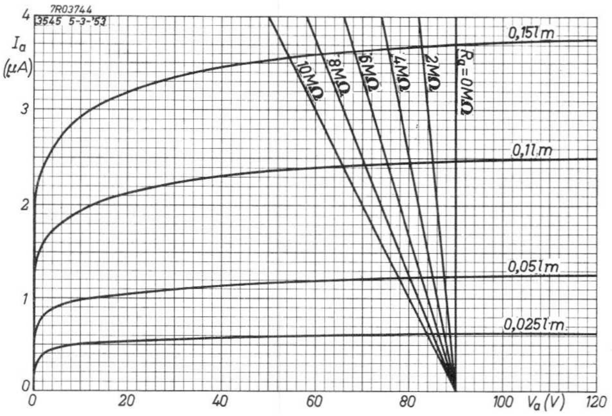




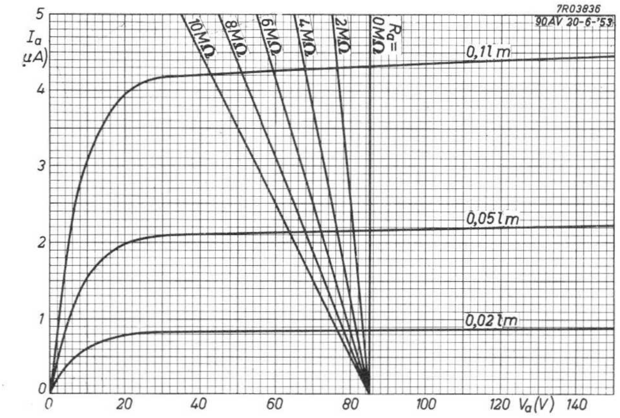




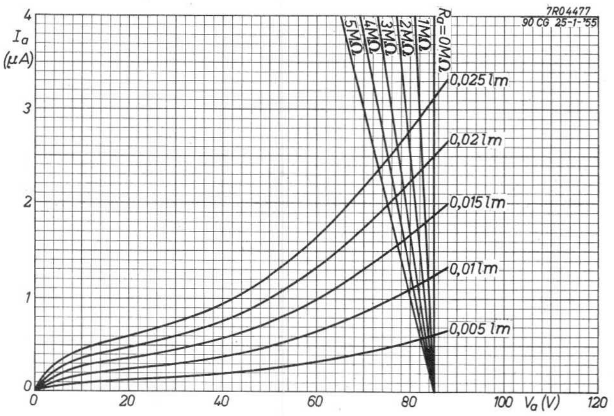
High-vacuum phototube 90CV.



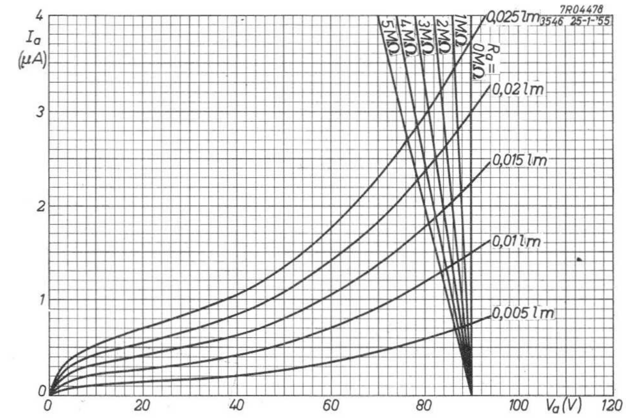
High-vacuum phototube 3545.



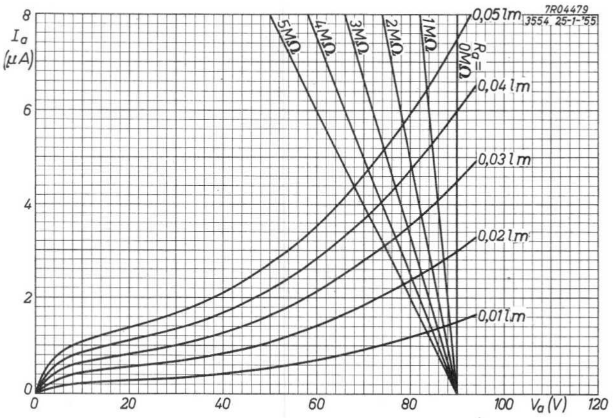
High-vacuum phototube 92AV.



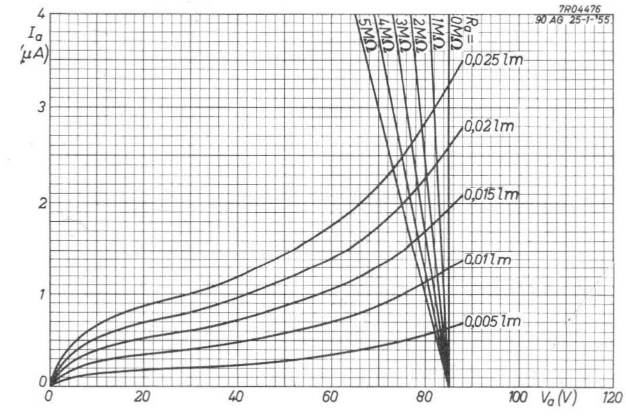
Gas-filled phototube 90CG.



Gas-filled phototube 3546.



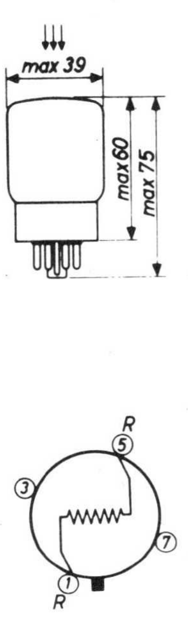
Gas-filled phototube 3554.



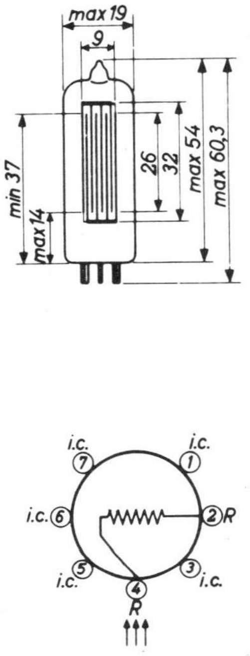
Gas-filled phototube 92AG.

ANODE CHARACTERISTICS OF
THE PHOTOTUBES

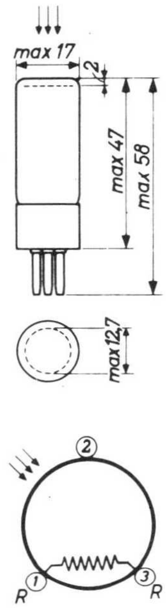
	ORP 30	ORP 90	ORP 11	ORP 60 ORP 61	LDR B8 731 03
spectral response	visible	visible	visible	visible	visible
photosensitive material	CdS	CdS	CdS	CdS	CdS
sens. area (cm^2)	4.5	1.8	1.25	2.5 10^{-3}	0.5
mounting position	any	any	any	any	any
sens. direction	top	side	top	top/side	top
CHARACTERISTICS					
dark current at V = and room temp. (μA)	300 V <5	300 V <2.5	100 V <5	100 V <0.15	dark resistance min. 10 MΩ
cell current (mA) at V = at 53.8 lx (= 5.0 ftc) colour temp. 2700 °K	10 V >12 =30 <48	10 V >3 =10 <16	10 V >3 =6 <14	30 V >0.2 =0.5 <0.8	light resistance 100-400 Ω (at 1000 lx)
LIMITING VALUES					
max. supply voltage	350 V_{dc} 250 V_{ac}	350 V_{dc} 250 V_{ac}	100 V_{dc} 70 V_{ac}	350 V_{dc} 250 V_{ac}	110 V_{pk}
max. dissipation	1.2 W (25 °C)	1 W (25 °C)	0.2 W (25 °C)	70 mW (25 °C)	0.2 W (up to 40 °C)
	0.35 W (70 °C)	0.3 W (70 °C)	0.05 W (70 °C)	20 mW (70 °C)	decreasing to 0 at 60 °C
ambient temp. range	-40/+70 °C	-40/+70 °C	-40/+70 °C	-40/+70 °C	-20/+60 °C



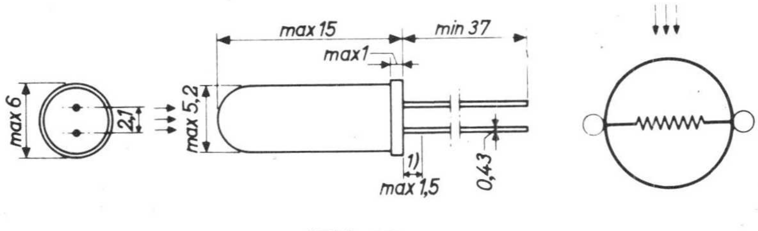
ORP 30



ORP 90

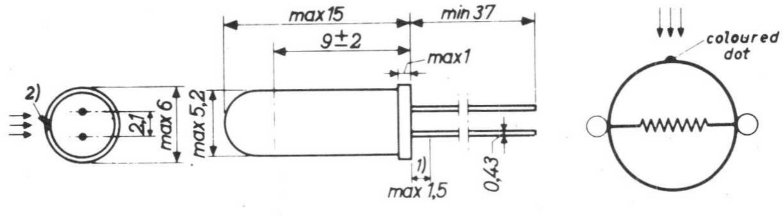


ORP 11



ORP 60

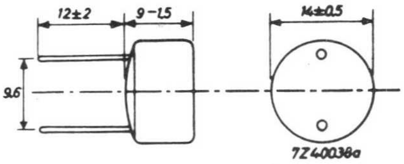
1) not tinned



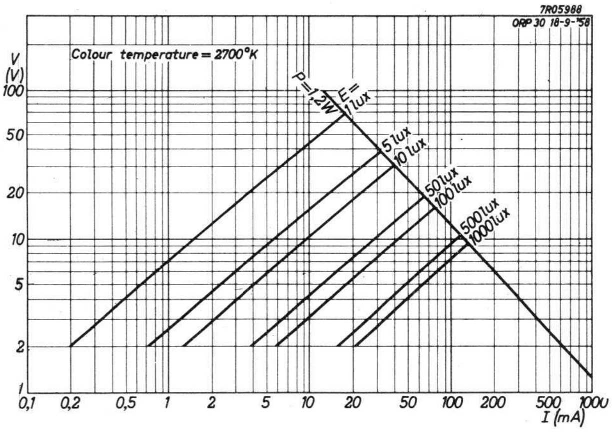
ORP 61

1) not tinned

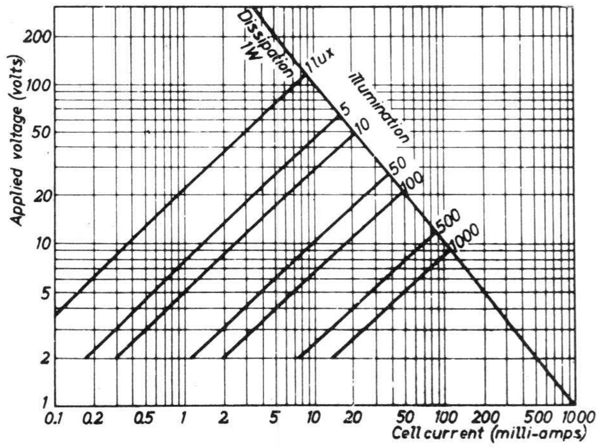
2) coloured dot



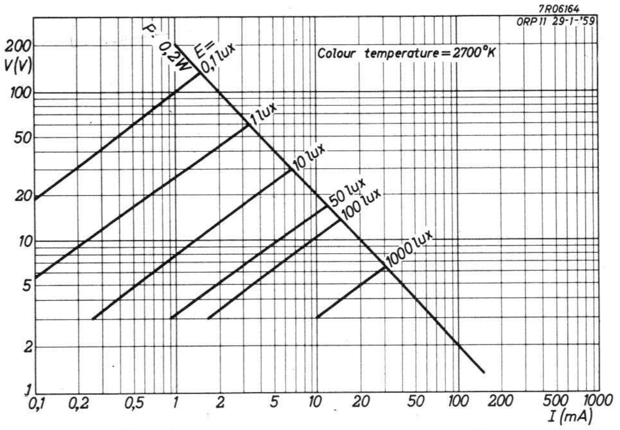
LDR B8 731 03



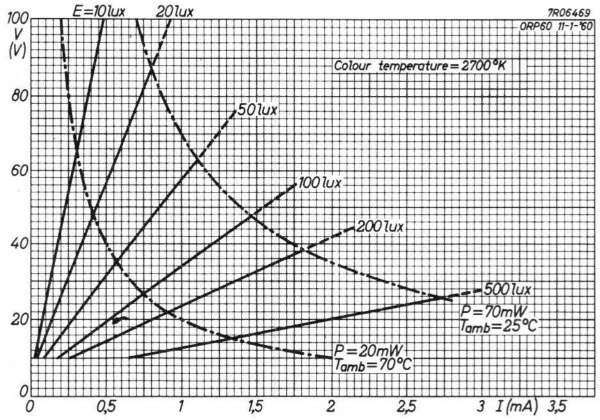
Cell voltage versus cell current of the photoconductive cell ORP 30.



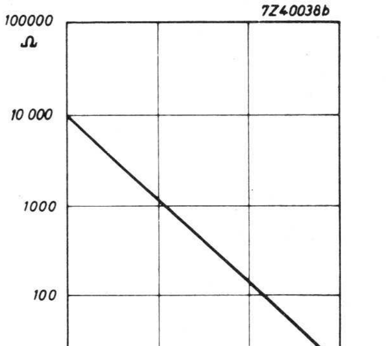
Cell voltage versus cell current of the photoconductive cell ORP 90.



Cell voltage versus cell current of the photoconductive cell ORP 11.



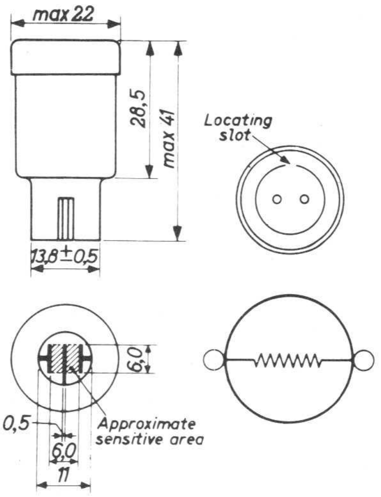
Cell voltage versus cell current of the photoconductive cells ORP 60 and ORP 61.



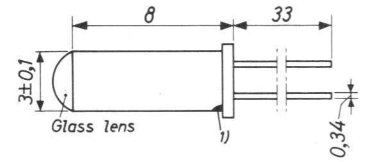
Variation of the resistance of the light-dependent resistor LDR as a function of the illumination.

	61 SV	OAP 12	OCP 70
spectral response	infra-red	visible/ infra-red	visible/ infra-red
photosensitive material	PbS	Ge	Ge
sensitive area	0.36 cm^2	1 mm^2	7 mm^2
mounting position	any	any	any
CHARACTERISTICS			
dark current (room temp.)	at 200 V 50 to 200 μA	at 10 V <15 μA	at V_{CE} = -4.5 V and I_B = 0 V I_{CEO} < -325 μA
sensitivity	180 $\mu V_{rms}/\mu W_{pk}$* at V = 200 V	5 μA/100 lx at T_c = 2500 °K	750 μA/807 lx at V_{CE} = -2 V and T_c = 2700 °C
series resistor	min. 0.2 MΩ		
LIMITING VALUES			
max. voltage	200 V	-30 V	$-V_{CEM}$ = 7.5 V $-V_{CE}$ = 7.5 V
max. current	0.3 mA	-3 mA	I_{CM} = -20 mA I_C = -20 mA
max. dissipation		P_j = 30 mW	P_C = 25 mW
max. temperature (junction)	60 °C	75 °C	75 °C

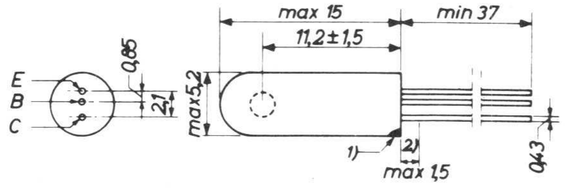
*) for radiation of a black-body of 200 °C, chopped at 800 c/s



61 SV



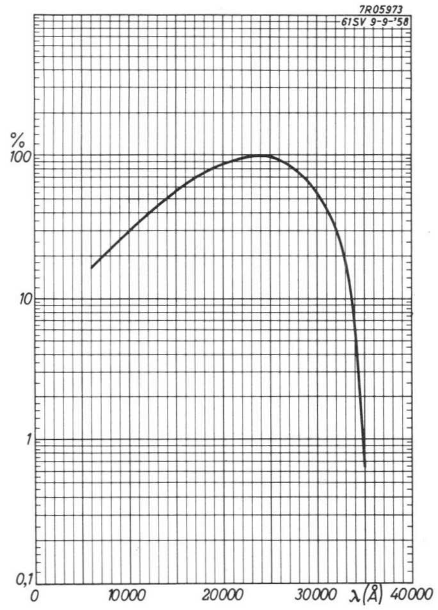
OAP 12



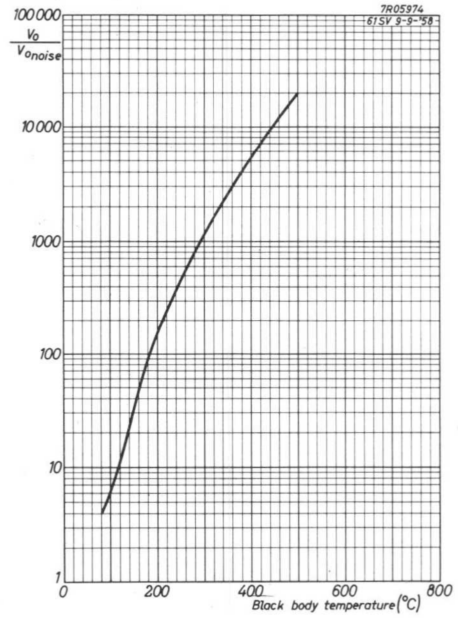
OCP 70

1) coloured dot

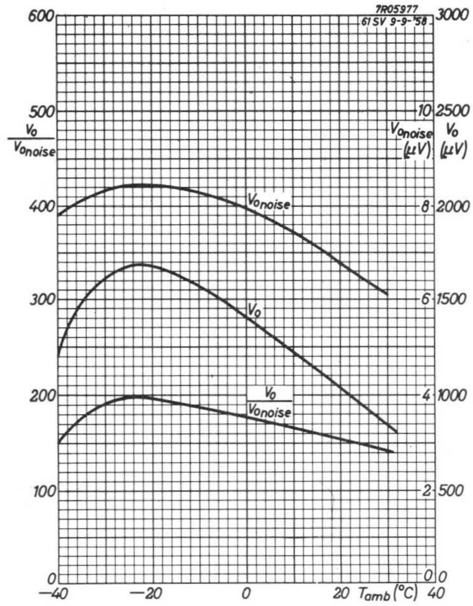
2) not tinned



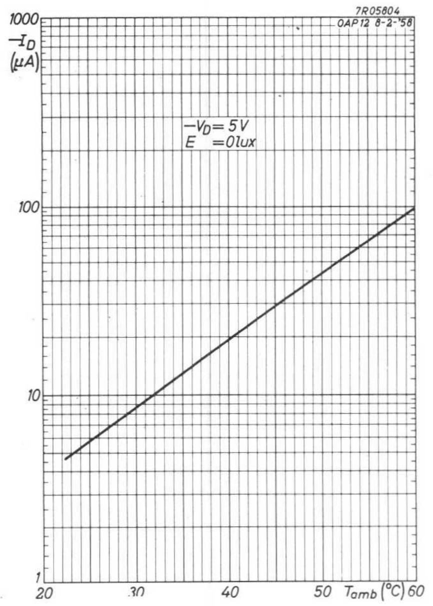
Relative spectral dependence of the signal-to-noise ratio of the lead-sulphide cell 61 SV.



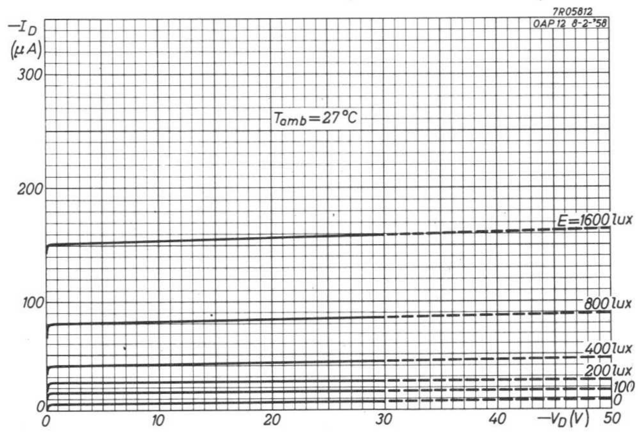
Signal-to-noise ratio as a function of the black-body temperature at irradiation of the 61 SV.



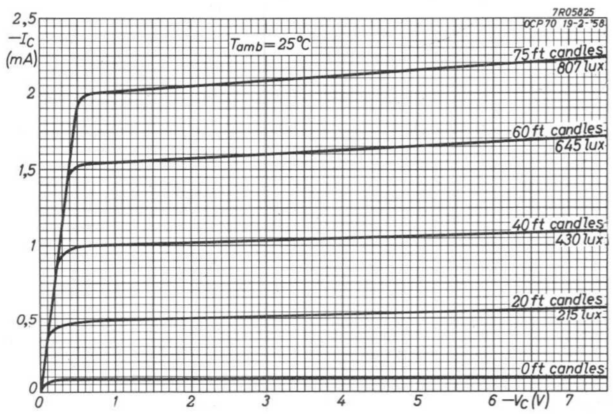
Signal-to-noise ratio, noise and signal plotted against the ambient temperature, at irradiation of the 61 SV with 4.9 μW from a 200 °C black-body source, interrupted at a rate of 800 c/s. The voltage across the cell and a 1 MΩ series resistor is 200 V.



Dark current of the OAP 12 as a function of the ambient temperature at a voltage of -5 V.



Characteristics of the photodiode OAP 12 at an ambient temperature of 27 °C.



Characteristics of the phototransistor OCP 70 at an ambient temperature of 25 °C.

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