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PHOTO-RESISTORS MADE OF COMPRESSED AND SINTERED CADMIUM SULPHIDE

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Research into the solid state has led, especially in recent years, to a number of new electronic devices, which have rapidly found a variety of practical applications. The germanium diode and the transistor, to give two examples, have assumed great importance in a very short space of time. Another recent development, which is likely to find wide application, is the cadmium sulphide photoconductive cell (photo-resistor).

The article which follows describes how these photo-resistors can be produced on an industrial scale and discusses some of their many possible applications.

Introduction

For a considerable number of years science and industry have been making use of devices capable of converting light into electrical signals. The oldest of these is the familiar *vacuum photocell.* This is an evacuated glass envelope containing a sensitive layer (the photocathode) from which electrons are freed by the action of light (photo-electric emission), and an anode which stands at a higher potential (about 100 V) and towards which the freed electrons move. The anode current is equal to the current constituted by the electrons released from the photocathode. The sensitivity of this type of photocell is approximately 10^{-8} amperes per lux; with normal intensities of illumination, therefore, the output signal has to be amplified considerably before it can be conveniently measured or used for some practical purpose.

A current several times greater than that of the liberated photo-electrons can be obtained from a cell of this kind by filling the envelope with a suitable gas. The photo-electrons traversing the field between the cathode and anode ionize the gas, so providing a current amplification. The higher the anode voltage, the greater is the amplification obtained in this way; but the voltage across the cell must, of course, remain well below the breakdown value.

The *photomultiplier* is a refined version of the vacuum-type photocell. One to ten millionfold amplification takes place in this tube by virtue of secondary electron emission from auxiliary electrodes (dynodes). Accordingly, the sensitivity of photocells of this type is as high as $\sim$ 0.1 ampere/lux, but they have the disadvantage of requiring a voltage between 1000 and 2000 V. Nevertheless, in certain applications amplification by secondary emission is a much more attractive proposition than the use of ordinary amplifying tubes.

The vacuum-type photocell and the photomultiplier distinguish themselves from all other types by virtue of their extraordinarily fast response, for they can handle periodic signals with frequencies up to 100 Mc/s. The gas-filled photocell is much less fast, being unable to cope with frequencies above 10 kc/s. The spectral region to which these three types of photocell are sensitive is determined by the nature of the cathode material. Only for a few materials is the long-wavelength limit (the so-called "red limit") in the long-wave half of the visible range or in the infra-red [1]).

[1]) More about the vacuum and gas-filled types of photocell may be found in Philips tech. Rev. 2, 13-17, 1937 and 4, 48-55, 1939. For the photomultiplier see Vol. **16**, 250-257, 1954/55.
A general account of the photo-electric effect and of photocells and their applications may be found in V.K. Zworykin and E.G. Ramberg, Photoelectricity and its application, John Wiley, New York 1949, or H. and A. Simon, Der lichtelektrische Effekt und seine Anwendungen, Springer, Berlin 1958.

More recently photocells have been developed whose action is based on the *internal* photo-electric effect occurring in certain solids which in darkness are poor conductors. Electrodes are fitted to a disc or block of a substance of this kind: depending on the nature of these electrodes we get a *photo-conductive cell* or *photo-resistor*, i.e. a device whose electrical conductivity varies with the intensity of the incident light, or a *photo-voltaic cell*, which is a device across which differences of electrical potential arise when light falls upon it. In the last few decades selenium photocells of the latter type (barrier-layer cells) have come into use on a considerable scale. One well-known application is in the photo-electric exposure meters used in photography. Photo-voltaic cells are more sluggish than the vacuum type, being unable to handle frequencies above 2 kc/s, but they are ten times as sensitive [2]). The spectral sensitivity curve of the selenium photo-voltaic cell exhibits a peak at approximately 6000 Å, which lies at about the centre of the visible spectrum.

Selenium photo-resistors have never found large-scale application. The *germanium point-contact diode,* the *germanium photo-transistor* and other devices that have been developed during the last ten years have proved to be more useful. Because their sensitive surfaces have a very small area, their sensitivity as defined above, in amperes/lux — their *lux* sensitivity — is on the low side; they do however have a high *lumen* sensitivity, i.e. a sensitivity measured in amperes/lumen. The photo-transistor is sensitive not only to the visible range but also to wavelengths well inside the infra-red band (to about 2 μ) [3]). Photo-resistors made of *cadmium sulphide* can have even higher lumen sensitivities. The photo-resistors made by Philips, which contain a sensitive layer of compressed and sintered cadmium sulphide, have a lumen sensitivity approaching that of the photomultiplier. Their lux sensitivity is also very high, being exceeded only by that of the photomultiplier.

To give an idea of the sensitivity of these cells, it may be mentioned that when exposed to an intensity of illumination of 1000 to 10 000 lux, their resistance is of the order of only 100 Ω. Their dark resistance is of the order of 100 MΩ. It is thus possible to control a relay by means of a simple arrangement consisting of relay and cell in series with a voltage supply.

It may be useful, to prevent any misunderstanding, to say something more about the two measures of sensitivity for photocells and photo-resistors. The lux sensitivity (in A/lux) may be worked out from the lumen sensitivity (in A/lumen) by multiplying the latter by the area (in m^2) of the sensitive surface of the cell or resistor. Of course, when stating the sensitivity of a photo-resistor in either of these units it is necessary to state also the applied voltage to which the sensitivity applies. The advantage of using the two measures of the sensitivity lies in the field of comparisons between photo-resistors and other kinds of photocell.

Before discussing the method of production of the light-sensitive material for the new photo-resistors, we shall give a brief account of the phenomenon of photoconductivity as it occurs in CdS and other substances. From this it will be evident which property is the best suited for characterizing the merits of a photoconductive substance, and how the optimum form of a cell based on that substance may be decided upon.

The phenomenon of photoconductivity in CdS

In a non-conductive solid all electrons are bound to the ions or atoms which go to make up the crystal lattice; free electrons such as exist in metals are absent or present only in very small numbers. This also applies to photoconductive substances like CdS, insofar at least as they are not exposed to radiation. When radiation falls on the crystal the energy of the radiation is absorbed by the lattice. Very briefly, a number of electrons then become more or less free, so that the substance ceases to be an insulator and becomes a conductor. We shall now determine the quantities governing the conductivity of a piece of crystalline photoconductive substance, and find out how its conductivity depends on them.

We shall denote by F the number of light quanta absorbed per cm^3 and per second, and by τ the average time elapsing before an electron is recaptured by an ion or atom that has lost one of its own electrons (τ is the "mean life time" of the free electron). Assuming that every absorbed light quantum liberates one electron, we can say that in equilibrium the number of free electrons present per cm^3 will be [4])

$$n = \tau F. \quad \quad \quad (1)$$

[2]) When the electrodes of a photo-voltaic cell are joined, a current flows which, provided the resistance of the external circuit is small (< 10 Ω), is independent of this resistance and proportional to the intensity of illumination. In this case the sensitivity can thus again be expressed in amperes per lux. Cf. Philips tech. Rev. **8**, 65-71, 1946.

[3]) One application in which sensitivity to infra-red is of particular importance is the transistor pyrometer described in Philips tech. Rev. **20**, 89-93, 1958/59 (No. 4).

[4]) Expression (1) is not based on any theory concerning the freeing or absorption of electrons but is a perfectly general statistical law.

If two electrodes are affixed to the CdS crystal and a voltage applied to it, the free electrons will move at a velocity v which is proportional to the field strength E in the crystal:

$$v = \mu E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The factor of proportionality μ is termed the *mobility* of the electrons. Using (1) and (2), the current density J, which is nev, can be written as

$$J = nev = \mu \tau eEF \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(e is the charge on the electron).

If the crystal has the shape of a rectangular slab of width l, thickness t and length d (see *fig. 1*; d is the distance between the electrodes), and if a voltage V is applied to it, then $E = V/d$. If Q light quanta strike the crystal per second and each of them liberates an electron, the (mean) value of F will be Q/ldt. The current through the crystal will accordingly be

$$i = Jlt = \mu \tau e \frac{V}{d} \frac{Q}{dlt} lt = \frac{\mu \tau eV}{d^2} Q . \quad . \quad . \quad (4)$$

With electrodes of suitable material, properly connected to the crystal material, electrons will be able to enter the crystal from the cathode and to leave it by way of the anode. It will thus be possible for a current of the above magnitude to flow permanently, and the crystal will constitute a practical photo-resistor. To obtain a high sensitivity, the product $\mu\tau$ (see eq. 4) must have a high value; in addition the distance between the electrodes must be kept small. We see that the lumen sensitivity — i.e. the ratio between i and Q, apart from a constant factor — will be independent of the area of the surface exposed to light. That being so, the lux sensitivity will be exactly proportional to that area. It is also plain that the current will increase in direct proportion to the applied voltage. If the highest possible sensitivity is desired, therefore, the voltage across the crystal should be high.

In deriving (3) it was tacitly assumed that when current flows through the crystal the charges are carried by electrons only. In some substances it is possible for the empty places left by liberated electrons in the ions (or atoms) to move, and so to contribute to the total current flowing. In CdS, however, the mobility of these "holes" is negligibly small compared with that of the electrons. No further assumptions were involved in the derivation of (3). It is therefore valid for all photoconductors in which electron conduction is predominant.

Consider now the magnitude of the current through the crystal as given by (4), measured in electronic charges per second, and compare this rate of flow with the number of electrons (Q) released per second. We see that the former is $\mu\tau V/d^2$ times greater than the rate of release. This "amplification factor" may have values of the order of 10^3 to 10^4. Enigmatic at first sight, the fact that in equilibrium it is possible for more electrons to leave the crystal than are liberated by the incident light becomes understandable when it is realized that there is nothing to stop free electrons entering from the negative electrode. It may therefore happen that an electron released inside the crystal passes round the circuit many times before it is recaptured. In the absence of radiation, however — in other words, when no free electrons have arisen inside the crystal and passed out of it via the anode — it is impossible for a large number of electrons to enter the crystal from the cathode, their passage being impeded by a space-charge effect.

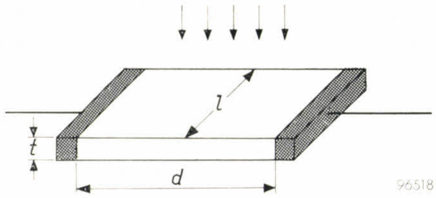


Fig. 1. The diagram represents a slab of photoconductive material fitted with two electrodes a distance d apart. The area exposed to radiation is $l \times d$.

The use of CdS as photoconductive material

Although it has been known for many years that it is possible in a group of CdS crystals to find individuals that exhibit an exceptionally high photosensitivity, the use of the compound for the large-scale production of photo-resistors has only recently become a practical proposition. For example, if a number of CdS single crystals are made by the Frerichs method [5]), large differences are found not only in the shape and dark resistance of individual crystals but also in their photosensitivity, which is considerable in some and poor or even nil in others. It is true that good crystals can be picked out, but the Frerichs method is not suitable for the production of photo-resistor material on a large scale.

During recent years research has been carried out on CdS and related compounds (e.g. cadmium selenide and cadmium telluride) in many quarters, and this has revealed that photoconductivity only occurs in CdS when certain impurities known as activators are present; other impurities act as inhibitors. The activators include the elements Cu, Ag, Cl and Ga [6]). Iron is an inhibitor, and must not be present in concentrations greater than one atom per million Cd atoms. The endeavour must therefore be to make

[5]) R. Frerichs, Phys. Rev. **72**, 594, 1947. In this method cadmium vapour is caused to react at 800 °C to 1000 °C with H_2S in a quartz tube through which a slow stream of H_2S and hydrogen is passed. The vapour is produced by heating metallic cadmium in the "upstream" portion of the tube. The CdS crystals form in the colder, "downstream", portion of the tube.

[6]) Only the first two are essential for the absorption of radiant energy. The usefulness of the other two lies in the fact that they cause the Cu or Ag or both to take up the proper positions in the crystal lattice.

cadmium sulphide crystals in which suitable impurities are present, and to do so by a process that allows the concentrations of the activators to be conveniently controlled. Such a process has now been developed. A precipitate of CdS is first prepared by passing hydrogen sulphide through a solution of a Cd salt. This provides very pure CdS in the form of an extremely fine powder, the size of the grains being 0.1 μ or less. To this powder are added the activators — copper and gallium in the case of the photo-resistors discussed in this article. The powder is then subjected to a temperature between 700 °C and 900 °C. This heat treatment, which lasts several hours, results in the formation of much larger grains (10 to 100 μ), in which the added activating material is uniformly distributed and which exhibit a high degree of photosensitivity.

To produce a homogeneous coherent material from this powder, having a photosensitivity little inferior to that of the grains, the following process has been developed in the Philips Research Laboratories. It proved quite practicable to compress the powder into tablets without using a binder. The filling factor of the compressed powder is approximately 90%, which is a very high figure compared with other substances and which can only be explained by the fact that the grains are to some extent plastic. The pressing operation gives rise to imperfections in the crystal lattice, and these tend to reduce the photosensitivity of the material very considerably. However, unlike the inhibiting impurities, the lattice imperfections can be considerably reduced or modified, this being done by a second heat treatment. Careful consideration must be given to the temperature to which the compressed powder is to be heated, the duration of the treatment, and the atmosphere in which it is carried out. In the course of this treatment the grains coagulate in such a way that finally a material is obtained which is fairly strong mechanically, besides possessing a high degree of photosensitivity. However, it is still possible to recognize the grains in the structure of the material; see *fig. 2*.

Heat treatment enhances the photosensitivity of the material, partly because it largely removes the lattice irregularities and partly because it improves contact between the grains. The dark resistance, which is less dependent on the intergranular contact resistance, is not seriously affected by the heat treatment. Needless to say, the chance of impurities being introduced into the material in the press must be carefully guarded against. The risk of contamination is reduced to a minimum by making the punch and die of suitable material and giving them a particularly fine finish.

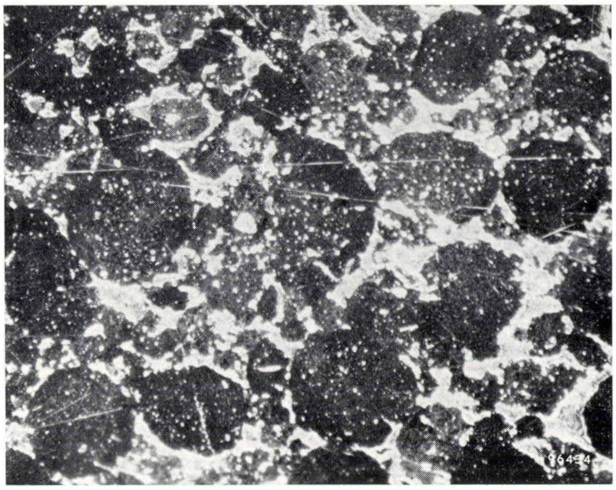


Fig. 2. Cross-section through a piece of compressed and sintered cadmium sulphide. Separate grains can still be discerned. Magnification approx. 150 ×.

If the properties of the material produced in this manner are compared with those of one in which coherence has been obtained by adding a binder, a striking difference is found in regard to photoconductivity: the effective value of the product $\mu\tau$ is considerably greater for the compressed and sintered material than for the other kind.

Certain further observations may be made with regard to the dosage of the additives. It has been found that there must be a very definite (constant) ratio between the copper and gallium concentrations. Too much Cu reduces the photosensitivity of the material, while a relatively high Ga concentration results in a low dark resistance. The higher the concentrations in which additives are present, the more serious are the effects of departures from the correct proportions. On the other hand it is desirable to add activators in fairly high concentrations so that these may be large in comparison with those of the impurities already present. This is the only way of making sure of getting a product whose properties are reasonably constant. All in all, there is not much freedom with regard to the choice of these concentrations.

The ORP 30 and ORP 90 photo-resistors

Fig. 3 shows two photo-resistors made of compressed and sintered cadmium sulphide. Both consist of a glass envelope (having the sole purpose of protecting the contents) inside which is a plate of photoconductive material 0.8 mm thick; coated on one side are metal film electrodes in the form of two interlocking combs; see *fig. 4*. The use of electrodes of this shape satisfies two conditions for high sensitivity, namely that the sensitive area should be large and the distance between the electrodes small — see formula (4). The "teeth" of the combs are 1 mm apart. The electrodes are formed on the plate by applying a mask to it and depositing upon it a suitable material (Cu, Ag, Al or Au) evaporated in a

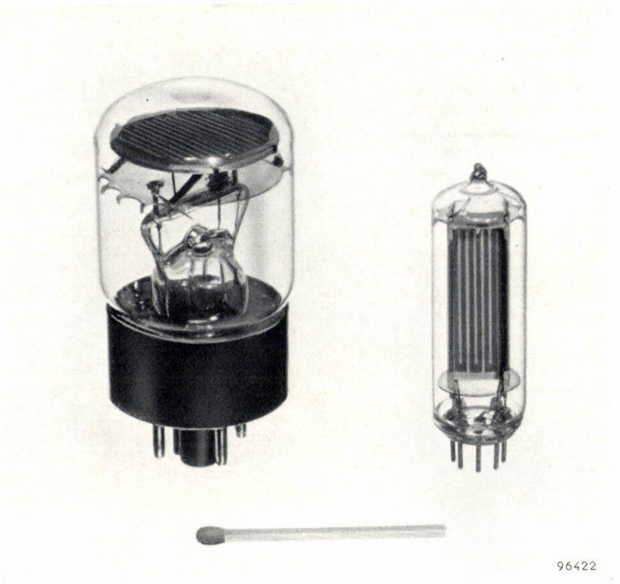


Fig. 3. CdS photo-resistors of type ORP 30 (left) and ORP 90 (right), developed by the Electronic Tubes Division of Philips.

vacuum. As equation (4) shows, the sensitivity of the resistor increases with the voltage across it. The highest voltage permissible is determined by the clearance between the electrodes. It will be noted that in the ORP 90 the CdS plate is mounted parallel to the axis of the tube, whereas the plate in the ORP 30 is perpendicular to the tube axis. The former tube is designed to respond to light striking its side, the latter to light coming from above. The ORP 90 has the same sort of base as a 7-pin miniature tube and is therefore uniform in this respect with the 90 CV and 90 CG photocells.

Measurements have provided the following information about the properties of the sensitive layer in these photo-resistors.

a) *Sensitivity*. The product $\mu\tau$ has been found to have an average value of 0.5 cm²/V [7]).

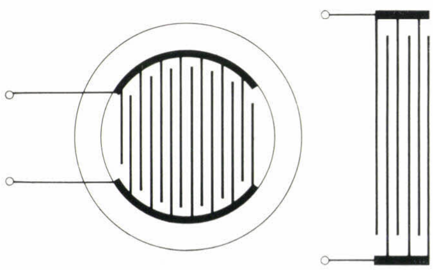


Fig. 4. Diagram showing the shape of the electrodes in the ORP 30 (left) and ORP 90 (right) CdS photo-resistors. This form of electrode makes it possible to combine the advantages of a large area of sensitive surface and a small clearance between the electrodes.

[7]) In single crystals of activated CdS, higher $\mu\tau$ values are found, of the order of 10 cm²/V; for layers made of powder containing a binder, the highest $\mu\tau$ values are between 0.01 and 0.1 cm²/V.

b) *Spectral sensitivity* (*fig. 5*). The resistors are sensitive throughout almost the whole of the visible range and a good way into the infra-red band. Their sensitivity peak occurs round about 6800 Å.

c) *Current-voltage relation*. The variation of the current through the resistor with applied voltage is roughly linear. The voltage exponent (see *fig. 6*) is between 1.05 and 1.10, which implies that Ohm's law is approximately obeyed. (This is not so for materials containing a binder, the current through these varying with a voltage exponent between 3 and 4.)

d) *Relation between current and illumination*. This relation is also roughly linear, the exponent being about 0.85 (*fig. 7*).

e) *Effect of temperature*. Temperature has very little effect, as may be seen in *fig. 8*: a rise from 0 °C to 40 °C causes the current to fall off by only 10%. In this respect the performance of cadmium sulphide photo-resistors is particularly good compared with that of other types.

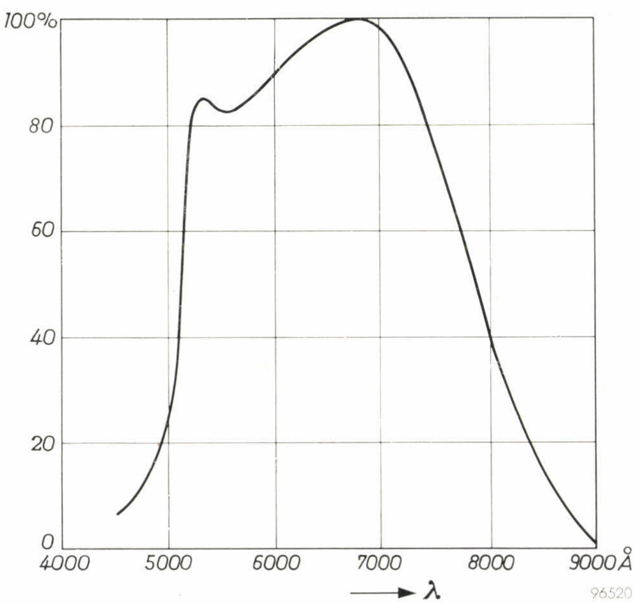


Fig. 5. Spectral sensitivity curve of photo-resistors made of compressed and sintered CdS. This material retains its high sensitivity well into the infra-red. The sensitivity peak occurs in the red part of the spectrum.

f) *Speed of response* (*fig. 9*). The photo-resistors are unable to follow rapid changes in the intensity of illumination. However, the more intense the illumination, the more quickly they react. After the tube has been exposed to 100 lux, the current decays to half-strength within 5 milliseconds; but after exposure to 0.1 lux, the current takes 0.25 s to decay to its half-value.

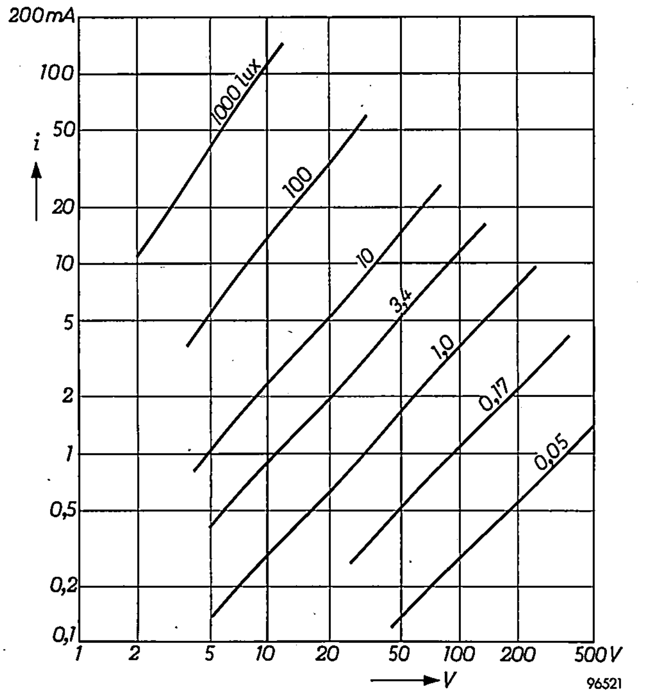


Fig. 6. Curves of current i versus voltage V, as obtained from measurements carried out on an ORP 90 photo-resistor exposed to various intensities of illumination. The current-voltage relation can be expressed by $i = \text{const.} \times V^{\alpha}$, i.e. the relation between log i and log V is linear. Since the value of α is close to unity (about the same for all the curves), the relation between i and V is practically linear, in other words pressed and sintered CdS roughly obeys Ohm's law (at a given illumination).

g) *Dark resistance.* The resistance of the ORP 30 in the dark exceeds 10^7 Ω, that of the ORP 90 exceeds 10^8 Ω.

A number of characteristic quantities relating to the new photo-resistors are summarized in *Table I*, to enable the properties of these devices to be conveniently compared with those of other types. Sensitivity is indicated both in amperes per lumen (S) and in amperes per lux (H). As already pointed

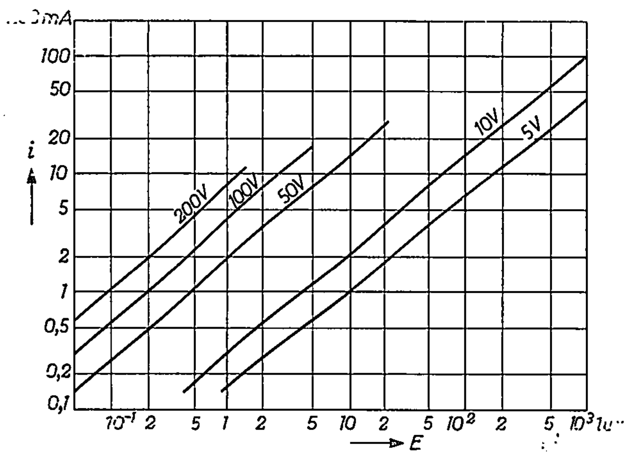


Fig. 7. Curves of i versus the intensity of illumination E, obtained from measurements carried out on the ORP 90 with various voltages applied to the cell. This relation too is an exponential function with a power close to unity; that is to say, i is roughly proportional to the illumination as well as to the applied voltage.

out, the ratio between the two sensitivity values is equal to the area (A) of the sensitive surface.

Inserting the above-mentioned value of 0.5 cm²/V for $\mu\tau$, 2×10^{16} for the number of quanta absorbed

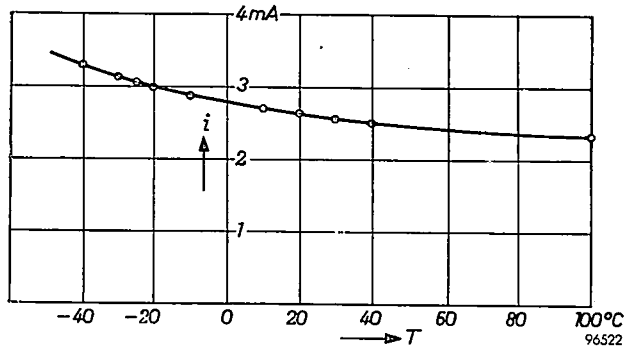


Fig. 8. The photoconductivity of resistors made of compressed and sintered CdS is but little dependent on temperature. The graph shows how the current i through an ORP 90 cell varies with the temperature T, for an illumination of 10 lux and a voltage across the cell of 10 V.

per lumen, and 1.6×10^{-19} coulomb for the charge on the electron, we obtain the following sensitivity values for CdS resistors:

$$S = 1.6 \times 10^{-3} \frac{V}{d^2} \text{ ampere/lumen} \quad . \quad . \quad . \quad (5)$$

and

$$H = 1.6 \times 10^{-7} \frac{AV}{d^2} \text{ ampere/lux.} \quad . \quad . \quad . \quad (6)$$

In the above formulae V is expressed in volts, d in cm and A in cm².

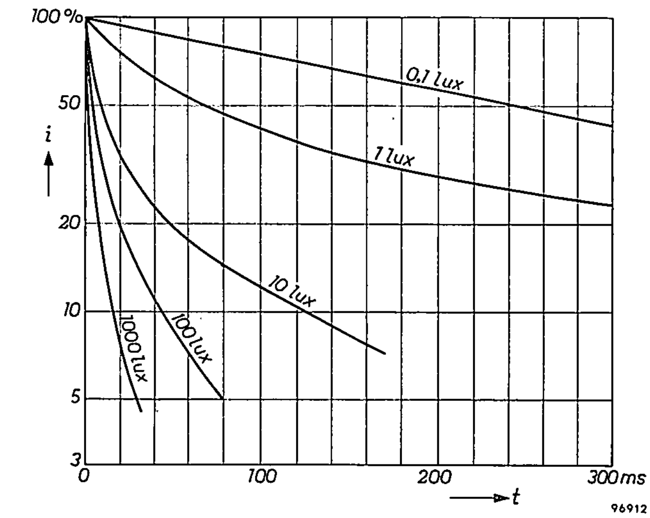


Fig. 9. Some idea of the inertia of CdS photo-resistors may be obtained by measuring how the current (i) changes with time (t) subsequent to removal of the incident light. The shape of the decay curve is found to depend on the intensity of illumination to which the cell was exposed immediately before. When the prior illumination was very intense, the current falls off very quickly to a small proportion of its original value; the decay is much slower where the intensity was low.

Table I. Comparison between the properties of various photosensitive devices. The sensitivity values express the response to radiation from a tungsten-ribbon lamp with a colour temperature of 2800 °C. The last four columns indicate respectively: N the number of quanta absorbed per lumen, I_{max} the highest permissible value of the current, Q_{max} the highest permissible power and f_{max} the highest frequency of fluctuations in the intensity of illumination to which the device can respond.

Type of cell or resistor	S (A/lumen)	A (cm²)	H (10^{-4} A/lux)	N (10^{16} qu/lumen)	I_{max}	Q_{max}	f_{max}
90 AV: vacuum-type photocell	0.00005	4	0.0002	1	10 μA	—	100 Mc/s
90 AG: gas-filled photocell	0.00013	4	0.0005	1	10 μA	—	10 kc/s
50 AVP: photomultiplier	500	8	4000	1	100 mA	—	100 Mc/s
Selenium photo-voltaic cell	0.0005	10	0.005	1	—	50 μW/lumen	2 kc/s
OAP 12: photo-diode	0.05	0.01	0.0005	20	—	0.12 W	50 kc/s
OCP 71: photo-transistor	0.3	0.07	0.02	20	—	0.10 W	750 kc/s
ORP 30: CdS photo-resistor (at 100 V)	16	2.5	40	2	—	1.2 W	3 c/s for 30 lux; 1 c/s for 4 lux

Applications of CdS photo-resistors

Vacuum and gas-filled photocells can usefully be replaced by CdS photo-resistors in any application where sensitivity is important but speed of response is less so. The great advantage of CdS photo-resistors in such applications is that they can be connected directly to a relay; amplifiers and thyratrons are not required. The resulting simplifications in circuitry are considerable.

These applications of the CdS photo-resistor are not new in principle, but there is a further group of applications of the device in which it cannot be replaced by vacuum or other types of photocell. We shall now go on to discuss one or two examples from each of these groups.

An example of the first group of applications is flame monitoring in automatic oil-heating installations, for which purpose type ORP 90 is generally used. The flame is "seen" by a photocell that is usually located in the air intake duct. The oil is ignited electrically, by a spark igniter of one kind or another. If the oil has not ignited by a certain time after the oil cock has been opened and the igniter excited, the monitoring system automatically cuts off the oil supply and causes an alarm signal to be given. If, on the other hand, ignition takes place promptly, after a brief delay the monitoring system switches off the ignition arrangement. If the flame should go out the oil supply is again cut off and an alarm signal given.

The "crackle-free potentiometer" is an entirely new application. Most potentiometers in common use are resistors with a movable tapping, and the changes in output voltage resulting from movement of the sliding contact are not completely continuous. Consequently crackling arises while the slide is in motion. Such phenomena may be objectionable in certain kinds of electronic equipment — in particular, in measuring instruments, amplifiers and radio and television receivers. A crackle-free potentiometer circuit can be made by putting a fixed resistor in series with a CdS photo-resistor. Changes in the luminous flux incident on the photo-resistor cause its resistance and hence the voltage across its electrodes to change (*fig. 10*). The luminous flux can be

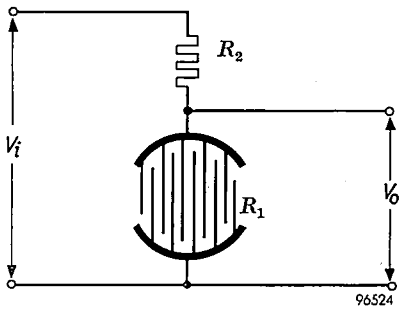


Fig. 10. Crackle-free potentiometer circuit, consisting of a fixed resistor R_2 and a photo-resistor R_1. An increase in the illumination causes a decrease in the resistance of R_1, and hence in the voltage V_0 tapped off across R_1. If a resistor of about 2 MΩ be used for R_2, the potentiometer is suitable as a volume control in a radio receiver.

altered by changing the current flowing through the filament of an incandescent lamp; the thermal inertia of the filament precludes abrupt changes in the light emission, so that no crackling arises [8]). A crackle-free potentiometer satisfying the requirements of the volume control in an ordinary radio receiver can be obtained by combining a CdS photo-resistor, which must have a dark resistance

[8]) Alternatively, the intensity of illumination can be regulated mechanically, for example by moving or turning one of two diaphragms mounted close together. If the intensity of illumination is required to increase logarithmically as a function of the angle turned through, say, by a factor of 10 000, the diaphragm will have to have a special shape. Such an arrangement will be crackle-free provided the mechanical finish of the diaphragms is good.

of at least 10 MΩ, with a fixed resistor having a value of about 2 MΩ. While the photo-resistor is not exposed to light, the voltage tapped off is 10/12ths or a good 80% of the voltage across both resistors. Exposed to an illumination of 10 000 lux, the photo-resistor only offers a resistance of about 200 Ω, so that the tapped voltage now falls to 1/10 000 of the supplied voltage. It is therefore possible for the voltage tapped by the potentiometer to vary by a factor of nearly 10 000, although the overall resistance of the potentiometer never falls below 2 MΩ.

The relation between the current and voltage in photo-resistors made of compressed and sintered CdS is almost linear (fig. 6), i.e. these devices roughly obey Ohm's law; hence their resistance is practically independent of the applied voltage, and the distortion introduced by the photo-resistor potentiometer as in fig. 10 is only very slight. The distortion is not more than 0.2% for an output voltage of 0.2 V. Since the volume control of a radio receiver is located at the *input* of the audio-frequency amplifier, the output voltage does not in practice attain this value and the amount of distortion arising in the volume control is therefore negligible. If the CdS photo-resistor in the circuit of fig. 10 were replaced by some other cell not obeying Ohm's law, the resulting circuit would be crackle-free, it is true, but quite useless for a radio receiver.

Fig. 11 shows a device in which a small CdS photo-resistor is combined with a miniature electric lamp to form a unit ideally suited to radio and television sets. It is enclosed in a light-tight tube to obviate interference from other light in the vicinity. Over part of its range, the output voltage of the simple potentiometer shown in fig. 10 increases exponentially with the resistance of the control rheostat in the lamp circuit (*fig. 12*).

By making CdS photo-resistors with more than two

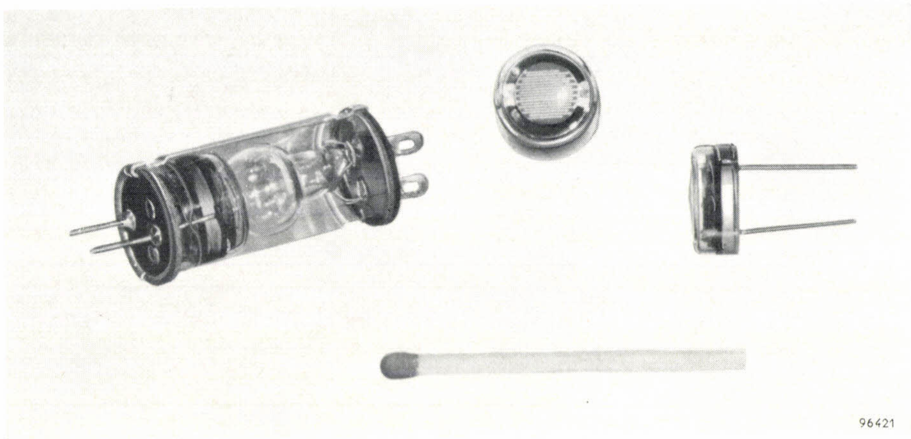


Fig. 11. If the illumination of a CdS photo-resistor forming part of a crackle-free potentiometer is to be controlled by varying the current flowing through an electric bulb, it is worth while to combine photo-resistor and bulb in one unit enclosed in a light-tight envelope. The photograph shows a device of this kind (the envelope has been partly cut away) developed by the Industrial Components and Materials Division of Philips. Two views of the CdS photo-resistor used in this device are also shown. Provided it is run at the rated voltage of 6.3 V, the bulb has a very long life.

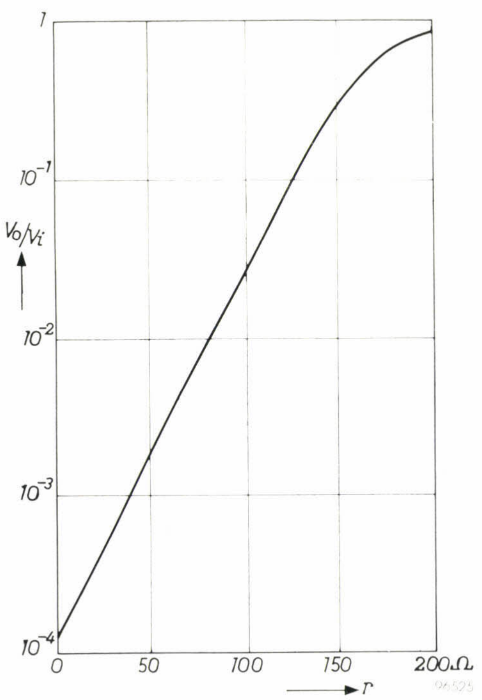


Fig. 12. The tapped voltage V_o (expressed as a fraction of the total voltage V_i) of a crackle-free potentiometer (CdS photo-resistor as in fig. 11 plus 2 MΩ fixed resistor) as a function of r, the resistance of the control rheostat in the circuit supplying the electric bulb. In the range where the tapped voltage is 10% of the total voltage or less, the relation between V_o/V_i and r is logarithmic. The lamp supply voltage was 6.3 V.

electrodes it is possible to design circuits to give so-called *physiological volume control* [9]). When its output voltage is small, a volume control of this kind attenuates low-frequency sounds to a less extent than high-frequency ones, the purpose served

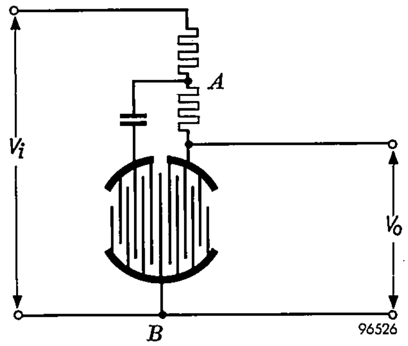


Fig. 13. Illustrating the principle of a "physiological" volume control embodying a photoconductive cell. The cell used in this circuit must have more than two electrodes (in this case it has three). As the intensity of illumination increases, the output voltage for low frequencies falls off less sharply than that for high frequencies.

being to stop the former becoming inaudible before the latter do as the output voltage is decreased. The principle of the circuit is shown in *fig. 13*. When the two variable resistors (the two parts of the photo-resistor) have a high resistance, the branch containing the capacitor plays little part, the other branch exercising the main control function. When the variable resistors have a low resistance (because strong light is falling on the photocell), the *A-B* section of the potentiometer, owing to the presence of the capacitor, offers considerably more impedance to low frequencies than to high; in other words the output voltage — at a given illumination a constant

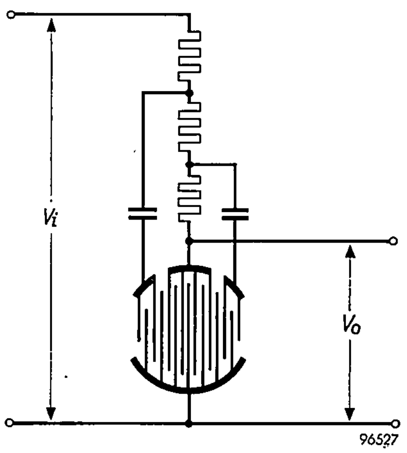


Fig. 14. Practical form of "physiological" volume control. The photo-resistor used here has four electrodes.

[9]) A brief account of a type of circuit normally used for this purpose (embodying a carbon potentiometer) is given in Philips tech. Rev. **19**, 47, 1957/58, and is shown on the extreme left of fig. 8, on page 46.

proportion, independent of frequency, of the voltage between *A* and *B* — represents a higher proportion of the input voltage for low frequencies than it does for high. The circuit of fig. 13 does not produce the desired effect to a sufficiently pronounced degree: the ratio of the output voltages for 100 and 1000 c/s is not greater than 3 or 4, whereas the ratio required is 10 to 20. In practice, therefore, a rather more complicated circuit is used; see *fig. 14*. Its frequency characteristics are given in *fig. 15*.

It might well be asked whether difficulties may not arise from the use of alternating current for supplying the lamp. The luminous flux may be expected to show some fluctuation (at double the mains frequency) and the voltage from the output of the photo-resistor potentiometer will exhibit

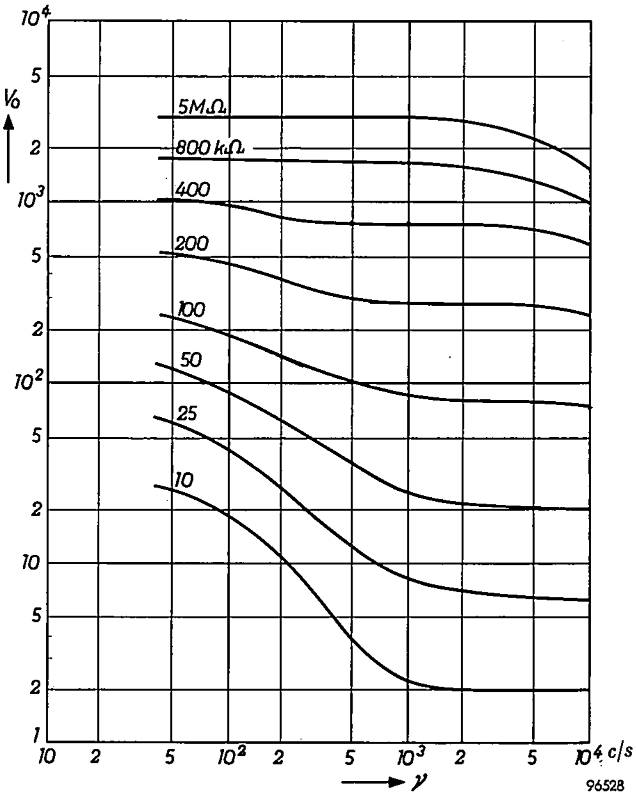


Fig. 15. Frequency characteristics of the circuit of fig. 14, each curve being appropriate to a different value of photocell resistance. When the resistance of the cell is high, the output voltage (V_0) is more or less independent of frequency over the range 50 c/s to 5000 c/s; when the cell resistance is low, V_0 is almost 10 times as high for 50 c/s as for 1000 c/s.

corresponding amplitude variations. It has been found that the 100 c/s modulation of the sound signal is inaudible provided its depth does not exceed 3%. The results of measurements are given in *fig. 16* and from these it is clear that, for the normal resistance values of the photo-resistor shown in fig. 14, the modulation depth will be very much less than 3%

(being 0.1% at 150 kΩ and 0.3% at 50 kΩ). Ordinarily, therefore, the ripple is quite inaudible. Only when the resistance of the cell (and thus the voltage across it) is very low, is the 3% limit slightly exceeded.

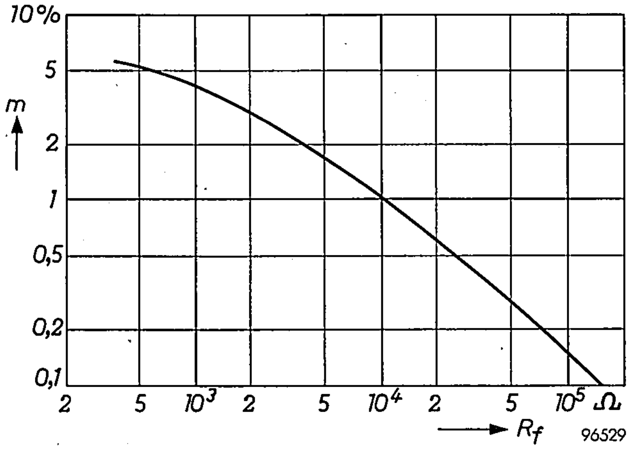


Fig. 16. Supplying the lamp in the circuit of fig. 14 with alternating current gives rise to modulation having twice the mains frequency; the depth m of this modulation decreases as the cell resistance R_f increases. The modulation remains inaudible ($m < 3\%$) so long as the cell resistance exceeds 2000 Ω, as it normally does.

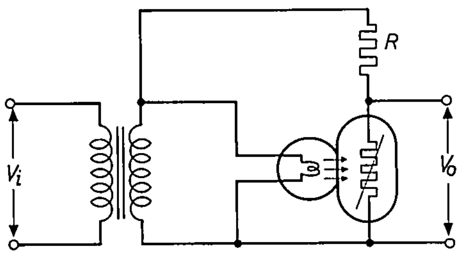
We have already seen that the conductivity of the resistor does not immediately drop to its minimum value when the incident light is removed (fig. 9), that is to say, the conductivity does not alter instantaneously in response to changes in illumination. Consequently a certain inertia is associated with the operation of a volume control of the kind described above. However, the response is quite fast enough for the purposes of a volume control.

Potentiometers embodying CdS resistors have advantages over and above freedom from crackle. There is no need for the control rheostat to be mounted in the immediate vicinity of the photo-resistor plus lamp, and each can therefore be given whatever location is most convenient. In the case of a volume control for an ordinary wireless set, the potentiometer unit can be placed close to the detector diode [10]), while the control rheostat is given a position such that it is within easy reach of the listener. One can even go so far as to enclose the rheostat in a separate box connected to the set by a few yards of cable — a simple way of providing remote control.

Between the CdS photo-conductor and the filament of the bulb there is no electrical contact whatsoever, and this form of remote control can therefore be employed in equipment in which the CdS resistor is in a high-potential part of a circuit; the control circuit can be kept at earth potential by supplying the bulb from a separate transformer or transformer winding.

Remote control with the aid of a CdS photo-resistor is suitable for all kinds of other applications. Amongst these mention may be made of the adjustment of brightness and contrast in television receivers and the control of volume in stereophonic sound reproduction.

A third application of the CdS photo-resistor is in a simple circuit for stabilizing an alternating voltage. The secondary of the transformer in this circuit (*fig. 17*) supplies both a potentiometer chain, of which a CdS photo-resistor forms part, and a small lamp that shines on the photo-resistor. If the voltage across the secondary should rise on account of an increase in the input voltage, the bulb will shine more brightly, so lowering the resistance of the CdS photo-resistor and reducing the proportion of the secondary voltage that appears at the output. With suitable resistance values, increases in the secondary voltage can be exactly compensated by the decrease in the output voltage, so that over a large range the latter is independent of the input. No current can however be taken from the output of this stabilized voltage supply.



V_i	V_o
260V	2,51V
220V	2,50V
170V	2,51V
130V	2,51V
120V	2,49V
80V	2,15V

96530

Fig. 17. Circuit incorporating a photo-resistor for stabilizing an alternating voltage. Over a large range of input voltages (V_i) the output voltage (V_o) hardly varies at all when no current is taken.

In conclusion we shall name one or two other possible applications, some of which are not new, it is true, except in the sense that the embodiment of a CdS photo-resistor simplifies the circuitry. Because the cells exhibit maximum sensitivity to red light, and are sensitive to infra-red with wavelengths up to 0.9 μ, they are particularly suitable for employment in fire-alarm systems. They can also be employed for the detection of smoke, for switching street lighting on and off automatically, for dimming the headlamps of cars automatically (the photo-resistor only needs a low voltage such as that already available in a car), for automatically adapting the contrast and brightness of a television image to the

[10]) With regard to the use of a diode as detector, and the associated volume-control arrangement, see for example M. Mandl, Handbook of basic circuits, Macmillan, New York 1956, A3 and A5, or F. E. Terman, Radio Engineers Handbook, McGraw-Hill, New York 1943, page 641.

room lighting level — here advantage is taken of the fact that the current through the cell is proportional to the illumination — and so on. We may add that, in those applications where some system or other has to be switched on or off, it is not always necessary to have the photo-resistor controlling a relay; in some cases the cell itself can be used as a switch.

To sum up, it may be said that CdS photo-resistors have already found application in many fields and that the future will prove their usefulness in many others, this in virtue of their great sensitivity to light, their low supply voltage, their high load capacity and their insensitivity to temperature changes.

Summary. Cadmium sulphide photo-resistors, highly sensitive to light, can now be manufactured on an industrial scale. The basic material is very pure powdered CdS (grain size 0.1 μ); to this certain substances containing copper and gallium are added, the mixture being subjected to a heat treatment. The result is a coarse powder made up of grains measuring 10 to 100 μ, in which the additives are now uniformly distributed; this is compressed into plates of the desired shape. Lattice defects created by the pressing process (and which reduce the photosensitivity of the substance) are largely removed or modified in a second heat treatment, which causes the grains to cohere. Photo-resistors made of this material have a sensitivity (A/lux) approaching that of the photomultiplier, far exceeding that of other types of photocell, and varying little with temperature. CdS photo-resistors can be used to operate relays directly. The potential applications of the device are legion. Established applications include flame monitoring and the construction of crackle-free potentiometers which can be remote-controlled.