

THE "PLUMBICON", A NEW TELEVISION CAMERA TUBE

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621.397.331.222

*In this article a description is given of the "Plumbicon" **), a new type of television pick-up tube. The use of photoconducting material as a light detector and the construction of the tube are such that the "Plumbicon" can in many ways be considered as a type of vidicon, with which it has in common simple construction and easy operation. The less favourable properties of the conventional vidicon, however, are absent: the picture quality and the speed of response are also excellent at low levels of illumination. With this new tube, which equals or surpasses the existing pick-up tubes in all respects important in broadcast television, particularly good results are obtained when using it in cameras for colour television. This is because the "Plumbicon" meets to a high degree the requirement that the signal supplied by one picture element depends solely on the amount of light falling on it — so it does not depend on the position of the picture element, or on its history, or on the situation in the neighbouring elements.*

Principles and construction of the "Plumbicon"

In view of the requirements imposed by television broadcasting, it has been necessary till now to use either an image iconoscope or an image orthicon for direct broadcasts. These were the only types of pick-up tube with sufficient resolving power and speed to respond adequately to the rapidly changing details of the broadcast scene. The vidicons, which far surpass these types in regard to simplicity and ease of operation, were unsuitable because the picture they supply to the receiver is too uneven at low light levels — a consequence of local differences in dark current; also, at low light levels vidicons have too slow a response ¹⁾. Their employment has been limited to applications where a high level of illumination is possible, as in film scanning.

The new camera tube we describe in this article, the "Plumbicon" (*fig. 1*), possesses the good properties of both classes of pick-up tube referred to above, and even surpasses them in certain respects:

the "Plumbicon" combines small size, simple construction and easy operation with having a low dark current, high sensitivity, high speed of response, and good resolution. The life of the "Plumbicon" is no shorter than that of other studio-quality tubes. It also affords striking advantages particularly in colour television and in X-ray television set-ups.

Broadly speaking, the electrode layout of the "Plumbicon" is like that of the vidicon, and the mode of functioning is much the same (*fig. 2*). A glass plate is coated with a thin transparent conducting layer of SnO_2 , on which is deposited a thin layer of photoconducting material, which in the "Plumbicon" consists of lead monoxide (PbO). The scene to be transmitted is projected via the glass substrate and the SnO_2 layer onto the PbO . A beam of slow electrons strikes the other side of the PbO layer. The SnO_2 layer, known as the signal plate, carries a potential of about +30 V with respect to the cathode of the electron gun. The side of the photoconducting layer facing the gun has roughly the same potential as the cathode when the layer is not illuminated; lighted areas periodically attain a potential of a few volts higher.

Although the "Plumbicon" may be considered in

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***) A short article about this tube appeared in the preceding volume: E.F. de Haan, Philips tech. Rev. 24, 57, 1962/63.

¹⁾ A description of the types of pick-up tube most used up to now may be found in D.G. Fink, Television engineering, McGraw-Hill, New York 1960.

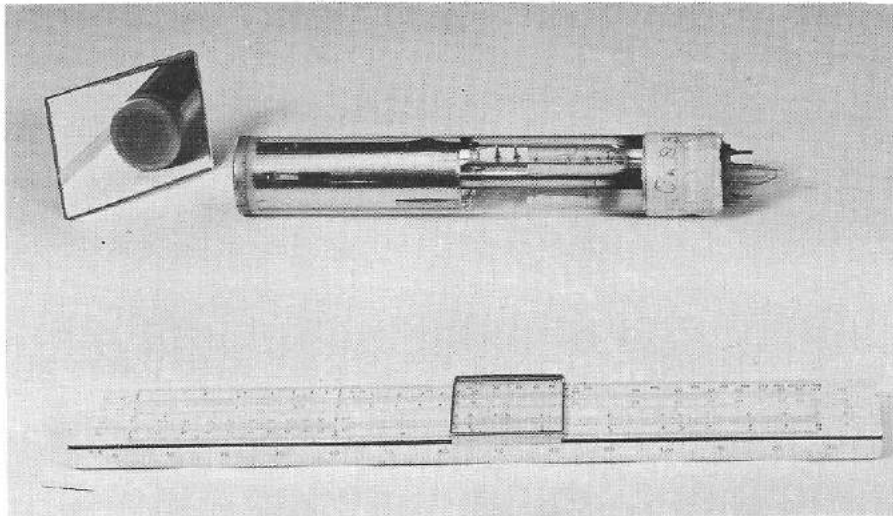


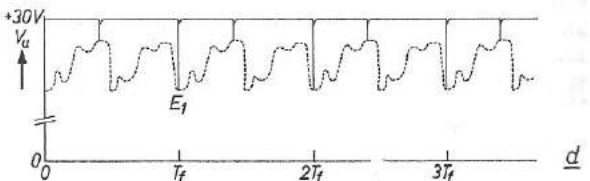
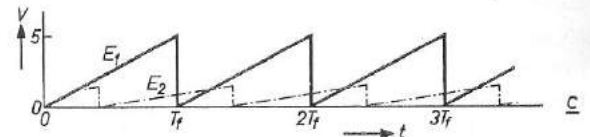
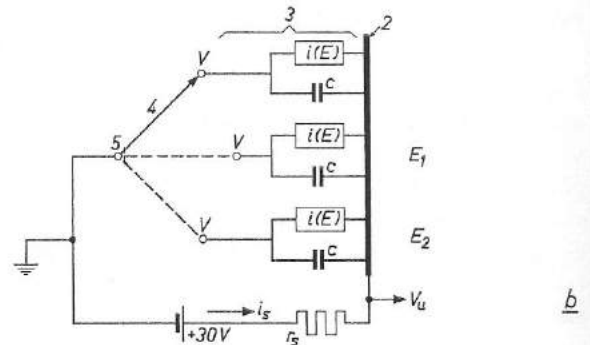
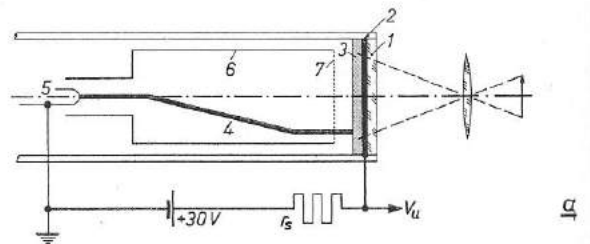
Fig. 1. A pick-up tube of the "Plumbicon" type. The tube is in the form of a cylinder having a diameter of 3 cm and a length of 19 cm. The target diameter is 2 cm.

Fig. 2. a) Electrode layout of the "Plumbicon" (schematic). In the front of the tube (on the right) is a glass window 1, on the inside of which have been applied, in that order, a transparent, conductive SnO₂ layer 2 and a photoconducting layer of PbO constituting the target 3. An image of the scene is projected on the target, the other side of which is scanned by the electron beam 4. The beam electrons are supplied by gun 5 and accelerated by anode 6. A mesh screen 7 has been fitted to the front of the anode in order to make the field between target and anode more uniform. The anode is at a potential of about +300 V, the SnO₂ layer (signal plate) is at about +30 V, both with respect to the gun cathode. As will be explained, when the tube is in operation the potential V of the free surface of the PbO target fluctuates within an interval ΔV of only a few volts, the lower limit of which is approximately equal to the cathode potential of the gun.

b) Equivalent circuit of the "Plumbicon" explaining the functioning of the tube. The electrode numbering is the same as in (a). The signal plate is on the right. The photoconducting target can be regarded as being made up of a large number of capacitors c , each of which is in parallel with a current source supplying a current i_f whose magnitude depends solely on E , the intensity of illumination; these capacitors represent "picture elements". The beam can be regarded as a multi-way switch that connects each of the picture elements in turn to the negative terminal of the battery supplying the voltage on the signal plate. Thus when a picture element is brought into circuit, the potential V on its free surface falls abruptly to zero (the cathode is earthed). During the remainder of the frame period T_f — the time elapsing before the electron beam returns to the same picture element, which is usually 1/25th of a second — c partially discharges owing to the flow of current i_f ; V therefore rises. The increase ΔV in V that takes place between successive scans is greater when the picture element is more strongly illuminated because i_f is then greater. A charging current i_s , proportional to ΔV , flows each time the beam completes the circuit containing an element, and this current causes a corresponding difference of potential to arise across signal resistor r_s . Consequently the potential V_u varies and an output signal is obtained. If E is changing rapidly, ΔV will have a value roughly corresponding to the mean of the intensity of illumination on the element during the frame period in question.

c) The variation over time t in the potential V on the free surface of two picture elements, one exposed to a high intensity of illumination E_1 and the other to a low intensity of illumination E_2 . Since, under normal operating conditions, i_f does not depend on the difference of potential $V_u - V$, between scans the variation in V is linear with respect to time.

d) The variation in V_u over time t , corresponding to (c). When the contributions of all the picture elements are taken into account, then V_u varies e.g. as shown by the dotted line.



many ways to be a kind of vidicon, there is a characteristic difference however between the "Plumbicon" and the present vidicons, and this concerns the photoconducting layer. Not only has this layer been made from a different photoconductor — Sb_2S_3 and sometimes As_2S_3 or Se have so far been used in ordinary vidicons — but what is more important, the PbO layer together with the SnO_2 layer form a unit consisting of three sublayers, each of differing conduction type. The inner sublayer consists of almost pure PbO, which is an intrinsic semiconductor. The PbO in the layer struck by the electrons is doped to make it a *P*-type semiconductor (hitherto not possible with Sb_2S_3). The SnO_2 signal plate is strongly *N*-type. The contact between the PbO and the SnO_2 may also give rise to a thin *N*-type layer in the PbO. The *P*-type and *N*-type layers are relatively thin, so that the inner (intrinsic) layer, the *I* layer, takes up most of the overall thickness of the PbO layer. For simplicity it is assumed in the following that the *N*-type PbO layer is always present ²⁾.

Examination under the electron microscope shows the PbO layer to be porous in structure; it is built up of crystallites having dimensions of about $1.0 \times 1.0 \times 0.1 \mu m$. The filling factor ranges from 30% to 50%. The dimensions of the crystals are small compared with the line spacing ($20 \mu m$). They are therefore too small to be detrimental to the resolving power. The overall thickness of the photoconducting layer ranges from 10 to $20 \mu m$.

The fact that the tube has many favourable properties for television broadcasting is thanks to the multilayer structure of its photoconducting target. Its ability to satisfy two of the main desiderata, namely low dark current and high sensitivity, is easily explained. When the tube is in operation its photoconducting layer — in contrast with a conventional vidicon — constitutes a reverse-biased diode. The dark current is the (small) inverse current through this diode. The tube owes its high sensitivity to the *I* layer sandwiched between the *P* and *N* layers. Conduction electrons and holes generated by light cannot contribute to a photo-current unless they originate in a region where a relatively high field-strength prevails. If the diode in question were simply a *P-N* device, the requisite field-strength would only be available in the immediate vicinity of the junction, and a large proportion of the charge-carriers generated in the PbO would be ineffective. In the "Plumbicon", however, there is a high field-strength throughout the *I* layer, in consequence of

the fact that this is a relatively poor conductor, and since the PbO layer consists almost entirely of *I* material, almost all the charge-carriers generated in the PbO contribute to the photo-current ³⁾.

In principle, an excessive dark current can be compensated by electrical means. In practice, however, electrical compensation is scarcely ever adopted: unless the dark current has the same value within close limits at all points on the screen, compensation leads to an uneven image signal which is undesirable and in colour television is quite unacceptable. An additional difficulty is that the dark current is strongly dependent on temperature. If, on the other hand, the dark current has a very low value (say 10^{-9} A, or about 1% of the signal current), local variations, even though quite large (the values differing by a factor of 2, for example) will not perceptibly affect the uniformity of the image.

In most other important respects — spectral characteristic, definition, speed of response and service life — the favourable properties of the tube are mainly dependent on a suitable choice of the parameters governing the properties of the sublayers, such as their thickness, the doping substance and its concentration, and so on. Although some of the demands of studio use give rise to conflicting requirements, it has not been necessary to make compromises between the various parameters. On the contrary, there is so much play that certain properties can be varied quite widely without interference with the others. This makes it possible to manufacture camera tubes of the "Plumbicon" type with properties very closely fitted to the demands of a given application. Left out of discussion are the very large variations encountered when the choice of photoconducting material is not restricted to PbO, but when e.g. PbS is added ⁴⁾.

Various points mentioned above will now be elaborated ⁵⁾. First however the relevant physical and chemical properties of PbO will be discussed; some observations will be made on the process of deposition of the PbO layer, and a brief account given of the way in which the potential of the free surface of the photoconducting layer varies during a frame period.

The properties of PbO; deposition of the photoconducting layer

Two modifications of PbO are known: the red (tetragonal) modification, which is stable at temperatures below $488^\circ C$, and the yellow (orthorhombic),

²⁾ The characteristics of the "Plumbicon" are compared with those of other tubes in an article by A.G. van Doorn and S.L.Tan, shortly to be published in this Review.

³⁾ For a succinct explanation of the physical principles underlying photoconductivity see e.g. L. Heijne, Philips tech. Rev. 25, 120-131, 1963/64 (No.5).

⁴⁾ See the article by E.F. de Haan, F.M. Klaassen and P.P.M. Schampers, shortly to be published in this Review.

⁵⁾ See also L. Heijne, thesis Amsterdam 1960, Ch. 8.

which is stable at higher temperatures. The red PbO is built up from "sandwiches" consisting of a plane occupied by O atoms, on either side of which is a plane occupied by half as many Pb atoms. These sandwiches have a thickness of 2.38 Å, and the spacing between the O planes is 4.99 Å.

The structure of the yellow modification differs considerably from that of the red. This too is built up from sandwiches, with Pb atoms on the outside, but the "filling" is more complicated. Accordingly, the thickness of the sandwich is rather greater (2.72 Å). Various investigators have demonstrated that oxygen can be inserted between the sandwiches (especially those of red PbO) without drastically modifying the crystal structure of the compound; in other words, departures from stoichiometric ratio are possible. It is in virtue of this important property, among others, that PbO can be turned into either an *N*-type or a *P*-type semiconductor. It has been found that PbO becomes a *P*-type semiconductor when an excess of oxygen is present, or when it has been doped with Tl, Cu or Ag. The compound becomes an *N*-type semiconductor when an excess of lead is present, or when it has been doped with Bi.

The energy gap ΔE of the forbidden zone between the valency band and the conduction band, the quantity that determines the upper limit of the range of wavelengths within which photo-excitation can occur, is 2.0 eV for red PbO and 2.7 eV for the yellow modification. The band gap of red PbO gives rise to a cut-off wavelength of about 6200 Å, that of yellow PbO gives about 4500 Å.

The production of the PbO layer in a tube of the "Plumbicon" type is by vapour deposition. PbO contained in a small platinum crucible is evaporated by inductive heating, and condenses on a window previously coated with SnO₂. The crucible temperature is held at about 900 °C; at this temperature evaporation proceeds at a reasonable rate. During the deposition process the window is likewise kept, within fairly close limits, at a certain temperature. A high temperature is especially undesirable because the crystals of the deposited PbO become too large to give the required image resolution. Deposition takes place not in vacuum, but in a certain gas atmosphere.

Owing to the considerable difference in the cut-off wavelengths of red and yellow PbO, the red-yellow ratio has an important effect on the spectral response of the "Plumbicon". An X-ray diffraction study, in which the diffraction pattern of PbO layers deposited by the normal process was compared with those of certain mixtures of yellow and red PbO powders, has revealed that these layers consisted of about 90% of the red modification and about 10% of the

yellow. At vapour pressures lower than the normal one, the proportion of yellow PbO was greater. Moreover, the red crystals were found to have a preferred direction.

Potential of the target surface; stabilization

As already stated, the free surface of the PbO target has a potential V that varies within a range close to the potential of the cathode. At the instant the scanning beam leaves an element of this surface, the potential of this element is roughly equal to that of the cathode; in the time elapsing before the beam returns, V rises by a few volts only. The actual range over which the surface potential varies is determined by the requirement that in the steady state, the amount of (negative) charge removed per unit time, in consequence of the flow of photo-current, must be equal to that supplied by the electron beam. (Since the negative charge is supplied intermittently, this equality is only valid if an interval of time is considered containing an integral number of frame periods.)

Fig.3 shows, schematically, how i_a , the net current flowing to a surface element of a PbO target under electron bombardment, depends on the potential V of the target surface. The various curves refer to different values of beam current, i.e. the current formed by the electrons leaving the electron gun. When V is the same as the cathode potential (which is zero), the deceleration of the electrons in the final part of their path is equal to their previous acceleration, with the result that only a few of them actually reach the target. The net flow of current to the target is even smaller, owing to secondary emission; it is on account of increasing secondary

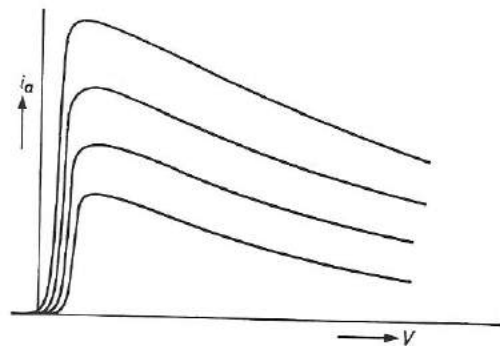


Fig.3. The net flow of current i_a to a surface element of a PbO target under continuous electron bombardment as a function of the potential V of the target surface (the cathode of the electron gun is assumed to have zero potential). As V increases, i_a also initially increases but subsequently falls off on account of increasing secondary emission. The above curves, which are schematic, relate to various values of beam current (i.e. the current constituted by the electrons leaving the gun).

emission that the net current to the target, after attaining a maximum for a certain potential value, falls off again as V is raised further. Fig. 4 gives an overall impression of the way the photo-current that flows through the target layers, and so removes negative charge from its free surface, depends on the potential difference U between the two faces of the PbO

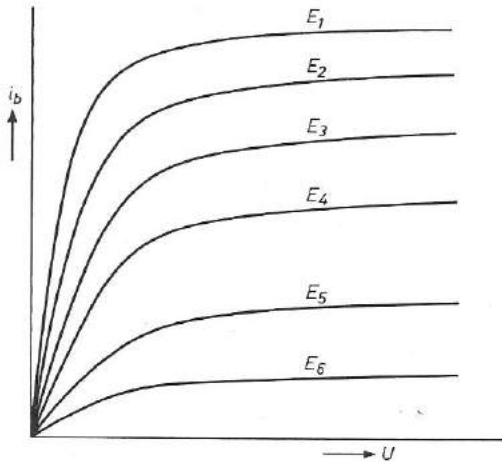


Fig. 4. The variation of i_b , the photo-current that removes (negative) charge from an elementary area of the free target surface, with the potential difference U across the target. The curves, which are schematic, hold for different values E_i of the illumination. The stronger the illumination, the heavier is the current i_b .

target ($U = V_u - V$; see fig. 2). The plotted quantity i_b is again the value of the current per surface element.

In fig. 5 one of the curves of fig. 3 has been combined with the family of curves in fig. 4. That, in fact, corresponds to the situation prevailing in the tube: the intensity of illumination may assume almost any value, but unless altered from outside the beam current always remains the same. For reasons that will shortly become clear, the ordinate values for the curves representing the current flowing through the target layers have been multiplied by a factor N representing the number of surface elements into which the surface is understood to be divided. Accordingly, the quantities plotted are i_a and Ni_b .

Consider first the imaginary case in which the beam electrons continuously bombard the same spot on the target surface, i.e. a spot whose area is $1/N$ th the total target area (this is what we call a picture element), and in which a constant photo-current Ni_b is flowing at this spot. The potential V of the spot then assumes a value given by the projection on the abscissa of one intersection point of the i_a curve with the relevant Ni_b curve: the loss of charge is then exactly balanced by the rate of supply. The points of intersection representing stable states have

been marked in fig. 5 with a dot. It will be noted that these points occur both on the rising and on the falling branch of the i_a curve. In the former case the value of V is close to zero, and the voltage U across the target is therefore roughly equal to V_u . The points of intersection on the falling branch represent states in which the value of V is close to the signal-plate potential, and U is very small.

Let us now consider the true situation, in which the beam scans the target and the current supplying a given picture element only flows for $1/N$ th of the time. On account of the surge-like character of the charge-supply process V does not assume a steady value; it can however be said that the range over which V varies must extend on either side of one of the stable-state values referred to above. Since the range of variation ΔV is normally small compared with V_u , these stable-state values nevertheless give a fairly good indication of the operating conditions that are possible in the tube: there are again *two* possibilities when the tube is operational. Operating conditions such that $V \approx V_u$, U accordingly being small, are extremely unfavourable, however: in the first place the equilibrium value of i_a differs very little with different intensities of illumination, with consequent loss of contrast, but apart from that, special forms of sluggish response are liable to occur at low U values.

Therefore in practice the beam-current value is chosen high enough for an intersection to be available on the *rising* branch of the i_a curve even at the highest intensity of illumination likely to occur on the PbO target during a broadcast. In this way a third, but no less important, disturbing effect is

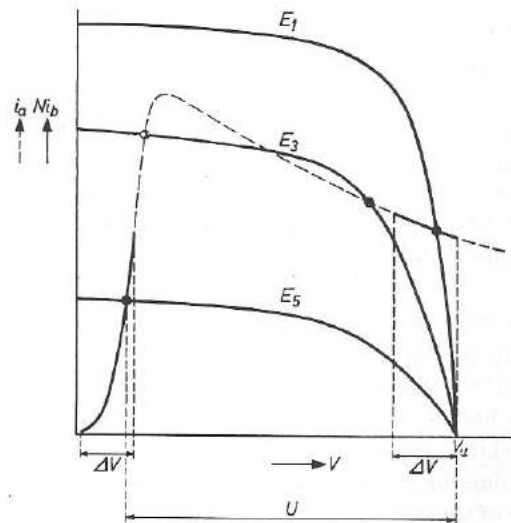


Fig. 5. To explain the fact that the interval ΔV can fluctuate in the neighbourhood of the cathode potential of the electron gun ($V \approx 0$), as well as in the neighbourhood of the potential of the signal plate ($V \approx V_u$).

avoided that occurs when one surface element has a potential close to V_u and the other a potential close to zero. In these circumstances the element with the higher potential will start to attract electrons towards it when the beam approaches, and continue to do so after the beam should have passed. In consequence, lighter-coloured parts of the scene will be "blown up", i.e. appear bigger than they really are.

The fact that V moves within an interval ΔV , contained between the abscissa values of the intersections of the i_a and Ni_b curves, can be proved as follows. During the short time T_p in which the beam passes a surface element, then for the (negative) charge:

$$dQ = (i_a - i_b)dt \approx i_a dt = cdV.$$

Here dQ is the charge supplied in time dt and c is the capacitance of the layer per surface element. It follows from this that $dV/i_a = dt/c$. In the time T_p , V decreases from V_2 to V_1 and so:

$$\int_{V_2}^{V_1} \frac{dV}{i_a} = \frac{T_p}{c}.$$

For the potential increase following from the flow of the discharge (photo-) current, we have by analogy:

$$\int_{V_1}^{V_2} -\frac{dV}{i_b} = \frac{T_f}{c},$$

or, as $T_f = NT_p$:

$$\int_{V_2}^{V_1} \frac{dV}{Ni_b} = \frac{T_p}{c}.$$

If $1/i_a$ and $1/Ni_b$ are both set as functions of V , then the areas under the curves between the ordinates $V = V_1$ and $V = V_2$ are equal. This implies that the curves must intersect at least once in the interval $V_1 - V_2$. So the same holds for the curves for i_a and Ni_b .

The target considered as a P-I-N diode

To obtain the smallest possible dark current and the greatest sensitivity possible in combination with it, then theoretically one must use a layer of an intrinsic photoconductor fitted with two contacts one of which, when current is flowing in a given direction, will hinder electron supply and the alter the hole supply ("blocking contacts"; see fig.6). In the "Plumbicon", the P layer acts as the contact hindering the entry of electrons, and the obstacle to the entry of holes is formed by the SnO_2 or by the PbO immediately adjoining it, when this region of the target has become an N -type conductor⁶⁾. The fact that blocking contacts have been attached to the photoconducting layer in the "Plumbicon" constitutes one of the most striking differences with the conventional vidicons.

⁶⁾ See F.A. Kröger, G. Diemer and H.A. Klasens, Phys. Rev. 103, 279, 1956.

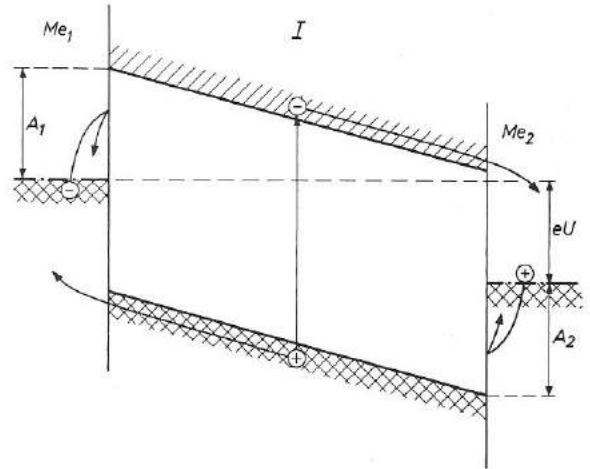


Fig. 6. Energy-band diagram (greatly simplified) of an intrinsic semiconductor (I) fitted with two metal contacts (Me_1 and Me_2). Me_1 has such a high work function (A_1) that electrons contained in it have very little chance of crossing the interface and entering the conduction band of the semiconductor. In the same way holes arriving from the metal Me_2 are unable to reach the valence band. On the other hand the charge-carriers that the incident light has liberated in the semiconductor, having moved over to the appropriate contact under the action of the electric field due to applied voltage U , encounter no obstacle hindering entry to that contact. (For simplicity, A_1 and A_2 have been chosen equal to $\frac{1}{2}AE$.)

The energy-band diagram of a $P-I-N$ diode is indicated in figs.7a and b. Fig.7a shows the details and fig.7b is a simplified diagram. It differs from the drawings in fig.6 in that the bands in the I layer are curved. This curvature can be explained as follows. In reality, the I layer can never be completely free from impurities; donor and acceptor centres in certain number are always present. The diagrams apply to the case where both concentrations are relatively high and roughly equal. When the concentrations are low the curved parts merge and the band diagram has the appearance indicated in fig.7c. Fig.7d shows how this diagram alters when a voltage is applied to the diode. The central layer (I), having by far the greatest resistance, shows the steepest fall-off in potential. However, because of the curvature of the bands the field-strength is not everywhere the same. Fig.8 shows how the potential variation in the middle layer differs from that of fig.7 when the donor and acceptor concentrations are unequal, so that the layer is either slightly P -type or slightly N -type. In the former case the steepest fall-off in potential (and the higher field-strength) is on the N -contact side; in the latter case, the steepest fall-off is on the P -contact side. The practical significance of all this will be discussed below.

Fig. 9 shows the band diagram of a single contact, along with the more important quantities that allow the shape of the potential barrier to be described,

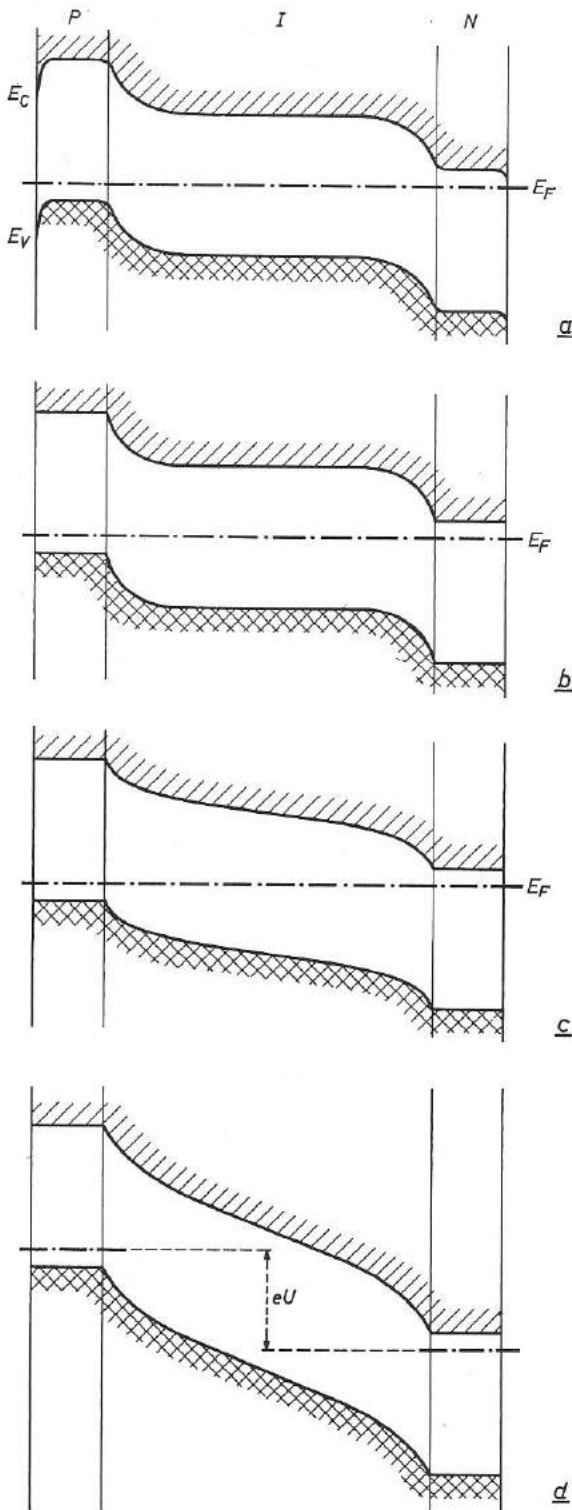


Fig. 7. a) Energy-band diagram of P-I-N diode. The curvature shown by the bands in the I layer is due to the fact that in practice this layer can never be completely free of impurities. In the case illustrated here, the concentration of impurities is relatively high. Diagram (b) is a simplified version of (a), the marked curvature exhibited in the two junctions having been converted into an abrupt change of slope. Diagram (c) is similar to (b) but relates to a diode with an I layer of such a high purity that the bands are nowhere horizontal and the curved

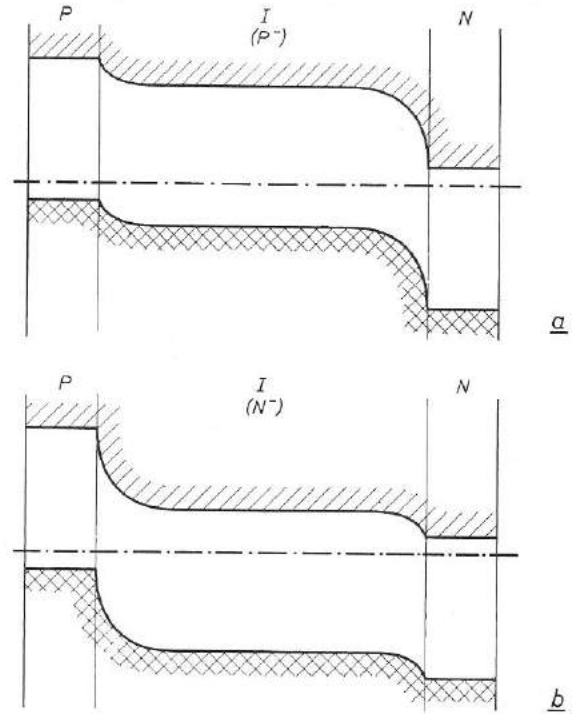


Fig. 8. Band diagrams simplified in the same way as fig.7b and relating to P-I-N diodes whose I layers are slightly P-type (a) and slightly N-type (b). In these cases there is a fairly steep fall-off of potential close to one contact and a region with a gradual potential fall-off (and consequently a very low field-strength) near the other.

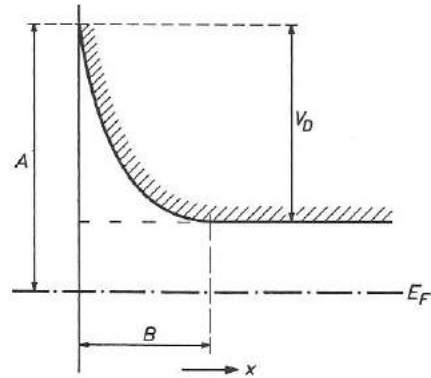


Fig.9. Near the interface between two regions of different conduction type a potential barrier arises which can be described in terms of the work function A , the diffusion potential V_D , and the width B of the barrier⁷⁾.

portions meet. Diagram (d) shows how (c) is modified when a voltage U is applied to the diode. It must be made plain that this band diagram is itself a simplification since it implies that the target material has a homogeneous structure while in reality the PbO is made up of a large number of small crystallites. However, the diagram is quite adequate for the purpose of explaining the action of the diode and its more important properties.

namely the work function (barrier height) A , the width B of the region in which the bands are curved, and the diffusion potential V_D ⁷⁾. B is given by the formula

$$B = \sqrt{\frac{2\epsilon(V_D + U)}{eN_D}}, \dots (1)$$

and the capacitance c' per unit area by

$$c' = \frac{\epsilon}{B} = \sqrt{\frac{\epsilon e N_D}{2(V_D + U)}} \dots (2)$$

Here ϵ and e are the dielectric constant and the absolute value of the electric charge respectively, N_D is the (small) donor concentration in the I region, and U is the applied voltage. Further, for the field-strength F in the barrier,

$$F = \frac{eN_D(x-B)}{\epsilon}, \dots (3)$$

in which x is the distance to the junction. Use is made of these formulae in the following section.

The dark current

As we have seen, the dark current is mainly determined by the inverse current through the $P-I$ and $I-N$ junctions. We shall now consider the magnitude of this current, taking only one of the contacts and only the kind of charge-carrier obstructed by that contact — the $P-I$ junction, say, and the electron current. For such a contact, when reversed biased, the density j_n of the electron current is given by

$$j_n(U) = n(0) e \mu_n F(0) = -n(0) e \mu_n \sqrt{\frac{2eN_D(V_D + U)}{\epsilon}}, \dots (4)$$

where μ_n is the mobility of the electrons and $n(0)$ is the electron concentration in the boundary plane. The value of $n(0)$ depends on the absolute temperature T , the work function A and the constant N_c (sometimes called the effective density of the states in the conduction band), being connected by the formula

$$n(0) = N_c e^{-A/kT} \dots (5)$$

Given the values of U , T , N_D , ϵ and μ_n , one can use (4) and (5) to calculate the minimum value A must have for the dark current to be smaller than, say, 10^{-8} A (roughly 10% of the signal current; this corresponds, since the target area is a good 3 cm², to a current density of $j_n \approx 3 \times 10^{-9}$ A/cm²). The

⁷⁾ See the article cited under ³⁾. Since the thermal work function solid-vacuum does not appear in this article, for simplicity the thermal work function contact-semiconductor A will be referred to as the work function.

results of a number of such calculations have been collected in Table I. These are based on the assumption that $U = 50$ V, $T = 300^\circ$ K and $\epsilon = 12 \epsilon_0$ (for non-porous PbO, $\epsilon = 26 \epsilon_0$).

Table I. Minimum values of A (eV), the relative work function of a contact on a photoconducting layer, appropriate to certain combinations of mobility μ_n (cm²/Vs) and donor concentration N_D (cm⁻³). The minimum values are obtained from the requirement that the dark current should not exceed 10^{-8} A when a voltage of 50 V is applied to the diode. (The relative dielectric constant is assumed to be 12, the absolute temperature 300°K, and the area of the layer 3 cm². The value of V_D has been put equal to zero.)

N_D	10 ¹⁴	10 ¹⁵	10 ¹⁶	10 ¹⁷	10 ¹⁸
μ_n					
1	0.79	0.81	0.84	0.87	0.90
10	0.84	0.87	0.90	0.93	0.96
100	0.90	0.93	0.96	0.99	1.02

As can be seen, over a wide range of μ_n and N_D values, the required value of A lies around 0.9 eV (it should be noted that the N_D value of 10^{14} cm⁻³ is for very pure material, that of 10^{18} cm⁻³ for heavily doped material). We can infer from fig. 7b that the band gap ΔE must be equal to or greater than A ; in other words, the band gap too must be at least about 0.9 eV. At higher temperatures a bigger work function and a wider band gap will be required (see eq. 2); but smaller A and ΔE values suffice at lower temperatures. Or expressed the other way round: the use of a material with a band gap of less than 0.9 eV is not impossible but then cooling is required to get a sufficiently low dark current. It will now be clear why an extremely low dark current can be achieved with a layer of PbO to which blocking contacts have been attached: the band gap of red PbO is no less than 2.0 eV. It can be seen in fig. 10 how the dark current in the "Plumbicon" varies with the potential difference across the target.

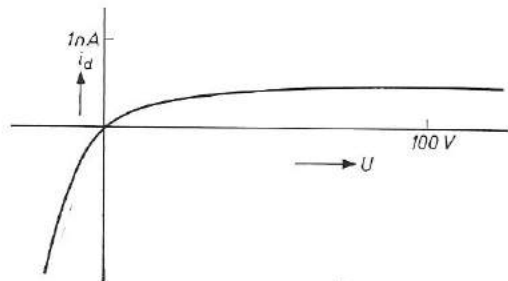


Fig. 10. The dark current i_d as a function of the potential difference U across the target. At no value of U likely to occur in practice does the dark current exceed 0.5×10^{-9} A. As might be expected, the curve resembles a diode characteristic. (In fact, the signal-plate potential V_a has been plotted along the horizontal axis; in practice V_a is nearly equal to U . The same holds for figs. 11 and 12.)

In the foregoing it has been tacitly assumed that there is negligible thermal generation of charge-carriers in the *I* region. Calculation confirms that this effect can, in practice, safely be neglected. (Only in the most unfavourable case, viz, that where the impurity levels lie at about half-height in the forbidden zone, can too strong a dark current be obtained when using a material with a band gap of 0.9 eV.)

Sensitivity

We shall now discuss the way in which the photocurrent flowing through the PbO depends on the potential difference between the *P* and *N* layers, on the character of the light and on the intensity of illumination, and examine how these relations are affected by the thickness and other characteristics of the sublayers composing the target. Fig. 11 is a graph of the photo-current i_f versus the applied voltage U

perfectly practicable, the breakdown voltage of the PbO target being so high that a value of 50 V, say, can safely be chosen for the applied voltage.

The reason why saturation is attained so quickly will now be explained. As is well known, a photocurrent saturates when the transit time, the time the charge-carriers take to reach a contact, is shorter than their mean life. The transit time depends not only on the applied voltage but also on the field pattern. In an *I* layer with a relatively high concentration of impurities, zones in which the energy bands are curved are rather narrow and in the middle of the layer there is a region of extremely low field-strength (see fig. 7 and formula 1). In these circumstances the transit time is very large and most charge-carriers recombine before reaching a contact. It is not until the applied voltage is raised so high that the zones just referred to extend pretty well through-

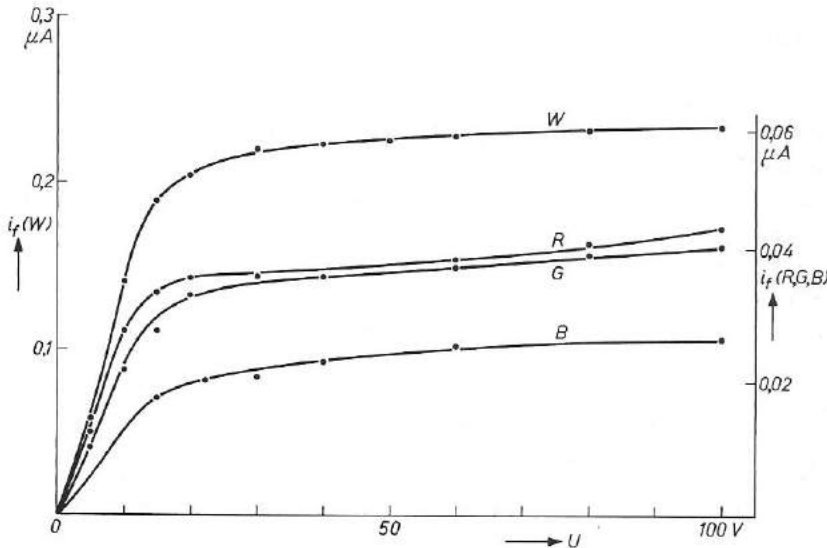


Fig. 11. The variation of the photo-current i_f as a function of the signal-plate voltage V_u for different kinds of light, the intensity of illumination remaining the same (measured on a randomly selected tube). Curve *W*, which is to be read in conjunction with the i_f scale on the left, relates to white light with a colour temperature of 2640°K. Curves *R*, *G* and *B*, to be read in conjunction with the i_f scale on the right, relate to red, green and blue light respectively; these latter were obtained by placing coloured filters in the path of the light, no other detail of the experimental set-up being altered. The filters in question have transmission characteristics similar to those of the red, green and blue filters used in a colour-television camera. (They are Gevaert R 586, G 537 and B 488 respectively.) For all four kinds of light, i_f already attains its saturation value at U values of the order of some tens of volts. The curves are slightly concave at the extreme low-voltage end.

for four kinds of light — red, green, blue and white. It will be seen that rising initially with U , the curves subsequently flatten out. This saturation, combined with the fact that the quantum efficiency is close to one, is an indication that the contacts are acting as required, and not supplying additional charge-carriers.

It will also be seen that for all kinds of light, the saturation value of i_f is attained at a U value that is

out the thickness of the layer, that the field-strength is high enough for all the charge-carriers liberated by the incident light to be able to contribute to the flow of current to the fullest extent. Now, in the "Plumbicon" the donor and acceptor concentrations in the *I* layer are so small that the band curvature extends through the whole thickness of the layer, even when the applied voltage is very small.

Moreover the impurity that is inevitably present is of a type that least affects the properties of the tube. To a very limited extent the middle sublayer is a *P*-type semiconductor. The region where field-strength is lowest and where, accordingly, most of the recombination takes place — from now on we shall call it the “field-free” region — is therefore to be found in that part of the *I* layer which lies next to the *P* layer (cf. fig.7a). Here the field-free region does much less harm than if it were close to the *N* layer (fig.7b), owing to the way in which PbO absorbs light. Red light is absorbed rather gradually as it passes through the target, but most of the blue is absorbed in the first 5 μm of the target thickness. In a target containing a wide field-free region immediately behind the *N* layer, charge-carriers generated by blue light make no contribution whatsoever to the photo-current. It is true that the field-free region shrinks as the applied voltage is increased, but those parts of it which lie immediately behind the window, and which absorb the greatest amount of blue light, are the last to be affected. In these circumstances the characteristic for blue light changes at the low-voltage end (fig. 12), and a far higher value of applied voltage is required for saturation than when the central layer has *P*-conducting properties and the field-free region is on the gun side.

From the point of view of service life, it is even an advantage for the *I* layer to be somewhat *P*-type, as is shown later.

In approximation, the field-strength can be equated with U/d in cases where the curvature of the bands is only slight, d being the thickness of the layer. The velocity of the charge-carriers is then $\mu U/d$, and for the transit time to be smaller than the mean life τ of the charge-carriers it is required that $d^2/\mu U < \tau$. For a U value of 10V and a layer thickness of 10μm the requirement becomes $\mu\tau > 10^{-7} \text{ cm}^2/\text{V}$.

The way in which i_f , the photo-current flowing through the PbO layer, depends on the incident luminous flux L may be found represented graphically in fig. 13. Plotted on log-log paper, this function appears as a straight line; that is to say, it can be

expressed by a formula of the type $i_f \propto L^\gamma$. The value of the exponent is close to unity. Generally, γ is found to have a value between 0.8 and 1.0, which means that the photo-current is more or less proportional to the incident luminous flux; a single value, uniform at all light levels, can therefore be quoted for the sensitivity of the “Plumbicon”⁸⁾.

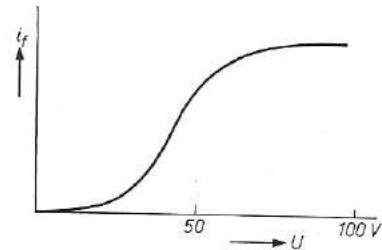


Fig. 12. When the *I* layer is too strongly *N*-type, the low-voltage end of the i_f, U characteristic will be depressed, and a high applied voltage will be required for i_f to attain its saturation value. This effect is strongest for blue light.

The significance of this will be further discussed in the article quoted in²⁾. For the tube whose characteristic appears in fig. 13, this value is 210 μA/lm. (For the conventional vidicons one value only cannot be quoted; γ differs widely from unity — roughly $\gamma = 0.5$ — and is even dependent on L .)

⁸⁾ Also when i_f is below the saturation value the photo-current is still proportional to the incident luminous flux, and from this fact we can probably conclude that the recombination is monomolecular.

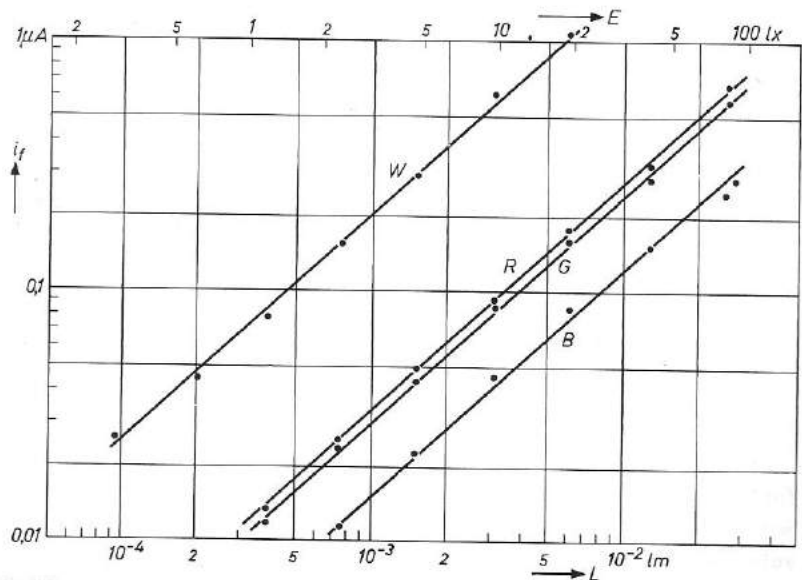


Fig. 13. The measured variation in photo-current i_f as a function of luminous flux L (or illumination E) for white, red, green and blue light (curves *W*, *R*, *G* and *B*), the applied voltage having been kept at a fixed value. In contrast to conventional vidicons, in the “Plumbicon” L and i_f are roughly proportional ($\gamma \approx 1$) for all kinds of light. Curves *R*, *G* and *B* were obtained in the same manner as the corresponding curve in fig.11. They have been plotted against the luminous-flux values for white light, i.e. the flux incident on the tube before the filter was interposed.

It has been found that tubes made in the same way show very little spread in sensitivity, the widest variation being of the order of $10 \mu\text{A}/\text{lm}$. Another point of interest is that higher sensitivity values can be achieved, where necessary, e.g. $400 \mu\text{A}/\text{lm}$, by modifying the deposition process or by depositing a thicker layer of PbO.

When sensitivity to different kinds of light is measured, γ still has a value around unity.

The spectral sensitivity distribution

It has already been pointed out that PbO does not absorb different kinds of light to the same degree. The shorter the wavelength, the higher is the degree of absorption; roughly speaking, blue light is almost completely absorbed after passing through the first $5 \mu\text{m}$ of PbO, but quite a high proportion of red light passes right through the target (fig.14). Clearly, then, the spectral sensitivity of the target can be varied between rather wide limits: a higher relative sensitivity to red light can be obtained by making the *I* layer thicker; maximum sensitivity to blue can be obtained by making the *N*-type layer as thin as possible, and by ensuring (for the reasons explained above) that there is no field-free region in the part of the *I* layer directly adjoining the *N* contact.

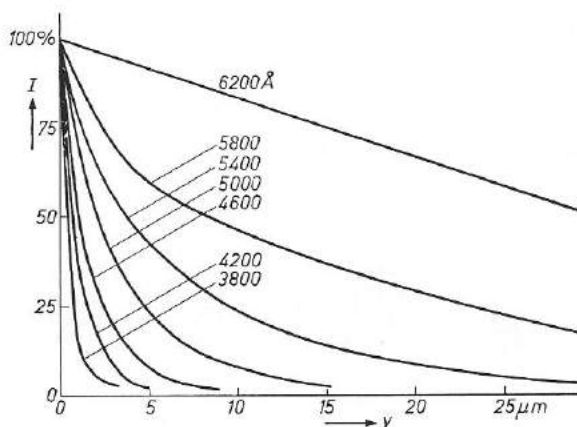


Fig. 14. The absorption of monochromatic light of different wavelength by PbO. The variation of the intensity *I* is plotted against the distance *y* the light has travelled.

The upper limit to the range of wavelengths within which the tube is sensitive is roughly the same as that for red PbO. A band gap of 2.0 eV corresponds, as already mentioned, to a cut-off at 6200 \AA . The lower limit depends on the thickness of the *N* layer and the distribution of potential in the neighbouring part of the *I* layer. (The upper limit can be shifted to considerably longer wavelengths, without cooling being required, by making the target of a

material having a smaller band gap. See the article quoted in 4).)

Fig. 15 shows the spectral sensitivity distribution of two tubes whose PbO targets were intentionally made in a different way. The dashed line represents the response of the human eye. Curve 1 is that of a tube whose PbO target was made by the standard process. By modifying the process to reduce sensitivity to blue — and possibly increase sensitivity to red — the peak of the characteristic can be shifted towards the right. It is even possible to shift it to the right-hand side of the response curve of the eye (curve 2).

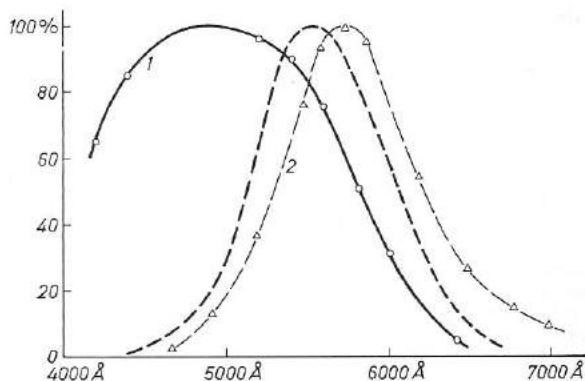


Fig. 15. The spectral sensitivity distribution of two tubes of the "Plumbicon" type. The thick dashed line represents the spectral sensitivity of the eye. Curve 1 is that of a tube whose PbO target was made by the standard process. The peak of the curve can if desired, be shifted to the right (curve 2), to the other side of the eye sensitivity curve.

Since the (standard) "Plumbicon" has a spectral sensitivity distribution much closer to that of the human eye than the corresponding characteristics of the ordinary vidicon (Sb_2S_3) or the image orthicon (Ag-Bi-O-Cs), it requires no filters when used in monochrome television, yet gives a far better gradation of colours than the tubes just named. Also for colour television the somewhat smaller sensitivity to red of the "Plumbicon", compared to the human eye, does not appear in practice to be a serious objection²⁾. In such a case, however, a tube with greater sensitivity to red offers a solution⁴⁾.

Resolution

A light-to-dark transition in the image of the scene projected on the window is not reproduced in the video signal with exactly the same abruptness. Apart from the properties of the electronic equipment to which the pick-up tube is connected, and the properties of the electron beam — factors we shall not be discussing here — this is due to the fact that the corresponding transition in the charge image formed on the free surface of the photoconducting

layer between two scans is less sharp. Two effects are responsible for this: in the first place a certain amount of the light is scattered in the target, and in the second place some transport of charge takes place in the PbO parallel to the target surface (cross-conduction). The latter effect can be subdivided into cross-conduction in the *P* layer and cross-conduction in the *I* layer.

It was found that the lack of definition caused by blue light is much less than that caused by red. If the target thickness is reduced, blurring of red outlines becomes less but that of blue remains the same. The reason will be clear if it is remembered that blue light does not penetrate so far into the target as does red (*fig.16*).

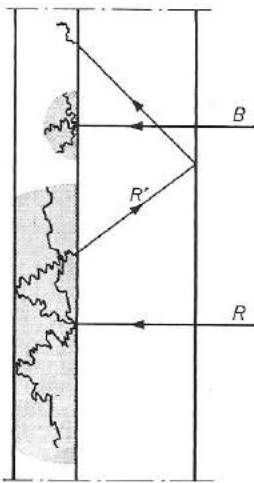


Fig. 16. PbO has a lower absorption for red light than for blue, and consequently the scattering of red light has a more adverse effect than that of blue on the resolving power of the PbO target. The shaded areas indicate, schematically, the extent of the zones penetrated by the diffused light originating from one narrow beam (*R* and *B* resp.).

A certain amount of diffused light escapes from the target by way of the front face of the target, but is then reflected back by the front face of the glass window; it is again the less rapidly absorbed red light (*R'*) that is mainly responsible for the contribution of this effect to the loss of definition.

Consequently from the standpoint of definition it is desirable to make the target as thin as possible. As we have seen, this will involve a reduction in sensitivity to red light; furthermore, the capacitance of the target will be increased and, for reasons which will be explained below, only a limited increase in target capacitance can be accepted. Thus there is not complete freedom of choice of the target thickness. (The difficulty disappears if the PbO is replaced by a basic material with a much greater absorptivity for red light⁴.)

Cross-conduction in the *P* layer can naturally be limited by making the layer as thin as possible; and further, the less the doping of the layer, the less

cross-conduction there will be. However, as we have seen, if the layer is too lightly doped the dark current will be excessive. Also, as will be explained below, from the viewpoint of service life it is advantageous to make the *P* layer thick and dope it heavily. Accordingly, here again the choice is not entirely free.

Cross-conduction occurs in the *I* layer when, owing to insufficient purity of the material, this layer contains a "field-free" zone. In such a zone the charge-carriers are liable to fan out instead of crossing the layer by the most direct route. This does not matter if the charge-carriers in question are electrons, since the point where these arrive on the signal plate has no bearing on the resolving power. But the place where the holes arrive is of course important: a hole that has not crossed the target by the most direct route alters the distribution of potential on the free target surface in a way that does not correspond to the light pattern of the broadcast scene. So from the viewpoint of resolving power also, it is desirable that the *I* layer be as pure as possible.

Before the values of resolving power relevant to the "Plumbicon" are quoted, first a word about how this resolving power is expressed in figures. Suppose that a pattern like that in the upper half of *fig.17* is being projected on the screen of the tube. The pattern consists of alternate vertical light and dark stripes of the same width. In some parts of the screen the width of the stripes is such that 20 light-and-dark pairs would completely fill the picture height (in the language of the television engineer this is called 40 "lines"); elsewhere this number is 200 (400

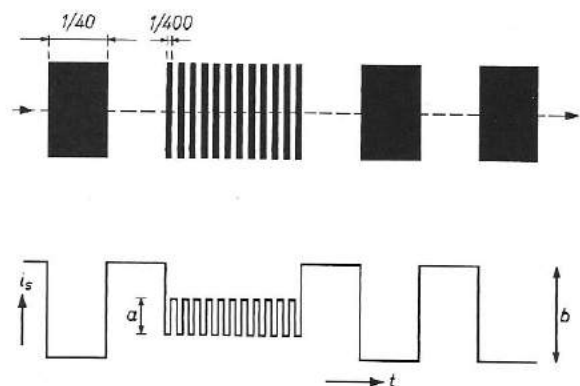


Fig. 17. Explanation of how the resolving power of a television camera tube is expressed in figures. A pattern of alternate light and dark vertical stripes, some having a breadth of 1/40th of the picture height and others a breadth of 1/400th of the picture height, is projected on the screen. This pattern is scanned in the direction of the dashed line. The broad and the narrow stripes give rise to alternating voltages with fundamental frequencies of 0.5 Mc/s and 5 Mc/s respectively. The ratio between amplitudes *a* and *b*, expressed as a percentage, and known as modulation depth, provides the required measure for resolving power.

"lines"). If an electron beam scans the corresponding charge image in the direction of the broken line, the signal current (fig.17, lower half) will have the form of an alternating current with fundamental frequencies of 0.5 and 5 Mc/s respectively (in the case of a 625-line system with a frame period of 1/25th second). Parts of the signal current corresponding to the broad dark stripes will have approximately the dark-current value, but the narrow dark stripes will give rise to higher current values. Parts of the signal current arising from the broad light stripes will have the same value as if the window were illuminated over its whole surface; the narrow stripes will yield lower current values. Let the letters a and b denote the difference between the light and dark values of i_f in the region of fast and slow alternations respectively. The ratio a/b expressed as a percentage, and known as the modulation depth, is commonly adopted as a measure of resolving power.

A more detailed impression of the tube properties is obtained if, instead of restricting the measurement of a to a pattern with 400 lines per picture height, the variation of a/b is investigated when a number of patterns with different stripe breadths are used. An example of this kind of measurement, done on a random-selected tube of the "Plumbicon" type, is shown in fig.18. It will be noted that at 400 lines the tube under investigation had an a/b ratio

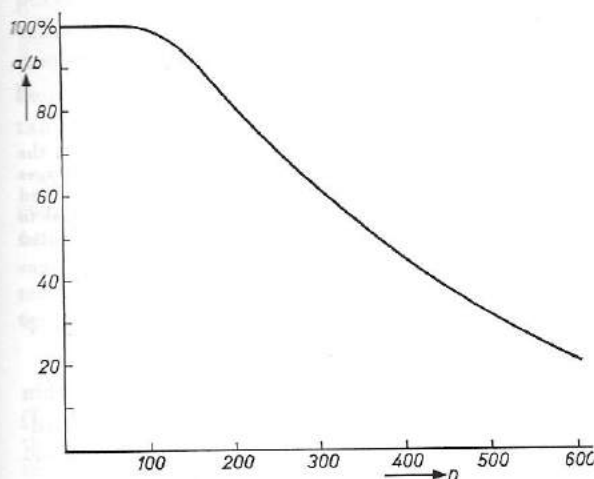


Fig. 18. A detailed description of resolving power can be obtained by plotting the variation in a/b against the breadth of the narrow stripes in the pattern appearing in fig. 17, the stripe breadth being expressed as the number n of black-white pairs of such stripes that would be required to fill one picture height. The figure shows the results of measurements done with white light on a random-selected tube of the "Plumbicon" type having a PbO layer 20 μm thick. As is inevitable, the ancillary equipment causes some interference; so normally such measurements give a figure that is lower than corresponds to the real performance of the tube. By adopting a very careful procedure, the difference is here reduced to a minimum.

of about 45%. In general a/b is found to be not less than about 35%.

Speed of response

When a sudden change occurs in the luminous flux incident on the photosensitive layer of a pick-up tube, the signal current does not immediately reach its new equilibrium value. When the target of a tube undergoes the variations of illumination shown in fig.19a, in the signal current the forms of response

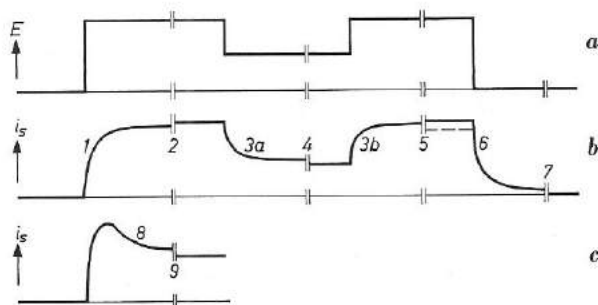


Fig. 19. The various forms of delayed response which, in principle, a "Plumbicon" may exhibit. In a good tube they are too slight to cause any trouble, and some are absent altogether. Diagram (a) shows the programme of varying intensity of illumination presented to the tube: the light is switched on, decreased in intensity after an appreciable time has elapsed, then brought back to its full intensity and finally switched off. The various forms of delayed response are represented in diagram (b). They are: 1) black-white inertia, 2) black-white trailing (a slight increase over a long period), 3a) and 3b) intermediate inertia, 4) intermediate trailing, 5) persistence (which may also manifest itself in attenuation of the signal), 6) white-black trailing, and 7) white-black inertia, and 8) and 9) fatigue and fatigue trailing.

illustrated in fig.19b may be encountered. The names that we have given these inertial effects may be found in the caption to that figure.

From the practical point of view one of the most important forms of response is "intermediate inertia". (Inertia effect occurring when the light intensity changes from white to grey or grey to white.) Black-white inertia only becomes noticeable under the most unfavourable conditions, and white-black trailing can be compensated electrically. Intermediate inertia is always fully manifest in the received picture, however, and the same applies to persistence and fatigue effects.

All the above forms of response can be regarded as resultants of two components, that are due to 1) the electron beam being incapable of supplying an unlimited amount of charge during the brief time in which it is directed on a given picture element; this component is accordingly called *beam-current- or discharge lag*, and 2) the presence of traps in the T layer. In the "Plumbicon" the contribution made

by both these factors have been reduced to a satisfactorily low level.

Both the discharge lag and that due to the presence of traps decrease with increasing target voltage U , although it should be observed that no further appreciable increase in the speed of response is achieved above a certain value of the applied voltage. The traces in fig. 20 show this effect. It will be noticed that

the initial rise (V low) is due to the fact that the electrons leaving the cathode do not all have the same velocity in the axial direction, the axial components of velocity having a quasi-Maxwell distribution. To a good approximation, the rising portion of the curve can be described by an expression of the form $i_a = ae^{b\Phi}$, where a is a constant connected with the beam-current and b is inversely propor-

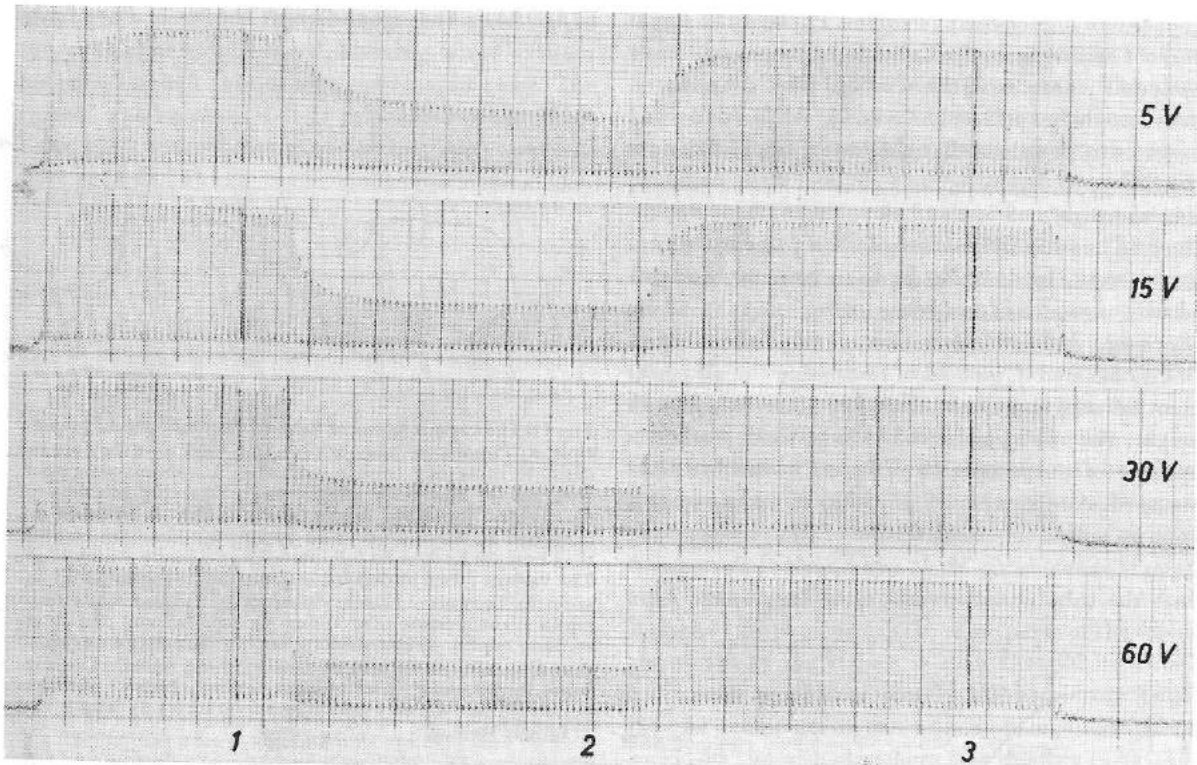


Fig. 20. The response of a randomly selected "Plumbicon" tube at four values of U , the voltage across the PbO target. At the relatively low U value of 30 V the response of the tube is already quite fast, and there is scarcely any persistence. The traces were obtained by illuminating the top half of the screen only, so that the signal current consisted of a train of pulses spaced at intervals of $1/50$ s (half a frame period because of the interlaced scanning). The programme of illumination was equal to that of fig. 19 and began in each case with a dark period lasting one minute. At the points 1, 2 and 3 the reading was interrupted for 10, 10 and 30 seconds respectively.

the highest speed of response is attained at the relatively low U value of 30 V. This speed of response is very satisfactory; the change in signal level resulting from a transition from strong to less strong illumination (and involving intermediate inertia) is 95% complete after only $3/50$ ths of a second.

The discharge lag

When we were discussing how the potential of the free surface of the PbO target adjusts itself to an equilibrium value, we found that the current flowing towards that surface was dependent on its potential V (fig. 3). The deflection and subsequent fall-off in the curve of current versus potential was explained as a result of an increase in secondary emis-

sional to the cathode temperature; Φ differs from V by a small constant amount.

Over the range of illumination values within which V remains small and the above formula accordingly remains valid, the discharge lag has the following properties:

- 1) It is independent of the beam-current.
- 2) It decreases with decreasing target capacitance C .
- 3) When the light intensity drops, the higher the new intensity the shorter the discharge lag.
- 4) The lower the cathode temperature, the shorter the lag.

Property (2) explains why the discharge lag initially decreases as voltage U is increased. At low U values the I layer contains a field-free region which,

in effect, forms part of the adjoining contact. This region becomes narrower and narrower as U increases. Consequently the distance between the capacitor "plates" becomes greater and the target capacitance decreases, giving a shorter discharge lag; see formula (2).

At higher intensities of illumination, corresponding to the region in which the i_a versus V curve starts to change direction, (1) ceases to apply: the discharge lag decreases with increasing beam-current when the light level is high. Property (2), relating to the low target capacitance desirable, is retained at high intensities of illumination; properties (3) and (4), for obvious reasons, are not.

In practice, for the decrease of the discharge lag, only the decrease of the target capacitance can be considered. If a time constant shorter than about 1/25th of a second is required for the response to a change from dark to light (to a moderate intensity of illumination giving rise to a photo-current of 10^{-8} A, say), then the target capacitance must not exceed about 2000 pF. Also at high intensities of illumination the discharge lag will continue to be negligibly short, provided it is possible to keep the target capacitance below 2000 pF.

These requirements can be fulfilled very comfortably with a target having the $P-I-N$ structure described above. For example, suppose that the PbO layer is $10\ \mu\text{m}$ thick and that it has an I layer so pure that it contains no field-free region at the U values employed in practice — when discussing sensitivity we saw that this degree of purity can actually be attained — then the target will have a capacitance ranging from 1000 to 1500 pF.

The four properties of the discharge lag at relatively low illumination levels, as listed above, can be inferred from the following. As before, we shall first assume that the beam is supplying charge *continuously*. The behaviour of V , the potential of the free surface of the target, is in accordance (cf. figs. 2b, 3, 4 and 5) with the differential equation

$$\frac{dV}{dt} = \frac{1}{C}(i_f - i_a).$$

(The whole target is imagined to be evenly illuminated; but the above equation applies equally to a single picture element, the capacitance C and the (negative) charge supply then being smaller in the same proportion.) Further:

$$i_a = ae^{b\Phi}.$$

Now suppose that a change in illumination abruptly raises the photo-current i_f from the value i_1 to the value i_2 ; the problem is to ascertain how i_a , initially equal to i_1 , arrives at its new value of i_2 .

On solving the above set of equations and eliminating V , we obtain:

$$i_a(t) = \frac{i_2}{1 - (1 - i_2/i_1) \exp(-bt_i/C)} \quad (6)$$

The four properties can be directly inferred from this formula. It can be shown, namely, that (6) remains valid when the fact that the beam supplies charge in surges is taken into account.

Just as there is, as we have seen, an upper limit to the capacitance of the target, there is also a lower one: to prevent the oncoming electrons from being excessively deflected by the charges on the target, the potential V must not vary over too wide a range during a frame period. Suppose for example that a limit of 10 V is placed on the variation of V and that a photo-current of up to 10^{-7} A is required, then C must not be smaller than about 800 pF.

The capacitance of the PbO layer in the "Plumbicon" has, it appears, a value such that on the one hand the lag is sufficiently short and on the other hand the influence of the electron beam on neighbouring picture elements can be neglected. The signal given by a picture element depends solely upon the intensity of the incident light, and is independent of its position, of its history, and of the situation in the surrounding picture elements. This is why the tube is so very suitable for colour television ²⁾.

Lag due to traps

Let us now go a little more deeply into the type of inertial response caused by traps. It is known from photoconductor theory ³⁾ that the presence of traps does not in the first instance affect the relationship between intensity of illumination and the steady-state electron concentration in the conduction band, or similar relationship; it does however have a bearing on the *speed* with which a new situation supervenes when the intensity of illumination is altered. Generally there are many more electrons in the traps than in the conduction band, the respective concentrations being c_t and c_c (much the same thing applies to the holes). If the illumination E is increased, with a consequent increase in c_c , the c_t/c_c ratio must nevertheless remain the same, and this implies a large absolute increase in the number of trapped electrons. Initially the demand is largely supplied by electrons liberated by the light incident on the target; c_c cannot therefore jump directly to the value corresponding to the change in E . The c_t/c_c ratio is proportional to N_t , the concentration of traps; the greater N_t is, then, the greater will be the (absolute) deviation of c_c at a given time after the increase in E . Similar reasoning applies if E is reduced: when this happens a large number of filled traps have to "dry out", and the higher the concentration of such centres, the greater will be the absolute deviation of c_c .

Since the concentration in the conduction band

falls off with increasing U , it is understandable that these inertial effects should become less noticeable at higher values of applied voltage.

Apart from these *direct* consequences of the presence of traps, which will not be further analysed, the traps have an *indirect* effect which at low U values may be clearly manifest in the response of the tube. The capture of charge-carriers in traps can modify the curvature of the energy bands in the I layer so drastically that the characteristics of the tube are affected. Any such modification is purely temporary, of course, beginning subsequent to a change in E and proceeding at the same rate as the establishment of a new value of space charge ($c_c + c_t$), so that for the observer it has the character of an inertial effect. We shall now look a little more deeply into this effect; for simplicity we take as an example the phenomena of *fatigue* and *black-white inertia*. To obviate misunderstanding it should be pointed out that in the discussion which follows, cases will only be considered in which the applied voltage U is chosen so small that a field-free region is present in the I layer.

Fatigue, a slow decay in photo-current following an abrupt increase, occurs because charge-carriers are trapped in such a way that the field-free region expands. Here a distinction must be made between cases in which the I layer is slightly N -type, and those in which it is slightly P -type.

As we have seen, if the I layer is slightly N -type there will be a field-free zone on the N -layer side when U is small. In consequence of hole capture this zone widens (see *fig. 21a*) with the result that the sensitivity of the target is modified, particularly its sensitivity to blue.

If the I layer is slightly P -type there will be a field-free zone on the P -contact side, which widens owing to electron capture (*fig. 21b*). This affects the tube's sensitivity to red light.

Under normal operating conditions U is high enough to eliminate the field-free zone or at least to reduce it to such small dimensions that the effects just described are of little importance.

In the case of *black-white inertia* there is, in addition to the direct effect of charge-carrier capture, a side-effect that is the opposite of that just discussed; here the field-free zone *shrinks*, causing the sensitivity of the target to increase (see *fig. 22*).

It will be clear that the properties of a tube in regard to speed of response allow conclusions to be drawn about the nature of the I layer. If for example the tube exhibits both *fatigue* and *black-white inertia*, this is an indication that both kinds of charge-carrier are being trapped, though the probabilities of capture are different for the two types.

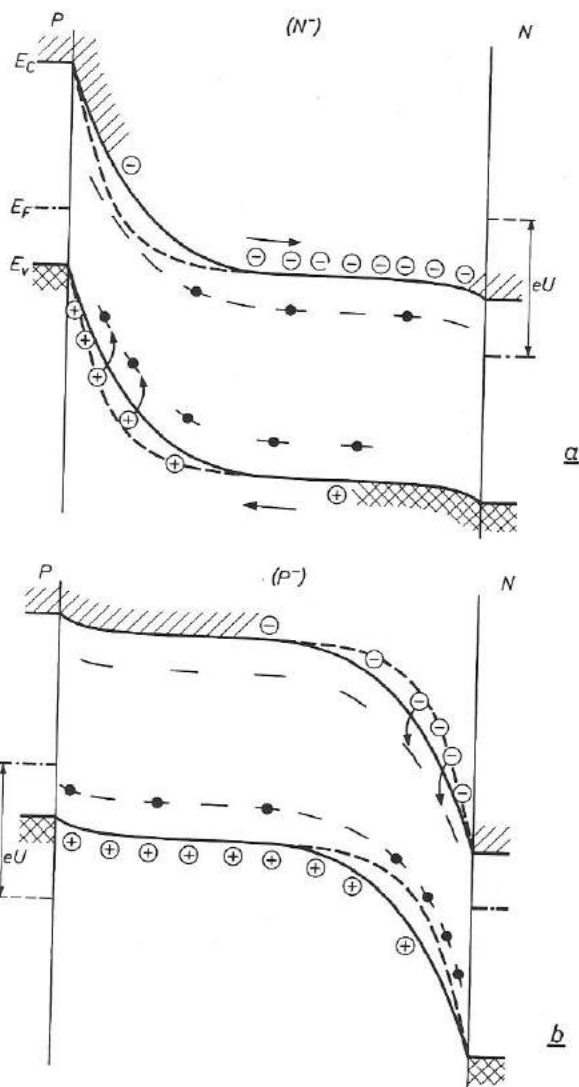


Fig. 21. To explain "fatigue".

Finally, it must be pointed out that there is yet another form of delayed response which is likewise a consequence of a change in the curvature of the energy bands but, in contrary, becomes more pronounced as U increases. This effect occurs in old tubes when, on account of long use, the P contact ceases to have an adequate blocking action. In such a case hole capture lowers the height A of the barrier to a point such that it no longer prevents the flow of current. So long as the target is illuminated and a relatively heavy photo-current continues to flow, this component will not be noticed; but it persists when the incident light has been removed, until the captured holes have left the traps. This "stimulated dark current" (one type of white-black trailing) is quite unacceptable and its occurrence is an indication that the tube has reached the end of its

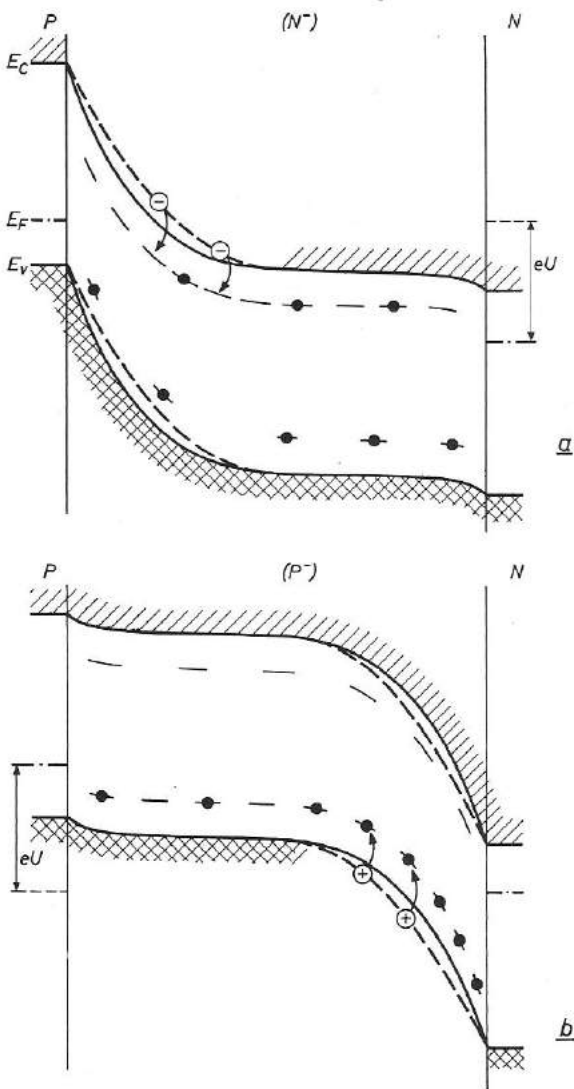


Fig. 22. To explain "black-white trailing".

service life. In the next section we shall see why the *P* contact deteriorates in this way.

Constancy of tube properties; service life

Any variation in the properties of a tube of the "Plumbicon" type in course of time is the result of the changes that take place in the PbO target. We shall review the most important of these changes and, amongst other things, explain how they ultimately make the tube unserviceable.

The changes in question are caused in the first instance by the diffusion of excess oxygen in the PbO target. As a result, small irregularities in oxygen concentration in the *P* and *I* layers are to some extent evened out. In addition, the transition between the *P* and *I* layer becomes less sharp. The evening-out of irregularities in the *I* layer naturally gives rise to

a more uniform fall-off of potential through the layer, and hence to greater sensitivity and a faster response. More important than internal oxygen migration — at least from the viewpoint of service life — is the overall loss of oxygen from the PbO target. Oxygen in gaseous form cannot remain free for long enough to build up any pressure within the tube; it immediately combines with a barium getter, or with residual gases, and in these circumstances the PbO slowly decomposes. The *P* layer, because it is at the free surface side of the target, is the one most affected. But owing to the porous nature of the target the regions more remote from the free surface, and in particular the *I* layer, gradually lose oxygen too. The oxygen loss of the *P* layer is accelerated by ion bombardment while the tube is in operation. Further, it is possible that the *P* layer loses some oxygen by electrolysis within the PbO.

One consequence of this removal of oxygen is that the *P* layer loses some of its *P*-type conductivity; the same applies to the *I* layer which, it will be remembered, is also to some extent *P*-type. It will now be clear why, for long service life too, it is advisable to make the *I* layer slightly *P*-type. In consequence of oxygen loss a truly intrinsic *I* layer would gradually become *N*-type, which as we have seen would not be altogether desirable.

The decrease in the *P*-conductivity of the *P* layer is no disadvantage in the first instance; from one point of view it is even the reverse. The decrease of conductivity also cuts down cross-conduction, of course, so improving the resolving power of the target. In the long run, however, the height of the barrier is reduced to such a point that the tube starts to exhibit the form of sluggish response ("stimulated dark current") discussed at the end of the preceding section; at a later stage the normal dark current also becomes excessive. When this happens, the tube has come to the end of its service life.

Very occasionally a tube becomes unserviceable because of the sudden appearance of a white speck in the received picture. The cause is again an excessive dark current, but here it is restricted to a small part of the target area. Speckling will be discussed in the next section.

Fig. 23 is a plot of a number of tube properties with respect to operating time. It will be noted that the overall life of the tube falls into two distinct parts. The earlier period is one of rapid change; a sort of "forming" process takes place. During this time the tube remains in the factory. The tube is ready for use as soon as it has entered the second phase of its life. From then on the quantities determining serviceability remain more or less constant for a

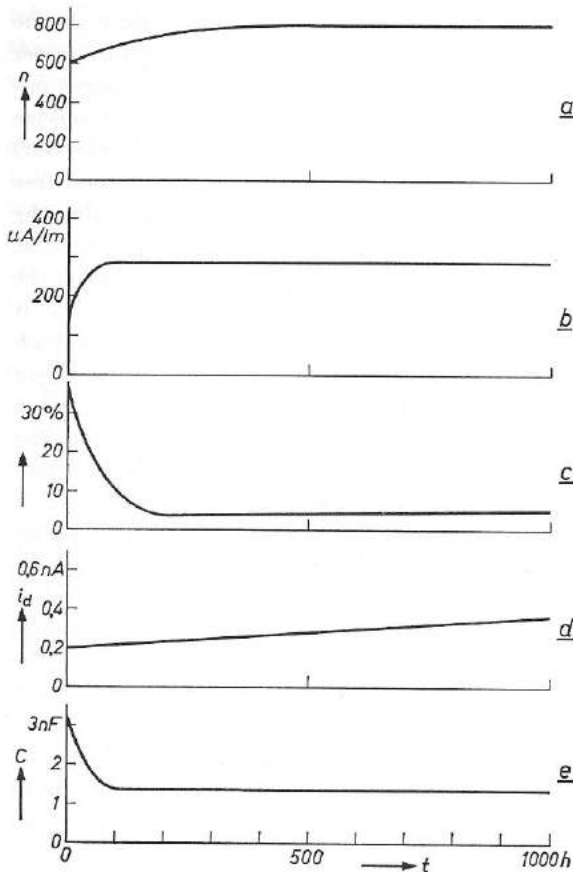


Fig. 23. Changes in various tube characteristics and in the capacitance of the PbO target, measured on a randomly selected tube of the "Plumbicon" type, during the first 1000 hours in operation. *a*) Resolving power, shown as the number of lines that can just be resolved by the eye (the corresponding a/b ratio — see fig. 18 — is roughly 5%). *b*) The sensitivity of the tube. *c*) The intermediate inertia, expressed as the proportion of the required change in signal current that has still to take place after a lapse of $3/50$ s following an abrupt change in illumination. *d*) The dark current. *e*) The capacitance C of the PbO target.

Initially, the characteristics of the tube under test changed considerably — a normal feature of the "Plumbicon"; the tubes remain in the factory during this early phase of their life. Thereafter their characteristics show a high degree of stability, as can be seen from the diagrams.

lengthy time (sensitivity and resolving power) or increase extremely slowly (dark current and the various forms of sluggish response). The most direct evidence of the changes that take place in the target, early on in the life of the tube, is obtainable from the curve of target capacitance as a function of time (fig. 23*e*). Since the target capacitance is inversely proportional to the effective thickness (see eq. 2), the variation in effective target thickness during the life of the tube can be determined directly from capacitance measurements. By the same means it is also possible to investigate how target behaviour is affected by changes in U or in the intensity of illumination.

Speckling

It has been stated that the PbO target can be regarded as a large flat $P-I-N$ diode; alternatively, since there is little cross-conduction, it can also be viewed as an aggregate of small diodes lying side by side corresponding to the picture elements. To obtain a good picture at the receiver it is necessary that all these little diodes should be roughly similar. If there is one picture element with properties differing greatly from those of the others, it will be visible as a speck in the received picture. Depending on the nature of the defect, the speck may be light or dark, sharp or diffuse, and of constant or variable luminous intensity. If the brightness variation is periodic the speck is said to "twinkle". We shall now briefly review the commonest defects and the kinds of speck they give rise to.

- 1) Regions of high local P -conductivity occur in the I layer, such that the fall-off in potential is very steep near the N contact, with the result that the barrier is extremely narrow. Thus a strong dark current flows and a white speck is produced. This strong dark current can be the cause of an "avalanche effect" owing to the very high field-strength, or of the tunnel effect: if the barrier is very small, a hole in a conduction-band level of the N region can be moved by the tunnel effect to the I region, and there appear in an equally high level of the valence band (see fig. 24). With regard to the avalanche effect it is very conceivable that the dark current can periodically vary in strength. In this case the speck "twinkles".
- 2) A similar situation arises if parts of the I layer have a relatively high N -conductivity; but now it is the P -layer side that is affected. The dark current resulting from the tunnel effect is now not a hole but an electron current.
- 3) Inadequate doping of a part of the P layer. This part of the target will have a much shorter life than the rest. A heavy dark current will soon start to flow there, producing a white speck in the received picture and making the tube un-serviceable.
- 4) Excessive thickness of the P layer in a part of the target (for example, because it has been doped excessively). Accordingly, the I layer is then too thin in the affected target area, and here the sensitivity — particularly sensitivity to red — is less than it is elsewhere in the target. The result is a dark speck in the received picture.
- 5) Excessive thickness of a part of the N layer. The result is again a local loss of sensitivity giving rise to a dark speck, but it is now the blue sensitivity that is mainly affected.

The defects listed above are essentially irregularities in the multilayer structure of the target; in addition, defects of a purely mechanical nature — due for example to the presence of a dust particle — are also possible.

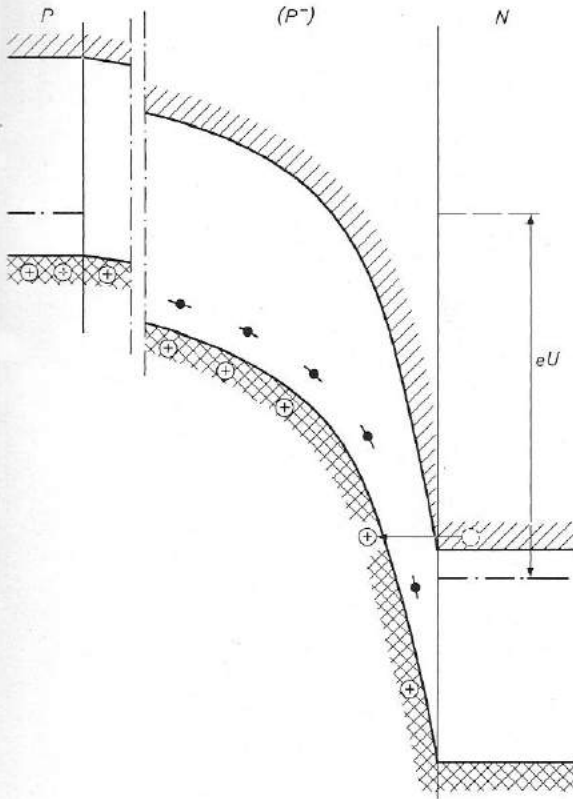


Fig. 24. To explain the occurrence of a strong dark current of holes, when the inner sublayer contains a limited region of high *P*-conductivity. The barrier can then be so narrow that tunnelling is possible (see arrow).

By arranging for fabrication of the tube under carefully controlled conditions in dust-free rooms, each part being subjected to rigid inspection, it has been possible to eliminate most of the causes of these defects, and the PbO targets now being produced are accordingly of consistently high quality in regard to freedom from speckling.

Summarizing the properties of camera tubes of the "Plumbicon" type, as discussed above, we can say first of all that the multilayer structure of the target leads to a very small dark current and to a much higher sensitivity than is obtainable with a simple *P-N* junction. In addition, it is possible by suitably choosing the individual layer parameters to give

the tube an excellent spectral sensitivity distribution, a very good resolving power and a high speed of response. The "Plumbicon" has made it a practical proposition to build small, lightweight television cameras with very good properties.

We have also seen that there is scope for a fairly wide range of variations on the basic design: some properties, such as the spectral sensitivity distribution, can be modified quite drastically without severe interference with the others. A further wide range of possibilities becomes available when the basic material PbO is abandoned in favour of PbO-containing material having a band gap smaller than 2.0 eV⁴).

In virtue of all these opportunities for varying the characteristics of the tube it is possible, for example, to make pick-up tubes of the "Plumbicon" type that possess a very high resolving power together with high sensitivity, qualities desirable in medical applications when the tube is used for radiological examination; or to make tubes combining high sensitivity with long service life and a reasonable speed of response, the qualities desirable in industrial closed-circuit applications and in traffic control at night; or to make tubes which, without any sacrifice of studio requirements for equipment to be used in live broadcast television, are eminently suitable for incorporation in colour-TV cameras.

Summary. The "Plumbicon", a new television pick-up tube, is a kind of vidicon whose photoconductive target is built up of micro-crystalline PbO. This PbO layer consists of a *P*-type sublayer at the gun side, an intrinsic sublayer (*I*) and possibly a thin *N*-type sublayer next to the signal plate. The signal plate is made from *N*-type SnO₂. The PbO layer and the signal plate form a unit having the properties of a *P-I-N* diode: the *P*-type sublayer hinders the entrance of electrons to the *I* layer, the signal plate (or the *N*-type sublayer) hinders the holes. When the tube is in operation this *P-I-N* diode is reverse-biased; the dark current (i.e. the inverse current through the diode) is therefore very small. The sensitivity of the tube, which is determined by the thickness of the *N* and *I* layers and by the distribution of potential through the *I* layer, can exceed 200 $\mu\text{A}/\text{lm}$; its spectral sensitivity can be matched to the human eye more closely than is the case for existing camera tubes, but this characteristic can be modified within wide limits. The thinner the *N*-type sublayer, the greater is the sensitivity of the target to blue light. Its overall sensitivity increases with the thickness of the *I* layer. Gamma is close to unity. Resolving power and speed of response are excellent (the depth of modulation is about 35% at 400 lines; response time approx. 3/50th of a second). The "Plumbicon" has a longer service life than other studio-quality tubes. On all points important in television broadcasting the "Plumbicon" equals or betters existing tubes, and above all when it is employed for colour TV. The tube's more important properties can be drastically modified without prejudicing the others, and because of this it is possible to make versions that are specially suited to widely divergent applications. A further wide range of designs becomes available if the basic target material is replaced by PbO-containing material having a smaller band gap (minimum 0.9 eV).