Photomultipliers and the transfer technique

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The improvement in the performance of photomultipliers has long been an important activity in the close cooperation between LEP and the Hyperélec works at Brive-la-Gaillarde.

In its application as a detector of light the photomultiplier is almost unsurpassed in speed of response and sensitivity, and on this account it is widely used for observing the scintillations produced in transparent materials by nuclear radiations. The photomultiplier thus acquired considerable importance in nuclear instrumentation, both for industrial and laboratory applications, and it is of great value in general photometric work. Since the requirements of the physicist are continuously changing, it is necessary to maintain a steady research effort, and in today's situation with new applications in fields such as space astronomy and lasers there is plenty to be done.

The history of these activities and the characteristics of this type of tube have been presented in an article in the previous volume of Philips Technical Review [1]. We shall confine ourselves here to the important contribution made by the transfer technique, a new method for activating photocathodes [2], in this search for ever better performance. The main virtue of the transfer technique is that it reduces the dark current, through an appreciable reduction in the field emission due to alkali metal deposited on all the electrodes of the photomultipliers.

This reduction in field emission also allows a more adequate study of new designs that make use of high voltages or high fields that could not easily be used previously and can give improvement in characteristics such as amplitude fluctuations and rate of response.

Conventional photomultipliers

In a conventional photomultiplier the signal from the photocathode is amplified by an avalanche process at a series of secondary-emission dynodes. To clarify the new developments it is perhaps advisable to recapitulate some facts already described in reference [1].

In most tubes the dark current is far greater than the thermionic emission of the cathode; the thermionic emission is always present, but as a rule forms only a small part of the observed current. For many types of tube the manufacturer is thus forced to adopt a "low-noise" solution. The thermionic emission of ordinary cathodes (SbCs or Sb-K-Cs) is of the order of 10 electrons per cm² per second. The main source of the additional current is the field emission, produced not at the cathode, where the electric fields are weak, but anywhere in the tube, at the irregularities and particles of dust that can never be completely eliminated. The electrons thus produced are rarely accelerated directly towards the useful surface of a dynode, where they would be multiplied by secondary emission. As a rule they are accelerated towards other surfaces (the back of a dynode, for example, or connectors or insulators), where they produce light or soft X-rays. The light and X-rays thus emitted may then reach the cathode or one of the first dynodes, where they cause the emission of photoelectrons or bunches of photoelectrons.

The considerable intensity of field-emission currents emitted at surface irregularities (10⁻⁹ to 10⁻¹² A) is due to the very low work function (typically 1.5 eV) of the metal surfaces which have adsorbed a thin film of alkali metal (especially caesium). This film, which is bound to the metal by an affinity even greater than the affinity that assures the stability of the photocathode, forms because there has to be a high vapour pressure of alkali metal in the tube while the cathode is being activated. In the transfer technique this operation is carried out in a subsidiary enclosure inside the bell-jar of the vacuum equipment, and the vapour pressure of the alkali metals always remains very low in the part of the tube separated from the window.

We should mention a few difficulties that do arise in applying the transfer technique. The film of alkali metal deposited on all the surfaces does not have an entirely negative effect since it also increases the secondary emission of the dynodes. Consequently, when the film is not present, the emission from the dynodes is slightly reduced and somewhat higher voltages have to be used for the same gain. This is not usually a serious handicap, and may even be an advantage if a rapid response is required. Furthermore, the alkali film acts as a getter in the tube, av ery useful role bearing in mind the effect of gases such as oxygen, hydrogen and carbon dioxide on the photocathode: if just a few atomic layers of these gases are adsorbed, the sensitivity is almost completely destroyed. The degassing of the components of the tube, particularly those

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subject to electron bombardment, therefore has to be carried out with particular care. However, the result on the dark current is truly remarkable (fig. 1).

A photomultiplier that gave serious problems in this respect in production is the XP 1020. In order to reduce fluctuations in transit time it proved necessary to use rather high electric fields between certain electrodes. Its dark current is on average $10^4$ electrons per second. But a few experimental tubes made using the transfer technique have a dark current which on average is a hundred times smaller.

One final point should be made: masks can be placed in the activation enclosure during the evaporation, in order to obtain a sharp delineation of photocathode surfaces. When such masks are used either a cathode of small surface area, and hence giving little thermionic emission, can be deposited on the window, or several electrically separated cathodes (PM 450 FH, PM 450 FQ). The emission of each cathode element can then be switched on or off at will by switching pulses. A photomultiplier of this type can be used as a detector of position.

The transfer technique is now being used at the Brive works in making short runs of ruggedized tubes derived from the PM 400. These tubes, represented typically by the PM 403 F, are suitable for use in space vehicles and satellites; their dark current lies between 20 and 50 electrons per second. A fact typical of the purely thermionic character of this current is that the amplitude distribution of the dark-current pulses is identical with that of the pulses produced by photoelectrons (curves 1 and 5 of fig. 1).

The example of the XP 1020 illustrates clearly the advantage to be gained by using the transfer technique in making fast-response tubes. In fact the speed of response increases with the voltage, and this is limited in practice to a value at which it does not give field emission. The transfer technique thus makes it possible in principle to break through this barrier and use tubes at markedly higher voltages. We hope to be able to exploit this possibility in the near future.

Let us now turn to two rather newer types of photomultiplier for which the transfer technique has made an even more noteworthy contribution.

### Hybrid photomultiplier

In a hybrid photomultiplier (fig. 2) the amplification of the photoelectric signal is no longer produced by secondary emission; the photoelectrons are accelerated to an energy $E$ (10 to 40 keV) and then absorbed at a semiconductor junction, where each photoelectron will cause a large number of electron-hole pairs, given by:

$$\frac{E - E_w}{E_0},$$

2. R. Legoux, The transfer technique, a new method for activating cathodes of phototubes, page 234 of this issue.
3. Developed under contract from Centre National d'Etudes Spatiales.
where $E_w$ is the energy lost in the window of the detector, and $E_o$ is the mean ionization energy of the semiconductor material (in general $E_o = 3.6$ eV for silicon). A reverse bias is applied to the junction and the depth of the space-charge region, where the charge carriers are liberated, is chosen to suit the depth of penetration of the photoelectrons, some tens of microns. The surface area of the junction, between 10 and 100 mm$^2$, has to be chosen as a function of the geometric spread of the electron beam (i.e. the focusing), of the permissible capacity, and of other parameters. The window, which is one of the electrodes of the junction, has a thickness which should be sufficiently small to absorb only a small part of the energy of the photoelectrons. These junctions are thus closely related to those currently used for the detection of charged particles. Without going further into the theory and practice of these detectors, we can just mention that their dark current and breakdown voltage are related mainly to leaks at the surface of the junction; these parameters are therefore extremely sensitive to any desorption or adsorption of impurity atoms.

Thus, two particular difficulties made themselves apparent during the early attempts to incorporate such elements in a phototube: The characteristics of the junction have to be maintained not only in the vacuum but also after baking out at 350 °C for several hours; on the other hand the alkali metals deposited on the detector surface must not increase its leakage current to an undesirable degree.

These semiconductor detectors are designed and produced at R.T.C. La Radiotechnique-Compélec (Caen laboratories). Various solutions for the first difficulty in making a hybrid photomultiplier were therefore investigated at these laboratories. The second difficulty, however, could be overcome by using the transfer technique. This is all the more important since the problems of field emission, which had already proved difficult with the voltages used in conventional photomultipliers (less than 3 kV), threatened to become inuperable at voltages between 10 and 40 kV.

The first hybrid photomultiplier was produced by R. Kalibjian [4], who was attempting to achieve a linear region for pulses up to and above 5 A. Work of this type is being carried out at Hyperélec (Brive) and also at R.T.C. Caen, where a detector based on the principle of "inverse epitaxy" [5] has been developed.

We shall now turn to another type of hybrid photomultiplier, developed at LEP, which has been devised for a different purpose, namely to give a reduced statistical fluctuation in the gain.

In a conventional photomultiplier [1] these fluctuations, which are proportional to $1/\sqrt{\delta}$, are large because the gain $\delta$ is small (about 3) and also because the number of secondary electrons collected varies from one dynode to the other. For scintillation detection ($\gamma$-spectroscopy) this increases the fluctuations due to the photomultiplier by 20-30% compared with the ideal case in which only the number of photoelectrons ($n$) fluctuates. If $n$ is very small, any information about its value is blurred to the point at which it is no longer possible to distinguish pulses corresponding to 1 or 2 photoelectrons by their amplitudes. The improvement obtained with the hybrid photomultiplier can be illustrated as follows: The absolute fluctuation $\Delta q$ in the collected charge is given approximately by $\Delta q \approx G \times q \times 1.5 \sqrt{n}$, where $G$ is the gain of the photomultiplier and $q$ is the charge of the electron. On the other hand, in a hybrid photomultiplier with a supply voltage of 35 kV the fluctuation about the mean value of $10^4$ electron-hole pairs produced, although not as small as the corresponding theoretical value of $1/\sqrt{10000} = 0.01$, is nevertheless considerably smaller than in a conventional photomultiplier. This fluctuation, which is usually quoted as a resolution expressed in keV, is in the hybrid photomultiplier related to the effect of various processes that take place in the semiconductor, to the fluctuation of its dark current, and to the noise of the amplifier. At the present time values of 10 keV are obtainable, which corresponds to an absolute fluctuation of the charge in the region of 0.3 $G q$ for a hybrid photomultiplier with a supply of 35 kV ($G = 10^4$). Retrodiffusion (inelastic reflection of a small part of the photoelectrons)
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Fig. 3. Amplitude distribution of pulses obtained from a hybrid photomultiplier developed at LEP, (a) with luminous pulses produced by a brief spark discharge, (b) with the scintillations produced by the $\beta$-rays of tritium in a liquid scintillator.

The density of pulses counted is plotted against the number of electrons liberated at the photocathode (total charge $Q$ measured in the electronic charge $q$ divided by gain $G$). The dashed lines indicate the spectra that would be obtained with a conventional photomultiplier.

introduces an inaccuracy that becomes greater as $n$, the number of electrons, increases. Fig. 3 shows various spectra obtained with a hybrid photomultiplier. The semiconductor used is a $P$-$N$ junction (of planar configuration) with a guard ring; its edges have been passivated by $SiO_2$ to limit leakage currents. Its surface area is 12 mm$^2$.

It is true that a photomultiplier of this type requires a power supply that gives very high voltage and low-noise amplifiers of high gain, but such units are now readily available. On the other hand, since the gain now varies linearly with the voltage (and not as $V^{10}$ or $V^{12}$), the regulation does not have to be so accurate. Finally, such a photomultiplier may well have a much better stability for variations in parameters such as the counting rate or the temperature.

The general properties of channel-plate multipliers have been described earlier in this journal [6]. Such a plate, which has a surface area of several square centimetres and a thickness between 1 and 10 mm, can be traversed by $10^8$ multiplier channels. An electron flux incident on one of the faces leads to the emission, at the other face, of a flux $10^4$ to $10^5$ times greater, with a voltage between the faces which is less than 1.5 kV. Methods for producing the channel plates are described in another article in this issue [7].

It seemed attractive to investigate the possibilities of using such multipliers in photomultipliers. One drawback immediately revealed itself: a large part of the photoelectrons are intercepted by the cross-section of the walls, so that the detection efficiency is greatly reduced. This means that such photomultipliers are of no use for nuclear spectroscopy. However, these multipliers could offer certain advantages because the thickness in the direction of propagation of the electrons is small (and hence the transit time is very short and consequently the fluctuations in transit time are small), while the surface area in the plane at right angles to the direction of propagation is large, allowing wide beams to be amplified. Moreover, the use of the transfer technique allows tubes to be made with the photocathode and multiplier set very close to each other, and also allows high electric fields to be employed between these plane electrodes with very little field emission. The obvious configuration to adopt therefore is the one shown in fig. 4. This shows a cross-section of a photomultiplier (see photograph fig. 5) which has a calculated transit

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time of 1 ns, a rise time of 0.2 ns, and a linear region extending beyond 1 A. Its gain is not very high, about $10^4$, and this limits its use to relatively intense luminous pulses, like the ones observed during rapid phenomena in plasma. The gain is limited by the generation of positive ions, which travel towards the cathode, liberating electrons and thus causing after-pulses or even a self-maintaining discharge. This tube therefore lies somewhere between the photoemissive diodes of the biplanar type, which are very fast, and the conventional photomultipliers with high gain but slower response.

One of the characteristics of this type of photomultiplier, however, prevents it from being used in certain applications: its electrical resistance should never be much less than $10^8 \, \Omega$ because it is difficult to conduct away the heat generated. The d.c. component of the signal cannot therefore exceed $10^{-5} \, \text{A}$, which limits the counting rate to $10^7$ electrons per second at a gain of $10^7$ (and in practice, these values are 10 or 100 times smaller). The maximum charge transported by a short pulse (e.g. 1 $\mu$s) is limited to about $10^{-9} \, \text{C/cm}^2$. This restricts the duration of 1-ampere pulses to about 1 ns.

**Conclusion**

It is as yet difficult to predict how widely the transfer technique will be used in making photomultipliers in the future. Possibly its rather high cost will limit its use to high-performance tubes, but this is a technique that may undergo considerable development. The encouraging results obtained at the Brive works with ruggedized photomultipliers with bi-alkali or tri-alkali cathodes indicate that photomultipliers of even better performance will become available to the physicist.

**Summary.** When the transfer technique for activating photocathodes is applied to photomultipliers of conventional design, there is a considerable improvement in their noise characteristics and, in certain cases, in their sensitivity. This new technique also makes it possible to develop new types of tube such as the “hybrid” photomultiplier, in which the multiplier is in fact a semiconductor electron detector (the electrons being accelerated to an energy ranging from 10 to 40 keV), or the microchannel photomultiplier, which includes an arrangement of channel electron multipliers. The hybrid photomultiplier is less subject to statistical fluctuations in amplitude and the microchannel multiplier gives a faster response.