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ELECTRON MULTIPLIER HAVING ELECTROSTATIC FIELD SHAPING ELECTRODES

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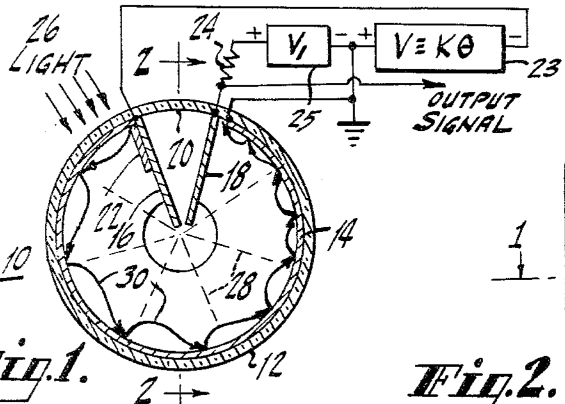

Fig. 1.

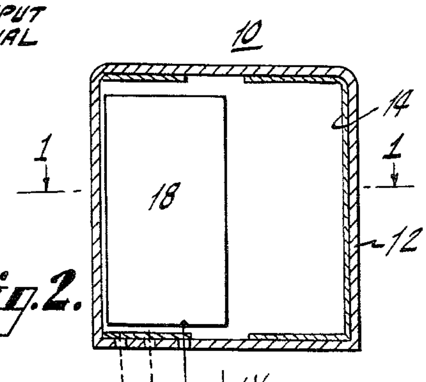

Fig. 2.

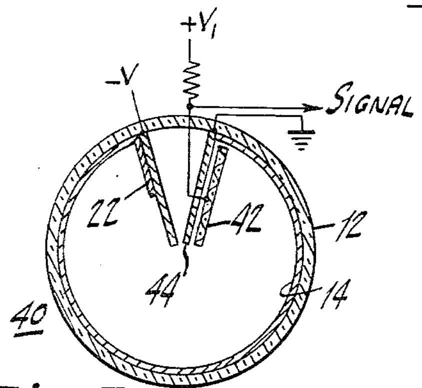

Fig. 3.

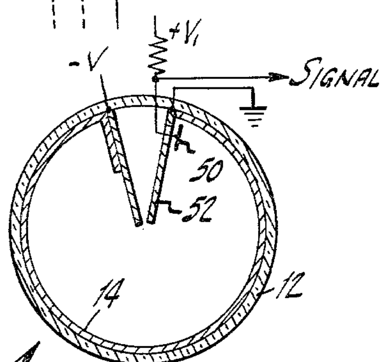

Fig. 4.

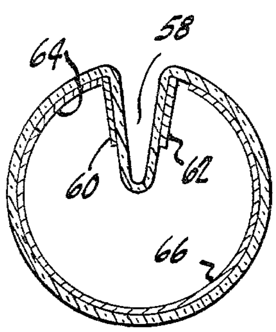

Fig. 5.

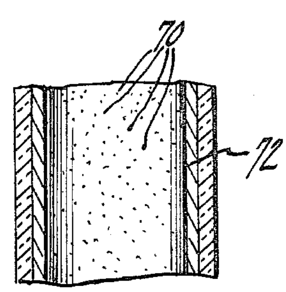

Fig. 6.

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ELECTRON MULTIPLIER HAVING ELECTROSTATIC FIELD SHAPING ELECTRODES

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This invention relates to electron multiplier tubes.

In the prior art there are many types of electron multiplier tubes. One class of electron multiplier tube which has found wide commercial interest is a photosensitive electron multiplier or photomultiplier tube. This class of photomultiplier tube includes types sensitive to visible light and types responsive to radiant energy of other wavelengths, e.g. ultraviolet.

One type of photomultiplier tube comprises a photocathode with one or more secondary electron emissive electrodes, or dynodes, spaced from the photocathode. The first dynode is of particular configuration so that the primary electrons will travel from the photocathode to the first dynode where they will be multiplied. The balance of the dynodes are also of particular configurations so that the multiplied electrons from the first dynode will, in turn, travel from the first dynode to the second dynode to be multiplied further. This process is repeated until the multiplied electrons are collected on a collector electrode.

Another type of photomultiplier tube is one in which two parallel insulating plates are provided within an envelope. Each of the plates has a resistive, secondary emissive, coating thereon. When a potential difference is applied between the opposite ends of each of the resistive coatings, and when the plates are pulsed to opposite polarities, at a frequency corresponding, e.g. to half the reciprocal transit time between them, i.e. one positive and one negative at one instance, and then the reverse, electrons go from one plate to the other because of the opposite polarity pulsing. The electrons travel down the length of the plates because of the potential gradient established between the ends of the resistive coatings.

Another type of known photomultiplier tube is one in which a pair of oppositely disposed parallel plates is provided, each having a resistive coating thereon. When a potential from one end of each plate to the other is applied, and the potential is such that the potential of any area of one plate is consistently more positive than the potential of the opposite area of the other plate, the electrons travel from one end to the other of the less positive plate if a magnetic field is applied parallel to the surfaces of the plates and at right angles to the potential gradient established on them, with electron multiplication taking place at successive impacts on the plate.

Thus, to accelerate the electrons in the desired direction, known photomultiplier tubes employ either special configurations of the various dynodes, the use of alternate polarity potentials, or the use of a magnetic field, or some combination of these.

It is an object of this invention to provide a novel electron multiplier.

It is a further object of this invention to provide an improved multiplier tube characterized in its simplicity of construction and operation.

These and other objects are accomplished in accordance with this invention by providing a substantially circularly cylindrical, insulating support having a resistive, secondary emissive coating deposited thereon. Within the space surrounded by the insulating support are two field-shaping electrodes extending in a plane from the inner surface of the cylindrical support substantially to the axis of symmetry of the cylindrical support. When a potential difference is maintained between the ends of the resistive coating, adjoining the field shaping electrodes, electron multiplication occurs as the electrons travel from their point of origin around the interior of the cylindrical support. Each time the electrons land on the secondary emissive resistive coating, electron multiplication occurs.

The invention will be more clearly understood by reference to the accompanying single sheet of drawings wherein:

FIG. 1 is a top sectional view of a photomultiplier tube made in accordance with this invention;

FIG. 2 is an elevational view taken along line 2—2 of FIG. 1;

FIGS. 3, 4, and 5 are top sectional views of other embodiments of multiplier tubes made in accordance with this invention; and

FIG. 6 is a sectional view of another embodiment of the secondary emissive surface in accordance with this invention.

Referring now to FIG. 1, there is shown a multiplier tube **10** made in accordance with this invention. The multiplier tube **10** comprises a substantially cylindrical envelope **12** which may be made of a material such as glass.

On the interior surface of the envelope **12** there is deposited a secondary electron emissive coating **14** using the glass as a substrate. Although the inner surface of the envelope **12** is shown as the support for the coating **14**, it should be understood that other support members than the envelope could be used and the inner surface of the the envelope is shown merely as an example. The secondary electron emissive coating **14** is a resistive coating and should have a surface resistivity of at least 10^5 ohms. The reason for the minimum resistivity is to limit the amount of power dissipation. Furthermore, the total resistance should be less than the ratio of the voltage applied to the dynode coating, to the desired output current. Thus, 10^{10} ohms is the approximate maximum surface resistivity.

The maximum resistivity is determined because the voltage drops across the resistive coating, resulting from current flowing in it, should be larger than the voltage drop which would be produced by the emission current flowing through the resistive coating. Thus, the emission current should not destroy the field distribution.

The resistive coating **14** may be both photosensitive and secondary emissive. For example, the coating **14** may comprise a cesium antimonide coating. A method of preparing such a coating may be found in a book by Zworykin and Ramberg, entitled Photoelectricity, published by Wiley, 1949, e.g., see page 96. Other resistive coatings, which are not photoemissive, such as magnesium oxide on a resistive substrate of tin oxide, which have a high secondary emission factor, may be used.

Within the envelope **12** are two planar field-shaping electrodes **16** and **18**. The field shaping electrodes **16** and **18** may be made of any conducting material such a nickel. As shown in the drawing, each of electrodes **16** and **18** extends radially inwardly from the envelope wall almost to the central axis of the cylindrical coating **14**, and the outer ends of the two electrodes **16** and **18** are respectively adjacent or close to the two ends of the coating **14**. It should be noted that an insulated gap **20** exists on the wall of the envelope between the two field shaping electrodes **16** and **18**. In other words, the resistive coating **14** does not cover the entire inner surface of the envelope **14**.

Part of the area of one of the field shaping electrodes **16**, i.e., the part adjacent to the envelope wall, may be coated with a photoemissive surface **22**, assuming that the coating **14** is not photoemissive. The photoemissive surface **22** may be selected for its sensitivity of any particular wavelength of energy and may comprise any suitable, known photocathode. Examples of known photocathodes are the S–11 photosurface described in U.S. Patent 2,676,282 to Polkosky issued Apr. 20, 1954, and the multi-alkali photosurface described in U.S. Patent 2,770,561 to Sommer issued Nov. 13, 1956. A still further alternative is to deposit photosensitive material on a short section of the envelope wall **12**, adjoining the negative field-shaping electrode **16**, while the balance of the coating **14** is selected for its secondary emissive properties.

During operation of the tube **10**, a potential difference of the order of one thousand volts to several thousand volts, is maintained, by means of an external power supply **23**, between the ends of the resistive coating **14** adjacent to the two field-shaping electrodes **16** and **18**. In other words, the end of the coating **14** adjacent to the field shaping electrode **16** is made negative, while that adjacent to field shaping electrode **18** is made positive. The negatively biased end of the resistive coating **14** may be electrically connected to the adjacent field-shaping electrode **16**, and also to the photoemissive surface **22** in certain embodiments. The positively biased end of the resistive coating **14** terminates close to but spaced from the adjacent field-shaping electrode **18** in the embodiment shown in FIGS. 1 and 2. During operation, the electrode **18** functions as an electron collector. A bias voltage is applied, by means of a source **25** which is preferably a direct current source, between the collector and ground through a signal resistance **24**.

The operation of the secondary emissive multiplier tube **10** is as follows:

Electrons are emitted from the photoemissive surface **22** when light **26** is incident thereon. As the electrons travel from their point of origin, the electrons are subject to an electric field which, for the indicated shape of the field-shaping plates **16** and **18** and for a uniform surface resistivity of the coating **14**, is at all points in a tangential direction. The field is illustrated by the radial equipotential surface lines **28** shown in FIG. 1. The electric field deflects the electrons in a direction along the tube wall toward the positive end of the resistive secondary electron emissive coating **14**. Such a path is illustrated by the typical idealized electron paths **30** shown in FIG. 1.

As will be shown in the appendix, the average displacement between the point of origin and the point of impact on the wall is, for a total applied voltage of the order of one thousand volts, approximately ½ radian. Since the coating extends over five radians (i.e. about ⅘ of the tube circumference) the energy of each impact will be about 100 electron volts. For this energy of impact, every primary electron ejects about four secondary electrons from a good secondary emitting surface. These four secondary electrons travel, on the average, another half radian, toward the collector electrode **18** before they impinge on the surface **14** to produce some sixteen secondary electrons. Under the indicated circumstances there are thus approximately ten stages of secondary electron multiplication resulting in a total current gain of about one million before the electrons reach the collector electrode **16**. The gain from the tube **10** will be less if the secondary emission factor of the resistive coating **14** is less than that indicated, i.e. less than four. On the other hand, the gain can be increased by increasing the potential applied between the ends of the resistive coating **14** since this increases both the energy of impact and the number of stages of multiplication.

The three external lead-ins required, namely to the negative or cathode end of the resistive coating **14**, the positive or anode end of the resistive coating **14**, and the collector electrode **18**, may be brought out of the tube **10** by any conventional vacuum tube base and pin contact arrangement. In the alternative, the lead-ins may be sealed directly through the side of the envelope wall **12**.

As an alternative, to the structure described, i.e., wherein the field-shaping electrodes **16** and **18** are formed as conducting plates or metal sheets, they may be of the form of conductive coatings on insulating plates.

If the electrode structure is open-ended, its length in the direction of the axis of the tube **10** should be at least equal to the diameter of the structure. The reason for this is to insure that the electric fields, near the central portion of the structure, are adequately defined by the field-shaping electrodes **16** and **18** and the resistive coating **14**. When the top and bottom ends of the resistive coating **14** extend to a point close to the axis of the tube **10**, i.e. along the top and bottom ends of the inner surface of the envelope in the position shown in FIG. 2, the height of the structure can be substantially less.

Referring now to FIG. 3, there is shown another embodiment of this invention. In this embodiment, a tube **40** is provided which differs from the embodiment shown in FIG. 1 in that a fine mesh screen **42** is provided in front of the positive field-shaping electrode **44**. The electrode **44** may be connected to the positive end of the resistive secondary emissive coating **14**. With a signal resistance and a bias supply V_1 the mesh screen **42** then functions as collector electrode during tube operation.

In the embodiment shown in FIG. 4, a solid collector electrode **50** is used. The collector electrode **50** is supported in front of a positive field-shaping electrode **52**. In this embodiment the positive field-shaping electrode **52** may be connected directly to the positive end of the resistive secondary emissive coating **14**.

Referring now to FIG. 5, there is shown a further embodiment of this invention wherein the envelope wall itself is pushed inwardly to form a V-shaped wedge **58**. The field-shaping electrodes **60** and **62** are then formed as separate conductive coatings, e.g. conductive tin oxide, on the wedge **58**. As shown in this embodiment, a photocathode **64** may be deposited adjacent to the negative field shaping electrode **60** and a different material used for the resistive secondary emissive coating **66**.

Referring now to FIG. 6, there is shown another embodiment of this invention which comprises a mosaic **70** of minute, conducting, secondary emissive elements deposited on a resistive surface film **72**. One of the advantages of this configuration is that no potential gradient exists within the secondary emissive elements of the mosaic **70** i.e., the gradient is in the resistive film **72**. One example of a secondary emissive mosaic **70**, as well as a photo-emissive mosaic, is the conventional mosaic used in an iconoscope type camera tube. Such a mosaic is conventionally made of cesium-activated globules of oxidized silver, in a known manner. The resistive film may, as an alternative, be made of cesium-activated patches of antimony evaporated through a fine mesh.

It should be clearly understood that the embodiment of the resistive film with a secondary emissive mosaic coating, such as that shown in FIG. 6, may be used with any of the structures shown and described in connection with FIGS. 1 through 5.

A magnetic field and/or an alternating polarity source are not required for tube operation. As will be shown in the appendix, tubes made in accordance with this invention are more efficient than those operated in a magnetic field. Thus, tubes made in accordance with the teachings of this invention are economical to construct and operate.

It should be clearly understood that the following appendix is for the purpose of explaining what is believed to be the theory of operation of the tubes described hereinabove. Thus, the invention should not be limited by any assumptions which are made in the appendix to explain this theory.

APPENDIX

The potential variation along the resistive coating **14** within the structure **10** is given by

$$\phi = K\theta$$

where ϕ is the potential measured with respect to the potential of the cathode, or negative end of coating **14**, as zero; θ is the azimuthal angle measured from the cathode toward the anode, or positive, end of coating **14**; and K is potential gradient applied to the resistive coating **14** in terms of volts per radian. The equations of motion of the electrons in this field are given by

$$\ddot{r}=r\dot{\theta}^2 \quad \frac{1}{r}\frac{d}{dt}(r^2\dot{\theta})=\frac{e}{m}\frac{K}{r} \quad \ddot{z}=0$$

Here, dots indicate differentiation with respect to the time t; r is the radial coordinate measured from the tube axis; $-e/m$ is the specific charge of the electron; and z is the longitudinal coordinate, measured parallel to the tube axis. After integration of the second equation, and substitution in the first, the following is obtained

$$\ddot{r}=\frac{1}{r^3}\left(\frac{eK}{m}\right)^2\left(t+\frac{mr_0^2}{eK}\dot{\theta}_0\right)^2 \quad \dot{\theta}=\frac{eK}{mr^2}t+\frac{r_0^2}{r^2}\dot{\theta}_0 \quad z-z_0=\dot{z}_0t$$

Here r_0, θ_0, z_0 represent the initial coordinates of the electron (at its point of emission from the inner wall of the tube) and $\dot{r}_0$, $r_0\dot{\theta}_0$, $\dot{z}_0$ its initial velocity components (at time $t=0$). The first two equations are readily solved for zero azimuthal initial velocity component ($\dot{\theta}_0=0$) if, furthermore, r on the right sides of the two equations is replaced by its initial value r_0. A more careful analysis shows (1) that the azimuthal initial velocity component plays a minor role in determining the point of impact and (2) that the electrons experience on the average a maximum radial displacement of only about 5 percent of the radius, justifying the second step. With these assumptions it is found that

$$r=\dot{r}_0t+\frac{t^4}{12r_0^3}\left(\frac{eK}{m}\right)^2 \quad \theta-\theta_0=\frac{eK}{2mr_0^2}t^2$$

The first equation shows that the electron returns to the wall (i.e. regains the value $r=r_0$) for

$$t=r_0\left[-12\dot{r}_0\left(\frac{m}{eK}\right)^2\right]^{1/3}$$

The azimuthal displacement of the electron between emission and impact thus becomes

$$\theta-\theta_0=\left[36\left(\frac{V_r}{K}\right)\right]^{1/3}$$

if the electron energy associated with its radial velocity of emission is

$$eV_r=\frac{m\dot{r}_0^2}{2}$$

For secondary electrons, the average total energy of emission is about 2 electron volts; half of this is associated with the radial component of velocity. Thus, writing, for V_r, 1 volt and, for K, 200 volts per radian, we find for the azimuthal displacement of the electrons between impacts

$$\theta-\theta_0=0.56 \text{ radian}$$

since this displacement varies only as the third root of the energy of emission and the applied potential gradient, it departs relatively little from the above value within the practical range of operation of the secondary-emission multiplier.

Substituting the same transit time in the expression for z leads to

$$\frac{z-z_0}{r_0}=3.6\frac{V_z^{1/2}V_r^{1/6}}{K^{2/3}}$$

where $eV_z=m\dot{z}_0^2/2$ is the energy of emission associated with the longitudinal component of initial velocity. Setting its average value equal to 0.5 electron volt, that of eV_r equal to 1 electron volt (in harmony with a total energy of emission of 2 electron volts) and K equal to 200 volts/radian, leads to

$$\frac{z-z_0}{r_2}=0.074$$

The average displacement for n stages of multiplication is obtained by multiplying this quantity by the square root of the number of stages. For 10 stages this average displacement is seen to amount to 23 percent of the radius of the cylinder wall.

Gain modulation by a magnetic field parallel to the axis

The gain of the multiplier can be effectively modulated by immersing it in a solenoid. The equation of motion of the electrons in the presence of a field B become

$$\frac{1}{r}\frac{d}{dt}(r^2\dot{\theta})=-\frac{e}{m}\frac{K}{r}+\frac{eB}{m}\dot{r}$$

$$\ddot{r}=r\dot{\theta}^2-\frac{e}{m}Br\dot{\theta}$$

The integration of these equations e.g. for $B=28.5$ gauss, $K=200$ volts/radian for an initial radial energy of emission of 1 electron volt shows that the distance between impacts is more than quadrupled in the presence of the field. Since the gain per stage for a good secondary emissive surface is increased at the same time only from about 4 to 8, the total gain can be expected to be decreased by nearly four orders of magnitude. The field required for this gain modulation would be produced by a coil with about 56 ampere turns per inch.

What is claimed is:

1. A photomultiplier tube comprising:

(a) a hollow substantially cylindrical envelope;

(b) a continuous coating of resistive secondary emissive material on the inner wall of said envelope extending over most of the inner circumference of said envelope;

(c) a pair of field forming electrodes each extending radially from said envelope wall substantially to the axis of said envelope;

(d) and a coating of photo-emissive material on a portion of one of said field forming electrodes.

2. A multiplier tube comprising:

(a) an elongated tubular evacuated envelope having a substantially cylindrical inner surface;

(b) a continuous resistive secondary emissive coating on the major portion of said inner surface; and

(c) a pair of field forming electrodes in said envelope;

(d) each of said field forming electrodes extending radially from a region close to a different end of said coating substantially to the axis of said inner surface;

(e) one of said field forming electrodes having thereon a coating of photoemissive material.

3. A multiplier tube as in claim **2** wherein said means has a resistivity within the approximate range of 10^5 to 10^{10} ohms.

4. A photomultiplier tube comprising:

(a) an elongated tubular envelope having a substantially circularly cylindrical inner surface;

(b) said envelope including a pair of end members each closing a different end of said elongated tubular envelope;

(c) a pair of field forming electrodes within said envelope;

(d) each of said field forming electrodes extending radially from said inner surface of said envelope substantially to the axis of said envelope;

(e) each of said field forming electrodes also extending substantially from one of said end members to the other of said end members;

(f) a continuous resistive secondary emissive coating on said inner surface of said envelope;

(g) said resistive coating extending substantially from one of said field-shaping electrodes to the other of said field-shaping electrodes;

(h) said resistive coating also extending from said inner surface of said envelope over at least a part of each of said end members; and,

(i) a photoemissive coating in said envelope.

5. An electron multiplier tube adapted for use without a magnetic field, comprising:

(a) an insulating support having a substantially cylindrical inner surface;

(b) a continuous resistive secondary emissive layer on the major portion of said inner surface;

(c) means for establishing a potential gradient from one end of said layer to the other end thereof;

(d) a pair of field-forming electrodes each extending radially from a region close to a different end of said layer substantially to the axis of said surface;

(e) said field forming electrodes being connected respectively to the ends of said layer; and

(f) a collector in front of and insulated from the positive one of said electrodes.

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