Oct. 9, 1962 J. H. COLEMAN 3,058,022

PHOTOELECTRIC GENERATOR

Filed April 14, 1959 2 Sheets-Sheet 1

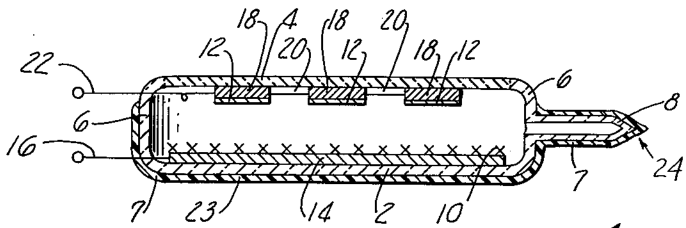

Fig. 1

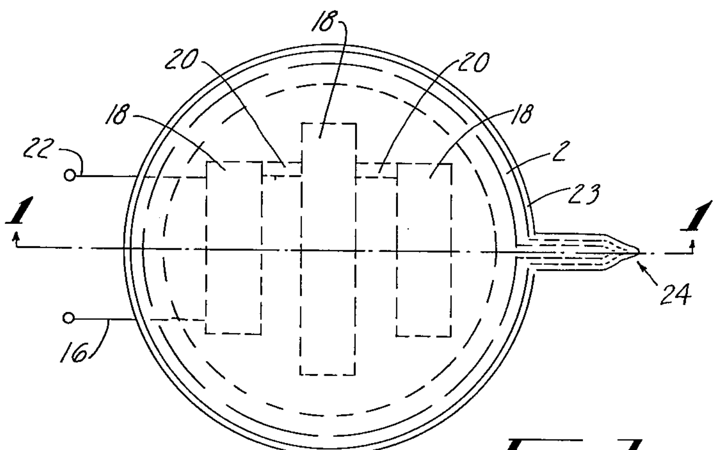

Fig. 2

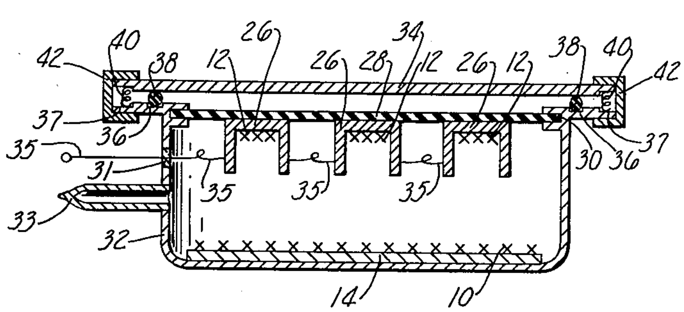

Fig. 3

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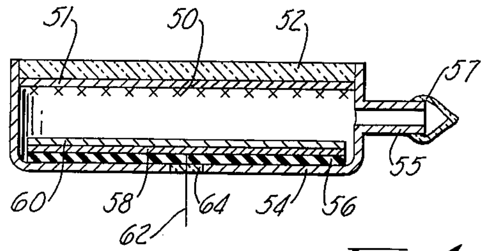

Fig. 4

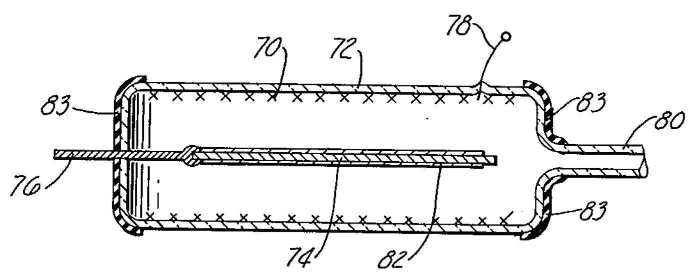

Fig. 5

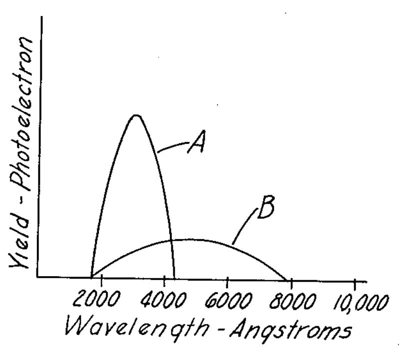

Fig. 6

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PHOTOELECTRIC GENERATOR

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This invention relates to new and improved electric generators employing the photoelectric effect. More specifically it relates to electric generators in which electrons, emitted by a photosensitive surface, are collected and made available as useful power.

It is well known that certain low work function surfaces have the characteristic of emitting electrons when exposed to radiation in the visible and ultraviolet regions of the light spectrum. The magnitude of the emitted photoelectric current is proportional to the intensity of the illumination, while the maximum velocity of the emitted electrons is independent of the intensity, but proportional to the frequency of the illuminating radiation. Since each material also has a characteristic binding energy or work function which must be overcome in order to cause release of photoelectrons, it also has a characteristic minimum, or cut-off, frequency of illuminating radiation below which incident irradiation will not excite photoemission.

In the past, advantage has been taken of these characteristics to fabricate photocells (or phototubes) having a photosensitive cathode and an anode to which an external potential is supplied. Upon illumination of the cathode, photoelectrons are emitted, which, in one type of tube, are electrostatically attracted through an evacuated space to the anode where they are collected and flow through the external circuit. Since the amount of current flowing in the external circuit is related to the intensity of illumination, the phototube may be used to measure the intensity of light falling upon its cathode.

In distinction to the aforementioned use made of the photoelectric effect, this invention utilizes electrons, photoelectrically emitted into an evacuated space and collected on a low-work function anode, without resort to an external source of electrical power. More specifically, advantage is taken of the fact that a large number of the electrons emitted by photoelectric excitation of a relatively low-work function cathode surface will have sufficient kinetic energy to develop a potential on a collector electrode surface and to supply power to an external circuit. It is one feature of the invention that the collector electrode surfaces used have very low work functions and that the emitter surface has a somewhat higher work function, so that the contact potential difference between the two materials serves to accelerate electrons emitted from the higher work function surface toward the lower work function surface, thus enhancing the output power. It is still another feature of the invention that losses due to photoelectrons emitted by the low work function collector surface (which, when exposed to the same radiation, is an inherently superior photoemitter than the higher work function emitter surface) are minimized by preventing the direct incidence of light upon the collector surface so that a net flow of electrons to the collector surface is assured.

These and other features of the invention will become clearer to the reader from the below appended description together with the attached drawings in which:

FIG. 1 is a view in cross-section of one embodiment of the invention;

FIG. 2 is a plan view of the embodiment of FIG. 1;

FIG. 3 is a view in cross-section of an alternative embodiment of the invention;

FIG. 4 is a view in cross-section of a third embodiment of the invention;

FIG. 5 is a view in cross-section of a fourth embodiment of the invention employing the mode of operation illustrated in FIG. 4; and

FIG. 6 is a chart showing the relative spectral sensitivities of the source and collector surfaces of the structure of FIG. 1.

Referring now to FIGS. 1 and 2, a photoelectric converter according to the teachings of the invention is assembled in shallow, dish-like enclosure **2**, which may be of glass, having light transparent cover **4** hermetically sealed to enclosure wall **6**. Glass tubulation **8** is sealed into wall portion **6** and provides means for evacuating the space within the enclosure. The principal electrodes of the photoelectric generator comprise photoemissive surface **10** supported on the large area inner surface of enclosure **2** and plural collector surfaces **12** on the inner surface of cover **4**.

Photoemissive surface **10** may comprise, for example, a thin layer of cadmium which has an intermediate value of work function ($\Phi=4$ electron volts). Photoemissive surface **10** may be applied to emitter supporting electrode or substrate **14** in such a way as to be relatively non-reflecting by evaporating it onto substrate **14** through a gaseous atmosphere, such as argon at 10 mm. of mercury. Alternatively, the gaseous atmosphere may comprise an oxygen containing mixture, such as air, in which case oxidation of the cadmium reduces the emitter surface work function to the neighborhood of 3 volts while, at the same time, production of a smooth, highly reflecting surface is avoided. As will be understood, the low reflectance collector surface may also be produecd by sintering finely divided surfacing material to the support, or by roughing the surface of the bulk metal by sandblasting, for example. Emitter support electrode **14** may, of course, be of a high work function metal, such as gold or platinum, evaporated on the bottom portion of the enclosure **2**.

The anode, or collector structure, utilized in this embodiment of the invention includes thin strips of silver **18** evaporated on the inner surface of transparent cover plate **4**. The work function of the surfaces of strips **18** facing photoemissive electrode **10** is lowered by oxidation and subsequent application of cesium coatings **12** in a manner well understood in the art. In this way, cesium-oxide-silver collector electrode surfaces **12** achieve a work function of the order of 1.6 electron volts which is somewhat lower than the work function of 2 electron volts for pure cesium. The ideal radiation response curve of collector surface **12** is shown by curve B of FIG. 6. The yield is seen to be low to reduce back current excited by reflected light but the threshold wavelength is preferably long (infra-red) corresponding to a low work function, in contrast to the high yield of emitter **10** (curve A).

The silver supporting layers of collector electrodes **18** are made sufficiently thick to limit oxidation of the silver to the cesium layer interfaces, thereby providing highly reflecting surfaces at the interfaces between the silver and the transparent cover plate **4**. In this way the collector electrode structure is made relatively insensitive, photoemission-wise, to incident light passing through cover plate 4, since, first, this top surface is an efficient reflector substantially preventing the transmission of light to the photosensitive surface and, at the same time, minimizing heating of the photosensitive surface so as to prevent thermionic emission; second, the silver supporting layer has a high work function and is therefore a photoemitter only in the ultraviolet portion of the spectrum; and third, little light can be transmitted through the thickness of the supporting layer to the low work function collector surface layer.

Transparent cover plate **4** should be made of a material having a good vacuum characteristic which is capable of transmitting radiation of short wavelengths. For example, lime glass may be used for cover plate **4** and other parts of enclosure **2** but this glass does not transmit wavelengths below approximately 2800 angstroms. Since oxidized cadmium is responsive only to radiation of wavelength less than about 3100 angstroms, quartz should be used for cover plate **4** since it transmits radiation wavelengths down to approximately 1800 angstroms and therefore an increased output current is obtained. When quartz is used for cover plate **4** in conjunction with a glass such as Pyrex for enclosure **2**, it will, of course, be necessary to employ a graded seal between the quartz and Pyrex in a manner well known in the art. Enclosure **2** may also be fabricated from metal, giving due consideration to the expansion coefficients of the cover plate material and of the metal of the enclosure. In order to minimize emission by collector surface **12** when an all glass enclosure is used (as shown), the exterior surfaces of enclosure **2** and side wall **6** are covered with an opaque coating **7**.

Interconnection between collector electrode substrates **18** may be provided by means of conductive strips **20** which may be narrow, light-transmitting bands of silver as shown, or thick, broader bands covered, as above, with low work function material to provide added collector surface. Connection between collector electrode substrates **18** and the exterior of the device is made by means of connecting lead **22** sealed through glass wall **6** and connected on the interior thereof to the interconnected collector structure in a manner well known in the art.

In operation, light incident upon transparent cover plate **4** is transmitted through the portions thereof which are not covered by the collector structure to strike upon photoemissive surface **10** which emits photoelectrons. If transparent cover plate **4** is made of quartz, photoelectrons are ejected from cadmium-oxide surface **10** by light of all wavelengths in the range between approximately 1800 angstroms, the wavelength at which quartz transmission cuts off, and approximately 4100 angstroms, the long wavelength limit of photoemission by cadmium. The cesium-oxide-silver collector surface is also sensitive to radiation of wavelenths as long as about 7800 angstroms, since it has a lower work function but, due to the shielding action of the higher work function silver substrate on which it is formed, it is screened from direct exposure to the radiation and is exposed only to light reflected from the inner surfaces of the structure. Collector electrode surfaces **12** therefore emit few photoelectrons in comparison to the number emitted by photoemissive surface **10**. In addition, when the photoemissive (cathode) surface is made of cadmium-oxide and the collector electrode surfaces are of cesiated silver-oxide, as in the illustrative embodiment, the contact potential difference between these materials produces an effective difference of potential between their respective cathode and collector electrode surfaces which accelerates the photoemitted electrons from the cathode surface. The initial kinetic energies of the electrons are thus increased by the difference in contact potential of about 1.4 electron volts, for the specified materials. Since the number of photoelectrons emitted by cadmium photoemissive surface **10** is much greater than the number of photoelectrons emitted by cesium collector surface **12**, the result is a net gain in negative charge by collector electrode **12**. The resultant difference of potential between emitter and collector surfaces may be applied to a useful load by means of connecting leads **16** and **22**.

A wide variety of emitter and collector surface combinations may be used in the structure of FIG. 1 with emitter work function being greater, less, or equal to the collector work function. It will be apparent however, that the difference of contact potential aids the output only when the work function of the emitter surface is maintained higher than that of the collector surface as in the above described embodiment of the invention. In addition, the emitter surface should have as high a yield and as low a work function as possible so as to utilize the longer wavelengths ordinarily available in solar radiation and thereby increase output current.

It is to be understood, however, that when maximum output power, maximum internal resistance, or maximum output voltage are the most desired characteristics, the larger differences of potential produced by using higher work function emitters can be significant. Thus, since power is the product of current and voltage, and internal resistance is the quotient of voltage divided by current, the loss of power resulting from the use of a narrower band of illuminating wavelengths may be more than offset by the gain resulting from the increased contact potential difference produced by a higher work function emitter. For example, an alkali metal such as sodium, which photoemits under radiation shorter than about 5800 angstroms corresponding to a work function of about 2.2 electron volts could be used as the emitter along with a cesium collector surface. Although the sodium emitter would respond to a larger fraction of the incident radiation energy, a decrease in output voltage would be realized with a cesium collector electrode surface since the difference in contact potential between sodium and cesium-oxide-silver is about 0.6 electron volts. While the current output of the device would be higher, assuming comparable yields, because of the larger fraction of incident solar energy utilized, the output voltage would be lower, as would the output impedance. Other metals whose work function is similar to cadmium when oxidized are zinc and antimony. Cerium and thorium are also suitable materials having comparable work functions. The alkali metals and alkali earths which have relatively low work functions (less than about 2.6 ev.) are not preferred emitter materials unless lowest internal resistance is required. In this event, in addition to sodium, lithium, potassium, rubidium and cesium can be used. Calcium, barium and strontium are also suitable. In most cases oxidation of the metal of the emitter surface increases the emission, although for maximum yield there should be a monolayer of pure metal on the surface of the oxide. In some cases, the action of the radiation is sufficient to produce this type of activation of the emitter surface, presumably by diffusion of a monolayer of metal to the surface of the oxide. As oxidation usually increases the wavelength of the threshold as well as yield, these factors should be considered in selecting materials to give particular electrical characteristics.

On the other hand, output voltage is enhanced by using materials having lower work functions for the collector surface. Alkali metals and their compounds have the lowest work functions of the chemical groups. Compounds such as $(NaK)_3Sb$ with a surface layer of cesium are known to have a work function of about 1.3 volts. However, the high photoelectron yield of this surface when so activated would offset the 0.3 volt increase in output voltage unless maximum internal impedance is required. Again the selection of materials will depend upon the desired output voltage per cell, the desired internal impedance and will be affected by problems of compatability of materials and fabrication techniques as will be understood by those skilled in the art.

The device illustrated in FIG. 1 has utility as an electrical generator either on the surface of the earth or in the vacuum of outer space. Should it be used in the latter environment, it will be understood that tubulation **8**, through which evacuation of the hermetically sealed enclosure **2** is evacuated, need not be closed, as would be the case if the device were used in the earth's atmosphere. Indeed, the vacuum of outer space is superior to that which may be achieved and preserved within the container in the earth's atmosphere by normal vacuum techniques. In the natural environment of outer space, contamination of the sensitive emitter and collector surfaces by the accidental leaks and slow outgassing encounted in earthbound vacuum devices may be eliminated. To take advantage of this fact, tubulation 8 (of the structure of FIG. 1) is provided with frangible glass tip 24 which may be broken easily upon arrival of the generator in space (as by impact from a released spring). Thus, if used in the environment of outer space, generator reliability far in excess of that possible in a terrestrial environment may be attained.

When the device is intended for space use, it may be tested in the earth's atmosphere while attached to the vacuum system employed for fabrication and then filled with an inert gas to reduce contamination of the collector and emitter surfaces by gases evolved from the envelope and other parts of the generator structure during storage. With some surfaces, such as those employing potassium, the use of hydrogen as a fill during storage may be preferable because of its beneficial effect. The gas fill, which may be at any suitable pressure, such as atmospheric, will, of course, be released when the generator arrives in space and frangible tip-off 24 is broken, and the generator will then operate with the vacuum of outer space.

The undesirable effects of incident light upon photosensitive collector surfaces may be further reduced by means of the structure shown in FIG. 3. In this embodiment photoemissive surface 10 is mounted on an emitter electrode 14, as was the case with the structure of FIGS. 1 and 2. Collector electrode surfaces 12 are, as before, mounted facing photoemissive surface 10, but are deposited in the form of striplike layers in the recesses provided by channel members 26 which now form collector electrodes. Channel members 26 are made of a material having a very high work function so as to produce a minimum number of electrons in response to incident radiation. Channel members 26 are maintained in position by fastening them to one or more narrow, dielectric strips 28 which are transversely supported in suitable recesses 30 on the inner surface of box-like metal enclosure 32. Electrical connection to collectors 12 is made by means of interconnecting leads 35 between channel members 26, the connection being completed through the wall of enclosure 32 by lead 35 sealed in glass eyelet 31. The side portions of each channel member 26 project away from the bottom interior portion holding the collector surface 12, thereby reducing the area of photoemitter 10 from which light is received by collector surface 12, and screening the surface from other, undesirable light. Because of the high work function of the channel member structures and because of the low work function of collector surface 12, an electrostatic lensing action is attained which directs photoelectrons emitted by emitter surface 10 to the collector surface 12. It will be apparent to those skilled in the art that the configuration, and more particularly, the depth and width of the recess of each channel member must be carefully selected for the desired operating potentials so as to avoid closing the electron lens against the incident photoelectrons. Thus the collector efficiency is increased because current loss from the collector surface due to light incident thereon is reduced, reducing also any undesirable side effect, such as increased space charge, etc.

FIG. 3 also illustrates an alternative manner of enclosing the invention for use particularly when the photoelectric generator is intended for use in outer space. For this purpose, removable wall member 34 is provided which cooperates with enclosure 32 to prevent contamination of the sensitive emitter and collector surfaces by the earth's atmosphere. To this end, enclosure 32 is provided with grooved flange 36 for receiving gasket or O ring 38 and peripheral surfaces 37 for seating cover release springs 40. Cover plate 34 may be of metal or it may be light transmitting so as to provide for operation in the earth's atmosphere. Cover plate 34 is held against O ring 38 by means of a number of peripherally distributed U-shaped clips or clamps 42 each of which is adapted for ready removal by means not shown, such as an explosive link, upon passage of the vehicle carrying the generator out of the earth's atmosphere. The hermetic enclosure thus provided is conventionally evacuated by means of pinch-off tubulation 33, the vacuum so provided being maintained by means of hermetic gasket 38. Upon arrival in outer space, closure member 34 is ejected from its seated position on gasket 38 by the removal of retaining clips 42 and the consequent release of springs 40. Removal of cover plate 34 permits the full spectrum of light to fall directly onto photoemissive surface 10 and the structure is thus capable of utilizing those high energy, short wavelengths not ordinarily transmitted by glass, quartz, or other materials, achieving a higher overall conversion efficiency. In addition (as was the case with the structure of FIG. 1), occluded gases are free to escape from the internal components of the device, prolonging life.

In the embodiment of the invention shown in FIG. 4, the shadowing effect of emitter layer 50 and conductive substrate 51 carried upon the inner surface of transparent cover plate 52 is used to reduce the effect of light incident upon oppositely disposed collector surface 60. Transparent cover plate 52 is hermetically sealed to the rim of pan-shaped, metal enclosure 54 with proper attention to expansion coefficients. For external evacuation, laterally projecting tubulation 55 is provided with glass tip-off 57. As was the case with the structure of FIG. 1, tip-off 57 may be made frangible for access to the outer space environment. The inner, flat, bottom surface of metal enclosure 54 is provided with dielectric collector electrode support 56 which, in turn, supports collector electrode 58. Electrode 58 need not be of a high work function metal since it is not exposed directly to solar radiation. Finally, the surface of collector electrode 58 facing transparent cover 52 is covered with a layer of low work function material 60 of a nature already described. Collector connecting lead 62 is brought out directly from collector electrode 58 through dielectric layer 56 by means of glass eyelet 64 hermetically sealed in the wall of metal enclosure 54. Connection to the emitter is made by means of metal enclosure wall 54, since emitter surface 50 and conductive substrate 51 are extended thereto. Conductive substrate 51 is utilized with emitter surface layers which, in themselves, have poor conductivity and therefore introduce undesirable losses into the generator system. To achieve this end without undue sacrifice of light transmission, gold, silver, platinum or other high work function metals may be laid down on the surface of glass face plate 52 in thicknesses of a few molecular layers. Photoemissive surface 50 is made sufficiently thin to cause efficient inward emission of photoelectrons from its free surface but is sufficiently thick to absorb most of the light transmitted to it by transparent cover plate 52, so that a significantly small proportion of light is transmitted to the collector surface. In this way the quantity of electrons emitted by collector surface 60 as a consequence of photoelectric excitation is significantly reduced in comparison to the number emitted by emitter surface 50. When cadmium is used for emissive layer 50, conductive substrate 51 comprises a few monolayers of platinum evaporated on the face of cover plate 52. Cadmium is then evaporated onto the surface of the platinum through 10 mm. of air, until the film is 95–99% absorbing to frequencies in its sensitive range. The cadmium thickness may be controlled during deposition by measuring transmitted light and evaporating until the desired absorption figure is obtained. Collector surface 60 can be cesium oxide-silver on a silver substrate prepared in a similar manner to that described in connection with FIG. 1. This combination, as before, develops an output voltage of about 1.4 volts, the difference in work functions of the cadmium-oxide emitter and cesium-oxide-silver collector. It will be noted that, unless special precautions to be described below are taken, a significant fraction of the radiation band between 4100 angstroms, the cut-off wavelength of the emitter, and 7800 angstroms, the cut-off wavelength of the collector, will pass through emitter surface 50 and excite photoemission from the collector surface. This is because the optical absorption coefficient of the emitter surface varies with frequency in a manner similar to ordinary photoelectric response, the light energy not utilized in the photoemission process being transmitted.

To reduce this emission from the collector, which reduces net current flow to the collector, the emitter 50 can be formed by evaporating a layer of antimony and alloying with cesium to form approximately Cs_3Sb. Surfaces of this type have a cut-off approximately the same as the cesium-oxide-silver but have a higher photoelectric emission. Because the antimony-cesium alloy is more conducting than the oxide, conducting film 51 can be omitted. The thickness of the cesium-antimony film 50 can be adjusted by absorption of light as before. With the similar work functions of the cesiated emitter 50 and collector 60 the output potential is lower, being the result of the kinetic energy of the emitted photoelectrons only. The current, however, is increased. Any other combination of photosensitive material described previously can be used to give the desired power and impedance.

As an alternative to matching the work function of emitter 50 to collector 60 to reduce emission from collector 60, an optical filter can be placed on the surface of face plate 52, or incorporated therein to absorb the long wavelength radiation beyond cut-off of the emitter 50. A wide variety of materials having characteristics suitable for use with secondary emitters having different cutoffs is available, as will be apparent to those skilled in the art.

FIG. 5 illustrates the application of the shadowing structure shown in FIG. 4 to an embodiment employing cylindrical geometry and an all glass enclosure and which is adapted for use, for example, with all-around illumination such as may be achieved by locating the converter axially at the focus of a parabola. Here, photoemissive layer 70 is deposited upon the inner wall of cylindrical glass ampoule 72. Elongated, cylindrical collector electrode 74 is coaxially positioned within emitter surface 70 by means of coaxial end support 76, hermetically sealed through the end wall of glass enclosure 72. End support 76 is conveniently made of metal, and so serves as an anode connecting lead as well as a mechanical support for collector electrode 74. A separate electrical lead 78 is sealed through the wall of glass enclosure 72 and connects to cylindrical photoemitter layer 70, thus providing the second electrical connection to the device. The opposite end closure of glass enclosure 72 is provided with tubulation 80 through which the device may be evacuated and by means of which it may be sealed off from the atmosphere. Emitter electrode surface 70 and collector electrode surface 82 may be selected according to the principles described in connection with FIG. 4 since they operate in the same manner. The effects of light entering the ends of the ampoule may be eliminated by means of opaque light shields 83 applied thereto by painting, for example.

While the invention has been described in particularity with respect to several embodiments, it will be understood by those skilled in the art that the principles of the invention are capable of wide variation in their application. For example, while the embodiments described have employed particular materials of specified work functions, it will be apparent to those skilled in the art that many other materials may be substituted therefor while following the teachings of the invention. In addition, it will be noted that while it is preferable to utilize materials for the collector surfaces which have lower work functions than the materials employed for the emitter surfaces in order to achieve maximum efficiencies, the structures of FIGS. 4 and 5 are particularly well suited for operation with collector surfaces of higher work function. It will

also be apparent to those skilled in the art that wide latitude exists for variation of the geometry of the collector and emitter surfaces without departing from the teachings of the invention. The below appended claims should therefore be interpreted in keeping with the spirit of the invention, rather than limited to the specific form taken by the illustrative embodiments.

I claim:

1. A photoelectric generator including spaced electrodes having spaced photosensitive emitter and photosensitive collector surfaces, said emitter surface being adapted for exposure to illuminating radiation and means for shielding said collector surface from said radiation.

2. The generator of claim 1 in which said collector surface is interposed between said emitter electrode and the source of said radiation and is shielded from said radiation by an intervening layer of high work function material.

3. The generator of claim 1 in which said emitter surface is interposed between said collector surface and the source of illuminating radiation.

4. The generator of claim 1 including means for hermetically sealing said electrodes in an enclosure with a controlled atmosphere.

5. The generator of claim 1 in which said collector surface comprises an alkali metal.

6. A photoelectric generator including an electrode having a photoemissive surface adapted for exposure to radiation, an electrode having a collector surface with a lower work function than said photoemissive surface disposed opposite said photoemissive surface, and a light barrier on the opposite side of said collector surface from said photoemissive surface.

7. A photoelectric generator including a shallow enclosure member, a transparent cover plate hermetically sealed across the opening of said enclosure member, a collector electrode having a low work function surface carried on the interior of said cover member, an electrode having a photoemissive surface on the inner wall of said enclosure member, and connecting leads for connecting said collector surface and said photoemissive surface to a load.

8. A photoelectric generator including a light-transparent support, an electrode having a photoemissive surface carried by said support, a collector electrode including a photosensitive surface for receiving electrons from said photoemissive surface disposed adjacent to and spaced from said photoemissive surface, and leads for connecting said photoemissive surface and said collector surface to a load.

9. The photoelectric generator of claim 8 in which said collector surface has a lower work function than said photoemissive surface.

10. The generator of claim 9 in which said light transparent support includes an element for substantially preventing transmission of radiation in the band defined by the work functions of said emitter and said collector.

11. The photoelectric generator of claim 8 in which said light-transmitting support is cylindrical, said photoemissive surface is disposed on the interior surface thereof, and said collector surface is coaxially disposed therein.

12. A photoelectric generator in accordance with claim 1, in which said photosensitive surfaces face each other.

13. A photoelectric generator including an enclosure having a light transparent portion, an emitter electrode having a photoemissive surface within said enclosure, a collector electrode including a photosensitive surface for receiving electrons from said photoemissive surface disposed adjacent to and spaced from said photoemissive surface and leads for connecting said emitter and collector electrodes to a load.

14. The generator of claim 13 in which said collector electrode is positioned in said light transparent portion of said enclosure and is constituted by a plurality of

spaced collector electrodes, whereby spaces between said collector electrodes enable light to pass therethrough.

15. The generator of claim 13 in which said collector surface comprises a metal oxide activated by an alkali metal.

16. The generator of claim 13 in which said emitter surface includes an alkali metal.

17. The generator of claim 13 in which said collector surface has a lower work function than said emitter surface.

18. The generator of claim 14 in which each of said spaced collector electrodes is opaque to light and has a high work function surface facing said light transparent portion.

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