Aug. 16, 1966 K. G. HERNQVIST 3,267,308

THERMIONIC ENERGY CONVERTER

Filed July 9, 1963

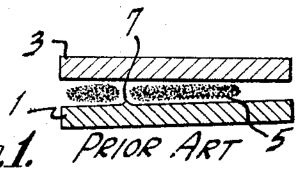


Fig.1.

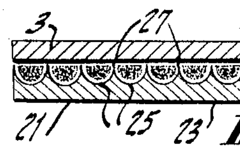


Fig.4.

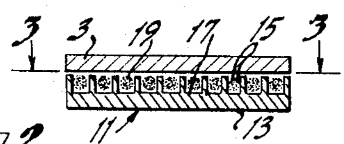


Fig.2.

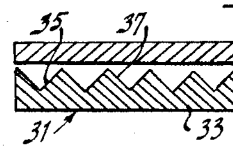


Fig.5.

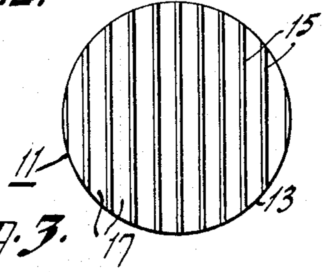


Fig.3.

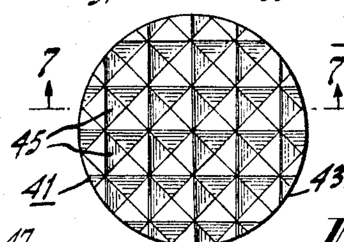


Fig.6.

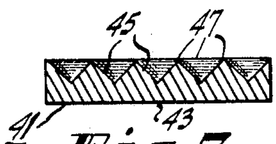
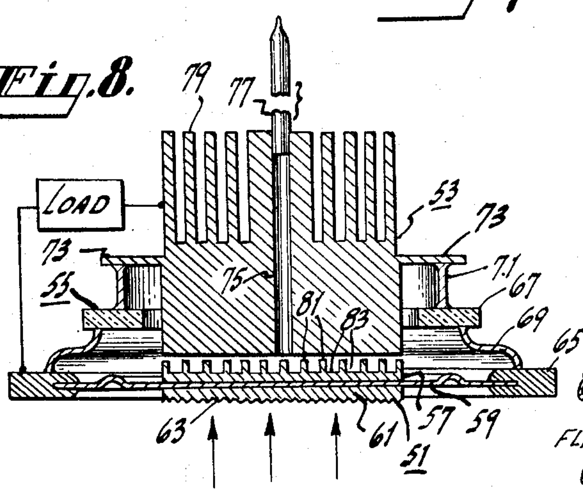


Fig.7.

Fig.8.



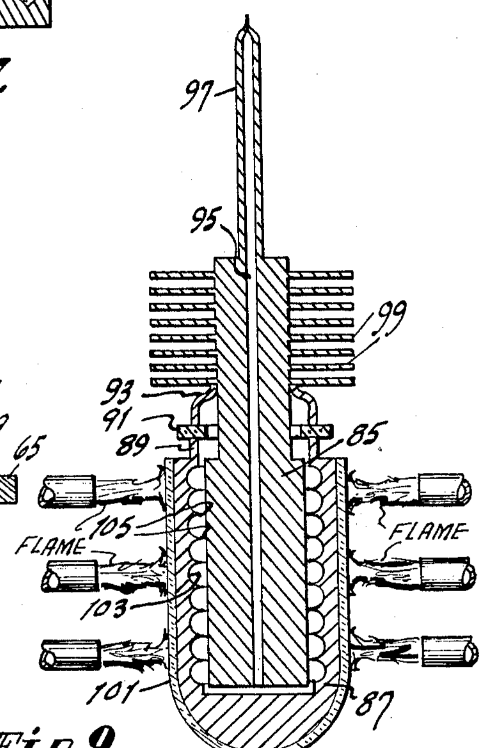


Fig.9.

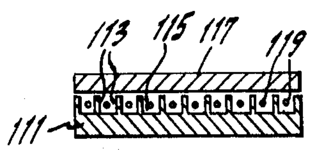


Fig.10.

INVENTOR.

KARL G. HERNQVIST

BY Thomas R. Webb

AGENT

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THERMIONIC ENERGY CONVERTER

Karl G. Hernqvist, Princeton, N.J., assignor to Radio Corporation of America, a corporation of Delaware
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12 Claims. (Cl. 310—4)

The present invention relates to thermionic energy converters, and particularly to an improved high pressure cesium vapor arc mode converter.

A thermionic energy converter is an electron tube, having a cathode and an anode, for converting heat energy applied to the cathode to electrical energy in the form of a voltage produced by the tube itself between the external cathode and anode terminals. A typical thermionic energy converter tube comprises a sealed envelope containing a cathode and an anode spaced apart to provide an electron path therebetween. Usually the cathode and anode form parts of, or are in good heat transfer relation with, the tube envelope, to permit direct heating and cooling, respectively, of these electrodes by external means. The materials of the cathode and anode are usually chosen so that the effective electron work function of the cathode is higher than that of the anode, to produce an internal electric field for accelerating electrons from the cathode to the anode during short circuit condition. Each electron collected by the anode generates heat energy therein of an amount at least equal to the anode work function, expressed in electron volts. The output voltage V is a function of the load resistance R. If the load resistance is such that the surface potentials of the cathode and anode are equal and there is no internal voltage drop, the output voltage is theoretically equal to the difference in work function of the cathode and anode, and the output power, $VI=I^2R$, is a maximum. In order to approach these optimum conditions, it is necessary to neutralize the negative space charge of the electrons by use of positive ions. Such ions can be produced in many ways, the best of which is to introduce an alkali metal vapor, preferably cesium, having a low ionization potential within the interelectrode space.

If the cathode were bare tungsten, for example, having an effective work function (4.5 volts) higher than the ionization potential (3.9 volts) of the cesium, operating at temperatures of the order of 2000° K., the cesium vapor atoms coming into contact with the hot cathode would be ionized by "contact" ionization. For this high temperature mode of operation, the cesium vapor pressure is adjusted, by controlling the temperature of the coldest portion of the tube envelope, to a relatively low value of about 10^{-3} mm. of Hg. In cases where high temperature heat sources are not available, this mode of operation cannot be used.

The same converter tube can be operated in a high-pressure, low-temperature mode known as the "arc mode" or "ball-of-fire mode," in which the cesium vapor pressure is relatively high (10^{-2} to 10 mm. of Hg). At these vapor pressures the tungsten cathode, instead of being bare with a work function of 4.5 volts, is partially coated with an adsorbed layer of cesium vapor which reduces the effective work function of the W–Cs surface and thereby reduces the required operating temperature for copious electron emission. For example, a tungsten surface in a cesium vapor tube having a bulb temperature of 573° K., which corresponds to a vapor pressure of about 1 mm. of Hg, has a maximum emission current density at 1500° K. of about 12 amperes/cm.^{2}, and an effective work function of about 2.3 volts. Since this work function is lower than the ionization potential (3.9 volts) of the cesium vapor, ions cannot be produced by the contact ionization process. Instead, the vapor atoms are ionized in the ball-of-fire mode as a result of a cumulative ionization process involving successive excitations of the atoms by photons and/or electron collisions. For example, the outermost electron in an atom of cesium vapor may be initially excited by a low energy electron or photon to a higher energy state and remain there long enough to be further excited by another electron or photon to the next higher energy state, etc., until it is completely removed from the atom to thereby produce a positive cesium ion. Other electrons, after excitation, return to lower energy states and radiate energy in the form of photons some of which may, in turn, produce excitation of other cesium atoms. Most of these processes involve the two resonance states $6P_{3/2}$ and $6P_{1/2}$. The lifetimes of the various excited states are so short that, for satisfactory operation in the ball-of-fire mode, considerable resonance excitation must be present. Each chain of photon-atom energy transfers should involve a large number of such transfers before it is terminated by a photon being trapped or absorbed by the tube wall, for example.

In operating thermionic energy converter vapor diodes made with planar cathode and anode surfaces in the ball-of-fire mode, it is noted that the glow plasma tends to form as nearly a spherical shape as possible. Moreover, if the electrodes are not uniformly spaced or have surface irregularities, the glow plasma tends to restrict itself to one or more small regions rather than fill up the space between the electrodes. Furthermore, the total emissive area of the cathode is small.

Therefore, the principal object of the present invention is to provide a new and more reliable and efficient thermionic energy converter for operation in the ball-of-fire mode.

In accordance with the invention, the emissive surface of the cathode of a thermionic energy converter vapor diode is formed by an array of similar recesses opening toward the anode. The portions of the recesses forming the side walls of the recesses are located close to the anode, and the width and depth of the recesses are large compared to the minimum spacing between the electrodes. For efficient ion production, the maximum cathode-anode spacing (within the recesses) should be at least ten mean free paths of electrons in the vapor. The recesses may be in the form of parallel grooves of square, semi-circular or triangular cross-section extending in one direction only, or may be egg crate type cells such as those formed by intersecting parallel ribs or vanes on the cathode base. The cathode is maintained at a relatively low operating temperature at which the effective work function of its emissive surface is below the ionization potential of the vapor. The anode is cooled to an operating temperature below that of the cathode at which the effective work function of the anode is below that of the emissive surface. The vapor pressure is preferably in the range from 10^{-2} to 10 mm. of Hg. The converter may be provided with auxiliary electrodes, mounted one in each recess, for initiating, improving or controlling the ball-of-fire operation of the tube.

In the companying drawing:

FIG. 1 is a transverse section view of the electrodes of a known thermionic energy converter diode;

FIG. 2 is a view similar to FIG. 1 of a converter diode embodying one form of the present invention;

FIG. 3 is a plan view of the cathode in FIG. 2, taken on the line 3—3.

FIGS. 4 and 5 are views similar to FIG. 2 of other embodiments of the invention;

FIG. 6 is a plan view of a cathode embodying another form of the invention;

FIG. 7 is a section view taken on the line 7—7 of FIG. 6;

FIG. 8 is a transverse section view of a complete tube structure incorporating the embodiment shown in FIGS. 2 and 3;

FIG. 9 is a similar view incorporating the embodiment of FIG. 4 in a tube with concentric electrodes; and

FIG. 10 is a view similar to FIG. 2 incorporating control electrodes in the recesses.

FIG. 1 shows the cathode **1** and the anode or collector **3** of a known vapor type thermionic energy converter operating in the ball-of-fire mode. As shown, if the emitter and collector surfaces are tilted relative to each other the glow plasma **5** formed therebetween tends to restrict itself to as near a spherical shape as possible, and thus recedes from the closer portions of the electrodes, to a degree dependent upon the vapor pressure. This reduces the amount of electron current that can be delivered by the tube, because of the lack of space charge neutralization in the regions with no plasma. Moreover, projections on the surface of the cathode, such as projection **7** shown, often cause the glow plasma to separate as shown.

FIGS. 2 through 10 show several embodiments of the present invention in which the cathode of the converter is so constructed that the glow plasma is systematically divided into substantially uniform regions which approximate in shape, in either two or three dimensions, the natural spherical shape of the plasma. This is done by providing a cathode surface having an array of substantially identical recesses open toward the anode. In addition to receiving the separate masses of the glow plasma, the recesses provide a substantially greater total emissive area than a planar cathode surface, which results in substantial increase in electron current as well as improved ion production efficiency.

FIGS. 2 and 3 show one embodiment of the invention in which the cathode **11** comprises a circular base **13**, of tungsten, molybdenum or tantalum, having upstanding thin vanes **15** extending across the emissive side thereof to form identical parallel grooves **17**. The upper edges of the vanes **15** should be close to the anode **3**, and the depth and width of the grooves **17** should be large compared to this minimum cathode-anode spacing, in order to divide the glow plasmas into separate regions, one in each groove.

Preferably, the width of the grooves **17** should be about equal to the distance between the bottom of the grooves and the anode, so that the glow plasma can assume substantially a circular cross section, as shown at **19**. It has been found that this distance, D, which is the maximum cathode-anode spacing, is a function of mean free path and cathode temperature, as follows:

$$D=K\lambda \qquad (1)$$

where λ is the mean free path of electrons in the vapor, and K is a factor dependent upon the kind of vapor and the cathode temperature. In general, for efficient ion production, D should be at least ten mean free paths, which determines the minimum practical value for K at about 10. If K is too great, the arc drop, V_{arc} is too high, and hence, the voltage output of the tube is too low. For cesium, Equation 1 can be written as follows:

$$D=0.4K/_{p} \qquad (2)$$

where D is in mils, and p is the vapor pressure in mm. of Hg. For efficient operations, K should be between 10 and 100.

The vanes **15** may be formed by machining grooves **17** in a cathode plate, or may be separate strips of the same material brazed to the base **13** while held in a jig.

In FIG. 4, the cathode **21** comprises a base **23** formed with parallel semi-circular grooves **25** bounded by ribs **27** which extend close to the anode **3**.

In FIG. 5, the base **33** of the cathode **31** has V-grooves **35** forming ribs **37** extending close to the anode **3**.

FIGS. 6 and 7 show a cathode **41** comprising a base **43** formed with a multiplicity of identical cellular recesses **45** in the form of inverted pyramids. The recesses **45** may be formed by a stamping or coining process, or by the electron discharge or "Elox" method. The upper rims of the pyramidal recesses form ribs **47** extending across the base **43** parallel to the two major axes in FIG. 6. By use of a multiplicity of cellular recesses that are symmetrical with respect to both major axes, as distinguished from the elongated grooves in FIGS. 2–5, the glow plasma is divided into a like multiplicity of nearly-spherical masses of uniform size and shape when the cathode **41** is mounted close to the anode.

It will be understood that other forms of cellular recesses can be used, such as egg-crate type recesses produced by adding a second set of parallel vanes at right angles to the vanes **15** in FIGS. 2 and 3, or by forming a multiplicity of similar cylindrical or hemispherical depressions in the cathode base.

FIG. 8 shows an example of the embodiment of FIGS. 2 and 3 incorporated into a complete tube structure. The tube, which has circular symmetry about the central axis of the cathode and anode, comprises a cathode **51**, an anode **53**, and a vacuum-tight envelope structure **55** mechanically connecting the two electrodes in electrically insulated relation. The cathode and anode form parts of the overall envelope of the tube, thus making it possible to both heat the cathode and cool the anode by external means.

The cathode **51** shown comprises a molybdenum disc **57** brazed to a thin tantalum supporting disc or ring **59**. If desired, a massive disc **61** of molybdenum may be brazed to the outer surface of the disc **59** to obtain more uniform temperature distribution over the cathode surface. The disc **61** may be serrated, as shown at **63**, to increase the surface area receiving heat. The outer periphery of the disc **59** is brazed to a copper ring **65** which serves as the cathode output terminal of the tube. The thin tantalum disc **59** serves as a heat dam for minimizing heat loss from the cathode disc **57**.

The envelope assembly **55** comprises a ceramic ring **67**, e.g., of alumina, to opposite sides of which are bonded, by a conventional ceramic-to-metal braze, two Kovar rings **69** and **71**. Ring **69** is brazed to terminal ring **65**, while ring **71** is brazed to an outwardly extending flange **73** on the anode **53**. All of the joints between elements **59**, **65**, **69**, **67**, **71**, and **73** are made vacuum tight.

The anode **53** is made of copper and formed with a hole **75** in the outer end of which is brazed a tube **77** which serves as both an exhaust tubulation and a cesium reservoir. The anode **53** may be cooled to the desired operating temperature by external heat radiating fins **79**, or by other means. The outer end of the cesium supply tube **77** is cooled to a temperature substantially lower than that of the anode to maintain the desired cesium vapor pressure within the envelope, since the cesium condenses on the coolest portions of the interior envelope surface. The length of the tube **77** may be designed for given cathode and anode temperatures so that the outer end will be cooled by radiation alone to the bulb temperature determining the desired cesium vapor pressure.

The cathode disc **57** is provided with upstanding thin vanes **81** forming parallel grooves **83**, like the vanes **15** and grooves **17** in FIGS. 2 and 3. For example, in a tube designed to operate in the ball-of-fire mode at a cesium vapor pressure of 1 mm. of Hg and a cathode temperature of 1500° K., the vanes may have a width (or height) of 25 mils, be spaced 5 mils from the anode **55**, and be spaced apart 30 mils. In this example, distance D of Equation 2 is 30 mils and K is about 80. At this vapor pressure and cathode temperature, the cesium coverage of the emissive surface produces an effective work function ϕ_c of about 2.3 volts. With this vapor pressure, if the anode temperature is 825° K., the effective work function ϕ_a of the cesium-copper collector surface is about 1.7 volts. The voltage output of the tube with an optimum load is approximately

$$(\phi_c - \phi_a) - V_{arc}$$

where V_{arc} is the arc drop in the interelectrode space. V_{arc} is usually about 0.3 volt, thus the output voltage in the example given would be about 0.3 volt. However, the current output is relatively high, of the order of 100 amperes for a cathode having a total area of 3 square inches, in which case the tube can deliver about 30 watts of power to a matched load. The voltage and power output can be multiplied by connecting tubes in series.

FIG. 9 shows a concentric diode tube structure having a molybdenum cathode embodying grooves similar to the grooves in FIG. 4. The tube comprises a cylindrical anode **85** surrounded by a hollow cylindrical cathode **87**. A tubular metal extension **89** of the cathode is brazed to a ceramic insulator ring **91** which, in turn, is brazed to a metal ring or flange **93** mounted on the anode **85**. The anode **85** is formed with a bore **95** and tubular extension **97** for evacuating and supplying the tube with cesium, as in FIG. 8. Cooling fins **99** may be provided on the anode **85**. Since it has been found that gases can permeate most metals at the high cathode temperatures involved in thermionic energy converter tubes, the major portion of the outside of the cathode **87** is provided with a fired coating **101** of a ceramic material such as alumina which not only seals the metal cathode gas tight but also provides a path of high heat conductivity from the external flame or other heat source to the cathode **87**.

The inner surface of the cathode **87** is provided with annular grooves **103** of semi-circular cross section bounded by annular ribs **105** positioned close to the anode **85**, like the linear grooves **25** and rigs **27** in FIG. 4.

In operating diode converters, such as those shown in FIGS. 1–9, in the ball-of-fire-mode it is sometimes necessary to start the operation by ionizing the vapor by some other means. For example, a voltage greater than the ionization potential of the cesium can be applied between the cathode and anode to initiate an arc discharge in the tube. Once a discharge is established, the voltage can be removed and the tube will operate thereafter in the ball-of-fire mode.

FIG. 10 shows a modification comprising a cathode **111**, having elongated vanes **113** forming grooves **115**, and an anode **117** close to the edges of the vanes, as in FIGS. 2 and 8. In addition, an auxiliary electrode **119**, e.g., a wire or rod, is mounted in insulated relation within each of the recesses formed by the grooves **115**. The electrodes **119** are connected together and provided with an external terminal (not shown), for application of a suitable potential relative to the cathode **111**. These electrodes **119** may be utilized in any manner known in the art to initiate, improve or control the ball-of-fire operation of the tube. For example, the electrodes **119** may serve as auxiliary electron emitters, positive ion emitters, or control electrodes.

What is claimed is:

1. A thermionic energy converter comprising an envelope containing an ionizable alkali metal vapor, a thermionic cathode, and an anode close to said cathode;
   (a) said cathode being adapted to be heated to an operating temperature, between 1000 and 2500° K., at which the effective work function of the emissive surface thereof is below the ionization potential of said vapor;
   (b) said anode being adapted to be cooled to an operating temperature below that of said cathode at which its effective work function is below that of said emissive surface;
   (c) said cathode emissive surface comprising an array of recesses open toward said anode;
   (d) the width and depth of said recesses being large compared to the minimum spacing between said cathode and said anode.

2. A thermionic energy converter as in claim **1**, wherein said width is approximately equal to the maximum cathode-anode spacing.

3. A thermionic energy converter as in claim **1**, wherein the maximum cathode-anode spacing is at least equal to ten mean free paths of electrons in said vapor.

4. A thermionic energy converter comprising an envelope containing an ionizable alkali metal vapor, a thermionic cathode, and an anode close to said cathode;
   (a) said envelope including means for adjusting the vapor pressure of said vapor to a value in the range from 10^{-2} to 10 mm. of Hg;
   (b) said cathode being adapted to be heated to an operating temperature, between 1000 and 2500° K., at which the effective work function of the emissive surface thereof is below the ionization potential of said vapor;
   (c) said anode being adapted to be cooled to an operating temperature below that of said cathode at which its effective work function is below that of said emissive surface;
   (d) said cathode emissive surface comprising an array of recesses open toward said anode;
   (e) the width and depth of said recesses being large compared to the minimum spacing between said cathode and said anode.

5. A thermionic energy converter comprising an envelope containing an ionizable alkali metal vapor, a thermionic cathode, and an anode close to said cathode;
   (a) said cathode being adapted to be heated to an operating temperature, between 1000 and 2500° K., at which the effective work function of the emissive surface thereof is below the ionization potential of said vapor;
   (b) said anode being adapted to be cooled to an operating temperature below that of said cathode at which its effective work function is below that of said emissive surface;
   (c) said cathode comprising a metal member formed with an array of recesses in the form of adjacent parallel grooves on the side thereof facing said anode;
   (d) the width and depth of said grooves being large compared to the minimum spacing between said cathode and said anode.

6. A thermionic energy converter as in claim **5**, wherein said member comprises a base portion having thin vane portions extending normal thereto to form channels of substantially square cross section.

7. A thermionic energy converter as in claim **5**, wherein said grooves are semi-circular in cross section.

8. A thermionic energy converter as in claim **5**, wherein said grooves are V-shaped in cross section.

9. A thermionic energy converter comprising an envelope containing an ionizable alkali metal vapor, a thermionic cathode, and an anode close to said cathode;
   (a) said cathode being adapted to be heated to an operating temperature, between 1000 and 2500° K., at which the effective work function of the emissive surface thereof is below the ionization potential of said vapor;
   (b) said anode being adapted to be cooled to an operating temperature below that of said cathode at which its effective work function is below that of said emissive surface;
   (c) said cathode comprising a metal member formed with a multiplicity of cellular recesses having relatively small dimensions compared to the dimensions of said cathode on the side thereof facing said anode;
   (d) the width and depth of said recesses being large

compared to the minimum spacing between said cathode and said anode.

10. A thermionic energy converter as in claim **9**, wherein said cellular recesses are inverted pyramids.

11. A thermionic converter as in claim **1**, wherein some, at least, of said recesses are provided with auxiliary electrodes insulated from said cathode and anode.

12. A thermionic energy converter comprising an envelope containing cesium vapor, a thermionic cathode, and an anode close to said cathode;

(a) said cathode being adapted to be heated to an operating temperature, between 1000 and 2500° K., at which the effective work function of the emissive surface thereof is below the ionization potential of said vapor;

(b) said anode being adapted to be cooled to an operating temperature below that of said cathode at which

its effective work function is below that of said emissive surface;

(c) said cathode emissive surface comprising an array of recesses open toward said anode;

(d) the width and depth of said recesses being large compared to the minimum spacing between said cathode and said anode;

(e) the maximum cathode-anode spacing being equal to $0.4K/p$, where K is a factor between 10 and 100, and p is the vapor pressure of the cesium in mm. of Hg.

No references cited.

MILTON O. HIRSHFIELD, *Primary Examiner.*

ORIS L. RADER, *Examiner.*

J. W. GIBBS, *Assistant Examiner.*