Dec. 6, 1966 R. FORMAN 3,290,523

METHOD OF OPERATION FOR A THERMIONIC CONVERTER

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FIG. 1

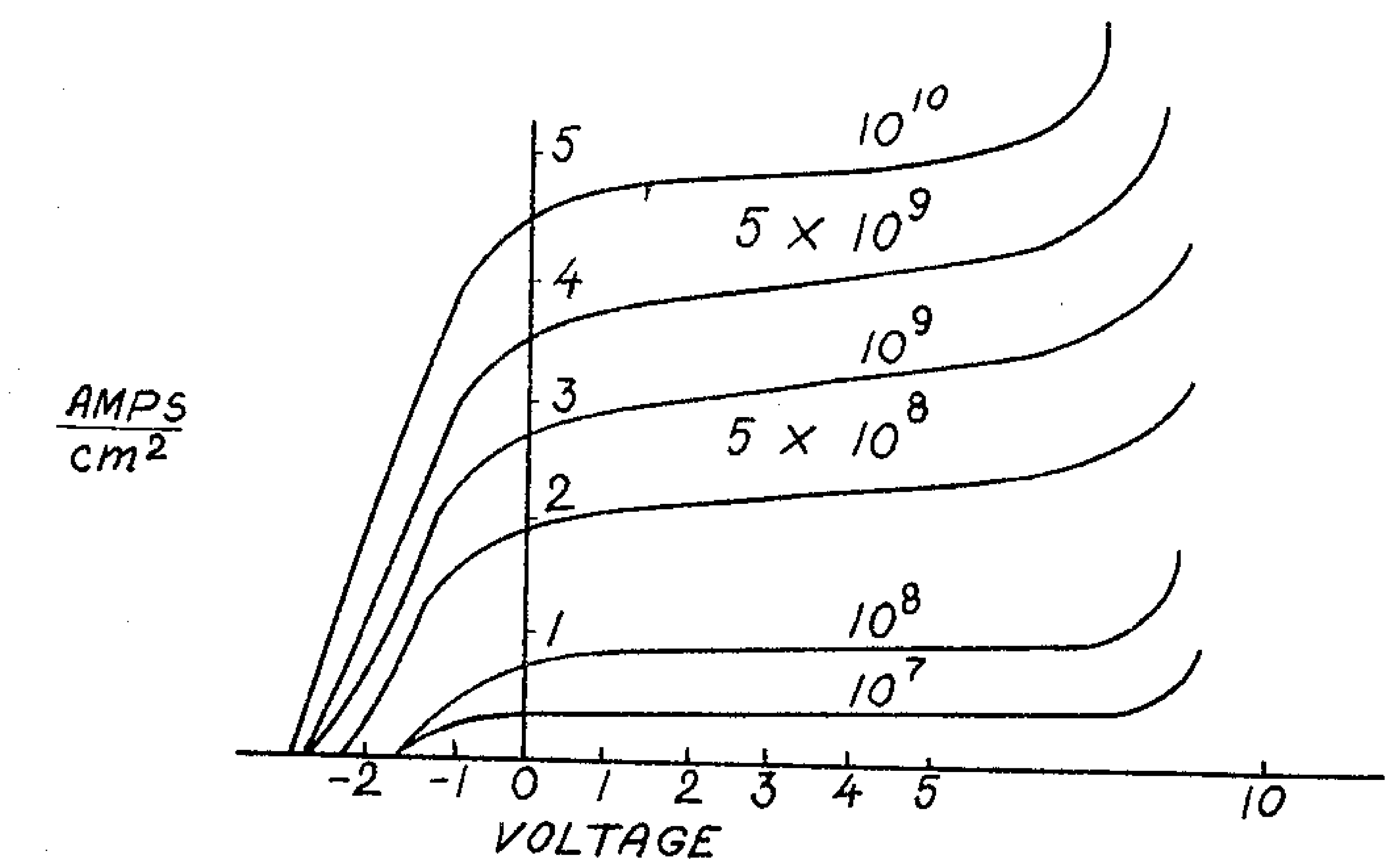


FIG. 2

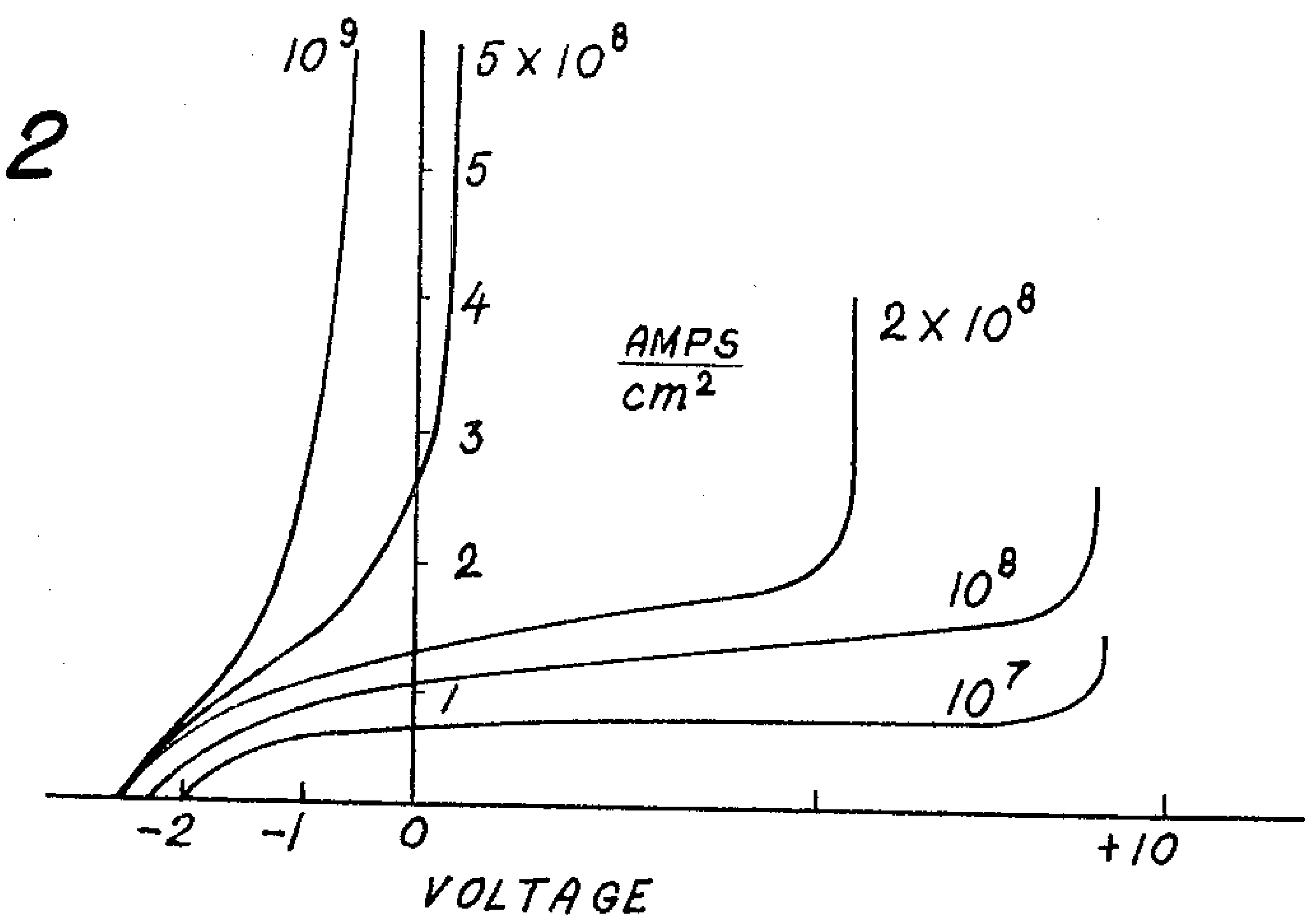
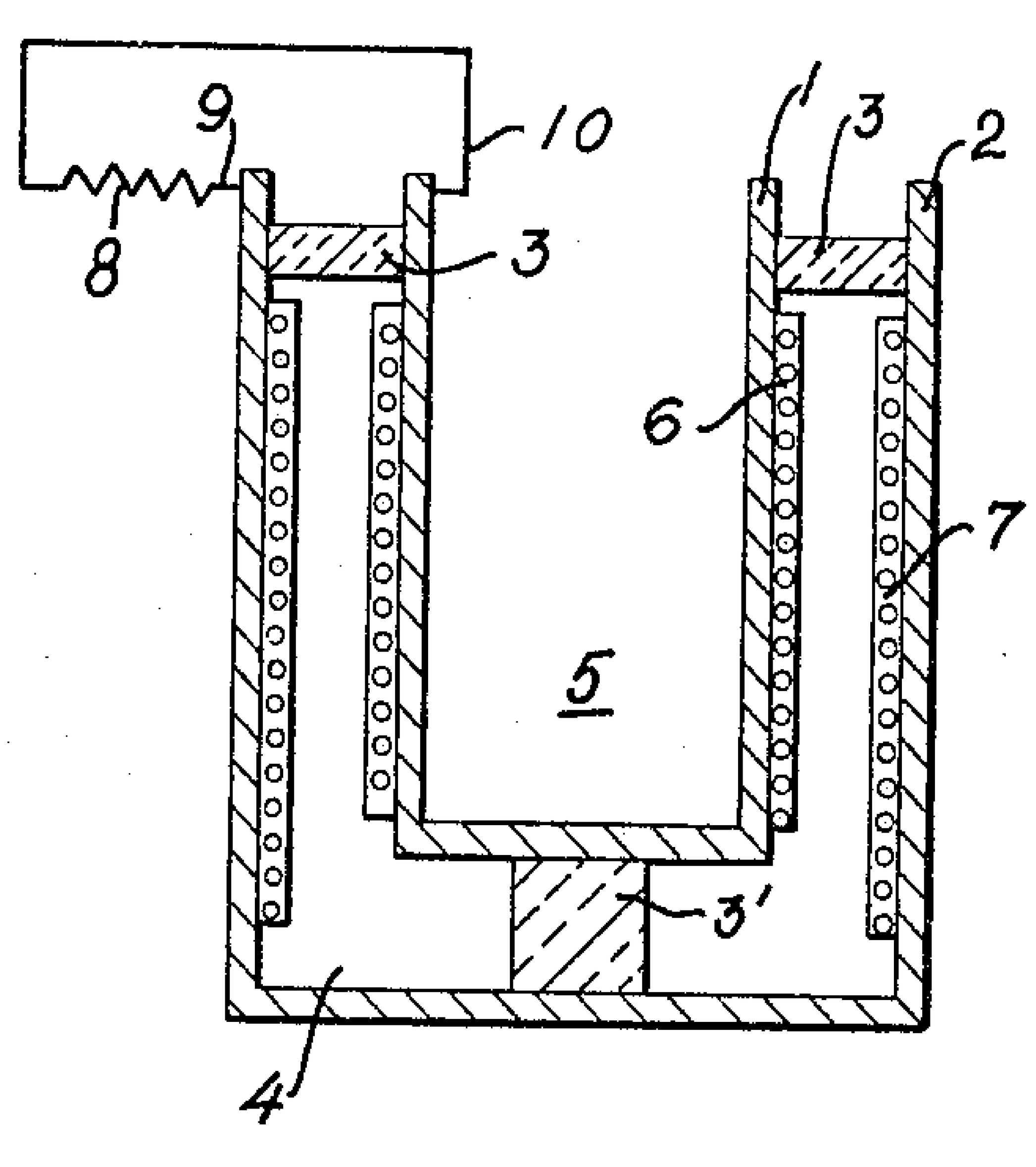


FIG. 3



INVENTOR.
RALPH FORMAN
BY Louis C. Smith
ATTORNEY

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FIG. 4

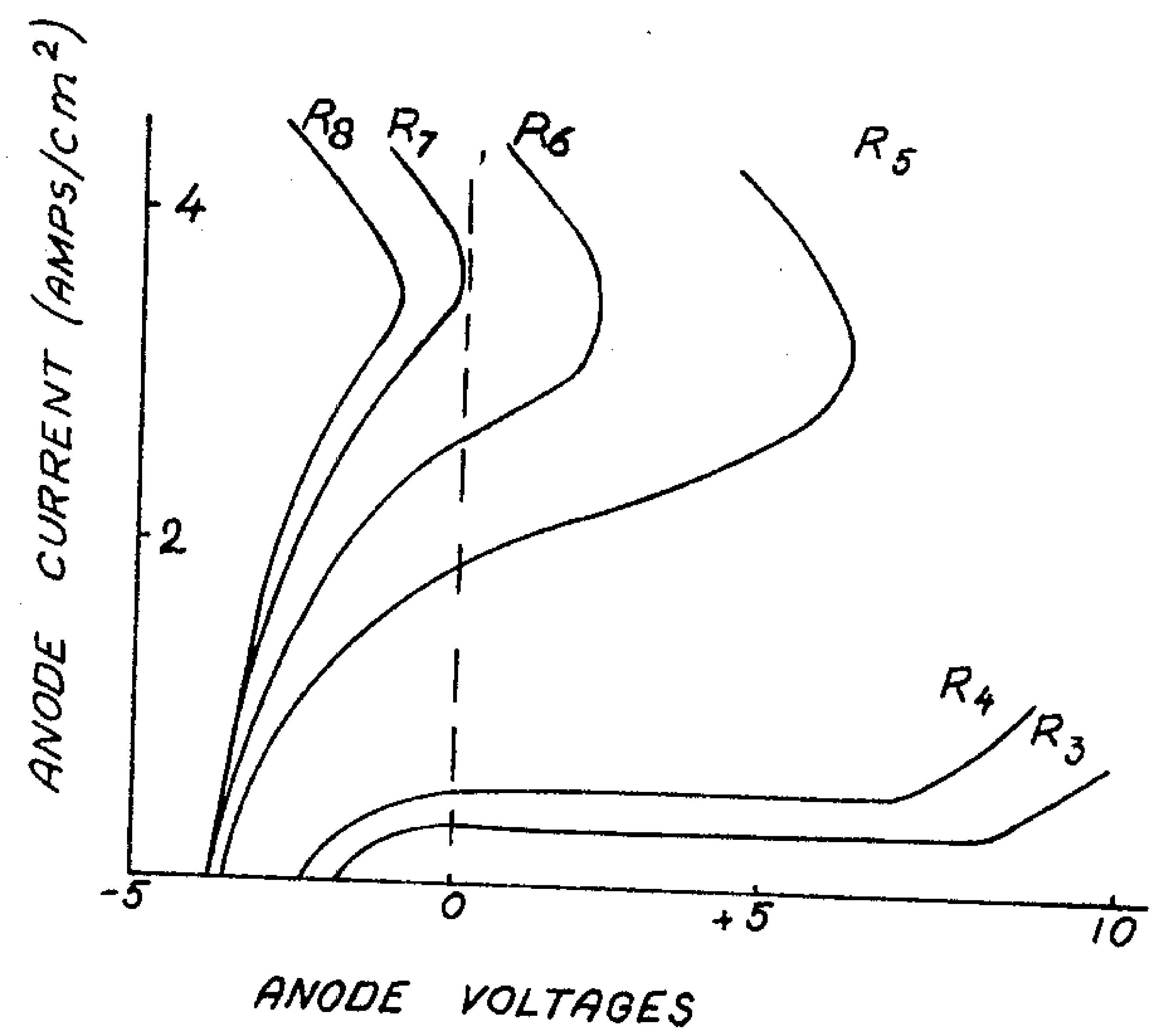
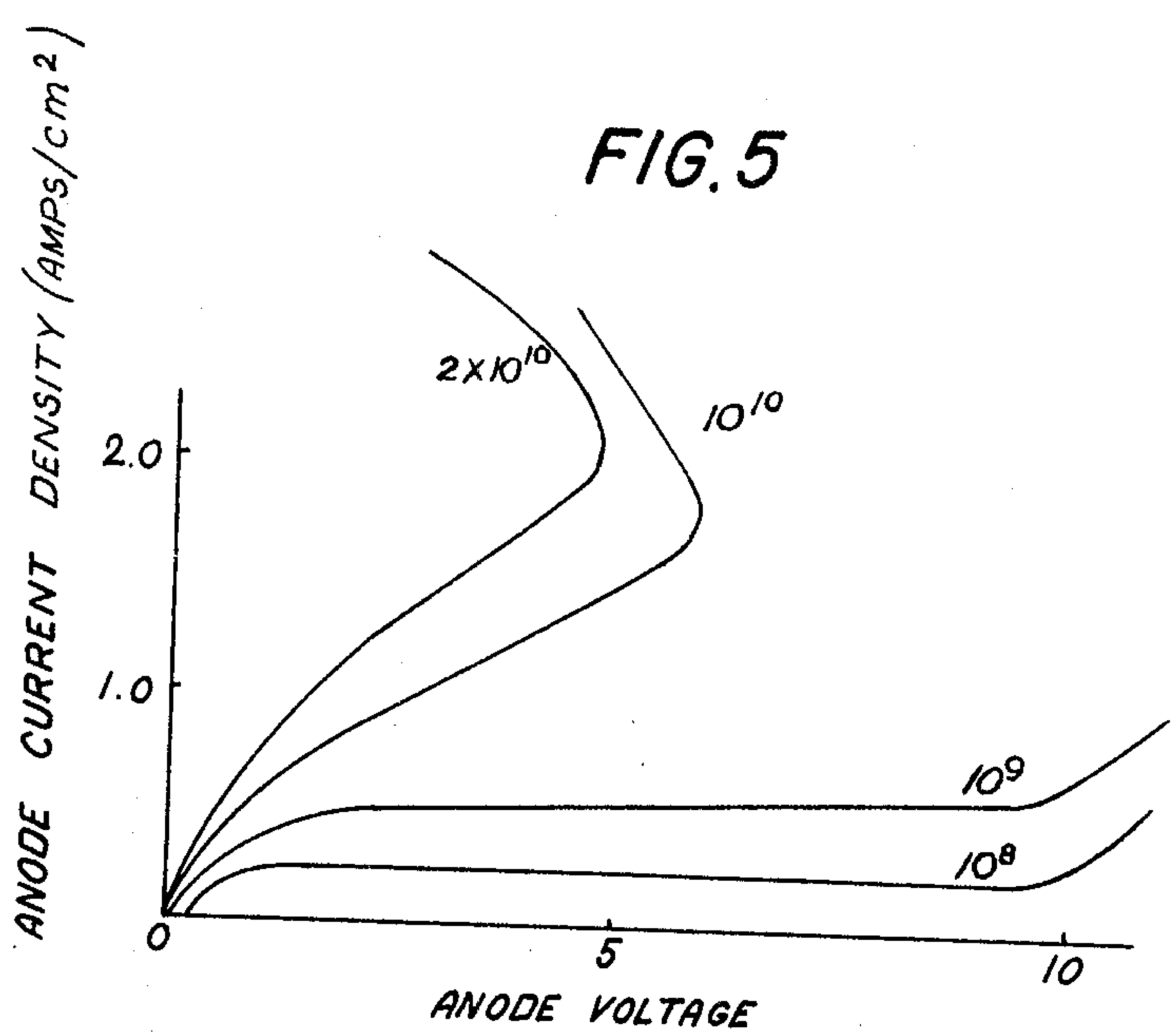


FIG. 5



INVENTOR.
RALPH FORMAN

BY Louis Smith

ATTORNEY

United States Patent Office

3,290,523

Patented Dec. 6, 1966

3,290,523

METHOD OF OPERATION FOR A THERMIONIC CONVERTER

Ralph Forman, Rocky River, Ohio, assignor to Union Carbide Corporation, a corporation of New York

Filed Nov. 16, 1962, Ser. No. 238,140
6 Claims. (Cl. 310—4)

This invention relates to thermionic conversion.

The main object of this invention is to provide an improved process for thermionic conversion by irradiation of a gas-filled diode.

Another object is to provide such a process which produces a current output higher than the electron current obtainable from the cathode.

A further object is to provide such a process which produces a high current output from a diode having a cathode with a relatively high work function.

A still further object is to provide such a process which produces a high current output at a relatively low operating temperature.

Other aims and advantages of the invention will be apparent from the following description and appended claims.

In the drawings:

FIGS. 1 and 2 are anode current-anode voltage characteristics which illustrate the operating principle of the present invention;

FIG. 3 is an elevation view in section of a preferred embodiment of the invention; and

FIGS. 4 and 5 are anode current-anode voltage characteristics for one specific embodiment of the invention.

In accordance with the present invention, there is provided a thermionic conversion process comprising providing a cathode and anode disposed in an ionizable gas, the cathode having a thermionic work function greater than the thermionic work function of the anode and being electrically connected to the anode through an external load circuit, the temperature of the cathode being sufficiently high to effect thermionic emission therefrom and the temperature of the anode being below the temperature of the cathode, and irradiating the ionizable gas at a radiation dosage sufficiently high to produce a discharge region in the anode current-anode voltage characteristic in the absence of an applied voltage. As used herein, the term "discharge region in the anode current-anode voltage characteristic" refers to a region where the anode current increases rapidly with little or no increase in the anode voltage.

In a gas-filled diode having a hot cathode with a thermionic work function greater than that of the anode, there is a certain contact potential between the cathode and anode which produces an extremely small output current in the absence of an applied voltage. As the gas between the cathode and anode is irradiated, some of the gas atoms are ionized by the release of electrons therefrom, thus forming an ion-electron plasma. The rate of formation of ions in the space between the cathode and anode is determined mainly by the pressure and type of the ionizable gas and the dose rate of the ionizing radiation, i.e., the energy, type, and flux of ionizing radiation employed. In general, the rate of ion formation increases with increasing gas pressure and radiation dose rate. In addition to the formation of gas ions, some of the gas atoms are excited by the radiation so that they can subsequently be easily ionized by the loss of electrons. As the concentration of these ions and excited atoms increases, the resistance of the plasma decreases, thereby increasing the current output of the diode generator. When the cathode has a limited supply of electrons, as in the case of a high work function cathode operating at a

low temperature, there is a certain level of radiation where the demands of the anode for electrons, due to the contact potential between the cathode and anode, exceeds the number of electrons which the cathode can supply at its operating temperature. This condition is generally referred to as cathode emission-limited current or temperature-limited cathode emission. At this point early breakdown sets in because the space close to the cathode becomes depleted of electrons and builds up an excess of ions (positive charge). This leads to a high positive field at the cathode, which accelerates electrons emitted from the cathode to energies of a few electron volts in a very short distance from the cathode surface These high energy electrons then ionize the excited atoms produced by the radiation and lead to a cascade effect in the production of ions and electrons. As a result, the diode generator operates at a discharge mode, i.e., the anode current output increases rapidly with little or no increase in the anode voltage, as evidenced by a discharge region in the anode current-anode voltage characteristic.

The operating principle of the present invention is illustrated by the anode current-anode voltage characteristics shown in FIGS. 1 and 2. The characteristics shown in FIG. 1 are for a typical gas-filled diode operating at about 1500° K. with a cathode capable of emitting about 5 amps/cm.^{2} at that temperature, an anode having a work function well below that of the cathode, and radiation dosages ranging from 10^7 to 10^{10} rads/hour. The characteristics shown in FIG. 2 are for a gas-filled diode identical to that represented by the curves of FIG. 1 (same gas, gas pressure, anode, temperature, geometry) except that the cathode is capable of emitting only 1 amp/cm.^{2} at the operating temperature of 1500° K. Comparing the curves of FIGS. 1 and 2, it can be seen that operating the tube of FIG. 1 at a radiation dosage of 10^9 rads/hr. and a voltage output of 1 volt gives a current of about 2.5 amps, whereas operating the tube of FIG. 2 at the same conditions gives a current of about 4 amps. Also, at the higher radiation dosages, the tube of FIG. 2 produces current outputs substantially higher than the maximum electron current obtainable from the cathode (1 amp/cm.^{2}). Thus, it is possible to use a cathode with a relatively high work function and, by increasing the radiation dosage sufficiently to cause the tube to operate at a discharge mode, obtain a high current output at a low operating temperature.

Interdependent factors which determine the exact radiation dosage required to create a discharge region in the anode current-anode voltage characteristic in the absence of an applied voltage in any given diode are the pressure and type of the ionizable gas around the cathode and anode, the temperature of the cathode, and the relative work function of the cathode and anode. It is preferred to use a rare gas such as argon, krypton, xenon, helium, or neon as the ionizable gas, and the preferred pressure range for the ionizable gas is from about 10 to about 1000 millimeters of mercury. The temperature of the cathode and the relative work functions of the cathode and anode should be such that some finite radiation dosage causes the diode to operate at a discharge mode. Any suitable electron-emitting material may be employed as the cathode, but it is preferred to use a material capable of emitting about 2 to 10 amps/cm.^{2} at the operating temperature of the device. Typical examples of suitable cathode materials are tungsten or nickel impregnated with barium and/or strontium compounds, thoriated tungsten, lanthanum boride, and refractory metals. The cathode must have a thermionic work function greater than that of the anode and must be electrically connected to the anode through an external load. When any of the cathode materials mentioned above are employed, the anode material may be an oxide cathode material (e.g., nickel coated with porous barium oxide-strontium oxide, which has a work function of about 1.0 ev.) or a metallic anode coated with a monolayer of alkali metal such as cesium or rubidium to give low work function. The anode temperature must be continuously maintained below the temperature of the cathode and sufficiently low that the thermionic emission from the anode is negligible in comparision with the thermionic emission from the cathode; the relative temperatures of the cathode and anode are preferably such that the thermionic emission from the anode is less than about 0.1% of the emission from the cathode. The only requirement on the cathode temperature is that it be sufficiently high to achieve effective thermionic emission therefrom, although the temperature should also be consistent with long cathode life. Although the spacing between the cathode and anode is not critical to the operability of the present invention, the efficiency of the device may be varied to some degree by varying the spacing.

The ionizing radiation employed in the present invention may be produced by any source that is capable of irradiating the ionizable gas at a dosage of about 10^9 rads/hour or higher. The preferred source of ionizing radiation is a nuclear reactor. The reactor may be used alone or in combination with a material having nuclei with a high cross section for an n,p (neutron in, proton out) or n, alpha (neutron in, alpha particle out) reaction. Examples of such materials are boron-10, lithium-6, and helium-3. The boron and lithium are solids and may be disposed within the ionizable gas in the diode in the form of a coating on the anode or on the inner walls of the diode container. Such coatings may be formed, for example, by electroplating. The boron-10 or lithium-6 need not be used in elemental form, but may be contained in a suitable compound, such as TiB_2. Helium-3 is a gas and may be mixed with the ionizable gas, or the helium-3 may itself serve as the ionizable gas. Absorption of slow neutrons from the reactor in helium-3, for example, produces high energy protons and tritons with kinetic energies of about 0.6 mev. and 0.2 mev., respectively. In a reactor having a slow neutron flux of 10^{12} neutrons/cm.^{2}-sec., pure helium-3 at a pressure of one atmosphere in a container having a radius greater than the 6-cm. range of the protons would be subjected to a dosage of 4×10^{10} rads/hour (in the center of the container) from the products of the n,p reaction. With the same conditions in a vessel having a radius of one centimeter, the dosage would be about 10^{10} rads/hour. A radiation dosage of about 10^9 rads/hour or higher is usually sufficient to produce a discharge region in the anode current-anode voltage characteristic in the absence of an applied voltage, although the exact value required depends on the particular pressure and type of ionizable gas employed, the cathode temperature, and the relative work functions of the cathode and anode.

A preferred embodiment of the invention will now be described in more detail.

Referring to FIG. 3, a rare gas such as argon, krypton, or xenon is contained in a sealed chamber **4** between an inner cylinder **1** and an outer cylinder **2** at a pressure of between 10 and 1000 mm. of mercury. The inner and outer cylinders **1** and **2** are separated by insulators **3** and **3'**. A thermionic emitter (cathode) with a work function of between about 2 and 5 ev. at the operating temperature is mounted in the form of a sleeve **6** on the outer surface of the cylinder **1**. The cathode sleeve **6** is heated to a temperature consistent with long operating life by a suitable heating means in the central cavity **5**, such as by employing the device in a nuclear reactor and inserting a fuel element (containing U235) or a boron or lithium compound (which can be heated by the n,alpha reaction) in the cavity **5**. A suitable anode material having a work function below that of the cathode **6** is mounted in the form of a sleeve **7** on the inner surface

of the outer cylinder **2**. A lead **9** from the conductive outer cylinder **2** and a lead **10** from the conductive inner cylinder **1** connect the cathode **6** and anode **7** to an external load **8**.

In order to determine the exact radiation dosage required for any given diode to operate at a discharge mode, the anode current (I_A)-anode voltage (V_A) characteristics are plotted at increasing dosages until a discharge region appears in the second quadrant, i.e., to the left of the line of zero voltage. A theoretical set of I_A–V_A curves for the device of FIG. 3 are shown in FIG. 4. Of course, an applied voltage must be used to obtain those portions of the curves to the right of the zero voltage line. As can be seen from FIG. 4, at relatively low radiation dosages, such as R_3 and R_4, the cathode is able to meet the demands of the anode for electrons, and the current output is plasma-limited (current is limited by the finite resistance of the plasma and is less than the saturated cathode-emission current). At higher radiation dosages, such as R_5 and R_6, a point is reached where the cathode can no longer meet the demands of the anode for electrons, and a breakdown region appears. However, the voltage at which breakdown occurs is sufficiently high that most of the breakdown region lies in the first quadrant. At even higher dosages, such as R_7 and R_8, the breakdown region appears in the absence of the applied voltage, and the diode can be operated at a discharging mode as a generator (without applied voltage). Once the diode is operating at a discharge mode as a generator, the external load impedance is adjusted to limit the output current to a level which the electrodes can sustain consistent with long life. By operating at a discharge mode, currents of 2 to 10 amps/cm.^{2} can usually be produced by using a cathode operating at a temperature which ordinarily gives a maximum current of about 1 amp/cm.^{2}.

In an example of the present invention, a conventional glass diode was filled with krypton at a pressure of 20 mm. of mercury and placed in the inner core of a swimming pool type nuclear reactor. The cylindrical diode tube was about 8 inches long and about 1.5 inches in diameter. The diode had a tantalum anode (work function of 4.0 ev.) concentrically mounted therein in the form of a cylindrical shell 0.25 inch in diameter and 0.5 inch long. The cathode was a thoriated tungsten (work function of 3.10 ev.) filament mounted coaxially within the anode shell. The cathode was heated to a temperature of about 2000° K. by passing electrical current therethrough, while the anode was at temperature below 500° C. In order to obtain the I_A–V_A characteristics of the tube, a variable anode voltage was applied and the I_A–V_A curves taken at various radiation dosages. The curves obtained are shown in FIG. 5. It can be seen that at the lower dosages (10^8 and 10^9 rads/hr.) the current was plasma-limited (current is limited by the finite resistance of the plasma and is less than the saturated cathode-emission current) and no breakdown occurred. However, at dosages of about 10^{10} rads/hr. and above, the current increased to about 2 amps/cm.^{2}, which was about the maximum electron current obtainable from the cathode, and the tube then began to operate at a discharge mode. By varying the pressure and type of gas employed and/or the tube geometry, the same effect can be obtained at a dosage of 10^9 rads/hr. It can also be seen from the curves that the breakdown point occurred at progressively lower voltages with increasing dosages.

The device used to obtain the curves shown in FIG. 5 produced no output current in the absence of an applied voltage because the cathode had a work function below that of the anode. In order to convert the device to a generator, and create a discharge region in the absence of an applied voltage, the device is provided with an impregnated tungsten cathode (work function of 2.2 ev.) and an anode of oxide cathode material (work function of 1.0 ev.). Since the device now has a cathode with a work function higher than that of the anode, curves similar to those in FIG. 2 are obtained.

While various specific forms of the present invention have been illustrated and described herein, it is not intended to limit the invention to any of the details herein shown.

What is claimed is:

1. A thermionic conversion process comprising:
(a) providing a sealed chamber containing a cathode and an anode disposed in an ionizable gas,
  (1) said cathode having a thermionic work function greater than the thermionic work function of said anode and being electrically connected to said anode through an external load circuit,
  (2) the temperature of said cathode being sufficiently high to effect thermionic emission therefrom and the temperature of said anode being below the temperature of said cathode;
(b) and irradiating said ionizable gas by means of a radiation source external to said chamber at a radiation dosage sufficiently high to produce a discharge region in the anode current-anode voltage characteristic in the absence of an applied voltage, said current-voltage characteristic lying entirely in the region of no applied voltage.

2. The thermionic conversion process of claim 1 wherein said ionizable gas is at least one gas selected from the group consisting of argon, krypton, xenon, helium, and neon.

3. The thermionic conversion process of claim 1 wherein said ionizable gas is at a pressure of between about 10 and about 1000 millimeters of mercury.

4. The thermionic conversion process of claim 1 wherein said anode is at a temperature sufficiently low that the thermionic emission from said anode is negligible in comparison with the thermionic emission from said cathode.

5. The thermionic conversion process of claim 1 wherein said radiation dosage is at least about 10^9 rads per hour.

6. A thermionic conversion process comprising:
(a) providing a sealed chamber containing a cathode and an anode disposed in an ionizable gas at a pressure of between about 10 and about 1000 millimeters of mercury,
  (1) said cathode having a thermionic work function greater than the thermionic work function of said anode and being electrically connected to said anode through an external load circuit,
  (2) the temperature of said cathode being sufficiently high to effect thermionic emission therefrom and the temperature of said anode being below the temperature of said cathode;
(b) and irradiating said ionizable gas by means of a radiation source external to said chamber at a radiation dosage of at least about 10^9 rads/hour so as to produce a discharge region in the anode current-anode voltage characteristic in the absence of an applied voltage, said current-voltage characteristic lying entirely in the region of no applied voltage.

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MILTON O. HIRSHFIELD, *Primary Examiner.*

ORIS L. RADER, *Examiner.*

J. W. GIBBS, *Assistant Examiner.*