Nov. 8, 1927. **1,648,183**

K. H. KINGDON ET AL

METHOD AND APPARATUS FOR CONDUCTING CURRENT

Filed Dec. 21, 1922

Fig. 1.

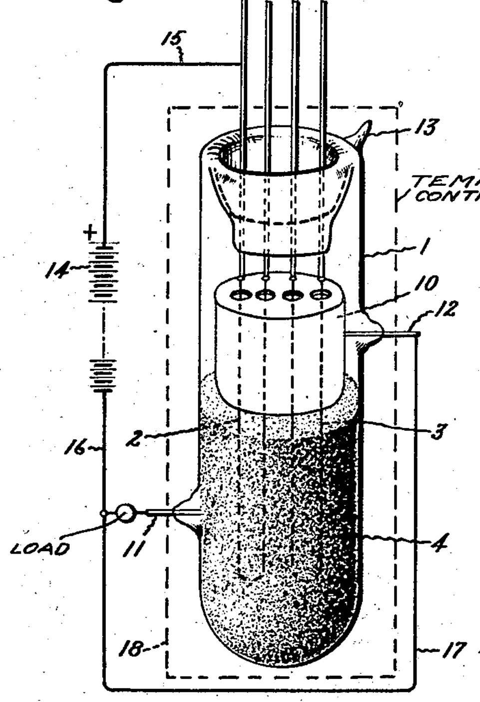


Fig. 2.

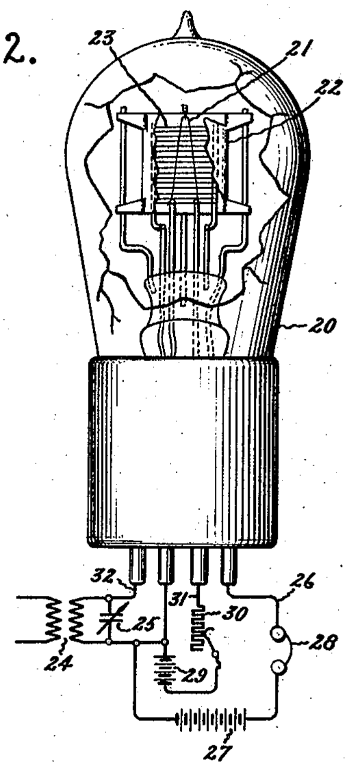


Fig. 3.

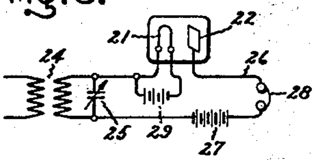
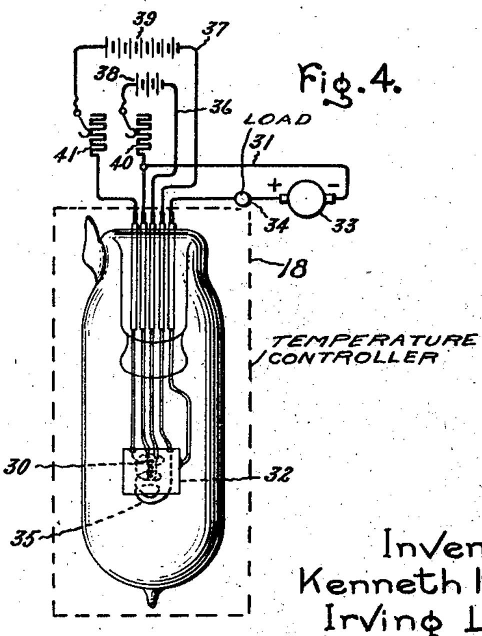


Fig. 4.



Inventors:
Kenneth H. Kingdon,
Irving Langmuir,
by Alexander S. Lunt
Their Attorney.

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UNITED STATES PATENT OFFICE.

KENNETH H. KINGDON AND IRVING LANGMUIR, OF SCHENECTADY, NEW YORK, ASSIGNORS TO GENERAL ELECTRIC COMPANY, A CORPORATION OF NEW YORK.

METHOD AND APPARATUS FOR CONDUCTING CURRENT.

Application filed December 21, 1922. Serial No. 608,198.

The present invention provides new electrical devices utilizing positive ions which are generated by a new method at one of the electrodes in a regular, controllable manner independently of and without electron impact.

Positive ion currents have been obtained previously from an electrode by scientific investigators but such currents have been too minute for practical purposes and in general have been transient. It has not been possible heretofore to generate positive ions from electrodes under reproducible conditions in amounts sufficient for useful purposes.

We have discovered that positive ions can be generated from suitably chosen gaseous material which comes into contact with a heated, positively charged electrode, the electrical properties of this gaseous material being correlated with the electrical properties of the generating electrode in a manner to be explained later. When the generating electrodes consist of tungsten, we find that the elements cæsium and rubidium, are particularly efficient for generating positive ions in useful amounts. The continuous presence of the vapor is assured by having an excess of the solid or liquid alkali metal in the device; and moreover, the vapor is constructed or regenerated from the positive ions by the recombination of the ions with electrons to form neutral atoms of the vapor during the operation of the device.

In devices embodying our invention positive ions may be utilized either as the sole current carriers, as for example, in the detection of radio signals, or positive ions may be utilized conjointly with electrons for the conduction of power currents at high efficiency.

The accompanying drawings show in Figs. 1 and 2 devices operating solely by positive ion conduction; Fig. 3 is a diagram of circuit connections, and Fig. 4 illustrates a device for conducting current by the conjoint action of electrons and positive ions.

The device shown in Fig. 1 illustrates an embodiment of our new device in which the positive ions are utilized to conduct current, and which is structurally particularly adapted to demonstrate the laws of the positive ion discharge. This device comprises a sealed container 1 consisting of refractory glass, quartz, or other suitable material, and containing the filaments 2 and 3, one of which is used as the ion-generating electrode, the other filament being used in the preparation of the film electrode 4 on the inner surface of the glass bulb. The ion-generating electrode for convenience will be referred to hereinafter as the genode.

The genode 2 may consist of tungsten, molybdenum or nickel. The filament 3, which is used as a source of metal vapor for forming the film electrode 4, preferably consists of tungsten, although other materials also could be used. The filaments, 2, 3 are connected respectively to suitable leading-in conductors 5, 6 and 7, 8 sealed into a stem 9 in the usual manner. A cylindrical electrode 10 surrounds the genode section adjacent the connection thereof to the leads for reasons later explained. The sealed in conductors 11, 12 serve to convey current to the electrodes 4 and 10. As the formation of film electrodes by vaporizing tungsten is described in Langmuir Patent 1,273,628 of July 23, 1918, and is generally understood, it will not be described herein.

When the material which serves to generate positive ions is introduced, the container and the electrodes should be free from gas and the space within the container should be evacuated. Cæsium or rubidium may be introduced from a reduction tube communicating with the discharge device and provided with a material capable of evolving the desired metal. For example, we may employ a mixture of cæsium chloride and a reducing agent such as magnesium or calcium, the latter being in excess. After sufficient cæsium, or other desired material, has been introduced to serve as a source of vapor, the tube is sealed off in the usual manner, as indicated at 13.

When for any purpose a device such as shown in Fig. 1 is to be operated solely by positive ion conduction, the positive electrode at which the ions are to be generated is heated to a sufficiently high temperature and a suitable positive potential is impressed upon this heated electrode. For example, the electrode 2 of Fig. 1 is heated by current conveyed by the conductors 5, 6 and a suitable source of potential 14 is connected by the conductors 15, 16 to the genode 2 and the film electrode 4, the genode being positive. A galvanometer or other measuring, or load device, is included in the circuit 16. The guard cylinder 10 is also connected to the source 14 by a conductor 17, but the current flowing therein is not measured. By this connection the laws of the device can be more definitely established than when the current flowing from the filament section cooled by the lead wires is included in the measurement.

The current obtained in the described device depends on the positive ion emission and the impressed voltage. (Hereinafter the adjective "positive" before "ion" will be omitted for the sake of brevity.) The ion emission depends on the temperature of the ion-generating electrode or genode, and the vapor pressure of the active gaseous material.

The critical genode temperature above which an emission of ions is obtained varies somewhat with the nature of the ion-generating material in the device and other conditions, but in general it may be said that there is a definite temperature for any given genode material above which atoms striking the genode leave the same as ions. In the case of a genode consisting of tungsten and containing cæsium as the active material, the critical temperature may range from about 1000 to 1200 degrees C. The ion emission is independent of the genode temperature providing the genode temperature is above the critical value. Above the critical temperature, the particular value of which may be determined under given conditions in any device, the ion emission obtained is proportional to the vapor pressure. The critical genode temperature varies with the vapor pressure in the case of a given ion-generating material. For example, in a device containing a clean, unoxidized tungsten genode and provided with a charge of cæsium the critical genode temperatures observed at bulb temperatures of 70° C., 50° and 30° C. respectively were 1030° C., 940° C. and 880°.

The vapor pressure may be fixed at different desired values by an external heater, or medium such as an oil bath which can be kept at a substantially constant temperature. This external temperature control device has been indicated in Fig. 1 by the dotted outline 18 about the device. It should be understood that similar heat control can be used in the other forms of the invention.

The choice of vapor pressure will depend on the use to be made of the positive ions. In general it is advantageous to generate positive ions in accordance with our invention under such conditions that there is no accompanying positive ionization by collision in the discharge space. In the case of a device such as shown in Fig. 1 employing only positive ion conduction, the pressure may be much higher than when electron conduction also occurs.

When electron conduction accompanies ion conduction and it is desired to control the electron current, as in the case of a device of the type shown in Fig. 4, the pressure should be maintained below a value at which the electron discharge in the vapor would be accompanied by appreciable ionization by collision, that is, below the pressure corresponding to a temperature of about 70 degrees C. in the case of cæsium. The specific temperature will depend on the geometrical construction of a particular device. At 70 degrees C. the vapor pressure of cæsium is about 0.0001 of a millimeter of mercury (a tenth of a micron). The pressure of vapor should not be so high that a self-sustaining discharge may occur between the electrodes at the applied potential.

With any given impressed voltage, the ions generated at the genode may not all reach the cathode because of the positive space charge of the positive ions carrying the current analogous to the negative space charge in electronic devices. By raising the impressed voltage to a sufficiently high value the effect of the positive space charge can be overcome and all the ions generated are drawn over to the cathode or negative electrode.

The cæsium ion, for example, is a stable positive unit capable of taking up an electron to form a neutral cæsium atom. This cæsium ion is about 237,000 times heavier than an electron. As the relative velocities are inversely proportional to the square roots of the masses, the velocity of a cæsium ion is about 1/487th of the velocity of an electron. Hence, when limited by space charge the ion current obtainable with a given impressed voltage is about 1/487th of the electron current obtainable in a given electron tube under similar conditions.

The positive space current varies as the 3/2 power of the impressed voltage up to a voltage value high enough to produce a saturation current and then becomes substantially constant for higher voltages. It is steady for a constantly applied voltage and reproducible for different voltages. For example, in a specific device, at a bulb temperature of 0.7 degrees C. the saturation positive current observed was 2.4 micro-amperes per sq. cm. of anode surface; at a bulb temperature of 46.5 degrees C. the current was 0.29 milliamperes per sq. cm. of anode surface, and at a bulb temperature of 53.5 degrees C. the observed current was 0.63 milliamperes per sq. cm. of surface.

As explained by Langmuir in the Transactions of the American Electrochemical Society, Vol. XXIX, 1916, page 125, there is an absorption of energy when electrons are emitted from incandescent metals. This energy is measurable as heat absorbed, and may be calculated in terms of a potential difference in volts, which is a quantitative measure of work done in separating an electron from an emitting surface reduced to the absolute zero of temperature. This value has been called the "electron affinity" of the emitting material. This electron affinity, also known as the "work function" of electron emission, has been determined for a number of materials. The value for tungsten is 4.52 volts, for tantalum 4.31 volts, and for molybdenum 4.31 volts. The values of these constants are a measure of the affinity of these respective metals for free electrons which are now generally assumed to exist in conductors. The higher the work function the more tenaciously, so to speak, the respective substance holds on to its free electrons, and therefore, the higher the temperature required to liberate the free electrons.

Not only are free electrons present in substances, but the atoms, constituting the substance itself, contain a system of electrons. When a free atom of a substance in space loses an electron it becomes positive to this extent and is said to be ionized. It requires energy which may be expressed in volts to remove an electron from an atom. In the case of a cæsium atom this potential is 3.9 volts. This ionizing potential is a measure of the electron affinity of the atom which, it will be seen, is less than that of a tungsten surface. Hence, when a cæsium atom with an ionizing potential of 3.9 volts strikes a hot, positively charged tungsten surface with an electron affinity of 4.52 volts, it leaves the heated surface in the form of a positive ion, having lost an electron to the tungsten.

Our experiments indicate that the alkali metals have the property of forming an adsorbed film upon a metal surface even though the metal surface is at a temperature materially higher than the temperature corresponding to the particular vapor pressure of the alkali metal in the environment of the metal surface. At a temperature materially below the critical temperature for ion generation, the genode surface will be largely coated with an adsorbed film of whatever alkali metal is present in the device. The electron affinity of such an adsorbed surface of cæsium for free electrons is about 1.4 volts, and hence when cæsium atoms leave a surface largely coated with cæsium they do not lose an electron, as the evaporating atoms have a greater affinity for electrons than does the surface.

When the temperature is progressively raised the surface of the metal is but partly covered with adsorbed cæsium, and the electron affinity of the surface is increased until some of the cæsium atoms will leave the surface as ions. For example, a tungsten surface 20 per cent of which is coated with cæsium will have an average electron affinity of about 3.9 volts as a resultant of the work function in volts of 4.52 for pure tungsten and 1.4 for cæsium, and 50 per cent of the cæsium atoms will leave the heated surface as ions. At a higher electron affinity a larger proportion of cæsium ions will be generated. Our invention, therefore, involves a coordination between the electron affinity of the surface at which the ions are generated and the ionizing potential of the substance from which the ions are generated. The phenomenon of ion formation which takes place when a gaseous material comes into contact with a heated surface of higher electron affinity than the ionization potential of said material, we desire to refer to herein as surface ionization.

Fig. 2 shows a positive ion radio detector 20 which contains in addition to a genode 21 and a cathode 22 also an intermediate input electrode or grid 23. The grid and genode are connected to the secondary of a radio transformer 24, a variable condenser 25 being provided in shunt to the secondary as is usual. The output circuit 26 contains a source of energy 27 represented by a battery, and a telephone receiver 28 connected between the genode and the cathode. Instead of having the telephone in the output circuit, suitable amplification of the audio current output may be provided in the well understood manner. A battery 29 and a variable resistance 30 are shown in the genode circuit 31 to heat the genode to a desired temperature. The bulb 1 is highly evacuated and contains a quantity of cæsium, or equivalent material. At the ordinary operating temperatures, that is, just above room temperature, the vapor pressure of the cæsium is about 0.002 of a micron of mercury. Several times higher vapor pressures are permissible, depending on conditions.

The voltages of the heating circuit 31 and the output circuit 26 are so chosen that the positive ion current is limited by space charge. Variations of the grid potential by the received signals in the circuit 32 vary the current in the output circuit 26 and produce audible signals in the telephone 28.

In some cases the grid may be omitted as shown in Fig. 3, the genode and the cathode 22 being connected directly in the plate circuit 26 which contains a battery 27, a telephone 28 and is connected to the secondary of the input transformer 24. The signal current is rectified by the unilateral conductivity of the positive ion device and becomes audible in the telephone.

When it is desired to utilize positive ions for the neutralization of space charge, an electron emitting cathode is employed which is adapted to function independently of positive ion bombardment as illustrated for example, in Fig. 4. In the device here shown the cathode also consists of a filamentary electrode 30, which is connected by an external circuit 31 to a cylindrical anode 32 in series with a source of current 33 and a load device 34. The genode 35 consists of a self-supporting coiled filament. Heating circuits 36 and 37 are provided respectively for the cathode 30 and the genode 35. These circuits respectively contain heating batteries 38 and 39 and variable resistances 40, and 41, as indicated, whereby the temperature of the respective electrodes may be regulated. The vapor pressure of the cæsium or other adsorptive material is maintained at a desired value by the external temperature controller 18.

As set forth more at length in an application Serial No. 608,217 filed concurrently herewith by Irving Langmuir on devices of the type illustrated in Fig. 4, the positive ion current generated at the genode 35 performs the important function of neutralizing the negative space charge of the electron current emitted by the cathode 30. As is well known, space charge is a term applied to the current limiting effect of the mutual repulsion of the negative electric charges of the electrons which must be overcome by the impressed voltage. In electrical devices heretofore used a considerable part of the impressed voltage has been required to overcome space charge and therefore electronic power devices could be operated at good efficiency only when the voltage consumed by the external load was relatively high. Otherwise, the fall of voltage in the device itself represented too large a proportion of the impressed voltage. It has been known that this high space charge could be neutralized by the presence of positive ions resulting from ionization by collision of electrons with gas atoms in the discharge space, and in certain industrial electronic devices an ionizable gas has been introduced to cause ionization by electron impact in order to lower the voltage drop in the device. The presence of such gas, however, is necessarily accompanied by certain limitations, as for example the tendency for the discharge to get out of control, and the disintegration of the cathode by excessive positive ion bombardment.

In the device shown in Fig. 4, the ions generated at the genode 35 are capable of neutralizing the space charge of an electron current emitted by the cathode 30 even though the value of the electron current is many times greater than the value of the positive current; as the operating temperature of the bulb may be maintained below a value at which gas ionization by electron impact becomes appreciable, the conduction of electricity through the evacuated space may occur by a new principle, namely electron conduction with low or negligible space charge without the limitations imposed by ordinary impact ionization of gas. The large neutralizing capacity of positive ions is due to their slower movement relative to the electrons which causes them to remain in the presence of the rapidly moving electron stream for a sufficient length of time to enable a much larger electron current to pass.

What we claim as new and desire to secure by Letters Patent of the United States, is:—

1. The method of generating a positive ion current independently of ionization by collision which consists is bringing into contact with a positively charged electrode a vapor of a substance chemically inert with respect to said electrode and having a lower electron affinity than said electrode, heating said electrode above a critical temperature at which positive ions are generated and carrying away said ions by an applied potential.

2. The method of conducting current which consists in bringing into contact with an electrode a vaporizable adsorptive material which is chemically inert with respect thereto and has a lower electron affinity than said electrode, heating said electrode to a temperature above 1000° C. to generate positive ions from said material and carrying away said ions in the absence of positive ionization by electron impact.

3. The method of generating positive ion current in an electric discharge device containing a plurality of electrodes which consists in providing in the environment of one of said electrodes vaporizable material having a lower electron affinity than said electrode, heating said electrode to a temperature as high as a critical temperature at which positive ions are formed by the vapor of said material at said electrode, charging said electrode to a positive potential with respect to another electrode to conduct away said ions, and maintaining said device at a temperature at which the vapor pressure of said material is sufficiently high to produce a substantial ion emission but below the value at which self sustaining discharge can occur in said vapor.

4. The method of conducting electric energy between electrodes in a space evacuated to a gaseous pressure so low that gaseous ionization by electron impact is substantially absent when an electron current flows between said electrodes at voltages above the ionization voltages of residual gas which consists in heating one of said electrodes to an elevated temperature, bringing into contact with said heated electrode a material having a lower electron affinity than the sur-

face of said heated electrode, thereby generating positive ions at said heated electrode and charging a second electrode to a potential which is negative with respect to said heated electrode to carry away said ions.

5. The method of generating positive ions in an electrical discharge device containing a plurality of eletrodes which consists in subjecting at least one of said electrodes to the vapor of an alkali metal having a substantially lower electron affinity than said electrode, heating said electrode in excess of a temperature at which an adsorbed film of said alkali metal remains thereon, and maintaining the vapor pressure of said alkali metal sufficiently low to enable an electron discharge to occur therein without appreciable ionization by electron impact.

6. The method of operating an electrical discharge device containing a cathode and a second electrode adapted to be operated at an elevated temperature which consists in heating said second electrode to a temperature of about 1000 to 1200° C., charging said second electrode positively with respect to said cathode and delivering to the environment of said positive electrode a vaporous material which has a work function of electron emission which is less than that of said positive electrode, and a pressure at which an electron discharge therein will be unaccompanied by appreciable gas ionization by collision.

7. The method of conducting electricity between electrodes one of which consists of a material having a high electron affinity which consists in liberating cæsium vapor in the space between said electrodes, heating said electrode of high electron affinity at least to a critical temperature at which ions are generated, and charging said heated electrode to a positive potential with respect to another electrode.

8. The method of generating a positive ion current in an enclosed space containing a nickel electrode and a cooperating electrode which consists in introducing cæsium into said space to the exclusion of other gases and vapors, charging said nickel electrode to a positive potential, heating the same to a temperature of at least about 1000° C., conducting away positive ions generated from cæsium vapor at said nickel electrode and maintaining the pressure of said vapor below about 0.0001 of a millimeter of mercury.

9. An electric discharge device comprising a sealed, evacuated container, electrodes therein one of which is operable at a temperature of at least about 1000° C., means for charging said electrode to a positive potential with respect to another electrode, means for heating said positive electrode, means for bringing into contact with said electrode a vapor having an electron affinity less than said positive electrode, and means for controlling an electric discharge in said device.

10. An electrical discharge device comprising a container, a plurality of electrodes therein, means for charging one of said electrodes to a positive potential, a vaporizable material in said container having an electron affinity less than the surface of said positively charged electrode and having a vapor pressure at the operating temperature of said container high enough to generate positive ions at said positive electrode in appreciable quantities, but being below the pressure at which appreciable ionization by collision will accompany electron conduction between said electrodes.

11. An electrical discharge device comprising co-operating electrodes, means for generating positive ions by surface ionization at one of said electrodes independently of electronic collision phenomena, and means for controlling the amount of said ion generation.

12. An electrical discharge device comprising an envelope, a plurality of electrodes therein, means for establishing a difference of potential between at least two of said electrodes, independent means for heating one of said electrodes, a vaporizable material in said envelope out of contact with said heated electrode for furnishing to said heated electrode a vapor capable of generating positive ions by contact with said heated electrode, said device being constructed to operate at a temperature at which the pressure of said vapor is less than about a tenth of a micron of mercury.

13. An electrical discharge device comprising an envelope containing a quantity of cæsium and being otherwise substantially free from gas, cooperating electrodes one of which has a higher electron affinity than cæsium, and a heating circuit for said electrode of high electron affinity, said device being constructed to operate at a temperature at which the vapor pressure of said cæsium is too low to permit a self-sustaining discharge to operate between said electrodes.

14. An electrical discharge device comprising cooperating electrodes, a source of potential connected thereto, means for heating the more positive electrode, and means for delivering cæsium vapor into contact with said electrode at a pressure sufficiently low to permit electron conduction between said electrodes unaccompanied by appreciable ionization by collision.

15. An electrical discharge device comprising an exhausted envelope, containing an elementary material capable of electrical coversion into positive ions, and being capable of regeneration by the discharge of said ions, electrodes one of which has a surface of higher electron affinity than said ma-

terial, and means for heating said electrode of higher electron affinity independently of a discharge between said electrodes.

16. An electrical discharge device comprising an evacuated container, an alkali metal in said container, electrodes therein one of which has a higher electron affinity than the ionizing potential of said alkali metal, means for charging one of said electrodes to a positive potential and controllable means for heating said positively charged electrode independently of an electron discharge between said electrodes.

17. An electron discharge device comprising an envelope, a quantity of cæsium therein, cooperating electrodes, one of which consists of a material having a higher electron affinity than cæsium at a temperature higher than about 1000° C., means for heating the latter electrode independently of a discharge between said electrodes, and means for controlling the vapor pressure of cæsium.

18. The combination of an electrical discharge device provided with means for generating positive ions by surface ionization, a work circuit connected thereto, a source of current in said circuit having a voltage so related to said ion generating means that an ion current having space charge characteristics is produced in said device and means for electrostatically controlling said discharge.

19. An electrical discharge device comprising a sealed envelope provided with cooperating electrodes and containing a material having a lower electron affinity than a positive electrode, and having at the operating temperature of said envelope a substantial vapor pressure, whereby positive ions may be generated in effective amounts when said positive electrode in said device is heated to a sufficiently high temperature.

In witness whereof, we have hereunto set our hands this 19th day of December, 1922.

KENNETH H. KINGDON.
IRVING LANGMUIR.