

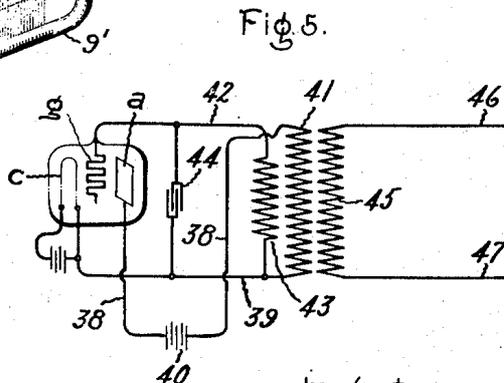
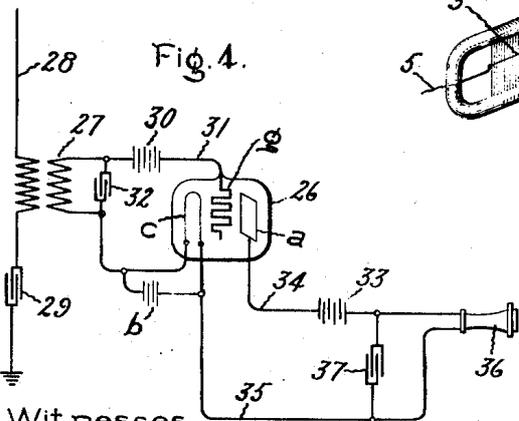
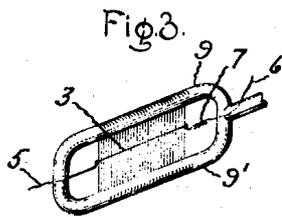
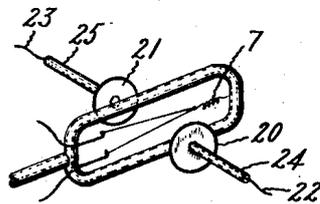
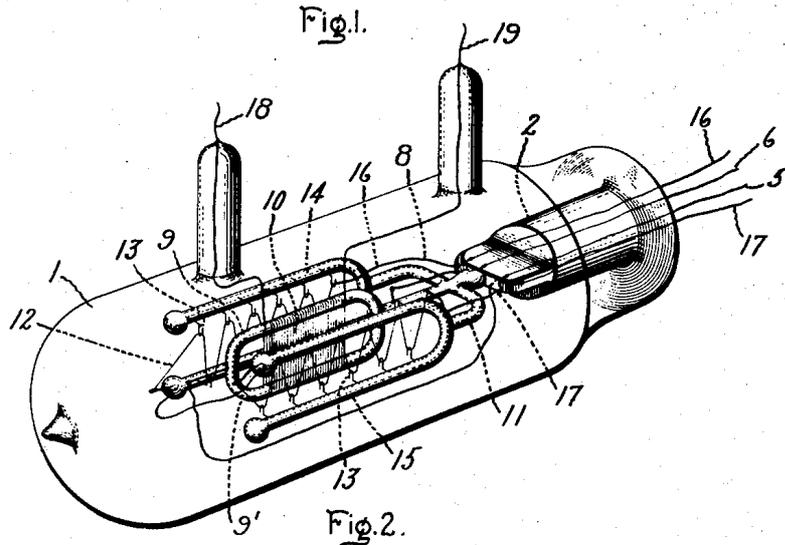
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1,558,436

I. LANGMUIR

ELECTRICAL DISCHARGE APPARATUS AND PROCESS OF PREPARING AND USING THE SAME

Original Filed Oct. 16, 1913



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UNITED STATES PATENT OFFICE.

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ELECTRICAL DISCHARGE APPARATUS AND PROCESS OF PREPARING AND USING THE SAME.

Application filed October 16, 1913, Serial No. 795,610. Renewed March 14, 1916. Serial No. 84,242.

To all whom it may concern:

Be it known that I, IRVING LANGMUIR, a citizen of the United States, residing at Schenectady, county of Schenectady, State of New York, have invented certain new and useful Improvements in Electrical Discharge Apparatus and Processes of Preparing and Using the Same, of which the following is a specification.

The present invention relates to electrical vacuum discharge devices, and it comprises devices in which the electrical current is carried by negative charges called electrons, emanating from the cathode, independently of gaseous ionization such as occurring, for example, in the ordinary Roentgen tube.

My present invention comprises improvements in electron-discharge apparatus which make possible a high load capacity and operation with the highest voltages but the invention is also applicable and useful for moderate loads and moderate voltages. The novel features of my invention will be pointed out with greater particularity in the appended claims.

Figs. 1 and 2 of the accompanying drawings, Fig. 2 being a partial view, illustrate two types of discharge devices embodying my invention; Fig. 3 is a fragmental view showing a cathode construction, and Figs. 4 and 5 are diagrams of electrical systems illustrating certain applications of my electron discharge tubes.

In order to distinguish electron discharge devices made in accordance with my invention from the prior art, I will explain briefly the character of a pure electron discharge as distinguished from a discharge through ionized gas. In a Geissler tube, and in a Roentgen or Crookes tube the conduction of current is accompanied by and depends upon gas ionization. Without a certain minimum amount of gas a Roentgen X-ray tube ceases to operate and as this minimum is approached the resistance of the tube steadily increases.

The passage of an electric current across a tube ordinarily involves the movement of negative charges called electrons which, under the influence of the impressed voltage, pass from the cathode to the anode through the vacuous space. If these electrons when moving above a certain velocity collide with gas molecules they tend to ionize the mole-

cules, splitting them up into electrons and larger and more slowly moving ions. Under these circumstances the phenomena of conduction across the tubes are the result of the action and interaction of the electrons and the ions; these phenomena are in general erratic and non-reproducible. The cathode under these conditions is disintegrated, technically it is "sputtered", which causes its rapid destruction. As gas ionization continues at higher voltages a blue glow may appear. The bombardment of the cathode by positive ions also causes heating of the cathode. The ionization of gases at low pressures by collision with electrons occurs at definitely determinable voltages, these voltages being known as the ionization voltages. These voltages are different for different gases. In the case of gases such as nitrogen, hydrogen, oxygen, argon, helium and neon, they are of the order of magnitude of fifteen to twenty-five volts.

The phenomena above described as being characteristic of devices involving gas ionization are taken advantage of in an incandescent cathode device with three electrodes known as the "Audion." This device has been used as a receiver for radio-telegraphy and depends in its operation upon the rapid change of the discharge current when gas ionization begins. This point depends upon various accidental conditions which cause such irregularities in the operation of various devices apparently identical that sometimes only one of a considerable number can be used. Ordinarily the gas ionization in the audion begins to be important somewhere between 20 and 30 volts. Another discharge device previously used to some extent was the Fleming valve. This was a two-electrode tube which, so far as I am aware, was always used at voltages well below the voltages at which positive ionization by collision occurs. It was not evacuated in such a manner as to permit it to be used at voltages materially above these ionization voltages without manifesting substantial positive ionization effects. No prior hot cathode devices are known to me operating with currents as great as about 5 milliamperes with voltages as high as about 200 volts; indeed no prior discharge devices are known to me operating in a practically usable manner and without substantial positive ionization

effects with currents as great as about one-tenth of a milliampere with voltages as high as about forty volts.

In devices made in accordance with my invention gas ionization is either entirely absent or is negligible and a discharge takes place which is distinct in its characteristics from the described discharge taking place in an ionized gas. The cathode is not heated by the discharge itself. Blue glow, glass fluorescence and in fact all readily visible indications of a discharge are ordinarily absent. In most devices of simple construction which embody my invention, the discharge current passing through a given space with the cathode at a sufficiently high temperature with respect to the voltages employed, varies directly with the $3/2$ power of the impressed voltages. This $3/2$ power law can be readily derived mathematically for a tube in which there is substantially no positive ionization on the assumption that the whole surface of the cathode is at a uniform potential, that the electrons escape from the cathode with negligible velocities and that the walls of the tube do not carry appreciable electric charges.

In most simple devices embodying my invention, these conditions are so well fulfilled that the current does vary in proportion to the $3/2$ power of the voltage over wide ranges of voltage above the ionizing voltages. This means that if the logarithm of the current is plotted against the logarithm of the voltage, the resulting plot is a straight line whose slope is $3/2$. Or, in many cases it is more convenient to make use of the equivalent relation, that the $2/3$ power of the current plotted as ordinates against the anode voltages as abscissæ gives a straight line.

In devices in which there is substantial positive ionization, on the other hand, even when the pressures of gas are so low that only very small currents could be carried by positive ions, the currents begin to increase with voltage more rapidly than according to the $3/2$ power law as soon as the anode voltage materially exceeds the ionizing potential of the gas.

In devices embodying my invention which have more than two electrodes, or with special constructions, as where the cathode is a filament, so long that it cannot be considered an equi-potential surface, the $3/2$ power law may be more or less masked. However, the effects thus introduced will be readily understood by those skilled in the art, and appropriate methods of identifying the pure electron discharge can easily be found corresponding to the special construction. For example, when such tubes have more than two electrodes and the temperature of the cathode is sufficiently high with respect to the voltages employed, the discharge will

usually be characterized by a linear relation between the $2/3$ power of the total electron current from the cathode and the voltage applied to any other electrode, the remaining electrodes being kept at constant potential. Another test that can often be made with a three electrode tube is to connect the grid directly to the anode, or to the negative end of the cathode, and observe whether the current varies as the $3/2$ power of the voltage.

If for a given cathode temperature the voltage is sufficiently high to cause all of the electrons emitted or liberated at the cathode to be drawn away, then a further increase in voltage produces substantially no change in the current. The current thus determined is called the saturation current, and the range of operation in which the current is substantially independent of the voltage or approaches this condition may be called the saturation range or more briefly designated merely as saturation. If for a given cathode temperature the voltage is not high enough to cause all of the electrons which are emitted or liberated at the cathode to be drawn away, the operation occurs in a range below the saturation range. Operation in this range may be spoken of as operation below saturation.

A change in the temperature of the cathode in a hot cathode device embodying my invention will produce no change in the discharge when the operation is below saturation, even though the ionization voltage is materially exceeded. That is, the current-voltage curve is not changed by a change in the cathode temperature under such conditions.

The discharge in devices embodying my invention is practically independent of the pressure when the pressure is below a certain value which depends upon the size and shape of the device and upon the current and voltage of the discharge.

As distinguished from discharges in the presence of positive ionization, the pure electron discharge is characterized by regularity and reproducibility with given conditions. In a device in which the conduction of current is purely electronic, and the effect of positive ions is negligible, the conduction of current is governed, over a certain range, on the one hand by the effect of the impressed voltage, which tends to propel the electrons across the vacuous space, and on the other hand by the mutual propulsion of the electrons in the space, which tends to limit or inhibit the current. This last mentioned phenomenon, the current limiting effect of the electric field of the electrons on each other, termed the "space charge effect," is discussed and analyzed by me in a paper read before the Physical Society on October 18, 1913, which was abstracted in the Physi-

cal Review for November, 1913, and published in full in the Physical Review for December, 1913, and again published in somewhat modified form in the Physikalische Zeitschrift for April 1, and May 15, 1914. It is the basis of the $3/2$ power law referred to herein.

The geometric proportions of the device also affect the amount of current which will pass with a given voltage, but as these conditions remain fixed for a given device they may be represented by a constant in an equation expressing the relation between the current and the voltage.

As stated above, the current (I) in the particular device described herein, when operating below saturation, will vary with the $3/2$ power of the voltage (V), the equation being:

$$I = aV^{3/2} \text{ (} a \text{ being a constant)}$$

As is well known, if we produce a logarithmic graph of any equation in which one variable of the equation varies as a power of the other variable, as for example, an equation of the general form $y = x^n$, (as by plotting logarithms of x as abscissæ and logarithms of y as ordinates) we find that this graph is a straight line. Hence the relation between current and voltage in a device operating below saturation and by pure electronic conduction independent of gas ionization may be expressed by the statement that when with a sufficient electron emission the logarithms of the current values transmitted between cathode and anode are plotted as ordinates against the logarithms of the respective voltages impressed between cathode and anode as abscissæ, the slope of the line obtained does not ordinarily increase for increasing voltage values over a working range of voltages extending materially above the ionization voltages.

A substantial amount of positive ionization ordinarily causes the logarithmic plot of the current with respect to the voltage to bend upwardly and away from the $3/2$ power line when the ionizing voltage is materially exceeded. The absence of a bend in the logarithmic plot at voltages somewhat above the ionization voltage is ordinarily a reliable indication that the tube is a pure electron discharge tube, though saturation complete or partial at voltages somewhat greater than the ionization voltages may prevent such a bend in the plot of an ionizing tube.

As above indicated, one of the indications of positive ionization is the occurrence of erratic readings in measuring devices connected in circuit with an electron discharge device under observation. Such erratic readings, of course, will produce a sudden change or discontinuity in the logarithmic graph plotted as above described, and any such ir-

regularities will be more manifest when observed as deviations from a straight line than when the readings are plotted directly.

The effect of positive ionization upon the magnitude of the discharge is especially marked in that region of operation where the current is limited by the space charge effect already discussed, and changes in curvature of the discharge characteristics may occur as indicated unaccompanied by any visible evidence of ionization such as blue glow or the like. At saturation on the other hand, the discharge is ordinarily much less sensitive, and in fact the discharge may actually exhibit marked blue glow effects along with a flat or straight saturation curve.

Devices made in accordance with my invention may be used for various technical purposes, such as relaying and detecting currents, producing oscillations and rectifying alternating currents, and such devices may be made which will operate without substantial positive ionization at voltages far above the ionization voltages with currents thousands of times greater than the currents at which the devices of the prior art were operable without substantial positive ionization. Devices made and operated in accordance with my invention are capable of transmitting currents materially exceeding one-tenth of a milliamperere without causing positive ionization to take any essential part in the operation of the device, though the voltage is materially above the ionization voltages.

Before describing the method of preparing my new type of apparatus, I will describe the structure of the apparatus illustrated by Figs. 1 to 3.

As shown in Fig. 1 the various parts of the apparatus may be mounted in a tube, or envelope 1, upon a pedestal 2, similar to the mount used in incandescent lamps. The cathode 3 is centrally located and may consist of a short straight filament not shown in Fig. 1, but indicated by the position of terminals 5, 6, and shown plainly in Fig. 3. The cathode shown in Fig. 2 consists of a V-shaped conductor. Either form may be used, the particular form of cathode being ordinarily determined by convenience of construction. Preferably the cathode conductor is held taut by a spring 7 to avoid contact of the cathode conductor with the grid by sagging when the metal is expanded at a high temperature. The filament 3 is mounted between two oppositely disposed supports, 9, 9', in this case constituting a closed loop, which may consist of insulating material, such as glass or quartz, but in some cases may to advantage consist of metal. Upon this frame-work is wound a discharge-varying conductor 10, ordinarily called a grid. The turns of the wire are closely adjacent to each other and are also very closely

adjacent to but are out of contact with the incandescent cathode. By means of this grid 10 potential may be applied to exert a static control upon the movements of the electrons. A negative potential applied on the grid reduces the flow of current from cathode to anode in proportion to the degree of negative charge. A positive grid potential assists and directs the flow of current from cathode to anode in proportion to the degree of its charge.

The supporting framework for the cathode and grid is attached to a rod 11, mounted upon the stem of the tube. Adjacent to the cathode and grid is the anode 12 which in the present case has been indicated as consisting of a wire strung in a zig-zag manner over hooks 13 upon fork-shaped supports 14 and 15, but it is not necessary that it should assume this particular form. Both anode and grid preferably consist of tungsten, but other refractory metals may be used. By constituting the anode a continuous conductor it can be conveniently heated by passage of current during evacuation of the device and for this purpose is attached to leading-in conductors 16 and 17. The grid is indicated in Fig. 1 as being attached to leading-in conductors 18 and 19 at opposite ends, although but one terminal is ordinarily necessary.

In some cases it is desirable to use a plate-shaped anode; Fig. 2 illustrates such an arrangement suitable particularly for rectifying alternating current. The tube itself and other extraneous parts have not been shown in Fig. 2, as they are similar to Fig. 1. The cathode construction has already been referred to and the anodes 20 and 21 also preferably consist of tungsten and may be connected electrically with each other. Current connections are made by conductors 22, 23, the supports 24, 25 being merely indicated. It will be noted that both in Figure 1 and Figure 2 the electrons are afforded a short and direct path from the cathode to the anode and that this path is so related to the position of the walls of the tube as to minimize the tendency for electrons to pass to the walls of the tube. In such a tube electron bombardment of the walls of the tube is avoided, together with the heating of such walls and the secondary emission of electrons therefrom which said bombardment causes. The energy of the discharge is delivered mainly, or entirely, at the anode, anodes, or upon other interior members instead of at the walls of the tube.

For the evacuation of the device the glass walls of the tube are carefully heated to a high temperature as the glass will stand without softening and in general the most approved methods of incandescent lamp exhaust are used. The evacuation of the tube

preferably while still heated is carried out by means of a suitable evacuating means, for example, a Gaede molecular pump, which removes vapors as well as gases. Chemical evacuating means such as electrically vaporized calcium or magnesium may also be used either before or during the evacuation the anodes may be heated, especially when the anodes are to be run at elevated temperature during the normal operation of the device. In this case the temperature is preferably carried close to brilliant incandescence. In the case of the structure shown in Fig. 1, the heating may take place by passing an electrical current through the wire 12. The heating, especially of solid anodes such as shown in Figure 2, may take place in a suitable vacuum furnace, the temperature preferably being raised to 2,500° C. or even higher. Bombardment is a very effective means of removing occluded gas from anodes.

The bombardment is carried out when the evacuation has proceeded to a high degree by applying a potential between the cathode 3 and the anode 12, Fig. 1, the value of which depends upon the character of the device. Care should be taken to use a voltage below that at which a blue glow appears as this indicates harmful gas ionization, and as already pointed out, sputtering and disintegration of the cathode accompanies or closely follows the blue glow phenomenon. The pump should be constantly operated to remove the gas. After the removal of the gas thus driven out the voltage impressed between the cathode and the anode, or anodes, as the case may be, is increased thereby driving out more gas. This process is continued step by step with a progressively higher voltage, the final voltage depending upon the character of the apparatus. In most cases the final voltage should be materially higher than the voltage at which the device is to be used in actual service. However, in the case of devices that use exceedingly high voltages, such as 50,000 volts or even higher, substantially all the gas may be removed from the anode without resorting to voltages higher than the normal operating voltage. In the case of a plate-shaped anode which cannot be readily heated by passage of current, the discharge voltage may be chosen great enough to convey sufficient energy to the anode to raise its temperature to redness or even higher, when the device is to be used with a discharge current adapted to heat the anodes.

After the metal has been freed from occluded gas reabsorption of gas will not readily take place even though it is exposed to the air or other gases. For example, anodes thus treated may be removed to other apparatus which then may be evacuated.

uated with less electron bombardment of the anode or anodes.

The evacuation of the device should be preferably carried to a pressure as low as a few hundredths of a micron, or even lower, but no definite limits can be assigned. The residual gas pressure should be below the value at which ionization by collision will take place at the given working voltage and current, with its accompanying phenomena of blue glow, disintegration of the cathode, and so forth. When the cathode and anode are located in close proximity and the discharge confined to the region between the same, the permissible pressure is higher than when the cathode and anode are at some distance. It is also true that when the anode has been carefully freed from gas, residual free gas, even if present in a sufficient amount to cause some gas ionization when the apparatus is first started, does little harm, as it is quickly removed by the gas clean-up effect when the device is operated.

Electron discharge apparatus thus provided with a gas-free pretreated anode or anodes, may be constructed to handle currents at a very high voltage by proper mechanical design of the parts subjected to static strains, suitable proportioning of the parts and so forth as described, for example, in my application Serial No. 795,609 filed concurrently herewith upon which Patent 1,273,783 was granted on July 23, 1918.

The asymmetric conductivity existing between the heated and unheated electrodes of a device of the character described may be utilized for various technical purposes. Reference has already been made to the rectification of current. As shown in Fig. 4 an electron discharge tube may be used for detecting electromagnetic waves in radio-telegraphy. As shown in this Fig. 4 the grid *g* and heated cathode *c* of an electron discharge tube 26 are connected respectively to the terminals of the secondary of a transformer 27, the primary of which is included in the antenna circuit 28. The antenna is grounded through a condenser 29 in the usual manner. The cathode *c* is heated by a local source of energy, as battery *b*. A battery 30 in the grid circuit 31 has its negative terminal connected to the grid *g*. A condenser 32 shunts the secondary of the loosely coupled transformer 27. The inductance of the transformer and the capacity of the condenser are adjusted to make the receiving circuit resonant to the frequency of the oscillations to be received. The oscillations set up by the incoming signals are superimposed upon the negative grid potential and causes a variation of current transmitted between cathode *c* and anode *a* by a local source of energy such as a battery 33 included in the

local or plate circuit 34, 35, of the discharge tube. This circuit is connected to an ordinary telephone receiver 36, preferably shunted by means of a condenser 37, whereby the signals are detected.

Fig. 5 illustrates how an electron discharge tube may be used in a system for producing alternating current from direct current. The anode *a* and cathode *c* are connected respectively to conductors 38, 39, one of which includes a local source of energy, such as a battery 40. The terminals of these conductors are connected to an inductive coil 41. The cathode and grid *g* are also connected respectively by conductors 39 and 42 to a second inductive coil 43 which may be in a variable inductive relation to the coil 41. As soon as a flow of current starts in the plate circuit 38, 39, current is induced in the coil 43 of the grid circuit 39, 42. When by reason of this current the grid becomes negatively electrified, the flow of current in the plate circuit is reduced, and as the plate current decreases the grid electrification changes to positive, which again allows the current in the plate circuit to increase. These changes take place with a frequency depending on the electrical characteristics of the circuits. Across the grid circuit 39, 42, of the discharge tube, in some cases is connected a condenser 44, the capacity of which may be varied to control the frequency of the oscillations set up by the system. The oscillations may be transformed to higher or lower voltage by a transformer coil 45 to the terminals of which are connected transmitting conductors 46, 47. The system shown in Fig. 5 is described and claimed in a copending application, Serial No. 797,987, filed October 29, 1913.

Residual gas, left in a tube when it is sealed off or occluded gas driven off from the inner wall of the tube, or from the electrodes, during the use of the tubes, varies in pressure from time to time according to the conditions of operation of the tube and may produce irregularities in the discharge when operating in the saturation region as well as when operating below saturation. The irregularities below saturation are due mainly to the disturbing effect of the resulting positive ions upon the space charge. The irregularities in the saturation region are due to changes in the rate of emission or liberation of electrons at the cathode. It is obvious that the advantages of stable and reproducible operation and freedom from destructive bombardment of the cathode by positive ions, which advantages are severally or collectively to be secured by the means hereinabove described, are not limited to operation below saturation but are also important in operation in the saturation region.

The positive ionization herein referred to is that positive ionization which occurs as the result of collisions between electrons and gas molecules in the space between the electrodes and causes, as by producing changes in space charge, unstable and non-reproducible operation.

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

1. A discharge tube having electrodes at least one of which is adapted to emit electrons, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of being so operated in a range below saturation and materially above ionization voltages that the governing or limiting action on the space current due to the electric field of said electrons is substantially unaffected by positive ionization and by secondary electron emission from the walls of the tube.

2. A discharge tube having a cathode adapted to emit electrons and an anode adapted to receive said emitted electrons, the tube walls being fashioned or shaped to permit the direct passage of a useful proportion of said electrons from cathode to anode, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of being so operated in a range below saturation and materially above ionization voltages that the space current is governed or limited by the electric field of said electrons substantially unaffected by positive ionization.

3. A discharge tube having electrodes at least one of which is adapted to emit electrons, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of being so operated in a range below saturation and materially above ionization voltages that in that range the space current is governed by the combined effect of the electric field of said electrons and the potentials applied to said electrodes, the governing or limiting of the current being substantially unaffected by positive ionization and by secondary electron emission from the walls of the tube.

4. A discharge device comprising a tube and electrodes therein one of which is adapted to emit electrons, the degree of evacuation and the relation of the parts of the device being such that the device is capable of being so operated, when voltages materially higher than ionization voltages are impressed upon electrodes of the device and when the electron emission has any value such that the space current is below the saturation region at such voltages, that the slope of the line obtained by plotting the logarithms of values of said current as ordinates against the logarithms of the corresponding values of said impressed voltages

as abscissæ shows no increase for increasing voltage values.

5. A discharge device comprising a tube and electrodes therein one of which is adapted to emit electrons, the degree of evacuation and the relation of the parts of the device being such that the device is capable of being so operated, when voltages materially higher than ionization voltages are impressed on electrodes of the device and when the electron emission has any value such that the space current is below the saturation region at such voltages, that the line obtained by plotting the logarithms of any values of said current below the saturation region as ordinates against the logarithms of the corresponding values of said impressed voltages as abscissæ is straight and continuous.

6. A discharge tube having electrodes at least one of which is adapted to emit electrons, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of being so operated, when voltages materially higher than ionization voltages are impressed on electrodes of the tube and when the electron emission has any value such that the space current is below the saturation region at such voltages, that said current varies as the three halves power of said impressed voltages.

7. A discharge device comprising a tube and electrodes therein one of which is an electron emitting cathode, the degree of evacuation of said device and the relation of the parts of the device being such that the device is capable of being so operated, when voltages materially higher than ionization voltages are impressed on electrodes of the device and when the electron emission is such that the space current is below the saturation region at such voltages, that said current is substantially independent of the cathode temperature and unaffected by secondary electron emission from the walls of the tube.

8. A discharge tube having electrodes at least one of which is adapted to emit electrons, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of being so operated in a range below saturation and materially above ionization voltages that the space current is governed or limited by the combined effect of the electric field of said electrons and the potentials applied to said electrodes, substantially unaffected by positive ionization, the heating effect in the tube due to said current occurring substantially only at one or more of said electrodes.

9. A discharge tube having a cathode adapted to emit electrons, an anode adapted to receive electrons and tube walls fashioned or shaped so as to permit the free passage

of a useful proportion of said electrons from cathode to anode, the gas content or residue of said tube and the relation of the parts of the tube being such that the tube is capable of operation with stable and reproducible results substantially unaffected by positive ionization, with currents of at least 5 milliamperes and with voltages of at least 200 volts.

10. An electrical discharge device comprising a gas-tight envelope, an electron-emitting cathode, a cooperating anode, and a discharge-varying conductor, the space in said envelope being evacuated to below the pressure at which deleterious gas ionization takes place, constituting a device in which the current passed when operated below saturation and over a working range of voltage materially above the ionization voltages is controlled by space charge substantially unaffected by positive ionization.

11. A high vacuum electron discharge device comprising an envelope, an incandescent cathode, and an anode, the space in said envelope being evacuated to such degree that the passage of current produces no appreciable positive ionization when the impressed voltage is as high as 200 volts.

12. An electrical discharge device, comprising a gas-tight envelope, an electron emitting cathode, an anode deprived of ionizable gas and a discharge controlling conductor, the space in the envelope being evacuated to a pressure not substantially in excess of a few hundred thousandths of a millimeter of mercury, said device being characterized by the fact that when operated below saturation and materially above the ionization voltages, the current is controlled by space charge substantially unaffected by positive ionization.

13. An electrical discharge device comprising a gas-tight envelope, an electron emitting cathode, a cooperating anode, the space and materials in said envelope being sufficiently free of gas so that substantially no positive ionization occurs when the impressed voltage is as high as 60 volts, and the current over a working range of voltage up to 60 volts varies with the $3/2$ power of the impressed voltage.

14. An electrical discharge device comprising a gas-tight envelope, a cathode adapted to be heated to incandescence, an anode from which substantially no ionizable gas can be evolved at operating voltages up to 100 volts with currents up to 1 milliampere, the envelope so shaped and the electrodes so positioned as to substantially avoid secondary electron emission from the wall of the envelope, the space in said envelope being evacuated to a pressure not in substantial excess of a few hundred thousandths of a millimeter of mercury.

15. A device comprising a gas-tight en-

velope, a cathode adapted to be heated to incandescence, an anode from which no ionizable gas can be evolved at operating voltages up to about 200 volts with operating currents up to about five milliamperes, the space in said envelope being evacuated at a pressure not in substantial excess of a few hundred thousandths of a millimeter of mercury, said device being characterized by the fact that with currents up to about five milliamperes at voltages up to about 200 volts, evidences of positive ionization are substantially absent and the current over a working range below saturation varies with the $3/2$ power of the voltage.

16. An electrical discharge device comprising a sealed envelope, an incandescent cathode, and a tungsten anode, said anode deprived of ionizable gas disengageable by electron bombardment, and the space in said envelope being evacuated to a sufficiently low pressure so that current flow produces substantially no phenomena of positive ionization when the impressed voltage is as high as 100 volts and the current is as large as 1 milliampere, and the energy of the discharge is delivered mainly upon said anode.

17. An electron discharge apparatus comprising an envelope, an electron emitting cathode, and an anode, said anode being free of gas disengageable by electron bombardment and said envelope being sufficiently free of gas, so that conduction of current can take place in the evacuated space independently of gas ionization at voltages materially above the ionizing voltages with currents of more than one-tenth of a milliampere, and with the energy of the discharge delivered mainly at said anode.

18. An electrical discharge device comprising a sealed envelope, a cathode, means for producing emission of electrons at said cathode independently of the operating voltage, an anode, and discharge varying means independent of the cathode and anode, said device being freed from gas to such extent that the same is operable to transmit current at an impressed voltage at least as high as about 200 volts without evidences of substantial positive ionization.

19. An electrical discharge device comprising a sealed envelope, an incandescent cathode, an anode and discharge-varying means independent of the cathode and anode, the gas residues in said device being so small that the conduction of current is stable and reproducible over a range of voltage materially above the ionization voltages with currents in excess of one milliampere and with the energy of the discharge delivered mainly upon electrodes.

20. An electrical device comprising the combination of a sealed evacuated envelope, a cathode adapted to be independently heated, and an anode within said envelope,

an external circuit connected to said electrodes, and a source of electro-motive force applied to said circuit, the degree of vacuity and the electron emission of the cathode being so related to the potential of said source that the flow of current over a range of voltage materially above the ionization voltage is governed by the electric field of the electrons in the vacuous space and the potential applied to said electrodes, operatively independent of gas ionization.

21. Apparatus for controlling an electric current comprising a vacuum tube, an anode and an electron emitting cathode in the circuit of said current and within said tube, the degree of evacuation of the tube and the relation of its parts being such that for voltages materially above ionization voltage the current is governed or limited by the electric field of the electrons in said tube substantially unaffected by positive ionization, and a third electrode in said tube by which an auxiliary controlling electromotive force may be superposed to modify the effect of said electric field and control said current in a stable and reproducible manner.

22. The method of controlling an electric current in one circuit by an electromotive force in another circuit which consists in causing said current at voltages materially above ionization voltages to pass as a discharge across a vacuous space between an electron emitting cathode and an anode, maintaining a high vacuum in said space, governing or limiting the current by a space charge effect in said space substantially unaffected by positive ionization, and superimposing the effect of said electromotive force on said space charge effect to control said current in a stable and reproducible manner.

23. A discharge device comprising a tube and electrodes therein, one of which is a cathode, the discharge passing in the main directly between electrodes, the degree of evacuation and the relation of the parts of the device being such that the device is capable of being so operated below saturation and at voltages materially higher than the ionization voltages, that the slope or location of the logarithmic line of current with respect to voltage is not changed by changes in the temperature of the cathode.

24. A discharge device comprising a tube and electrodes therein, one of which is a cathode adapted to be heated and to emit electrons thereby, the discharge passing directly between electrodes, the degree of evacuation and the relation of the parts of the device being such that the device is capable of being so operated below saturation and at voltages materially higher than the ionization voltage, that the plot of the current against the voltage is not changed with changes in the temperature of the cathode.

25. A discharge device comprising a

sealed off envelope having therein a cathode adapted to be heated independently of the discharge and to deliver electrons thereby, and an anode, the inner wall of the envelope and the electrodes being sufficiently free of occluded gas, and the free gas within the envelope being such, so that the finished device is capable of sustained operation below saturation in a stable and reproducible manner with currents of more than one milli-ampere at voltages materially higher than the ionization voltages and with the energy of the discharge delivered mainly at an electrode or electrodes.

26. A discharge device comprising a sealed off envelope and electrodes therein, the envelope being shaped and the electrodes located so that the energy of the discharge is delivered mainly upon one or more of the electrodes, the inner wall of the envelope and electrodes being so free from occluded gas and the pressure in the tube being sufficiently low, with respect to the spacing of the electrodes and the energy of the discharge, so that the device is capable of passing a sustained discharge of one tenth of a milliamperere at forty volts, without developing any substantial positive ionization effects.

27. A discharge device comprising a sealed off envelope and electrodes therein, one of which is a cathode adapted to be heated independently of the discharge and to emit electrons thereby, the inner wall of the envelope and the electrodes being so free from occluded gas that the device is capable of passing a sustained discharge of one milliamperere at fifty volts with the energy of the discharge delivered mainly at an electrode or at electrodes without liberating any substantial amount of gas into the space within the envelope.

28. A discharge device comprising a sealed-off envelope and electrodes therein, one of which is a cathode adapted to be heated independently of the discharge and to emit electrons thereby, the inner wall of the envelope and the electrodes being so free from occluded gas that the device is capable of passing a sustained discharge of two milliampereres at one hundred volts with the energy of the discharge delivered mainly at an electrode or at electrodes without liberating any substantial amount of gas into the space within the envelope.

29. An electrical discharge device comprising a gas-tight envelope, a cathode adapted to be heated to incandescence, an anode from which substantially no ionizable gas can be evolved at operating voltages up to forty volts with currents up to one-tenth milliamperere, the envelope so shaped and the electrodes so positioned as to substantially avoid secondary electron emission from the wall of the envelope, the space in said en-

velope being evacuated to a pressure not in substantial excess of a few hundred thousandths of a millimeter of mercury.

5 30. In the process of producing a discharge device, removing the occluded gas from the interior surface of the envelope thereof and from the electrodes to such an extent that the finished sealed-off device will operate, without liberating any substantial
10 amount of gas into the space within the envelope, at voltages materially above the ionization voltage with currents greater than one milliamper and with substantially all the energy of the discharge delivered to an
15 anode or anodes.

31. In the process of producing a hot cathode discharge device, treating the interior surface of the envelope and the operating parts to liberate therefrom occluded gas,
20 and removing from the envelope gas liberated by said treatment and free gas originally contained therein, continuing these operations until the occluded and original free gas is so thoroughly removed as to enable
25 the finished sealed-off device to operate below saturation in a stable and reproducible

manner at a voltage above fifty volts and with a current greater than one milliamper and with the energy of the discharge delivered mainly at one or more anodes.

32. The process of producing a discharge device which consists in treating the envelope and enclosed parts thereof to liberate gas therefrom and removing from the envelope gas which is thereby liberated and
35 free gas originally contained in the envelope, the treatment being sufficiently powerful and being sufficiently prolonged and the removal of the liberated and original free gas from the envelope being sufficiently
40 thorough, so that the finished sealed-off device is capable of sustained operation substantially without positive ionization at voltages as high as one hundred volts with currents as great as one milliamper and
45 with substantially the entire energy of the discharge delivered upon the anode or anodes of the device.

In witness whereof, I have hereunto set my hand this 15th day of October 1913.

IRVING LANGMUIR.