March 3, 1936. I. LANGMUIR 2,032,620

ELECTRON DISCHARGE APPARATUS

Original Filed Sept. 2, 1930

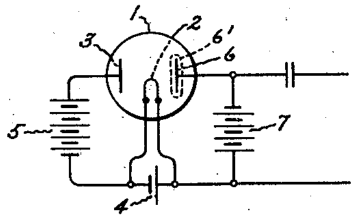


Fig. 1

Fig. 2

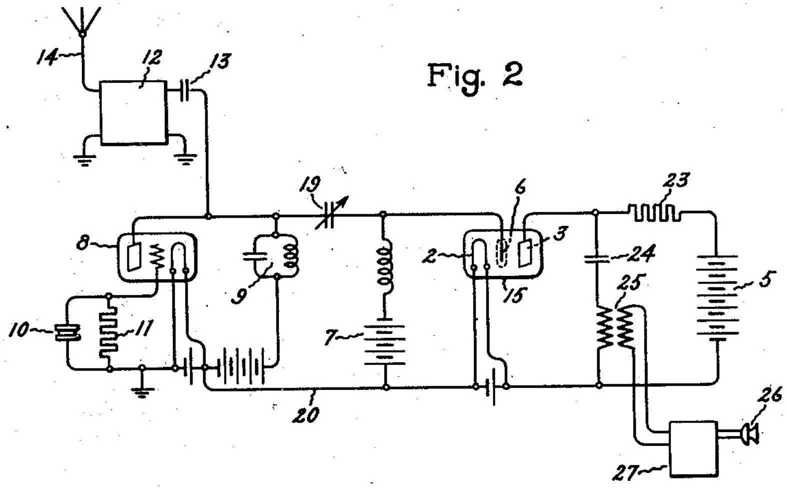


Fig. 3

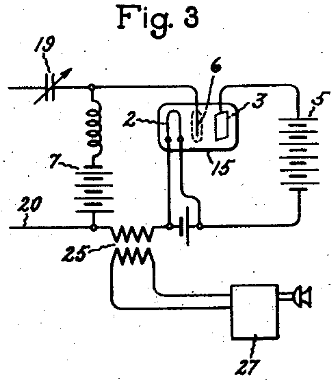


Fig. 4

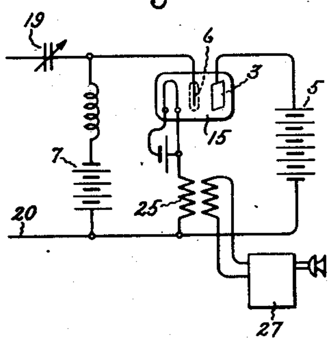
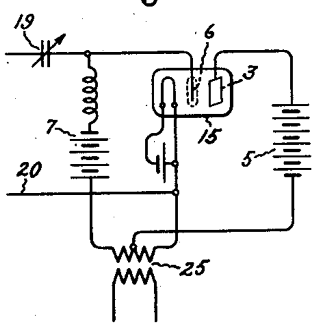


Fig. 5



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Patented Mar. 3, 1936

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UNITED STATES PATENT OFFICE

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ELECTRON DISCHARGE APPARATUS

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Application September 2, 1930, Serial No. 479,228
Renewed July 30, 1935

25 Claims. (Cl. 179—171)

My invention relates to electron discharge apparatus and more particularly to the use of an electron discharge device as a capacitance.

In an article published in the General Electric Review for November of 1923, pages 731 to 735, I have explained the phenomenon that when a negatively charged electrode is placed in a strongly ionized gas at low pressure it becomes covered with a sheath of positive ions, the volume of which is substantially free from negative electrons. While the causes of the formation of this sheath are already well known, they will be briefly stated hereinafter.

I have found that this sheath has a certain capacitance and that it may be utilized in electrical circuits for the same purposes for which condensers of ordinary construction may be utilized and that it has many uses to which a condenser of ordinary construction cannot be applied. Thus by analogy with the condenser of ordinary construction the plates of the condenser of my invention are constituted by the electrode itself and the outer surface of the positive ion sheath, the voltage between the electrodes of the condenser being the voltage across the sheath.

The capacitance of the condenser of my invention, however, in contradistinction to the condenser of ordinary construction is independent of the relative position of opposite mechanical electrode members and may be controlled electrostatically, as will be later explained.

Thus as a part of my invention I have discovered that a capacitive effect results from the natural distribution of negative electrons and positive ions about a negatively charged electrode in an ionized gas. Thus one of the objects of my invention is to provide a novel form of condenser in which the capacitive effect is due to the behavior of negative electrons and positive ions about a negatively charged electrode. Another of the objects of my invention is to utilize this capacitance; i. e. this positive ion sheath which is thus formed in electrical circuits for purposes for which condensers of ordinary construction and of comparable capacitance have heretofore been utilized.

Still a further object of my invention is to provide a condenser the capacitance of which may be controlled electrically, and of which the capacitance may be varied at rates independent of the inertia of mechanically moving parts.

A further object of my invention is to provide means whereby the capacitance of the positive ion sheath formed as above indicated may be varied and controlled in any desired manner, as for example in accordance with desired signals whereby it may be utilized in electrical circuits for frequency control purposes and the like.

Still a further purpose of my invention is to provide a method and means whereby the frequency of oscillation of an oscillation generator may be controlled in accordance with the capacity of the positive ion sheath formed upon such an electrode.

The novel features which I believe to be characteristic of my invention are set forth with particularity in the appended claims. My invention itself, however, both as to its organization and method of operation together with further objects and advantages thereof may best be understood by reference to the following description taken in connection with the accompanying drawing in which Fig. 1 represents an electron discharge device which may be employed in accordance with my invention; Fig. 2 represents a signal system employing a capacitance of the type to which my invention relates to control the frequency of an oscillation generator; and Figs. 3, 4 and 5 represent different modifications thereof.

With reference to Fig. 1 of the drawing, I have shown therein an electron discharge device comprising an evacuated envelope 1 which is filled with an attenuated gas such as mercury vapor, or any of the so-called inert gases. To cause ionization of the gas, a heated cathode 2 and an anode 3 are arranged within the envelope, the cathode being heated by a source of electromotive force 4 and the anode being maintained at a suitable positive potential with respect to the cathode, sufficient to maintain ionization of the gas, by the source of electromotive force 5. At 6 I have shown an additional electrode arranged within the vessel 1 and which is maintained at a negative potential with respect to the cathode by a source of electromotive force 7.

The gas within the vessel of the discharge device preferably is sufficiently attenuated to cause approximately uniform ionization throughout the volume of the gas. However, if the discharge device be one, having the form of, or in which the discharge takes place in a column, such for example as those used primarily for purposes of illumination, somewhat higher gas pressures may be employed. The electrode upon which the sheath forms may then be placed within the highly ionized region about the discharge column.

As thus arranged, and as explained in the above cited publication, a positive ion sheath, the surface, or boundary of which I have indicated by a dotted line 6', is formed about the electrode 6. This sheath is the result of the fact that negative electrons, which are moving about in the ionized gas, are prevented from approaching near the electrode 6 by the negative charge which is impressed thereon by the battery 7. On the other hand the positive ions which are moving about in the ionized gas may freely approach and fall into the electrode 6. The resulting current through the battery 7, however, is very small since it is carried entirely by positive ions. Thus there is a layer of gas about the electrode which, for the present purposes, may be understood to be free from electrons and to contain only positive ions, this layer of gas thus constituting the positive ion sheath.

This positive ion sheath has a definite thickness. Its thickness is of course dependent upon the negative potentinal of the electrode 6 and, as we will presently see, upon the intensity of the ionization of the gas. Thus about the negatively charged electrode 6 there is an electric field. This field extends out to such a distance that it is exactly neutralized by the field of the positive ions in the surrounding gas. In other words, we may assume that each line of force projecting from the electrode 6 must terminate in a positive ion in the sheath. Thus the less the intensity of ionization of the gas the farther the electric field of the electrode extends and the thicker the positive ion sheath, whereas the greater the intensity of ionization of the gas the thinner the positive ion sheath. The thickness of this sheath may be calculated from the space charge equations as indicated in my above mentioned article and may be shown to be equal to $0.0015 \frac{V^{3/4}}{I^{1/2}}$ centimeters where V is the voltage across the sheath and I is the positive ion current in amperes per square centimeter of electrode surface.

Thus the thickness of the sheath may be controlled and varied as desired by variation of either or both of the two sources of potential 5 and 7, the former controlling the intensity of ionization of the gas and the latter controlling the charge upon the electrode 6.

As above stated I have found that this positive ion sheath also has a certain capacitance which may be calculated and measured. Thus this sheath may be visualized as a non-conductive region, since electrons cannot enter it, between two conductive surfaces, one being the electrode 6 carrying a negative electron charge and the other being the surface of the sheath which is at the potential of the gas within the envelope, that is, with gases at low pressure, at approximately the potential of the anode 3. This gas is conductive since negative electrons are moving freely about in it. As such this sheath is in reality a condenser. The distance between the plates of the condenser, that is, the thickness of the sheath, however, varies with the voltage upon the electrode and with the intensity of ionization of the surrounding gas as already explained and hence the capacitance of the condenser varies in accordance with this electrode potential and the intensity of ionization of the gas.

Since the thickness of the sheath can be readily determined as above indicated, the capacity thereof may of course be calculated from well known considerations with respect to condensers and has been found to be equal to $\frac{0.09}{X}$ micro-farads per square centimeter where X is the thickness of the sheath in centimeters.

This value of the capacitance of the sheath, however, is true only in that range of frequencies of the controlling electromotive force impressed either on the electrode 6, or anode 3, which is so high that the relatively slow moving positive ions cannot adjust themselves in accordance with the instantaneous voltage. In other words, this value of capacitance is true only in that range of frequencies in which the period of the alternating current cycle is short as compared with the time required for a positive ion to traverse the sheath.

On the other hand over the range of frequencies in which the positive ions are able to adjust themselves in accordance with the instantaneous voltage and are therefore continuously in a state of substantial equilibrium, the capacitance of the sheath has a value equal to one-third of the former value.

Between these two frequency ranges there appears a somewhat critical frequency or, narrow band of frequencies, of which the period of the cycle is comparable with the period required for a positive ion to traverse the sheath. In this range of frequencies the capacitance of the sheath shifts from one of the above mentioned values to the other and it probably bears within this band, a proportionate relationship to the frequency.

The electrode 6 may of course be of any suitable construction and may desirably have the form of a plate or grid.

Referring to Fig. 2, I have shown a signaling system in which signals are transmitted by variation of the frequency of the transmitted oscillations, the frequency of these oscillations being controlled by a capacitance of the type herein discussed. I have represented at 8 in this figure an electron discharge device of the three-element type having an oscillatory circuit 9 connected between the anode and cathode thereof, and a piezo electrical crystal 10 connected between the grid and cathode. Also connected between the grid and cathode is the usual grid leak resistance 11.

As thus arranged oscillations are produced in the oscillatory circuit 9 as the result of oscillatory electromotive force produced upon the grid of the discharge device through vibration of the piezo electric crystal. These oscillations may be supplied to a suitable amplifier or frequency multiplier 12 through a coupling condenser 13, from which they may be supplied to any suitable load circuit which is represented in the drawing as an antenna 14.

In order to vary the frequency of the oscillations generated by the device 8, I have shown an electron discharge device 15 arranged to serve as a capacity in shunt with the oscillatory circuit 9 of the oscillation generator 8. This discharge device is of the type shown in Fig. 1 and has its third electrode 6 connected to one side of the oscillatory circuit 9 through a coupling condenser 19, and its cathode 2 connected to the cathode of device 8 through the conductor 20. Thus the space between the third electrode and cathode of discharge device 15 may be considered as connected in parallel with the oscillatory circuit 9. The third electrode 6 is maintained at a strong negative potential with respect to the cathode by means of a battery 7 as in Fig. 1 and the anode of the device 15 is maintained at a positive potential by means of a source of potential 5, this source of electromotive force being connected between the cathode and anode through a suitable inductance or resistance 23. Thus the previously discussed positive ion sheath is formed about the third electrode 6 the capacity thereof being in shunt with the oscillatory circuit 9.

In order to vary the frequency of the oscillator 8, the circuit comprising a blocking condenser 24 and the secondary winding of a transformer 25 is connected between the anode 3 and the cathode 2. The primary winding of the transformer 25 is energized with voice frequency currents which may be generated by means of a telephone transmitter 26 and amplified by means of an amplifier 27. As thus arranged it will be seen that the frequency of oscillations is determined by the crystal 10 and the tuning of the oscillatory circuit 9, the capacitance of the positive ion sheath about electrode 6 being considered as a part of the oscillatory circuit 9. When voice waves are impressed upon the anode 3 by means of the transformer 25 and condenser 24, the anode potential of course varies and thereby varies the degree of ionization of the gas within the discharge device 15. This in turn causes an expansion and contraction of the positive ion sheath in accordance with the voice signals, this variation serving to control the frequency of the oscillation generator correspondingly. Thus the frequency of the oscillations produced is modulated in accordance with the voice waves, the frequency being multiplied by the frequency multiplier 12.

It will be noted, however, that in the arrangement of Fig. 2 two partially compensating effects are produced. The control electromotive force being applied between the cathode and anode not only controls the degree of ionization of the gas but it also controls the potential difference across the sheath. This follows, of course, from the fact that the outer surface of the sheath is substantially at the potential of the anode whereas the electrode 6 is maintained at a definite potential with respect to the cathode. An increased potential upon the anode has the effect of increasing the ionization of the gas and hence diminishing the thickness of the sheath. On the other hand, the increased potential difference across the sheath, which results from increasing the potential of the anode, has the effect of increasing the thickness of the sheath. Thus the change in capacitance is due to a resultant of, or difference between, these two effects.

In Fig. 3 I have shown a modification of the arrangement shown in Fig. 2 in which the secondary winding of transformer 25 is connected between the cathode and the third electrode, or grid 6 of the device 15. Thus in this figure the degree of ionization of the gas is maintained constant whereas the voltage across the sheath is varied. Thus the change in capacitance is due to this single effect.

This latter manner of control of the capacitance of the sheath possesses an additional advantage in that the current flowing between electrode 6 and the cathode is very minute, the desired control being effected entirely by variation of potential upon the electrode 6. On the other hand a certain amount of current necessarily flows from the cathode to the anode 3 to produce the desired ionization of the gas within the vessel. The variation in the capacitance is brought about in the arrangement of Fig. 2 largely through variation of this current. Thus larger potential variations are necessary to bring about the desired variations of capacity. Further the anode potential being constant in the arrangement of Fig. 3, there is no danger of the ionization of the gas becoming interrupted, whereas with the arrangement of Fig. 2, to avoid distortion of the transmitted signals, the minimum potential of the anode must be sufficiently high to maintain the ionization of the gas.

In Fig. 4 I have shown still a further modification of the invention in which the secondary winding of transformer 25 is connected in a lead common to the circuit of both the anode 3 and electrode 6. Thus in this figure when the positive potential of the anode is increased the negative of the electrode 6 is correspondingly decreased. The potential difference across the sheath thus remains constant, the change in capacitance being due entirely to change in ionization of the gas.

In Fig. 5 I have shown a further modification of my invention in which the anode is connected to an intermediate point upon the secondary winding of transformer 25 of either Fig. 3 or Fig. 4. In this way the effects mentioned in connection with these figures are combined in aiding relation. Thus in this figure the right hand portion of the secondary winding is connected in the circuit of both the anode 3 and electrode 6. It therefore has the effect described in connection with Fig. 4, namely, a change in gas ionization without a change in voltage across the sheath. On the other hand the left hand portion of the secondary winding is connected solely in the circuit of electrode 6 and accordingly has the effect described in connection with Fig. 3, namely, a change in voltage across the sheath without change in gas ionization. Since an increase in ionization of the gas due to the right hand portion of the secondary winding occurs simultaneously with a decrease in voltage across the sheath due to the left hand portion of the secondary winding, and since these two effects both tend to decrease the thickness of the sheath and increase its capacitance, it will be seen that the two voltages act in aiding relation.

While I have shown a particular application of my invention in which the discharge device 15 is utilized to control the frequency of a crystal oscillator, it will of course be understood that it is not to be limited thereto since the condenser provided in accordance with my invention may be employed for practically any of the purposes for which an ordinary condenser, of comparable capacitance may be used. Similarly, while I have shown particular modifications of the invention, it will be understood that these modifications have been selected for the purpose of clearly illustrating the principles involved and that I do not wish to be limited thereto since many modifications of the invention may be made. I contemplate by the appended claims to cover my invention in any of its various applications together with any such modifications thereof as fall within the true spirit and scope of my invention.

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

1. The combination, with an electric circuit requiring capacity connected between a pair of terminals, of an electron discharge device comprising an envelope containing ionized gas, an electrode arranged in said electron discharge device and connected to one of said terminals, and means for maintaining said electrode at a negative potential with respect to the potential of said gas, the

other of said terminals being connected to a second electrode in said discharge device whereby a positive ion sheath is formed about said first mentioned electrode, said negative potential and the intensity of ionization of said gas being so adjusted as to cause said sheath to have the capacitance required by said circuit.

2. A condenser, comprising a vessel filled with attenuated gas, a plurality of electrodes arranged within said vessel, means for energizing certain of said electrodes thereby to produce ionization of said gas, means to maintain another of said electrodes at a potential sufficiently negative with respect to the potential of said gas to cause a positive ion sheath to form upon said other electrode, one of the terminals of said condenser being connected to said other electrode, and the other terminal being connected to a different one of said electrodes in conductive relation with the gas.

3. The method of controlling the capacity of a condenser comprising a vessel filled with ionized gas and an electrode within said vessel maintained at a negative potential with respect to said gas, which includes controlling the intensity of ionization of said gas in accordance with the capacity desired.

4. The method of controlling the capacity of a condenser comprising a vessel filled with ionized gas and an electrode within said vessel maintained at a negative potential with respect to said gas, which includes controlling the negative potential upon said electrode in accordance with the capacity desired.

5. The method of controlling the capacity of a condenser comprising a vessel filled with ionized gas and an electrode within said vessel maintained at a negative potential with respect to said gas, whereby a positive ion sheath is formed upon said electrode which includes controlling the thickness of said sheath in accordance with the capacity desired.

6. The method of controlling and utilizing the reactance of a capacity utilization circuit, which includes an electron discharge device having electrodes spaced apart and connected in said circuit which includes varying the actual capacity within said device between the electrodes thereof by variation of the potential between certain of said electrodes, said variation of potential being sufficient to produce a reactance variation of a desired amount to be utilized in said circuit.

7. The method of controlling the reactance of an electric circuit, which includes an electron discharge device having electrodes spaced apart in an atmosphere of ionized gas and connected in said circuit which includes controlling the distribution of ions and electrons about one of said electrodes to produce desired capacitance in said circuit.

8. The method of controlling the reactance of an electric circuit including an electron discharge device having electrodes spaced apart in an atmosphere of ionized gas and connected in said circuit, which includes impressing a potential upon one of said electrodes negative with respect to the potential of the gas and varying said potential in accordance with the capacity desired.

9. In combination, an oscillation generator, an electron discharge device comprising a vessel containing ionized gas, means for varying the intensity of ionization of said gas, and means for controlling the frequency of said generator in accordance with the intensity of ionization of said gas.

10. In combination, an oscillation generator, an electron discharge device comprising a vessel containing a gas, an electrode arranged in said gas, means for causing a positive ion sheath to form about said electrode and means for controlling the frequency of said generator in response to the thickness of said sheath.

11. The method of varying the capacity of a glow discharge tube which includes varying the potential applied between an electrode within said glow discharge tube and another electrode of said tube in accordance with the desired variations in capacity and utilizing said desired capacitance variations.

12. In combination, a condenser comprising a plurality of electrodes, an ionized gaseous medium interposed between said electrodes, and means to vary the state of ionization of said gaseous medium thereby to vary the capacity between said electrodes by a desired amount, and means to utilize the variation in capacity produced by said last means.

13. The method of varying the capacity of a condenser having an ionized gas interposed between electrodes of the condenser which includes varying the ionization of said gas by a proper amount to produce a desired variation of capacity, and utilizing said desired variation of capacity.

14. In combination, a vessel containing a pair of electrodes surrounded by an attenuated gas of such density as to produce substantial ionization, a third electrode, and means to vary the capacity between said third electrode and one of the electrodes of said pair by a desired amount, said means comprising means to vary the potential between said pair of electrodes by an amount sufficient to produce said desired amount of capacitance variation, and means to utilize said desired amount of capacitance variation.

15. In combination, a vessel containing a pair of electrodes surrounded by an attenuated gas of such density as to produce substantial ionization, a third electrode, and means to vary the capacity between said third electrode and one of the electrodes of said pair by a desired amount, said means comprising means to vary the potential between said third electrode and said one electrode by an amount sufficient to produce said desired amount of capacitance variation, and means to utilize said desired amount of capacitance variation.

16. The combination, with an electric circuit, requiring capacity connected between a pair of terminals, of an electron discharge device comprising a vessel containing ionized gas, and having a pair of electrodes connected to said terminals and disposed in cooperative relation with said gas, and means to control the state of said gas in accordance with the capacity required between said terminals.

17. The combination, with an electric circuit, requiring capacity connected between a pair of terminals, of an electron discharge device comprising a vessel containing ionized gas, and having a pair of electrodes connected to said terminals and disposed in cooperative relation with said gas, and means to control the potential between said electrodes in accordance with the capacity required between said terminals.

18. In combination, an electron discharge device comprising a vessel containing gas, means to subject said gas to an electromotive force, said gas having sufficient density to produce substantial ionization when exposed to said electromotive force, and said discharge device comprising

a surface in proximity to which a positive ion sheath forms due to ionization of said gas, and a capacity utilization circuit connected to utilize the capacity of said sheath.

19. In combination, an electron discharge device comprising a vessel containing gas, means to subject said gas to an electromotive force, said gas having sufficient density to produce substantial ionization when exposed to said electromotive force, and said discharge device comprising a surface in proximity to which a positive ion sheath forms due to ionization of said gas, and a circuit connected between said gas and surface requiring capacity having the value of the capacity existing between said surface and said gas.

20. In combination, an electron discharge device comprising a vessel containing gas, means to subject said gas to an electromotive force, said gas having sufficient density to produce substantial ionization when exposed to said electromotive force, and said discharge device comprising a surface in proximity to which a positive ion sheath forms due to ionization of said gas, a capacity utilization circuit connected to utilize the capacity of said sheath, and means to vary the ionization of said gas in accordance with capacity variations desired in said capacity utilization circuit.

21. In combination, an electron discharge device comprising a vessel containing gas, means to subject said gas to an electromotive force, said gas having sufficient density to produce substantial ionization when exposed to said electromotive force, and said discharge device comprising a surface in proximity to which a positive ion sheath forms due to ionization of said gas, a capacity utilization circuit connected to utilize the capacity of said sheath, and means to vary the thickness of said sheath in accordance with capacity variations desired in said capacity utilization circuit.

22. A variable substantially inertialess condenser comprising, a gaseous discharge tube having spaced electrodes immersed in a gas between which electrodes an electronic stream is designed to pass, a conducting plate located adjacent the path of said stream to form therewith the plates of a condenser, the capacity of which is measured by the intensity of said electron stream and a capacity utilization circuit connected to utilize said capacity.

23. A variable condenser comprising, a gaseous discharge tube having spaced electrodes immersed in a gas between which electrodes an electronic stream is designed to pass, a conducting plate located adjacent the path of said stream to form therewith the plates of a condenser, the capacity of which is measured by the intensity of said electron stream, leads passing through the walls of said tube to said spaced electrodes to apply thereto varying potentials which in turn vary the intensity of said electron stream, and leads connected to one of said electrodes and to said plate for applying the capacity variations produced between said stream and said plate to a utilization circuit.

24. A variable substantially inertialess condenser comprising, a gaseous discharge tube having spaced electrodes immersed in a gas between which electrodes an electronic stream is designed to pass, a conducting plate located in the path of said stream to form therewith the plates of a condenser, the capacity of which is measured by the intensity of said electron stream and a capacity utilization circuit connected to utilize said capacity.

25. A variable condenser comprising, a gaseous discharge tube having spaced electrodes immersed in a gas between which electrodes an electronic stream is designed to pass, a conducting plate located in the path of said stream to form therewith the plates of a condenser, the capacity of which is measured by the intensity of said electron stream, leads passing through the walls of said tube to said spaced electrodes to apply thereto varying potentials which in turn vary the intensity of said electron stream, and leads connected to one of said electrodes and to said plate for applying the capacity variations produced between said stream and said plate to a utilization circuit.

IRVING LANGMUIR.

Certificate of Correction

Patent No. 2,032,620. March 3, 1936.

IRVING LANGMUIR

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows: Page 2, first column, line 20, for "potentinal" read *potential*; and line 38, strike out

$$\text{``}\frac{V^{3/4}}{I^{1/2}}\text{''}$$

and insert the same before the word "centimeters" in line 41, first column; and second column, line 3, strike out

$$\text{``}\frac{0.09}{X}\text{''}$$

and insert the same after the word "to" in line 5, same column; page 3, second column, line 16, before "of" insert *potential*; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 12th day of May, A. D. 1936.

[SEAL]

LESLIE FRAZER,
Acting Commissioner of Patents.