Sept. 2, 1947. F. B. LLEWELLYN 2,426,626

ELECTRON DISCHARGE APPARATUS

Filed Oct. 29, 1942 2 Sheets-Sheet 1

FIG. 1

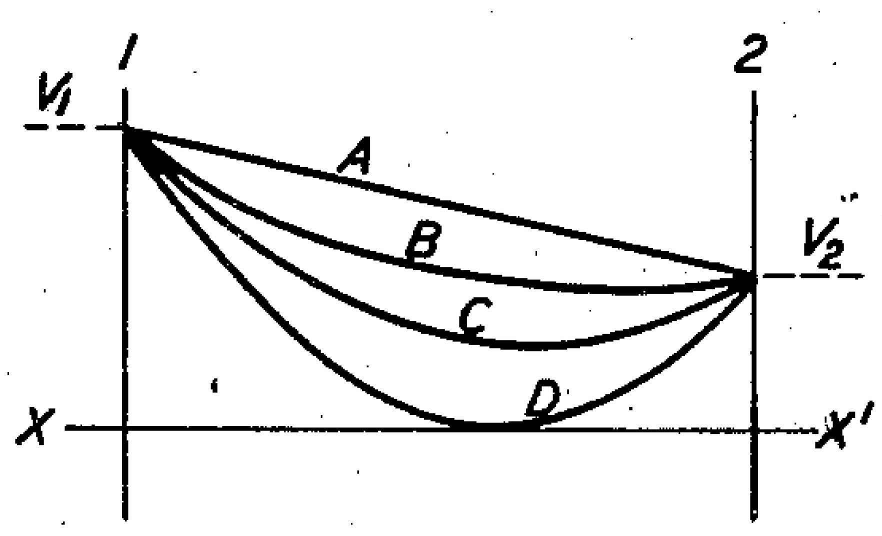


FIG. 2

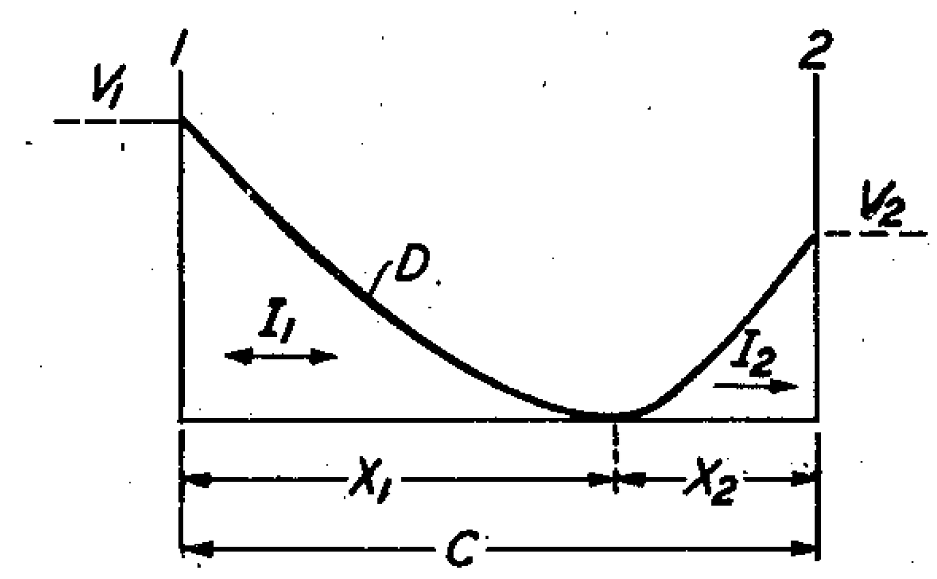


FIG. 3

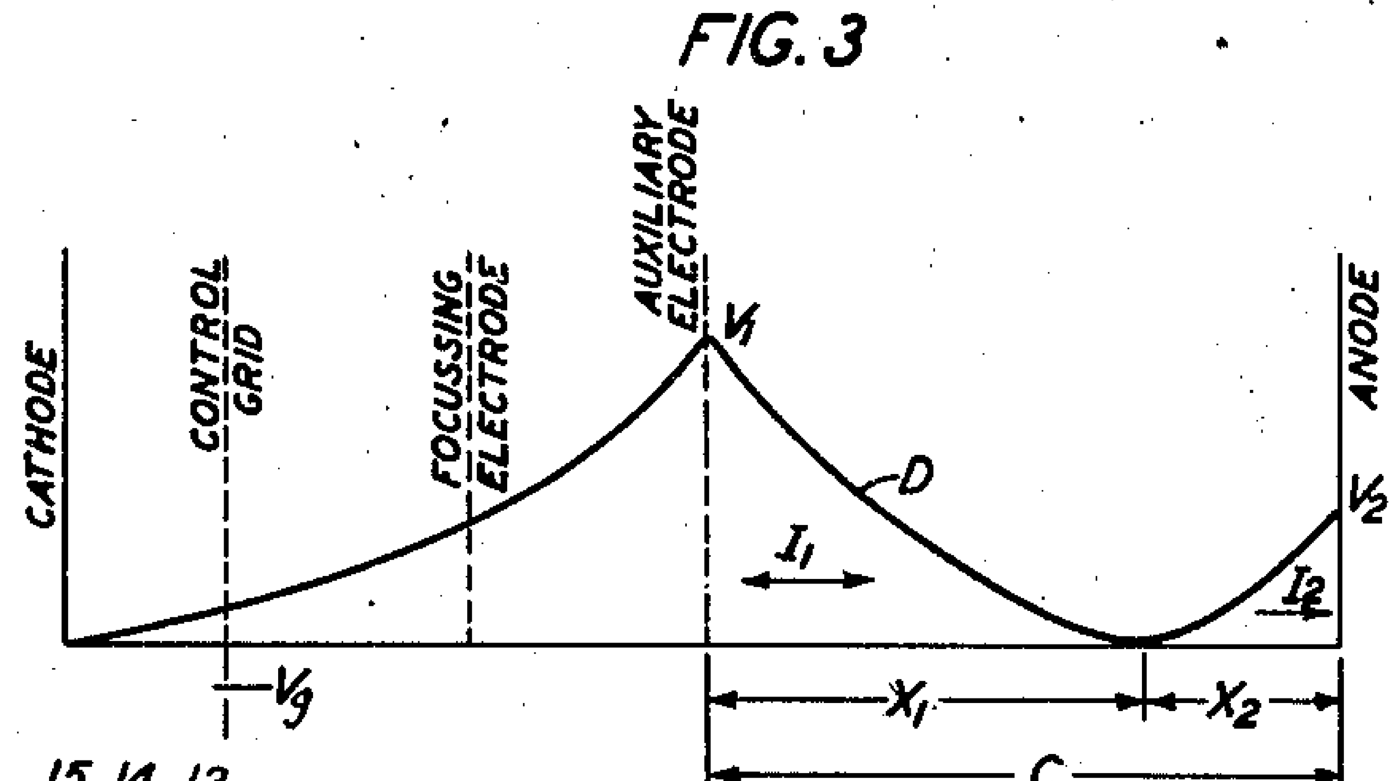


FIG. 11

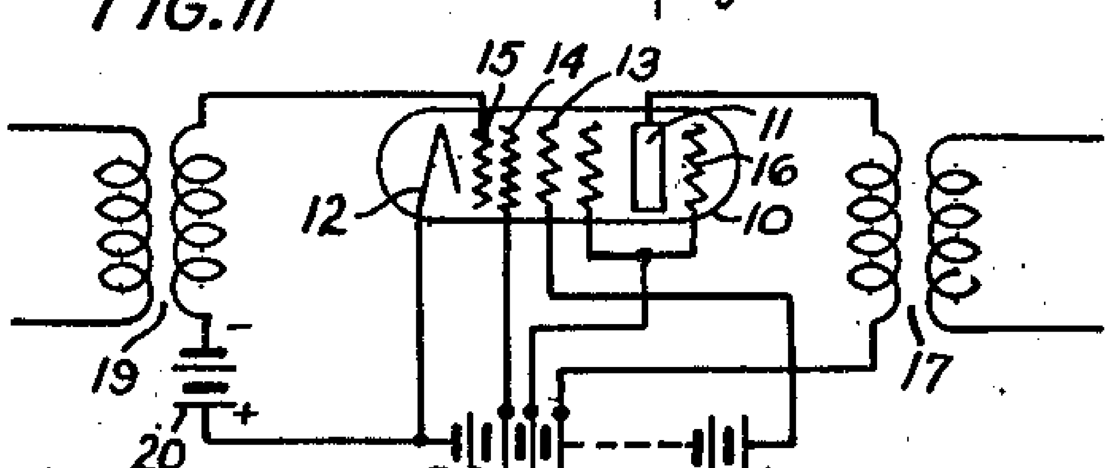


FIG. 4

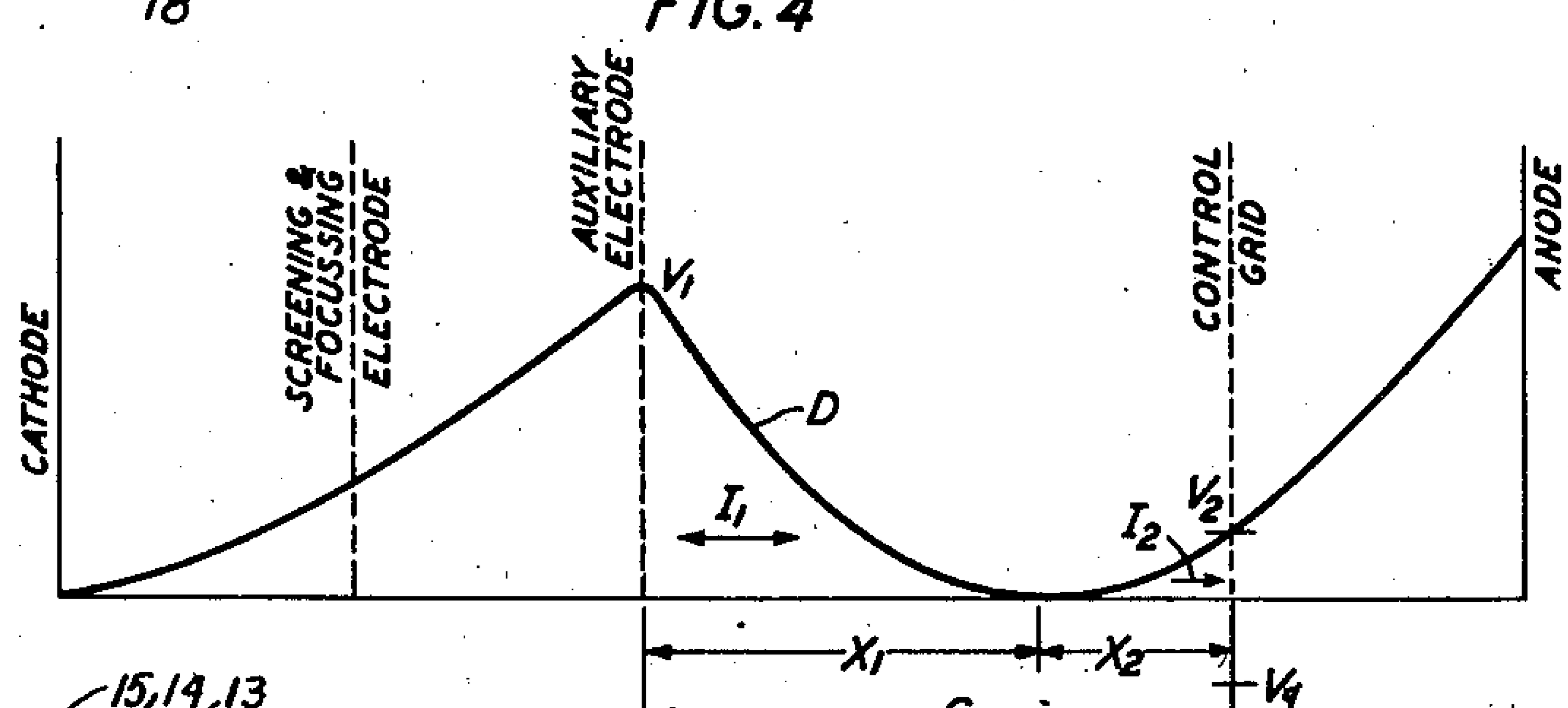
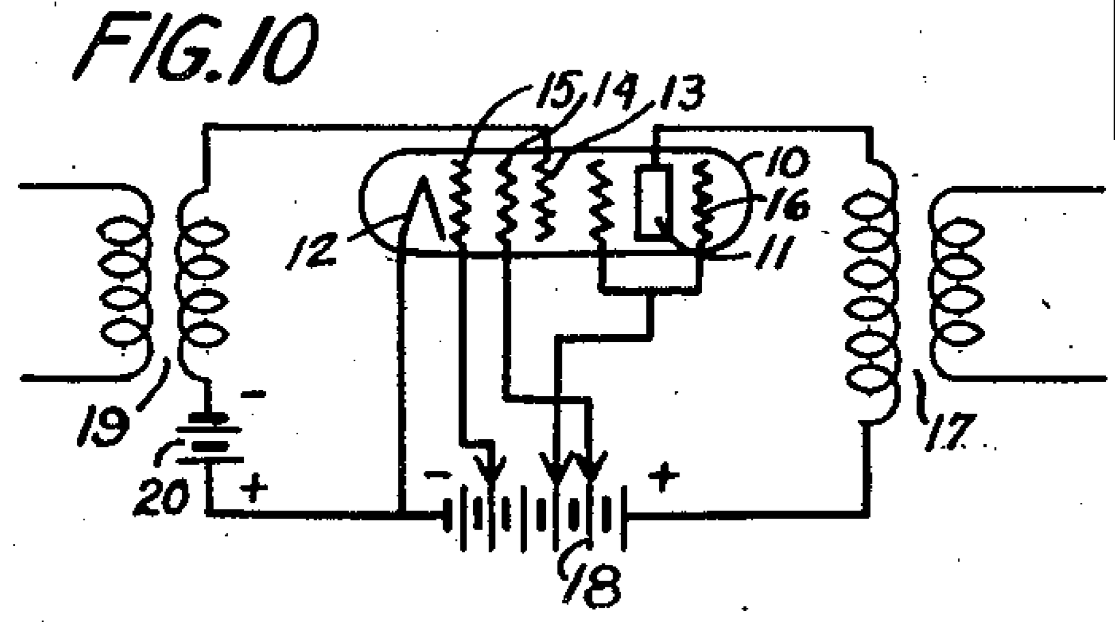


FIG. 10



INVENTOR
F. B. LLEWELLYN
BY
Walter C. Kiesel
ATTORNEY

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Filed Oct. 29, 1942 2 Sheets-Sheet 2

FIG. 5

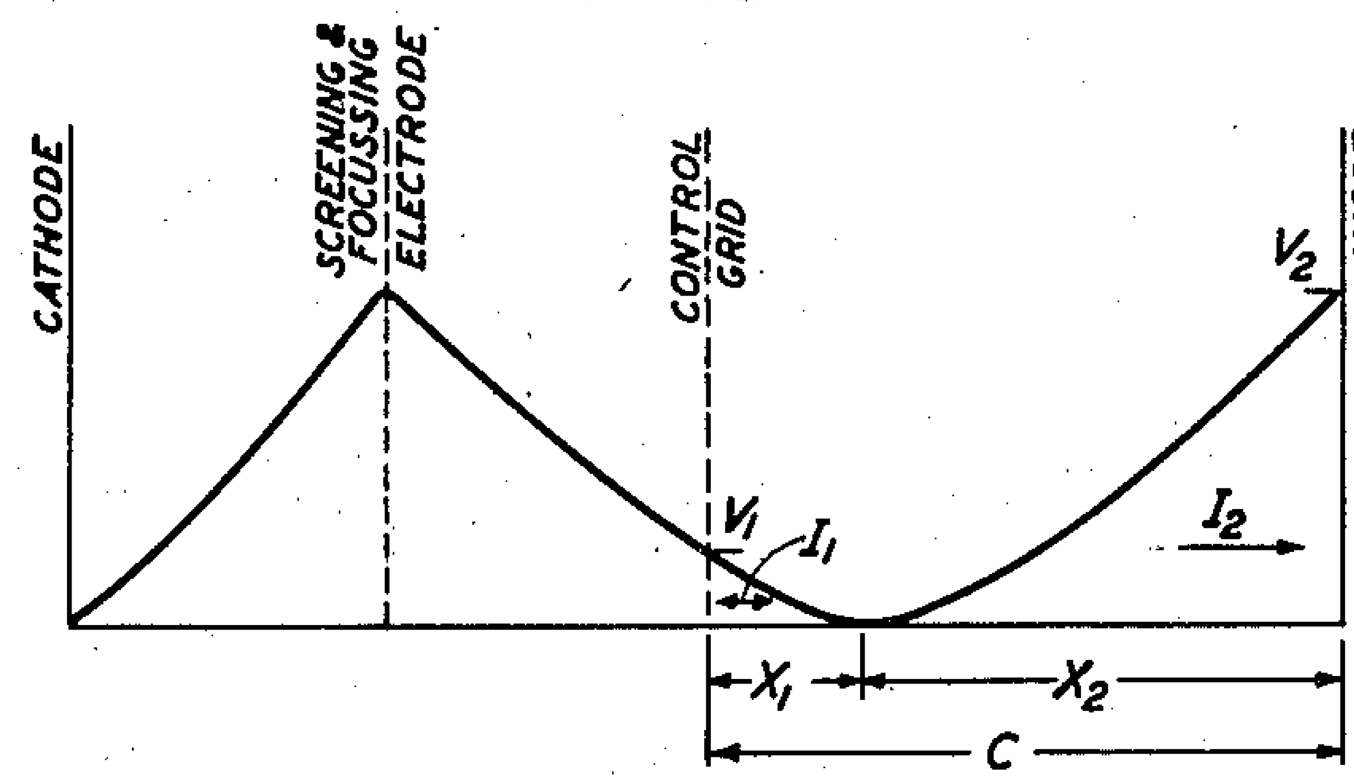


FIG. 8

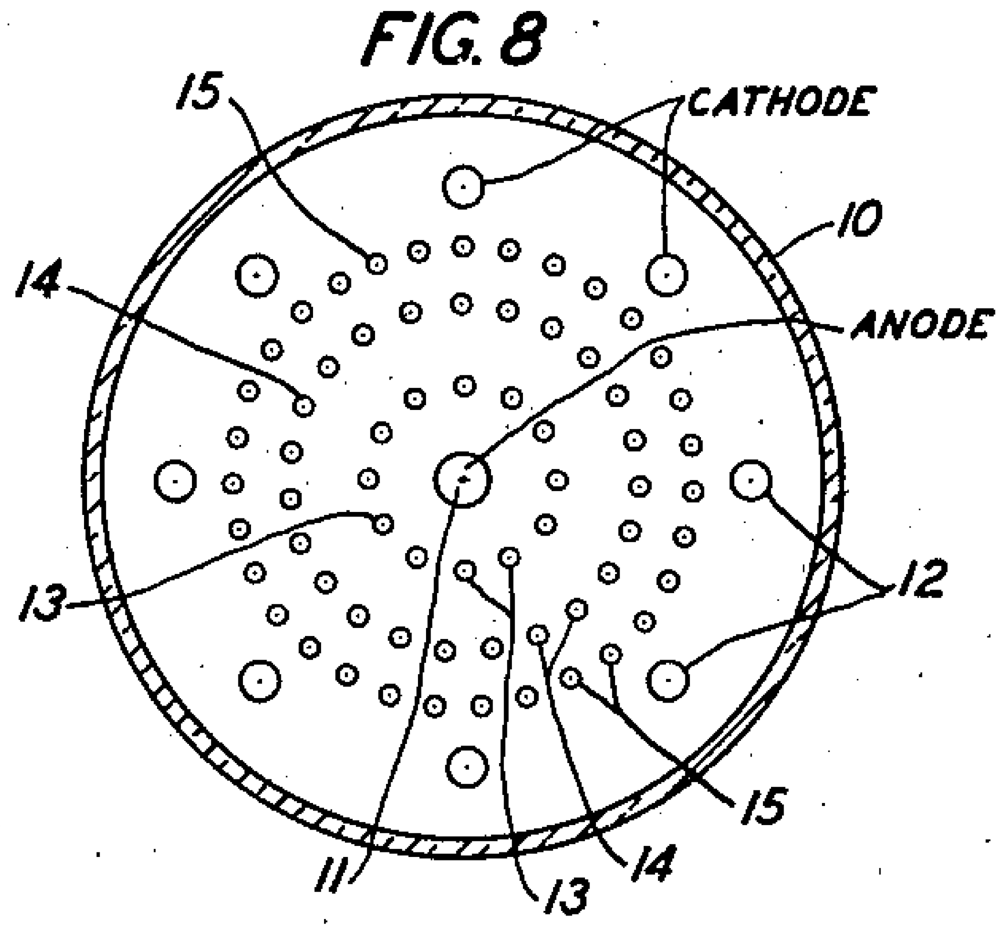


FIG. 9

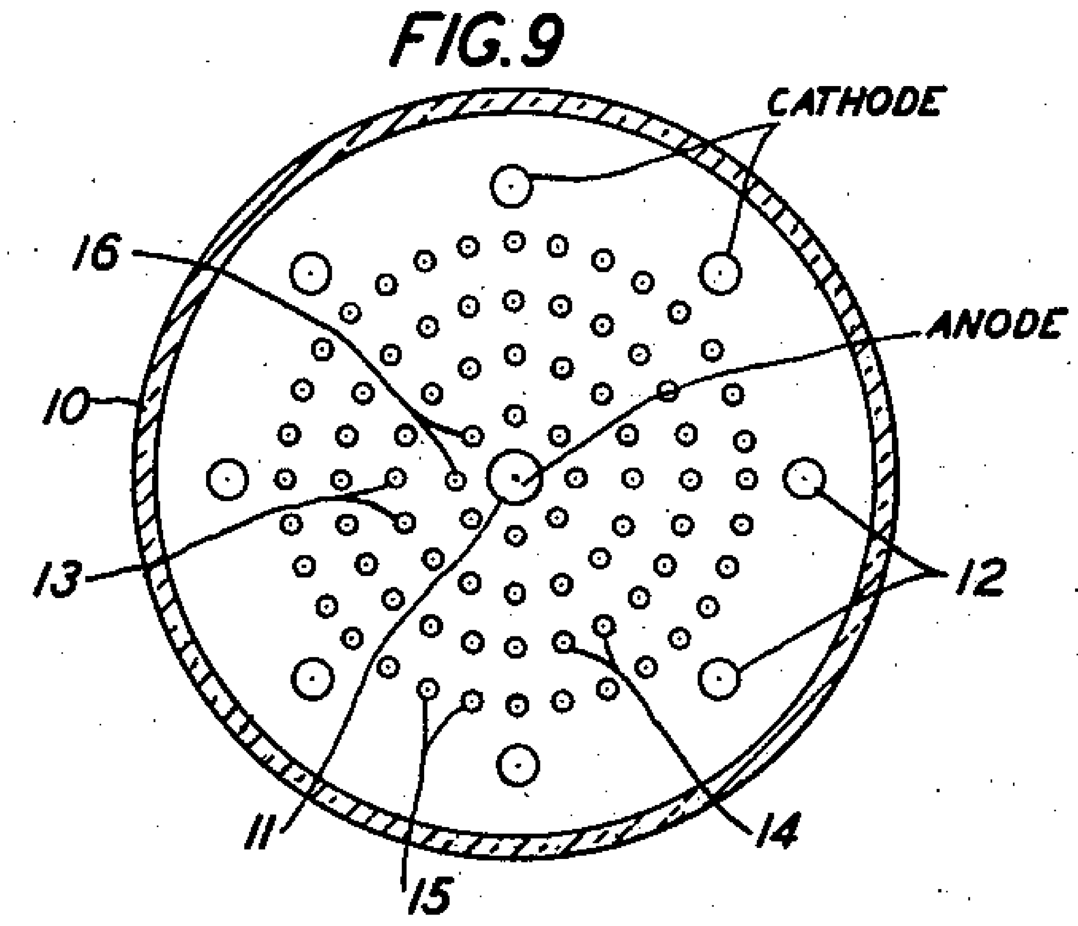


FIG. 6

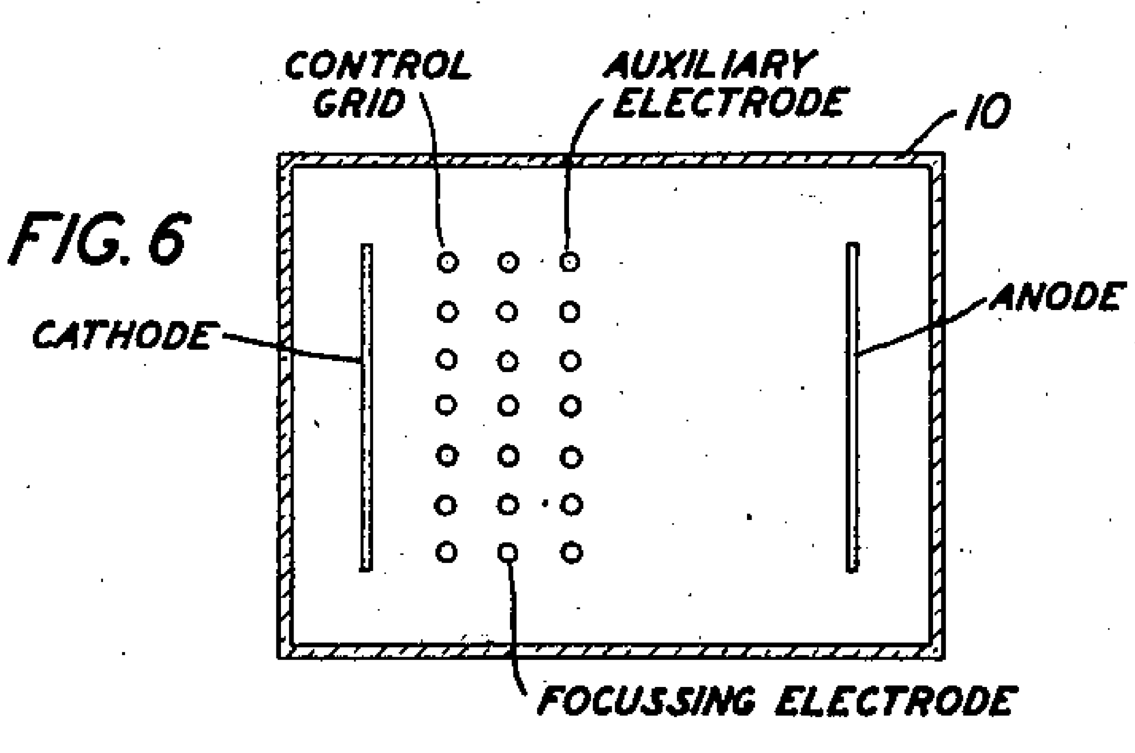


FIG. 7

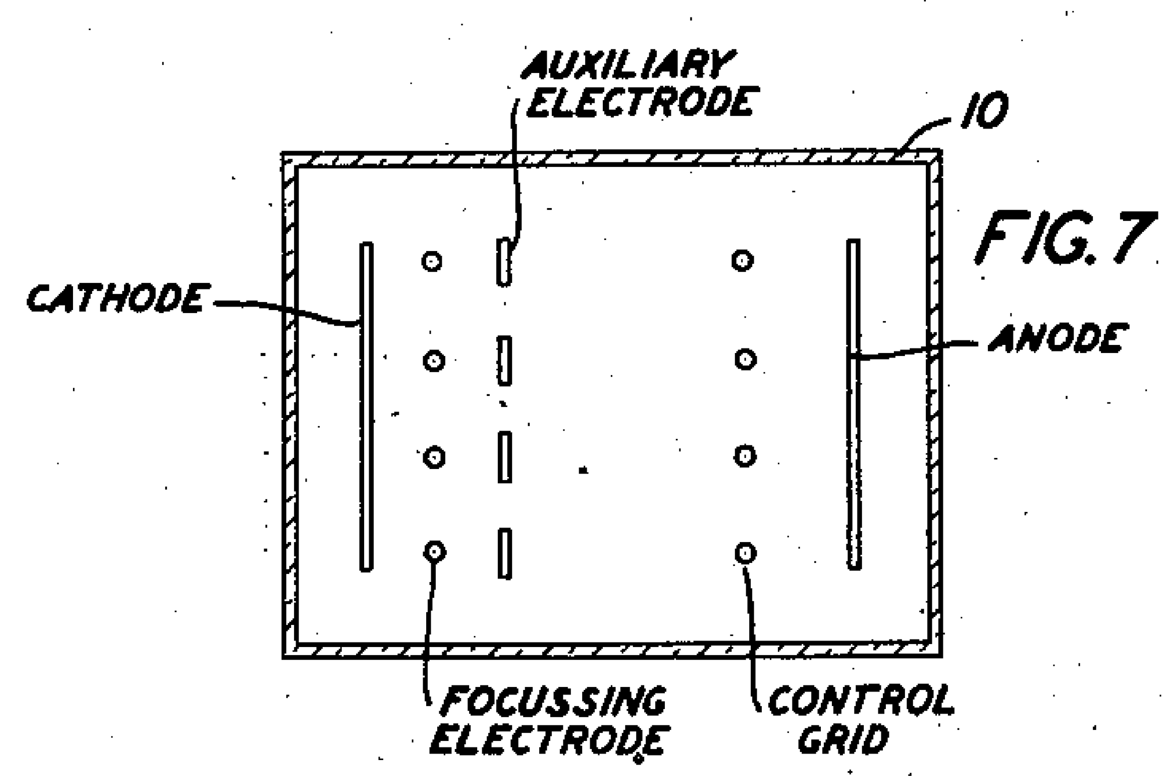
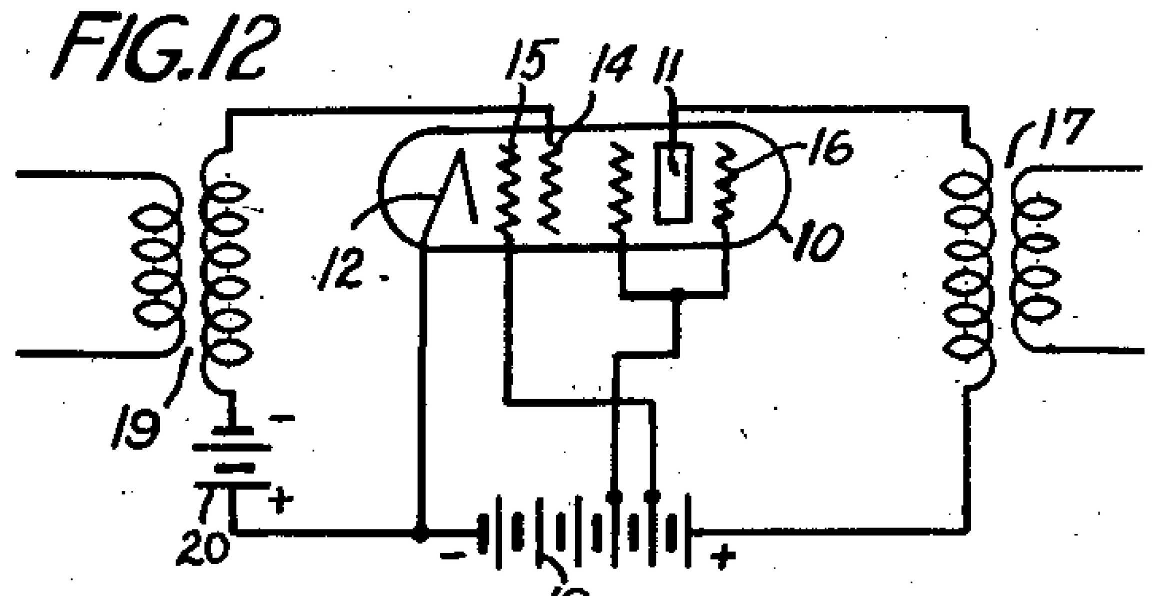


FIG. 12



INVENTOR
F. B. LLEWELLYN
BY
Walter C. Kiesel
ATTORNEY

Patented Sept. 2, 1947

2,426,626

UNITED STATES PATENT OFFICE

2,426,626

ELECTRON DISCHARGE APPARATUS

Frederick B. Llewellyn, Summit, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application October 29, 1942, Serial No. 463,823

17 Claims. (Cl. 179—171)

1

This invention relates to electron discharge apparatus and more particularly to electronic amplifiers including electron discharge devices of the space charge virtual cathode type.

In the number of fields of use of electron discharge apparatus, for example in amplifiers, it is highly desirable that signals within a wide band of frequencies be transmitted uniformly, faithfully and with high gain. A criterion for rating the efficacy of an electron discharge device as a transmission element is the figure of merit of the device, the figure of merit being defined as the ratio of the transconductance to the sum of the control electrode or grid and anode capacitances.

Space charge virtual cathode devices offer a possible means of obtaining large values of transconductance, either positive or negative in sign. However, known devices of this type are characterized by instability so that the advantages of the high transconductance are counterbalanced in a large measure by the disadvantages of instability and critical fluctuations with operating conditions.

The two factors, namely transconductance and capacitance, determinative of the figure of merit of an electron discharge device are related and, in general, in devices of conventional construction, when the parameters involved are correlated to effect an increase in the transconductance, this increase is accompanied by a substantially corresponding increase in the capacitance so that little, if any, effective change in the figure of merit results.

One general object of this invention is to obtain a high figure of merit and stable operation for electron discharge devices. More specifically, objects of this invention are to:

Increase the transconductance of electron discharge devices without proportionately increasing the interelectrode capacitances therein;

Obtain stable operation of high transconductance electron discharge devices of the virtual cathode type;

Obtain stable negative transconductance of high value in electron discharge devices;

Facilitate the formation of a virtual cathode in electron discharge devices having one or more space charge electrodes;

Substantially prevent feedback from the anode to the control electrode in space charge virtual cathode devices suitable for use in high frequency and high gain circuits; and

Realize a high operating efficiency for electron discharge devices of the space charge virtual cathode type.

2

In one illustrative embodiment of this invention, electron discharge apparatus comprises a device having a cathode, an anode, a control electrode, and one or more positively biased auxiliary or space charge electrodes pervious to electrons mounted between the cathode and the anode, appropriate potentials being applied to the various electrodes to result in the formation of a virtual cathode between the real cathode and the anode. The several electrodes may be substantially plane and parallel or cylindrical and coaxial.

In accordance with one feature of this invention, the several electrodes are so constructed and arranged that a substantially critical and appreciable portion of the electrons flowing in the device is collected or captured by the auxiliary electrode or electrodes, whereby very high values of transconductance with stable operation are achieved.

In accordance with another feature of this invention, the various electrodes are so constructed and arranged that less than a certain portion of the electrons are collected or captured by the auxiliary electrode or electrodes, whereby stable operation with a high negative transconductance is realized.

In accordance with a further feature of this invention, the control electrode is biased at such negative potential and the auxiliary electrode or electrodes and anode are biased at such positive potentials that a potential minimum is established between two positive electrodes, whereby a virtual cathode is formed between these two electrodes.

In accordance with still another feature of this invention, the electrodes are cylindrical and mounted in coaxial relation with the anode the innermost and the cathode the outermost electrode of the structure, whereby the formation of the virtual cathode, with relatively low emission currents, is facilitated and relatively small output capacitance is obtained.

The invention and the above-noted and other features thereof will be understood more clearly and fully from the following detailed description with reference to the accompanying drawing in which:

Figs. 1 and 2 are diagrams illustrating the potential distribution between two positive electrodes in a vacuum, for a number of space charge conditions;

Figs. 3, 4 and 5 are diagrams illustrating the potential distribution in electron discharge devices having one or more space charge grids and operated under such conditions that a virtual cathode is formed;

Figs. 6 and 7 are diagrammatic views of electron discharge devices illustrative of those constructed in accordance with this invention wherein the electrodes are substantially plane and parallel;

Figs. 8 and 9 are sectional views of electron discharge devices illustrative of those constructed in accordance with this invention wherein the electrodes are mounted in coaxial relation; and

Figs. 10, 11 and 12 are circuit diagrams showing illustrative manners of operating electron discharge devices constructed in accordance with this invention.

Referring to Fig. 1 of the drawing, if two plane electrodes 1 and 2, having positive potentials of V_1 and V_2, respectively, measured with respect to some reference axis X—X', are mounted in parallel relation in a vacuum and no electrons are present between these electrodes, the potential distribution between the electrodes may be represented by the straight line A. If electrons are injected into the region between electrodes 1 and 2 at the plane of electrode 1 and with a velocity in the direction of the X axis corresponding to the potential V_1, these electrons will move toward the electrode 2 and some or all of these electrons, depending upon the rate at which electrons are injected, will be collected by the electrode 2. For a relatively small injected current, the potential distribution between the electrodes may be represented by the curve B. If the rate at which electrons are thus injected, with the same velocity, is increased, the potential distribution curve will sag as represented by the curve C.

If the rate of injection is increased further, at some critical value, the potential distribution curve will sag sharply and touch the X axis as indicated by the curve D. If the rate of injection is increased still further beyond the critical value, the point at which the curve D touches the X axis shifts to the left or right in Fig. 1 in such a way that a varying number of electrons flow to the electrode 2 and the remainder turn back and are collected by the electrode 1. Effectively, therefore, when the critical value of injected current is reached, a virtual cathode is established in the immediate proximity of a plane parallel to the electrodes 1 and 2 and passing through the point where the curve D touches the X axis.

The conditions necessary for the establishment of a potential minimum, and, hence, for the formation of a virtual cathode may be determined from the following considerations, with reference particularly to Fig. 2. In this figure, curve D represents the potential distribution when a virtual cathode has been formed, X_1 and X_2 are the distances between the electrodes 1 and 2, respectively, and the point where the curve D touches the X axis, C is the distance between the electrodes, I_2 is the current flowing to the electrode 2 from the virtual cathode and I_1 is the sum of the currents carried by the electrons originally injected at the plane of electrode 1 and that carried by the electrons which flow from the region of the potential minimum back toward the electrode 1. If I_s is the injected current,

$$I_1=I_s+(I_s-I_2)=2I_s-I_2 \quad (1)$$

It can be shown that the general relationship requisite for the formation of a virtual cathode is

$$C\alpha^{-1/2}=V_1^{3/4}I_1^{-1/2}+V_2^{3/4}I_2^{-1/2} \quad (2)$$

where $\alpha=2.33\times10^{-6}$, current being in amperes per square centimeter and potential in volts above the cathode from which the injected electrons emanate.

In order to obtain a high transconductance, it is necessary that I_2 be changed to a large extent when some other variable is changed to a relatively small extent. For purposes of general discussion, this variable may be designated as Z and the following variational relation is then obtained from Equation 2:

$$\frac{3}{2}\left(V_1^{-1/4}I_1^{-1/2}\frac{\delta V_1}{\delta Z}+V_2^{-1/4}I_2^{-1/2}\frac{\delta V_2}{\delta Z}\right)=V_1^{3/4}I_1^{-3/2}\frac{\delta I_1}{\delta Z}+V_2^{3/4}I_2^{-3/2}\frac{\delta I_2}{\delta Z} \quad (3)$$

It will be understood that Z may be any one of a number of factors. The three most important cases of control of I_2 for practical purposes are:

1. Control by variation of the potential of a third electrode, e. g., a control grid,
2. Control by variations of V_2, and
3. Control by variation of V_1.

A typical arrangement for the first case is shown in Fig. 3 wherein there is illustrated the potential distribution in an electron discharge device comprising a cathode, an anode, a positively biased auxiliary electrode, a positively biased focussing or shielding electrode and a negatively biased control electrode arranged as shown, the auxiliary, focussing and control electrodes being perforate, e. g., grids. It may be noted that in Fig. 3 the portion D of the distribution characteristic corresponds to the curve D in Fig. 2.

If the potential V_g of the control electrode is considered as the variable Z noted above, Equation 3 may be written as

$$V_1^{3/4}I_1^{-3/2}\frac{\delta I_1}{\delta V_g}+V_2^{3/4}I_2^{-3/2}\frac{\delta I_2}{\delta V_g}=0 \quad (4)$$

The quantity

$$\frac{\delta I_2}{\delta V_g}$$

it will be noted, is the transconductance of the device. As shown by Equation 4, the value of this transconductance depends upon the factor

$$\frac{\delta I_1}{\delta V_g}$$

This factor and hence the transconductance,

$$\frac{\delta I_2}{\delta V_g}$$

is dependent upon an important effect of the grid structures constituting the auxiliary and focussing electrodes, namely, the capture by these electrodes of a portion of the electron current. By constructing the device in accordance with a feature of this invention, less than a certain portion of the electrons are captured whereby highly desirable operating characteristics and, more particularly, desirable values of transconductance, for the device are achieved.

The effect of the capture of electrons by the grid structures will be understood from the following considerations: Let β be the fraction of the electrons which the auxiliary and focussing electrodes allow to pass and I_c the electron current flowing away from the vicinity of the cathode. The fraction of the electrons captured by the auxiliary and focussing electrodes is, then, $(1-\beta)$.

Electrons moving away from the vicinity of the cathode toward the potential zero or virtual cathode region come under the effect of the focussing and auxiliary electrodes. At these electrodes a portion $(1-\beta)I_c$, of the electrons is captured and the remainder, βI_c, flow to the virtual cathode region. From this region, an electron current I_2 proceeds forward toward the anode and a current $(\beta I_c - I_2)$ flows backward toward the auxiliary electrode. Hence, it will be seen that

$$I_1 = \beta I_c + (\beta I_c - I_2) = 2\beta I_c - I_2 \quad (5)$$

A portion of backward flowing current is captured by the auxiliary and focussing electrodes. The capture effect of these electrodes upon the backward flowing electrons may be assumed to be the same for electrons moving in either direction. Although the assumption is not strictly correct, it is sufficiently accurate to determine the effect of the capture action of the electrodes and to indicate for practical purposes what design is to be employed. On the basis of the assumption noted, the portion of the backward current captured which passes through the focussing electrode and flows toward the cathode is $\beta(\beta I_c - I_2)$. Hence, the total electron current I_d in the vicinity of the cathode, both the forward and backward currents being considered, is

$$I_d = I_c + \beta(\beta I_c - I_2) = (1+\beta^2)I_c - \beta I_2 \quad (6)$$

It is this current which produces the space charge near the cathode and which is controlled by the effective control grid potential in accordance with the well-known Child's equation.

From Equations 5 and 6, by elimination of I_c,

$$I_d = \frac{1+\beta^2}{2\beta} I_1 + \frac{1-\beta^2}{2\beta} I_2 \quad (7)$$

If, now, V_g is varied, it follows that

$$g_c = \frac{\delta I_d}{\delta V_g} = \left(\frac{1+\beta^2}{2\beta}\right)\frac{\delta I_1}{\delta V_g} + \left(\frac{1-\beta^2}{2\beta}\right)\frac{\delta I_2}{\delta V_g} \quad (8)$$

g_c, it will be noted, is the transconductance of a negative grid triode operating with as its anode potential, the equivalent potential of the focussing electrode.

Solving Equation 8 for

$$\frac{\delta I_1}{\delta V_g}$$

substituting in Equation 4 and then solving for

$$\frac{\delta I_2}{\delta V_g}$$

the over-all transconductance is determined, to wit:

$$\frac{\delta I_2}{\delta V_g} = \frac{\dfrac{2\beta}{1-\beta^2} g_c}{1 - \left(\dfrac{V_2}{V_1}\right)^{3/4}\left(\dfrac{I_1}{I_2}\right)^{3/2}\dfrac{1+\beta^2}{1-\beta^2}} \quad (9)$$

The importance of the capture fraction $(1-\beta)$ in the determination of the transconductance will be appreciated from an analysis of Equation 9. It will be noted that the current I_1 always is greater than I_2 and further that the term

$$\frac{1+\beta^2}{1-\beta^2}$$

always is greater than unity. Further, it will be noted that the sign of the transconductance

$$\frac{\delta I_2}{\delta V_g}$$

is dependent upon the magnitude of the second term in the denominator on the right-hand side of Equation 9. That is, when this term is greater than unity, the transconductance is negative in sign and when this term is less than unity, the transconductance is positive in sign. Generally, unless V_2 is much less than V_1, the transconductance is negative in sign.

When the term noted approaches unity, it will be seen that the transconductance approaches infinity. Theoretically, it would appear that if this term were increased progressively from a value less than unity to a value greater than unity, the transconductance would pass through infinity and then become negative in sign. Actually instead of this occurring, when infinite values of transconductance are approached too closely, the potential distribution jumps to one of its other possible shapes and the infinite transconductance does not materialize.

It is important to note the effect of limiting values of the capture fraction. When the capture fraction is very small, i. e., when substantially no electrons are captured by the focussing and secondary electrodes, β approaches unity and the transconductance

$$\frac{\delta I_2}{\delta V_g} = -\frac{g_c}{\left(\dfrac{V_2}{V_1}\right)^{3/4}\left(\dfrac{I_1}{I_2}\right)^{3/2}} \quad (10)$$

from which it will be seen that a negative transconductance of greater magnitude than the triode transconductance is obtainable when V_2 is so small in comparison with V_1 that the denominator in the right-hand side of Equation 10 is less than unity. For these conditions, the transconductance

$$\frac{\delta I_2}{\delta V_g}$$

is negative in sign, of large magnitude and not subject to the sudden jumps in the form of potential distribution previously noted when the two terms in the denominator of the right-hand side of Equation 9 are nearly equal.

The stable high negative transconductance is obtained by constructing the focussing and auxiliary grids of fine wires widely spaced and operating the device with the potential V_2 at as low a value as is practical.

At the other extreme of the possible values of β is the condition where the focussing and auxiliary electrodes collect or capture nearly all of the electrons. For this condition, β is very small and may be disregarded in Equation 9 in comparison with unity, so that

$$\frac{\delta I_2}{\delta V_g} = \frac{2\beta g_c}{1 - \left(\dfrac{V_2}{V_1}\right)^{3/4}\left(\dfrac{I_1}{I_2}\right)^{3/2}} \quad (11)$$

It is seen from an inspection of Equation 11 that the transconductance may be positive or negative in sign depending upon whether the second term in the denominator of the right-hand side of the equation is less than or greater than unity. This, in turn, depends largely upon the ratio V_2/V_1 inasmuch as, as pointed out heretofore, I_1/I_2 always is greater than unity. V_2/V_1 must be less than unity in order that the transition point from positive to negative transconductance shall be approached. In the vicinity of this transition point very large magnitudes of transconductance may be obtained inasmuch as the denominator of the right-hand side of Equation 11 is then very small. Such magnitudes are rather critical and vary greatly with small changes in any of V_1, V_2, I_1, I_2 or β and the high transconductances obtained in the manner indicated are of use in cases where the advantages of their magnitude outweigh the disadvantages of the instability and fluctuations with operating conditions associated therewith.

Between the two extreme values of the capture fraction considered hereinabove, there is a range of values of β for which the stable properties of transconductance attending operation with small values of β and low values of V_2/V_1 may be combined with the very high transconductances occurring when the two terms of the denominator of Equation 9 approach equality. This latter condition requires that β be less than a certain value for, as noted heretofore, if β is too large, the second term in the denominator of Equation 9 exceeds the first. Therefore, in order to obtain the very high transconductance indicated to be realizable by balancing the two terms in the denominator of Equation 11, the focussing and auxiliary electrodes must be constructed so that the capture fraction thereof is appreciable when the device is operated with the desired bias potentials applied to the electrodes.

It has been determined that the high transconductance and stable operation are obtainable if the focussing and auxiliary electrodes are constructed so that the capture fraction is approximately 0.2, that is, so that β is substantially 0.8. For a value for β of 0.8, Equation 9 becomes

$$\frac{\delta I_2}{\delta V_g}=\frac{4.45g_c}{1-4.56\left(\frac{V_2}{V_1}\right)^{3/4}\left(\frac{I_1}{I_2}\right)^{3/2}} \tag{12}$$

From Equation 12, it is apparent that very high values of the transconductance

$$\frac{\delta I_2}{\delta V_g}$$

will obtain when

$$\left(\frac{V_1}{V_2}\right)^{3/4}\left(\frac{I_2}{I_1}\right)^{3/2}$$

is comparable with 4.56. As noted heretofore, I_2 always is less than I_1 and, therefore, V_1 must be made much greater than V_2. For example, if

$$\frac{I_2}{I_1}\text{ were } 0.9$$

the required ratio of V_1/V_2 would be 9.3 so that if V_1 were 93 volts, V_2 would be only 10 volts. In the case under consideration, V_2 is the anode potential and, thus, it will be seen that a high transconductance is obtained with a low anode potential. Such low anode potential enables realization of high operating efficiencies.

In cases where a low output impedance for the device is not desired, a grid screen or shield electrode may be employed as the electrode providing the potential V_2 and the output anode may be mounted behind the shield or screen electrode with reference to the cathode.

In the second case noted above, the current I_2 to the anode is varied by changing the potential V_2 in Fig. 2. As shown in Fig. 4, in a typical structure illustrative of this case, the positive auxiliary electrode having the potential V_1 is shielded from the cathode by a perforated electrode which may serve also to focus the electrons from the cathode upon the openings in the positive auxiliary electrode. The structure includes also a control grid positioned at a plane of potential V_2 between the auxiliary electrode and anode, the anode having applied thereto a potential of the order of that upon the auxiliary electrode. Although, as seen in Fig. 4, the effective potential of the control grid is slightly positive, the external bias applied to the control grid is negative, inasmuch as the effective potential of a negative grid, as is known, differs from the actual potential of the grid wires.

For this case, if V_2 is the variable Z in Equation 3, it can be shown in a manner similar to that used in arriving at Equation 9 that

$$\frac{\delta I_2}{\delta V_2}=\frac{\frac{3}{2}\frac{I_2}{V_2}}{1-\left(\frac{V_1}{V_2}\right)^{3/4}\left(\frac{I_2}{I_1}\right)^{3/2}\left(\frac{1-\beta^2}{1+\beta^2}\right)} \tag{13}$$

from which it will be apparent that, as in the first case noted above, very high values of transconductance are obtainable if the second term in the denominator of the right-hand side approaches unity and that the term in question depends markedly upon the capture fraction $(1-\beta)$. Such very high values of transconductance are obtainable only if the focussing efficiency is not extremely high so that β does not approach unity too closely. It will be noted from Equation 13 that the transconductance tends toward $^3/_2 I_2/V_2$ if the focussing efficiency is high so that β very closely approaches unity. This value may be augmented by so constructing and arranging the electrodes that the positive auxiliary electrode V_1 collects an appreciable portion, for example, of the order of 20 per cent, of the current flowing to the region thereof from the cathode.

For practical purposes it is desirable that V_2 be much smaller than V_1 in order that the control grid may be biased negatively. This requires, as indicated by Equation 13, that I_2 must be correspondingly less than I_1 in order that the second term of the denominator on the right-hand side may approach unity.

If, as in the first case, β is taken as 0.8, it will be apparent from Equation 13 that very high transconductances are obtainable when

$$\left(\frac{V_2}{V_1}\right)^{3/4}\left(\frac{I_1}{I_2}\right)^{3/2}$$

is approximately equal to 4.56.

In the third case noted above, control of the anode current I_2 is effected by varying V_1. A typical structure for this case is illustrated in Fig. 5 and comprises a cathode, an anode, a positive screening and focussing grid and a control grid, the latter being mounted in a plane corresponding to a potential V_1. It will be noted that the relative position of the electrodes in Fig. 5 is similar to that in Fig. 4 with the difference that whereas in Fig. 4 the spacing between the positive auxiliary electrode and the control grid is large in order to allow the formation of the virtual cathode with moderate values of currents, in Fig. 5 the spacing of the control grid and anode is large for the same reason.

Considering V_1 as the variable Z in Equation 3, for this third case it can be shown that the transconductance is given by the relation:

$$\frac{\delta I_2}{\delta V_1}=\frac{\frac{3}{2}I_1/V_1-\frac{2\beta}{1+\beta^2}g}{\left(\frac{V_2}{V_1}\right)^{3/4}\left(\frac{I_1}{I_2}\right)^{3/2}-\frac{1-\beta^2}{1+\beta^2}} \tag{14}$$

where g is the change in the sum of outward and inward bound cathode currents produced by a change in the potential V_1.

As will be apparent from Equation 14, the transconductance tends toward infinite values only if the focussing efficiency is not too high just as in the case considered previously. This tendency may be obtained by so constructing and arranging the electrodes that the quantity β is of the order of 0.8.

Typical devices constructed in accordance with this invention are illustrated in Figs. 6 and 7 wherein the several electrodes are substantially plane and parallel. The control, focussing and auxiliary electrodes are formed of parallel wires, corresponding wires of the several electrodes being aligned. These wires may be circular, as illustrated in Fig. 6, of very small diameter and widely spaced to provide a capture fraction of substantially 0.2 for the focussing and auxiliary electrodes. As illustrated in Fig. 7, the auxiliary electrode may be formed of wire strips in alignment with the wires of the focussing electrode and control grid to obtain the desired value for the capture fraction.

In electron discharge devices of the types discussed hereinabove, the attainment of the high transconductances depends, as is apparent, upon the establishment of a virtual cathode by space charge effects. The location of the virtual cathode is dependent upon the space charge which in turn is determined by the density of electrons. A high electron density and, hence, a ready formation of the virtual cathode may be obtained with relatively low emission currents from the actual cathode if the area of the electrode having the potential V_2 is less than that of the electrode having the potential V_1.

Illustrative structures for facilitating the formation of a virtual cathode with relatively low emission currents are shown in Figs. 8 and 9. In the structure shown in Fig. 8, the electron discharge device comprises an evacuated enclosing vessel 10, a central linear rod anode 11 and a cathode 12 comprising a plurality of equally spaced linear elements parallel to the anode 11 and mounted in a cylindrical boundary coaxial therewith. The cathode elements may be filaments connected in series or parallel or they may be equipotential indirectly heated members. Alternatively, the cathode may be a cylinder coaxial with the anode, indirectly heated and having the inner surface thereof coated with a thermionic material.

Mounted between the cathode and anode and coaxial therewith are a plurality of cylindrical grid electrodes 13, 14 and 15 each of which comprises a plurality of equally spaced, linear elements parallel to one another and to the anode 12. Corresponding elements of the several grids 13, 14 and 15 may be readily aligned or not so aligned.

In structures operated as described hereinabove for the second and third cases, it is often important that the anode be screened from the control grid to prevent feedback in high frequency and high gain circuits. This may be effected, as illustrated in Fig. 9, by providing a grid electrode 16 in proximity to the anode, this grid electrode comprising, for example, a plurality of equally spaced linear elements parallel to one another and to the anode and mounted in a cylindrical boundary coaxial with the anode.

In the structures illustrated in Figs. 8 and 9, it will be noted that the output capacitances may be made relatively small because of the small areas of the electrodes, particularly of the anode, and of the relatively large spacings employed. Hence, inasmuch as the figure of merit is inversely dependent upon the interelectrode capacitances, these structures not only facilitate the formation of a virtual cathode relatively remote from the actual cathode but also enable the attainment of an increased figure of merit by reducing the interelectrode capacitances.

A circuit illustrating one manner of utilizing devices of the constructions shown in Figs. 8 and 9 is shown in Fig. 10 which illustrates operation for the second case described above. The anode 11 is connected to the cathode 12 through the primary winding of an output transformer 17 and is maintained at a positive potential, for example of the order of 100 volts, with respect to the cathode by a source such as battery 18. The grid 15, which serves as a screening and focussing electrode, is maintained at a positive potential, for example, of the order of 10 volts, and the gird 14, which serves as an accelerating electrode, is maintained at a positive potential somewhat lower than that of the anode, for example, of the order of 80 volts. The grid 16 is maintained at a positive potential, for example, of the order of 80 volts. The grid 13, which serves as the control electrode, is connected to the cathode through the secondary winding of an input transformer 19 and has applied thereto a negative bias, for example, of the order of 5 volts, by a source such as a battery 20.

In a similar circuit illustrated in Fig. 11, for operation for the first case described above, the grid 15 serves as the control electrode and is connected to the cathode through the secondary winding of transformer 19 and negatively biased by the battery 20 and grid 13 serves as the accelerating electrode and is connected to a positive point on the battery 18.

In a similar circuit, illustrated in Fig. 12, for operation for the third case noted above, the grid 13 is omitted and the grid 14 serves as the control electrode and is connected to the cathode through the secondary winding of the transformer 19 and biased negatively by the battery 20.

Although specific embodiments of this invention have been shown and described, it will be understood that they are but illustrative and that various modifications may be made therein without departing from the scope and spirit of this invention as defined in the appended claims.

What is claimed is:

1. Electron discharge apparatus comprising a pair of electrodes mounted in spaced relation, one of said electrodes being apertured, means including a cathode and a focussing electrode for injecting an electron stream through said apertured electrode into the space between said pair of electrodes, means biasing said pair of electrodes at positive potentials with respect to said cathode such that a virtual cathode is established between said pair of electrodes, and means for controlling the current from said virtual cathode to the other of said pair of electrodes, said one electrode and said focussing electrode being grids having a capture fraction of the order of 0.2.

2. Electron discharge apparatus in accordance with claim 1 wherein the bias applied to said one electrode is large compared to the bias applied to said other electrode and wherein said controlling means comprises a negatively biased control electrode between said cathode and said one electrode.

3. Electron discharge apparatus in accordance with claim 1 wherein said controlling means comprises a control electrode positioned adjacent the region of said virtual cathode and biased negative with respect to said cathode.

4. Electron discharge apparatus comprising a pair of electrodes mounted in spaced relation, one of said electrodes being a grid formed of fine wires widely spaced whereby its capture fraction is very small, means including a cathode and a

focussing electrode for projecting an electron stream through said grid into the space between said pairs of electrodes, said focussing electrode being a grid formed of fine wires widely spaced, a control electrode between said cathode and said focussing electrode, and means applying positive potentials to said pair of electrodes such that a virtual cathode is formed between said pair of electrodes, the potential applied to said one electrode being greater than the potential applied to the other of said pair of electrodes, and the potential applied to said other electrode being as small as practical whereby the quantity

$$\frac{\delta I_2}{\delta V_g}$$

is negative in sign, I_2 being the current to said other electrode and V_g being the potential of said control electrode.

5. Electron discharge apparatus comprising a cathode, an electrode spaced from said cathode, a control electrode between said cathode and said first electrode, auxiliary electrode means between said cathode and said first electrode, and means applying a positive potential to said auxiliary electrode means and a smaller positive potential to said first electrode, such that a potential minimum is established between said auxiliary electrode means and said first electrode, said auxiliary electrode means having a capture fraction of substantially 0.2.

6. Electron discharge apparatus comprising a cathode, an electrode spaced from said cathode, a control electrode between said cathode and said first electrode, auxiliary electrode means between said cathode and said first electrode, means applying a positive potential to said auxiliary electrode means and a considerably smaller positive potential to said first electrode such that a virtual cathode is established between said auxiliary electrode means and said first electrode, said auxiliary electrode means having an appreciable capture fraction and said positive potentials being related so that the quantity

$$\left(\frac{V_2}{V_1}\right)^{3/4}\left(\frac{I_1}{I_2}\right)^{3/2}\frac{1+\beta^2}{1-\beta^2}$$

approaches unity, where V_2 is the potential of said auxiliary electrode means, V_1 is the potential of said first electrode, I_1 is the total electron current in the space between said auxiliary electrode means and the region of said potential minimum, I_2 is the current flowing to said first electrode and $(1-\beta)$ is said capture fraction.

7. Electron discharge apparatus comprising a cathode, a first electrode spaced from said cathode, a control electrode between said cathode and said first electrode, auxiliary electrode means between said cathode and said first electrode including a grid composed of fine wires widely spaced such that the capture fraction thereof is very small, and means applying positive potentials to said first electrode and said auxiliary electrode means, such that a virtual cathode is formed between said first electrode and said electrode means, the potential applied to said first electrode being small in comparison with the potential applied to said auxiliary electrode means such that the quantity

$$\left(\frac{V_2}{V_1}\right)^{3/4}\left(\frac{I_1}{I_2}\right)^{3/2}$$

is less than unity, where V_2 is the potential of said first electrode, V_1 is the potential of said auxiliary electrode means, I_2 is the space current to said first electrode and I_1 is the total electron current in the space between said auxiliary electrode means and the region of said virtual cathode.

8. Electron discharge apparatus comprising a cathode, a first electrode spaced from said cathode, a control electrode between said cathode and said first electrode, auxiliary grid means between said cathode and said first electrode, and means biasing said grid means and first electrode at positive potentials relative to said cathode such that a virtual cathode is established between said grid means and said first electrode, said grid means having a capture fraction of substantially 0.2, and the potential of said grid means being of the order of ten times the potential of said first electrode.

9. Electron discharge apparatus comprising a cathode, an anode, a pair of grids in spaced relation between said cathode and said anode, an output circuit connected to said cathode and said anode, an input circuit connected to said cathode and one of said grids, and means applying such positive potentials to said anode and the other of said grids that a potential minimum obtains between said anode and said other grid, said other grid being so constructed and arranged that it collects of the order of 20 percent of the electron current flowing from said cathode toward said anode.

10. Electron discharge apparatus in accordance with claim 9, wherein said one grid is mounted between said anode and said other grid and in proximity to the region at which the potential minimum obtains.

11. Electron discharge apparatus in accordance with claim 9 wherein said one grid is mounted between said cathode and said other grid.

12. Electron discharge apparatus in accordance with claim 9 wherein said other grid is of an area greater than the area of said anode.

13. Electron discharge apparatus comprising an anode, a cathode encompassing said anode, a pair of spaced grids between said anode and cathode and encompassing said anode, an output circuit connected to said cathode and said anode, an input circuit connected to said cathode and one of said grids, and means for applying such potentials to said grids and said anode that a potential minimum obtains in the region between said anode and the grid nearest thereto.

14. Electron discharge apparatus in accordance with claim 13 wherein said one grid is between said cathode and the other of said grids and said other grid is maintained at a positive potential several times as great as the anode potential.

15. Electron discharge apparatus in accordance with claim 13 wherein said one grid is between said anode and the other of said grids and in proximity to the region at which the potential minimum obtains.

16. Electron discharge apparatus comprising a linear rod anode, a cylindrical cathode encompassing and coaxial with said anode, a pair of spaced cylindrical grids between said cathode and said anode and coaxial therewith, an output circuit connected between said cathode and said anode, an input circuit connected between said cathode and one of said grids and including means for applying a negative bias to said one grid, and means maintaining said anode and the other of said grids at positive potentials with respect to said cathode, said potentials and bias being such that a potential minimum obtains

in the region between said anode and the grid nearest thereto.

17. Electron discharge apparatus in accordance with claim 16 wherein said one grid is between said anode and the other of said grids and in proximity to the region of the potential minimum.

FREDERICK B. LLEWELLYN.

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