

Oct. 8, 1940.

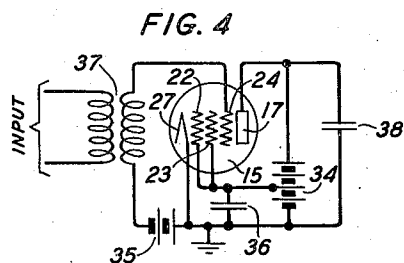
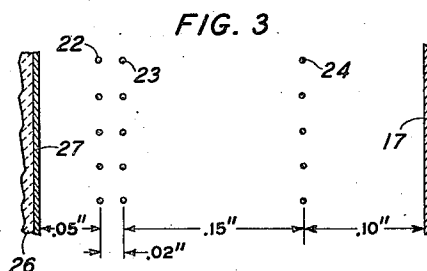
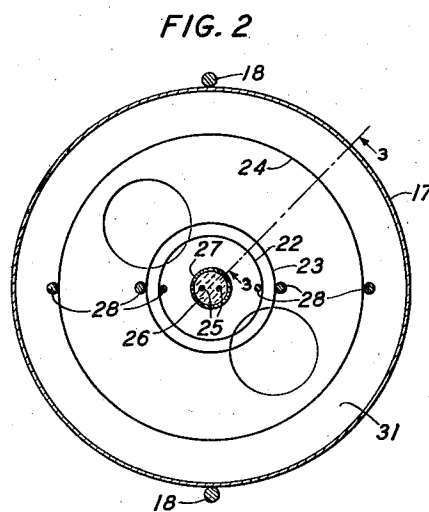
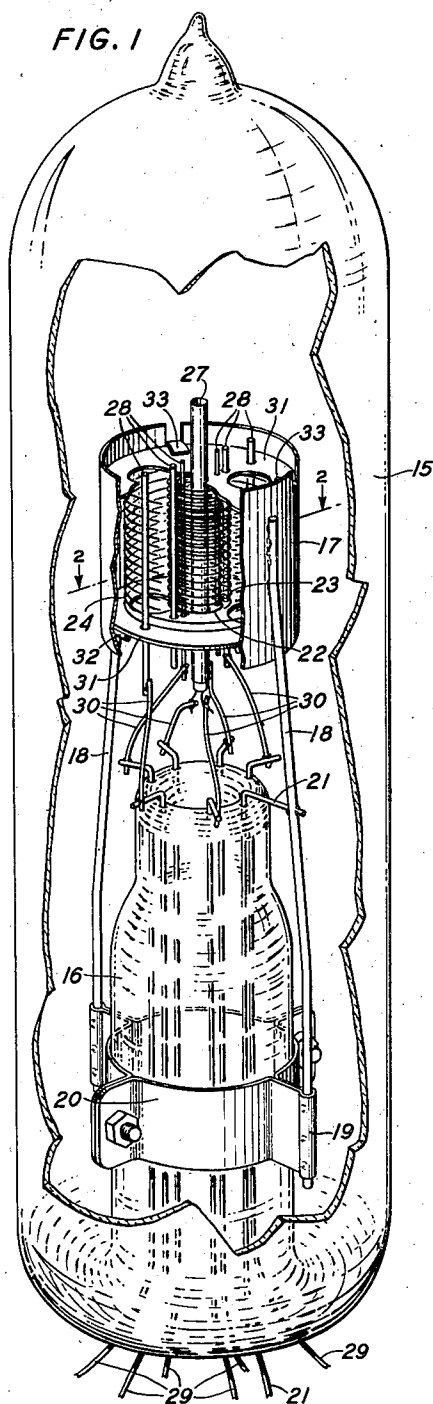
L. C. PETERSON

2,217,417

ELECTRON DISCHARGE APPARATUS

Filed March 31, 1939

2 Sheets-Sheet 1



INVENTOR
L.C. PETERSON
BY *Stalter C. Kiesel*
ATTORNEY

Oct. 8, 1940.

L. C. PETERSON

2,217,417

ELECTRON DISCHARGE APPARATUS

Filed March 31, 1939

2 Sheets-Sheet 2

FIG. 5

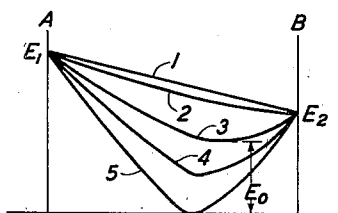


FIG. 6

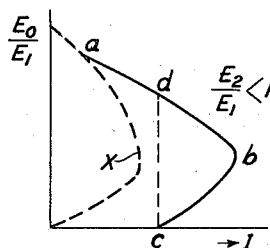


FIG. 7

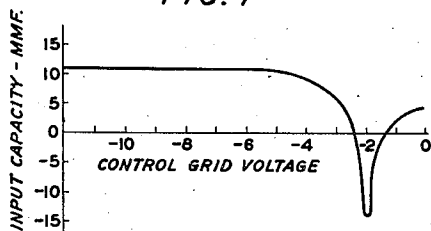


FIG. 8

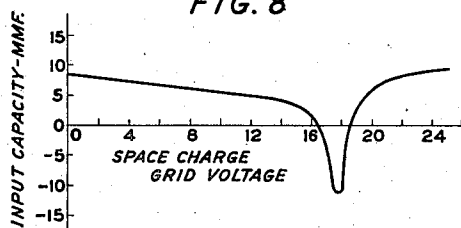


FIG. 9

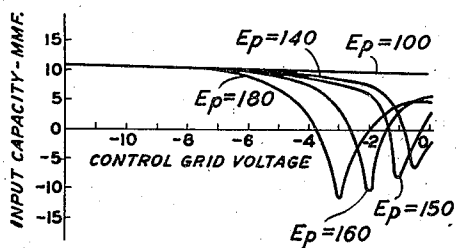


FIG. 10

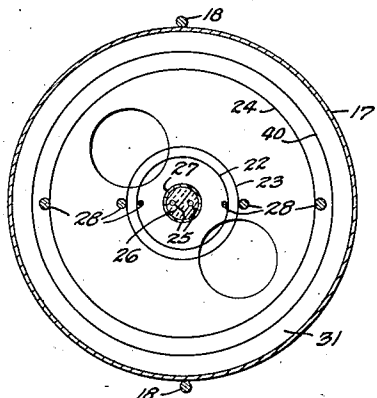
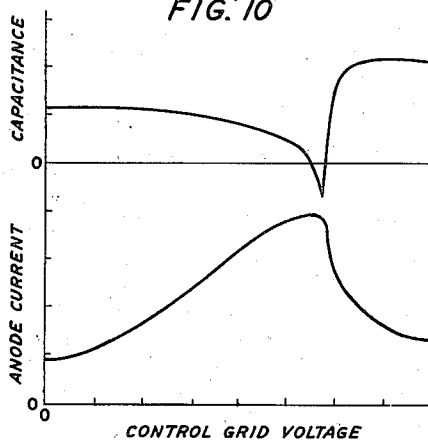


FIG. 11.

INVENTOR
L. C. PETERSON

BY

Walter C. Kiesel
ATTORNEY

UNITED STATES PATENT OFFICE

2,217,417

ELECTRON DISCHARGE APPARATUS

Liss C. Peterson, Madison, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application March 31, 1939, Serial No. 265,128

6 Claims. (Cl. 179-171)

This invention relates to electron discharge apparatus and more particularly to multigrid electron discharge devices especially suitable for the generation and amplification of high frequency waves, for example up to 50 megacycles.

One general object of this invention is to decrease the input impedance of electron discharge devices. More specific objects of this invention are:

10 To obtain a negative capacitance electronically;

To reduce the active grid loss in electron discharge devices capable of operation at high frequencies; and

15 To increase the frequency range of stable operation for high frequency electron discharge apparatus.

In one illustrative embodiment of this invention, electron discharge apparatus comprises an electron discharge device including a cathode, an anode, a control electrode or grid between the cathode and anode, and one or more space charge or accelerating electrodes or grids between the cathode and the control electrode or grid. The space charge or accelerating electrodes or grids are by-passed to ground for alternating currents and are maintained at a positive direct current potential with respect to the cathode. The control grid is maintained at a negative potential with respect to the cathode.

20 In accordance with a broad feature of this invention, the mechanical and electrical parameters of the electrodes are correlated so that a negative input capacitance for the electron discharge device obtains. More specifically, in accordance with a feature of this invention, the control electrode and the space charge or accelerating electrode nearest thereto are so spaced relative to one another and to the cathode and are maintained at such direct current potentials that the dielectric constant of the space charge is negative whereby the capacitance between the cathode and the control electrode is negative in sign.

45 The invention and the foregoing and other features thereof will be understood more clearly and fully from the following detailed description with reference to the accompanying drawings in which:

50 Fig. 1 is a perspective view of an electron dis-

charge device illustrative of one embodiment of this invention, a portion of the enclosing vessel and of the electrode structure being broken away to show details of the structure more clearly;

Fig. 2 is a view in section along line 2-2 of Fig. 1 of the electrode assembly, showing the form and disposition of the electrodes;

Fig. 3 is an enlarged fragmentary view in section along line 3-3 of Fig. 2, of the electrode assembly;

Fig. 4 is a circuit diagram illustrating one manner of operating the electron discharge device illustrated in Fig. 1;

Fig. 5 is a diagram illustrating the potential distribution between two electrodes of fixed potentials for various values of injected current;

Fig. 6 is a diagram illustrating the relationship between the injected current and the ratio of the potential minimum to potential of one electrode for a given ratio of the potentials between two electrodes;

Fig. 7 is a graph showing the variation of input capacitance with control electrode or grid potential in the device shown in Fig. 1, for particular values of the potential of the accelerating or space charge electrodes;

Fig. 8 is a graph showing the relationship between the input capacitance and the potential of the accelerating or space charge electrodes for a particular value of control electrode bias in the device shown in Fig. 1;

Fig. 9 is another graph including a family of curves illustrating the input capacitance as a function of the control electrode bias for a number of values of anode potential in the device shown in Fig. 1;

Fig. 10 is still another graph showing the input capacitance and the anode current as a function of the control electrode bias in a device of the construction shown in Fig. 1; and

Fig. 11 is a view in cross-section, similar to Fig. 2, illustrating another embodiment of this invention.

Referring now to the drawings, the electron discharge device illustrated in Figs. 1, 2 and 3 comprises an evacuated enclosing vessel 15 having an inwardly extending stem 16 which supports an electrode assembly. The electrode assembly includes a cylindrical metallic anode 17 supported by a pair of metallic rods or up-

rights 18 extending from and secured to flanges 19 on a split metallic band or collar 20 clamped about the stem 16. Electrical connection to the anode 17 may be established through a leading-in conductor 21 sealed in the inner end of the stem 16 and affixed to one of the rods or uprights 18.

Mounted within the anode and concentric therewith are a cathode, a pair of accelerating or space charge grids 22 and 23 and a control grid 24. The cathode may be of the indirectly heated equipotential type and include a heater filament 25 encased in insulating material 26, and a metallic sleeve 27, the outer surface of which is coated with an electron emissive material. It will be understood, of course, that other types of cathodes, for example filamentary, may be employed. Each of the grids 22, 23 and 24 comprises a wire helix carried by a pair of the metallic rods or uprights 28, the uprights lying in a diametral plane of the anode as shown clearly in Fig. 2. The grids may be of other forms, for example reticulated or slotted cylinders. As illustrated in Fig. 3, corresponding turns of the several grids may be in alignment. Preferably, the openings in the grids, particularly those in the control grid, are very small to minimize the effect of the anode upon the cathode-control grid region. In an illustrative structure, such as shown in Fig. 1, the grid laterals may be of 7-mil wire and spaced .032 inch center to center, the electrode spacings being as shown in Fig. 3.

Electrical connection to the cathode and the grids may be established through leading-in conductors 29, sealed in the stem and connecting wires 30.

The cathode and grids may be maintained in proper space relation by a pair of insulating members 31, such as mica discs, fitted in the anode and having apertures in which the cathode sleeve 27 and rods or uprights 28 are fitted. The insulating members 31 may abut the end turns of the grids and are suitably locked in place. For example, the lower insulating member 31 may be maintained in position by a split ring 32 affixed, as by welding, to the anode, and the upper insulating member may be maintained in position by bent-over tabs 33 integral with the anode.

Preferably, only the portion of the cathode sleeve 27 between the insulating members 31 is coated with electron emissive material so that all electrons emanating from the cathode are directed toward the grids.

During operation of the device, the anode 17 is maintained strongly positive with respect to the cathode 27, as by a battery 34, and the control grid 24 is biased negatively, as by a battery 35. The accelerating or space charge grids 22 and 23 may be connected together and to an intermediate point on the battery 34 and thus maintained positive with respect to the cathode 27, and may be by-passed to ground for alternating potentials by a large capacity condenser 36. An input signal may be applied to the control grid 24 through a suitable transformer 37 and the output circuit may include a condenser 38. If the device is utilized as an amplifier with a resistance or inductance load, preferably, as illustrated in Fig. 11, an additional or shield grid 40 is provided between the control grid and the anode to prevent reaction of changes in the anode potential upon the input impedance.

It has been determined that, for an electron discharge device, for example of the construction shown in Fig. 1 and described heretofore, space

charge conditions may be established whereby a negative input capacitance obtains. The factors determining the requisite conditions for the existence of such negative capacitance may be seen from the following considerations.

It is known, of course, that a variety of space charge conditions may exist between two electrodes. For example, as illustrated in Fig. 5, in the region between two parallel planes A and B having potentials E_1 and E_2 , respectively, E_1 being greater than E_2 , in a vacuum and if no electrons are present, the potential distribution may be represented by a straight line 1. If an electron current is injected into this region, from A toward B, and normal to the planes A and B, the linear distribution no longer obtains and the potential distribution may be as indicated by the curve 2. If the injected current is increased, a potential minimum develops, as indicated by E_0 on curve 3. A still further increase to a certain critical value in the injected current results in a decrease in the potential minimum, as indicated by the curve 4. When this state has been established, any further increase, even though slight, in the injected current, causes the potential minimum to fall to zero, as indicated by curve 5 and a virtual cathode is formed. As the current is increased further, the virtual cathode moves toward the electrode A.

As illustrated in Fig. 6, for a fixed value of the ratio of

$$\frac{E_2}{E_1}$$

less than unity, a definite relationship exists between the injected current, plotted as abscissae, and the ratio of the potential minimum, E_0 , to the potential, E_1 , at the plane of injection, plotted as ordinates. In this figure, the area embraced by the dotted line X corresponds to a region in which no potential minimum occurs so that within this region the potential distribution departs very slightly, if at all, from that in a free space region.

In the full line curve in Fig. 6, the point *a* corresponds to a value of injected current at which a potential minimum has just set in. As the injected current is increased, the curve slopes downwardly to a point *b* which corresponds to the critical value of the injected current. Any further increase in the current, as pointed out heretofore, causes the potential minimum to fall to zero. It will be seen from Fig. 6 that the values of injected current between those corresponding to *c* and *d*, and *b*, two potential distributions are possible, namely that corresponding to the upper part *db* of the curve and that corresponding to the lower part *bc*. It can be shown that the capacitance is positive for the upper part of the curve and negative for the lower part.

If now a negative electrode, such as a negatively biased control grid, is interposed between the positive electrodes A and B, and the electrodes A and B are by-passed to ground so that their alternating current potentials are zero, it can be shown that the capacitance between this negative electrode and the positive electrode A will be negative for space charge conditions in a region corresponding to a part of the full line curve in Fig. 6 between *a* and *b*. The location of the point to the left of *b* will be determined by the direct current potentials upon the electrodes.

The magnitude of the input capacitance of an electron discharge device having a negatively biased control grid between a positive space

charge grid and the anode may be expressed by the relation

$$\frac{1}{c} = \frac{1}{C_g} + \frac{1}{C_0} \frac{1 - J_0 \frac{t_1^3}{6d_1}}{1 - J_0 \frac{t_1^2}{2v_2}} \quad (1)$$

where c = the capacitance,
 C_g = the capacitance between the control grid and a plane immediately adjacent thereto whereat the electron stream is substantially uniform,

$C_0 = \frac{\epsilon}{d}$ is the cold capacitance, ϵ being the permittivity of a vacuum = 8.85×10^{-14} farads/cm., and d the distance between the control grid and the accelerating or space charge grid nearest thereto,

$J_0 = \frac{eI_0}{kme}$, I_0 being the injected current in amperes per square centimeter, $k = 10^{-7}$, and m the electron mass in grams,

t_1 = the electron transit time between the control grid and the space charge grid nearest thereto, and

v_2 = the direct current electron velocity in the immediate vicinity of the control grid.

The capacitance C_g , it is apparent, is inherently large so that the first term on the right-hand side of Equation 1 is relatively small.

It will be seen from Equation 1 that the capacitance c will be negative if the second term on the right-hand side of the equation is negative and numerically greater than the first term.

The capacitance given by the second term changes from positive to negative, i. e., passes through zero, when

$$J_0 \frac{t_1^2}{2v_2} = 1 \quad (2)$$

or, in other words, when

$$v_2 = \frac{J_0 t_1^2}{2} \quad (3)$$

The electron velocity v_2 is determined by the relation

$$v_2 = v_1 + a_1 t_1 + \frac{J_0 t_1^2}{2} \quad (4)$$

where

v_1 = The direct current electron velocity at the space charge grid nearest the control grid, and

a_1 = the electron acceleration at this space charge grid.

Hence, in order that the capacitance may be negative, it is necessary that

$$v_1 = a_1 t_1 = 0 \quad (5)$$

Both v_1 and t_1 are inherently positive so that in order that the relation given by (5) may obtain, the acceleration a_1 must be negative.

Therefore, it will be seen that a negative dielectric constant necessitates a finite electron velocity and a retarding field at the surface at which the electron current is injected. In other words, as to the field, in order that the input capacitance may be negative, it is necessary that the potentials upon the anode, control grid and the accelerating or space charge grid be such that the effective field upon the electrons at this space

charge grid produces a retarding or decelerating force upon the electrons.

The terms

$$\frac{J_0 t_1^2}{2v_2} \text{ and } \frac{J_0 t_1^3}{6d_1}$$

may be expressed as rather complex functions of dimensionless parameters Q and R ,

$$Q = \frac{V_1}{V_0}$$

and

$$R = \frac{V_2}{V_1}$$

where

V_1 = the direct current potential in the plane of the space charge grid nearest the control grid,

V_2 = the direct current potential in the plane of the control grid, and

V_0 = the potential minimum.

If the dielectric constant is plotted in terms of these functions, it will be found that theoretically a negative dielectric constant is obtainable in perfectly stable space charge regions and that as the parameter R is made smaller the dielectric constant passes through zero and becomes negative for smaller values of Q . It will be found also that in the regions of negative dielectric constant, the constant is substantially independent of the space charge parameter Q . Experience and tests have indicated, however, that in order to obtain a negative capacitance it is necessary that the conditions be such that a virtual cathode might form in the region between the space charge and control grids. It appears that the regions of negative capacitance set in either when a virtual cathode begins to form or when such virtual cathode begins to break up. It has been established that these requisite conditions for negative capacitance will obtain if the distance between the control grid and the space charge grid is 1.5 times or more the distance between the cathode and this space charge grid and the potentials of the control and space charge grids are properly correlated.

In an electron discharge device of the construction shown in Fig. 1 wherein the electrodes were spaced as indicated in Fig. 3 and the space charge grids 22 and 23 were tied together and operated at the same direct current potential, the input capacitance was found to vary as illustrated in Figs. 7, 8 and 9. For the curves shown in Figs. 7 and 8, the anode 17 was maintained at 160 volts positive with respect to the cathode 27 and an alternating voltage of 0.18 volt root mean square of 50 kilocycles was applied to the control grid 24. With the space charge grids 22 and 23 maintained at a direct current potential of 18 volts positive with respect to the cathode, as shown in Fig. 7, the input capacitance is negative for negative control grid bias between about 2.5 and 1.5 volts. For a negative bias of 2 volts, the capacitance increases with both positive and negative increments in control grid potential. As shown in Fig. 8, with the control grid biased at 2 volts negative, the input capacitance is negative for potentials upon the space charge grids 22 and 23 (tied together) between approximately 16.5 and 18.5 volts positive.

As indicated in Fig. 9, the negative input capacitance may be obtained for various values of anode potential. The curves shown are for a control grid bias of 2 volts negative and for a

positive potential of 18 volts upon the space charge grids. In this figure the legend E_p indicates anode potential.

It has been found also that the negative input capacitance may be accompanied by a negative input resistance and a negative transconductance. A typical transconductance curve for a device of the construction shown in Fig. 1 is illustrated in Fig. 10 from which it may be seen that the transconductance becomes negative in the region just beyond the region of negative capacitance. The resistance becomes negative at approximately the same point at which the negative input capacitance appears.

The attainment of such a negative resistance, it will be apparent, is of considerable advantage in amplifier and oscillator devices, particularly those operable at high frequencies, in that it enables compensation for active grid loss.

The negative input capacitance may be utilized either per se as an impedance or in a variety of applications. For example, in amplifiers, such capacitance may be utilized to compensate for parasitic capacitances and thereby extend the frequency range of stable operation.

Although a specific embodiment of the invention has been shown and described, it will be understood 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 cathode, an anode, a space charge electrode between said cathode and said anode, a control electrode between said space charge electrode and said anode, means maintaining said anode at a positive potential with respect to said cathode, and means maintaining said space charge electrode at a positive potential and said control electrode at a negative potential with respect to said cathode, said space charge and control electrodes being so spaced relative to one another and to said cathode and the potentials applied thereto by said second means being such that a potential minimum obtains in the region between said control and space charge electrodes and the effective field at said space charge electrode is retarding with respect to electrons flowing through said space charge electrode toward said control electrode, whereby the capacitance between said cathode and said control electrode is negative in sign.

2. Electron discharge apparatus in accordance with claim 1 wherein the potentials of said space charge and control electrodes are such that said capacitance increases with both positive and negative increments in the potential of said control electrode.

3. Electron discharge apparatus comprising a cathode, an anode, a space charge electrode between said cathode and said anode, a control electrode between said space charge electrode and

said anode, said space charge and control electrodes being spaced from each other a distance at least 1.5 times the distance between said cathode and said space charge electrode, means maintaining said space charge electrode at a positive potential with respect to said cathode, and means applying a negative bias to said control electrode, said potential and said bias being such that a potential minimum obtains in the region between said space charge and control electrodes.

4. Electron discharge apparatus comprising a cathode, an anode, a space charge electrode between said cathode and said anode, a control electrode between said space charge electrode and said anode, means maintaining said space charge electrode at a positive potential with respect to said cathode, and means maintaining said control electrode at a negative potential with respect to said cathode, said positive and negative potentials being such that an unstable space charge obtains in the region between said control and space charge electrodes and the effective field at said space charge electrode is retarding with respect to electrons flowing through said space charge electrode toward said control electrode.

5. A high frequency amplifier comprising a cathode, an anode, a space charge electrode between said cathode and said anode, a control electrode between said space charge electrode and said anode, an input circuit connected to said cathode and said control electrode including means for biasing said control electrode negatively with respect to said cathode, an output circuit connected to said cathode and said anode, means maintaining said space charge electrode at a positive direct current potential with respect to said cathode, and means for by-passing said space charge electrode to said cathode for alternating currents, the spacing between said space charge and control electrodes and said cathode and the bias upon said control electrode and the direct current potential of said space charge electrode being such that the dielectric constant of the region between said space charge and control electrodes is negative in sign.

6. Electron discharge apparatus comprising a cathode, a cylindrical anode encompassing said cathode and coaxial therewith, cylindrical space charge and control grids between said cathode and said anode and coaxial therewith, each of said grids including a plurality of closely spaced wires, corresponding wires of said grids being in alignment, said control grid being between said space charge grid and said anode and spaced from said space charge grid a distance at least 1.5 times as great as the distance between said cathode and said space charge grid, means applying a positive potential to said space charge grid, and means applying a negative bias to said control grid, said potential and bias being such that an unstable space charge obtains in the region between said grids.

LISS C. PETERSON.