July 25, 1961 D. J. BELKNAP ET AL 2,994,011

LATERAL-CURRENT CONTROL OF COLD-CATHODE DISCHARGE DEVICES

Filed Aug. 9, 1957

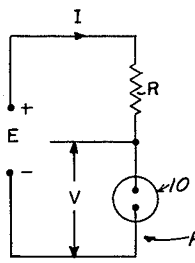


FIG. 1

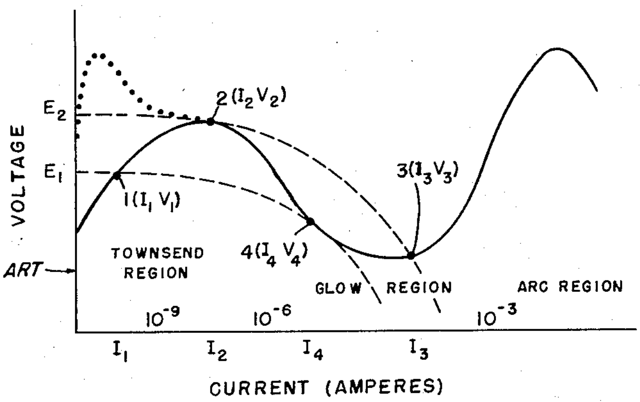


FIG. 2

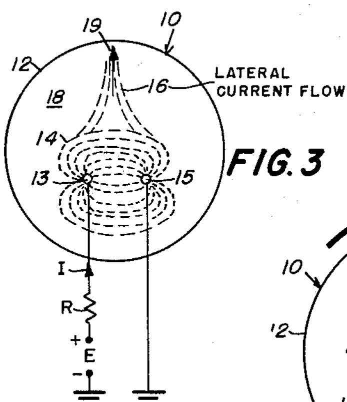


FIG. 3

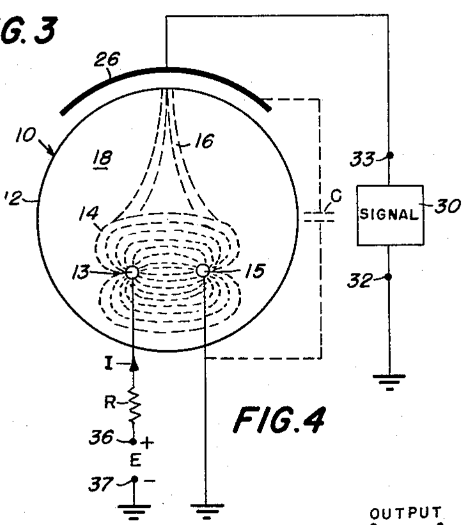


FIG. 4

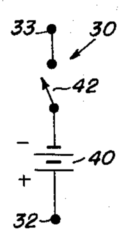


FIG. 5

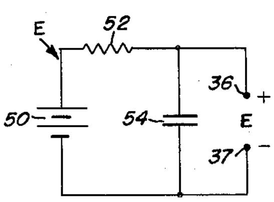


FIG. 6

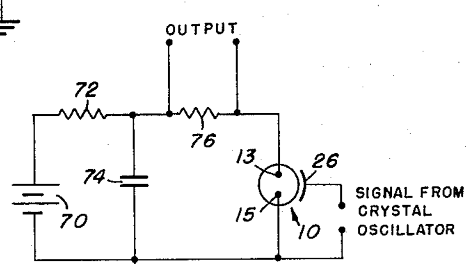
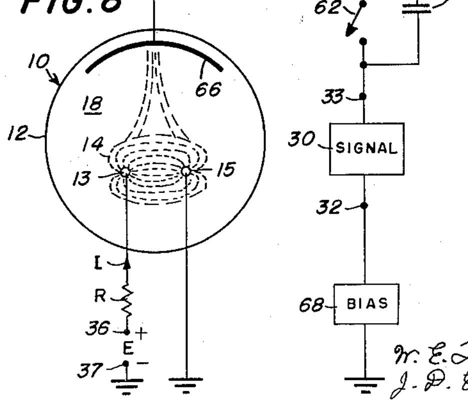


FIG. 7

FIG. 8



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LATERAL-CURRENT CONTROL OF COLD-CATHODE DISCHARGE DEVICES

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4 Claims. (Cl. 315—169)

(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment to us of any royalty thereon.

This invention relates to cold-cathode gas discharge tubes and applications thereof. More particularly this invention relates to cold-cathode gas discharge devices having lateral-current control means.

A cold-cathode gas discharge tube usually consists of two or more electrodes enclosed in a rarefied gas, such as a mixture of argon, neon, helium, etc. The electrodes are supplied with a voltage to establish a small current through the gas medium. When the voltage is such that the current exceeds a certain value, and the resistance in series with the tube is not too large, the gas breaks down and conducts.

The utility of the cold-cathode gas discharge tube is greatly increased when control of its gas discharge characteristics is possible. In the prior art this control has been accomplished in a variety of ways. However, in the prior art only partial control was obtainable, and such control was not always predictable.

In our invention means are provided for establishing lateral-current flow from the main discharge stream occurring between the electrodes of a cold-cathode gas discharge tube. We have found that this lateral-current flow greatly affects the gas discharge characteristics of a cold-cathode tube in all regions. By providing accurate control of this lateral-current flow, we have been able to provide a very sensitive, predictable and complete control for a cold-cathode gas-filled tube in all operating regions. Such control was never before available in the prior art even though cold-cathode diodes have been available for many years. With this increased control a wide variety of new applications for cold-cathode tubes is now possible.

The term "lateral-current flow" will be used in this application to designate a current flow from the region of influence of the main discharge to a region where the ions or electrons, which have been removed from the main discharge stream, have a negligible effect on the main discharge. The term lateral-current flow will be restricted to refer only to a current flow from the main discharge stream which is sufficiently small so that the main discharge remains substantially between the two main discharge electrodes, as in the conventional cold cathode diode. The term lateral-current flow is used because it gives a good physical picture as to the type of control mechanism which is involved in this invention. It should be carefully noted that "lateral-current flow" as used herein is not necessarily limited to current that flows at right angles to the main discharge stream.

An object of this invention is to provide an improved method of controlling the gas discharge of a cold-cathode gas-discharge tube.

Another object is to provide an improved cold-cathode discharge device.

Another object is to provide a cold-cathode discharge device having improved control means.

A further object is to provide a switching circuit which is triggered by the time rate of change of the applied trigger signal.

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Still another object of this invention is to provide an improved trigger circuit which is triggered by the D.-C. current level of the applied signal.

An additional object is to provide a cold-cathode switching circuit in which the glow discharge can be switched both on and off while the anode voltage and the external work circuit remain fixed.

Another object is to provide a repeatable and reliable time-delay cold-cathode circuit.

A further object is to provide a cold-cathode gas discharge amplifier.

Yet another object is to provide a combined amplifier and switching device.

An additional object is to provide a cold-cathode relaxation oscillator which can be synchronized with a low power A.-C. control frequency over a wide range of frequencies.

An additional object is to provide a cold-cathode device which differentiates and amplifies an applied signal.

The specific nature of the invention, as well as other objects, uses, and advantages thereof, will clearly appear from the following description and from the accompanying drawing, in which:

FIGURE 1 is a simple cold-cathode diode circuit.

FIGURE 2 is a typical current-voltage static characteristic curve for a cold-cathode diode.

FIGURE 3 is a schematic representation of a cold-cathode tube showing the basic lateral-current flow mechanism.

FIGURE 4 is a schematic representation showing one type of means for establishing lateral-current flow in accordance with the invention.

FIGURE 5 is a schematic representation of a circuit which may be used as the signal **30** in FIGURE 4 to provide operation of FIGURE 4 as a time-delay trigger circuit.

FIGURE 6 is a schematic representation of a circuit which may be used as the supply voltage E in FIGURE 4.

FIGURE 7 is a schematic representation of a synchronized relaxation oscillator in accordance with the invention.

FIGURE 8 is a schematic representation showing another type of means for establishing lateral-current flow in accordance with the invention.

To understand how lateral-current flow affects the gas discharge of a cold-cathode tube, the behavior of a simple cold-cathode gas-filled diode will first be considered. FIGURE 1 shows a cold-cathode diode **10** connected in series with a D.-C. voltage E and a work circuit represented by the resistor R. The voltage across the diode **10** is represented as V and the current through the diode **10** is represented as I. FIGURE 2 shows typical current-voltage static characteristic curves for a typical cold-cathode diode which may be connected as the diode **10** in the circuit of FIGURE 1. The voltage is plotted on a linear scale and the current is plotted on a logarithmic scale. The exact shape of this static curve will in general be dependent on tube geometry, type of gas used in the tube, gas pressure, condition of electrode surfaces, etc. In addition, the shape of the curve in the Townsend region will be dependent on the magnitude of electron emission from the cathode or state of ionization within the gas derived from external energy sources. This is illustrated in FIGURE 2 where the dotted curve refers to operation in near darkness and the solid curve refers to operation in room light. The difference between the two is accounted for by a difference in photoemission from the cathode due to external radiation. Further description and details concerning the basic mechanisms which determine the current magnitude in various regions of the curve can be found in the literature (see M. J. Druyvesteyen and F. M. Penning, Rev. Mod. Phys. 12

(1940)). The well-known terms for the various regions—Townsend Region, Glow Region, and Arc Region—of current magnitude are shown in FIGURE 2. The voltage values V_1, V_2, V_3 and V_4 and the current values I_1, I_2, I_3 and I_4 refer to the voltages across, and the currents through, the diode **10** at points **1**, **2**, **3** and **4**, respectively. The numbers 10^{-9}, 10^{-6}, 10^{-3} and 1 indicate general orders of magnitude for the current in amperes.

The dashed curves in FIGURE 2 are load lines for a particular value of the series resistor R and for two values of the supply voltage E in FIGURE 1. Because of the semi-log plot necessitated by the large current range, these load lines are curved rather than straight as they would be on a plot having a linear scale. The general shape of such load lines is constant for a given selection of scale magnitudes. The load line curve shifts to the left or right as R is increased or decreased and shifts up or down as the D.-C. voltage source E is raised or lowered.

For a supply voltage E_1 and a series resistor R, the load line is the lower dashed curve of FIGURE 2. The intersection of this lower dashed load line and the static voltage-current characteristic curve determines the operating point of the circuit. This point is designated point **1**. At point **1** a voltage V_1 is across the diode **10** and a current I_1 is flowing in the circuit. If now the supply voltage E is slowly raised to the value E_2, the load line slowly moves upward and the operating point moves along the voltage-current characteristic curve to point **2** at which the upper dashed characteristic load line is tangent to the curve. A voltage V_2 is now across the diode **10** and a current I_2 is flowing in the circuit. A further slight increase in the supply voltage E causes the operating point to suddenly move to point **3** with a sudden increase in current from I_2 to I_3. This current discontinuity is frequently referred to as breakdown or a firing of the diode. The voltage at which this occurs is referred to as the breakdown voltage. The current through the diode may change by several orders of magnitude, and visibly the tube may change from a dark condition to a glow. If the series resistor is sufficiently small, and if the right hand peak of the static curve is lower than the left, the discharge can pass into the arc region with even much larger currents resulting. If now the supply voltage E is gradually lowered back to E_1, the operating point moves along the static curve to point **4** where the lower dashed load line is again tangent to the curve. A slight further reduction in the supply voltage E causes the operating point to suddenly move back to point **1** with a reduction in current from I_4 to I_1. This discontinuity is referred to as an extinguishing of the glow discharge and the diode voltage V at which it occurs is referred to as the threshold voltage.

This cycle, using a particular value of series resistance R, is illustrative of the ways in which the current through the diode may vary. In general, the ratio of current I change to supply voltage E change at any point on the static curve is dependent on the value of this series resistor R.

Under conditions of operation such as just described, several types of elementary processes are going on within the diode **10**. Electrons travelling under the influence of the electric field which exists between the electrodes are producing ionization and excitation. This results in the production of new electrons, positive ions, photons, and in some gases metastable atoms. Loss of charge is also occurring within the gas due to recombination. At the cathode surface secondary electrons are being emitted due to impinging positive ions, photons, and metastable atoms if present. At both electrodes charges are being moved due to the flow of current in the external circuit.

At any point on the static curve of FIGURE 2 all of these processes, with perhaps others, are in equilibrium. The state of equilibrium at a given point is expressed in terms of the current I flowing through the tube and the voltage V across it. Any modification of the tube or circuit which changes the magnitude of one of these variables disturbs the equilibrium condition within the tube and will result in a new equilibrium condition being set up in which both the diode current I and the voltage V generally will have changed. This interdependence leads to the commonly employed method of controlling the discharge—that is, adjusting the anode supply voltage E to produce the desired current I through the tube. This may be done directly or it may be done indirectly by changing the external work circuit R.

In a variety of ways, the prior art has been able to obtain some control of the diode current without changing the anode supply voltage E or the external work circuit R. However, only partial and limited control was possible, and for the most part the results were not predictable. Using the lateral-current flow mechanism of our invention, we have been able to obtain a complete and accurately predictable control of a cold-cathode tube without changing the anode supply voltage or the external work circuit. Such control was never before available in the prior art even though cold-cathode diodes have been known and use in the art for many years.

FIGURE 3 is a schematic representation of the basic lateral-current flow mechanism of our invention. A supply voltage E establishes a main discharge stream **14** between the main discharge electrodes **13** and **15** of a cold-cathode tube **10** having an envelope **12** and an enclosed gas **18**. The electrode **13** serves as an anode and the electrode **15** serves as a cathode. A current I is flowing through the external work circuit represented by the resistor R. Means are provided, indicated generally by the arrow **19**, for establishing a lateral-current flow **16** from the main discharge stream **14**. As mentioned previously, the term lateral-current flow has a very particular meaning. It is not restricted to a current flow from the main discharge stream which is necessarily lateral in the physical sense, as appears in FIGURE 3. The term lateral-current flow in this application is being used to designate any current flow from the region of influence of the main discharge stream **14** to a region where the ions or electrons, which have been removed from the main discharge stream **14**, have a negligible effect on the main discharge stream **14**. The term lateral-current flow is restricted, however, in the sense that it refers to a current flow from the main discharge stream **14** which is sufficiently small so that the main discharge stream remains substantially in the region of the main discharge electrodes **13** and **15**. Any cold-cathode structure, in which this lateral-current flow can be produced as described above, may be substituted for the schematic representation of FIGURE 3. For most structures, the flow **16** from the main discharge stream **14** will have to be only a small portion of the main discharge stream **14** in order to maintain the main discharge stream in the region of the main discharge electrodes **13** and **15**.

To understand the effect of lateral-current flow, consider again a point on the static curve of FIGURE 2 in which all processes occurring within the cold-cathode tube are in equilibrium. The magnitude of current flowing between the main discharge electrodes **13** and **15** of the tube **10** is dependent on the equilibrium rate at which electrons and positive ions are produced and lost in the gas **18** and at the bounding surfaces. Any change in the rate at which charge is produced or lost will be accompanied by a change in the current being conducted through the tube **10** and the external work circuit R. Thus, if a lateral-current flow **16** from the main discharge stream **14** is established, the previous equilibrium conditions will be disrupted and the main discharge stream **14** between the electrodes **13** and **15** will readjust itself until a new equilibrium condition is established taking into consideration this lateral-current flow **16**. We have found that the sensitivity of this mechanism is such that a small change in lateral-current flow **16** is able to produce a much larger change in the main discharge stream **14** and thus in the current I flowing through the external circuit. This increased sensitivity is believed to result because a considerable part of the main discharge stream **14** is indirectly obtained as a result of the secondary emission produced by positive ions striking the cathode electrode **15**. Some of the ions striking the cathode **15** will cause an electron to escape because of secondary emission. Each electron which escapes from the cathode **15** increases the ionization of the gas by collision with gas molecules on its way to the anode **13**. Since one electron ordinarily collides with many molecules on its way to the anode **13**, a multiplied increase in ionization results. Increasing the number of ions striking the cathode **15** therefore will result in an amplified increase in the main discharge stream **14**. And conversely, decreasing the number of ions striking the cathode **15** results in an amplified decrease in the main discharge stream.

Ions may be prevented from reaching the cathode **15** by establishing a lateral-current flow of ions from the main discharge stream **16**. On the other hand, more ions may be made to strike the cathode **15** by establishing a lateral-current flow of electrons from the main discharge stream **14**. This increases the ratio of positive ions to electrons in the main discharge stream **14** causing a decrease in the positive ions which recombine with electrons on their way to the cathode **15**. As a result, a great number of ions will strike the cathode **15**. An amplified effect on the current I in the external circuit can thus be obtained by controlling the lateral-current flow of ions or electrons from the main discharge stream **14**. These amplified changes can be obtained in any region of operation of the gas discharge tube **10**.

Control of the lateral-current flow **16** from the main discharge stream **14** provides complete switching control from region to region without changing the supply voltage E or the external work circuit R. This makes it possible to conveniently initiate and extinguish the diode glow discharge as desired for any particular application merely by controlling the lateral-current flow **16**. To explain how this switching control is obtained, assume first that there is no lateral-current flow **16** and the optrating point is initially in the Townsend region. The supply voltage E is adjusted to have a value between the breakdown voltage and the threshold voltage as defined in connection with FIGURE 2. The resistor R is chosen to be sufficiently small to permit operation in the glow region. The above adjustments provide two stable operating points, one in the Townsend region and the other in the glow region. If a lateral-current flow of electrons is now established from the main discharge stream **14**, the number of ions striking the cathode **15** will increase causing an increase in the ionization of the gas **18** within the tube **10**. If this lateral-current flow of electrons is large enough, initiation of the glow discharge will occur. Since the supply voltage E is larger than the threshold voltage, the tube **10** will remain in the glow region after this lateral-current flow of electrons ceases. If a lateral-current flow of ions is now established, a decrease in the ionization within the tube **10** will occur. If this lateral-current flow of ions is large enough, ionization of the gas **18** will fall below the level needed to maintain the glow discharge, and the glow discharge will be extinguished, returning the operating point to the Townsend region. Since the supply voltage E is below the breakdown voltage, the tube will remain in the Townsend region after this lateral-current flow of ions ceases. The tube may thus be switched between the two regions. If the lateral-current flow is maintained after triggering, switching is possible even if the tube **10** has only one stable operating point since the continuing lateral-current flow will maintain operation in the other region. This means that the supply voltage E need not be adjusted to be between the breakdown and threshold voltages, but may be considerably above the breakdown voltage. For zero lateral-current flow, operation will be in the glow region, and for a continuous lateral-current flow of ions above a minimum value, operation will be in the Townsend region. Exploratory tests indicate that similar switching control as illustrated above can be expected between the glow region and the arc region.

Within any particular region, the device of FIGURE 3 may also be used as an amplifier because changes in the lateral-current flow **16** cause an amplified change in the current I in the external circuit as explained previously. To obtain amplification, the lateral-current flow **16** is varied in accordance with the signal to be amplified. The operating region may be chosen as desired for the particular application. For use as an amplifier, the operating conditions, as determined by the supply voltage E and the external work circuit R, should be adjusted to prevent switching between regions. If operation is desired in the Townsend region, for example, this may be accomplished by making the resistor R large enough to prevent switching to the glow region. Likewise, if operation is desired in the glow region, the resistor R may be made sufficiently small to prevent switching to the Townsend region and sufficiently large to prevent switching to the arc region.

It should be noted that the effects of lateral-current flow have been considered only in regard to cold-cathode diodes. It is not expected that this lateral-current flow mechanism will be effective in controlling heated-cathode diodes because of the different equilibrium conditions existing. In the heater-type of gas diode, a tremendous quantity of electrons is always available at the cathode. Secondary emission electrons produced by positive ions bombarding the cathode will thus have a negligible effect on the main discharge stream. Lateral-current flow, therefore, would be practically insensitive in a heated-cathode type of gas diode.

On the other hand, it has been shown that the main discharge stream **14** in a cold-cathode tube is very dependent upon the lateral-current flow **16** from the main discharge stream **14**. The means for establishing this lateral-current flow **16** are generally indicated by the arrow **19** in FIGURE 3. FIGURES 4 and 8 are examples of two types of means for establishing this lateral-current flow **16**.

In FIGURE 4, numeral **26** represents an electrode external to the gas **18** within the tube **10**. This external electrode **26** may be a conductor placed outside of, or near, the cold-cathode tube **10**. For example, the outside of the envelope **12** could be given a conductive coating and this coating used as the external electrode **26**. The intervening air, glass of the envelope **12**, and the gas **18** form the dielectric of a coupling capacitance represented by the dashed capacitor C. To produce the lateral-current flow **16** from the main discharge stream a varying voltage signal **30** is applied to the external electrode **26**. Or, alternatively, the value of the coupling capacitance C may be varied such as might be produced by relative physical motion between the tube **10** and the external electrode **26**. Because of the capacitive type of coupling, the lateral-current flow **16** will vary as the time rate of change of the voltage signal **30**. To obtain a constant value of lateral-current flow **16**, therefore, the voltage varying signal **30** must rise or fall at a constant rate.

Since the lateral-current flow **16** is dependent upon the time rate of change of the signal **30**, the circuit of FIGURE 4 can be advantageously used as an amplifying and differentiating device in any desired region of operation. The signal **30** will produce a lateral-current flow **16** which varies as the time rate of change of the voltage signal **30**, thereby causing an amplified variation in the current I in the external circuit. A voltage may thus be obtained across the resistor R which is the differentiated and amplified voltage of the voltage varying signal **30**. Of course, the operating conditions of the circuit and the rate of change of the voltage varying signal **30** must be adjusted so that operation does not switch to another region. This may be accomplished by methods described previously in connection with FIGURE 3.

The device of FIGURE 4 may also be advantageously utilized as a special type of triggering circuit which can be triggered either "on" or "off" only by the time rate of change of the voltage varying signal and not by the D.-C. level of the signal. As described previously, establishing a lateral-current flow **16** of sufficient magnitude, and in the proper direction, will cause switching from the Townsend region ("off" condition) to the glow region ("on" condition), or vice versa. A rising signal **30** turns the tube "on" and a falling signal **30** turns the tube "off." To maintain the lateral-current flow would require that the voltage varying signal **30** be continuously falling or continuously rising as the case may be. Since such a signal cannot be practically produced for any length of time, it will be necessary to provide two stable operating points so that the operating point will remain in the region to which it has been switched after the rising or falling signal ceases. This may be accomplished by adjusting the supply voltage E to be between the threshold voltage and the breakdown voltage as described in connection with FIGURE 3.

The advantage of using the circuit of FIGURE 4 as a trigger circuit is that switching is obtained only in response to the time rate of change of the triggering signal or relative motion between the tube **10** and the external electrode **26**. A D.-C. voltage many times that which would normally produce breakdown can thus be maintained on the external electrode **26** with practically no effect on the main discharge stream **14**. A trigger device according to FIGURE 4 was constructed using an ordinary Ne-2 type of cold-cathode diode with a conductive coating serving as the external electrode **26**. With this device adjusted to have two stable operating points, triggering between the Townsend region ("off" condition) and the glow region ("on" condition) was obtained in 10 to 20 milliseconds for a voltage varying signal **30** changing as slow as 5 to 10 volts per second. This is an indication of the considerable sensitivity of the lateral-current flow control mechanism. For large rate of rise signals switching was obtained in less than 100 microseconds. Because the device of FIGURE 4 can conveniently be cut "on" or "off," it is ideally suited for use as a binary element in computer circuits.

The device of FIGURE 4 also lends itself to use as a time-delay trigger circuit because of a unique feature of this device. For such use, the battery **40** and the switch **42** shown in FIGURE 5 are used as the signal **30** in FIGURE 4. The operating point of the tube **10** is chosen so that the tube is initially in the Townsend region or the glow region. The switch **42** is initially open. The time delay is triggered by closing the switch **42** which suddenly applies the negative voltage of the battery **40** to the external electrode. This produces a large negative rate of rise signal which causes the current I in the external circuit to be greatly reduced. If the negative voltage of the battery **40** is high enough, we have observed that the current I does not return to its initial value, but there is a time delay during which the current I remains at the value it was reduced to upon closing the switch **42**. The length of this time delay may be a fraction of a second, several seconds, or a minute or longer depending upon the voltage of the battery **40** and the value of the coupling capacitance C. For a given negative voltage of the battery **40** and the capacitance C, we have been able to obtain repeatable time delays over a wide time-delay range.

A logical explanation for this effect may be obtained by considering the effect of a rapidly rising negative signal on the equilibrium conditions within the tube **10**. Assume that the operating point is initially in the Townsend region with an initial current I flowing in the external circuit. Application of a rising negative signal to the external electrode **26** causes positive ions to be drawn out of the main discharge stream **14**. If a sufficient number of ions are still available in the main discharge stream **14**, a new equilibrium condition will be established with a reduced value of current I resulting from this lateral-current flow of ions. When the negative rising signal levels off, the tube will return to its original operating point and the current I will return to its initial value. If, on the other hand, the negative signal is so large that the rate of rise signal resulting sweeps practically all of the ions out of the main discharge stream **14**, the main discharge will be rapidly extinguished due to the loss of most of the positive ions within it. The state of ionization drops to a low level and the impedance through the gas in the signal circuit greatly increases. The charging circuit for the coupling capacitance C will thus have a considerable time constant and a lateral-current flow will continue for a considerable time until the capacitance C charges to the potential of the battery **40**. This lateral-current flow maintains the current I at its reduced value during this charging time period. When the capacitor C becomes fully charged to the potential of the battery **40**, the current I returns to its initial value.

In order to have this tme delay it is not necessary that the initial operating point be in the Townsend region. The operating point may be in the glow region, or the tube may be in a state of relaxation at the time the switch **42** is closed. In any case, if the ionization is swept out by the rising voltage signal, a time delay will occur which can be varied by proper choice of signal and circuit.

If the initial operating point is in the Townsend region, it is possible with suitable circuitry to cause the tube **10** to pulse into the glow region before returning to its initial operating point in the Townsend region. To accomplish this, the battery **50**, the resistor **52**, and the capacitance **54** of FIG. 6 may be used to obtain the supply voltage E in FIGURE 4. The voltage of the battery **50** is chosen to be above the breakdown value of the tube **10**. The resistor **52** is chosen so that the current I at the operating point in the Townsend region causes the voltage E across the capacitor **54** to be between the breakdown voltage and the threshold voltage of the tube **10**. When switch **42** is closed, the current I reduces to a very small value causing the capacitor **54** to charge to a voltage which is above the breakdown voltage. This charging should occur before the end of the time-delay period. Thus, when the lateral-current flow of ions ceases and the operating point returns to its original position in the glow region, the voltage E will be above breakdown causing the tube **10** to pulse into the glow region. This type of circuit provides a tube with a very small standby current in the Townsend region, which, following a predetermined time delay, will give a sharp pulse into the glow region and then return to its initial standby condition.

Another unique application of the device of FIGURE 4 is as a synchronized relaxation oscillator, as shown in FIGURE 7. The battery **70** has a voltage above the breakdown value, and the resistor **72** is sufficiently small to permit the capacitor **74** to charge to a voltage above the breakdown value. With no signal applied to the external electrode **26**, the circuit will be in a state of relaxation oscillation at a frequency determined by the circuit parameters. We have observed that application of a signal between the external electrode **26** and the cathode electrode **15** will cause the relaxation oscillation to be synchronized with the frequency of the signal over a wide range of frequencies. This synchronization is particularly advantageous when the applied signal is the output of a crystal oscillator as in FIGURE 7. Almost no power would be required from the crystal oscillator, while a signal of considerable power could be obtained across the load resistor **69** at the exact frequency of the crystal oscillator. It will also be evident that by properly choosing the circuit parameters, the frequency of the signal obtained across the resistor **69** could be either multiplied or divided by any desired small integer. It has also been observed that with suitable circuitry the relaxation oscillation can be amplitude modulated and to a somewhat lesser extent frequency modulated.

A second means of providing lateral-current flow is shown in FIGURE 8. An additional conducting electrode **66** is placed within the envelope **12** in contact with the gas **18** in a relatively weak electric field region of the main discharge stream **14**. This will insure that the internal electrode does not affect the action of the main discharge stream **14**. This electrode may be placed along the inside surface of the envelope **12**, or, the envelope **12** itself, if made of conductive material, may be used as the electrode **66**. This internal electrode **66** is provided with an external connection to which a signal **30** may be directly applied. If the switch **62** is open so that the capacitor **65** is in series with the internal electrode **66**, and the bias **68** is omitted, operation of the device of FIGURE 8 will be identical with that of FIGURE 4. That is, the lateral-current flow **16** will be dependent upon the time rate of change of the applied signal. The device of FIGURE 8, therefore, can be directly substituted for the device of FIGURE 4 in all applications described in connection with FIGURE 4. The FIGURE 8 device, however, is more versatile since the capacitor **65**, which corresponds to the coupling capacitor C in FIGURE 4, can be chosen as desired for any particular application.

If the switch **62** is closed so that no capacitive coupling is employed, it can be seen that the lateral-current flow **16** between the main discharge stream **14** and the internal electrode **66** is now identical with the current **61** in the signal circuit. Therefore, any type signal which produces a change in the signal current produces a corresponding change in the lateral-current flow **16**.

Switching either "on" or "off" may be accomplishtd using the device of FIGURE 8 merely by providing a signal which produces the necessary current **61** in the signal circuit. The big advantage of the device of FIGURE 8 is that the lateral-current flow **16** may be very easily maintained merely by maintaining the signal current **61** which caused triggering at a constant value. This makes it unnecessary to have two stable operating points as was required for switching "on" and "off" in FIGURE 4 and the supply voltage E can now be varied over wide limits. For example, if the supply voltage E is above the breakdown voltage, and it is desired to switch from the glow region ("on" condition) to the Townsend region ("off" condition), the operating point may be maintained in the Townsend region by maintaining the signal current **61** which caused switching even though the voltage E is above breakdown. Because of this added versatility of the device of FIGURE 8, the supply voltage E can be varied over wide limits with very little effect on switching response. This device of FIGURE 8, therefore, is very advantageous in a great number of applications, because there is no necessity for special aging techniques or other means to obtain tubes with uniform breakdown voltages as was required in the prior art.

A further desirable feature of the device of FIGURE 8 is that the main discharge stream **14** does not slowly die out (deionize) as in the case where the supply voltage E is removed, but because of the presence of the additional internal electrode **66** is forced out by sweeping charge out of the main discharge stream **14**. This makes it possible to improve the frequency response of a cold-cathode tube and makes it usable in applications where fast response is necessary.

It is apparent that the device of FIGURE 8 is very well suited for operation as an amplifier. The bias **68** provides a D.-C. biasing current which may be used in conjunction with the supply voltage E and the work circuit resistance R to choose any desired operating point in any region. The operating point will generally be chosen so that operation will be in the Townsend region for amplification of very small currents, and in the glow region and arc regions for amplification of larger currents. If the signal **30** superimposes a varying cuurrent on the bias value, an amplified variation is obtained in the current through the work circuit resistance R. The same methods may be employed as described in connection with FIGURE 4 for maintaining operation within a single region.

The device of FIGURE 8 can also be advantageously operated as a combination amplifier and switching circuit. This is possible because switching between regions can be obtained by the simple expediency of changing the D.-C. level of current flowing through the signal circuit. For this type of operation, the work circuit resistance R is chosen to permit operation in both the Townsend region and the glow region. For small variations in signal current, an amplified signal will be obtained across the resistance R. By changing the D.-C. level of the signal current, switching between the two regions may be accomplished as desired. Large signal currents which cause switching between regions, produce high power pulses across the resistance R. Those skilled in the art will find many uses for these unique characteristics obtained for this type of operation of the device of FIGURE 8.

It will be apparent that the embodiments shown are only exemplary and the various modifications can be made in construction and arrangement within the scope of the invention as defined in the appended claims.

We claim as our invention:

1. A synchronized cold-cathode relaxation oscillator comprising in combination: a cold-cathode gas discharge tube comprising a gas-filled envelope, two main discharge electrodes enclosed within said envelope across which a main discharge current stream occurs, and a control electrode external to said envelope; means connected to said two main discharge electrodes to cause relaxation oscillation of said main discharge stream; and means applying a synchronizing signal between said external control electrode and one of said main discharge electrodes, the frequency of said relaxation oscillation thereby being synchronized with the frequency of said synchronizing signal.

2. A method of electrically switching a cold-cathode gas discharge tube having two discharge electrodes enclosed within a gas-filled envelope between its Townsend and glow regions of operation, and vice versa, said method comprising the steps of: connecting a direct current voltage and load across said two discharge electrodes so that operation of said tube is possible only in the Townsend and glow regions, placing an external electrode in close proximity to said envelope, applying a rising voltage having a time rate of change above a minimum value between said external electrode and one of said discharge electrodes to switch said tube from the Townsend region to the glow region, and applying a falling voltage having a time rate of change above a minimum value between said external electrode and one of said discharge electrodes to switch said tube from the glow region to the Townsend region.

3. A method of operating a cold-cathode gas discharge tube having two main discharge electrodes within a gas-filled envelope in a region selectable from the group consisting of the Townsend region and the glow region to provide simultaneous differentiation and amplification of an input electrical signal, said method comprising the steps of: connecting a direct current voltage and a load in series with said two discharge electrodes to provide a main discharge current, adjusting the magnitudes of said voltage and said load so that operation of said tube is

possible only in one of said regions, placing an external electrode in close proximity to said envelope, applying said input signal between said external electrode and one of said main discharge electrodes to establish a lateral-current flow, and controlling the magnitude of said main discharge current by varying said lateral-current flow in response to said input signal so that a differentiated and amplified output signal is obtained across said load.

4. A time-delay circuit comprising in combination: a cold-cathode gas discharge tube having a gas-filled envelope and two main discharge electrodes enclosed within said envelope for providing a main discharge stream; a control electrode external to said envelope in close proximity to said envelope; a supply voltage source and a resistance connected in series with said two main discharge electrodes; a negative voltage source and switch

means connected in series with said control electrode; said negative voltage source applying a negative voltage above a predetermined negative value to said control electrode when said switch means is closed, said negative voltage source and the coupling capacitance between said control electrode and one of said main discharge electrodes providing a predetermined time delay.

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