Cold Cathode Gas Tubes for Telephone Switching Systems

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Cold cathode gas tubes perform both switching and memory functions in telephone switching systems. One measure of the performance of a switching diode is the switching voltage gain, defined in terms of the characteristics of the device. Some of this gain must be sacrificed in order to increase the switching speed in a way which is analogous to the gain-bandwidth property of a conventional amplifier. In this paper, methods of achieving a high switching-voltage gain are described in terms of the gas discharge processes. An example is given of an application of these principles to a tube for use as a switch in series with the talking path in an electronic telephone switching system.

INTRODUCTION

Gas discharge tubes have found extensive use in telephone switching and other digital systems. Most of these applications take advantage of the fact that both switching and memory can be provided by a single gas discharge device. The switching characteristics result from the fact that the device is an essentially open circuit when the gas is not ionized and a closed circuit when the gas is ionized. The memory function is possible because the tube can be held in a high current condition, once it is ionized, by a voltage which is too low to initiate this conduction. Thus a triggering signal which ionizes the tube is "remembered" until the holding voltage is removed and the tube is allowed to de-ionize.

In some applications, gas tubes are used as switching devices in series with voice frequency circuits. For this purpose, the tube must offer a low impedance to audio frequency signals in addition to meeting requirements of switching and memory.

This paper first describes some switching characteristics of gas tubes considered as circuit elements. Desirable performance objectives are established in terms of these device characteristics. Following this, physical processes within the tube are described as they relate to circuit performance. Finally, a description is given of a new talking path tube in which improved switching and transmission performance have been achieved.

EXTERNAL SWITCHING PROPERTIES

From the point of view of the external circuit, a gas diode may often be treated as a device which is an open circuit so long as the applied voltage is low, and which becomes a conductor if the applied voltage is raised above a threshold or "breakdown" value for a sufficient length of time. When the tube is conducting currents of the order of a few tens of microamperes or higher, the voltage is relatively independent of current and has a value, referred to as the "sustaining voltage", which is less than the breakdown voltage.

Although the details of actual circuits differ, it is possible to illustrate some important switching principles by the simplified circuit of Fig. 1(a). A gas diode is shown with the cathode connected to a bias voltage E through a load resistor. A signal source, assumed to have zero internal impedance is connected to the anode. The output voltage waveform corresponding to a pulse input is shown in Fig. 1(b). Note that after a time delay, t, the output rises to a voltage that differs from the total applied voltage by an amount equal to the sustaining voltage of the tube. The memory function is illustrated by the fact that the output signal remains after the input signal is removed.

It is often desired to use the output signal resulting from the triggering of one tube to switch one or more additional tubes. Since the input signals can be a few microamperes and the output signal can be tens of milliamperes, a large current gain is available from a gas tube. In many applica-

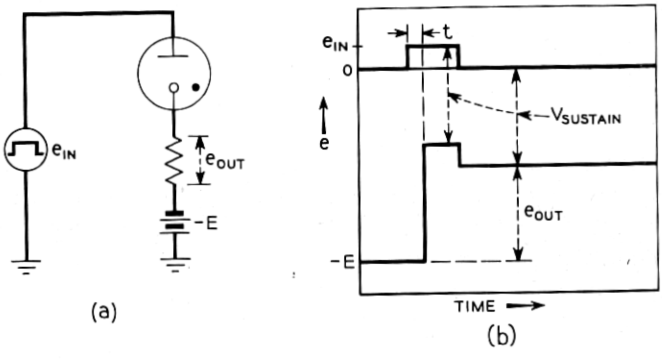

Fig. 1 — Simplified gas diode switching circuit.

tions, however, it is desired to apply the output voltage directly to other tubes without impedance transformation. In this case, voltage gain is of more interest than current gain. The maximum voltage gain per stage, defined as the maximum output voltage divided by the minimum input signal, is limited by variation in tube characteristics as will now be shown.

The bias voltage E of Fig. 1 is expected never to cause breakdown during times when the input voltage is zero. This establishes the upper limit of E as

$$|E| \leqq V_{B\,\mathrm{min}} \tag{1}$$

where $V_{B\,\mathrm{min}}$ is the minimum breakdown voltage at any point in the life of any tube to be used in the circuit. As the bias voltage E approaches breakdown, the input signal voltage required for triggering approaches zero, and if there were no variation in breakdown voltage or bias voltage, and no noise voltages, the gain could be made to approach infinity.

The input signal, added to the bias, must be made large enough always to cause breakdown. Thus the minimum input signal is determined by $V_{B\,\mathrm{max}}$, the maximum breakdown voltage at any point in the life of any tube to be used in the circuit:

$$e_{\mathrm{in}} \geqq V_{B\,\mathrm{max}} - E \tag{2}$$

Combining (1) and (2)

$$e_{\mathrm{in}} \geqq V_{B\,\mathrm{max}} - V_{B\,\mathrm{min}}$$

or

$$e_{\mathrm{in}} \geqq \Delta V_B \tag{3}$$

where ΔV_B is the maximum variation in breakdown voltage among all tubes to be used in the circuit.

The output signal is the difference between the bias voltage and the sustaining voltage of the tube:

$$e_{\mathrm{out}} = E - V_{\mathrm{sus}} \tag{4}$$

The minimum output voltage corresponds to the maximum sustaining voltage, $V_{\mathrm{sus\,max}}$. It is this value that must be used in calculating the maximum gain per stage as limited by the tube characteristics. The gain is then calculated as

$$G = \frac{e_{\mathrm{out}}}{e_{\mathrm{in}}} = \frac{E - V_{\mathrm{sus\,max}}}{\Delta V_B} = \frac{V_{B\,\mathrm{min}} - V_{\mathrm{sus\,max}}}{\Delta V_B} \tag{5}$$

This gain cannot be realized in practice because additional allowances must be made for the variation in power supply voltages and protection against noise. In some cases the need for higher speed reduces the gain still further, as will now be shown.

In Fig. 1 a delay, t, is indicated between the application of the triggering signal and the appearance of the output signal. Part of the delay is statistical in nature and part is occasioned by the building up of ionization within the tube. As will be discussed later, the delay can be reduced by tube design techniques. However, for any given tube, the delay is a function of the excess of the tiggering voltage over the breakdown voltage. The larger this overvoltage, V_{ov}, the shorter is the breakdown delay. Since this overvoltage must be added directly to the input signal, the gain is reduced.

Although not shown in Fig. 1, the tube is turned off by applying a signal that reduces the anode-to-cathode voltage below the sustaining value. This turn-off signal must have sufficient duration so that the tube does not again break down at the return to normal bias conditions. If the turn-off pulse duration is less than that needed for complete recovery, the effective breakdown voltage is reduced. Equation (5) can be modified to show the effect of this reduction in turn-off time by defining a quantity V_r, the reduction in breakdown voltage resulting from incomplete recovery of the tube. The combined effects of V_r and V_{ov} are then

$$G = \frac{(V_{B\,\min} - V_r) - V_{\text{sus}\,\max}}{\Delta V_B + V_{ov}} \tag{6}$$

Equation (6) shows that faster turn-on obtained by increasing the over voltage V_{ov} and faster turn-off obtained by allowing for decrease in breakdown voltage by an amount V_r, both result in a reduction in voltage gain. Thus the familiar trade of speed for gain extends to gas tube switching circuits. Summarizing, it can be seen by (5) that constant breakdown voltage and large difference between breakdown and sustain are desirable switching properties. Also, as shown in (6), the tube should be designed so that the overvoltage needed to cause fast breakdown is small and the recovery of breakdown voltage after the tube is turned off is fast. It is useful to consider now the internal physical processes of a cold-cathode glow-discharge tube in order to see how the desired external properties can be obtained.

PHYSICAL PROCESSES OF A COLD CATHODE GLOW DISCHARGE

Since the gas particles are neutral and the cathode does not spontaneously emit electrons, current flow requires an auxiliary supply of charged particles. A small amount of radioactive material to ionize some

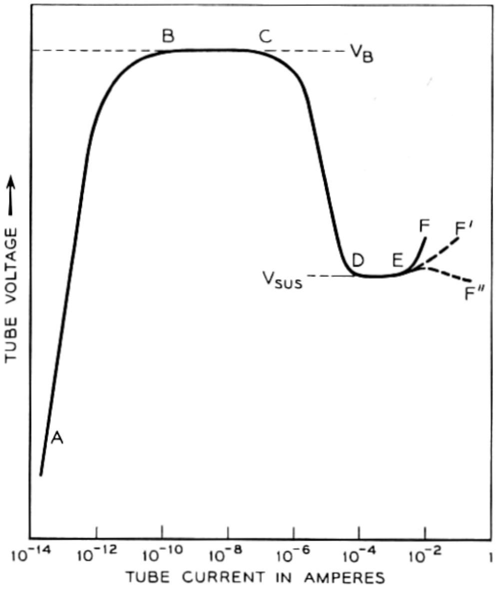

Fig. 2 — Voltage versus current curve of typical gas diodes.

of the gas or very small photoelectric emission of electrons from the cathode are commonly used for this auxiliary supply. A typical voltage-current curve is shown in Fig. 2. At low voltage, the current is very small, often being in the range of 10^{-14} ampere or less. The current increases with the voltage because collisions of electrons with neutral gas atoms produce additional excitation and ionization in the gas. Some of the new ions and excited gas atoms release new electrons by secondary emission when they strike the cathode.

The rate of increase of current with voltage depends on the kind and the pressure of the gas filling, the cathode material, and the tube geometry. An important characteristic of the gas is defined by an ionization coefficient η, which represents the number of new electrons (and ions) produced by a single electron moving through the gas a distance corresponding to one volt of potential difference.[1] This coefficient is a function of the kind of gas and of the quantity E/p_0 where E is the voltage gradient and p_0 is the normalized gas pressure. The fact that there is an optimum E/p_0 at which η is a maximum will be important to later discussion. The electron current at the anode, i_a, produced by gas amplification of a photoelectric current i_0 at the cathode is[1]

$$i_a = i_0 e^{\int_{V_0}^{V} \eta dV} \tag{7}$$

where V is the anode voltage and V_0 is the initial voltage through which the electrons must travel before they can ionize.

The ions produced in the space by this process flow back toward the cathode. The ion current i_p resulting from this process is

$$i_p = i_0(e^{\int_{V_0}^{V} \eta dV} - 1) \tag{8}$$

As mentioned above, new electrons are released at the cathode by positive ions, neutral atoms excited to a metastable state, and photons generated in the gas. These secondary processes can be grouped together by defining a coefficient γ as the number of new electrons released at the cathode by all of these processes for each positive ion generated in the cathode-anode space. Thus each electron passing from cathode to anode, on the average, results in the release of M new electrons where

$$M = \gamma(e^{\int_{V_0}^{V} \eta dV} - 1) \tag{9}$$

Each new electron from the cathode is also amplified in the gas so that after n multiplication cycles, the electron current at the anode is[2]

$$i_n = i_0 e^{\int_{V_0}^{V} \eta dV}(1 + M + M^2 + \cdots + M^n) \tag{10}$$

When M is less than unity and $n \rightarrow \infty$ (the equilibrium state), (10) reduces to a steady state value of

$$i = \frac{i_0 e^{\int_{V_0}^{V} \eta \, dv}}{1 - M} \tag{11}$$

Since the current is dependent on the initial current i_0, the discharge is said to be non-self-sustaining. This corresponds to the portion AB of the curve of Fig. 2.

If the applied voltage is made high enough, the multiplication factor approaches unity, the current of (11) becomes independent of the initial current, and the tube is said to have broken down. This condition corresponds to the horizontal portion BC of Fig. 2. To control this breakdown voltage, the cathode secondary emission coefficient γ and the gas ionization coefficient η must be controlled.

The secondary emission coefficient is highly sensitive to the surface conditions of the cathode. Pure metals such as molybdenum are often preferred to coated surfaces because they permit highly stable and reproducible emission. With the cathode surface determined, the breakdown voltage can be adjusted by changing the gas filling and tube geometry. Fig. 3 shows the breakdown voltage for a tube having parallel-plane

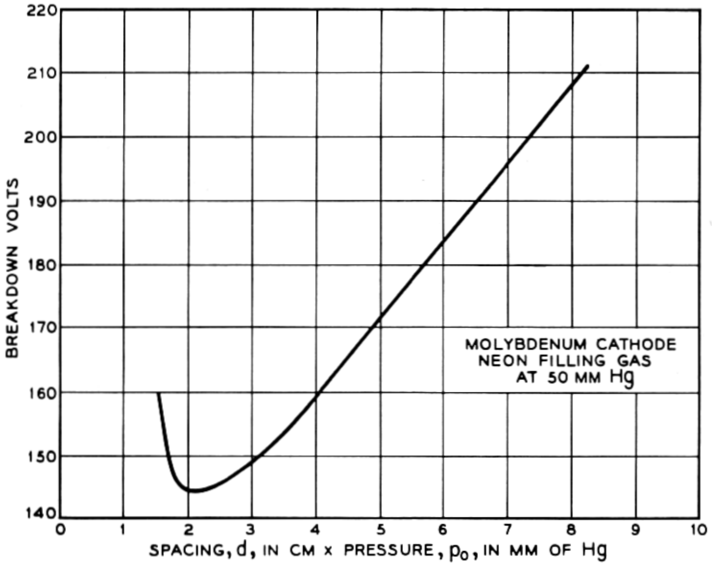

Fig. 3 — Breakdown voltage as a function of spacing and pressure for parallel plane anode and cathode.

anode and cathode geometry, a molybdenum cathode, and neon filling gas. The curve is plotted as a function of the product of pressure p_0 in mm Hg and electrode separation d in cm. Approximately the same plot would obtain for other pressures because both η and γ are functions of (E/p_0) and, for uniform fields, E is simply the voltage divided by the separation

$$\frac{(E)}{(P_0)_{\text{at breakdown}}} = \frac{V_{Bd}}{d}\frac{1}{p_0} \tag{12}$$

Since the variation of γ with E/p_0 is small and may be ignored in this elementary discussion, the minimum breakdown voltage corresponds very nearly to the optimum value of the ionization coefficient η. At spacings or pressures less than optimum, η is reduced because some electrons strike the anode without colliding with gas atoms. At spacings or pressures greater than optimum, η is reduced because electrons do not gain enough energy between collisions to ionize efficiently.

It can be seen that a way of meeting the switching requirement of constant breakdown voltage would be to design the tube to operate at the minimum of Fig. 3. Minor changes in spacing or filling pressure from one tube to another and changes in pressure with tube operation would result in small changes in breakdown voltage. The advantages of op-

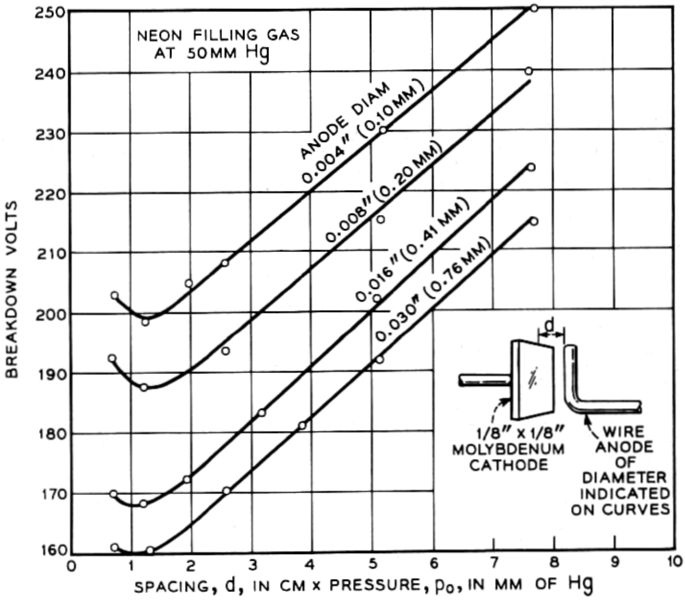

Fig. 4 — Breakdown voltage as a function of spacing and pressure for small wire anodes parallel to cathode surface.

eration at the minimum of the p_0d curve can be retained and the breakdown voltage made higher by resorting to non-uniform geometry. Typical curves are shown in Fig. 4. The cathode was a small rectangular plate and the anode was a wire placed parallel to the cathode surface. It is seen that as the anode diameter is decreased, the minimum of the breakdown curve is increased. The practical limit is set by mechanical stability of the anode and by transmission requirements, as will be discussed later.

The rise in minimum breakdown voltage as the anode size is reduced can be explained on the basis of the distortion of the electric field. Near the cathode, E is lowered, and near the anode, E is increased, as compared to the parallel plane case. If the spacing is adjusted for optimum E/p_0 with parallel planes, then η is necessarily less than optimum for the distorted fields.

Returning now to Fig. 2, we note that, as the current is increased beyond breakdown, the tube voltage falls to a lower sustaining value and again is relatively constant with current. This lower voltage corresponds to the development of a space-charge layer of positive ions near the cathode and an increased voltage gradient at the cathode. This higher field results in an increase in the ionization coefficient η, and, in some cases,[3] a larger effective value of the secondary emission coefficient γ. This is because electrons released by the secondary emission processes may strike neutral gas atoms and be reflected back to the cathode. A higher gradient increases the probability of escape of such an electron. Thus the multiplication factor M of (9) can equal unity at a lower total applied voltage.

Practical tubes filled with neon or argon gas have sustaining voltages near 100 volts when pure molybdenum or tungsten cathodes are used. Cathodes coated with barium and strontium oxide may sustain at 60 volts. However, since this lower sustain is accompanied by a lower breakdown voltage, the difference between them is not increased. Also, since the coated cathode surface is more variable between tubes and with tube operation, the switching voltage gain may be reduced with such cathodes.

The gas pressure and cathode geometry determine the length of the flat portion DE of Fig. 2. Over this current range, the area covered by the glow discharge increases with current until at E the cathode is completely covered. Increasing the cathode area or gas pressure increases the total current required for coverage. At still larger currents, the sustaining voltage increases rapidly as indicated by the solid curve EF. Broken curve EF′ applies to a special cathode geometry called a hollow cathode.[4] Such a cathode may be formed by the interior of a cylinder or by placing two plane cathodes close together so that the negative glow regions overlap. Under this condition electrons, ions, and excited atoms generated near one cathode can aid in current flow from the other cathode. Dotted curve EF″ applies to a particular form of hollow cathode[5] in which cathode shape and gas pressure have been selected to give a negative slope in the high current region. This negative slope represents a negative resistance and permits audio-frequency signals to be transmitted through the tube without loss.

Anode effects have not been discussed. In general, the anode shape and location do not affect the sustaining voltage or the ability of the discharge to transmit audio frequency unless the anode-cathode spacing is too large. The basic requirement is that the anode should be large enough to intercept enough electrons to carry whatever current is required by the external circuit. Even a small anode placed near the cathode space-charge region can meet this requirement. Thus the sustaining voltage of a tube designed to have a breakdown voltage near the minimum of Fig. 3 or Fig. 4 will not in general be sensitive to the anode size or shape.

The transition from low current to high current in a gas diode can thus be thought of as the process of introducing a space charge of positive ions in the region near the cathode. This is done by raising the voltage temporarily above the breakdown value. To switch back to the low current, it is necessary to decrease the multiplication factor M below unity by temporarily lowering the voltage and allowing the ions and excited atoms to diffuse out of the cathode and anode region. Both the turn-on and the turn-off processes impose time restrictions on the switching characteristics.

The multiplication factor M of (9) applies to an average process. Thus, even though M is greater than unity, it is possible that the ionization and excitation produced in the gas by any individual electron may not release a new electron at the cathode. It is therefore necessary on the average to wait for more than the time between initiating electrons before the discharge starts to build up.

The average statistical delay is then equal to the average time between successful starting events. If N_0 photoelectrons per second are emitted from the cathode and W is the fraction of these which successfully initiate a discharge, the average statistical delay is[6]

$$t_{\mathrm{AV}} = \frac{1}{WN_0} \tag{13}$$

The fraction W would be expected to increase with an increase in the multiplication factor M and hence with the overvoltage above breakdown. It has been shown theoretically and experimentally[7] that this is the case. For voltages only slightly in excess of breakdown, i.e., small overvoltages, V_{ov}, the expression for average statistical delay can be approximated by

$$t_{\mathrm{AV}} \approx \frac{k_s}{V_{\mathrm{ov}}} \tag{14}$$

In practical tubes with overvoltages of 10 volts, the average statistical delay may be of the order of milliseconds with radioactive sources of ionization. Short delays of the order of microseconds are obtained by providing an auxiliary "keep-alive" discharge to a separate electrode or by illumination that provides a photoelectric current in the range of 10^{-12} amperes.

A formative delay in breakdown also occurs because time is required for current to build up to the final value. This time is equal to the product of the number of multiplication cycles and the time per cycle. The number of multiplication cycles required is reduced as multiplication factor M is increased with increasing overvoltage. The multiplication factor M includes electrons released at the cathode by slow moving metastable gas atoms as well as those released by the faster positive ions. At very low overvoltages, these slow components must be included before the current can build up.[8] At higher overvoltages enough positive ions are produced so that M is greater than unity without waiting for the slow components. Thus the effective time per multiplication cycle is reduced with increasing overvoltage. Since the number of cycles and the time per cycle are both decreased the formative delay decreases rapidly with increasing overvoltage. A typical formative delay for a neon filled, molybdenum cathode switching tube at 5 volts overvoltage might be of the order of 100 microseconds.

APPLICATION TO A TALKING-PATH SWITCHING DIODE

The principles discussed above have been applied in the development of a cold-cathode gas diode for use as a switch in series with the speech path in an electronic switching system. The objectives were a switching voltage gain as high as possible, a breakdown time of less than a few hundred microseconds, and a low transmission impedance for audio-frequency signals.

A sketch of one version of the resulting tube is shown in Fig. 5. The cathode is a molybdenum rod which has a small hollow cathode portion in the upper end. The anode is a small molybdenum wire placed near the minimum breakdown distance and slightly to one side of the opening in the end of the cathode. A barium getter is flashed to one side of the bulb wall and a small tungsten wire spring is arranged to make electrical contact with the getter flash. A neon filling gas at a pressure near 100 mm Hg is used.

The cathode geometry has several interesting properties. It was found that the shape of a cylindrical hollow cathode is unstable at very high current densities and that it will rapidly grow into a spherical cavity with a small orifice.* Typical dimensions are a sphere diameter of 0.030 inch and an orifice diameter of 0.008 inch. At an operating current of 10 milliamperes, the current density in the orifice is of the order of 50 amp/cm^2. Once the sphere has stabilized it will operate many thousands of hours with relatively small changes in shape. The transmission properties of the stabilized spherical cavity cathode are similar to the earlier negative resistance hollow cathode tubes.[5] Typical im-

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* This cathode was developed by A. D. White of Bell Telephone Laboratories and will be described more completely by him in a forthcoming publication.

pedance values are 300 ohms negative resistance and 50 ohms inductive reactance at 10 milliamperes operating current, with a superimposed audio-frequency signal of 3,000 cycles per second.

Even though the cathode geometry is stable, some cathode material escapes through the orifice and will rapidly collect on an anode placed directly over the opening. It is therefore necessary to locate the anode to one side of the orifice. The extremely high ionization density near the cathode orifice allows considerable flexibility in anode location without affecting the sustaining voltage or destroying the negative resistance.

High switching-voltage gain is obtained by using a small anode formed by a 0.005-inch diameter molybdenum wire placed perpendicular to the end of the cathode at a spacing of approximately 0.005 inch. Breakdown voltage is nominally 190 volts with a range of ±10 volts over all tubes and over the nominal operating life of 4,000 hours. The sustaining volt-

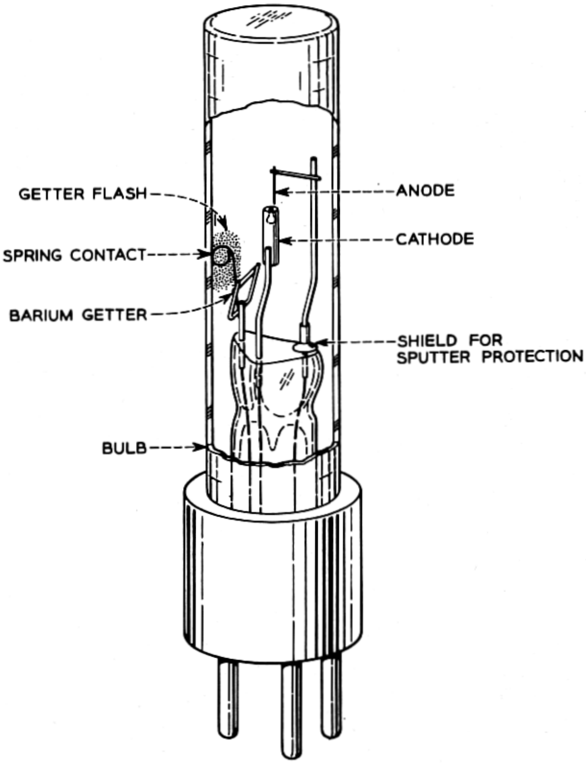

Fig. 5 — A talking-path switching diode.

age at the operating current of 10 ma is 99 ± 2 volts. Thus the switching gain from (5) is (180–101)/20 or 3.9. In practice, switching is often done without allowing the full 100 milliamperes operating current to flow. Under these conditions, the sustaining voltage may be 10 or 15 volts higher, with a consequent reduction in switching voltage gain.

Short breakdown times were desired for this tube. It was not desirable to use enough radium to obtain the needed initial ionization, since it is expected that large numbers of these tubes will be concentrated in a relatively small space. Also, the molybdenum cathode does not emit photoelectrons unless short wavelength ultraviolet illumination is used. The solution chosen was to use the barium getter flash as an auxiliary photocathode. An electrical contact is made to the getter deposit and this is connected through a high resistance to the main cathode. Visible light or long wave ultraviolet light is readily transmitted through the bulb and produces photoelectric current in the auxiliary gap. This current is amplified by the gas, but remains a non-self-sustaining discharge. Currents of 10^{-10} amperes are readily available with a few foot-candles of illumination. This current is too small to affect the breakdown voltage of the main gap, but produces enough residual ionization to allow breakdown times of the order of 100 microseconds to be obtained with a few volts overvoltage. The high resistance connection to the main cathode may be of the order of 20 to 50 megohms. It protects the photocathode from deterioration which might result from high currents when the main gap is conducting.

Recovery of breakdown voltage following conduction is rapid. Measurements indicate that the breakdown voltage is within the limits of 190 ± 10 volts in less than 500 microseconds. The relatively high gas pressure and close spacings speed up the deionization process.

The tube described has not been designed for large scale manufacture although several hundred models have been made and tested to establish the feasibility of the design.

SUMMARY

Some useful switching properties of gas diodes can be described by defining the switching-voltage gain. This gain is shown to be equal to the difference between the breakdown and the sustaining voltage divided by the variation in the breakdown voltage. The gain is reduced if faster switching times are required.

The switching-voltage gain is discussed in terms of the physical processes in a gas discharge. It is shown that a high gain can be obtained by using an inefficient anode operating at the minimum of the curve of breakdown voltage versus the product of gas pressure and anode distance.

A tube is described which uses these principles to achieve a high gain over a useful operating life of 4,000 hours, and which has a negative resistance to audio frequency signals superimposed on the dc operating current. Fast switching is obtained by an auxiliary photoelectric cathode formed by making an electrical connection to a barium getter flash. Satisfactory tube operationg has been obtained for continuous operation for times which are equivalent to 20 to 40 years of intermittent operation in switching systems.

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