Experimental plasmatron

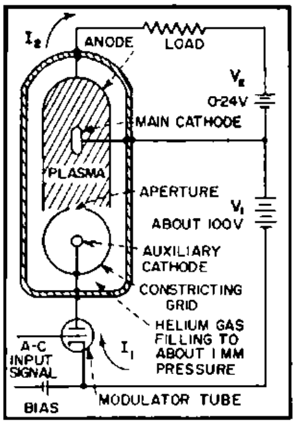


FIG. 1—Tube cross-section and associated external circuit

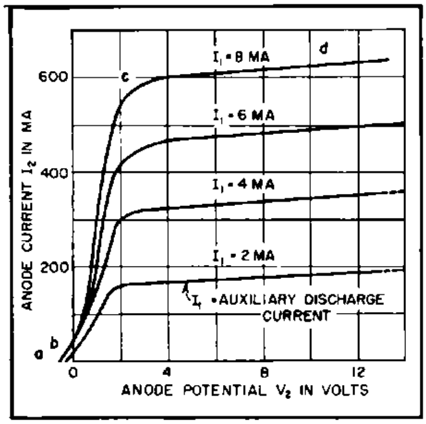


FIG. 2—Current-voltage characteristic with auxiliary discharge current as parameter

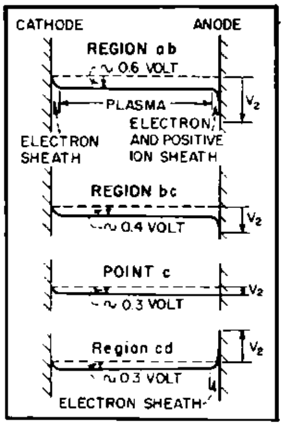


FIG. 3—Potentials between cathode and anode

Controllable Gas Diode

Construction and characteristics of the plasmatron, a hot-cathode helium-filled diode capable of controlling large currents continuously at low voltages. Small control current acts on auxiliary discharge that provides ionization to neutralize space charge

By **E. O. JOHNSON**

RCA Laboratories Division
Radio Corporation of America
Princeton, N. J.

THE TYPICAL grid-controlled vacuum tube, by virtue of its space-charge-limited anode current, is a relatively high-impedance device which is most effective in high-impedance circuits. Since a grid-controlled gas tube such as the thyratron is a low-impedance device as a consequence of its neutralized space charge, it has limited applicability in low-impedance circuits because of its lack of continuous grid control. Need exists for an electron tube which has both the continuous control feature of the vacuum tube and the low-impedance characteristic of the thyratron.

The "plasmatron", a developmental tube, gives good promise of helping to fulfill this need. It operates at anode potentials as low as several volts and has a continuously controllable output current of hundreds of milliamperes.

The tube's name is derived from the word "plasma", which designates a unique part of a gas discharge's anatomy that is instrumental in providing the tube with these unusual characteristics. A plasma[1] is a region which contains high but approximately equal densities of free electrons and positive ions, and is usually evidenced by the familiar glow which can be seen in gas discharge tubes. The charge neutrality plus the high electron density and mobility make the plasma a good conductor of electron current; in addition, this conductivity is proportional to the plasma density. Thus, in the plasmatron, an independently produced plasma is used as a conductor between a hot cathode and an anode. By controlling the small discharge current which generates this plasma, we can effect a continuous control of the plasma conductivity and hence of the cathode-anode current.

A cross-section of a plasmatron tube, accompanied by its associated circuit, is shown in Fig. 1. Potential V_1 creates a discharge between the auxiliary cathode and the main electrodes, giving rise to an auxiliary current I_1 whose magnitude is limited by the modulator tube. This tube is an ordinary vacuum tube such as the 6J5. The discharge is responsible for a high degree of ionization, as manifested by the formation of a plasma in the region between the main cathode and the anode.

The plasma density is enhanced, for any given value of I_1, by forcing the auxiliary discharge to pass through the narrow aperture in the constricting grid. The increase in the plasma density follows from the fact that the constriction in the discharge path raises the voltage drop across the auxiliary discharge. This in turn gives the discharge electrons more energy so that they ionize more effectively.

The free positive ions and electrons in the plasma, generated by the auxiliary current I_1, diffuse to the end micas and other available surfaces where they are lost by recombination. (The recombination of the charged particles in the interelectrode spaces of these structures, at the 1-mm pressure of helium used, is relatively negligible.) The steady-state density of the charged particles in the plasma is then a function of the generation and loss rates and turns out to be approximately proportional to the magnitude of the auxiliary current I_1. Thus the input signal, by exercising an essentially linear control over I_1, can effect an approximately linear control over the plasma density and hence its conductivity.

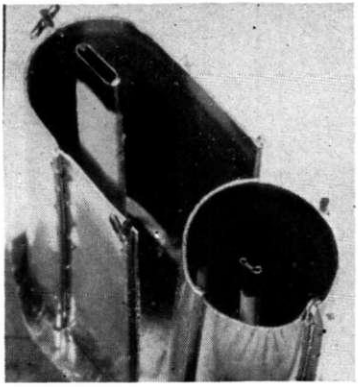
The presence of the plasma in the region of the main electrodes now makes possible the passage of large currents between the main cathode and anode even though the anode voltage may be as low as several volts. Since the effective conductivity of the plasma is directly proportional to its density, the anode current can be controlled by means of the input signal to the grid of the modulator tube.

Anode supply voltage V_2 must never be high enough to cause ionization. This restricts V_2 to a maximum value of about 24 volts when the tube contains helium. Voltages higher than this would result in a discharge between the main cathode and anode in a manner similar to that encountered in an ordinary gas diode. The controlling ability of the auxiliary current is then lost.

The auxiliary cathode is an ordinary oxide-coated cathode with an area of about one square centimeter. However, since it need only supply small currents, it could have been several times smaller in size. The main cathode is also a standard oxide-coated cathode and has an effective area of about three square centimeters. For normal operation the size of this cathode must be sufficient to provide a total emission current which is at least twice the maximum required anode current.

Plasma Behavior

Since the plasma is a good conductor and as such is essentially a uni-potential entity, we need only take into account its behavior at the boundaries where it contacts the anode and cathode surface. At such boundaries the plasma reacts to the electric field from the electrode by setting up a narrow region, termed a sheath, which absorbs this electric field. As a consequence of this protective action the main body of the plasma is not penetrated by the field and so in almost all cases is never appreciably affected by electrode potentials.



Demounted internal structure of plasmatron. Auxiliary cathode is inside cylinder, and oval-shaped main cathode is inside U-shaped anode. Electrode sizes are not critical, and tube works just as well in miniature sizes as in proportions for handling amperes of plate current. Available main cathode emission limits anode current

The sheath contains the field and is characterized by the presence of a considerable net space charge that is comprised of particles in transit to the electrode. These particles can be of either sign depending on the electrode potential. Thus, when the electrode is negative with respect to the plasma most of the electrons will be repelled and the sheath will contain mostly positive ions. The converse is also true.

When the sheath contains particles of one sign, its thickness is related to the potential across the sheath and the particle current through it by the familiar 3/2 power law. For the plane case this is

$$j = \frac{2.33 \times 10^{-6}}{\sqrt{M/m}} \frac{V^{3/2}}{d^2} \qquad (1)$$

Here j is the particle current density in amperes per square centimeter, V is the potential across the sheath in volts, d is the sheath thickness in centimeters, M is the particle mass and m is the mass of an electron.

The magnitude of the current density j is fixed by the plasma density adjacent to the sheath edge and can be expressed as

$$j = Ne\bar{v} \qquad (2)$$

Here N is the particle density in particles per cubic centimeter, e is the electronic charge in coulombs, and $\bar{v}$ is the average particle velocity, due to conditions within the plasma, in a direction normal to the sheath boundary. This velocity can be computed from kinetic theory in terms of temperature and the mass of the particle. For electrons in a typical plasma, $\bar{v} = 7.7 \times 10^6$ centimeters per second. Thus, in our plasma, where $N = 10^{11}$, $j = 10^{11} \times (1.6 \times 10^{-19})\ (7.7 \times 10^6) = 120$ ma per sq cm. For the same volume density of positive ions the current would turn out to be less than a hundredth of this. This follows primarily from the fact that the larger mass of the ion gives it a much smaller value of $\bar{v}$. Consequently, in discussing the plasmatron currents we will deal only with those due to the electrons.

It is important to notice that Eq. 2 implies that the current j is independent of the electrode potential. Thus, if an electrode is made more positive with respect to the plasma the electron current to it remains unchanged.

Current-Voltage Characteristic

A typical current-voltage characteristic is shown in Fig. 2. The characteristic is seen to be very similar in form to that of a pentode vacuum tube. This interesting result can be understood by considering the potential distributions which exist in the tube for different applied anode voltages. Shown in Fig. 3 are the different modes of this distribution which correspond to the various regions *ab*, *bc* and *cd* of the 8-milliampere characteristic.

In region *ab*, the electron current to the anode is negligible because of the large retarding field in the anode sheath. At the cathode we can consider two currents as flowing. One is an electron current from the plasma into the cathode according to Eq. 2. The other is a current from the cathode into the plasma. For equilibrium these must be equal.

Since the total temperature-limited cathode emission current is normally much greater than the first current, a small retarding field, in the direction shown, must appear at the cathode to bring the currents into equality. The resulting potential depression is found to have a magnitude of about one-half volt, the actual value depending primarily upon the total cathode emission and the plasma density.

As the anode potential is raised to put the system in region *bc* of the characteristic, the retarding field at the anode is diminished to the point where a considerable electron current can flow to the anode. This current increases rapidly with voltage, as is shown by the curves. Meanwhile, at the cathode, the retarding field must be less so that more current from the cathode can enter the plasma to supply the drain to the anode. Since the current-voltage relationship at the cathode is of an exponential nature the slight changes in the plasma potential, as indicated in the diagram, are sufficient to account for the large current changes.

When the system is at point *c* the anode has reached plasma potential and collects an electron current whose density is given by Eq. 2. Further increases in anode potential, corresponding to operation in region *cd*, leave the anode current virtually unaffected, as evidenced by the nearly horizontal slopes of the characteristic. These increases in the anode potential will serve only to expand the electron sheath at the anode in accordance with Eq. 1 in which j is given by Eq. 2.

When operation is in this saturated current region the device can be treated as a close-spaced vacuum diode with its cathode at the plasma edge of the anode sheath. The emission current density of this virtual cathode is then given by Eq. 2 and the diode spacing by Eq. 1.

The fact that the point of current saturation does not occur at negative anode voltages, as indicated by Fig. 3, can be accounted for by the contact potential differences acting in the tube along with the potential drop in the plasma.

Current Gain

The relationship between the auxiliary and main currents is shown in Fig. 4. The average slope corresponds to a current amplification of about 90:1 and is seen to be fairly linear. However, if the currents are pushed beyond the point where the retarding field at the cathode is eliminated, the cathode emission approaches the temperature-limited state and the curve saturates to a value equal to the temperature-limited emission current from the cathode.

The relations which express the rate of ion generation and loss in the plasma, in terms of the auxiliary current, fix the value of N in Eq. 2 which determines the anode current. As implied previously, the approximate linearity of the relationship between the currents arises from the fact that N and hence I_2 are approximately linearly related to I_1.

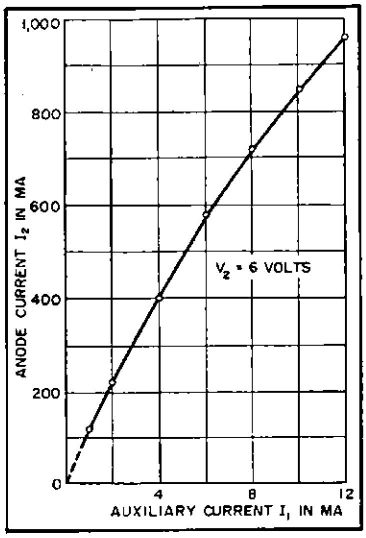


FIG. 4—Current amplification characteristic of new tube

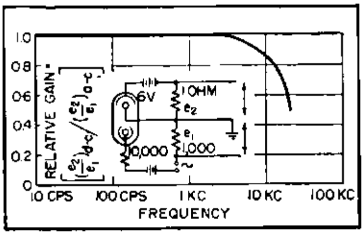


FIG. 5—Frequency response characteristic

The frequency response, normalized to the d-c current amplification, is shown in Fig. 5. The rapid reduction in gain which occurs at frequencies higher than 10 kc can be attributed to the fact that a definite time is required for changes in plasma density to take place. The times involved are determined by the rate of diffusion of the participating charged particles to the available boundary surfaces. This time is comparable to the plasma decay time constant and is readily computable.[2] Its value is such as to account for the observed frequency response. This time constant of plasma decay varies directly as the gas pressure, directly as the square root of the mass of the gas atoms and directly as the square of the geometrical dimensions of the plasma region.

Applications

Experimental forms of the tube have been used with encouraging results in audio output stages with direct speaker drive, in motor control circuits, in oscillators, and in pulse circuits.

Whereas such factors as life and uniformity have yet to be studied in detail, no difficulties beyond those usually experienced in ordinary hot-cathode gas tubes are anticipated. In fact, since the tube is never subjected to the large voltages often experienced by tubes such as thyratrons, it is expected that the gas cleanup and cathode life problems should be relatively simpler. The main cathode seems to be well protected from ion bombardment by the retarding field which exists around it during normal operation.

Summarizing, it can be said that the plasmatron offers excellent promise for low-frequency, low-impedance applications which require a continuously controllable current.

REFERENCES

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(2) M. A. Biondi and S. C. Brown, *Physical Review*, **75**, p 1700, 1949.