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Hollow-cathode discharge characteristics of glow-modulator tubes

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Abstract. The hollow-cathode glow-modulator tube has a cylindrical molybdenum cathode cavity and ring anode. An abnormal glow discharge is formed between these electrodes in a low pressure neon–argon gas mixture to create a high intensity source of light which passes out through the anode. The tube is used mainly in scanning and facsimile equipment.

Impedance–frequency measurements have been made over the range 200 Hz to 6 MHz which at low frequencies have been related to the static voltage–current curves of the discharge. The effects of sputtering over periods up to 200 h have been observed and the cathode cavity has been sectioned and photographed. The results for various depth/diameter ratios are shown, each of which forms a spherical hollow after many hours of operation. The noise characteristics in a 6 kHz bandwidth have been measured over the range 5 kHz to 6 MHz and are explained with reference to the basic gas processes and the impedance characteristics. Identification has been made of the spectral lines from the discharge which are linearly proportional to current for the gas atoms and proportional to current cubed for cathodic atoms.

1. Introduction

The glow-modulator tube is a gas-filled cold-cathode device (figure 1) which is used to provide an intense source of light of small area (Rees 1964). A hollow cathode (crater) is surrounded by a ceramic insulating sleeve and the anode, mounted above the crater, has a central hole through which the light in the blue-violet region of the spectrum passes. The tube operates in the abnormal glow region with a low pressure neon–argon mixture and the light output is modulated by varying the direct discharge current through the tube.

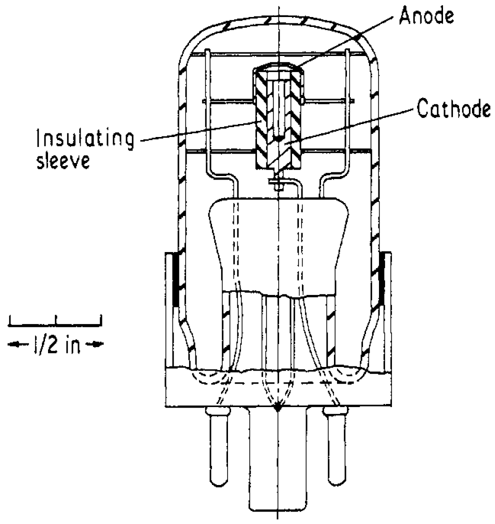


Figure 1. Glow-modulator tube.

The main uses of this tube are with photographic materials in the output stages of telephoto, scanning and facsimile equipment, particularly in systems producing pictures from space vehicles for scientific and meteorological purposes (Myers 1968).

Early work on cold-cathode crater tubes was done by Townsend and Depp (1953) who found that the tube impedance had a negative-resistive component over the voice-frequency range; and for a suitable hollow-cathode effect to occur the hollow should be at least a few times the width of the cathode gap but not too deep, as the glow might not completely fill the hollow unless large currents were used. Allis (1957) produced a theory of the spherical cathode hollow and White (1959), using spherical hollows of typically 1 mm diameter, made measurements of voltage/current and impedance/frequency characteristics. He also showed that, to produce the hollow-cathode effect, a certain amount of overlap must exist between the negative-glow regions from opposite sides of the cathode and that this shape of a spherical hollow was nearly invariant under sputtering.

Musha (1962) further investigated the effect of cathode sputtering on running-voltage–current curves and also found that radiation from the glow was increasingly composed of radiation from cathodic atoms as the discharge current increased. The references to the majority of other work in this field up to 1965 can be found in Sturges (1965) who lists over 200 references in a summary of papers published up to that date.

The results of work presented here include impedance–frequency characteristics over the frequency range 200 Hz to 6 MHz and spectral noise from 5 kHz to 6 MHz together with some optical radiation output curves. The tubes used had cavities 3 mm deep drilled out of $\frac{1}{4}$ inch diameter molybdenum rod and the discharge operated in a gas pressure of a few tens of torr.

2. Measurements and results

Since the impedance–frequency characteristic at low frequencies depends to a large extent on the static characteristic of the discharge, initial measurements were made of the running-voltage–current curves over the useful life of several tubes. A typical result of this

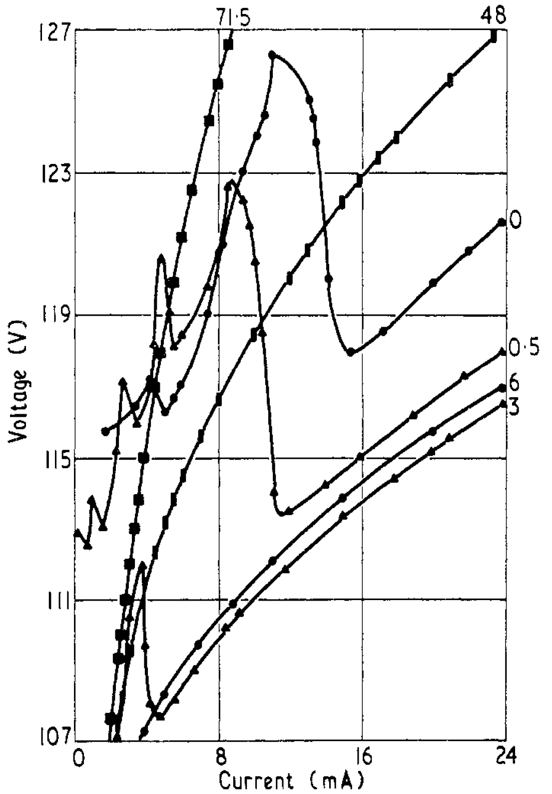
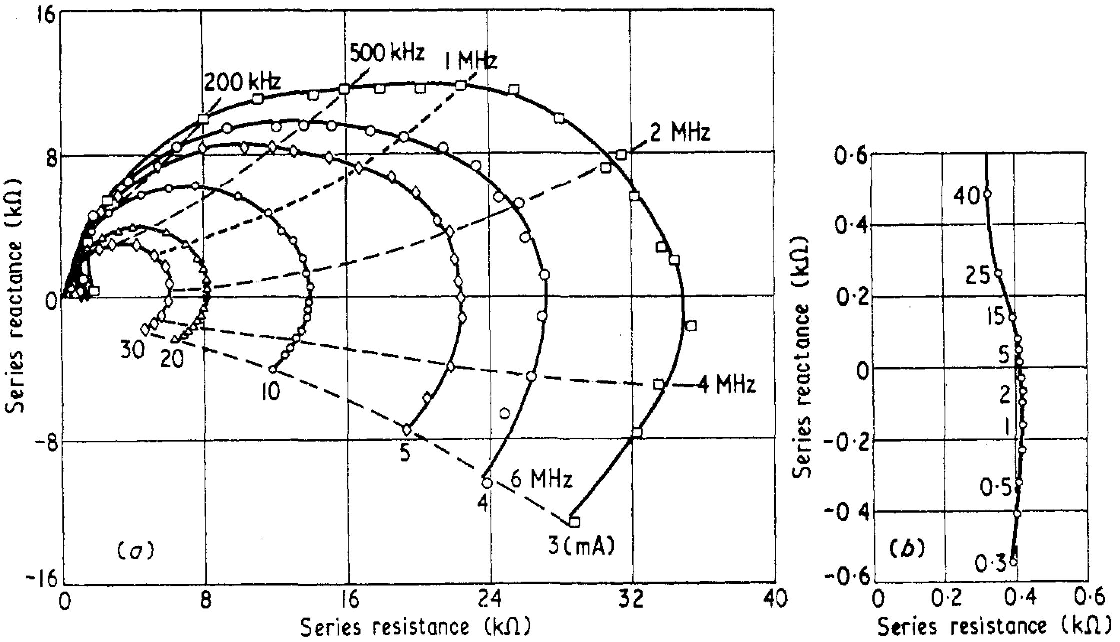


Figure 2. Variation of static characteristic with time. Numbers at limit of curves indicate time in hours.

investigation is shown in figure 2. The tube was run at 20 mA for over 70 h until sputtered material had short-circuited the discharge path.

The discharge impedance measurements were made over the range 200 Hz to 6 MHz using two impedance bridges, as described by Benson and Bradshaw (1965), and the results are shown in figure 3. Before each series of measurements the discharge tubes were run to enable thermal equilibrium to be reached, and, for new tubes, irregularities in the voltage–current characteristic were removed by a somewhat longer operating period. The upper current limit of measurement was within the tube's rated operation and the lower limit, when a normal glow appeared at the rim of the crater, was set by the stability of the discharge.



(*a*) (*b*)

Figure 3. Impedance–frequency loci at several tube currents (mA). (*a*) Broken line indicates line of constant frequency. (*b*) Numbers indicate frequencies in kHz. Tube current is 20 mA.

To test the validity of measurements of impedance made over a period of time, impedance–frequency curves were plotted over the lifetime of several tubes and it was found that cathodic sputtering had very little effect on the characteristics except at low frequencies. Here the low frequency intercept varied by as much as 25 % which was not unexpected since this is closely related to the static characteristic which varied greatly with time. In general at higher frequencies the discharge impedance decreased slightly with tube life.

The spectral noise measurements over the range 5 kHz to 6 MHz were made by a direct comparison method using an A2087 noise-generating diode, operating at a saturated anode current of 6 mA, as the reference noise-voltage source. A detailed description of the technique can be found in Barker and Benson (1966). The results, with reference to a 6 kHz bandwidth, are shown in figures 4 and 5.

Measurements made on tubes with higher pressure fillings than normal showed a decrease of impedance and noise as pressure increased. Although the electrical life of the tubes also increased the optical life was limited by blackening of the glass dome. These tubes and those with deep craters possessed oscillations which seemed to be associated with the formation of an anode fall and the switching of the discharge from the normal to abnormal modes. Thus measurements were limited to those ranges of current not affected by oscillations and as this effect is not normally exhibited in operational tubes a detailed investigation was not carried out.

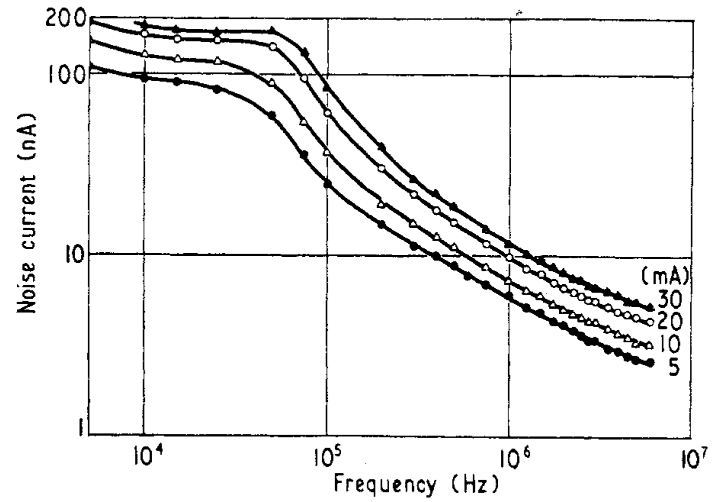


Figure 4. Spectral noise current characteristic at several tube currents (mA).

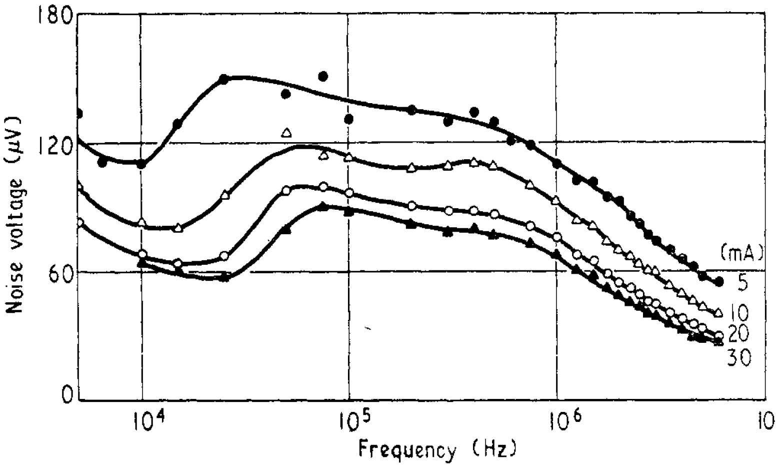


Figure 5. Spectral noise voltage characteristic at several tube currents (mA).

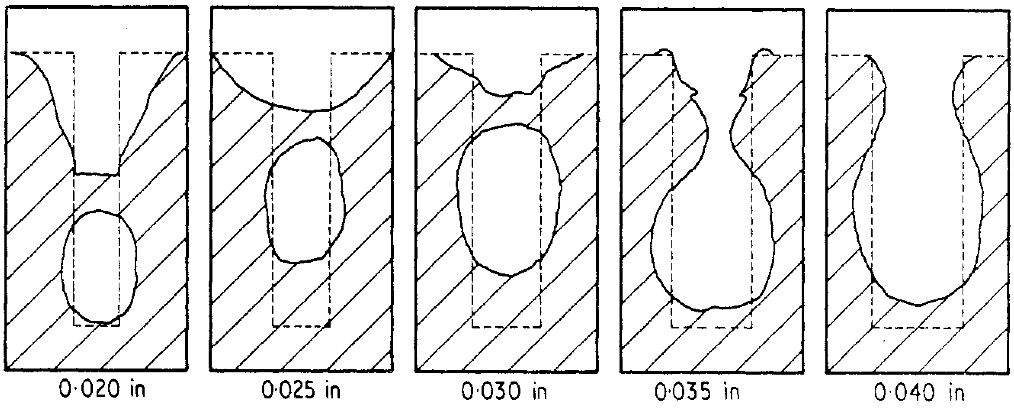


Figure 6. Cavity shapes after 190 h operation at 25 mA. Original cavity diameters indicated; all had initial depth of 3 mm.

An investigation into the crater formation as a function of hole depth (effectively hole depth/diameter ratio) gave the results shown in figure 6. The 0·020 inch diameter cathode crater tube short-circuited after 110 h at 25 mA and all other tubes were run at the same current for 190 h. The corresponding voltage–current curves showed a dramatic rise in running voltage in the latter stages of the sphere development, typically, 122 V constant up to 80 h rising sharply to 142 V after 105 h. This was followed by a slow increase up to 150 V and a 70 h decrease back down to 143 V. Some of the 3 and 4 mm deep holes formed double spheres in sequence before sputtering caused a short circuit.

The radiation measurements were performed on flat-top tubes having a non-dispersive specular surface, identifying the lines by comparison with an iron arc and obtaining the intensity–current characteristics with a monochromator and photomultiplier system. The neon and argon lines investigated were found to be continuous from 30 mA to 0·8 mA discharge current but those of molybdenum virtually disappeared below a few milliamps. This was the current at which the glow came out of the cavity and the discharge operated in the normal mode on the rim of the cathode. Relative intensity against current variations of some gas and cathodic lines are shown in figure 7.

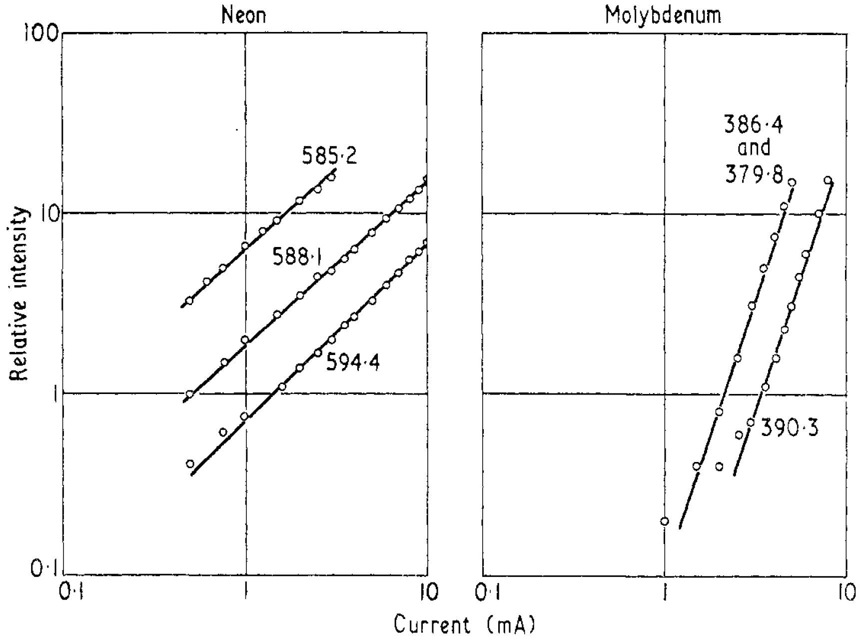


Figure 7. Relative intensity of some neon and molybdenum lines as a function of current. Numbers indicate wavelength (nm).

3. Discussion

The curves of figure 2 show that after 6 h of running all discontinuities in the voltage–current characteristic have been eliminated as the cathode surface has been smoothed out by sputtering. It is clear though that if the slope is measured at low currents during the first few hours of the tube's life then almost any value, positive or negative, could be found. The general decrease in running voltage up to a few hours is due to the stabilization of the discharge observed in normal glows and this is followed by a rapid rise in voltage as the sphere is formed. Before this rise begins, the irregularities in the curves become less with time and thus the sputtering effects are beneficial over the initial period.

Since Townsend and Depp's (1953) investigation many workers have observed a negative component of resistance in the impedance of a hollow-cathode discharge. However, as shown, the low frequency (audio) impedance is very much dependent on the slope of the static characteristic and although not inherent in this type of crater discharge it is possible to find a negative component. It is highly unlikely after some hours of crater formation.

The impedance of the discharge over the range from a few kilohertz to a few megahertz is inductive. The reason for this is that the discrete discharge processes take time to react to a change in applied voltage. If the tube voltage is suddenly increased then this increase will appear across the cathode fall, causing an increase in ionization. The increased number of charged particles will move under the field creating secondary ions and electrons in the gas and at the cathode. All the discrete processes will take a finite time before equilibrium is again reached and these delay times are responsible for the inductive reactance of the discharge. The cathode fall region acts as a capacitance (Benson and Bradshaw 1965) and in an equivalent circuit of the discharge would be in parallel with the inductive delay times associated with the transit times of ions and electrons in this region; hence a capacitive resultant component of impedance at higher frequencies (figure 3(*a*)). The tendency of the impedance to become capacitive at low frequencies cannot possibly be associated with any physical capacitance in the discharge because of its size. A likely explanation is that it is formed by a thermal lag associated with the localized heating of the gas causing expansion and consequent pressure changes.

The noise curves show the characteristic increase of noise voltage with decrease of tube current. This is due entirely to the much greater increase in impedance than decrease in noise current as the tube current decreases. This noise current is formed of three basic noise sources which all have a white spectrum (van der Ziel and Chenette 1957), but these are amplified by the current multiplication processes operative in the discharge. These processes are gradually put out of action as the frequency is increased and thus the noise current falls. At a frequency above the shortest amplification process the noise current will remain at a constant value. This frequency has not been reached in these measurements.

The investigation into the effects of sputtering on the crater shape were completed by sectioning the cathode, polishing and etching before photomicrographs were taken. The results, shown diagrammatically in figure 6, indicated that material removed from the walls of the initially cylindrical crater was deposited at the bottom and top of the forming sphere until closure was effected. The 0·035 and 0·040 inch craters were too wide to close within the time of the experiment, though it is doubtful whether the latter would have closed at all.

The closure of the spherical crater is associated with the steep rise in voltage described in §2. Once the cavity has closed the new glow shape sputters the cathode so that the discharge becomes more efficient and the voltage gradually drops.

The results shown in figure 7 are from the strongest of the neon and molybdenum lines, the argon characteristic being the same as that for neon. The log–log function shows that the radiation from the gas is proportional to current and that from the cathode material is proportional to the current cubed. In the normal working region of the tube the output is mainly in the blue region but at low currents the proportion of red to blue will increase as the glow becomes normal with a possibility of almost total absence of molybdenum radiation. At currents above the tubes rated maximum the radiation continues to increase until the current density forces the cathode glow on to the cathode rim surface and eventually onto the supporting pins. In this condition the light output saturates.

The results shown in figure 6 and those from life/light output measurements have led to the conclusion that a 0·035 inch diameter cavity is about the optimum for this tube running with the stated currents. Lower pressure fillings lead to a much faster closure of the cavity with subsequent end of life by short circuit sputtering while higher pressures give a longer electrical life but blackening of the tube dome by sputtering causes operation failure.

4. Conclusions

The hollow-cathode glow-modulator tube is a highly intense source of light mainly from excitation of the cathode atoms which is proportional to the cube of the discharge current. The cylindrical hollow cathode is a self-destructing form of crater which tends to become spherical under intense sputtering. This sputtering is beneficial in smoothing the non-linear voltage–current curves over the first few hours of operation but can lead to blackening of the optical path and eventual short circuiting of the anode–cathode insulation. The impedance of the discharge is capacitive at very high and low frequencies but within the range of a few kilohertz to a few megahertz appears inductive. The noise current of the discharge decreases with decreasing tube current and with an increase in frequency. The optimum cavity depth to diameter ratio appears to be about $3\frac{1}{2}:1$.

Acknowledgments

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